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WIND ENERGY SYSTEMS

PROGRAM SUMMARY
Fiscal Years 1981 and 1982

U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Office of Solar Electric Technologies
Wind Energy Technology Division
Washington, D.C. 20585

January 1983

Appendix C
Index of Current Contractors

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Wind Energy Systems

Program Summary
Fiscal Year 1984 and 1985

December 1986

Prepared by:
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Under Contract AC02-77-CH00178

Prepared for:
The U.S. Department of Energy
Assistant Secretary
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Washington, DC 20585

A Product of
The Solar Technical Information Program

II. Highlighted Accomplishments by Field Laboratories in FY 1984 and FY 1985

NASA Lewis Research Center

- Developed an **unsteady aerodynamic test facility** for the wind tunnel at Ohio State University to measure airfoil lift and drag under dynamic stall conditions at Reynolds numbers above 1 million.
- Developed **instrumentation systems** to measure the dynamic aerodynamic pressure distribution around an operating wind turbine blade. The systems were used on the MOD-0 and MOD-2 turbines.
- Successfully designed a **wind turbine simulator**, the WEST-3, and bench-tested critical components to verify computational speeds equal to or exceeding those of state-of-the-art computers.
- Tested a **cycloconverter-type**, variable-speed, constant-frequency generator on the MOD-0 wind turbine to a power level of 80 kilowatts.
- Successfully developed and tested **aileron-controlled blades** with a 38% chord aileron on the MOD-0 wind turbine. The system satisfactorily controlled rotor speed and power and provided safe turbine braking.
- Installed and successfully tested an **improved low-speed shaft assembly** and other design improvements on the 2.5-megawatt MOD-2 wind turbine. The experimental three-turbine cluster returned to operation at Goodnoe Hills, Washington (June 1985).
- Generated **over 12 gigawatt-hours of energy on the MOD-2 cluster** after having operated for over 10,000 hours as of November of 1985.
- Established the **DOE/Department of Interior cooperative test program** at Medicine Bow, Wyoming, for a comparative performance evaluation of large, upwind (MOD-2) and downwind (WTS-4) turbine systems.
- Conducted a **national workshop on large HAWT technology** on May 8-10, 1984. The workshop was held in Cleveland, Ohio, and 138 attendees presented 41 technical papers.
- Presented the **MOD-0A Wood Blade Rotor**, measuring 125 feet from tip to tip, for public display in front of DOE Headquarters in Washington, DC.
- Completed final machine **design for the MOD-5A 7.3-megawatt machine** (General Electric) and documented results.
- Began to fabricate **MOD-5B wind turbine hardware**, and began site preparation in Hawaii. Executed a sales agreement with Hawaiian Electric Industries to purchase the prototype Boeing 3.2-megawatt MOD-5B wind turbine.

SERI/Wind Energy Research Center

- Measured the **spectral content of the wake turbulence** downwind of a Medicine Bow, MOD-2 turbine and also at the NOAA Boulder Atmospheric Observatory tower to characterize aeroacoustic and aeroelastic impact on machines located downwind.
- Developed a **new lifting-surface, prescribed-wake performance prediction analysis** for the detailed design of HAWTs.
- Investigated **post-stall airfoil characteristics** using low turbulence wind-tunnel tests for predicting peak power as influenced by blade aspect ratio, airfoil thickness, Reynolds number, and radial flow effects.
- Developed a **simplified dynamics code for a teetering rotor** (University of Utah). WERC researchers conducted tests and analyses to verify this model, and preliminary results were presented at a major industry technical meeting.
- Upgraded and exercised the **FLAP rotor-dynamics code**, and results compared well with experimental data and with predictions made using the MOSTAB code. In FY 1985, researchers made over 25 case runs of the code with various wind turbines, which resulted in additional modifications.
- Synthesized **fixed-pitch airfoils** tailored for HAWT designs to have performance characteristics specifically tailored for enhanced rotor performance.
- Performed **value analyses** for wind turbines in utilities applications; results varied according to fuel mix, load/wind matching, and the spinning reserve requirement for each utility.

- Identified **elastic blade twist** as a possible cause of inaccuracies in present predictions of peak power.
- Intensively tested a **soft-rotor, 10-meter wind turbine** at the WERC for data to enable aerodynamic and structural code verification and cyclical loads analysis.
- Successfully conducted wind tunnel tests on the **special-purpose laminar airfoils** developed in 1984. This demonstrated their suitability to the 10- to 20-meter rotors for which they were designed.
- Predicted the **television interference** created by wind turbines and, with field verification, conducted measurements at Goodnoe Hills, Washington.
- Held **three planning workshops for wind-industry R&D**. The workshops, held throughout the United States in May of 1984, provided an opportunity for the wind industry to participate in federal program planning.
- Held the **seventh wind workshop**, Windpower '85, in partnership with AWEA in San Francisco, California, on August 27-30, 1985. Some 600 representatives from 20 countries attended the meeting, and they presented over 112 technical papers.
- Prepared and published the **Federal Wind Energy Program's five year research plan**.
- Conducted **reimbursed test projects** for industry, including dynamometer tests, system performance tests, and in-the-field blade load measurements.
- Developed a **hybrid multisource energy system** incorporating wind, photovoltaic, battery, and fossil-fuel energy sources. The wind turbine evolved from a high-reliability prototype developed under DOE sponsorship (see Figure 7).
- Formed the **SERI Wind Energy Research Center (WERC)** from the former SERI and Rockwell International wind energy programs.

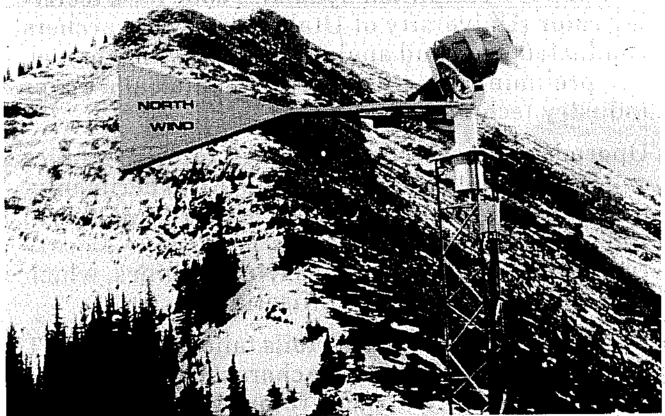

Figure 7. This multiple-source hybrid system powers an ultrahigh-reliability translator and repeater station for low-power (50-watt) television. The wind turbine evolved from a prototype developed under DOE funding at the Wind Energy Research Center, which receives and analyzes performance data.

Pacific Northwest Laboratory

- Adapted a **three-dimensional, mass-consistent, wind-flow model** as a basis for preliminary research on flow modeling in complex terrain for micrositing.
- Developed **computerized shaded relief displays** using gridded terrain data to allow the indirect visual inspection of terrain complexity at a prospective turbine site.
- Analyzed the data taken at Clayton, New Mexico, for a **vertical-plane anemometer array**. Data were analyzed in the rotating frame to be incorporated into a model of wind experienced by a rotor.
- Tested **hot-film anemometers** to be used on the blade of a MOD-2 turbine with the measured response of the turbine rotor.
- Tested a **nonintrusive, time-of-flight laser anemometer** for measuring two-dimensional winds in a small-sampling-volume plane with a range that extends beyond the maximum height of any possible blades.
- Completed an **updated national summary wind energy resource atlas** for the United States and its territories (see Figure 8).
- Completed the **6-month collection of wind data from anemometers** elevated at 105 feet in 9 locations for flow mapping within the MOD-2 site at Goodnoe Hills, Washington.
- Analyzed **MOD-2 wakes** from the 1982 turbine power data and meteorological tower wind data.
- **Developed a micrositing model** using the existing NOABL flow merged with an optimization scheme. This allows the model to determine from a few wind measurements the optimum parameters of atmospheric stability and general wind direction, which were formerly required as user-estimated input to the model.
- **Tested the micrositing model** with data supplied by wind farm developers under cooperative, no-exchange-of-funds agreements.
- Developed a **matrix of wake cases** from data collected in FY 1985 at the MOD-2 site in Goodnoe Hills, Washington.
- Reported on **rotationally sampled turbulence time series**, and also on **spectra theory, simulation, and verification**.
- Prepared for installation a **microscale turbulence-measurement tower**, with seven levels of anemometry, to be located 1.75 rotor diameters upwind of the WTS-4 at Medicine Bow, Wyoming.
- Completed the **basic design of a ring array of anemometers** for use with the 34-meter Darrieus test bed. This was a joint effort with Sandia and the U.S. Department of Agriculture (USDA).

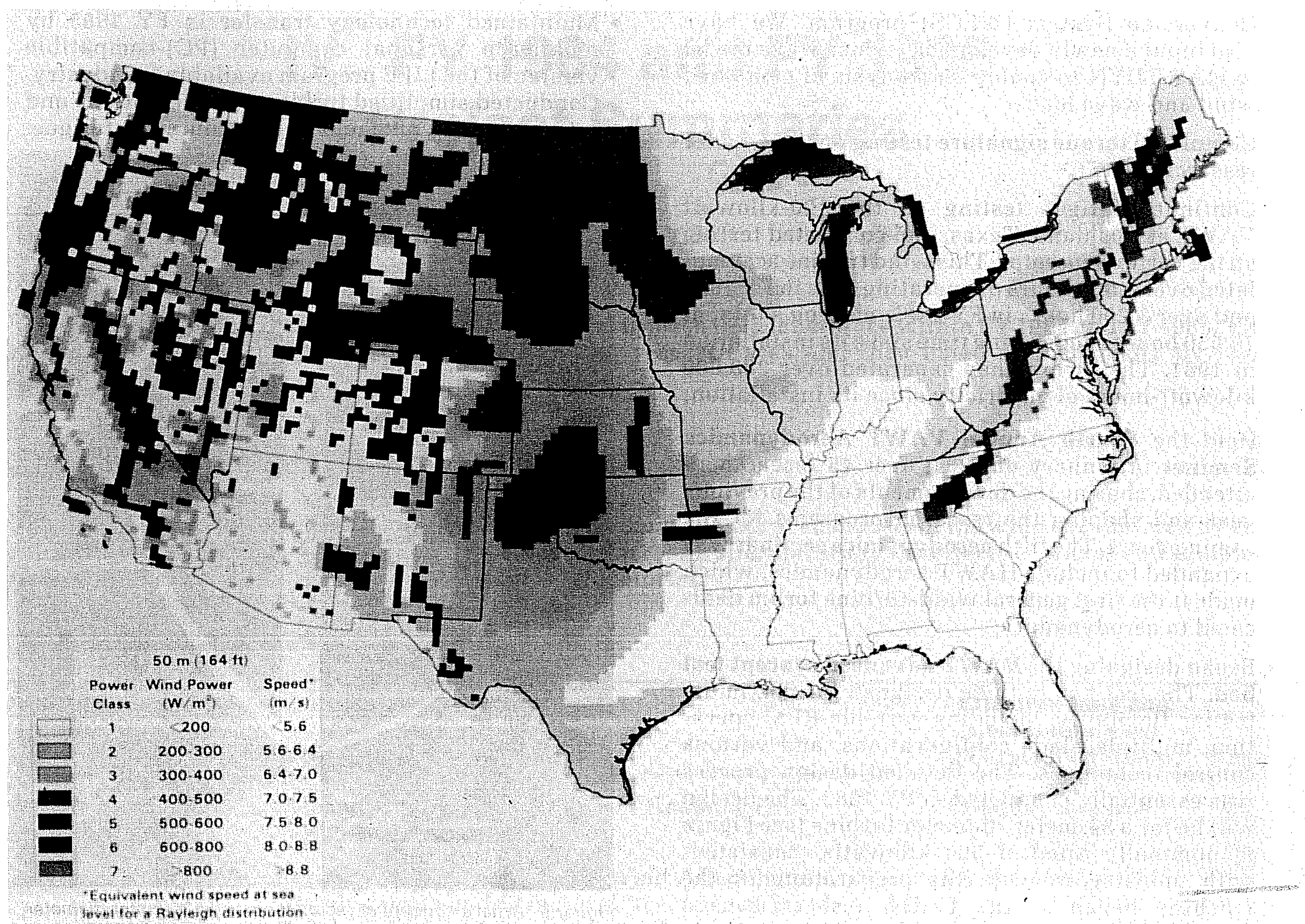

Figure 8. Wind resources in the United States.

Sandia National Laboratories

- Updated the **unsteady airfoil model**, USTAR2, using a linearly varying vorticity (distribution versus the lumped vorticity previously used). This new method has shown marked improvement in model results for predicting the aerodynamic loads used to input structural models.
- Developed an **independent double multiple streamtube model (INDOMS)**, which allows streamtube interference factors to more accurately model the actual turbine flow field.
- Tested **natural laminar flow baldes** on the center section of the 17-meter research VAWT for passive stall control and research on increased energy-conversion efficiency. Initial test data indicate that performance is following predictions.
- Began **dynamic-stall tunnel testing** for performance data on both National Advisory Committee for Aeronautics (NACA) and special laminar flow airfoil sections.
- Tested **blade-perforation geometries** in the wind tunnel to determine an optimum design for pumped-spoiling stall control.
- Conducted **tests on flow visualization** on the 17-meter research VAWT to determine blade air-flow separation characteristics under normal operating conditions. Testing of the hybrid natural laminar flow blade on the 17-meter research VAWT continued through FY 1985 in conjunction with the aerodynamic performance testing.
- Modified the **NASTRAN-based FEEVD computer program finite element procedure** for determining rotor stresses to accommodate hybrid conventional/natural laminar flow blades. Also incorporated aeroelastic effects into the FEVD and FEEVD VAWT programs.
- Updated the **HAWTDYN model** (the NASTRAN-based, stress determining procedure adapted to HAWTs) to include a teetered hub, yaw-spring inputs, and stochastic winds. The model has also been applied to the IEA offshore Wind Energy

Conversion System (WECS) program. We have also input a newly developed random-wave model to HAWTDYN to enable an analysis of combined wind and wave loads.

- Completed **torque signature testing** on the 5-meter research VAWT.
- Continued **fatigue testing** on the 100-kilowatt VAWT at Bushland, Texas, and completed testing on the vortex generator. This wind turbine accumulated over 2,000 hours of operating time in FY 1984 and over 3,200 hours in FY 1985, making a total of 10,550 hours of operating time since its installation in 1981. The turbine has generated over 288,000 kilowatt-hours of electricity since its installation.
- Held the **Fourth Annual VAWT Aerodynamics Seminar** in January of 1984; over 45 researchers attended, sharing the developments of the previous year and shaping the research programs for the coming years. The fifth aerodynamics seminar was expanded to include HAWT aerodynamics, which made it the first general wind-turbine forum dedicated to aerodynamics.
- Began designing the **VAWT advanced concept test bed**. The test bed is to be designed for maximum testing flexibility, including variable-RPM operation, multiple blade configurations, and various control techniques. The detailed design process was essentially completed in FY 1985. The design will be for a 34-meter diameter turbine (see Figure 9) nominally rated at 500 kilowatts (consistent with industry trends). Site preparation for the machine began at the USDA test station at Bushland, Texas.
- Maintained **technology transfer** in FY 1985 by making a personal computer (PC)-compatible version of the LIFE program available to industry. Conducted simplified turbine life evaluations and fatigue testing, and held a short course on fatigue.

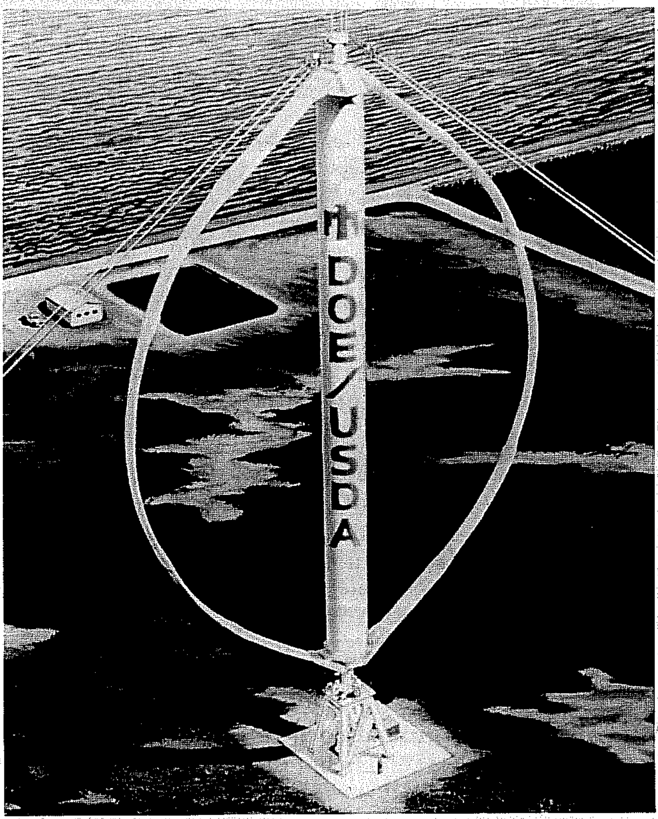

Figure 9. Artist's concept of the experimental 34-meter diameter, vertical-axis wind turbine at the USDA site in Bushland, Texas.

III. Future R&D Role

As described in the wind energy five year research plan, the Federal Wind Energy Program will continue to focus on the basic science of wind turbine dynamics to understand the nature of the wind, the wind's complex interaction with the wind turbine, and the effects of this interaction on the wind turbine's design. Research on advanced components and systems will focus on such areas as identifying and testing high-performance airfoil concepts designed specifically for wind turbines.

The Federal Wind Energy Program is designed to take advantage of a strong partnership with industry, whereby industry can ultimately achieve the long-term goal of developing broadly competitive wind machines and self-sustaining R&D capabilities of its own. Therefore, program research activities will help build a technology base that will be transferred to industry. Industry can then use these new design tools and advanced concepts to reduce costs, improve performance, and increase system lifetime.

To ensure that these tools and concepts are properly applied, a Wind Technical Assistance Center is being contemplated to provide technical support to developers on a quick-response basis.

IV. FY 1984 and FY 1985 Project Summaries

This section summarizes all of the projects conducted by each field laboratory within FY 1984 and FY 1985. The summaries are grouped by individual wind-energy research area and then listed alphabetically by field laboratory affiliation.

Atmospheric Fluid Dynamics

The objectives of Atmospheric Fluid Dynamics are to develop improved models of the wind encountered by the rotor, develop improved models of atmospheric flow across a site, and study the effects of wakes and complex terrain. Refer to Appendix A for the individual laboratories.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
Pacific Northwest Laboratory (PNL)	Measure and Analyze Wakes at Goodnoe Hills	In-house research	22
PNL	Rotational Measurements of Wind Affecting the Aerodynamics and Structural Response of Wind Turbines	In-house research	23
PNL	Models of Turbulent Wind Characteristics Seen by a Rotating Turbine Blade for Large and Small Wind Turbines	In-house research	25
PNL	Energy Capture and Airflow Near Turbine Rotors	In-house research	26
PNL	Improved Methods of Rotationally Sampled Wind Measurements	In-house research	27
PNL	Theory of Rotationally Sampled Wind	10/84 — $114,000	28
PNL	Goodnoe Hills Flow Experiment	10/84 — $162,000	30
Colorado State University	Modification of Turbulent Airflow Near Rotor	10/84 — $40,000	32
National Oceanic & Atmospheric Administration	Analysis of Rotational Sampling Measurements from Doppler Lidar Anemometers	8/83 — $38,000	34
Michigan State University	Turbulent Wind Velocity Profiles at a Coastal Sand Dune Site	10/84 — $21,000	35
University of Massachusetts	Tethersonde and Kite Anemometer Evaluation	5/85 — $19,000	36
PNL	Site Wind Variability Characterization	10/84 — $27,500	37
PNL	Flow Characterization at Wind Turbine Sites	In-house research	39
PNL	Shape and Size of Turbulent Eddies	10/84 — $27,000	40

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
PNL	Measured Rotationally Sampled Wind	10/84 — $116,000	41
Solar Energy Research Institute (SERI)			
Rockwell International	MOSTAB Parametrics and Comparison Study	10/83 — $175,000	50

Aerodynamics Research

The objective of Aerodynamics Research is to investigate the dynamic interaction between atmospheric flow and the turbine rotor, which would enable the development of accurate models for predicting performance and loads under all operating conditions.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
NASA Lewis Research Center (NASA LeRC)	Three-Dimensional Aerodynamic Flow Regimes over Rotor Airfoil Surfaces	In-house research	94
Aerovironment, Inc.	Rotor Blade Tip Configurations	9/82 — $168,707	96
Ohio State University	Measurements of Lift and Drag Coefficients of Airfoils in Stalled Flow Conditions at High Reynolds Numbers	9/82 — $360,000	97
NASA LeRC	Rotor Blade Surface Roughness Effects on Performance	In-house research	99
Oregon State University	Performance Modeling for Horizontal-Axis Wind Turbines: Supplement Dynamic Stall	7/83 — $21,000	100
Oregon State University	Improvements in PROP and VORTEX Wake Codes for Calculating Rotor Performance	4/84 —$80,000	101
NASA LeRC	Control of Wind Turbine Rotors Through the Use of Aileron Controls	In-house research	102
Wichita State University	Development of Airfoil-Trailing Edge Surfaces for Rotor Control	9/79 — $751,000	104
Wichita State University	Measurements of Lift and Drag Coefficients of Airfoils in Stalled Flow Conditions at Low Reynolds Numbers	9/79 — $751,000	106
NASA Langley Research Center	Acoustic Emission of Wind Turbines	Interagency agreement	107
NASA LeRC	Energy Capture Characteristics of Various Sized Rotors Having Full and Partial Span Control Surfaces	In-house research	108
NASA LeRC	Rotor Airfoil Control Surface Effects on Systems Response in Turbulent Flow	In-house research	109
NASA LeRC	Rapid Yaw Maneuver Effects on System Response in Turbulent Flow	In-house research	110
Sandia National Laboratories (SNL)	Analytic Models — Aerodynamic Research	In-house research	74
SNL	Vortex Generators (VAWT)	In-house research	75

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
SNL	Laminar Flow Section Testing 17-m	In-house research	76
SNL	Controller/Algorithm	In-house research	77
SNL	Technology Transfer	In-house research	89
Ohio State University	Dynamic Pitch Testing	9/83 — $200,000	78
Solar Energy Research Institute (SERI)	WECS Aeroacoustics Research	In-house research	51
Aerovironment, Inc.	Blade Element/Momentum Performance Code	10/82 — $307,000	52
Computational Methodologies, Inc.	Lifting-Surface/Prescribed-Wake Performance Code	10/82 — $243,000	53
Airfoils, Inc. and University of Utah	Advanced Airfoils Development	9/82 — $336,000	54
Texas A&M University	Airfoil Testing	10/82 — $265,000	55
Oregon State University	Yaw Stability and Induced Loads	10/82 — $202,000	56
SERI	Spectral Characterization of MOD-2 Wake	2/85 — In-house research	57

Structural Dynamics

The objective of Structural Dynamics research is to develop accurate models of the stresses induced by unsteady loads and understand the effects of these stresses on component lifetime.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
NASA Lewis Research Center (LeRC)	Variable-Speed Generator Effects on Drive Train Torsional Flexibility, Damping, and Dynamic Response Near Resonance	1/82 — In-house research	111
Oregon State University	Wind Turbine Structural Design and Analysis	6/80 — $129,000	112
Cleveland State University	Wind Turbine Performance, Dynamic Loads, and Economics Analysis	2/80 — $641,950	113
NASA LeRC	Integration of Rotationally Sampled Wind Harmonics with Influence Coefficients Obtained from Digital Simulation to Produce Dynamic Rotor Loads	In-house research	114
NASA LeRC	Real-Time Domain Hybrid Simulation — WEST-1 and WEST-2	In-house research	115
Paragon Pacific, Inc.	Real-Time Domain Hybrid Methods for Simulations of Systems Influenced by Transient Mass Flows and Correlation with Experimental Data	10/81 — $763,121	116

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
NASA LeRC	Exposure Test of Wood Blade Section	In-house research	117
Gougeon Brothers, Inc.	Ninety-Foot, All-Wood Rotor	9/81 — $718,995	118
University of Dayton Research Institute	Wood Fiber Veneer/Epoxy Resin	3/82 — $89,500	119
Applied Technology Lab, U.S. Army	Fort Eustis Fatigue Test	2/83 — $10,000	120
IIT Research Institute	Rotor Sub-Structures Subjected to Ultra-High Cyclic Loading and Effect on Crack Initiation and Propagation	10/81 — $158,412	121
NASA LeRC	Response of Variable Rotor Speed on One-, Two-, or Three-Bladed Rotors on Near Aerodynamic Stall Conditions	In-house research	122
Sandia National Laboratories (SNL)	Analytic Models — Structural Research	In-house research	79
SNL	Fatigue Life Evaluation	In-house research	80
SNL	Fatigue Life	In-house research	81
SNL	Fatigue and Braking Experiments	In-house research	82
SNL	Wake Characterization	In-house research	83
SNL	Advanced Analytic Models — Structural Research	In-house research	84
Solar Energy Research Institute (SERI)	MOD-2 Structural Response Analysis	10/83 — $513,000	58
SERI	Structural Response Testing	2/85 — $140,000	59
SERI	Fatigue Estimation Under Spectrum Loads	2/85 — $193,000	60

Advanced Concepts Research

The objective of Advanced Concepts Research is to develop the technology base necessary to achieve major improvements in machine cost, performance, and lifetime. This category involves activities in advanced concepts research, supporting research, applied technology testing and analysis, and multimegawatt systems.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
Pacific Northwest Laboratory	Applications Testing of Advanced Remote Sensing Systems	In-house research	43
Sandia National Laboratories (SNL)	New Advanced Research Test Bed	In-house research	85
SNL	Advanced Airfoils	In-house research	86

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
Solar Energy Research Institute (SERI)			
Rockwell International	Variable-Speed, Generator System Implementation and Control	10/82 — $1,789,000	61

Supporting Research

The objective of Supporting Research is to provide the tools, assessments, and data necessary for users to make informed decisions about wind technology.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
Pacific Northwest Laboratory (PNL)	SWECS Wind Farm Flow and Wake Analysis	In-house research	44
PNL	Wind Turbine Array Correlation Analysis and Model Testing	In-house research	46
PNL	Wind Energy Data Assimilation and Resource Verification	In-house research	47
NASA Lewis Research Center (LeRC)			
Michigan State University	Effect of Accuracy of Wind Power Prediction on Power System Operation	4/83 — $139,647	123
Fairchild Weston Systems	Wind Energy Remote Data Syctem Operational Data	9/76 — $3,292,000	124
Oregon State University	Improvements in Prop and Vortex Wake Codes for Calculating Rotor Performance	4/84 — $80,000	101
Sandia National Laboratories (SNL)	Offshore WECS (HAWT)	In-house research	88
RANN Incorporated	A Comparative Analysis of the Aerodynamics and Structural Dynamics of Wind Energy Turbine Systems	9/82 — $232,000	90
New Mexico Engineering Research Institute	Special Research and Development/Wind Energy	9/81 — $197,269	91
Solar Energy Research Institute (SERI)			
University of Michigan	Electromagnetic Interference by Wind Turbines	8/81 — $159,000	62
SERI	WECS Performance and Value Analysis	In-house research	63

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
SERI	Wind-Diesel Hybrid Research	2/85 — $146,000	64
Regional Systems Services Group, Inc.	WECS Applications in Non-Generating Utilities	3/79 — $219,000	65
Rockwell International and American Wind Energy Association	Support to Industry Standards Development	10/83 — $358,000	66
Oregon State University and University of Utah	Rotor Code Refinement and Validation	10/82 — $676,000	67
Rockwell International	Systems Analysis Research	10/82 — $547,000	68

Applied Technology Testing and Analysis

The objectives of Applied Technology Testing and Analysis are to provide test facilities and support collaborative efforts between industry and government to field test industry machines in support of general wind energy R&D.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
Solar Energy Research Institute (SERI) and Rockwell International	Industry Cooperative Test and Analysis — Operating Rocky Flats Wind Energy Research Center	In-house research	69
SERI	Cooperative Field Test Program	2/85 — $735,000	70
SERI	Historically Black Colleges and Universities Project	9/83 — $420,000	71

Multimegawatt Systems

The objectives of Multimegawatt Systems research are to complete the design, construction, and test phases of the MOD-5B, and to continue to document performance and loads to better determine how fundamental processes relate to machine scale.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
NASA Lewis Research Center			
Boeing Aerospace	Goodnoe Hills Multimachine (MOD-2) Research Testing	4/84 — $3,419,000	125

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1985)	Page
Boeing Aerospace/ PNL/BPA	Multimachine Dynamic Response and Aerodynamic Wake Effects on Utility Network and Machine Performance (MOD-2)	In-house research	126
Bureau of Reclamation — Lower Missouri Region	Medicine Bow Multimachine (WTS-4/MOD-2) Research Testing	7/84 — $600,000	127
General Electric	Design, Fabricate, and Install Advanced Multimegawatt Wind Turbine (MOD-5A)	9/80 — $28,000,000	128
Boeing Aerospace	Design, Fabricate, and Install Advanced Mutlimegawatt Wind Turbine (MOD-5B)	9/80 — $39,550,000	129
Boeing Aerospace	Design, Fabricate, and Test Three Experimental, 300-Foot Diameter Wind Turbines (MOD-2)	8/77 — $40,893,000	130

Appendix A
Index of Contractors

Appendix B
List of Acronyms and Abbreviations

ALO	Albuquerque Operations Office
ANSI	Americal National Standards Institute
ASES	Americal Solar Energy Society
ASME	American Society of Mechanical Engineers
ASTER	aeroelastic stability of a teetering rotor
ASTM	Americal Society for Testing and Materials
AWEA	American Wind Energy Association
COO	Chicago Operations Office
DOE	Department of Energy
DOE/HQ	Department of Energy Headquarters
DOI	Department of Interior
EPRI	Electric Power Research Institute
FEEVD	forced finite element VAWT dynamic code
FEVD	finite element VAWT dynamic code
FLAP	structural dynamics code
FWEP	Federal Wind Energy Program
FY	fiscal year
HAWT	horizontal-axis wind turbine
HBCU	historically black colleges and universities
Hz	hertz
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
kW	kilowatt(s)
kWh	kilowatt hour(s)
LeRC	Lewis Research Center (NASA)
MOD-0,(1,2,5)	"Model" 0, (1,2,5) experimental wind turbine
MOSTAB	modular stability derivative program
MW	megawatt(s)
NACA	National Advisory Committee for Aeronautics (predecessor to NASA)
NASA	National Aeronautics and Space Administration
NASTRAN/FFEVD	forced finite element VAWT dynamic code
NLF	natural laminar flow
NOAA	National Oceanic and Atmospheric Administration
NOABL	new objective analysis boundary layer
OSU	Oregon State University
	Ohio State University
	Oklahoma State University
PNL	Pacific Northwest Laboratory
PROP	aerodynamic prediction code
PROPSH	aerodynamic prediction code
Q	quarter (of the fiscal year)
R&D	research and development
RPM	revolutions per minute
SEACC	systems engineering and analysis computer code
SERI	Solar Energy Research Institute
SNL	Sandia National Laboratories
SNLA	Sandia National Laboratories, Albuquerque

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Wind Energy Systems

Program Summary
Fiscal Years 1986 and 1987

October 1988

Prepared by:
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Prepared for:
The U.S. Department of Energy
Assistant Secretary
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A Product of:
The Solar Technical Information Program

II. Highlighted Accomplishments by Field Laboratories in FY 1986 and 1987

Pacific Northwest Laboratory

- Tested a **theoretical model** that simulates time series of winds experienced by a point on a rotating blade. The model was found to be accurate in tests against hot-film anemometer measurements for VAWT cases.
- Distributed an IBM PC version of the **STRS-2 wind model** for first review and revision.
- Made **hot-film anemometer measurements** from multiple points on a rotating boom to provide phase relationship information to be used in developing a multipoint theoretical model. With the much-improved apparatus, the first two-point, three-dimensional turbulence measurements were made from a rotating boom. Improvement also began on the speed and angle ranges for which hot-film anemometers are understood.
- Conducted **smoke visualization tests** in a wind tunnel with a model wind turbine to examine the induction physics phenomena. The first research on rotor airflow induction on a model wind turbine was completed and reported.
- Collaborated with SERI to establish **two vertical-plane arrays and one single-tower array** in front of Cooperative Research Program (CRP) wind turbines. Resultant data were analyzed.
- Conducted **kite and balloon measurement tests**, which showed that, except under conditions of light or small-scale turbulence, significant errors in turbulence measurements are made by these systems.
- Performed **verification tests** of a micrositing model, which showed root-mean-square (RMS) errors on the order of 5% for velocity and 10% for power estimates. The model consisted of the NOABL flow model combined with a mathematical optimization scheme.
- Tested **a micrositing model** to the point that it was deemed ready for application and further testing in the wind-energy community. The model consisted of the NOABL flow model combined with a mathematical optimization scheme.
- Completed the **user's guide** for the micrositing model for applications testing.
- Analyzed the **flow variability over the MOD-2 site** at Goodnoe Hills, Washington, from the synoptic data file that was created from wind measurements from nine towers and power measurements from the three turbines. The results indicated generally low spatial variability for time-averaged conditions.
- Developed a **new technique of collecting wind measurements** from anemometers mounted on a beam suspended in a wind turbine wake. The technique was successfully tested in a wake model-validation experiment.
- Prepared a **wind energy resource update** for the Caribbean region for the CORECT program.
- Participated in the **technical evaluation of proposals** to the Cooperative Field Test Program (CFTP) managed by SERI, and provided technical monitoring assistance on several of the projects involving micrositing and wake research.
- Provided consulting assistance on the design of a **wind-measurement strategy**, and also on the towers and anemometers, to conduct the measurements for several CFTP projects designed to measure wind turbine response.
- Organized and conducted a **DOE Workshop on Micrositing and Wind Turbine Wakes** for 60 participants on March 9-10, 1987, in Livermore, California.
- Developed a technique for **graphical analysis of eddy flow structure**. Preliminary analyses showed a well-organized structure over a wide range of time and space scales.

SERI/Wind Energy Test Center

- Refined the **PROPSH aerodynamic prediction code** to include dynamic stall effects.
- Initiated a major **University Participation Program** by awarding subcontracts to Ohio State University (for airfoil tests), the University of Utah (for a yaw control study), and Oregon State University (for aerodynamics research).
- Completed intensive **dynamic-response testing** of the Hamilton Standard WTS-4 wind turbine at Medicine Bow, Wyoming. Data correlating wind input characteristics with rotor structural loads and strains were collected in a wide range of wind speeds up to 60 mph.
- Continued to refine the **Force and Loads Analysis Program (FLAP)** structural-dynamics code to include teetering-hub effects and predicted teetered rotor loads in nonturbulent winds within 10% of measurements. This code was exercised, and the results were compared with blade load and dynamics data collected from the WTS-4 wind turbine.
- Incorporated a **new turbulence subroutine** in the FLAP structural-dynamics code and began the validation process.

- Completed **wind-tunnel tests** of the primary airfoil of an advanced family of thin airfoils for wind turbines. The wind-tunnel test results verified the desired improvement in the airfoil's performance over those commonly used by wind turbine designers. SERI transmitted preliminary data to DOE and AWEA for industry peer review.
- Issued and received responses to a competitive solicitation for **atmospheric tests of the thin-airfoil family**. A technical evaluation of the proposals was completed; two awards are anticipated in early FY 1987 for testing to confirm the theoretical and wind-tunnel-predicted performance improvements.
- Performed testing on **a slip-recovery variable-speed generator and a cycloconverter variable-speed generator** on the MOD-0 test bed; completed 16 test programs that comprised over 200 hours of operation. Reduction and analysis of the data is proceeding.
- Prepared and received preliminary approval of a **comprehensive plan** for a cooperative SERI/industry variable-speed test program.
- Provided initial cooperative technical support to **industry aeroacoustics measurements** at the U.S. Windpower wind farm at Altamont Pass.
- Requested, received, and evaluated proposals resulting in four major subcontracts and cooperative agreements under the **SERI Wind/Diesel Research Initiative**.
- Designed and issued a subcontract for fabricating an advanced, state-of-the-art, pulse-code modulated (PCM), research-grade **instrumentation system** capable of collecting and processing up to 164 channels of high-quality research data.
- Developed a **field-grade data-acquisition system (DAS)** and checked it successfully in bench tests. The inexpensive and portable system uses a small personal computer with a Keithley DAS Model 500 analog-to-digital converter. It will be used in cooperative research programs, particularly those that involve data collection at industry wind farms.
- Initiated the **Cooperative Field Test Program** with industry by assisting DOE in the award of 10 cooperative agreements. The research tests include dynamic-response measurements (performed by Southern California Edison, Westinghouse, and Northern Power Systems), siting issues (investigated by FloWind, Fayette Manufacturing, and Altamont Energy Systems), and the effects of precipitation on performance (studied by Pacific Wind Energy).
- Planned and completed two **cooperative dynamic-response tests** with (1) Southern California Edison on the J. Howden 330-kW wind turbine in cooperation with PNL, and (2) the Westinghouse 600-kW wind turbine in Hawaii.
- Assumed responsibility for operating and managing the **DOE MOD-0 and MOD-2 wind turbines** and the associated supporting subcontractors.
- Initiated four **user-designated facility** projects with industry participants; the projects include wind-systems atmospheric tests, dynamometer tests of drive-train components, analytical work, and support to acoustic noise-measurement programs.
- Continued technical and financial support to **AWEA industry standards development** in cooperation with the American Society for Testing and Materials (ASTM).
- Conducted a successful **Performance Measurements Workshop** to provide guidance for revising the AWEA performance testing standard. The working meeting was attended by 28 representatives of manufacturers, wind farm operators, and research organizations.
- Determined experimentally that **blade elastic twist** is not a cause of error in power and loads prediction.
- Brought Phase I of the **Combined Experiment** to its final development stages. This experiment will provide the first integrated look at how the wind turbine rotor responds to wind input, using advanced testing techniques formerly used in helicopter research.
- Published the **lifting-surface, prescribed-wake aerodynamic prediction code**, which provides wind turbine designers and researchers with a powerful, highly accurate PC-based tool for predicting performance and loads.
- Established a **major cooperative link with Sandia National Laboratories** to plan and implement a broad-based fatigue analysis and prediction program.
- Collected substantial **dynamic-response data** on a third test involving the Northern Power Systems (NPS) 125-kW wind turbine installed on a wind farm near Livermore, California.
- With Airfoils Inc., **refined the first family of special-purpose airfoils** designed for wind turbines. The airfoils are predicted to increase performance by 10% and improve the operational characteristics of current wind systems by restraining peak power and providing relative insensitivity to roughness effects caused by insect soiling and blade surface wear.
- Sponsored a well-attended course in **using the Eppler airfoil design code**. The course, attended by key industry designers and university researchers, marked the first time that this important code was made generally available to the U.S. research community.
- Monitored two SERI subcontracts to **fabricate and test the new SERI airfoil families**, as they neared the blade fabrication phase at the end of FY 1987. The atmospheric tests will be made side by side with older airfoils and have already provided improved hub-root attachment designs to help eliminate a series of composite blade failures.
- Coordinated the successful **Windpower '87 conference** (the seventh biennial wind energy conference and workshop) in cooperation with AWEA and ASME.
- With **newly developed instrumentation systems**, obtained state-of-the-art home- and field-based wind research instrumentation capabilities. These systems include an advanced, state-of-the-art, PCM research-grade instrumentation system and a field-grade (midscale) DAS, which were used successfully in cooperative research field tests of the Westinghouse 600-kW and NPS 125-kW wind turbines.

NASA Lewis Research Center

- Received **all major hardware for the 3.2-MW MOD-5B wind turbine** at the installation site on Oahu, Hawaii. The foundation was installed, and the 200-foot tower was erected. Full-scale pitch testing of the blade tips and controls was completed. First rotation came on July 1, 1987, and first power production came later in July. After the 500-hour acceptance testing was completed, the turbine was sold to HERS in January 1988. To date, the MOD-5B has performed better than the design estimates. By the end of March 1988, the turbine had produced 2,643,000 kWh of electricity during 2,400 hours of operation, thereby saving 4,400 barrels of oil.
- Reconfigured the MOD-0 unit to the **two-blade configuration**; this was required by the research tests proposed by SERI following the Westinghouse variable-speed, constant-frequency (VSCF) (cycloconverter) and single-blade rotor tests. All testing was completed, and the machine was decommissioned.
- Completed all testing on the three **2.5-MW, experimental MOD-2 turbines**. The last series of wake and performance tests were completed, and the three units were shut down. Disassembly began in early FY 1987. Several reports on the wind turbines, which successfully accumulated 8000 hours of test operations and generated over 10 million kWh of electricity during the last year of research testing, are being prepared for publication.
- Selected **editorial board members and chapter authors** for writing the first of three volumes of the ASME/DOE Wind Turbine Technology handbook. This document will summarize the results of 10 years of research and nearly 2000 technical reports. It will be published as a product of ASME in 1988.

Sandia National Laboratories

- Began **construction of the experimental 34-m VAWT test bed** in late FY 1986 with foundation installation and initial fabrication and erection at the United States Department of Agriculture (USDA) Agricultural Research Station at Bushland, Texas. Initial testing of the system is scheduled to begin in early 1988.
- Held the **VAWT Aerodynamics Technical Review** in January 1986 and the VAWT Aerodynamics Seminar in April 1987. In each meeting, researchers representing government, academia, industry, and other nations shared technical progress during the past year and shaped plans for future research.
- Conducted **flow-visualization preliminary tests** on the 17-m research VAWT to determine blade airflow separation characteristics. A television system was specifically designed for onboard data acquisition of flow information in chordwise and spanwise directions.
- Modified the **Eppler aerodynamics code** to generate random surface contour changes subject to certain tolerances and waviness criteria.
- Continued **hybrid natural-laminar-flow blade testing** on the 17-m research VAWT to determine passive stall control and increased energy-conversion efficiencies at various turbine rpms. Testing was completed at 50.6, 54.8, and 58.4 rpm.
- Completed an **unsteady airfoil model**, known as ADAM, which is an updated version of USTAR2. ADAM provides a more accurate representation of separated viscous flows than does the Eppler model.
- Designed a **novel braking system** for the DOE/SNL 34-m VAWT test bed. The system is spring-applied and hydraulically released, and it has a high capacity and eliminates side loads on the calipers.
- Modified the **NASTRAN-based forced finite element VAWT dynamic code (FFEVD)** for determining rotor stresses, and incorporated stochastic wind and lateral turbulence.
- Modified the **ASYM economics code** to incorporate the LIFE fatigue code. Also incorporated were the effects of high wind cutouts and start/stop damage accumulation.
- Progressed with the development of the **offshore wind energy conversion system (WECS) structural analysis code**. New capabilities allow for calculating coherence and phase between two independent time signals, resolving wave forces coming from any direction into accurate normal point forces, and converting wave velocities into forces being developed.
- Completed **fatigue testing** on the 100-kW VAWT at Bushland, Texas, at the end of FY 1985. The VAWT was disassembled in FY 1986, and fatigue-critical components and sections were sent to SNL for a detailed analysis.
- Began to develop a **new time-domain structural-response** model for VAWTs. The new code will incorporate stochastic wind.
- Began the **LIFE2 fatigue code update** including definition of algorithms; programming is in progress.
- Developed an **improved version** of an unsteady-flow, two-dimensional airfoil code, ADAM2, and published a report and user's manual.
- Completed the **initial analyses of VAWT aerodynamic loads** generated by one-dimensional turbulent winds, and showed these loads to be much more severe than had been previously assumed.
- Continued to utilize the **unsteady-airflow test facilities** at Ohio State University, where three separate wind tunnels have been modified to duplicate airfoil section operating environments. Improved associated software now allows rapid data reduction and analysis.
- Essentially completed extensive **refurbishment of the SNL 17-m VAWT**, increasing the reliability and versatility of this modestly sized, conveniently located research system.
- Designed and began construction of a **calibration facility** for unsteady viscous flow sensors so that state-of-the-art sensors can be used in wind tunnels and field tests with meaningful interpretable outputs.
- Successfully demonstrated the use of **liquid-crystal flow-visualization techniques** on WECS airfoils in a wind tunnel, with the ultimate objective of using this technique in the field.

- Obtained additional significant results from **frequency-domain, structural-response models** incorporating stochastic wind inputs. Also, a parallel effort was begun to develop time-domain models, with the output of both models providing essential information for predicting WECS component fatigue life.
- Developed a **rotationally sampled wind model** convenient for use with any aerodynamics loads model. One version will be combined with an ocean wave model for dynamic analysis of offshore structures.
- Successfully conducted **modal tests on the world's largest VAWT**, the Canadian 4-MW machine, and verified the finite-element models. In addition, modal tests were conducted on subsystems of the DOE/SNL 34-m VAWT test bed, including blade sections, entire blades, and the erected tower.
- Validated the **new, modular LIFE2 code** against the original LIFE code to provide an expanded capability for component fatigue life. Results were also published that demonstrated that nonlinear fatigue analyses of WECS are numerically tractable and can be incorporated into the LIFE2 code.
- Initiated contracts to experimentally determine the **fatigue characteristics of 6063 Aluminum**, the most commonly used material for VAWT blades. In cooperation with SERI, efforts were also begun to characterize fiberglass blade materials; the efforts included advising Southern University and hosting one of their students through the SNL historically black colleges and universities (HBCU) summer program.
- Designed, fabricated, and fielded a **fatigue damage gauge** that will help validate both the material characterizations and the fatigue-analysis numerical framework. Units were installed on an NPS HAWT (under a SERI CRP contract) and the DOE/SNL 34-m VAWT test bed.
- Continued the **evolutionary design process** for the VAWT-specific natural laminar flow (NLF) airfoil sections (SAND 0018/50), and completed the dynamic testing in the Ohio State University wind tunnels. A major technical breakthrough was achieved when the largest-to-date aluminum blades (including the NLF sections with 36-in. and 42-in. chord lengths) were successfully extruded, assembled, and bent.
- Designed and evaluated the performance of **second-generation, low-Reynolds-number airfoils** using the Ohio State University wind tunnels. Dynamic wind-tunnel tests on airfoil sections incorporating vortex generators were also conducted. These efforts are to improve WECS aerodynamic performance.
- Provided design data for a **pumped-spoiling stall-control system** tested in a static wind tunnel using the SAND 0018/50 airfoil. Results indicate the cost-effectiveness for midsized VAWTs.
- Developed software for the **programmable controller** that, through the VSCF generator, will allow research to begin on variable-speed operation of the DOE/SNL 34-m VAWT test bed. Strategies were also initiated to study the effects of braking algorithms on dynamic loads.
- Completed and published results for a **design code (ASYM)** that evaluates the impacts that various VAWT control strategies have on energy costs and fatigue life.
- Completed all **hardware acquisitions and 90% of all erection work** on the DOE/SNL 34-m VAWT test bed at the USDA/ARS site in Bushland, Texas. Only the assembled blades have yet to be mounted. Significant achievements include:
  - Production of the world's largest multivoid aluminum extrusions for the turbine blades
  - Successful assembly and bending of the multicomponent blade sections and fabrication of the entire blades
  - First use of an off-the-shelf, commercially available, VSCF electrical generating system in a WECS.
- Continued **direct technology transfer to industry** in the areas of fatigue analysis capabilities (LIFE and LIFE2 codes) and WECS material characteristics, and assisted with the fatigue aspects of the SERI/NPS CRP contract.
- Defined a **cooperative research program** with members of the U.S. VAWT industry to transfer and demonstrate NLF airfoil technology to increase the performance and cost-effectiveness of VAWTs.

IV. FY 1986 and 1987 Project Summaries

This section summarizes all of the projects conducted by each field laboratory within FY 1986 and 1987. The summaries are grouped according to individual wind-energy research area and are then listed by field laboratory affiliation.

Atmospheric Fluid Dynamics

The objectives of Atmospheric Fluid Dynamics are to develop improved models of the wind encountered by the rotor, develop improved models of atmospheric flow across a site, and study the effects of wakes and complex terrain. Refer to Appendix A for a complete listing of federal laboratories and contractors involved in wind energy research during FY 1986 and 1987.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
PNL	Theory of Rotationally Sampled Wind	10/84—$170,000	19
PNL	Measured Rotationally Sampled Wind (Medicine Bow)	10/84—$326,000	20
Colorado State University	Modification of Turbulent Airflow Near Rotor	10/84—$83,000	22
Colorado State University	Multipoint Rotational Measurements of Turbulence Using Hot-Film Anemometers	10/83—$317,000	23
University of Massachusetts	Tethersonde and Kite Anemometer Evaluation	05/85—$20,000	24
PNL	Wind Farm Flow Analysis (Altamont Pass)	10/85—$250,000	25
PNL	Goodnoe Hills Flow Analysis and Modeling	10/84—$352,000	26
PNL	Wake Model Validation Experiment	10/85—$180,000	27
SERI/ University of Massachusetts	Techniques for Measuring Atmospheric Turbulence and Turbulent Atmospheric Wind	05/87—$69,950	52
SNL	Unsteady Viscous Flow Research	10/85—$480,000	81

Aerodynamics Research

The objective of Aerodynamics Research is to investigate the dynamic interaction between atmospheric flow and the turbine rotor, which would enable the development of accurate models for predicting performance and loads under all operating conditions.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
SERI	Spectral Characterization of MOD-2 Wake	02/85—$336,800	56
SERI	Flow Research	10/82—$1,256,400	39

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
SERI	WECS Aeroacoustics Research	10/80—$1,791,000	54
SERI	Advanced Airfoils	10/86—$1,104,300	48
Oregon State University	Aerodynamic Transient and Yaw Effects on HAWT Loads and Performance	04/86—$226,090	53
Aerovironment, Inc., Computational Methodology Associates	Aerodynamics Research — Rotor Code Validation and Improvement	10/82—$705,000	55
SERI	Combined Experiment	01/87—$596,300	37
SERI	Atmospheric Testing of a Special-Purpose HAWT Airfoil Family	01/87—$209,000	44
SERI	Elastic Twist Determination	07/86—$81,269	45
NASA LeRC	Three-Dimensional Aerodynamic Flow Regimes over Rotor Airfoil Surfaces	11/81—$52,000	70
AeroVironment, Inc.	Rotor Blade Tip Configurations	1982—$168,707	71
Ohio State University	Measurements of Lift and Drag Coefficients of Airfoils in Stalled Flow Conditions at High Reynolds Numbers	09/82—$360,000	72
Wichita State University	Development of Airfoil Trailing Edge Surfaces for Rotor Control	1979—$751,000	73
SNL	Validated Model for Aerodynamicists	In-house research	79
SNL	Unsteady Airfoil Testing	In-house research	83
SNL	Strut/Blade Interaction	10/85—$60,000	82
SNL	34-m VAWT Test Bed Development	In-house research	77
SNL	Vortex Generators (VGs)	In-house research	89
SNL	Pumped Spoiling	In-house research	93
SNL	Advanced Airfoil Designs	10/83—$250,000	91
SNL	Symmetrical Natural Laminar Flow Airfoils	In-house research	90
PNL	Correlation of Wind with Wind Turbine Response	10/86—$47,000	32
PNL	3-d Turbulent Winds and Unsteady Aerodynamics	10/86—$233,000	34

Structural Dynamics

The objective of Structural Dynamics research is to develop accurate models of the stresses induced by unsteady loads and understand the effects of these stresses on component lifetime.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
SERI	Dynamic Response and Fatigue Research	02/85—$2,012,600	40
SERI	Load Phasing and Fatigue	02/85—$415,900	41
SERI	Structural Response Testing and Analysis	02/85—$1,167,000	42

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
SERI	Electrical Systems Theory	10/86—$1,304,300	43
NASA LeRC/ University of Toledo, Cleveland State University	Response of Variable Rotor Speed on One-, Two-, or Three-Bladed Rotors on Near Aerodynamic Stall Conditions	08/83—$70,283	68
Applied Technology Laboratory, U.S. Army	Wood/Epoxy Blade Material Fatigue Test	02/83—$10,000	65
NASA LeRC	Variable-Speed Generator Effects on Drive Train Torsional Flexibility, Damping, and Dynamic Response Near Resonance	01/82—$243,000	69
SNL	Models Incorporating Stochastic Wind Input	In-house research	80
SNL	VAWT Analytical Models	In-house research	84
SNL	Advanced Fatigue Models	In-house research	86
SNL	Code Modification and Documentation	In-house research	87
SNL	EOLE Modal Testing	In-house research	88
SNL	Fatigue Life Controller Algorithm Studies	10/85—$190,000	94
SNL	VAWT Braking Methods	In-house research	95
SNL	Offshore WECS	In-house research	96
SNL	VAWT System Dynamics Response Model	10/86—$150,000	85

Advanced Concepts Research

The objective of Advanced Concepts Research is to develop the technology base necessary to achieve major improvements in machine cost, performance, and lifetime. This category involves activities in advanced concepts research, supporting research, applied technology testing and analysis, and multimegawatt systems.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
SERI	Variable-Speed Generator System Implementation and Control	10/82—$2,546,400	58
SNL	Advanced VSCF Generators for VAWTs	In-house research	92
SNL	Variable-Speed Testing	In-house research	78

Supporting Research

The objective of Supporting Research is to provide the tools, assessments, and data necessary for users to make informed decisions about wind technology.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
PNL	International Wind Resource Update (CORECT Support)	10/85—$150,000	28
SERI/ University of Utah	Yaw Dynamics of Horizontal-Axis Wind Turbines	04/86—$163,254	47

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
SERI	Optimization Studies of Wind/Diesel Systems	05/87—$130,000	50
SERI	Wind/Diesel Research	02/85—$576,000	49
SERI	Analytical Codes for Dynamic Response	10/82—$1,178,200	46
SERI	Systems Analysis Research	10/82—$702,400	59
American Wind Energy Association	Support To Industry Standards Development	10/83—$646,500	60
SERI	Computer Simulation of Wind/Diesel System Operation	04/87—$139,223	51
NASA LeRC	ASME/DOE Wind Turbine Technology Book	01/87—$150,000	66
PNL	Cooperative Research Program — Direct Technical Support (Fatigue Tests)	10/86—$70,000	31
PNL	Transfer of Microscale Turbulence Technology	10/86—$190,000	33

Applied Technology Testing and Analysis

The objectives of Applied Technology Testing and Analysis are to provide test facilities and support collaborative efforts between industry and government to field test industry machines in support of general wind energy R&D.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
PNL	Cooperative Field Test Program — Technical Monitoring	10/85—$80,000	29
PNL	Cooperative Field Test Program — Direct Technical Support	10/85—$90,000	30
SERI	Cooperative Research Programs	02/85—$1,883,100	38
Prairie View A&M University, Southern University, Tuskegee University, University of Texas at San Antonio	Historically Black Colleges and Universities Project	09/83—$565,000	57
SERI, Rockwell International	Industry/Cooperative Test and Analysis	10/82—$2,087,000	61
SNL	Cooperative Programs	10/86—$550,000	97

Multimegawatt Systems

The objectives of Multimegawatt Systems research are to complete the design, construction, and test phases of the MOD-5B, and to continue to document performance and loads to better determine how fundamental processes relate to machine scale.

Organization	Project Title	Effective Date and Cumulative Cost (Through FY 1987)	Page
NASA LeRC/ Boeing Aerospace Company	Design, Fabricate, Install, and Test an Advanced Multimegawatt Wind Turbine (MOD-5B)	1980—$58,400,000	67

Appendix A
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DOE/CH10093-42
UC Category: 261

Wind Energy Program Summary

Volume II: Research Summaries Fiscal Year 1988

U.S. Department of Energy

Programs in Renewable Energy

April 1989

FY 1988 Research Accomplishments

Pacific Northwest Laboratory

- Demonstrated the sensitivity of selected turbulence parameters to different degrees of terrain complexity.
- Completed preparation and testing of anemometry and the data acquisition system scheduled to be used in the turbulence measurements around the DOE/SNL 34-m Vertical-Axis Wind Turbine (VAWT) Test Bed at Bushland, Tex.
- Developed a personal computer based version of the PNL theoretical turbulence model for simulating spectra or time series of rotationally sampled turbulence.
- Developed and tested a unique system for performing efficient and precise calibrations of anemometer systems that measure three components of the wind simultaneously.
- Acquired and tested the Canadian and Danish versions of the Jackson-Hunt flow models to be used in comparative evaluations with mass-consistent flow models.
- Provided technical assistance to the American Wind Energy Association siting committee in preparation for a micrositing technical meeting in Santa Clara, Calif., in June 1988.
- Performed an analysis of small-scale turbulent eddies at 30 meters above the ground, in which a high degree of order was observed.
- Assimilated research results from a collection of published and draft reports and papers on wake and wind farm array loss studies in preparation for the production of a comprehensive summary document.
- Developed a positive interaction with the wind energy community participants through technical monitoring efforts in the DOE Cooperative Research Program.
- Completed a wind energy resource assessment for selected areas of the Pacific Island region.

Sandia National Laboratories

- Completed construction and formally dedicated the DOE/SNL 34-m VAWT Test Bed at the United States Department of Agriculture Agricultural Research Service at Bushland, Tex.
- Completed initial resonance testing of the test bed, verifying accuracy of the finite element model used to predict natural frequencies and structural response of the turbine.
- Achieved full operational status for the minicomputer-based data acquisition and analysis systems used for acquiring data from the test bed and the SNL 17-m VAWT, located in Albuquerque, N. Mex. Several software modifications were implemented to improve the ease of acquiring, storing, and analyzing large amounts of strain gauge, environmental, and performance data.
- Continued development of advanced airfoil designs for use in low-Reynolds-number locations on VAWTs. The most promising method of enhancing low-Reynolds-number airfoil performance appears to be the addition of vortex generators to NACA 00XX airfoils.
- Continued the evolutionary design process for the VAWT-specific natural laminar flow airfoil sections (SAND 0018/50), and continued dynamic testing of the NACA 0021 airfoil (with and without vortex generators) in the Ohio State University wind tunnels. Results are being analyzed to gain insight into the effects of dynamic stall on the natural laminar flow and vortex generator equipped airfoils.
- Continued development work on the ASYM turbine simulation code, which allows evaluation of various VAWT control strategies in terms of energy capture and fatigue life consumption. This code has been extensively modified to better model the 34-m test bed and its control system. Preliminary results indicate that the use of regenerative braking on the test bed can augment energy production by as much as 10%-12% while significantly reducing fatigue damage during normal shutdowns.
- Held the VAWT Aerodynamics Technical Program Review in April 1988 at Bushland, Tex. Researchers in government, academia, and industry from the United States and other nations shared technical progress during the preceding year and discussed plans for future research.
- Continued hybrid natural laminar flow blade testing on the 17-m research VAWT to determine blade performance at rotational speeds of 50.6, 54.8, 58.4, 63.4, and 66.2 rpm with particular emphasis on passive stall control and energy-conversion efficiencies.
- Continued the analyses of VAWT aerodynamic loads generated by turbulent winds to investigate the effect of three-dimensional turbulent winds. The loads generated by the simulated three-dimensional winds are somewhat less than those generated by one-dimensional turbulent winds, but they are still quite severe.
- Completed extensive refurbishment of the SNL 17-m research VAWT, increasing the reliability and versatility of this modestly sized, conveniently located research turbine.
- Developed personal computer based versions of the VDART3 vortex code and a discrete local circulation method code for predicting VAWT performance. These codes are relatively rudimentary, but continuing development work will incorporate most of the capabilities currently found in the mainframe versions of these codes.
- Developed a three-dimensional, finite-difference technique for analyzing laminar viscous flow around groups of VAWTs.

Solar Energy Research Institute

- Completed first phase tests of the Combined Experiment wind turbine to correlate inflow, blade pressure measurements, and structural response data, and to provide flow-visualization data. Atmospheric test results were verified by bracketing them between controlled wind tunnel tests at Ohio State University.
- Verified, through Combined Experiment tests, the performance of a SERI-developed video imaging technique for wind systems, consisting of a hub-mounted, high resolution video camera that revolves with the rotor. This camera produced acceptable images of blade-mounted tufts and liquid crystals.
- Collaborated with SNL, through initial Combined Experiment tests, to demonstrate the applicability of the liquid crystal test technique to visualizing boundary layer phenomena.
- Completed an initial definition of the SERI Wind Energy Test Center wind flow regime to develop a comprehensive test matrix for the Combined Experiment.
- Completed current wind turbine acoustics research studies with documentation of acoustic tests of the MOD-2 wind turbine and development of a proposed standard for assessing the potential of wind turbine low frequency noise emissions that affect communities.
- Demonstrated that the dynamic flapping moments sustained by a flexible two-bladed rotor are significantly lower than those for a stiff, three-bladed rotor wind turbine.
- Continued making improvements to the Force and Loads Analysis Program structural dynamics code, including the validation and documentation of a new version of the code incorporating teeter effects and the development of a turbulence subroutine that consists of a filtered noise model. The turbulence version of the code produces time-series results that can be used to determine peak loads and can be rain-flow counted to estimate fatigue damage rates.
- Utilized the Force and Loads Analysis Program code extensively to analyze experimental data results from Cooperative Research Program tests of the Howden 330-kW, Westinghouse 600-kW, and Northern Power Systems 125-kW wind systems.
- Completed fatigue tests of an advance industry wind turbine in cooperation with Northern Power Systems, obtaining a data set with more than 400 hours of high-quality wind inflow, fatigue, and structural response data over a wide range of wind speeds.
- Published preliminary results of dynamic response tests of the Westinghouse 600-kW wind turbine and the Northern Power Systems 125-kW wind turbine.
- Completed development, at the University of Utah, of a single degree of freedom code that incorporates skewed wake aerodynamics to predict wind turbine yaw dynamics. The model was demonstrated for the case of a 1/20th scale model of the MOD-2 wind turbine. Development of an advanced yaw model (YawDyn) was initiated.
- Initiated a cost-shared project with industry to fabricate and test advanced SERI "thick" airfoils (designated S809).
- Assisted consultants in the development of improved fiberglass blade root attachment joining techniques that are being used by industry to alleviate blade failures, which are a problem at wind farms. A seminar on this problem was organized by SERI at a technical conference to apprise industry of the problem and possible solutions.
- Used the new root attachment techniques developed by WestWind Industries to improve the design of blades WestWind is fabricating for tests of the SERI special purpose "thin" airfoil family (designated S805). At the end of FY 1988, WestWind's subcontractor, Phoenix, was ready to begin final blade mold development.
- Performed analyses that showed the importance of restrained airfoil performance at high tip speed ratios to maximize annual energy output from stall-controlled wind turbines. These results were documented in a white paper to industry.
- Initiated a no exchange of funds cooperative agreement with SeaWest Energy Systems (a major U.S. wind farm developer) to perform comparative tests of 9.0-m and 7.5-m wind turbine blades incorporating various advanced airfoils, including the SERI special purpose airfoils.
- Initiated advanced turbine studies to define wind system configurations that will be competitive in the 1990s in moderate wind regimes of 13 mph average wind speeds.
- Completed AeroVironment's modification of the DOE SOLSTOR II code to include modeling capabilities for the performance and economics of wind-diesel systems.
- Initiated wind-diesel test and analysis activities with Atlantic Orient Corporation and Northern Power Systems, under the DOE Cooperative Research Program. One of the efforts is investigating advanced architectures for wind-diesel systems; the other is modeling the effect of high penetrations of wind systems on grid stability and diesel generating system performance.
- Initiated tests of small-scale hybrid wind-electric water pumping systems in cooperation with Energy Wind Systems and the Alternative Energy Institute.
- Completed power quality tests of a wind farm on the main island of Hawaii with the cooperation of the Hawaiian Electric Power Company.
- Continued financial and technical support of wind industry consensus standards development efforts. The American Wind Energy Association completed a performance rating standard and a design criteria standard. The Institute of Electrical and Electronics Engineers published standards on utility interconnection of small wind systems and recommended practices for the electrical interconnection of wind farms.

Wind Energy Program Summary

Volume II: Research Summaries

Fiscal Year 1989

U.S. Department of Energy

Prepared by the
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FY 1989 Research Accomplishments

Pacific Northwest Laboratory

- Prepared a draft atlas of the wind energy resource for selected areas of the Pacific Island region.

- Conducted a field experiment in which turbulent wind measurements were recorded from six three-component anemometers, equally spaced at hub height around the DOE/SNL/USDA 34-m Vertical-Axis Wind Turbine (VAWT) Test Bed at Bushland, Tex. The power spectral density analyses of the turbulence and the blade bending moments were used to compute response functions for the turbine.

- Completed testing of the computer-driven calibration device developed for efficient wind tunnel calibration of three-component anemometer systems with unprecedented precision.

- Performed high-precision calibrations on several Gill UVW anemometers and produced much more accurate cosine-correction factors at low angles to the propeller disk than previously possible.

- Completed a user's guide for a theory-based turbulence model that simulates both power spectral density and time series of turbulent wind encountered at a specified radius along a wind turbine blade.

- Began a cooperative effort with SERI to adapt the turbulence simulation code so that the output is more easily assimilated by the FLAP2 load prediction code.

- Completed a comparative evaluation of a mass-consistent flow model and the two Jackson-Hunt type flow models for two contrasting terrain types.

- Demonstrated that acceptable accuracy can only be achieved with current flow models if wind measurements are available at several appropriate locations in the domain of interest.

- Completed testing of analyses techniques that provide a two-dimensional depiction of eddy structure superimposed on the mean flow. These techniques were used to examine the coherent structure of the turbulence in the wind over a turbine array as well as the inflow to, and the wake behind, a single turbine.

- Completed a detailed analysis of wake and free-flow characteristics at Goodnoe Hills, Wash. The few stands of trees around the site provide an excellent opportunity to study the effects of trees on the shear and turbulence in the inflow to a single turbine or an array.

- Completed a study showing that most of the variability in wind turbine power curves determined in the field comes from the variation in the wind shear over the rotor disk.

- Prepared a proposal for several turbulence characterization systems to be used in a cooperative effort with organizations in the wind energy community to establish
  - turbulence criteria for turbine design and
  - a standardized approach for cost-effective and reliable turbulence characterization.

- Received about 20 responses from members of the wind energy community to a letter of inquiry and intent concerning the turbulence characterization system. The recommendations for system requirements will be used in setting final specifications.

Sandia National Laboratories

- Released a "user friendly" version of the LIFE2 fatigue analysis code to the U.S. wind industry for comment.

- Completed and released a two-volume user's manual for the LIFE2 fatigue analysis code. The first volume of the manual is a reference for the code, and the second describes the mathematical formulation of the code.

- Coded a rain-flow counting algorithm into the LIFE2 fatigue analysis code. Validation of the code is in progress.

- Completed a statistical analysis of the fatigue characteristics of 6063 aluminum that is suitable for fatigue analyses of wind turbines and that is formulated in a manner suitable for inclusion in reliability analysis.

- Completed the fatigue experiments on 6063 aluminum that characterize its behavior when subjected to the load spectrum encountered by wind turbine blades.

technology, and coincident domestic and international standards meetings.

- Continued its technical support to AWEA domestic and international standards development activities. Three domestic standards documents were made ready for publication in 1989, including installation, a wind-diesel architecture guidebook, and the first tier of a multilevel acoustics standard.

- Developed a code that permits predictions of the long-term (5-min period) operational behavior and performance of wind-diesel systems, including energy flows of the wind turbine and diesel and the effect of storage on start-stop cycles. This work was performed by the University of Massachusetts, under subcontract to SERI.

- Provided detailed, hands-on technical assistance to eight wind-related firms, including GearTech, International Wind Systems, Arbutus, SecondWind, AeroTurbine, and R. Lynette & Associates.

- Initiated a major research test collaboration with SeaWest Energy Group in San Gorgonio Pass, Calif. Tests of 9- and 7.9-m blades, yaw drive systems, dynamic brakes, and windfarm wakes were included.

U.S. Department of Energy

Programs in Utility Technologies

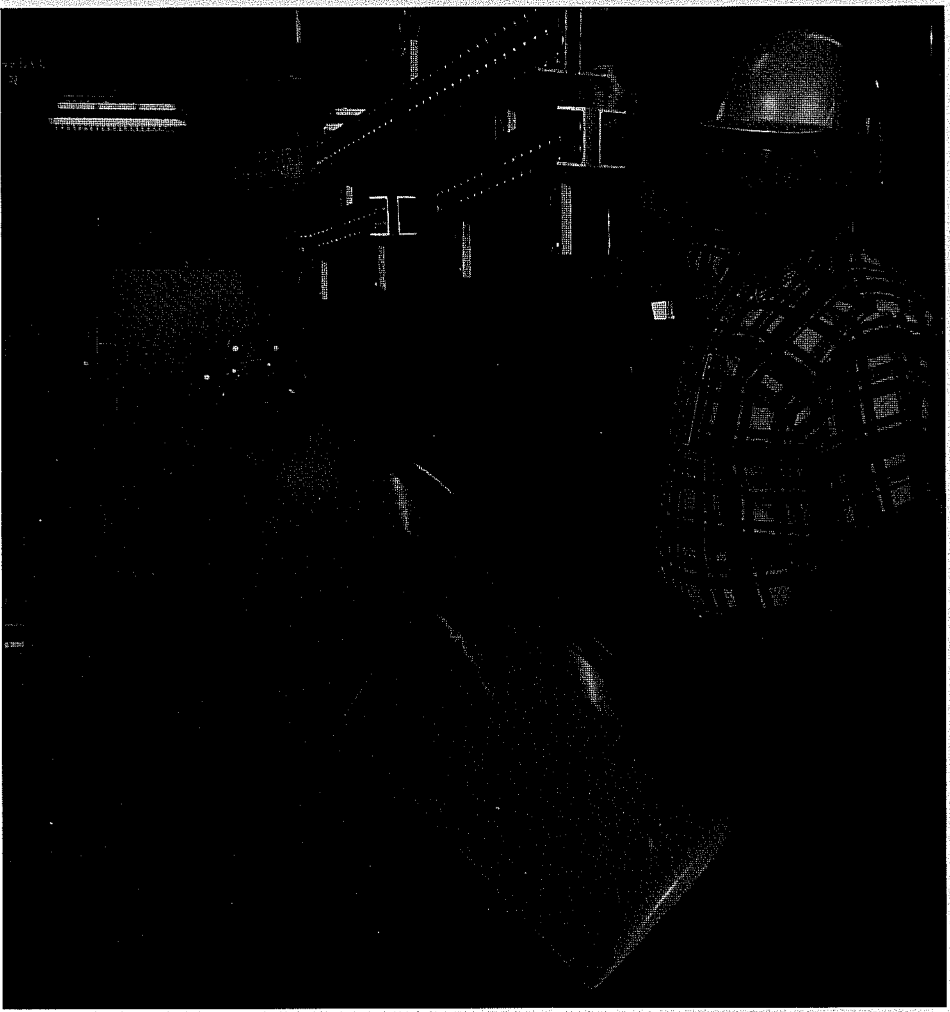
Fiscal Years 1990-1991

WIND ENERGY PROGRAM OVERVIEW

Wind Energy Research Highlights for FYs 1990 and 1991

The DOE Wind Energy Program is helping U.S. industry develop the advanced technologies required to economically exploit the vast U.S. wind resource.

Wind energy research is designed to answer questions relevant to the improved operation of today's commercial wind turbines and to assist in the advancement of new concepts leading to new technologies. Objectives include a detailed understanding of wind turbulence and its interaction with wind turbine rotors, a knowledge of factors causing stress and damage to wind turbines and the means for reducing or alleviating these stresses, a comprehensive characterization of turbine materials, and the creation of advanced components and systems. DOE maintains close contact with utilities and industry in setting a national wind energy research agenda. DOE conducts many cooperative research projects with utilities, manufacturers, and power plant operators, and it transfers research results to industry as soon as they become available. During FYs 1990 and 1991, DOE spent $20.2 million on wind energy research.



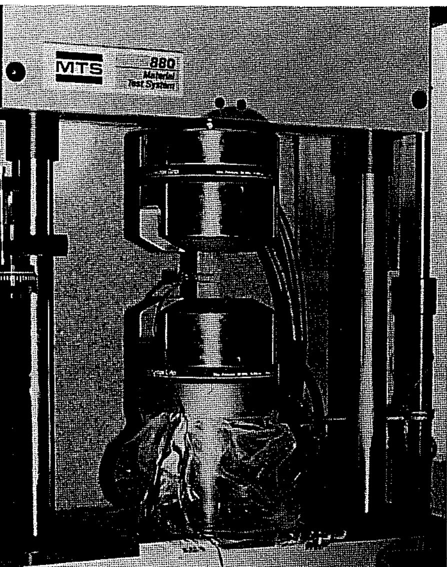
NREL completed construction of a new Structural Test Facility at its Wind Energy Test Center in FY 1990. The facility, which contains a composite materials testing laboratory and Fatigue Test Stand, will conduct full-scale wind turbine blade mechanical tests.

The following research highlights provide an overview of the achievements of the DOE Wind Energy Program in FYs 1990 and 1991. A more complete description of all research projects under way in FY 1990 is contained in the *Wind Energy Contract List, Fiscal Year 1990*.

Structures and fatigue research aims to improve turbine life expectancy

Sitting atop towers 100 to 160 ft (30 to 50 m) above the ground, wind turbines operate in a harsh and challenging environment where they are subjected to atmospheric turbulence, insects, dust, pollution, temperature extremes, high winds, rain, snow, sleet, and wind shear. The result is continuous wear and tear on blades and other exposed parts. In addition, wind turbines experience considerable stress from predictable forces, such as gravity, centrifugal force, and startup/shutdown cycles. Research on structures and fatigue focuses on gaining a better understanding of the induced stress and fatigue behavior of wind turbines. This understanding is a necessary ingredient for designing cost-effective components and systems to last for 20- to 30-year service lifetimes.

In FY 1990, NREL completed construction of a new Structural Test Facility at its Wind Energy Test Center. At the facility, which contains a Composite Materials Testing Laboratory and Fatigue Test Stand, researchers are conducting full-scale wind turbine blade mechanical tests. These tests include coupon tests, in which small samples of blade material are subjected to repeated cyclic stresses until they fail; static failure tests, in which blades experience increasingly higher loads until they break; full-scale component fatigue tests, in which blade and rotor substructures are subjected to loads that mimic real-life conditions as closely as possible; and photoelastic tests, in which polarized light is reflected off plastic panel-coated blades to reveal areas of high stress. These tests



n FYs 1990 and 1991, researchers at /lontana State University used this pparatus to run tests on coupons (small ections of blade materials) provided by wo U.S. manufacturers.

rovide the wind industry with a much- ieeded structural test capability and upport research to develop new blade lesigns resistant to fatigue damage. They lso give industry a method for evaluating he strength of turbine materials.

In FY 1990, Sandia assisted NREL n setting up the Structural Test Facility's irst coupon tests, which supplement ngoing tests conducted at Montana State Jniversity (MSU) under a Sandia sub- ontract. In FY 1991, MSU also received unding from NREL for its fatigue and oupon tests under DOE's University Participation Program. MSU was one of ive universities accepted in 1991 into he program, which provides funding to cademic research projects relevant to he wind industry.*

In FYs 1990 and 1991, researchers at Sandia, NREL, Southern University, and MSU ran tests on coupons provided by two U.S. manufacturers. They developed coupon fabrication and testing techniques, began fatigue tests up to 10 million cycles on composite blade materials, and examined blade material flaws, including broken fibers and other irregularities. NREL researchers also performed photoelastic tests on a set of commercial turbine blades supplied by one of the same firms.

The new structural and fatigue test capability not only benefits industry but also gives wind energy researchers the opportunity to test and refine their fatigue damage models. Mathematical models,

Computer Codes and Modeling

The cornerstone of technological innovation is incremental improvement in existing hardware. Unlike science, where a single breakthrough can alter our view of the universe, technology proceeds slowly, building upon past experience to create new products. The evolution of wind energy technology is no exception.

In today's world, however, a new commercial wind turbine costs more than $100,000. Advanced turbine development typically costs millions of dollars. At these costs, it is too expensive to try out every new idea by building hardware. Fortunately, technologists have a powerful tool to assist them in evaluating new design ideas: the computer.

For the past 10 years, the development of computer codes and models has been an indispensable element of the DOE Wind Energy Program. Today, there are turbulence codes that model wind behavior, aerodynamics codes that predict machine performance, structural codes that predict whether components and systems are strong enough to meet design requirements, and fatigue codes that calculate the cumulative effects of stresses and predict how long components will last. These codes are important tools for evaluating new turbine designs before any hardware is ever built.

Computer code development is a lengthy process. First, a mathematical model is developed to reflect what is understood about a given topic. Then, the model is broken down into hundreds or even thousands of simple equations. Next, the model is tested against real experimental data to see whether it works. Codes are typically refined many times before they begin to mimic real-life conditions. Even when they succeed in modeling reality, there is always room for improvement.

In FY 1991, for example, Sandia modified an existing aerodynamics code to study the effects of literally thousands of tiny design changes that could potentially improve the performance of commercial VAWTs. In a separate study, researchers had to go back and modify a code describing stall in VAWTs when wind tunnel experiments showed that stall behavior in wind turbines is quite different from that in helicopters, which was the basis for the original computer code.

For more than a decade, Sandia has played a leading role in government research to develop elegant computer codes and models. Sandia's powerful TRES4 code can now model wind turbulence, its interaction with wind turbine blades, the loads created by this interaction, and the effects of all this on turbine structures—but only for VAWTs that operate at constant speed. The VAWT-SDS code, refined in FYs 1990 and 1991, models variable-speed operation, looks at the effects of aerodynamic interactions on structural problems, and evaluates the effects of controls on turbine behavior.

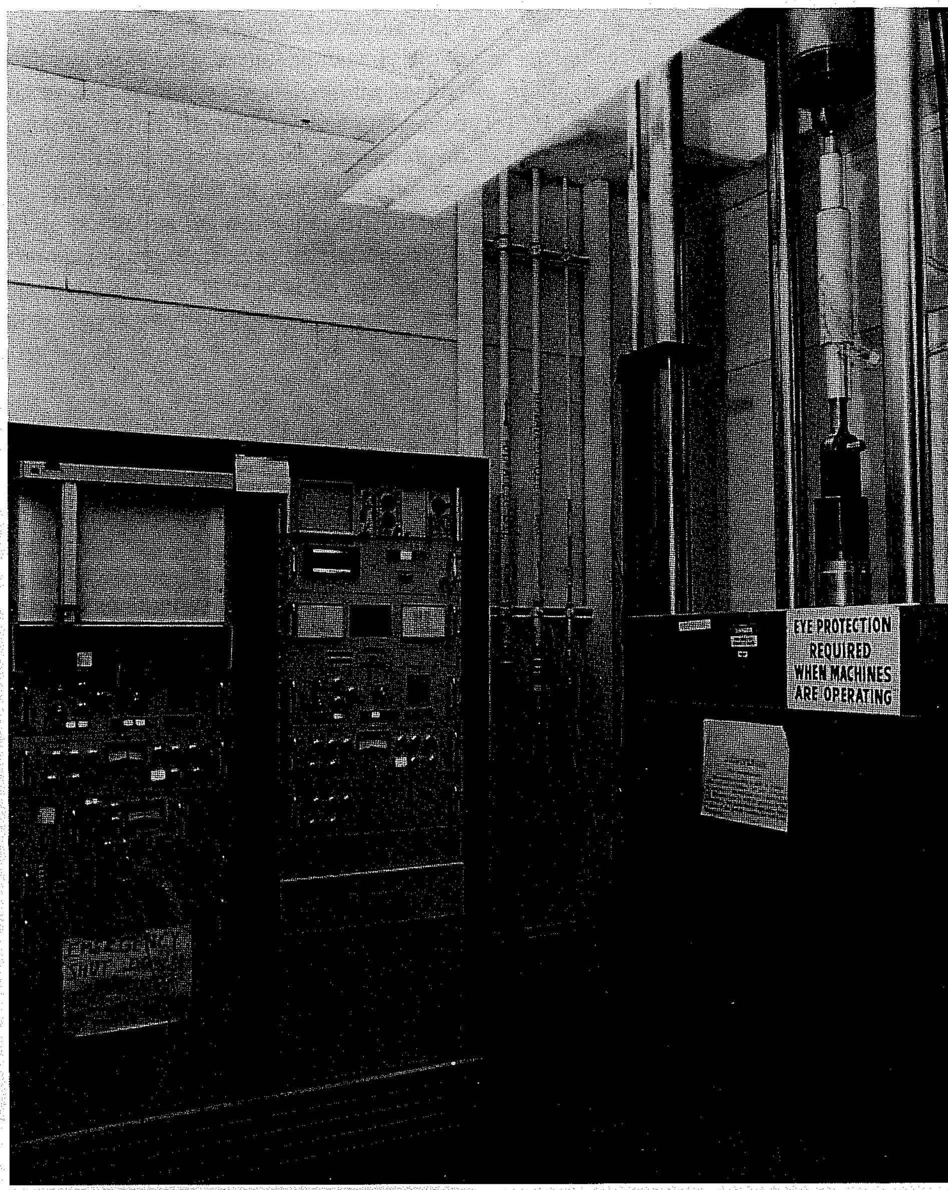
Until 1991, NREL's codes and modeling activities emphasized loads and fatigue analysis of HAWT components. Both the FLAP and YAWDYN codes were developed as part of this research. Studies are now under way to enhance the FLAP code for advanced turbines and to develop a variable-speed rotor code. In the future, NREL will focus on systems codes to model blades, hubs, drive trains, free yaw, and tower motions.

Montana State University, Ohio State University, Oregon State University, the University of Colorado, and the University of Utah joined DOE's FY 1991 University Participation Program.

ıch as the Force and Loads Analysis rogram (FLAP), were created to predict oads (the forces imposed on a turbine by ravity, wind pressure, or the motion of ıe turbine itself) and turbine responses ɔ them. They are an invaluable part of esearch to understand structures and atigue. In FY 1990, the FLAP code was xpanded to better predict loads and esponses for different types of turbines, ncluding a two-bladed, teetering-hub otor. FLAP was also modified to include ıe effects of wind turbulence. In FY 1991, esearchers compared the FLAP model's redictive values with experimental data athered on operating turbines to deter- ıine the code's effectiveness. They also egan to evaluate a new, general-purpose tructures code, called ADAMS, that ncludes all motions of a wind turbine.

In FYs 1990 and 1991, Oregon State Jniversity worked on advanced aero- ynamic models that will be used to nhance the FLAP code. The new models vill predict the loads and responses of a wo-bladed, teetering-hub wind turbine ndergoing variable-speed operation. They vill also incorporate turbulence and the ffects of adding aerodynamic brakes to ırbine blades. Once validated, the codes vill play an important role in the evolution f several advanced turbine concepts.

In FY 1990, researchers at the Univer- ity of Utah continued to refine and alidate the Yaw Dynamics Code YAWDYN). In addition to comparing ode predictions to test data gathered at ıe Wind Energy Test Center, program- ıers refined the code to make it user- riendly in anticipation of its release to ndustry in FY 1991. In FY 1991, Utah omputer scientists began work to incor- orate new experimental information n turbine performance into both the 'AWDYN and FLAP codes.



Sandia launched a new study in FY 1991 to evaluate the strength and reliability of common blade joints. This experimental setup was used to study cylindrical bonded joints, the simplest type of blade joint.

Sandia transfers the results of its metal blade study to industry

In FY 1990, Sandia completed a comprehensive fatigue characterization of 6063 Aluminum, a material widely used for VAWT blades in California's wind power plants. In 1990, final metal-blade analyses, based upon data gathered at Sandia's 34-m test bed, were released to industry. This information will enable industry to design more reliable blades and blade joints using aluminum. A paper summarizing the study's results was presented at the April 1990 American Society of Mechanical Engineers (ASME) meeting, where it received an award for best conference paper.

In other fatigue-related studies, Sandia began a new project in FY 1991 to analyze turbine blade joints. A turbine blade usually cracks or breaks at the weakest point—the place where different blade sections are joined together. The new study is evaluating the strength and reliability of common blade joints, beginning with the simplest attachment: the cylindrical bonded joint.

Sandia researchers continued to refine their unique simulation code, known as ASYM. This code is used to determine the best turbine-control strategies for achieving maximum energy output with minimum stress to the turbine and its components. In FYs 1990 and 1991, they customized the code for the 34-m test bed and added variable-speed operation.

In FY 1990, Sandia released its LIFE2 code, designed for wind turbine fatigue analysis, to six members of the U.S. wind industry for evaluation and feedback. This code will help industry realistically estimate the service life of wind electric conversion systems. In FY 1991, researchers refined the LIFE2 code to model the effects of realistic wind speed and turbulence variations, which can occur from minute to minute. Sandia evaluated the refined code with data gathered from the 34-m test bed, then delivered it, with documentation, to the same six companies for further study.

Wind turbulence research studies the impact of inflow variation on wind turbines

Understanding variations in wind inflow, including turbulence, wind shear, and large eddies, is critical to cost-effective wind turbine design. Basic research in atmospheric physics and aerodynamics is providing industry with the information it needs to develop new turbine designs and improve existing technologies, site selection, and operating methods. In atmospheric physics, meteorologists study a variety of wind characteristics that influence turbine behavior. Aerodynamics researchers investigate how variations in wind speed and direction interact with the rotating blades of a wind turbine.

In a wind power plant, the interaction of the natural inflow, local terrain features, and upwind turbines can significantly lower the power output of downwind turbines. Understanding this interaction is critical not only for siting new wind power plants, but also for placing individual turbines within the plants. In FY 1990, a PNL study showed that upwind trees can cause a 30% reduction in wind speed and a two- to threefold increase in wind turbulence. These results suggest that wind turbines will experience reduced power output, more start/stop cycles, increased stress, and more variation in power output if they are sited downwind from trees. A second study showed that wind shear and turbulence are important factors when measuring the power curve of a wind turbine.

In related research in FYs 1990 and 1991, NREL scientists undertook several studies to determine how wind turbulence impacts turbine loads. At the SeaWest Energy Group power plant in San Gorgonio Pass, for example, researchers carefully measured wind conditions at the entrance to the power plant, at the exit, and at the location of two Micon-65 turbines being used for NREL's 7.9-m thin-airfoil tests. These turbines are sited near the back of the power plant, where turbines have sustained a high degree of damage. The study showed that this area was subject to extreme disturbances resulting from a complex interaction of the natural wind flow with wakes created by other turbines. NREL researchers interpret their results to mean that turbine designers are going to have to create more durable machines for locations that routinely experience such conditions.

In cooperation with industry, NREL also performed a gearbox fatigue analysis on one of the Micon-65 wind turbines instrumented for the thin-airfoil tests. An experiment was designed to see whether the turbine brake was causing frequent gearbox failures in the field. Comparison tests showed that a new dynamic brake reduced braking loads.

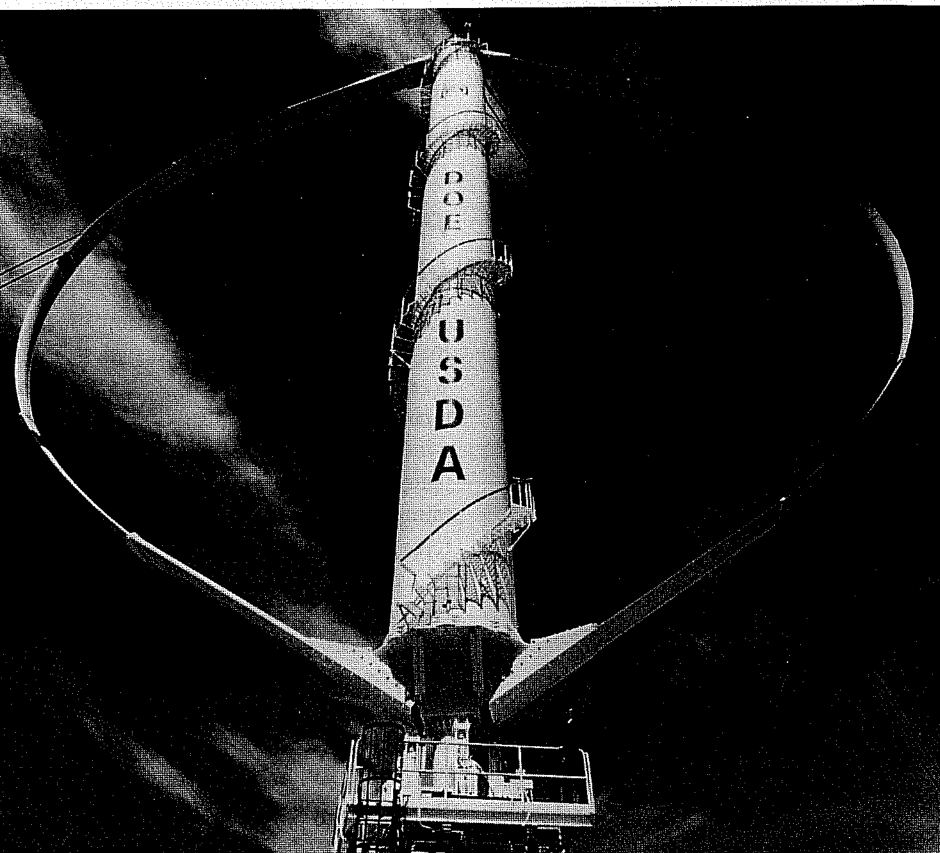
PNL studies address utility concerns

The nature of the wind resource is a major factor in investment decisions in wind energy. PNL addresses this concern through research into the nature of the wind, improved methods for siting power plants to maximize energy capture and minimize power losses, improved wind forecasting methods, and studies of the requirements of utility companies. In FY 1990, PNL began evaluating whether chaos theory could be used to accurately predict wind variability. (Chaos theory is a mathematical formulation for describing an apparently random sequence of events.) PNL's initial steps included working with the Nonlinear Dynamics Laboratory at Los Alamos National Laboratory. The laboratory studied the aspects of wind variability relevant to wind power production and provided information on using chaos as a tool for prediction.

In FY 1991, PNL began a new approach to evaluating National Weather Service forecasts. PNL is comparing official weather forecasts with actual weather conditions that occurred at the California wind power plants, where PNL conducts its ongoing turbulence measurement studies. In addition, PNL is comparing wind forecasts made by its meteorologists and the National Weather Service with wind conditions at the laboratory site in Richland, Washington.

NREL studies forces that affect wind turbine performance

The aerodynamic interactions between the wind and a wind turbine blade are quite complex. To identify the fundamental



Y 1990 tests at Sandia's 34-m test bed in Bushland, Texas, opened the door to the
ommercialization of an advanced, vertical-axis wind turbine.

nteractions, researchers at NREL designed ne Combined Experiment, a simple wind urbine instrumented to measure pressure long the blade. With assistance from andia, NREL researchers also developed arious methods to observe wind flow long the blade, including using a video amera to provide a record of flow visualzations, which later could be synchronized vith blade measurements to allow qualitaive and quantitative analyses.

In FY 1990, NREL's Combined Experiment continued to yield new insights into he stall behavior of wind turbine blades. Stall is the term denoting the loss of lift hat occurs when airflow becomes letached from the blade. Because stallontrolled turbine blades spend anywhere rom 20% to 40% of their service lifetime n stall, the condition affects both peak erformance and turbine loads.

In FYs 1990 and 1991, Combined Experiment tests showed that centrifugal forces create a flow of air out toward the blade tip that is experiencing stall. Researchers think this effect may increase the lift on inner portions of the blades, thereby yielding higher than predicted power output. These forces also lead to significantly higher blade stresses and probably account for many wind turbine failures. This study is already helping researchers develop and validate more sophisticated aerodynamics and fatigue codes. These will soon allow designers to better estimate peak wind turbine loads and build larger, more efficient, and durable wind turbines.

Sandia seeks blade performance improvements

Sandia launched two new studies in FY 1991 aimed at improving turbine blade performance. The first looks at the effect of adding small perpendicular tabs to blade sections near the tower. Called vortex generators, these tabs are widely used on airplane wings to re-energize the airflow and keep the flow attached to the wing. If they perform as expected on turbine blades, vortex generators will delay stall and increase the turbine's energy capture.

Another study will investigate why increased power output is associated with bug debris accumulation on Sandia's new Natural Laminar Flow (NLF) VAWT blades. Sandia researchers postulate that this may occur because the bugs on the blades act like tiny vortex generators and delay stall. Researchers at Ohio State University are investigating this phenomenon.

Advanced components research supports the development of advanced wind turbines

One approach to successful technological innovation is through incremental improvements in existing technology. In FYs 1990 and 1991, researchers at NREL and Sandia continued to develop and test advanced components that promise to lower the cost of energy for HAWTs, VAWTs, and wind/diesel hybrid systems.

FY 1990 tests at Sandia's 34-m test bed in Bushland, Texas, have opened the door for the commercialization of an advanced VAWT. This program began in the early 1980s with the design of NLF blade crosssections for VAWTs. The test-bed blades contain these NLF sections, which are tailored to the environment at appropriate regions of the rotor blade. In the test bed evaluation, using an NLF blade crosssection resulted in a 15% increase in nergy capture when compared with a raditional blade. The NLF blade also chieved a significant reduction in the urbine's peak power output while main-aining a constant level of energy capture. This reduction in peak power output trans-ates to important cost savings for future /AWTs because it means they may require ess massive and durable construction han today's machines.

In another experiment, the NLF blades vere streamlined by covering rough spots long the blade where different sections oin together. Using the streamlined blade urfaces led to a measurable improvement n turbine performance at low wind speeds.

In addition to blade tests, Sandia also onducted a series of vibration and other erformance tests on the test bed to vali-ate and further refine Sandia's analytic odes and models. The test results sug-ested that the new NLF blades and other esign improvements built into the test bed ould lower energy costs by as much as ne half—if they were incorporated into commercial turbine design.

Sandia researchers conducted a theoreti-al design study, in which they identified hose components and systems in the 34-m est bed that were appropriate for a second-eneration, commercial VAWT. An anal-sis of their design indicated that such a urbine could improve energy capture from 0% to 50% over existing commercial nits, with resulting new energy costs pproaching $0.05 to $0.06/kWh. These esults were presented to wind industry epresentatives in May 1990 and at an ASME meeting in March 1991. In FY 1991, Sandia began transferring this ew technology to industry to encourage s incorporation into future commercial urbines.

NREL airfoils win industry and government awards

NREL's successful multiyear study o develop new special-purpose airfoil amilies for stall-controlled HAWTs received widespread recognition in FYs 1990 and 1991. The Federal Laboratory Consortium awarded the Advanced Airfoils Project Test Group its 1990 Award for Excellence in Technology Transfer. The American Wind Energy Association awarded NREL its Technical Achievement Award "for pointing the way toward substantial improvements in wind turbine blade performance." The project leader also received a 1990 NREL Staff Award for Outstanding Achievement "for the design, development, and testing of new special-purpose airfoils, which are recognized by the wind industry as a significant breakthrough in wind turbine performance and control." The series of honors culminated in 1991, when the new NREL airfoil family won a prestigious R&D 100 award. This award is given every year by *Research & Development* magazine to the year's 100 most important inventions and new products.

Widely considered as one of wind power's most significant technical improvements, the NREL airfoils have now been incorporated into two new types of blades, 7.9-m and 9.7-m long. Tests conducted in FYs 1990 and 1991 showed that both blades increase annual energy production by up to 30%. The NREL design blades are potential replacement blades for more than 5000 turbines currently operating in California wind power plants.

University of Colorado and NREL launch an advanced generator project

Under DOE's University Participation Program at NREL, the University of Colorado has begun studying a permanent magnet generator that can operate at variable speed. The generator design, which incorporates power electronics, eliminates the need for a gearbox. Researchers say it could cost less and be significantly more reliable than today's generators.

Computer studies enhance wind/diesel systems

Studies of hybrid wind/diesel systems have several key objectives: to improve the understanding of wind/diesel systems under a variety of operating conditions, to identify and study the control characteristics of wind/diesel systems, and to establish a reliable method for assessing wind/diesel costs.

In FYs 1990 and 1991, two NREL subcontractors, the University of Massachusetts and Electrotek Concepts, Inc., made important progress in developing computer models of wind/diesel systems. At the University of Massachusetts, researchers upgraded software to improve the operation of the university's wind/diesel simulator. They also refined their University of Massachusetts Long Term Model wind/diesel system modeling software for a 1990 presentation to Alaskan officials interested in wind/diesel systems for remote power production. Most recently, they programmed the model to determine the cost trade-offs for using wind to reduce diesel fuel consumption for power generation.

Electrotek used a commercially available program for modeling power system behavior, the Electromagnetic Transients Program, to model the generator that would be used in a typical wind/diesel system. Researchers also used the program to model a dynamic brake, in which the generator soaks up energy from the machine and brings it to a stop.♦

U.S. Department of Energy

Wind Energy

Program Overview FY 1992

Wind Turbine Development

The development of technologically advanced, high-efficiency wind turbines is a high priority of the U.S. wind industry and the federal wind program.

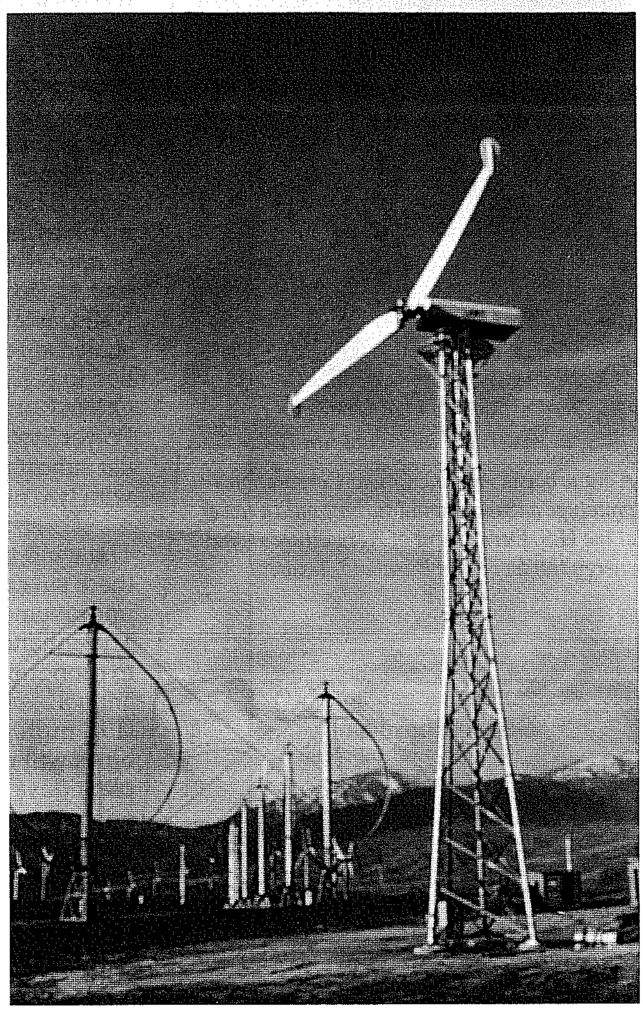
The next 5 years are critical for the U.S. wind industry. Market opportunities in the United States, Europe, and the rest of the world are multiplying as national governments, utilities, and the public become aware of wind energy's potential for delivering affordable electricity while protecting the environment. In the attempt to capture a significant share of these markets, the U.S. wind industry will face stiff competition throughout the 1990s from well-capitalized European and Japanese firms. DOE has designed its turbine development programs to help the U.S. wind industry meet this challenge.

The Advanced Wind Turbine Program

In FY 1992, the program continued to support the U.S. industry in developing and integrating advanced technologies into utility-grade wind turbines. DOE expects the first wave of advanced turbines from the AWT Program to be commercially available between 1993 and 1995. These turbines are being designed to produce electricity for $0.05/kWh at sites with moderate annual average wind speeds of 6.9 meters per second (mps) (15.4 mph) at turbine hub heights. Such energy costs will make wind energy competitive with the most expensive forms of conventional electric generation. However, with the new 1.5¢/kWh production tax credit, wind plants equipped with these new advanced turbines should be competitive with many electric power technologies.

AWT Program: Conceptual design studies

In early FY 1992, industry subcontractors completed the first phase of the AWT Program, conceptual design studies for advanced wind turbines. The conceptual design studies allowed industry designers to comprehensively analyze many different turbine improvement ideas. These efforts did not include building hardware. This work began in 1990 and identified improvements to existing wind turbine designs and manufacturing methods that would make wind energy more competitive by the mid-1990s. The project also produced conceptual



R. Lynette & Associates

R. Lynette & Associates developed this prototype advanced wind turbine as part of DOE's Advanced Wind Turbine Program.

AWT

This is the logo of the AWT Program.

Dave Jager, NREL

A crane hoists Atlantic Orient Corporation's prototype advanced wind turbine onto a tower at the U.S. Department of Agriculture's wind energy test facility in Bushland, Texas.

studies of innovative wind turbines designed for low-cost, bulk power generation over large geographic regions in the 21st century.

The conceptual design studies revealed several improvements to existing turbines that could reduce the cost of energy. These improvements included larger rotors incorporating advanced airfoils developed at NREL, flow-through rotor structures, aileron controls, and integrated gearbox/mainframe systems. During the second phase of the AWT Program, industry subcontractors will incorporate many of these improvements into advanced wind turbine prototypes.

AWT Program: Development of improved turbines by the mid-1990s

The second phase of the AWT Program (the Near-Term Product Development Project) began in FY 1992. This phase involves the development and testing of improved turbines for the mid-1990s' market. To accomplish this objective, NREL awarded $4.4 million for cost-shared subcontracts totaling $7.3 million to R. Lynette & Associates, Atlantic Orient Corporation, and Northern Power Systems. Negotiations for similar subcontracts are still under way with two other companies.

The wind turbines resulting from these subcontracts will incorporate improvements into existing machines. The enhanced turbines should be able to economically generate electricity at annual average wind speeds of 6.9 mps (15.4 mph) at hub height. The new turbines will make it possible for wind plant developers to take advantage of windy areas in the Pacific Northwest, the Great Plains, and the Midwest.

Engineers at R. Lynette & Associates are developing a prototype turbine as part of the company's AWT subcontract. The new turbine should be ready for field testing in FY 1993. Based on the ESI-80, it will include an improved rotor system tested at Smith Wind Energy Corporation under the DOE Wind Technology Applications Projects (WTAP, see p. 13). The WTAP supported the fabrication and testing of a new set of 12-m, wood/epoxy blades built by Gougeon Manufacturing Corporation during early 1992. Incorporating advanced NREL-designed thick airfoils, the new blades performed well, increasing energy production by more than 50%. Researchers also tested new tip brakes mounted on the blades. Tip brakes pop out at the end of a turbine blade to prevent a rotor from overspeeding and therefore damaging the turbine.

Under another 1992 WTAP subcontract, Gougeon Manufacturing Corporation produced new 7.5-m wood/epoxy blades as potential replacement blades for aging Enertech-44 wind turbines, hundreds of which still operate in California wind power plants. The blades incorporated NREL-designed airfoils and passed a grueling fatigue test at NREL's Wind Energy Test Center.

Atlantic Orient Corporation now plans to test a new rotor system incorporating these new blades on a prototype 50-kW wind turbine currently under development as part of its AWT subcontract. Under a cooperative agreement signed with the U.S. Department of Agriculture (USDA) in FY 1992, the company will test the new turbine at USDA's wind energy test facility in Bushland, Texas.

During FY 1992, Northern Power Systems also successfully launched its advanced turbine development project by developing new aileron controls. In designing new controls, the company combined its own ideas with a wealth of information from earlier DOE-sponsored work with the National Aeronautics and Space Administration (NASA). Northern Power tested its new controls on two wind turbines, and, in both cases, the ailerons performed well.

AWT Program: Development of next-generation wind turbines

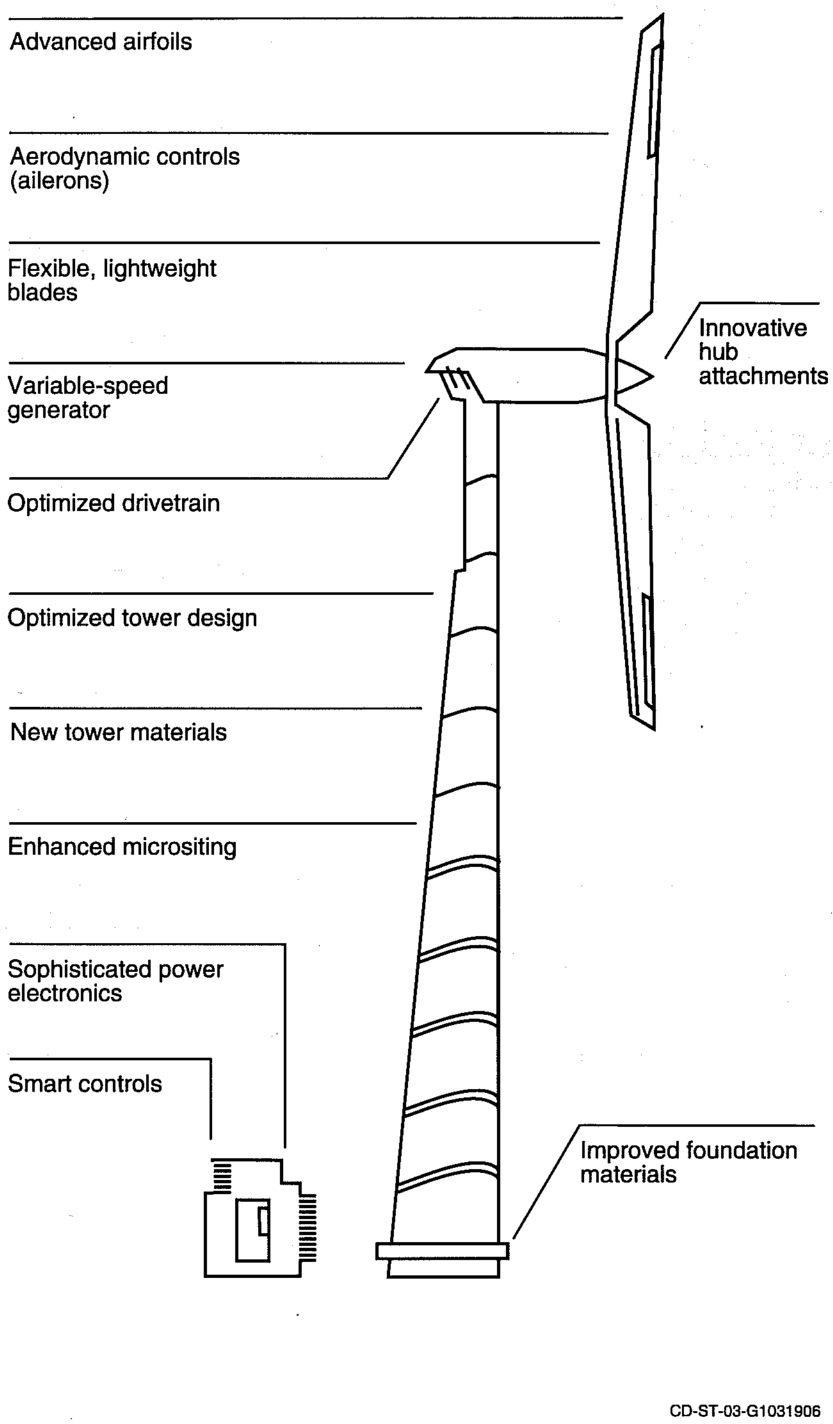
Even as its subcontractors were successfully developing improved near-term wind turbines, NREL began making plans for the third phase of the AWT Program: the development of next-generation, utility-grade wind turbines. DOE expects these turbines to feature a variety of innovations, some of which were identified in the program's conceptual design studies. These innovations included improved airfoils optimized for aerodynamic controls such as ailerons; structurally tailored blades; aerodynamically shaped, rotating towers; advanced materials; integrated drivetrain assemblies mounted to tower top castings; and taller towers. These innovations should significantly reduce turbine costs and improve turbine performance.

The next-generation product development project will begin in FY 1993. The AWT Program's goal is to develop, by 2000, innovative utility-grade turbines that produce electricity for $0.04/kWh or less at sites with moderate annual average wind speeds of 6.9 mps (15.4 mph) at 30-m hub heights.

Innovations for next-generation wind turbines

During FY 1992, researchers worked on several innovative components and systems for wind turbines. At the University of Colorado (CU), for example, researchers developed four designs for permanent magnet generators capable of low-speed, variable-speed operation. Variable-speed generators allow the turbine rotor to slow down or speed up, depending on the wind. This reduces wear and tear on the rotor and drivetrain and can increase energy capture by 10% to 15%.

The Advanced Wind Turbine Concept



This is an artist's rendition of the proposed turbine enhancements under consideration in the Advanced Wind Turbine Program.

CU's designs are for generators that spin at the same rate as the rotor. This allows the generator to be directly connected to the wind turbine rotor shafts, eliminating the need for heavy and expensive transmission and gearing.

Researchers have selected a promising design for development and testing. Unique Mobility, Inc., a Colorado company that specializes in lightweight, durable electric motors for automobiles and buses, will assemble the new generator in FY 1993.

Expert control systems may one day operate wind power plants

Wind power plant operators direct plant operations and maintenance from a central control center. This saves time and money, because operators can ascertain the status of a malfunctioning wind turbine before dispatching maintenance personnel into the field.

With an eye to the future, Sandia researchers have begun evaluating the potential of an existing computerized turbine control simulation. In FY 1992, they identified several advanced control concepts for further development during the next few years. Sandia researchers believe they can eventually create advanced, expert control systems. An expert control system uses computer software that incorporates artificial intelligence. Such a system could control a single wind turbine, an array of turbines, or even supervise all of the turbines in a wind plant.

An expert control system could detect a wind gust at the entrance to a wind plant and then adjust turbines in the path of the turbulent air to maximize energy capture and minimize damage to the turbines. These adjustments might include commands to shut down, start up, deploy tip brakes, change the orientation of the rotor with respect to the wind, or reorient ailerons on the blade.

In the 21st century, expert control systems will automatically manage turbines by evaluating wind conditions, site characteristics, seasonal and diurnal wind patterns, and turbine operating conditions. At any given moment, the control systems could issue instructions to individual turbines to maximize total power plant output.

In FY 1992, Sandia researchers also made steady progress on a computer-based maintenance system to help maintenance personnel troubleshoot an ailing wind turbine. They made the computer program for the system more "user friendly." They also developed a similar maintenance system that runs on personal computers instead of Sandia's mainframe Cray computer.

Innovations appear on the horizon

Although it's impossible to anticipate all the innovations that could find their way into the next generation of wind turbines, a few have already appeared on the horizon.

Aerodynamic controls will incorporate movable blade parts like ailerons into turbine blades. These controls change the amount of lift and drag on the turbine blades and can provide reliable power regulation and braking in high winds.

Structurally tailored blades made of soft, flexible materials will change shape in response to aerodynamic and structural loads. These blades will capture the maximum possible wind energy because wind speeds will control the shape of the airfoil. The blades could also change shape to reduce loading during high winds.

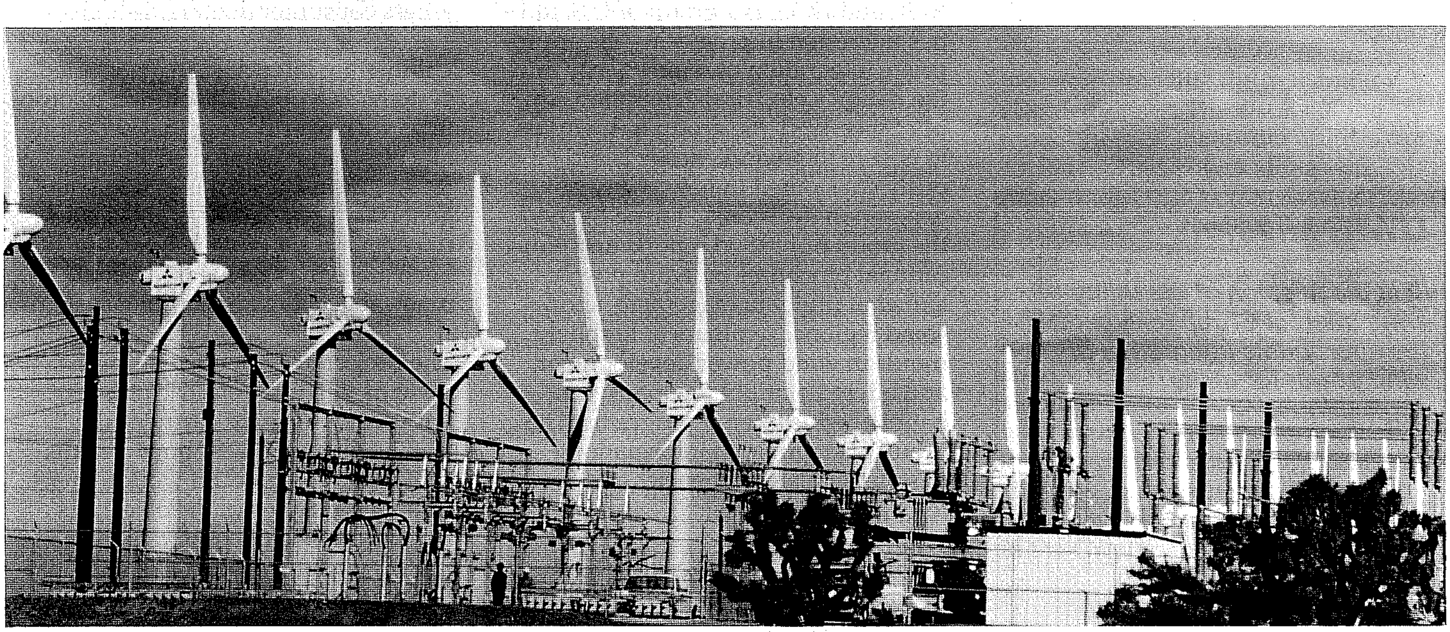
Rotating, airfoil-shaped towers made of stronger, lightweight materials will be twice as tall as today's models. Because taller towers expose the turbine to higher wind shear and lower wind turbulence, they significantly improve energy capture. The innovative shape will help eliminate turbine noise and the unwanted vibrations caused when the turbine blades pass behind the tower.

Utility Programs

DOE and the Electric Power Research Institute (EPRI) are working together to help utilities play a central role in the evolution of wind energy technologies.

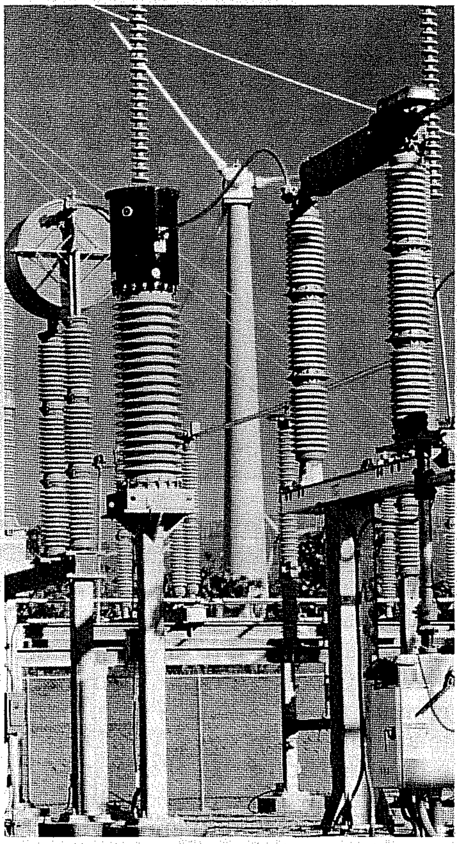
The U.S. utility industry is the primary market for wind turbines developed under DOE's AWT Program. Opening up this market requires that utilities gain direct, hands-on experience operating wind power plants. DOE and EPRI designed the Utility Wind Turbine Performance Verification Program to give utilities the opportunity to gain first-hand experience with a modern wind power plant that uses the latest technology. This will allow utilities to study costs, utility integration issues, turbine reliability, and the environmental impacts of wind energy in a typical utility environment. The program will provide a bridge from today's turbine development programs to commercial purchases of utility-grade wind turbines. It will also help educate energy decision makers and the general public about the cost-effectiveness of wind energy and its environmental and energy-security benefits.

Launched in FY 1992, the new program is taking a major step toward a national goal of accelerating the commercialization of wind power. EPRI and DOE plan to support up to four projects in different regions of the country. Each project will include a minimum of 20 turbines, with a nominal rating of 300 kW each, for a total of approximately 6 MW. DOE estimates that the cost of each new wind plant will be approximately $10 million, with EPRI and DOE contributing up to $3 million of this amount.



SeaWest Industries, Inc.

California's wind power plants have reliably delivered electricity to utilities for more than 10 years.


SeaWest Industries, Inc.

Host utilities will evaluate wind energy as a resource for meeting U.S. electricity needs in the 1990s and beyond.

A competitively selected host utility (or consortium of utilities) will lead each project. The host utility will select the power plant site, solicit bids for turbines from wind industry vendors, and purchase the turbines. The host utility will also be responsible for power plant design, construction, and start up. With assistance from DOE and EPRI, the host utility will conduct a minimum of 3 years of testing, evaluation, and documentation of the new wind power plant.

In parallel with the Turbine Verification Program, DOE is supporting wind initiatives issued by the Bonneville Power Administration as part of its activity to expand energy resource alternatives in the Pacific Northwest. In the future, DOE plans to work closely with the nation's power marketing administrations to develop the nation's wind resources.

Utility Wind Interest Group members support wind energy initiatives

The Utility Wind Interest Group (UWIG), organized and supported by EPRI and DOE, is a group of U.S. utilities interested in promoting the appropriate integration of wind energy into the nation's electrical generation supply. Since 1990, the group has worked to ensure that wind energy is seriously considered in new utility power generation decisions. During FY 1992, the group published reports and educational brochures on wind power aimed at utility management, sponsored regional seminars to highlight trends in wind power development, and offered a utility perspective to national wind energy programs. The group also provided information to state regulatory agencies and legislative programs.

During FY 1992, the New England Power Service Company, the Pasadena Water and Power Department, the United Power Association, and the Wisconsin Electric Power Company joined the group. Other active UWIG members included the Bonneville Power Administration; Green Mountain Power Corporation; Hawaiian Electric Industries, Inc.; Niagara Mohawk Power Corporation; the Northern States Power Company; the Pacific Gas and Electric Company; Southwestern Public Service Company; and the Western Area Power Administration.

UWIG Mission

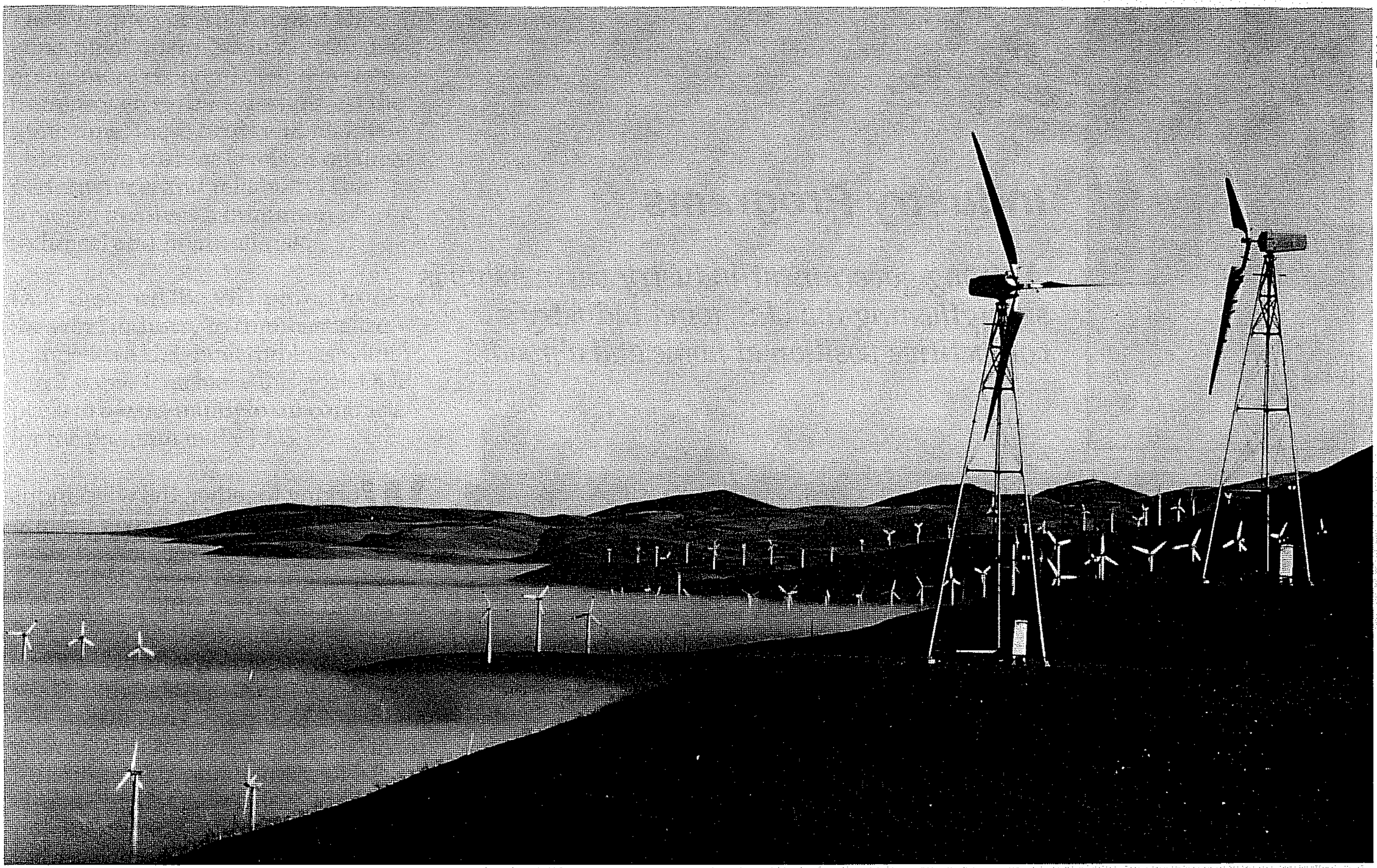
It is the mission of the Utility Wind Interest Group to expedite the appropriate integration of wind power for utility applications.

DOE launches distributed wind generating system project

The DOE Wind Energy Program assists utilities by sponsoring projects to explore novel applications of wind energy. In FY 1992, NREL developed a cost-shared utility/industry project to evaluate distributed wind generating systems. Distributed systems deploy small power-producing facilities at different locations, rather than using a large, central-station generating facility. This project will assess the benefits of adding small wind turbine systems (rated at 50 kW or less) to a utility distribution network at sites where consumer demand is high.

Utilities are interested in distributed systems as a possible solution to problems with overloading that occasionally occur in existing distribution feeder lines. The idea is to add small generating systems near areas where the demand for power is greatest. Such areas may be ideal for small, renewable energy generating systems.

The project to evaluate distributed systems will team electric utilities with wind industry partners; the teams will then assess how well distributed systems could work to meet utility needs. One of the objectives of the project is to demonstrate the benefits of matching predictable wind patterns with the demand for electricity.



Ed Linton

During windy summer periods in Northern California, wind energy produces as much as 8% of the electricity used within Pacific Gas and Electric Company's service area.

Researchers study utility issues

As interest in wind energy grows, utilities are beginning to grapple with the problem of putting a value on this energy source. Previous assumptions that wind is not dispatchable (because it is intermittent) may not tell the whole story. Experience in California's Altamont Pass and Solano County has shown that winds are predicted reasonably well in those areas. If utilities know that there is a high probability of wind power at certain times of the day, or at certain times of the year, then wind energy may have value in offsetting baseload capacity. If so, wind energy would deserve some capacity credit. The question is, how much?

In FY 1992, NREL researchers began trying to answer this question with a computer model developed by the Environmental Defense Fund. Called "ELFIN," this electric utility financial and production cost model is designed to explore the economic and environmental implications of different strategies for utilities to increase generating capacities.

NREL researchers incorporated wind data from a California utility into the ELFIN model and ran several test cases. They then used the model to estimate the value of a 100-MW wind plant to a utility. Preliminary results suggested that the value of wind energy is significant to utilities with a predictable wind resource. The value is even higher if the winds blow at the same time that the demand for electricity rises. The results of the model suggest that some utilities can consider wind power along with more traditional resources when they plan for future generation needs.

During FY 1992, DOE also sponsored a study of transmission issues related to wind energy and other renewable energy resources. Researchers evaluated transmission capacity in areas with high wind resources, studied the prospects of sharing transmission facilities, and evaluated the economics of developing two resource areas in the Great Plains.

Industry Programs

A strong government/industry partnership is strengthening the U.S. wind industry's competitive position at home and abroad.


R. Lynette & Associates

Under the Value Engineered Turbine Project, researchers will look at ways to make proven wind turbine designs more cost competitive in today's global energy markets.

Working together, the wind industry, independent power producers, utilities, and the U.S. government have brought wind energy to the threshold of being a utility-scale, power-producing technology. They've also made wind energy a key technology for village electrification and water pumping. The government/industry partnership is proving crucial to maintaining U.S. competitiveness in global wind energy markets. In support of this important objective, the DOE Wind Energy Program supports a variety of cooperative programs with industry.

DOE establishes new Value Engineered Turbine Project

In FY 1992, the DOE Wind Energy Program began a Value Engineered Turbine (VET) Project to improve the cost effectiveness, reliability, and manufacturing quality of the wind turbines operating in today's wind power plants. DOE designed the new project to directly profit from the expertise of California wind plant operators. Although many of the wind turbines they use are very reliable, the cost of energy from these 1980s-vintage machines is too high to be competitive in today's rapidly evolving global markets.

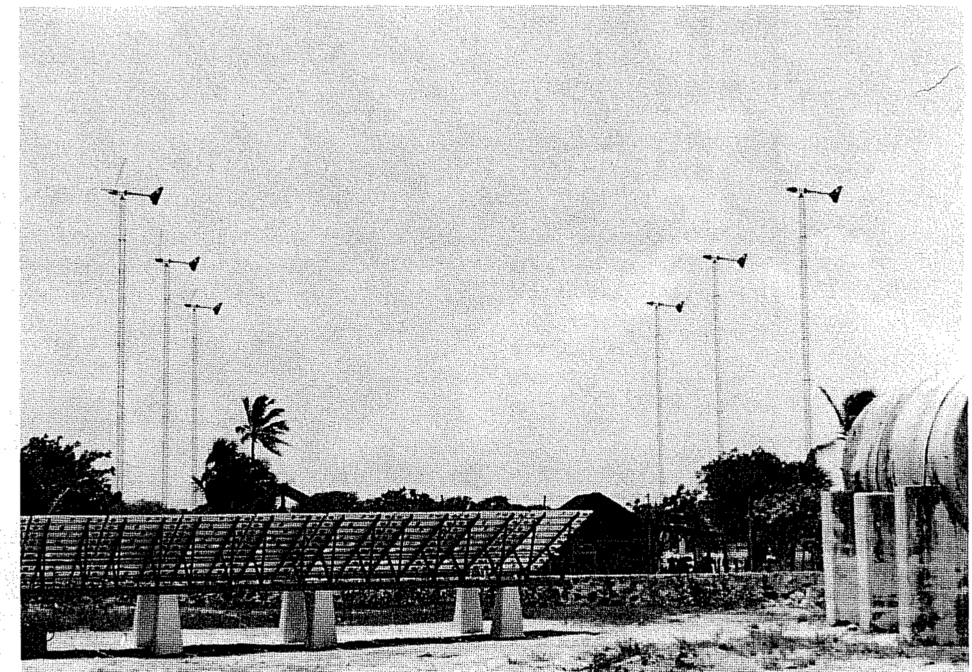
The VET project will support U.S. wind plant operators in rapidly developing more economic wind systems from proven turbine designs. At the same time, these firms will maintain or improve current levels of quality, performance, and reliability. This strategy involves a minimum of technical and financial risk.

DOE designed the VET project to allow the wind industry to commercialize competitive U.S.-built turbines within 1 to 2 years. To achieve this goal, DOE plans to award multiple subcontracts for the program in FY 1993.

DOE funds new Wind Technology Applications Projects

In FY 1992, DOE funded seven cost-shared subcontracts to industry under its Government/Industry Wind Technology Applications Projects. The projects focus on enhancing the performance, efficiency, and reliability of wind plants; encouraging regional diversity for wind power in the United States; and defining new wind energy applications.

DOE's industry partners include Northern Power Systems; Bergey Windpower; Zond Systems, Inc.; Hawaiian Electric Renewable Systems; FloWind Corporation; Atlantic Orient Corporation; and Smith Wind Energy Corporation. These companies are providing from 23% to 93% of the funding for the cooperative projects. The projects include design support for a new village electrification system, a power inverter development project, a wind power plant performance improvement project, an aileron retrofit project for 600-kW wind turbines, a project to develop and test a new rotor for a vertical-axis turbine, and two activities to develop new blades for horizontal-axis turbine rotors. In a related area, DOE also funded a wind/diesel system analysis.



Bergey Windpower

Bergey Windpower installed six wind turbines near Xcalak, Mexico, to help provide electricity for a remote fishing village.

Remote wind energy systems to compete in overseas markets

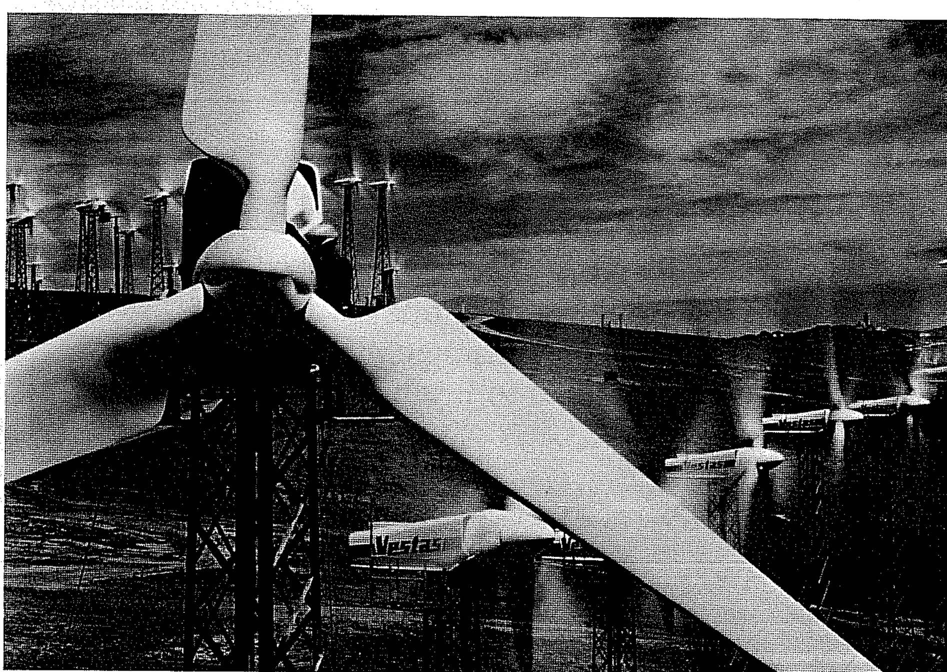
Village electrification in regions currently without electricity represents a significant market opportunity for small wind systems. Northern Power Systems hopes to tap this market with its modular "rotary village power system" unit. The hybrid power plant consists of a diesel engine, a battery bank, system controllers, a power conditioning unit, and one or two 50-kW wind turbines. The company plans to install the stand-alone system in a remote area of Alaska. NREL and Sandia's Design Assistance Center will assist the company in evaluating the system at the site.

In August 1992, Bergey Windpower installed six 10-kW wind turbines near Xcalak, Mexico, on the southeastern tip of the Yucatan peninsula. The turbines were part of a village electrification project to provide power for 41 homes in the remote fishing village. The project replaced diesel generators that had been abandoned.

Technical assistance and funding are provided through the federal Committee on Renewable Energy Commerce and Trade (CORECT).

During FY 1992, the University of Massachusetts enhanced its computer model of a wind/diesel hybrid system to include three diesel engines and up to 20 wind turbines. Researchers also added battery storage and an option to add a module of photovoltaic cells to the model. In the laboratory, researchers upgraded their wind/diesel system simulator by modifying the system controller and adding a second, variable-speed diesel engine. Variable-speed engines are expected to operate more efficiently over a wider range of conditions and can save a substantial amount of fuel.

Bergey Windpower received funding for a project to improve the design of inverters used with stand-alone renewable energy systems. Inverters change direct current into alternating current. Bergey's new inverter should be more rugged than were the older



Lloyd Herziger, Zond Systems, Inc.

During FY 1992, Zond Systems, Inc., began a joint project with NREL to look at ways to improve the performance of its 65-MW wind plant located in California's Tehachapi region.

models. Its current output will also be adjustable to conform to the power requirements in either Europe or the United States.

New project aims at improving wind power plant

During FY 1992, Zond Systems, Inc. and NREL began a joint project to evaluate ways to improve the performance of a 65-MW wind plant located in the Tehachapi region of California. Several activities are under way to accomplish this goal. In one series of tests, researchers are comparing the performance of new fiberglass turbine blades with conventional blades. The new blades incorporate NREL-designed thin airfoils, and the conventional blades use standard LS-1 airfoils. In 1992, researchers evaluated the performance of the LS-1 airfoil under normal operating conditions and in a simulated roughness test. For the latter test, researchers took strips of tape embedded with metal particles and attached them to the blades. The tape simulated soiling from insects and dirt.

Researchers also looked at loads induced on the turbine rotor when metal extenders were placed between the rotor hub and the blades to increase rotor diameter. Then they compared the loads induced by blades with these extenders with loads on normal blades. During FY 1993, researchers will repeat these tests on the same wind turbine equipped with blades that incorporate NREL-designed airfoils.

As part of this project, Zond also plans to measure the effects of yaw control improvements on loads and performance. In addition, the company plans to evaluate the potential for improving energy capture by relocating turbines within the wind plant. Zond will use computer models to predict energy output from proposed wind park layouts. The company will use an advanced data-acquisition system it developed for NREL (see p. 15) to instrument wind turbines for its many project activities.

New aileron controls enhance turbine performance

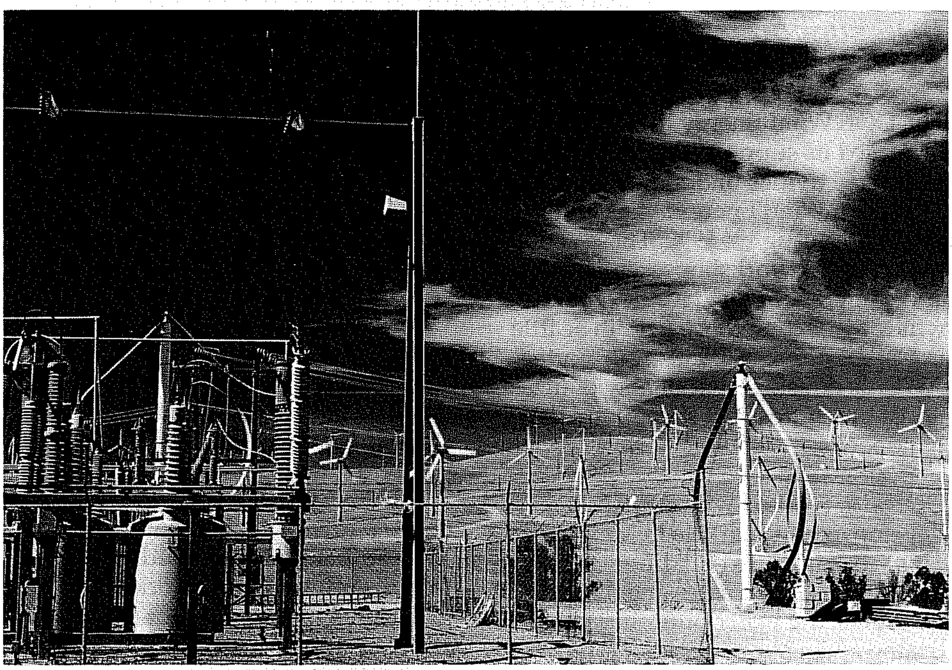
In FY 1992, Hawaiian Electric Renewable Systems, Inc. began a joint project with NREL to develop aileron controls for the company's 600-kW wind turbines located on the island of Oahu. When extended out from the turbine blade, aileron controls slow a rotating wind turbine. Company officials expect the aileron controls to replace the turbines' trouble-prone hydraulic pitch-control systems.

Ailerons effectively control aerodynamic forces on a turbine rotor. They also allow turbines to respond more effectively to high winds. During severe turbulence, the Hawaiian turbines must run at half their rated power to avoid power spikes that may damage the drivetrain and generator. With aileron controls, the turbines could safely run at their full rated power.

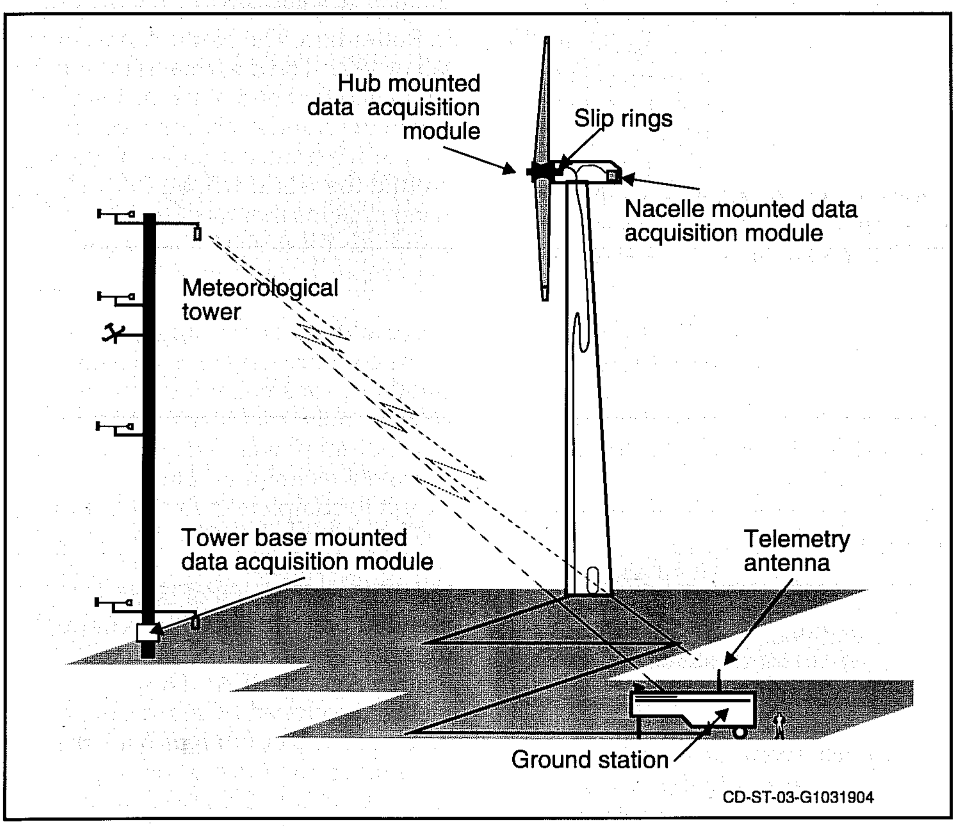
During 1992, project participants completed three designs for aileron controls, tested them in Wichita State

Hawaiian Electric Renewable Systems, Inc.

These 600-kW wind turbines will get new aileron controls developed under a Wind Technology Applications Project launched in FY 1992.



As part of a cooperative research project, FloWind Corporation will develop and test a new, high-energy rotor for its vertical-axis wind turbines, shown here.



Advanced data acquisition system developed by Zond Systems, Inc. for NREL.

University's wind tunnel, and selected a design to use in a full-scale test on one of the Hawaiian turbines in 1993.

Sandia and FloWind develop new rotor for vertical-axis turbines

In FY 1992, FloWind Corporation and Sandia began a cooperative project to develop, test, and evaluate a new, high-energy rotor for FloWind's 19-m vertical-axis wind turbine. (Eggbeater-shaped, vertical-axis turbines rotate parallel to the ground.) FloWind's new rotor will incorporate natural laminar airfoils developed at Sandia. These airfoils are specially designed to keep air flowing smoothly over them. Because the airfoils effectively regulate maximum power output, the new rotor will be larger, produce more power, and operate at lower wind speeds. The new rotor should also dramatically increase the turbine's annual energy output.

During FY 1992, Sandia transferred computer codes developed for vertical-axis turbines to FloWind. Sandia set up the codes to assist FloWind in optimizing its rotor design in terms of the design's impact on projected revenue streams from the wind plant. FloWind has already begun evaluating the optimum size for the new rotor and is looking at low-cost methods for building new blades.

NREL sponsors advanced measurement system for wind turbines

In FY 1992, NREL awarded Zond Systems, Inc. a subcontract to develop an accurate, reliable measurement system designed to obtain experimental data from operating wind turbines in the field. Developed in just 3 months, Zond's rugged and low-cost advanced data-acquisition system (ADAS) promises to make field test measurements simple, accurate, inexpensive, and reliable.

The modular system uses digital electronics and telemetry to obtain signals from multiple sources simultaneously. This means that wind plant operators or researchers can mount ADAS modules directly on rotating blades, towers, nacelles, control systems, meteorological towers, or electrical stations. The modules operate accurately even when subjected to temperature extremes, vibration, noise, or other harsh environmental conditions. Unlike other measurement systems, they do not require lengthy, cumbersome cables to relay information to central data storage areas.

PNL, wind industry collaborate on turbulence studies

Since 1990, PNL has collaborated with the wind industry to better understand wind turbulence and its effect on power production. Turbulence results from the interaction of uneven terrain and vegetation with variable atmospheric conditions and wind velocities. It can affect power output and damage turbine components. PNL is currently studying wind turbulence at six sites: four in California, one in Vermont, and one in New York.

During FY 1992, these studies showed that an array of comparatively low-cost towers and sensors can accurately measure the effects of local terrain features on the wind inflow to turbine blades. In particular, PNL demonstrated that special processing of pulsed signals from a rugged and inexpensive anemometer works as well as using a more expensive, but less sturdy instrument.

During FY 1992, PNL also developed new analysis methods that can relate upwind terrain features to specific kinds of damaging turbulence. This work has provided new insights into both wind turbine design and site selection.

DOE supports wind industry activities

The DOE Wind Energy Program increased its support of technology transfer activities undertaken by the American Wind Energy Association (AWEA) during FY 1992. These activities included workshops, seminars, and conferences, such as the annual windpower conference held in Seattle in October 1992. DOE also supported AWEA's development of new educational brochures, fact sheets, and user handbooks.

DOE also worked with AWEA to develop export markets in Mexico. This work included holding workshops on resource assessment and wind/electric water pumping, establishing an anemometer loan program, and supporting a reverse trade mission in which representatives from Mexico visited U.S. wind plants and attended U.S. wind energy conferences and workshops. In addition, the U.S. Agency for International Development agreed to sponsor a joint project for the development of wind power in Mexico. Under a contract signed in late 1992, AWEA, NREL, and Sandia will conduct a cooperative wind resource assessment in Mexico.

DOE, AWEA work to develop international standards

During FY 1992, DOE continued its ongoing work with AWEA to develop industry consensus standards for wind turbine generating systems. These activities, carried out in conjunction with the International Electrotechnical Commission, are vital to U.S. competitive interests. Matching international wind turbine standards to U.S. industry standards will ensure that U.S.-made turbines can compete in the multibillion dollar worldwide wind energy markets expected to develop by 2000.

Working with AWEA, the Wind Energy Program is working to develop uniform standards for the design, installation, performance, and safety of wind systems around the world.

Activities to establish international standards made significant progress during 1992. Representatives from AWEA, NREL, Sandia, and PNL were active participants in these endeavors. The commission combined proposals from its original three working groups into a single standards document entitled "Wind Turbine Systems." The commission distributed the draft document along with a strategic policy statement (written in English and French) at a meeting held in Rotterdam, The Netherlands, in the fall of 1992. The draft standard will be circulated for comments during 1993. When the standard is approved by the participating countries, utilities around the world will be able to buy wind systems that meet uniform standards for design, installation, performance, and safety.

Three additional working groups of the commission are establishing standards for small wind turbines, acoustic noise measurement techniques, and power performance measurement techniques. These groups expect to complete their work during 1993. In addition, NREL, PNL, and industry technical staff are supporting the development of recommended practice documents under the auspices of the International Energy Agency (IEA). These documents, developed by groups of international experts, often provide the basis for future International Electrotechnical Commission standards.

The Wind Resource

Wind energy is not resource-limited in the United States.

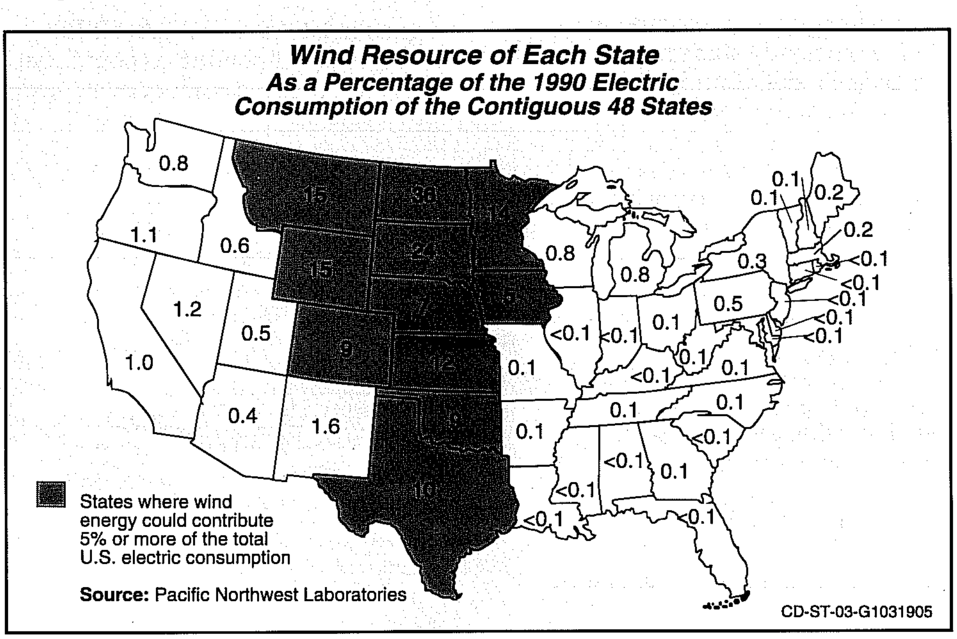
According to ongoing studies at PNL, there is enough wind potential in the continental United States to produce approximately 4.4 trillion kWh of electricity each year. This is more than one and one-half times the 2.7 trillion kWh of electricity consumed in the United States in 1990.

In developing wind electric potential estimates for all 48 contiguous states, PNL excluded urban areas, half of the nation's forested ridge crests, 30% of agricultural lands, and 10% of rangelands. The laboratory also excluded parks, wilderness areas, wildlife refuges, and other areas where wind energy development would be prohibited or severely restricted.

In FY 1992, PNL refined its estimates of wind electric potential within each individual state. PNL researchers developed detailed maps that show the distribution of windy areas suitable for wind energy development. The new maps display this information in grid cells measuring 1/4° latitude by 1/3° longitude, or about 28 km by 28 km (15 mi. by 15 mi.).

In windy areas of the Great Plains, there are several individual grid cells where wind energy could generate more electricity than could all of California's wind plants combined. With the addition of adequate transmission, these regions could begin exporting wind-generated electricity to more populous regions of the country. Such developments would mean that wind energy could meet a substantial fraction of projected U.S. demands for electricity.

PNL's wind potential estimates presume that advanced wind turbines currently under development will be commercially available. These larger, more sophisticated turbines are designed to economically capture energy from Class 4 winds or greater. Class 4 is one of seven wind power classes used to express the energy contained in wind. These power classes range from Class 1 (for winds containing the least energy) to Class 7 (for winds containing the greatest). The classes are based on average "wind power density," which is expressed in watts per square meter (W/m^2) of swept rotor area. This term incorporates the combined effects of the time variation of wind speed and the



This map shows the contribution that wind energy could make to the electrical needs of the nation. For example, North Dakota alone has enough energy from good wind areas, those of wind power Class 4 and higher, to supply 36% of the 1990 electricity consumption of the 48 contiguous states.

dependence of wind power on both air density and the cube of the wind speed. Each wind class is based on a range of average wind speeds at specified heights above the ground.

Class 4 winds, with an average power density of 320 to 400 W/m^2, have average wind speeds ranging from 6.5 to 7 mps (14.5 to 15.7 mph) at 30 m (100 ft) above ground. (The typical hub height for today's wind turbines is 30 m.) The ability to generate cost-effective electricity from the nation's Class 4 winds is a prerequisite for significantly expanding wind power in this country. The nation's wind electric potential will grow sevenfold with the introduction of advanced wind turbines able to economically tap Class 4 wind resources.

During FY 1992, PNL representatives provided information about the scope of the U.S. wind resource to utilities, state energy organizations, wind plant developers, wind turbine designers, university faculty and students, and AWEA. PNL also worked with AWEA to develop a plan for a wind resource assessment in Mexico, Poland, and other countries. AWEA believes that Mexico will prove to be a large export market for wind energy in the coming years.

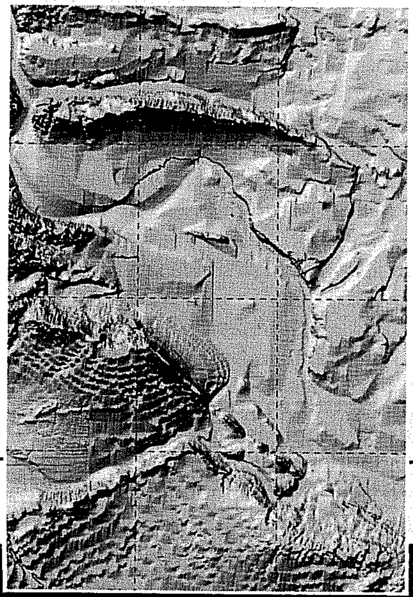
Prospecting for Wind Plant Sites

The wind industry has a new tool for finding new wind plant sites, thanks to PNL and the United States Geological Survey (USGS). This tool will make it much easier for the wind industry to prospect for new wind plant sites in known windy areas.

In 1992, PNL used its own software and the data supplied by USGS on terrain elevations to produce shaded relief maps using a laser printer. The format of the new maps is compatible with the state wind power maps in the U.S. Wind Energy Atlas. The resolution of the new maps ranges from several hundred meters (as in the U.S. map) down to 90 meters.

Using the highest possible resolution, PNL's prospecting software creates a shaded relief map enhancing terrain features that are exposed to the wind. The maps make it relatively easy to identify specific locations for taking wind measurements and locating wind plants.

The shaded relief map (insert) shows an area of Washington state near Richland. West of Richland is an area known as Rattlesnake Mountain. North of Rattlesnake Mountain is Saddle Mountain. Wind developers have proposed wind plants for both areas.



Pacific Northwest Laboratories

The U.S. Geological Survey used its digital height data to produce this shaded relief map of the United States. Using this information, PNL's software can produce maps of prospective wind plant sites in all 50 states. (Inset) The shaded relief map above shows Rattlesnake Mountain and Saddle Mountain. Both are locations of proposed wind power plants.

Wind Energy Applied Research Highlights for FY 1992

DOE Wind Energy Program applied research supports the development of advanced technologies to exploit the U.S. wind resource and to help the U.S. wind industry compete in global markets.

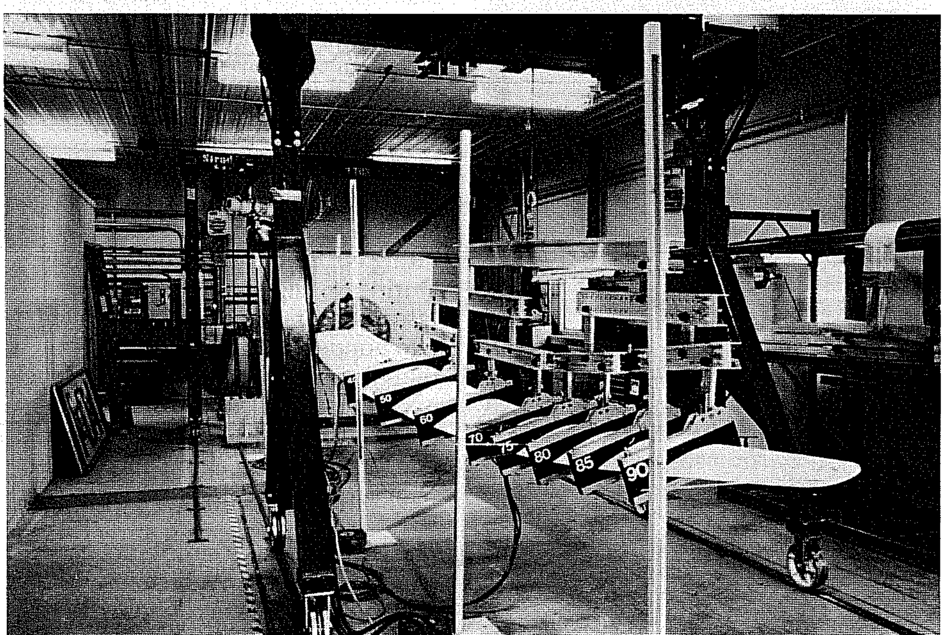
Wind energy research has two goals: to answer questions relevant to the operation of today's commercial wind turbines, and to assist in the advancement of new concepts leading to new technologies. Primary objectives, then, include understanding the wind and its interaction with turbine rotors, identifying factors that cause stress and damage to wind turbines, and finding ways to reduce or alleviate these stresses. Research also focuses on developing computer codes and integrating them into the research, testing, and design of advanced components and systems.

In setting its national wind energy research agenda, DOE maintains close contact with utilities and the wind industry. For example, DOE conducts cooperative research projects with utilities, turbine manufacturers, and power plant operators. As soon as research results become available, the national laboratories transfer the information to industry through workshops, conferences, and publications.

The following research highlights provide an overview of the achievements of the DOE Wind Energy Program in FY 1992.

Structures and fatigue research to improve turbine life expectancy

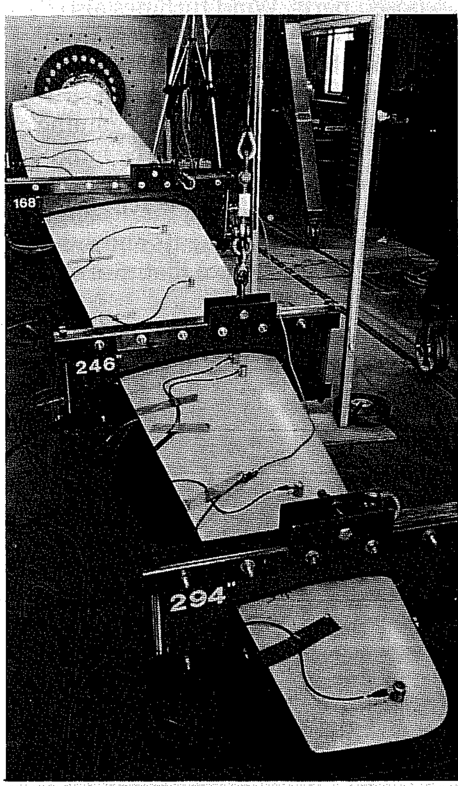
Sitting atop towers 18 to 50 m (60 to 160 ft) above the ground, wind turbines operate in a harsh and challenging environment. There they are subjected to atmospheric turbulence, insects, dust, temperature extremes, high winds, rain, snow, sleet, and wind shear. This results in continuous wear and tear on blades and other exposed parts. Wind turbines also experience considerable stress from forces such as gravity and start-up/shut-down cycles. Research on structures and fatigue focuses on gaining a better understanding of the fatigue behavior of wind turbines. This understanding is essential for designing cost-effective components and systems to last for service lifetimes of 20–30 years.



Warren Gretz, NREL

Researchers at NREL's Wind Energy Test Center used this machine to conduct static load tests on blades for U.S. Windpower's Model 56-100 wind turbine.

During FY 1992, NREL and U.S. Windpower performed extensive structural testing on more than 20 representative blades from the more than 4000 operating U.S. Windpower turbines. Conducted under a cooperative research and development agreement (CRADA) at the Wind Energy Test Center, the tests included both static load tests and fatigue tests. The static load tests evaluated the forces, or loads, that damage or break turbine blades. During the tests, researchers used an apparatus that gradually increased loads until the blades broke. Such tests measure the ability of turbine blades to withstand extreme winds.



Warren Gretz, NREL

During FY 1992, NREL and Sandia researchers performed three simultaneous tests on a turbine blade: an acoustic emission test, shearography, and a static load test.

Fatigue tests evaluated the continuous wear and tear on turbine blades during normal operation. For these tests, researchers applied fluctuating loads on the blades, thus simulating the repeated flexing and bending of rotating blades. Because blade failures differed in static load and fatigue tests, researchers performed both to gain a better understanding of how loads damage blades.

In FY 1992, researchers also performed photoelastic and modal testing on selected blades. In photoelastic testing, researchers apply a special coating to turbine blades. This coating shows the distribution of strain inside the blade as loads are applied, thus helping researchers visualize how loads travel within the blade. Researchers used modal testing to identify the natural vibration frequencies of the turbine blades. Turbine operators want to be sure that turbine blades don't vibrate excessively at these natural frequencies during operation.

U.S. Windpower will use the results of these tests to compare turbine blades that incorporate two different airfoils. During FY 1993, the company will work with NREL to test new blades for the firm's 33M-VS advanced wind turbine.

During FY 1992, NREL's Wind Energy Test Center also performed static load tests on a 7.9-m turbine blade incorporating NREL-designed thin airfoils. During testing at NREL's center, researchers from Sandia conducted two nondestructive fatigue tests on the same turbine blade. Sandia developed these tests as part of a larger project to devise noninvasive methods for inspecting aging aircraft wings for fatigue damage.

The first test was a simple acoustic emissions study, in which researchers used an array of microphones to listen to the blade as loads were applied to it. This allowed the researchers to locate the point where the blade broke before anything was visible to the eye. The test also indicated several other points along the blade that were close to failure when the blade broke.

During the second test, called shearography, researchers also located areas of high stress on the blade. This process involved photographing the turbine blade with a laser before and after loading, and comparing the resulting images. The technique was developed by Pratt & Whitney, an aircraft engine manufacturer. Company representatives assisted with the test at NREL.

Shearography works well for discovering structural flaws, areas prone to failure, and high-stress regions. During the cooperative tests, for example, researchers discovered a subsurface manufacturing flaw in the test blade. They verified the existence of this flaw through the acoustic emissions test.

Both noninvasive techniques show promise for locating manufacturing flaws in blades as they come off the assembly line. With further development (to adapt them to rugged field conditions), both methods should also prove invaluable in identifying and tracking potential problems in aging turbine blades.

NREL and Sandia support turbine blade material tests

During FY 1992, NREL and Sandia supported ongoing tests of small material samples and blade substructures at Montana State University. The tests are part of the university's materials research program, which includes developing fiberglass composite materials suitable for turbine blades. As part of this process, the university evaluates samples of blade material, joints, and other substructures with the goal of making better fatigue life predictions of more complex blade structures. This work complements composite materials research at NREL.

Computer code development bolsters wind turbulence research

In FY 1992, NREL researchers developed a new computer code that simulates the wind turbulence encountered by operating wind turbines. Such turbulence can form over all types of terrain and within a large wind plant. In complex situations, several factors, including the operating turbines themselves, may interact to create wind turbulence.

Researchers will now use the new code to analyze loads on two different wind turbine rotors. One rotor included a set of NREL-designed thin airfoil blades, and the other used AeroStar blades. The rotors were attached to two adjacent Micon-65 turbines located near the rear of a very large wind plant in San Gorgonio, California. Turbines in this area of the wind plant typically produced less power and required more maintenance than other turbines in the plant. Researchers collected data on the two turbines during 1989 and 1990.

A recently completed analysis revealed that both turbines regularly encountered severe wind turbulence, which increased turbine loads. The turbulence resulted from a complex interaction of the natural wind flow, the surrounding terrain, and wakes created by other turbines. The analysis also showed that there were some small differences in the loads experienced by the two turbines. The larger swept area of the NREL rotor and the greater weight of the AeroStar rotor accounted for these differences. However, the underlying response of both rotors to the turbulence was similar. Researchers concluded that the turbulent wind was the most important factor in creating the damaging loads. Next, researchers plan to use the new turbulence simulation code to generate conditions that statistically mimic the real winds that cause such damaging structural loads.

Computer codes becoming powerful new tool for industry

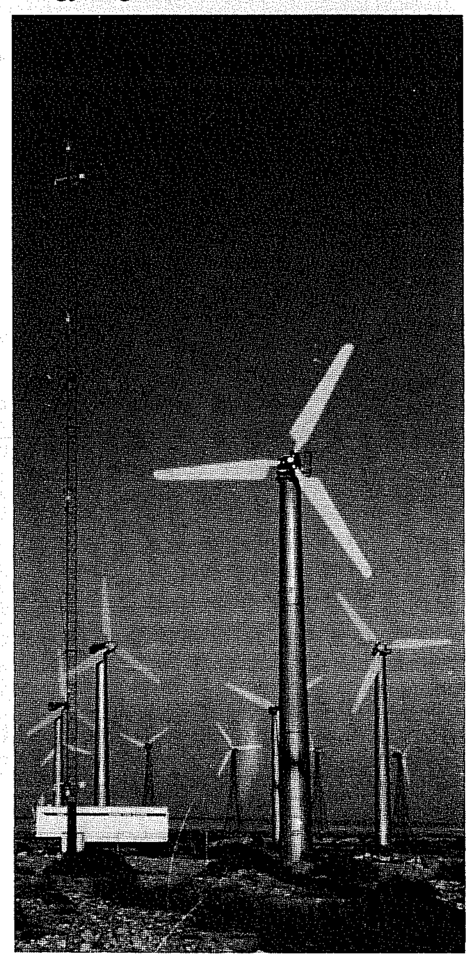
NREL and Sandia made significant progress on the development of advanced computer codes for wind turbine analysis during FY 1992. NREL adapted a sophisticated structural dynamics code, called ADAMS, to simulate the interactions between the wind and wind turbines (see box on p. 22). Sandia developed and improved codes to analyze turbine reliability, fatigue, and vibration.

In 1992, Sandia began a program to look for better ways to estimate the reliability of wind turbines. Instead of looking at fatigue in terms of estimating the working lifetime of a particular machine or component, Sandia researchers decided to develop a method for estimating the likelihood that an individual component will have an abbreviated lifetime. The advantage of such a method is that industry can start with the turbine lifetime it would like to achieve, then calculate the probability of reaching that goal. By looking at the uncertainty inherent in each component's performance, the method would allow turbine designers to focus on extending the lifetimes of the most expensive components, rather than those of the entire system. Once developed, this method will help industry make better long-term economic decisions.

During the next 3 years, Sandia researchers plan to survey other industries to see how they deal with reliability issues. Then they plan to develop a simple software package for the wind industry to estimate reliability. As part of the project, they will also write new subroutines (sequences of computer instructions for a particular task) for the LIFE 2 fatigue analysis code. These subroutines will allow the code to estimate fatigue life using limited amounts of experimental data.

Warren Gretz, NREL

The development of new computer codes and models is an important part of the DOE Wind Energy Program.



Jim Tangler, NREL

An analysis of the loads on these identical wind turbines equipped with different rotors showed that most of the loads came from wind turbulence.

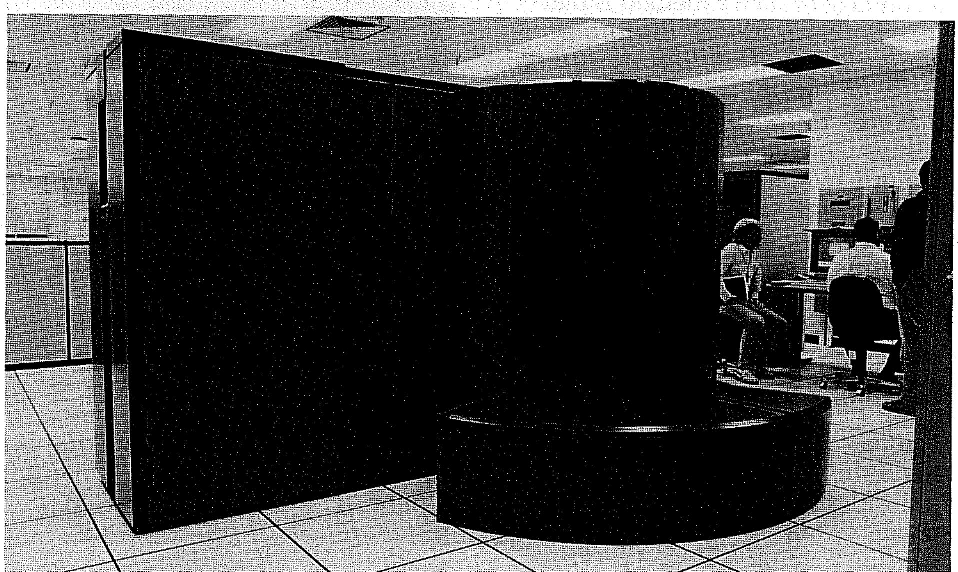
Industry Code Enhances Wind Turbine Analysis

During FY 1992, NREL researchers developed a powerful new computer model that produces a comprehensive, realistic simulation of interactions between the wind and a wind turbine. Unlike earlier computer codes that focused on one component or even a single turbine response, the new model analyzes a wind turbine as a complete system. NREL adapted the model from the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) software created by Mechanical Dynamics, Inc.

Already used in the aerospace, robotics, and automotive industries, the software promises to revolutionize the wind turbine design process. It will allow designers to rapidly simulate a new turbine design, evaluate individual components and subsystems, and optimize the entire system—before any hardware is built. This should make the process of building and testing new turbine prototypes much less expensive and time consuming. This translates to lower costs of energy for innovative U.S. wind technologies.

With ADAMS, NREL researchers can look at loads resulting from numerous interactions between the wind and the tower, blades, drivetrain, generator, gearbox, and drive shaft. They can also write new subroutines specifically tailored to wind systems. In less than a year, NREL researchers modified a Sandia wind turbulence code (SNLWIND) to work with ADAMS. The modified subroutines accurately model the structure of wind and wind turbulence. During 1992, University of Utah researchers also adapted unsteady aerodynamics codes for the new ADAMS simulation.

During FY 1993, researchers will test and validate the ADAMS simulation complete with wind-system-specific subroutines. Eventually, they plan to modify the output of ADAMS to make it compatible with the LIFE 2 fatigue analysis code.



Sandia National Laboratories

Sandia researchers use a powerful Cray computer to develop better computer models for the wind industry.

Sandia improves LIFE 2 fatigue analysis code

The LIFE 2 code received a lot of attention from researchers during FY 1992. Working with NREL's extensive data base on horizontal-axis wind turbines, Sandia and NREL researchers demonstrated that LIFE 2 is a useful design tool for estimating component lifetimes. In addition, the researchers solved a long-standing problem with the code: they developed a way to translate experimental data, which include the number of load cycles during operation, into life expectancies. Finally, they improved the code's ability to model two-dimensional stresses on wind turbine blades. Sandia then released an upgraded version of the LIFE 2 code to more than a dozen U.S. companies and wind energy consultants. These people will now validate the code by seeing how well it models real-life conditions.

Sandia introduces vibration analysis technique

During FY 1992, Sandia completed a new computer program that can estimate a wind turbine's response to vibrations caused by the wind. In the past, researchers had to strike the turbine with a hammer or other device, then measure how the ensuing vibrations faded over time (a process engineers call "damping"). With the new program, researchers can look at a turbine's response to the wind, then infer its damping response. Sandia is now using the program to analyze damping in different machines under normal operating conditions.

Also in FY 1992, Sandia completed the documentation for a series of analysis codes for vertical-axis wind turbines. Researchers modified the codes to make them more user-friendly and made sure they would run on personal computers. Sandia then transferred the codes to industry and arranged for training in their use.

The series of codes model turbine performance, which can then be validated by field tests of turbine hardware. Once the computer models are validated, they can guide turbine enhancements, aid inspections, and help identify damaged components. The combination of testing and analysis also shows promise for quality assurance at manufacturing facilities.

Sandia also created user-friendly documentation for the VAWT-SDS code in FY 1992. This code models variable-speed operation, looks at the effects of aerodynamic interactions on structural problems, and evaluates the effects of controls on turbine behavior.

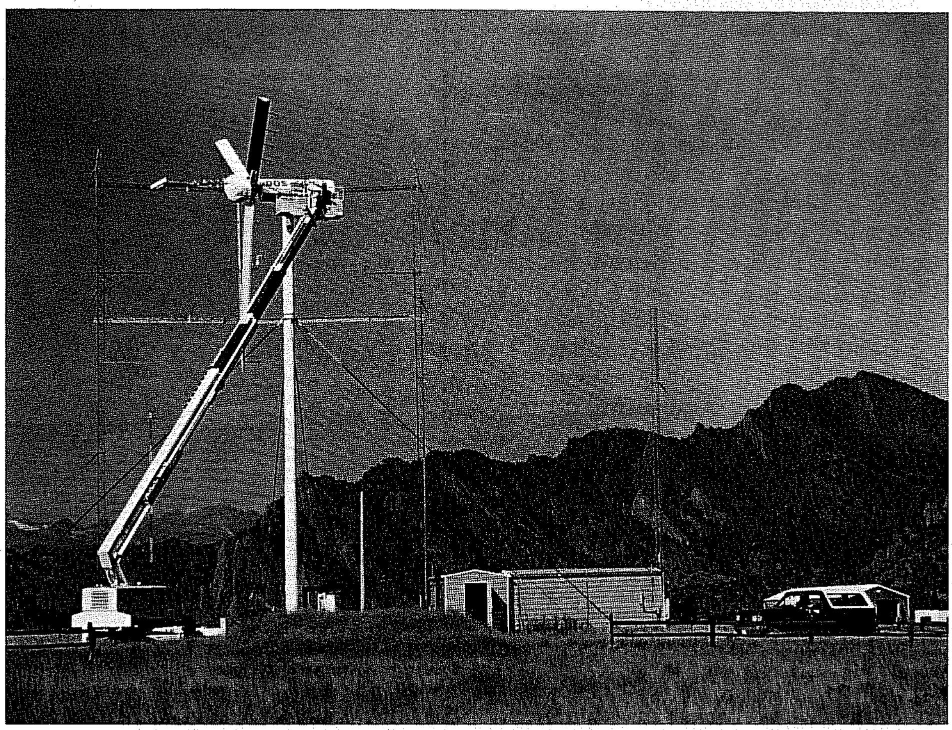
NREL studies unsteady aerodynamics

Interactions between the wind and a turbine blade are quite complex because the wind is almost always turbulent. Turbulent winds greatly affect both the performance of the turbine and the magnitude of the aerodynamic loads on the turbine blades.

To control these loads, turbine designers often use the natural tendency of airfoils to stall in high winds. (Turbines of this type are known as stall-controlled turbines.) Stall is the loss of the aerodynamic force, called "lift," that drives a wind turbine.

When a turbine operates in very turbulent or rapidly changing winds, a temporary condition know as dynamic stall can occur. Under dynamic stall, the air flow will separate over part of the blade, causing uneven aerodynamic forces over the blade. Or the flow may fail to separate from the blade, resulting in large aerodynamic loads on the blade. Even if short-lived, these large forces can cause fatigue and shorten blade life.

During FY 1992, researchers began using a sophisticated computer model to analyze wind turbine


Warren Gretz, NREL

NREL researchers are developing new computer models to analyze the complex data gathered in the Unsteady Aerodynamic Experiment, shown here.

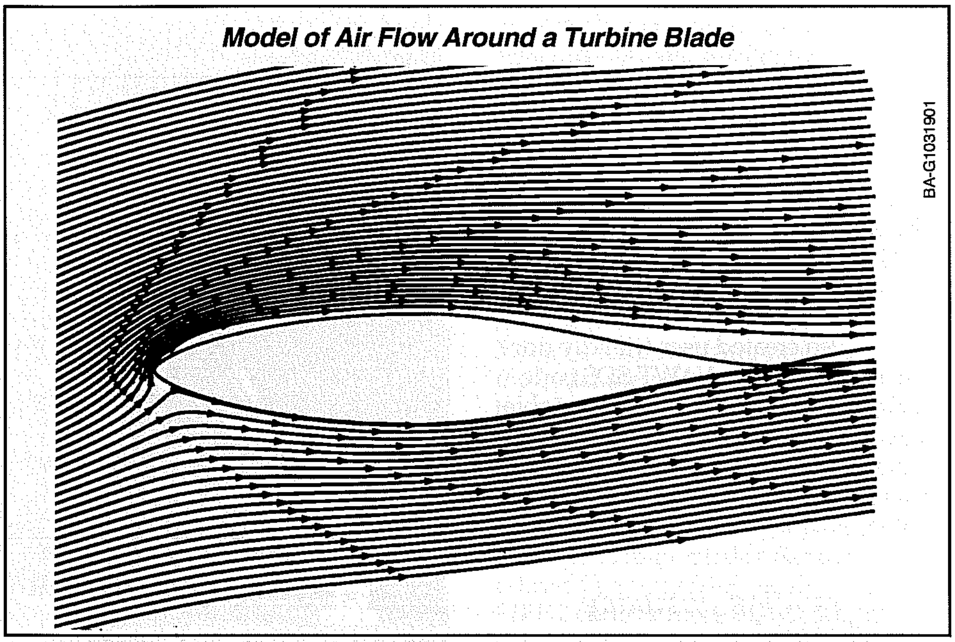
behavior in dynamic stall. The model will help them analyze a wealth of experimental data gathered during the NREL Unsteady Aerodynamic Experiment. The experiment, which ran from 1989 to 1991, consisted of a simple wind turbine instrumented to measure air pressure along a blade. Researchers hope the analysis of this data will help them understand the forces that control the unsteady aerodynamic forces at work during dynamic stall. In related work, NREL began a cooperative partnership with researchers at CU to study the basic physics of the unsteady aerodynamic response of wind turbine blades.

During FY 1992, NREL also participated in work to set up a new international research project similar to the Unsteady Aerodynamic Experiment. Under the IEA Annex 14, established on October 1, 1992, researchers will spend 3 years gathering and sharing information from experiments designed to elucidate the physics of wind/turbine interactions. Experiments run under the auspices of IEA Annex 14 will repeat procedures used in the Unsteady Aerodynamic Experiment, but this time on different wind turbines in a variety of wind regimes. The experiments should help researchers identify characteristics common to all turbine blades.

Sandia studies physics of air flow around turbine blades

Sandia has begun using computers to solve a series of basic mathematical equations that describe the way air flows around a turbine blade. By solving these equations, researchers hope to get a better idea of what's happening when air flow becomes separated from the blade during stall. It will also help them design better experiments. Eventually, their work should help industry design higher performance turbines.

The Sandia researchers are using an analysis called "computational fluid dynamics" on a natural laminar flow airfoil. A natural laminar flow airfoil is specially designed to keep air flowing smoothly around the airfoil to capture more energy. During FY 1992, Sandia researchers studied the air flow that remains attached to the blade. In FY 1993, they will investigate air flow around the airfoil during stall. They also plan to model the effects that ailerons would have on air flow.

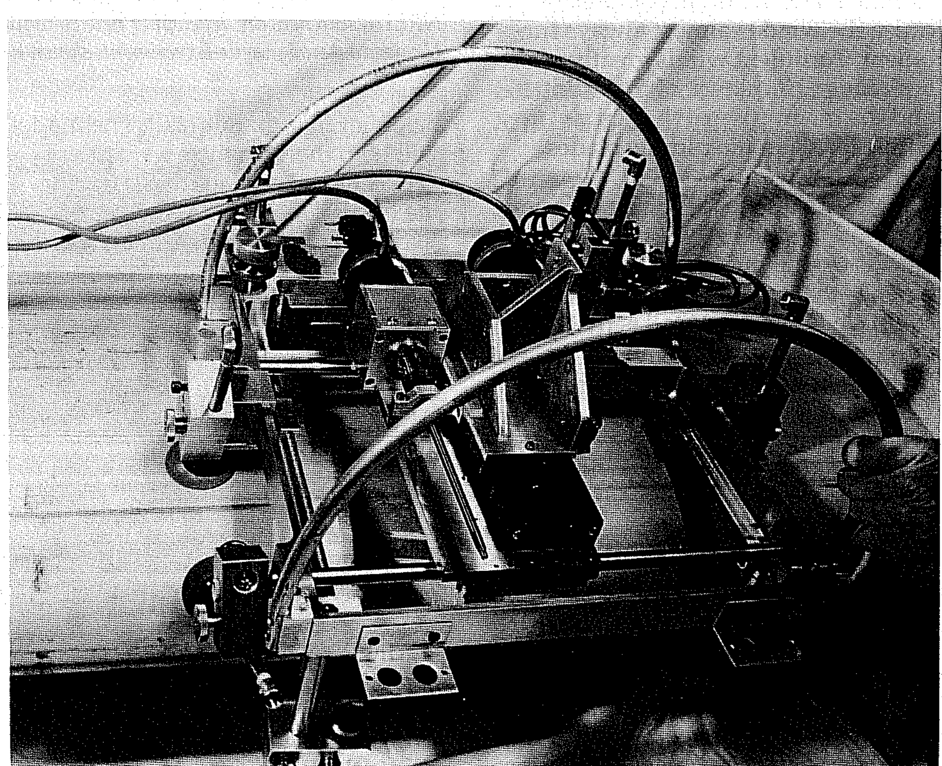


Sandia researchers generated this picture of air flow around a turbine blade using a computer-based mathematical model.

New laser profilometer scans turbine blades for defects

During FY 1992, a Sandia subcontractor built an innovative device that can accurately scan the surface of a turbine blade without touching it. The device is called a "laser profilometer." It can detect and identify sources of surface roughness (such as sand or insects) on a turbine blade. This is important because soiled blades capture less energy from the wind.

The laser profilometer is a spin-off from the electronics industry. It uses a laser, sensitive optical sensors, and a computerized control system to evaluate surface irregularities on the blade. Because it can move across and scan an entire blade, Sandia researchers believe it could one day be an important tool for inspecting manufacturing molds and dies to see whether they conform to design specifications. It could also inspect turbine blades as they leave the assembly line, ensuring good quality. During 1993, Sandia will work with the USDA at Bushland, Texas, to develop the laser profilometer prototype into a rugged device capable of inspecting turbine blades in the field.



Warren Gretz, NREL

This laser profilometer can accurately scan a wind turbine blade for surface irregularities. Such irregularities can reduce power output.

Wind Energy Program Overview
Fiscal Year 1993

U.S. Department of Energy

Contents

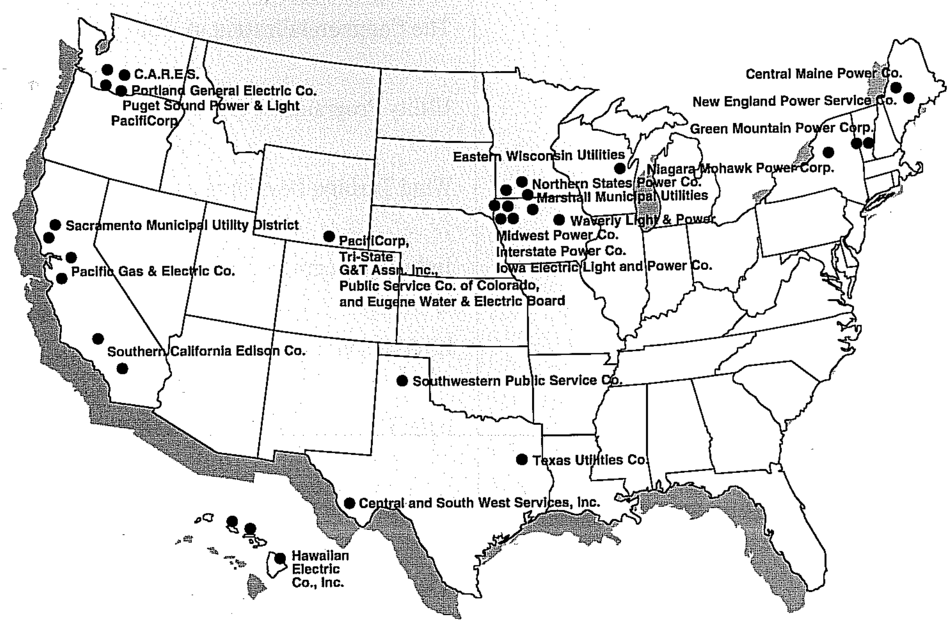
The Commercialization of Wind Power

High-tech, affordable wind energy systems can help the nation reduce energy-related emissions of greenhouse gases and acid-rain precursors.

At the end of 1993, wind power stood on the brink of a new era in commercialization. With the introduction of new technology, developed in part under the federal Wind Energy Program, costs for electricity from wind fell from an average of $0.07/kilowatt-hour (kWh) to about $0.05/kWh—very close to the cost of power from conventional generation. Unnoticed by many utilities, wind power quietly became an option for new power generation.

Wind technology is now in a position to compete with fossil-fuel generation in energy markets in the United States and around the world. Since 1991, 40 megawatts (MW) of new wind capacity has come on line in the United States, bringing the total to 1600 MW.

California currently has about 16,000 operating wind turbines, which produced approximately 2.7 billion kWh of electricity in 1993. The majority of these turbines, manufactured by American, European, and Japanese firms, were installed during the 1980s. For more than a decade, independent power producers have proved the feasibility of utility wind generation. Their efforts set the stage for a renaissance in wind energy during the 1990s.

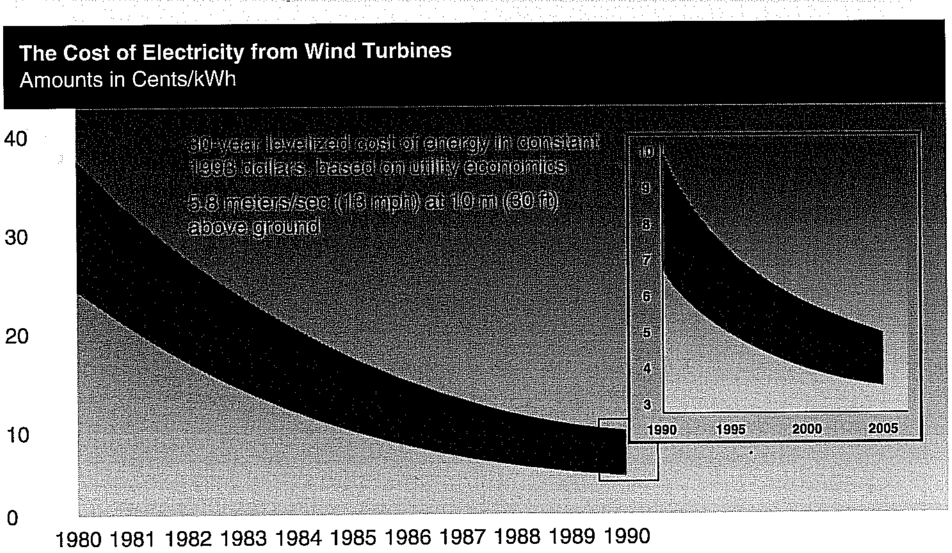


In 1993, utilities across the nation had announced plans to operate wind power plants or purchase wind power from independent power producers.

The American Wind Energy Association (AWEA) recently set a goal of reaching 10,000 MW of installed wind capacity in the United States by 2000. AWEA's goal reflects the industry's faith in new technology. The federal wind program is committed to helping the U.S. industry meet its goal.

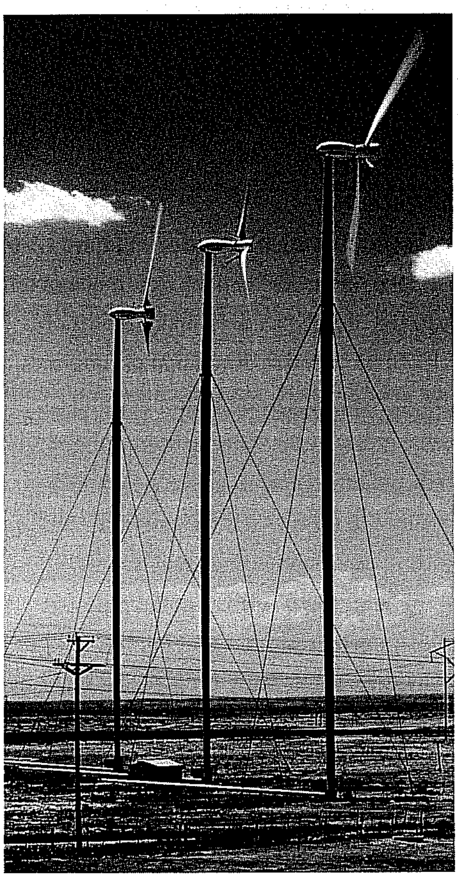
More than a dozen utilities and several independent power producers have already announced plans to develop new wind power plants before 2000. The majority of these new installations will be located in the Pacific Northwest, the Midwest, and the East. New wind facilities are planned for Alaska, Iowa, Maine, Massachusetts, Minnesota, Montana, New York, Texas, Vermont, Washington, Wisconsin, and Wyoming. The new power plants will add significant amounts of capacity.

In October 1993, Kenetech Windpower began building a 25-MW wind power plant near Lake Benton, Minnesota, under a power-purchase agreement with Northern States Power Company, a large Midwestern utility. The wind project is the first segment of a planned 100-MW installation. As part of its Resource Supply Expansion Program, Bonneville Power Administration (BPA)



In 1993, new technology brought wind energy costs down to $0.05 /kWh.

conducted contract negotiations during 1993 with FloWind Corporation and Kenetech Windpower to develop two wind power plants, one in Washington State and the other in Wyoming. Kenetech Windpower and two Oregon-based utilities plan to develop a 50-MW power plant in Wyoming's Carbon County. FloWind and the Conservation and Renewable Energy System (CARES) plan to build a 25-MW power plant in Klickitat County, Washington. CARES is a Seattle-based consortium of eight utilities. The Washington plant will use advanced wind turbines developed by R. Lynette & Associates as part of the U.S. Department of Energy's (DOE) Wind Turbine Development Program. The BPA projects demonstrate how utilities, the wind industry, and the federal government can work together to commercialize new energy technologies.



Southwestern Public Service Company

Southwestern Public Service installed these 300-kW turbines in Amarillo, Texas.

Technology Status*	Before 1975	Current	Post 2000
Cost/kWh	$0.50-$1.00	$0.05-$0.07	<$0.04
Operating Life	1-5 Years	20 Years	30 Years
Capacity Factor (Average)	10%	20%-25%	30%
Availability	60%-70%	95%	95%+
Size Range	<20 kW	200-500 kW	300-1000 kW

*For a 6.9-mps (15.4-mph) annual average wind site. Wind speeds measured at 30-m (100-ft) height.

In fiscal year (FY) 1993[1], wind developers also proposed a 10-MW demonstration project in east-central Wisconsin, a 250-MW development in the Midwest, and a 225-MW power plant in Maine.

U.S. companies also are securing new contracts for wind installations overseas. During FY 1993, U.S.-made turbines came on line in the United Kingdom and Spain. Contracts were in place for turbine sales in the Netherlands, Canada, Japan, and the South Pacific. And companies formed as joint ventures with Kenetech Windpower were building turbines in Spain and Ukraine. Initial turbines were installed in a planned 500-MW wind plant in Ukraine, a newly independent state of the former Soviet Union.

New markets for wind energy are creating jobs and stimulating local economies. An AWEA study in 1993 showed that the employment benefits to the State of California from wind power were equivalent to 460 jobs per billion kWh of annual generation. A 1992 Danish study yielded 440 jobs per billion kWh of wind generation. By 2000, when major global wind markets develop, the impact on jobs could be significant—on both sides of the Atlantic.

Since 1990, European nations have made major commitments to wind as a clean, renewable utility generation technology. By the end of 1993, these nations had installed a total of 1000 MW of wind capacity. The European Union plans to have 4000 MW of wind capacity on line by the year 2000 and 20,000 MW by 2010. A number of European nations, including Denmark, Germany, the Netherlands, the United Kingdom, and Italy, all have active wind energy research, development, and commercialization programs.

In October 1993, President Clinton announced his administration's Climate Change Action Plan. This comprehensive strategy for reducing U.S. greenhouse gas emissions underscored the benefits of public/private partnerships in developing and commercializing renewable energy technologies, including wind. Such partnerships have played a role in the introduction of new wind energy technologies since the late 1980s.

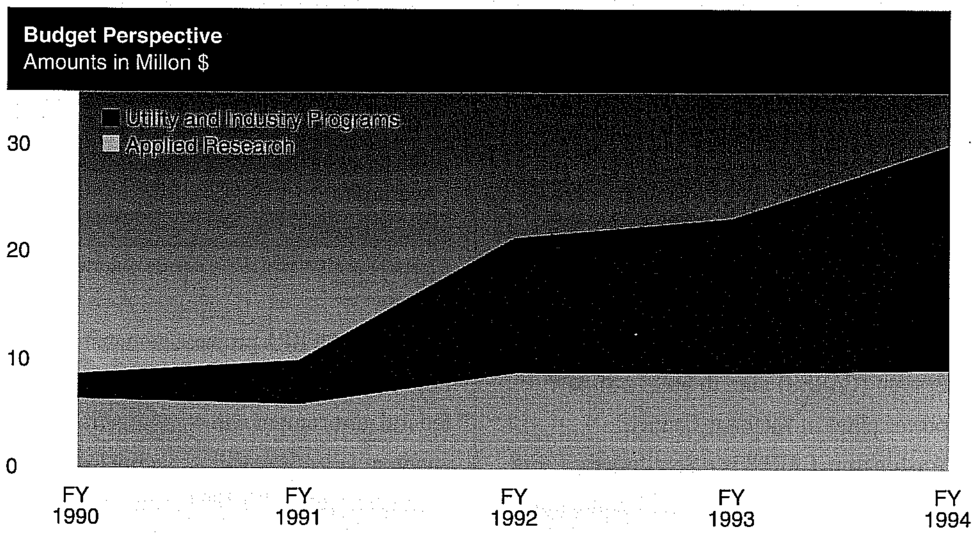
From policy makers to business leaders to average citizens, Americans recognize that every time a wind turbine generates power, the environment benefits. Unlike technologies that rely on fossil fuels, wind power plants avoid emissions that pose a threat to global climate or that endanger the environment. To the extent wind replaces coal, oil, or gas for electricity generation, it reduces

[1] Fiscal year 1993 ran from October 1, 1992 through September 30, 1993.

the amount of carbon dioxide (a major greenhouse gas), ash, and acid-rain precursors such as NO_x and SO_x entering the atmosphere. In 1993, for example, U.S. wind power plants prevented the emission of more than 1.2 billion kilograms (2.7 billion pounds) of carbon dioxide into the atmosphere.

National Wind Technology Center to Open in 1994

In recognition of wind energy's growing importance as an electrical generation technology, DOE will establish a world-class wind energy research and testing center. The National Wind Technology Center will be located on 280 acres of land about 15 miles north of Golden, Colorado. The National Renewable Energy Laboratory (NREL) will operate the new facility. DOE is spending $5 million to upgrade existing structures at the site and to build a new facility dedicated to advancing wind technology. The facility will incorporate sophisticated computer systems, research and certification testing, and component test stands. It will be available to the wind industry.

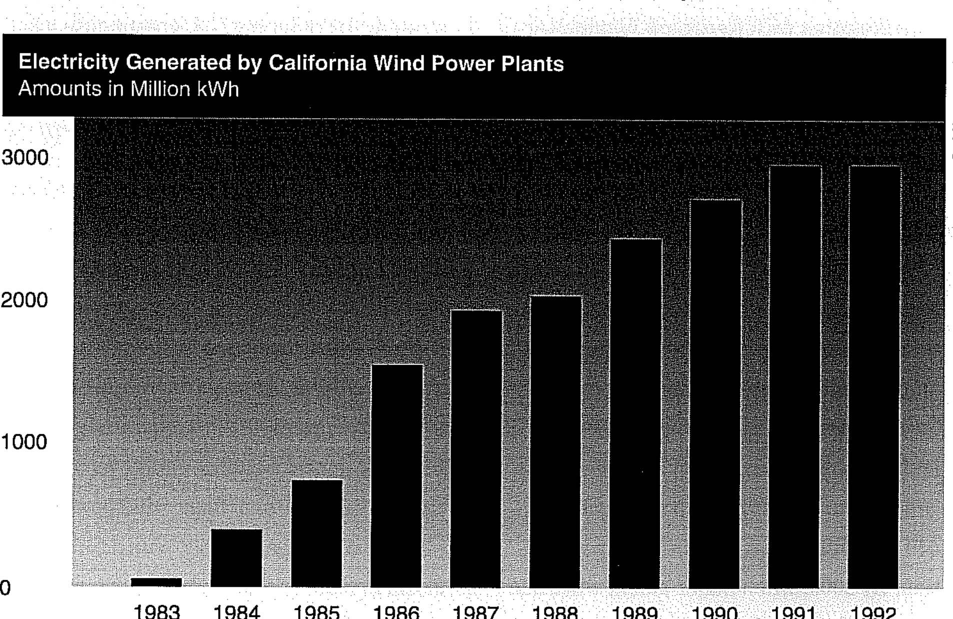


The need to curb emissions of greenhouse gases has made investment in new wind technology an important priority.

The center will house NREL's Wind Technology Division. During FY 1994, wind program managers and staff members plan to move into newly refurbished offices at the center. By the end of the fiscal year, the center will be the nucleus of the nation's wind turbine development activities, utility integration program, collaborative wind programs, international development activities, and applied research.

Within 2 years, the center will have six to eight wind turbines under test, including turbine prototypes developed as part of DOE's cooperative development programs, two advanced research turbines, and a wind-solar-diesel hybrid system. DOE expects the center to act as a technology magnet to attract new industry and create jobs in the surrounding area.

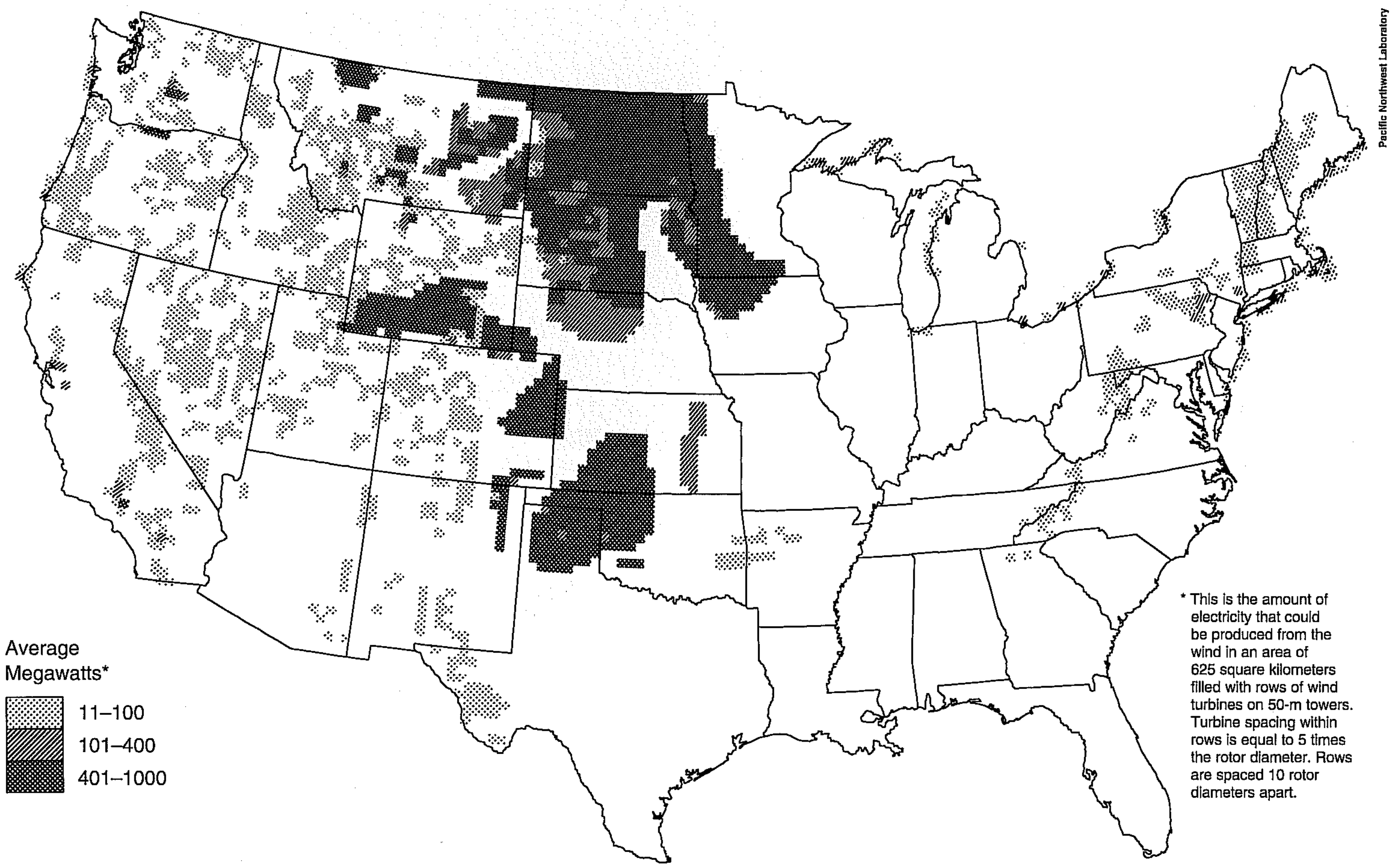
In addition to NREL, Sandia National Laboratories (Sandia) and Pacific Northwest Laboratory (PNL) conduct supporting research for the DOE Wind Energy Program.



Paul Gipe & Associates

California's wind power plants generate approximately 2.7 billion kWh of electricity annually.

The U.S. Wind Resource



The bulk of the U.S. wind resource suitable for wind power development is in the Great Plains. The map above shows the annual wind electric potential for wind turbines in areas with wind resources of Class 4 and above that can be developed economically. Class 4 is one of seven wind power classes used to express the energy contained in wind.

There is sufficient wind potential in the continental United States to produce more than 4.4 trillion kWh of electricity each year, according to studies at PNL. This is more than one and one-half times the 2.7 trillion kWh of electricity consumed in the United States in 1990. Eleven states in the Great Plains contain about 90% of the nation's usable wind resource. North Dakota alone has enough energy in its windy areas to supply 36% of the electricity consumed in the United States during 1990.

Detailed information about the U.S. wind resource is now available through AWEA. Developed by researchers at PNL, this information is invaluable for general wind resource prospecting. The *Wind Energy Resource Atlas* contains detailed color maps of the wind resource in the United States. State resource information sheets also are available. The information sheets tell how much windy land each state contains and describe how much electricity could be produced by developing the state's wind resource.

New *Shaded-Relief Elevation Maps for Wind Prospectors*, created by PNL, also are available from AWEA. The shaded-relief maps enhance terrain features and make it relatively easy to identify specific locations for taking wind measurements and siting wind plants.

Utility Programs

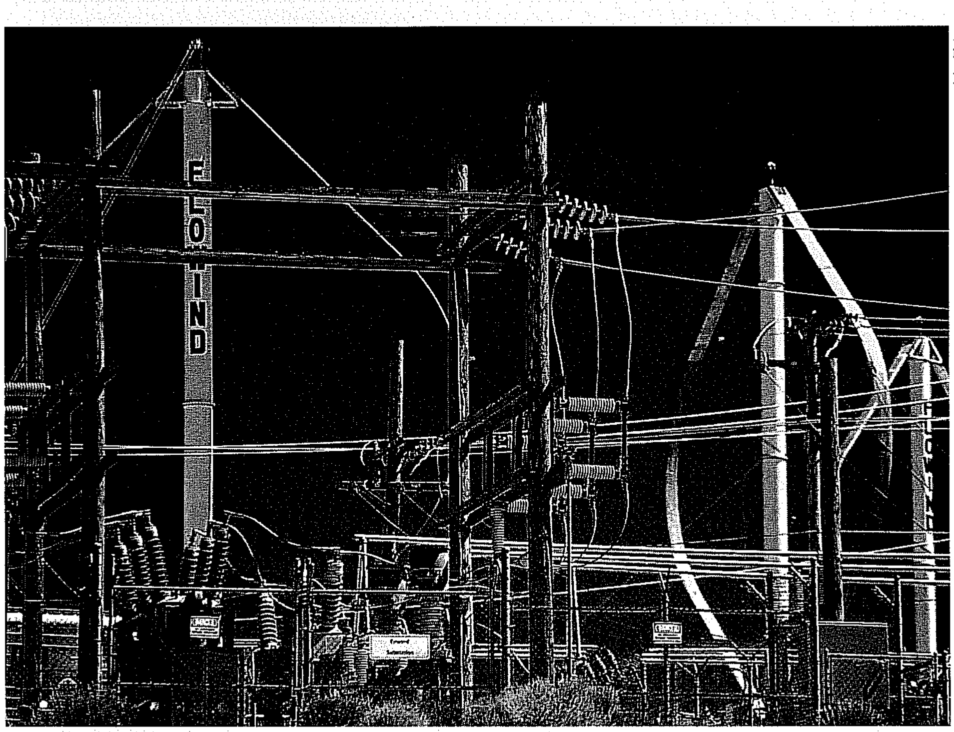
DOE and the Electric Power Research Institute are working together to build a bridge from today's advanced turbine development to tomorrow's high-tech wind power plants.

The U.S. utility industry is the largest potential market in the world for new wind energy technologies. Since 1990, DOE has worked with utilities and the wind industry to build a bridge between research and development programs and the commercial purchase of utility wind turbines.

The Utility Wind Turbine Performance Verification Program, a joint effort between DOE and the Electric Power Research Institute (EPRI), is the centerpiece of DOE's efforts to demonstrate the value of wind energy to utilities. The $40 million turbine verification program is an extension of DOE's advanced Wind Turbine Development Program. It will give utilities first-hand experience operating a modern wind power plant using the latest technology developed by the American wind industry. Such experience will allow utilities to make informed decisions when considering wind energy for replacing an outdated power plant or adding new capacity.

DOE encourages utility involvement in wind energy with research addressing key utility issues, such as land use, resource assessment, distributed generation, environmental concerns, transmission, and the value of wind energy to the utility network. DOE participates in EPRI's new Wind Users Support Group and supports the Utility Wind Interest Group.

The Wind Users Support Group is a utility association formed in FY 1993 to deal with issues affecting the integration of wind energy into the nation's electric supply. Open to EPRI-member utilities, the association focuses on solving problems of interest to its members. Current projects include developing improved methods for wind resource planning and analysis, publishing a comprehensive guide for utilities considering new wind power capacity, and creating a clearinghouse for proposals related to new wind energy projects. DOE and NREL support the group by attending meetings and serving as technical advisors.



John Ripley

California's wind power plants have reliably delivered electricity to utilities for more than 10 years.

Organized and funded by EPRI and DOE, the Utility Wind Interest Group is an association of utilities interested in promoting the integration of wind energy into the nation's electrical generation supply. During FY 1993, the group provided a utility perspective to national wind energy programs. It also visited two wind power plants, published two new educational brochures in a series on wind energy aimed at utility management, and provided information about utility wind systems to legislative programs and state regulatory agencies.

The Utility Wind Interest Group's role in furthering the adoption of wind energy is expected to expand as market mobilization efforts multiply in the future. The group will become a clearinghouse for new ideas and a catalyst for problem solving. Organizations like DOE, EPRI, the Edison Electric Institute, and the American Public Power Association will work with the group and supporting organizations, such as the user support group, to foster collaborative commercialization efforts.

EPRI Selects Participants for Wind Power Plant Testing Program

DOE's goal in supporting the Utility Wind Turbine Verification Program is to bring new American technology rapidly into the field for testing and evaluation. In FY 1993, one utility and a utility service company were selected to participate in the first phase of the program. Vermont's Green Mountain

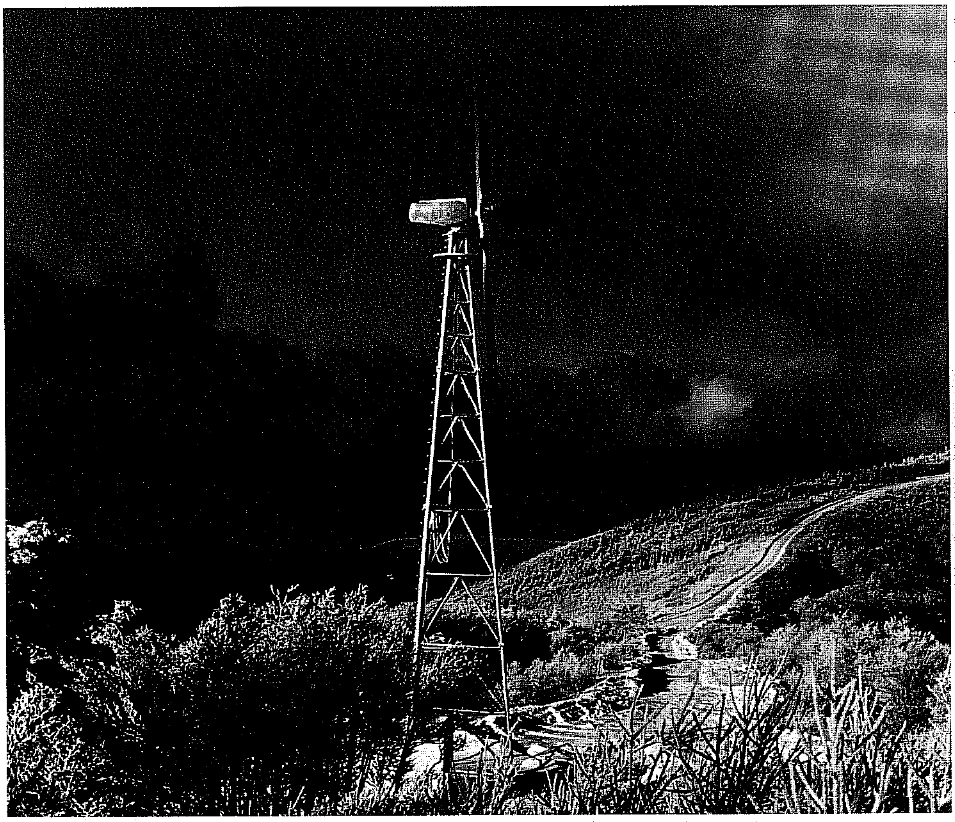
Power Corporation and Central and South West Services, Inc. of Dallas, Texas, will take part in the 5-year power plant development and testing program to evaluate advanced wind turbine technologies.

Each project in the turbine verification program will install at least 20 advanced wind turbines, with a nominal rating of 300 kW each. To qualify for DOE funding, the turbines must be purchased from a domestic manufacturer. At least five U.S. wind firms have plans for or have already introduced new turbines that meet program requirements.

Each utility will select the wind power plant site, solicit bids from wind industry vendors, and purchase the turbines. The utility also will be responsible for power plant design, construction, and start up. DOE and EPRI will assist the utility in conducting a minimum of 3 years of testing, evaluation, and documentation of the new wind power plant. DOE also will provide technical reviews of wind power plant operations and compliance with the National Environmental Policy Act.

In FY 1993, both utilities began the process of siting their new wind power facilities. Green Mountain selected a ridge-top site in a wooded area 10 miles east of Bennington, Vermont. The utility applied for permits from the U.S. Forest Service to build the new facility. It also erected five meteorological towers at different locations around the proposed site. Green Mountain will use these towers and a sixth that has been in place for several years to monitor seasonal wind patterns.

EPRI and DOE awarded Green Mountain $3 million for its 6-to 8-MW demonstration project. Because it plans to own and operate the new wind power plant as a commercial generation facility, the utility also plans to include its costs for the project in its rate base in the future.



Green Mountain Power Corporation

Green Mountain Power Corporation used this turbine for 4 years to conduct research on its wind resource. In 1993, EPRI and DOE awarded the utility $3 million under the Utility Wind Turbine Verification Program to build a new wind power plant.

During FY 1993, Central and South West Services continued to monitor the wind resources in the service areas of all four utilities it serves. The company will make a definite site selection (most likely in West Texas) by the time it solicits bids for new turbines in the spring of 1994. Central and South West Services plans to install two different turbines at its 6-MW demonstration power plant to compare their performance. EPRI and DOE awarded the company $2 million for the project.

In FY 1994, EPRI and DOE plan to award an additional $6 million for as many as four new turbine performance verification projects.

DOE Helps Utilities, Industry with Site Selection

DOE is committed to helping utilities and industry with the process of selecting sites for new wind power plants. PNL researchers helped by developing better maps for resource assessments.

In FY 1993, PNL refined its estimates of the amount of electricity that windy areas in the United States could produce. By analyzing the seasonal variability of the winds, PNL researchers discovered that winter and spring have the highest wind-electric potential in most areas of the United States (California is the notable exception). The study also showed that there is an excellent match between the wind-electric potential and electric energy use during the winter months in the northern tier of states.

During FY 1993, PNL produced 950 digitized shaded-relief maps of the terrain over the contiguous United States. PNL made these maps available to the wind industry by providing them to AWEA. Shaded-relief maps provide a three-dimensional view of terrain. This perspective helps wind prospectors locate specific sites for wind measurements or new power plants. In FY 1993, PNL refined the process for generating shaded-relief maps to offer oblique views of specific sites. The oblique views display terrain features from the perspective of looking at the ground from an airplane. Relative heights are much easier to discern from this perspective.

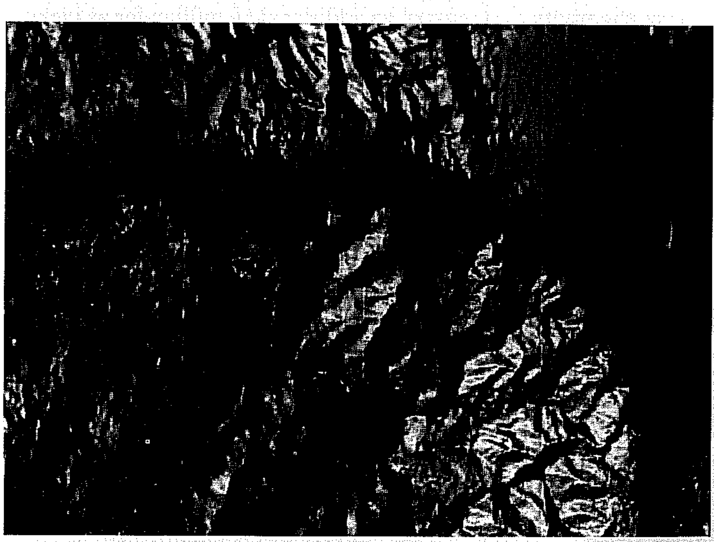
In support of industry, NREL sponsored cooperative research into specific environmental issues and offered assistance in dealing with federal environmental regulations. During FY 1993, NREL, EPRI, and Kenetech Windpower launched a multi-year study to monitor birds of prey, including golden eagles, in Altamont Pass, California. The study will monitor the behavioral patterns of birds as they fly through wind power plants to see what causes rare, but fatal, interactions with wind turbines. NREL believes such information will aid industry in developing mitigation strategies. The study also will provide developers with guidelines for designing new facilities to avoid or mitigate such issues in the future.

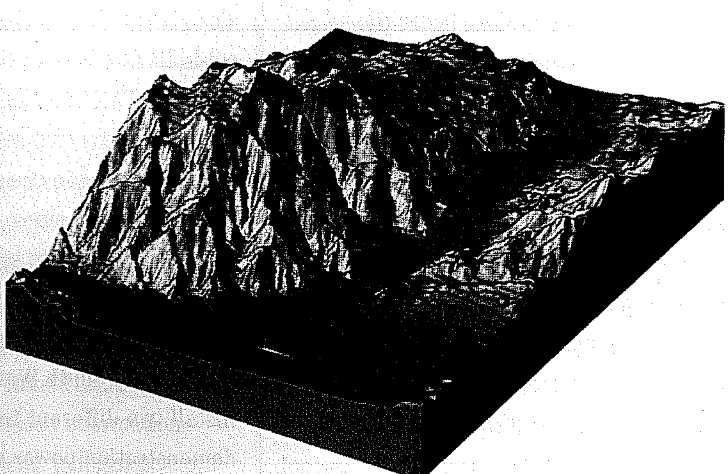
NREL Investigates the Value of Wind Power to Utilities

As utilities consider wind energy, they must grapple with the problem of determining a value for wind as an energy source. With an intermittent resource like wind, determining this value can be challenging. Factors such as the nature of the wind at a specific site; the size and performance characteristics of the wind turbine generators; the characteristics of the utility's existing power plants, such as their size and ability to change output; and how well the wind resource corresponds to the utility's daily or seasonal load all influence the value of wind to a particular utility.

Economic considerations also influence wind's value. Penalties for emissions, credits for offsetting emissions, the capacity credit for wind plants, and the utility's avoided costs all figure into a cost-benefit analysis for wind energy.

To help utilities evaluate whether wind generation makes sense for them, NREL investigated the cost-benefit problem with a computer model called "ELFIN," developed by the Environmental Defense Fund.





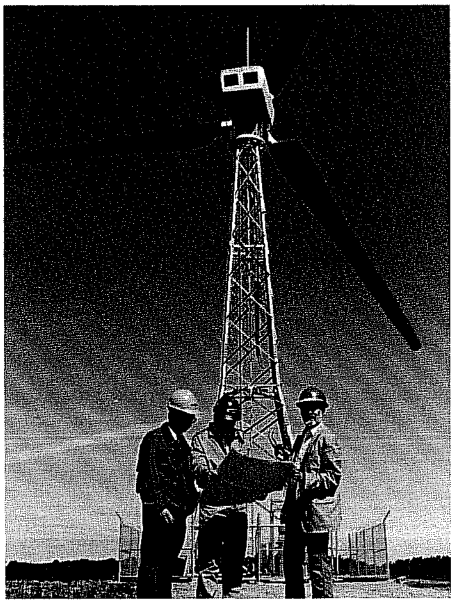
Pacific Northwest Laboratory

PNL has developed shaded-relief maps to help wind prospectors look for new power plant sites. The maps shown here are for an area near Palm Springs, California. The oblique view (right) provides a better perspective on the relative heights of the mountains.

California utilities are required to use ELFIN to analyze the impact of new power plants on rate decisions. In FY 1993, the ELFIN model calculated the value of adding a new wind power plant at two different sites, with different wind regimes, for two different utilities. It also looked at the differences in value to utilities of using two different wind turbines.

The study showed that the value of wind to a utility is significant when the resource is predictable, if the wind blows at the same time the demand for electricity rises, and when wind energy costs are competitive. The costs of wind energy vary substantially at different locations. The study also showed that at moderate penetration levels wind appears to have little or no impact on utility system reliability. These promising results encouraged researchers to extend their evaluation of wind to another, more sophisticated utility resource and operations planning model developed by the P Plus Corporation. In the future, NREL plans to compare the results of the two different computer models.

During FY 1993, NREL began a survey of transmission capacity in regions of the country where wind power development appeared likely. Soon after this study began, the North American Electric Reliability Council mandated that all ten regions under its jurisdiction publish information on existing and planned transmission capacity by April 1994. Because much of this information was formerly kept confidential by companies owning the transmission lines, it will be valuable to utilities and wind developers desiring to build new wind power plants.



Renate Gaddis, Niagara Mohawk Power Corporation

Utilities that are already involved with wind power welcome the opportunity to share their knowledge with other utilities.

Electric utilities, independent power producers, state officials, regulators, wind equipment manufacturers, service providers, consumer and environmental groups, and DOE are working together to establish a market mobilization collaborative for wind energy technologies. This effort comes in response to President Clinton's Climate Change Action Plan, which was announced late in 1993. The collaborative's objective is to accelerate the deployment of wind energy to help meet the nation's energy requirements and reduce emissions of greenhouse gases.

In preliminary discussions, key stakeholders have identified a range of activities that could foster a wider use of wind energy in an environmentally responsible manner. These activities may include (but are not limited to) expanding technology deployment programs, such as the EPRI/DOE Utility Wind Turbine Performance Verification Program; government agency, power marketing administration, or collective purchases of new technology; market conditioning activities in the United States and abroad; creative public/private financing arrangements; and educational programs. The collaborative will develop a detailed plan of action during FY 1994.

Wind Turbine Development

The federal Wind Energy Program and the U.S. wind industry have made the development of technologically advanced, high-efficiency wind turbines a top priority.

DOE sponsors a multifaceted Wind Turbine Development Program to help the American wind industry produce competitive, high-performance technology for global wind energy markets. Market opportunities are multiplying as policy makers, utilities, and the public increasingly realize wind energy's potential for delivering affordable electricity *and* protecting the environment. DOE has designed its turbine development efforts to help the U.S. wind industry capture a significant share of new wind markets in the face of stiff competition from well-capitalized European and Japanese firms.

DOE's wind turbine development activities, a cost-shared effort with industry, seek to lower the cost of wind-generated electricity to be competitive with fossil-fuel generation in most regions of this country. The first new turbines developed under the program became commercially available in 1993.

The new turbines are a result of DOE's near-term product development effort. They are designed to produce electricity for $0.05/kWh or less at sites with moderate annual average wind speeds of 5.8 mps (13 mph) at a height of 10 m (30 ft). At these costs, wind energy becomes competitive with the more expensive forms of conventional electric generation. With the introduction of a $0.015/kWh production tax credit on January 1, 1994, however, the cost of energy from new turbines should be competitive with many electric power technologies.

A Value-Engineered Turbine (VET) Project and supporting research and testing round out the near-term activities. The VET project, which focused on improving today's turbine technology, is briefly described on p. 13. Research and testing activities provided technical support to all facets of the turbine development program.

FY 1993 saw important progress in DOE's cooperative efforts to develop wind turbines capable of economically exploiting windy areas of the Pacific Northwest, the Great Plains, and the Midwest. NREL subcontractors completed component qualification testing and full-system modal tests of near-term technology. Modal tests profile a wind turbine's natural vibration frequencies. Exciting a turbine at these frequencies during operation can cause it to sustain very high fatigue loads.

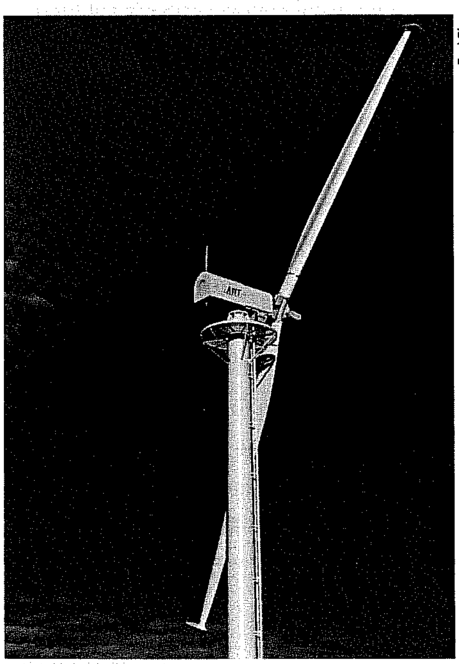
NREL also undertook an effort in FY 1993 to reduce the risks associated with developing near-term turbines. This effort will support additional analysis, prototype testing, and evaluation of turbines already under development.

DOE expects next-generation technology to be ready by the turn of the century. A whole new generation of wind turbines is expected to produce electricity for $0.04/kWh or less at moderate wind sites. The next-generation turbine development activity, which began in FY 1993, is a two-pronged effort that includes (1) the development of innovative turbine subsystems and (2) the development and testing of advanced full-system turbine prototypes.

DOE's Wind Turbine Development Program also supported the EPRI/DOE Utility Wind Turbine Performance Verification Program (described previously in Utility Programs).

AWT-26 Selected for New Wind Power Plant

The AWT-26 turbine, developed by R. Lynette & Associates of Redmond, Washington, will be used by FloWind Corporation, which markets the turbine, to develop a 25-MW wind power plant in Washington State's Columbia Hills. As part of DOE's near-term development effort, R. Lynette & Associates installed and tested two prototypes of the 275-kW AWT-26 at FloWind's wind power plant in the Tehachapi area in California.



Paul Gipe

This AWT-26 production prototype included a new tube tower, an integrated drive train, and an improved control system. R. Lynette & Associates is developing the advanced turbine as part of DOE's Wind Turbine Development Program.

The first prototype turbine, which is a down-wind, two-bladed machine employing an innovative teetered rotor, was installed in March 1993. Teetered rotors are designed to rock back and forth in response to wind gusts, thereby dissipating loads. The turbine underwent more than 250 hours of successful testing by the end of the fiscal year. The machine's energy output was slightly better than predicted. Under the DOE program, the test results were used to develop the second production prototype turbine, which was installed in Tehachapi in November 1993.

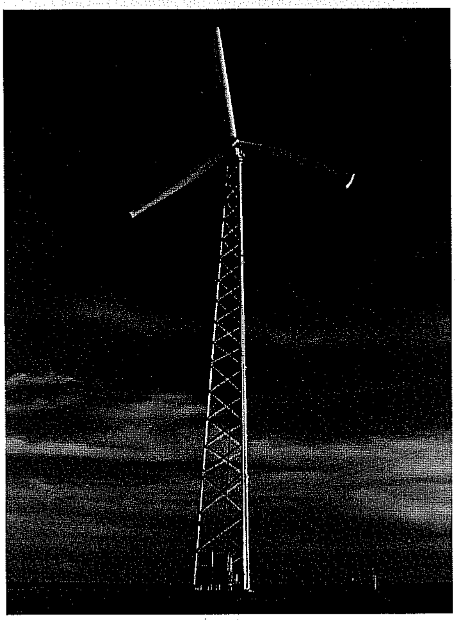
The second AWT-26 production prototype included a new tube tower, an integrated drive train, an improved design for aerodynamic tip brakes, a cast mainframe to support the nacelle, an enhanced generator, and an upgraded control system. In an integrated drive train, the housing for the transmission connecting the rotor to the generator is manufactured as a single unit. Aerodynamic tip brakes are located at the end of turbine blades. When deployed, they slow the rotor.

The cost of energy for the turbine stayed within 5% of early design estimates.

AOC 15/50 Undergoes Testing at Bushland, Texas

As part of DOE's near-term product development effort, Atlantic Orient Corporation of Norwich, Vermont, tested its new 50-kW prototype turbine in FY 1993 at the U.S. Department of Agriculture's (USDA) wind energy test facility in Bushland, Texas. The downwind turbine featured passive yaw control, NREL-designed advanced airfoils, tip and dynamic brakes, and an integrated drive train. Yaw controls turn a turbine into or out of the wind. With passive yaw control, the wind itself determines turbine orientation. Dynamic brakes use the generator to slow or stop the turbine rotor.

Although the turbine performed as expected, Atlantic Orient made improvements to the dynamic brake and control system before building additional prototypes. The company plans to install new



Atlantic Orient Corporation

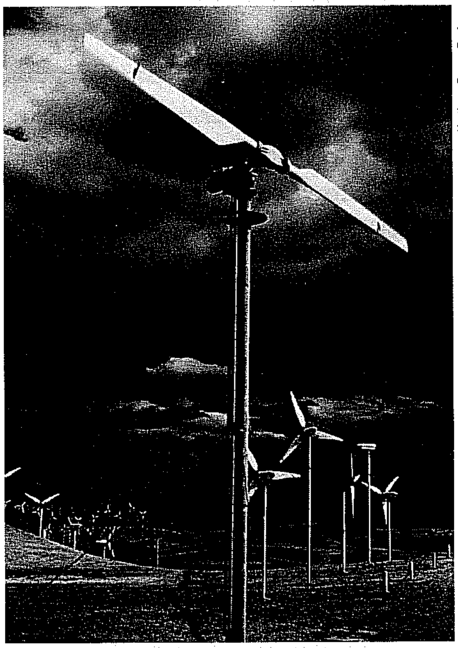
Atlantic Orient Corporation tested its new 50-kW prototype turbine at Bushland, Texas, during 1993.

machines in California, Vermont, and Canada during FY 1994. The company's next round of field testing will focus on evaluating loads and the effects of cold weather operation.

Atlantic Orient also conducted component qualification tests on the turbine blades, tip brakes, mainshaft, and other drive-train components. The company created a computer model of its new turbine using the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) software created by Mechanical Dynamics, Inc. and modified for wind systems by NREL and its subcontractors. The company used test data to validate the new model. Atlantic Orient completed tooling for the new machine, which is now commercially available. At the end of 1993, Atlantic Orient was negotiating turbine sales with both U.S. and foreign utilities.

Northern Power Systems Completes New Turbine Design

Under another near-term product development effort, Northern Power Systems of Moretown, Vermont, completed a proof-of-concept design for its new Northwind-250 wind turbine and began construction of a pre-prototype machine in FY 1993. The 2-bladed, upwind turbine features an integrated drive train, aileron controls, and an innovative teetering rotor that is fabricated as a single unit. Like flaps on an airplane wing, ailerons on a turbine blade can slow the speed of the rotor. The company plans to install a pre-prototype machine for field testing at the San Gorgonio wind power



Northern Power Systems

Northern Power Systems tested a new rotor retrofitted with aileron controls on the company's Northwind-100 machine during 1993.

plant near Palm Springs, California, in early 1994.

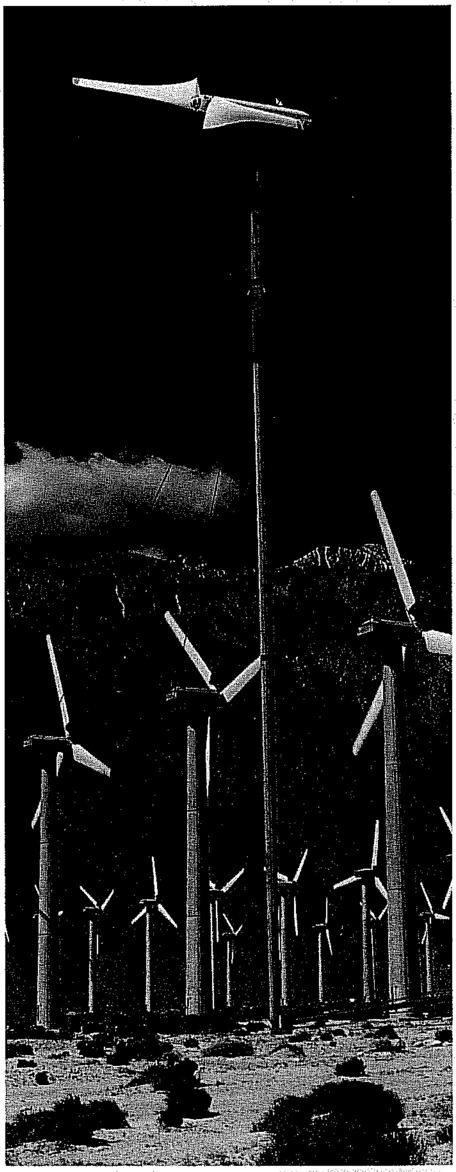
Northern Power completed wind tunnel testing of its aileron controls at Wichita State University during 1993. In related efforts, the company conducted field tests of aileron controls retrofitted to its Northwind-100 turbine. The tests demonstrated that aileron controls could modulate power and slow a fully operational turbine rotor.

Northern Power also completed qualification testing on the new turbine's drive train, the aileron actuator mechanism, and the yaw brake system in FY 1993. It designed the protocol for constructing turbine blades, scheduled for fabrication in 1994. And, it began fatigue tests of the rotor's center joint with NREL at the National Wind Technology Center.

New Subcontractor Selected to Develop Advanced Turbine

A fourth subcontractor, Carter Wind Turbines, Inc. of Burkburnett, Texas, was selected to participate in the DOE near-term turbine development effort during FY 1993. NREL awarded Carter a subcontract to improve its 300-kW, high performance turbine. The 2-bladed, downwind turbine is very lightweight, flexible, and sits atop a 50-m (167-ft) tube tower anchored by guy wires. The tall tower is lowered to the ground with a winch for turbine maintenance. Being able to perform maintenance on the ground rather than 50 m in the air is a significant advantage for maintenance personnel.

Under the new 3-year contract, Carter is designing new rotors that incorporate NREL-designed airfoils into its turbine blades. Carter plans to evaluate the new rotor's potential to increase energy capture. The company will also design a new controller, explore advanced generator concepts, and significantly increase the height of the tower. The tower, already the industry's tallest, could grow to a height between 81 and 90 m (270 to 300 ft). At this height, the turbine could significantly increase its energy capture in regions where there is a large increase of wind speed with height (wind shear). As part of this effort, Carter plans to create a new turbine that fully complies with European standards for certification. Compliance will open up international markets for this innovative U.S. turbine.



In FY 1993, NREL selected Carter Wind Turbines to develop an improved turbine based on the company's CWT 300 machine. The turbine sits atop a 50-m tower.

Maintenance workers can lower the CWT 300 turbine to the ground in about 20 minutes for servicing or repair.

In FY 1993, Carter sold 10 wind turbines to the Great Orton Wind Facility in the United Kingdom. In 1 year of operation, the turbines have demonstrated good availability and excellent energy production. They also survived a week of sustained 90-mph winds. In the same year, the company also sold three turbines to Texas Utilities for a renewable energy demonstration project located near the Dallas-Fort Worth airport.

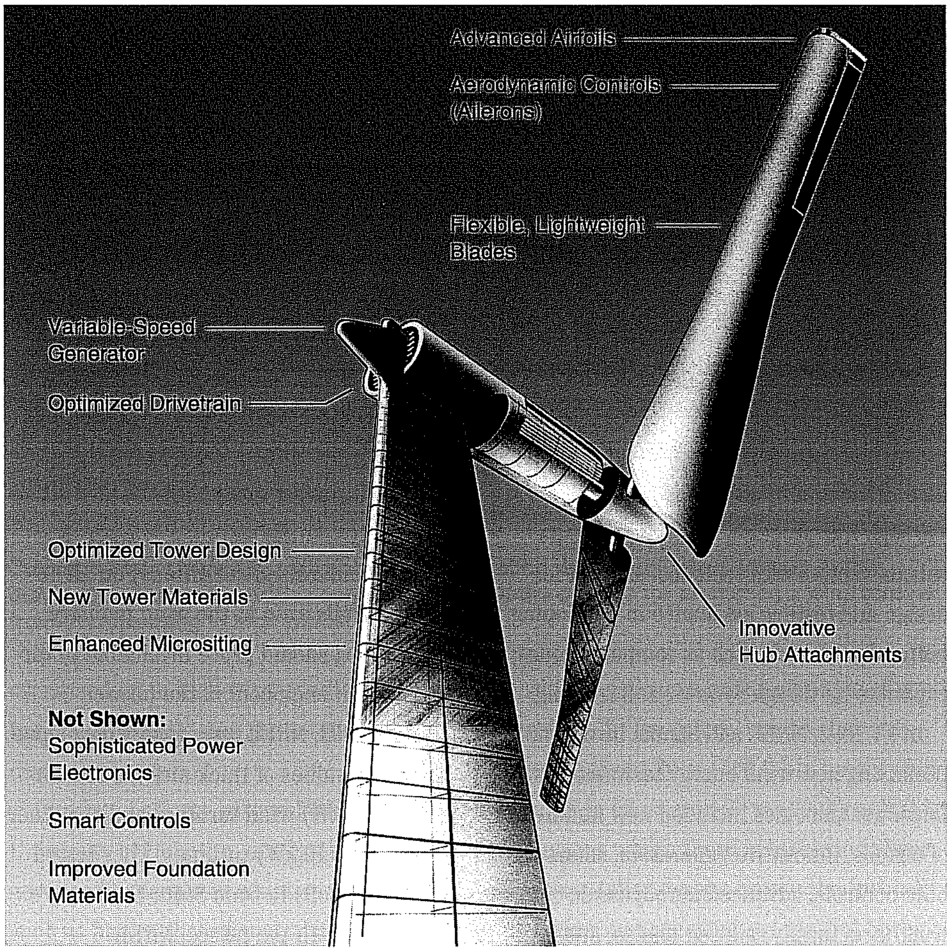
Negotiations Under Way for Value-Engineered Turbine Subcontracts

DOE's Value-Engineered Turbine Project supports U.S. wind power plant operators in rapidly developing wind turbines that can compete in today's wind energy markets. Based on turbines operating in California's wind power plants, the new turbines will be value-engineered to improve current levels of quality, performance, and reliability—at lower costs. The majority of existing installed turbines produce electricity for $0.07 to $0.09/kWh. Such costs are too high to compete with emerging advanced wind technologies in the United States and abroad.

In FY 1993, NREL issued a solicitation for the project and began negotiations with three successful proposers, all of whom have extensive experience operating wind power plants.

DOE Launches Next-Generation Wind Turbine Development

In FY 1993, DOE began a new phase of its Wind Turbine Development Program: the development of next-generation, utility-grade wind turbines that can produce electricity at $0.04/kWh or less at moderate wind sites. The objective of this initiative is to stimulate the wind industry to explore new design concepts employing cutting-edge technology. The new designs are destined for a new generation of utility wind turbines expected to come on line between 1998 and 2000. Some of the original ideas for the new turbines came from conceptual design studies completed under the DOE program in FY 1992. Others will emerge in the turbine-development process during the next several years.



Ray David, NREL

An artist's rendition of a next-generation, advanced wind turbine is shown here.

To inspire industry to depart from traditional designs, DOE split the next-generation turbine development phase into two projects: the Innovative Subsystems Project and the Turbine Development Project. The objective of the Innovative Subsystems Project is to encourage industry to design creative components and subsystems to improve turbine performance and reliability while reducing costs. The project involves designing, fabricating, testing, and analyzing an innovative turbine subsystem. Participants must contribute a minimum of 30% of project costs.

In FY 1993, NREL issued a solicitation for projects to develop innovative subsystems. The Laboratory received a dozen proposals and began negotiating subcontracts with approximately half of the respondents. Proposed innovative subsystems included a variable-speed generator, an advanced rotor, an advanced turbine control and data management system, and a new tower. NREL plans to award a total of approximately $5 million for multiple 2-year projects. Under the Turbine Development Project, NREL plans to analyze the requirements for developing innovative utility-grade wind turbines. On completion of these studies, NREL plans to select two or three participants for the fabrication and testing of three prototype next-generation, utility-grade wind turbines. Between 1995 and 2000, DOE plans to provide a minimum of $20 million for the cost-shared Turbine Development Project.

Innovations on the Horizon for Tomorrow's Advanced Turbines

DOE's Turbine Development Supporting Research & Testing Program supports the development of advanced technology. Through this program, NREL provides its subcontractors with technical support for design and testing; assistance in developing better design tools such as computer codes; expertise for design reviews; and training.

In FY 1993, NREL and Sandia investigated promising new wind energy technologies. These technologies included new families of airfoils, innovative generators, smart turbine controls, advanced aerodynamic controls, structurally tailored blades, and advanced tower designs.

Since 1984, NREL researchers have developed families of both thick and thin airfoils specifically designed for wind turbine blades. Using these airfoils on stall-controlled turbine rotors typically increases energy capture by as much as 30%. Stall-controlled rotors take advantage of the tendency of air flow to detach from turbine blades at high rpm to control rotor speeds in high winds.

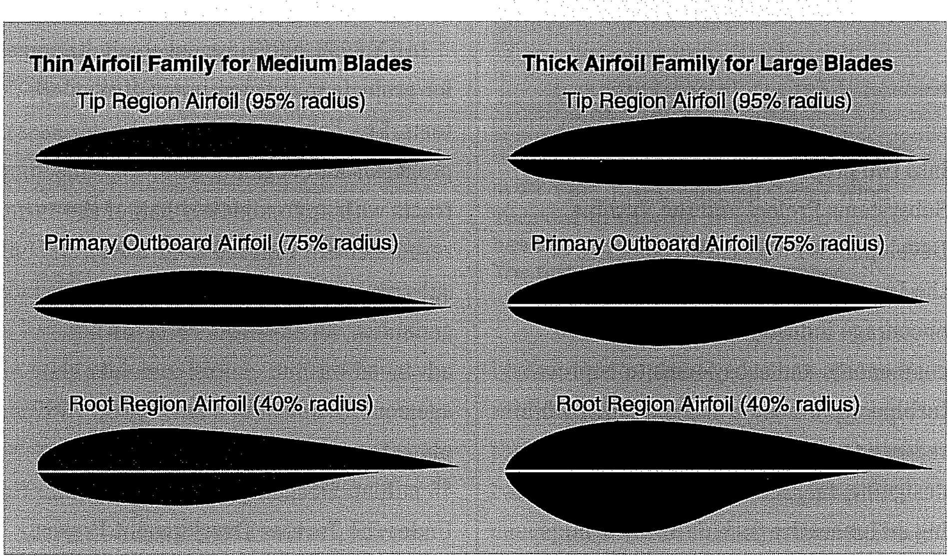
NREL researchers began compiling test data from the NREL-designed airfoils into a catalog during FY 1993. The catalog will eventually contain test data (gathered under standardized conditions) on all major airfoils used in the wind industry. The catalog should prove invaluable to turbine design engineers in the future.

In FY 1993, NREL researchers developed two new families of thick airfoils, one for large (500 kW) wind turbines and the other for small (5-10 kW) turbines. They tested the new airfoils in Ohio State University's wind tunnel. In the future, NREL researchers plan to develop new airfoil families for wind turbines using pitch-blade controls and variable speed. Pitch-blade controls actively regulate the angle of the turbine blades with respect to the wind.

During FY 1993, the University of Colorado completed the design for a direct-drive, variable-speed, permanent-magnet generator. The low-speed generator spins at the same rate as the rotor (60 rpm to 120 rpm). When installed in a wind turbine, the generator can be directly connected to the turbine rotor shaft, eliminating the need for costly transmission and gearing. The variable-speed generator allows the turbine rotor to slow down or speed up, depending on wind velocity. This reduces wear and tear on the rotor and drive train and increases energy capture.

Unique Mobility, Inc., a Colorado company specializing in building permanent-magnet generators for automobiles, began building this innovative generator in FY 1993. Researchers plan to install the new direct-drive generator on a research turbine at the new National Wind Technology Center in FY 1994. They will compare the turbine's performance with a similar variable-speed wind turbine using a standard induction generator.

With an eye to the future, Sandia researchers continued their efforts to develop smart wind turbine controls during FY 1993. Their goal was to create an advanced, expert control system capable of controlling a single wind turbine, an array of turbines, or an entire power plant. Smart systems would be able to detect wind gusts and adjust turbines throughout a wind power plant to maximize energy capture and minimize damage to the turbines. Eventually, expert control systems will



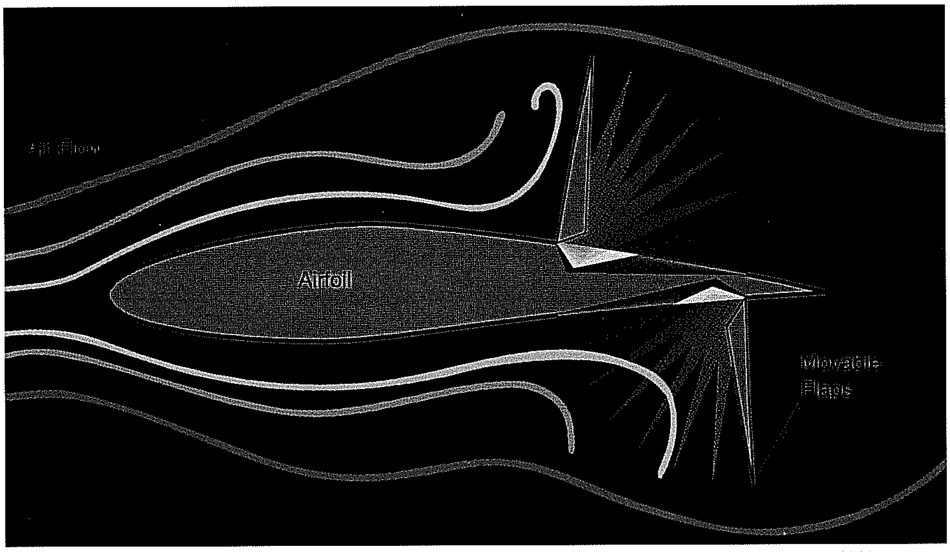
Since 1984, NREL researchers have developed families of both thick and thin airfoils. During FY 1993, NREL researchers developed two new families of thick airfoils.

automatically manage a wind power plant by evaluating wind conditions, site characteristics, turbine operating conditions, and utility load requirements.

Expert control systems could manage individual turbine operation by monitoring and adjusting advanced aerodynamic devices incorporated into turbine blades. Such devices could be used to optimize energy capture, control loads, and control rotor speed.

During FY 1993, NREL began a program to explore advanced aerodynamic devices. Researchers at Wichita State University conducted wind tunnel tests on aerodynamic speed brakes. Speed brakes regulate power production in high winds and also provide protection against overspeed events. One such device is an adaptation of the double-split flap developed in 1942 by the National Advisory Committee for Aeronautics as a dive brake for high-performance aircraft. It uses two split flaps mounted on opposite sides of the trailing (downwind) edge of a wing (or turbine blade). Under an earlier DOE program, NASA flight tested flap concepts on a 100-kW experimental turbine and proved that flaps could be used to start and stop fixed-pitch turbine rotors.

Colorado State University researchers are evaluating these double-split flaps along with newly-developed "spoiler flaps" to see which ones have special promise for wind turbines. If successful, these devices could not only prevent the turbine from overspeeding in high-wind conditions, but could actually stop the rotor in these circumstances.



Colorado State University researchers are evaluating double-split flaps (shown in this drawing) and other innovative concepts to find better devices for protecting a wind turbine from overspeeding in high winds.

In related efforts, researchers at the University of Delaware are investigating advanced concepts in adaptive structures, such as blades that change shape in response to the wind. A blade's ability to change shape in response to the wind should significantly increase energy capture while reducing loads. As a first step in designing adaptive blades, the Delaware researchers plan to embed a network of sensors in a turbine blade. The sensors will provide complete information on what the blade is experiencing under different environmental conditions.

Advanced tower designs also are likely to receive significant attention as industry begins to develop a new generation of wind turbines. In the future, towers that now average about 30 m (100 ft) in height could stretch to 60 or even 90 m (200 ft to 300 ft) in regions where there is high wind shear. Because taller towers expose the turbines to higher average wind speeds and lower turbulence, they can significantly enhance energy capture, particularly in the Great Plains. Tower shapes may change as well. For instance, rotating, airfoil-shaped towers made of strong, lightweight materials could help eliminate noise and vibrations caused when turbine blades pass behind the tower.

Industry Programs

A strong government/industry partnership is helping protect the world's climate by accelerating the adoption of wind energy systems at home and abroad.

Forward-looking utilities, independent power producers, the wind industry, and the U.S. government have worked together to make wind technology a utility-scale, energy-producing technology. The challenge now is to demonstrate wind energy's technical, economic, and environmental benefits to the nation's utilities, state regulators, policy makers, and public. DOE supported the development of advanced wind energy technologies and their rapid adoption at home and abroad with a variety of cooperative programs with industry in FY 1993.

DOE Programs Help Industry Evaluate New Designs

During normal operation, wind turbines experience continuous wear and tear on blades and other components. They are exposed to atmospheric turbulence, wind shear, insects, dust, temperature extremes, high winds, rain, snow, and sleet. Wind turbines also experience significant stress from gravity, tower shadow, and start-up/shut-down cycles. The ability to predict the effects of these stresses in advance would help designers build more durable machines. And, operators could maintain them more effectively.

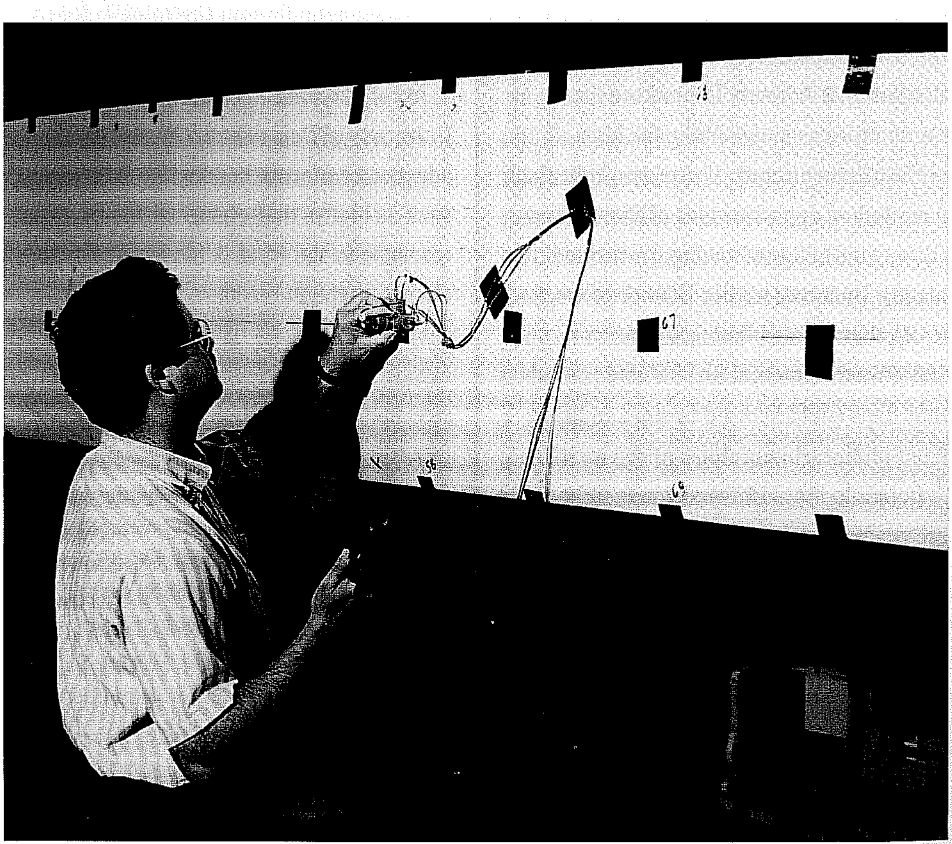
Design engineers must take all these factors into account when designing a new turbine. One challenge is to design components rugged enough to last the 30-year lifetime of the machine. Another challenge is to create a turbine that can withstand a single extreme event, such as a hurricane-force wind gust. DOE's structures and fatigue testing activities help industry analyze how well their design engineers have succeeded in meeting these challenges. Fatigue testing is widely used to estimate the service lifetime of wind turbine systems and components.

Sandia and NREL hosted a workshop in FY 1993 entitled "Fatigue Life Methodologies." The purpose of the workshop was to bring experts together to discuss the prediction and measurement of infrequent events that contribute to wind turbine damage. The workshop participants developed several strategies to address these occurrences.

Modal Testing Helps Industry Assess Improved Wind Turbines

During FY 1993, researchers from Sandia and NREL ran a series of experimental modal tests on wind turbines. Their goal was to develop new modal testing methods. Modal testing helps researchers identify the natural vibration frequencies of turbine components such as blades and towers. Designers need this information to ensure that a turbine will not excite at natural frequencies during operation. A structure that is excited for any length of time at its natural frequency can literally shake itself apart.

Sandia conducted a short-duration, full modal test on the 34-m vertical-axis wind turbine test bed in Bushland, Texas. Researchers wanted to see how vibrating the turbine while it was running would affect the turbine. If the test bed were as well designed as predicted, it would deaden the vibrations set in motion during



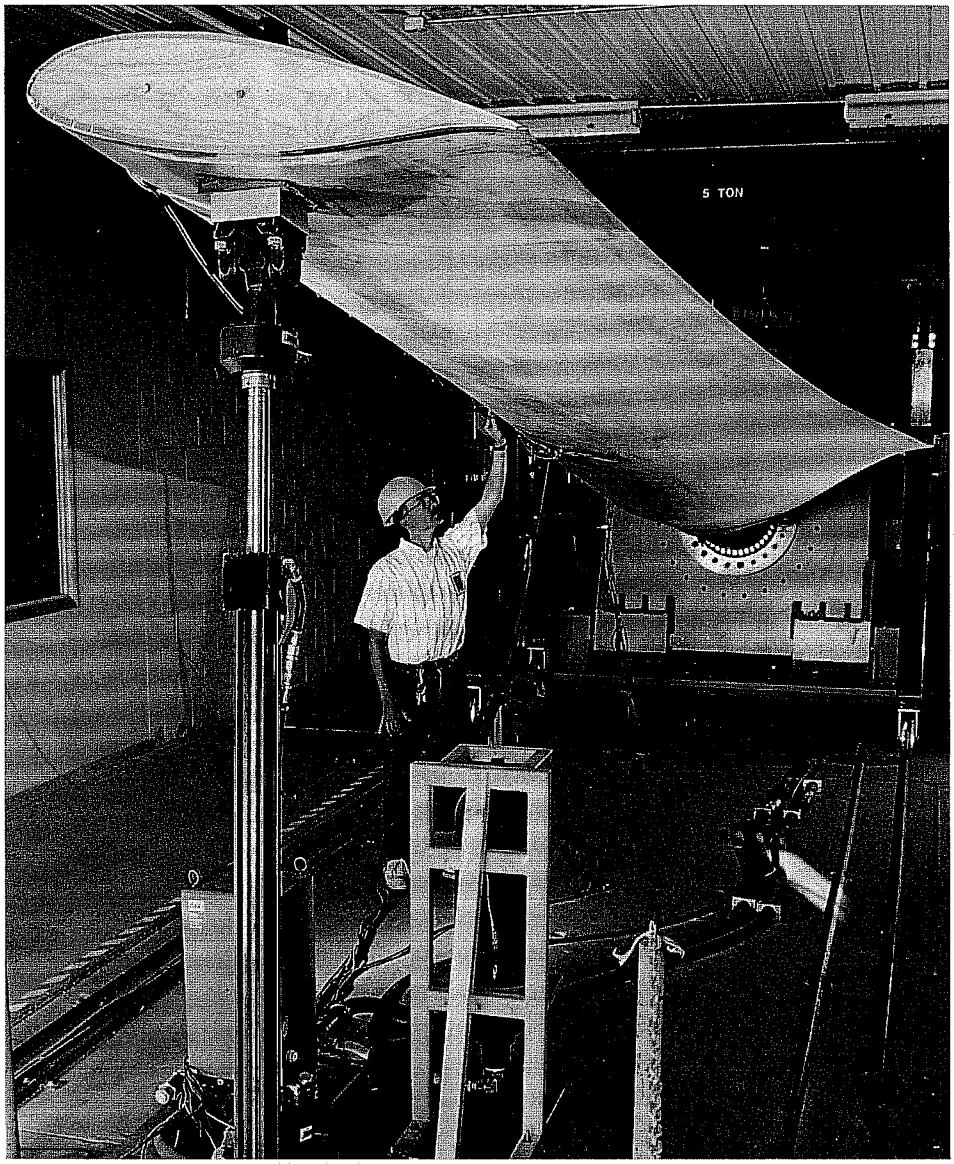
Researchers from NREL and Sandia conducted a series of modal tests during FY 1993. Modal tests identify natural vibration frequencies of turbine components and systems.

the test. Preliminary test results confirmed that the test bed effectively deadened vibrations. Sandia will use detailed analyses of the test data to validate computer models of the turbine.

In FY 1993, Sandia also worked with NREL to perform a new type of modal test on a blade designed for Kenetech Windpower's 33M-VS wind turbine. NREL and Sandia's goal in doing this experiment was to see whether modal testing could distinguish a damaged blade from a healthy one. Researchers first ran a modal test on a 33M-VS blade scheduled for fatigue testing; they then repeated the modal test several months later after the blade had undergone the fatigue testing. Data analysis will show researchers whether modal testing successfully detected any changes in the blade. Kenetech Windpower plans to use the information from the modal tests to fine-tune turbine operation to avoid exciting the blades and damaging the turbine.

In related work during FY 1993, NREL engineers developed a technique for conducting full-systems modal testing on prototypes developed under DOE's advanced Wind Turbine Development Program. Until this occurred, NREL researchers had been limited to performing simple tests on a full turbine. With new hardware, including a hydraulic shaker large enough to induce vibrations in a large wind turbine, NREL researchers completed full-systems modal tests on two turbines at the National Wind Technology Center.

NREL researchers performed full-systems modal tests on both of R. Lynette & Associates' AWT-26 prototype turbines in Tehachapi. During FY 1993, NREL



Lester Lefkowitz

Fatigue tests are necessary for evaluating the effects of continuous wear and tear on turbine blades and other components.

researchers also conducted a modal test on Atlantic Orient's new AOC 15/50 wind turbine at the USDA's Bushland, Texas, wind test facility. They plan to use data from this test to validate the company's new computer model of the turbine.

In related efforts during FY 1993, Sandia continued work on a computer analysis to characterize a wind turbine's structure using vibrations caused by the wind. The vibration analysis technique is less expensive than modal testing. It also can be used in aging aircraft, offshore drilling rigs, and bridges.

During FY 1993, Sandia prepared a monograph on a method for calculating the fatigue life of wind turbines using the LIFE2 code. The monograph, entitled

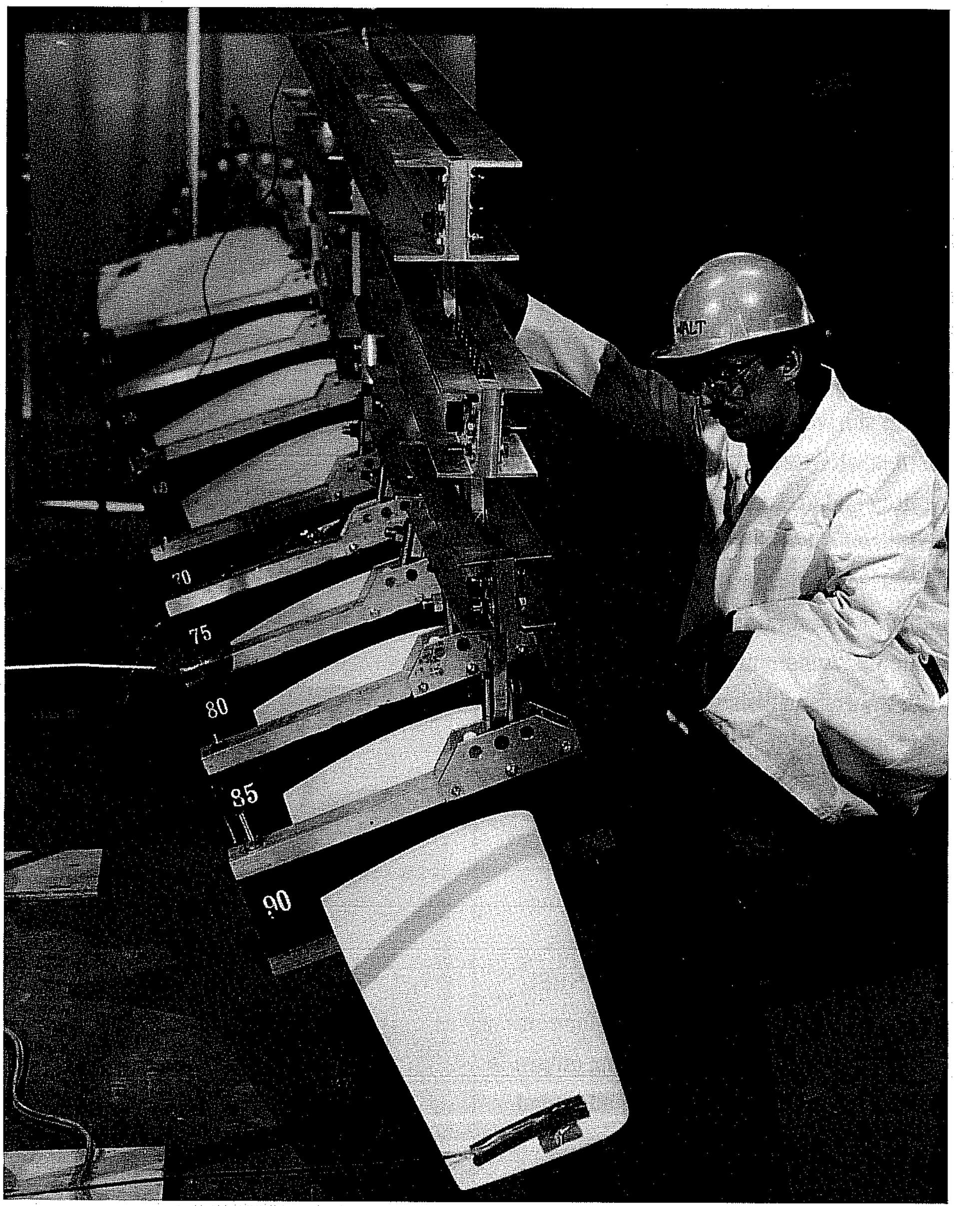
"Case Studies for Fatigue Education," will be included in an engineering course at the University of Wisconsin.

Fatigue Testing to Improve Reliability of Turbine Components

During FY 1993, NREL and Kenetech Windpower performed static loads and fatigue testing on blades from the company's 33M-VS variable-speed wind turbine. The tests were run under a cooperative research and development agreement (CRADA) that began in FY 1992 and will continue through FY 1995. The static strength test evaluated the forces, or loads, that damage or break turbine blades. During the test, researchers used an apparatus that gradually increased loads on the blade until it broke. The test, which measured the ability of the blade to withstand extreme winds, showed the 33M-VS blade to be 50% stronger than its design requirements.

The fatigue test evaluated the effects of continuous wear and tear on the blade. For this test, researchers applied fluctuating loads on the blades. This technique simulates the repeated flexing and bending of rotating blades in an operating turbine. The fatigue test showed the 33M-VS blade to be exceptionally strong. It took the equivalent of more than 60 years of normal operation to damage the blade, whose design life is 30 years.

During the tests on the 33M-VS blade, researchers from Sandia performed two additional, non-destructive blade tests. These tests included the modal testing experiment (described on p. 16) and an acoustic emissions test. In the acoustic test, researchers mounted an array of microphones directly on the 33M-VS turbine blade during fatigue testing and recorded sounds emitted by the blade.



Warren Gretz, NREL

Static loads tests help researchers determine the strength of new blade designs.

A preliminary data analysis indicated that the acoustic test detected areas of damage on the blade before visible breaks appeared. Sandia researchers concluded that acoustic emissions testing shows promise for evaluating new blades, for testing blades after manufacture (quality assurance), and for evaluating the condition of aging turbine blades in the field.

During FY 1993, NREL also completed a fatigue test of the AOC 15/50 wind turbine blade. The 7.2-m wood/epoxy composite blade was built by Gougeon Manufacturing Corporation and incorporates NREL-designed airfoils. The fatigue test showed that the AOC 15/50 blade design meets Danish fatigue performance levels, a necessary prerequisite for competing in European markets.

DOE Supports Turbine Blade Materials Testing

NREL and Sandia support ongoing tests of blade materials and substructures at Montana State University. The tests are part of an effort to develop improved fiberglass composite materials for turbine blades. The Montana State researchers repeatedly test small samples of new materials before evaluating full-sized turbine blade substructures or elements.

During FY 1993, Montana State researchers developed a new method for testing their samples that is five times faster than older techniques. In these tests, researchers subject material samples to a combination of stresses—pulling, twisting, and compressing.

In related research during FY 1993, Sandia conducted fatigue tests on bonded glue joints in relatively small, cylindrical specimens. Bonded joints, which are used in wind turbines to attach the blade to the hub, are the most likely place for fatigue failures in any structure. Tests subjected the joints to a combination of pushing, pulling, and bending. The tests allowed researchers to study stress in the joints and validate computer models.

Cooperative Projects with Industry Aim to Improve Wind Power Plants

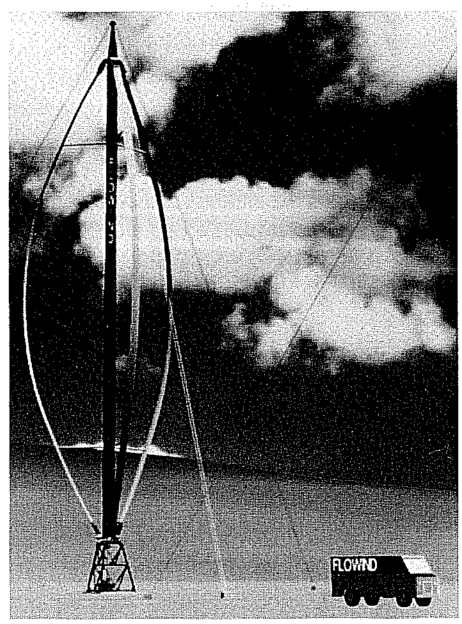
During FY 1993, DOE supported four ongoing projects to enhance the performance, efficiency, and reliability of wind power plants. These projects were part of the cooperative government/industry Wind Technology Application Project, which encouraged cost sharing by industry.

Zond Systems, Inc. and NREL continued a joint project to identify ways to improve the performance of turbines in the company's 65-MW wind plant located in the Tehachapi region. In one series of tests, researchers discovered that new fiberglass blades incorporating NREL-designed airfoils performed better than the LS-1 airfoils used on Zond's turbine blades. When both sets of blades were clean, the NREL blade produced 9% more energy; when both blade sets were soiled (with tape strips simulating dirt and insects), the NREL blades produced 25% more energy. Because turbine blades frequently accumulate insects and dirt during operation, NREL blades could significantly increase wind plant power production (and profits).

Researchers investigated the impact of placing metal extenders between the rotor hub and blades to increase rotor diameter. The extenders, which increased the turbine's swept area by 14.6%, increased energy capture by 13%. Except for slightly higher yaw loads, increases in blade and drive-train loads fell within acceptable design limits.

In a related activity, Zond modified a computer model of wind flow to take into account the Tehachapi region's complex terrain. The revised model was able to predict wind speeds at several locations with variable terrain features. The company plans to refine the model until it can predict the energy output from proposed wind park layouts.

In another Wind Technology Applications Project, FloWind Corporation and Sandia completed a new rotor design for the company's vertical-axis wind turbine. FloWind's new 17-m rotor is much taller and thinner than the existing 19-m rotor. The new rotor's fiberglass composite blades incorporate Sandia-designed airfoils to keep air flowing smoothly over the turbine blades. FloWind expects the new rotor to effectively double the turbine's annual energy output. The company plans to build a prototype turbine incorporating the new rotor in FY 1994.



Gregory L. Brown, FloWind Corp.

FloWind and Sandia completed a new rotor design for FloWind's vertical-axis wind turbine in 1993. An artist's rendition of the new turbine is shown here.

Late in FY 1993, Macani Uwila Power Corporation of Oahu, Hawaii, announced plans to reactivate a joint project with NREL to develop aileron controls for the company's 14 600-kW Westinghouse wind turbines. The project had been on hold since the company, which is a subsidiary of New World Power Corporation, purchased the turbines from Hawaiian Electric Renewable Systems, Inc. in early 1993.

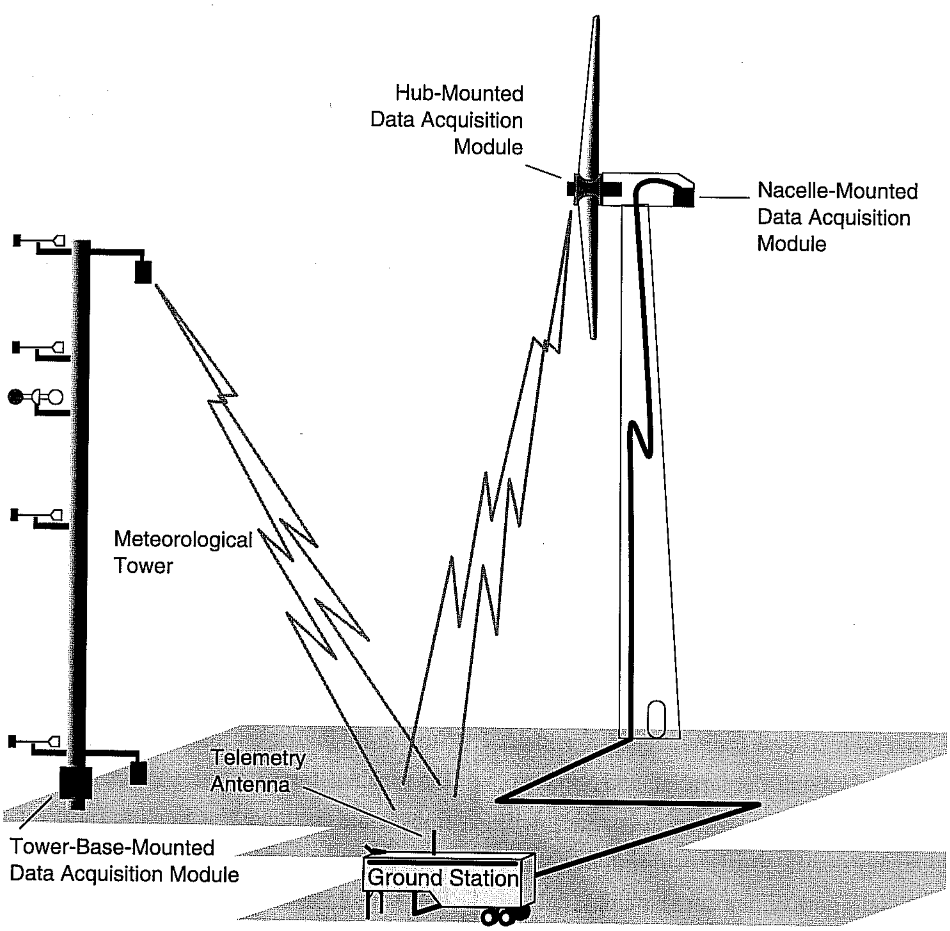
In another cooperative research project, PNL worked with industry partners to study wind turbulence at six sites: four in California, one in Vermont, and one in

New York. The goal of these studies was to better understand wind turbulence and its effect on power production. In FY 1993, PNL issued a solicitation for a new phase of the study that will concentrate on evaluating wind sites in the Great Plains and Midwest.

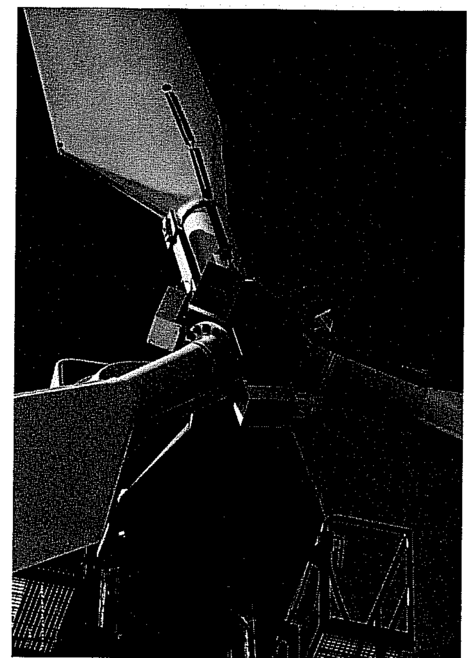
Advanced Wind Turbine Measurement System Now Available

Field tests of Zond Systems, Inc.'s new Advanced Data Acquisition System (ADAS) in 1993 confirmed the system's ability to make simple, accurate, inexpensive, and reliable measurements of operating wind turbines. DOE supported the development of the new system. Zond installed the system on turbines at its wind power plant in Tehachapi to verify operation of a 500-kW wind turbine. Measurements included ambient pressure, air temperature, yaw position, blade pitch angle, and the position and speed of the mainshaft.

The modular measurement system uses digital electronics and telemetry to obtain simultaneous signals from multiple sources. Wind plant operators can mount modules directly on rotating blades, towers, nacelles, control systems, meteorological towers, or electrical stations. The rugged, low-cost system is now available from Zond.



Zond Systems developed this Advanced Data Acquisition System under an NREL subcontract. The system is now commercially available.



Lloyd Herziger, Zond Systems, Inc.

The wind turbine shown here has Advanced Data Acquisition System modules mounted directly on the rotor. The modules transmit information about the rotor via telemetry to a ground station.

DOE Supports Wind Industry Activities

DOE supported technology transfer and new market development activities undertaken by AWEA during FY 1993. These activities included the publication of new educational brochures, fact sheets, and user handbooks; workshops; seminars; and conferences such as the annual wind power conference held in San Francisco, California, in July 1993. AWEA also participated in the National Association of Regulatory Utility Commissioner's Renewable Energy Conference in Savannah, Georgia, in October 1993. AWEA provided the group with information on new technology and regulatory issues relevant to wind energy.

In other activities, DOE and AWEA co-sponsored a workshop entitled "The 'undamentals of Wind Energy" in Boston n May 1993. DOE also supported an AWEA inance and investment workshop held in une 1993 in New York City.

In October 1993, NREL and the Desert Vind Energy Association held a technical xchange workshop in Palm Springs, California. The workshop had three key bjectives: (1) to provide training for wind lant operators and technicians in wind nergy technology; (2) to facilitate an xchange of information between wind plant perators and the federal research program; nd (3) to define potential collaborative prorams between NREL and the wind industry.

In April 1993, DOE and the National Conference of State Legislators hosted a ound-table discussion at the National Solar Energy Forum in Washington, D.C. The meetng, coordinated by the American Society of Aechanical Engineers and the American olar Energy Society, included speakers from DOE, EPRI, industry, and state governments.

DOE, AWEA Work to Develop International Standards

DOE and AWEA continued working oward developing industry consensus stanards for wind turbine generating systems uring FY 1993. This work, carried out in onjunction with the International Electrotechnical Commission, is vital to J.S. competitive interests. Matching U.S. ndustry standards to international stanards is necessary to ensure that U.S.-made turbines can compete in projected multibillion dollar global wind energy markets.

American Wind Energy Association

DOE's Wind Energy Program works with AWEA to develop standards for the design, installation, performance, and safety of wind turbines around the world.

During 1993, AWEA gathered comments from the U.S. wind industry on the draft design standards for wind turbine systems. In December 1993, the U.S. wind industry voted overwhelmingly in favor of approving these standards as written. Once the design standards are approved by the European Union, utilities around the world will be able to buy wind energy systems that meet uniform standards for design, installation, performance, and safety. The design standards are already providing a sharper focus for design work carried out in conjunction with DOE's advanced wind turbine program. In the future, they will provide a foundation for developing a U.S. certification program for wind turbines that is in harmony with similar programs in Europe.

In related efforts, the U.S. industry is reviewing draft standards documents for small wind turbines and for measuring acoustic noise. A fourth standards document, covering power performance, is currently being revised before being released for industry comment.

New Publications

DOE supported the development of user handbooks and other publications by AWEA in 1993. New titles included:

- *Economics of Small Wind Systems*
- *Introduction to Small Wind Systems*
- *Removing Barriers to Wind Energy: Directions for State Regulatory Action*
- *Understanding Your Wind Resource*
- *Wind Energy for Sustainable Development*
- *Wind for Regulators: A Handbook for Utility Regulators*

NREL Developing Plans for U.S. Certification Program

In FY 1993, NREL began developing plans for a U.S. wind turbine certification program. NREL's efforts came in response to a 1993 recommendation for such a program from AWEA's board of directors. NREL has recommended that certification testing of turbine components and subsystems take place at the National Wind Technology Center and other locations that meet program requirements. On completion of testing, the data would be forwarded to an independent agency that would certify U.S. technology according to established procedures.

International Programs

DOE provides technical assistance to the U.S. wind industry in developing international wind energy applications and market opportunities.

New market opportunities for wind energy systems are developing all over the world. These opportunities include sales of wind power plants, village power systems, wind-electric water pumping systems, and stand-alone wind systems for such applications as homes or remote telecommunications sites.

DOE supports U.S. industry in developing international market opportunities by offering foreign policy makers, engineers, and business representatives technical assistance in wind resource assessment, technology development, education, training, feasibility studies, performance monitoring, systems modeling, and communications. The department also provides technical assistance and funding for projects through the federal Committee on Renewable Energy Commerce and Trade (CORECT).

In the industrial world, concerns about global climate change, acid rain, and air pollution are encouraging utilities and government officials to look at cost-effective renewable energy systems such as wind. The U.S. wind industry is already marketing utility wind turbines and, in some cases, complete wind power plants for grid-connected applications outside the United States. Since 1990, U.S. firms have installed new turbines in Canada, the Netherlands, Mexico, South America, Spain, the United Kingdom, and other countries. DOE has supported the U.S. wind industry's efforts with its advanced Wind Turbine Development Program. DOE also has offered technical assistance on a case-by-case basis to foreign utilities, private industry, and government agencies interested in developing grid-connected wind energy systems.

Carter Wind Turbines

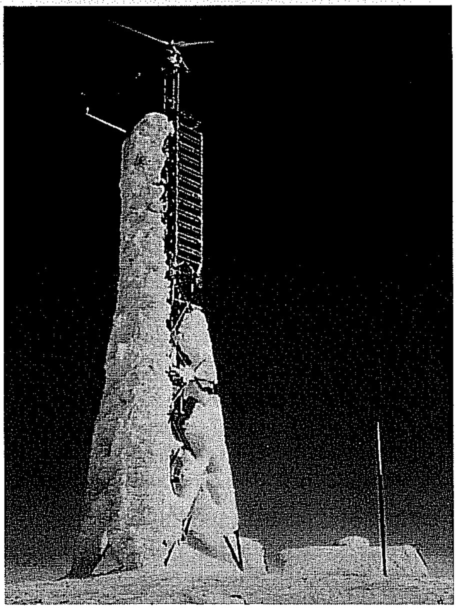
Carter Wind Turbines installed these 300-kW wind turbines at Great Orton, the United Kingdom, in 1993.

Demand for Electricity Growing in the Developing World

In the developing world, many nations are committed to bringing electricity to rural areas and raising the standard of living of their poorest inhabitants. Bringing electrical power into remote areas poses major technical, economic, cultural, and environmental challenges. Clean, affordable wind energy systems are well suited for village electrification projects and self-contained applications.

The growth in demand for electricity in the developing world far outstrips that of the industrial world. This growth comes at a time when most nations recognize the urgent need to control energy-related emissions of greenhouse gases and other air pollutants. Consequently, DOE's international program places a strong emphasis on wind energy applications to meet the needs of the developing world for electricity.

For many rural inhabitants of the developing world, a single, stand-alone power system may be sufficient. One wind turbine with battery storage can power an individual home or support specific community services such as water pumping, water treatment, communications, ice making and cold storage, grain grinding, small industries, health clinics, schools, or community centers.



Northern Power Systems

Wind turbines are ideally suited for providing power to remote telecommunications sites. This telephone repeater (located above the Arctic Circle) belongs to the Norwegian Transit Authority.

Larger community services may require more power than a single turbine can provide, however. Hybrid power systems may be required. Hybrid systems incorporate one or more wind turbines, other renewable generation sources such as photovoltaic (PV) collectors, and battery storage or back-up diesel generators. Back-up generation is necessary because wind, like some other renewable energy resources, is intermittent.

Hybrid wind energy systems are becoming the technology of choice for village power systems in areas with a good wind resource. Over their service lifetime, hybrid wind energy systems cost less, are more reliable, and have far less impact on the environment than stand-alone diesel generators.

DOE Supports Development of Village Power Systems

DOE sponsored a program to improve the performance and lower the costs of hybrid village power systems during FY 1993. DOE supported tests of Atlantic Orient Corporation's new 50-kW wind turbine prototype. The new turbine was specifically designed for remote village applications, including integration into wind/diesel hybrid systems.

In FY 1993, NREL selected Bergey Windpower to develop a family of more powerful and reliable inverters. Inverters change direct current into the alternating current required to run household devices. Bergey plans to design a basic inverter that will allow turbine operators to adjust output power from the turbine to conform to requirements in either Europe (50 cps) or the United States (60 cps). Bergey will design a second inverter for a wind energy system incorporating short-term battery storage and a third inverter tailored to wind-diesel systems.

In FY 1993, NREL and Sandia, in cooperation with the State of Alaska, supported Northern Power Systems in developing an innovative village power system known as the Hybrid Renewable MicroGrid Power Plant. The hybrid power plant consists of a diesel engine, a battery bank, system controllers, a power conditioning unit, and one or more 50-kW wind turbines. The company plans to install a prototype of the hybrid power plant in Wales, Alaska, in the summer of 1994. NREL and Sandia's Design Assistance Center will assist the company in monitoring the Wales power plant.

Sandia Supports Hybrid Power System in Mexico

Working with the Instituto de Investigaciones Electricas (a Mexican utility research organization), Sandia provided funding and technical support for a new village electrification project in 1993. The new hybrid power system is located in the village of Xcalak on the southeastern tip of the Yucatan peninsula. It includes six Bergey 10-kW wind turbines, an 11.7-kW PV array, a 40-kW inverter, a battery bank, and a manual control system. The hybrid system also has a backup diesel generator. The Xcalak system is the largest hybrid village electrification system operating in the Americas. It currently provides power to 80 homes, a restaurant, and a small resort.

During FY 1993, Sandia, NREL, and the Mexican utility research organization began data collection and analysis on the Xcalak system. Since being installed in August 1992, the project has delivered power reliably to the remote fishing village, which has a resident population of approximately 400 people. Since installation, the average load on the system has been

Bergey Windpower

Sandia monitored the performance of this hybrid wind village power system near Xcalak, Mexico. The system, which serves 400 inhabitants of a remote fishing village, is the largest system of its kind in the Americas.

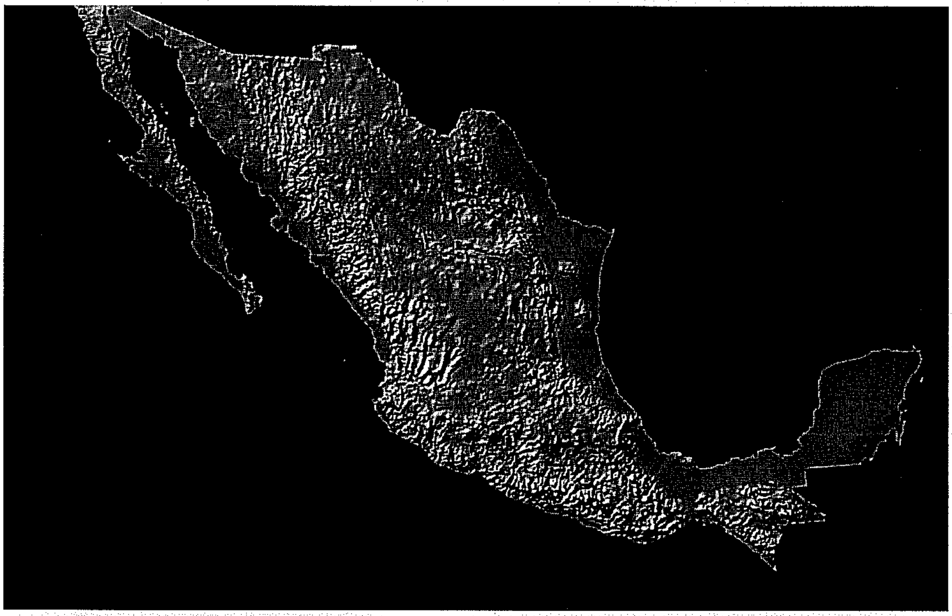
25% higher than anticipated. Fortunately, the wind resource has been higher than original estimates to partially make up the difference in demand. However, the load growth rate in Xcalak is sufficiently high that the system may require additional generation and storage capacity.

Latin America Offers Market Opportunities for U.S. Wind Industry

Mexico has one of the world's most aggressive rural electrification programs that uses wind and other renewable energy systems. The Xcalak project is one of eight hybrid wind projects already providing electricity to rural communities. Because Mexico has regions of good wind resource and growing demands for electricity in rural areas, DOE began focusing on developing that nation's wind energy markets during 1993.

Like Mexico, much of Latin America has excellent wind resources. During FY 1993, NREL provided technical assistance in planning a 4-year, joint U.S.-Brazilian rural electrification pilot project. The project will install renewable energy projects, including wind hybrid power systems, in at least seven Brazilian states.

DOE and the U.S. wind industry worked together during FY 1993 to launch the Americas' 21st Century Program. The program is a joint venture to develop sustainable, environmentally sound renewable energy projects in Latin America and the Caribbean. The program's first major initiative will be a conference on "Renewable Energy in the Americas" to be held in Puerto Rico in 1994.


Pacific Northwest Laboratory

PNL worked with Mexican authorities in FY 1993 to develop a wind energy atlas of Mexico. The atlas, together with shaded-relief maps such as the one shown above, will help Mexican firms identify good sites for wind power plants.

DOE Provides Technical Assistance to Develop International Markets

In FY 1993, DOE supported U.S. industry through AWEA in developing export markets in Mexico, Latin America, Indonesia, and the newly independent states of the former Soviet Union. Their efforts included workshops on resource assessment, anemometer loan programs, and an annual reverse trade mission, known as the Wind Energy Applications and Training Symposium. DOE also supported wind resource assessments in Mexico, Poland, Estonia, Latvia, Lithuania, and Indonesia. The Mexican and Polish resource assessments were done in cooperation with the U.S. Agency for International Development (USAID).

As part of the resource assessment project, PNL began working with Mexican authorities in FY 1993 to develop a wind energy atlas of Mexico. The laboratory reviewed meteorological data for Mexico provided by U.S. and Mexican agencies and developed a preliminary resource map. To refine the map, PNL and industry worked with CIEDAC and CONDUMEX, two Mexican firms interested in wind energy and rural economic development, to put up new meteorological towers. The project will continue through FY 1994.

PNL also developed preliminary estimates of the wind resource in Poland during FY 1993. PNL based its new estimates on data from existing meteorological stations in Poland. In March 1993, representatives from AWEA, NREL, an American turbine manufacturer, and a U.S. utility visited Poland to assess opportunities for wind energy development and evaluate opportunities for joint turbine manufacturing ventures. NREL also participated in a multi-agency effort to develop renewable energy resources in Armenia.

Sandia's Design Assistance Center sup-
orted AWEA's international program
fforts in FY 1993. The center offered
vorkshops on wind-electric water
umping in Mexico City and Guatemala;
ssisted with wind resource assessment
rojects in Mexico, Guatemala, the Virgin
slands, and Indonesia; and helped install
small wind energy system as part of a
emonstration project in St. John, U.S.
irgin Islands.

Educational Programs Key to Developing New International Markets

Since 1987, AWEA has held the annual Vind Energy Applications and Training ymposium in conjunction with the associ- tion's annual wind power conference. Iore than 100 planners, policy makers, ngineers, and business representatives rom developing countries have come to ne United States to learn about U.S. wind nergy technologies, companies, and overnment programs.

In FY 1993, 24 representatives from 7 nations visited USDA's wind energy est facility at Bushland, Texas, and wind ower plants in California's Altamont ass. The visitors attended special semi- ars on wind energy, resource assessment, and the integration of wind energy into the utility grid. They also attended the Windpower '93 conference. The symposium offered U.S. industry a chance to explore potential foreign markets and establish the necessary links to do business there. DOE co-sponsored the 1993 symposium with the State Department, USAID, and CORECT.

In related educational efforts, NREL hosted a Village Power/Rural Electrification workshop in July 1993. The workshop's goal was to bring together representatives from the wind industry and the federal government to discuss strategies for implementing rural electrification projects and improving communications among participants. Workshop participants agreed to hold an annual village power conference and to circulate a monthly newsletter highlighting key projects in different areas of the world.

AWS Scientific, Inc.

Baltic Anemometer Loan Program seminar participants pose with their new instruments in Kärdla, Estonia. During 1993, AWEA offered the seminars in Mexico, Indonesia, and the newly independent states of the former Soviet Union.

Wind Energy Applied Research Highlights for FY 1993

DOE's applied research efforts support the development of advanced technologies to help the United States increase productivity and competitiveness while reducing energy-related emissions of greenhouse gases.

Wind energy research has two goals: (1) to gain a fundamental understanding of the interactions between wind and wind turbines; and (2) to develop the basic design tools required to develop advanced technologies. A primary objective of applied research activities is to develop sophisticated computer codes and integrate them into the design, testing, and evaluation of advanced components and systems. Computer models have become a necessary and integral part of developing new high-tech wind energy systems. A computer-based design strategy allows designers to model different configurations and explore new designs before building expensive hardware.

DOE works closely with utilities and the wind industry in setting its applied research agenda. As soon as research findings become available, the national laboratories transfer the information to industry through workshops, conferences, and publications. The following research highlights provide an overview of the achievements of the DOE Wind Energy Program in FY 1993.

Design Tools Spurring Advanced Technology Development

NREL and Sandia transferred key advanced computer codes to industry during FY 1993. This transfer marked an important milestone in the goal of helping industry design and test advanced technology with computer simulations.

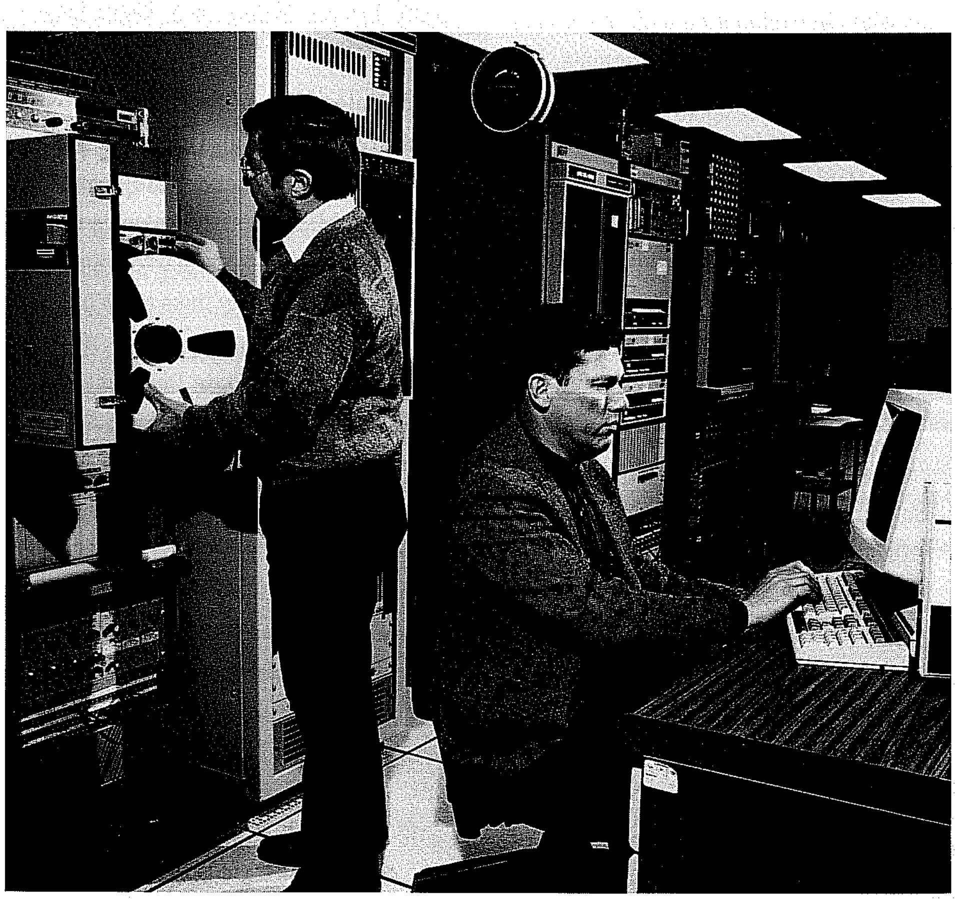
Early in FY 1993, NREL held an industry training course on using the ADAMS software. The aerospace, robotics, automotive, and wind industries currently use ADAMS to model their mechanical systems. The course was held at the Ann Arbor, Michigan, offices of Mechanical Dynamics, Incorporated, which developed the software.

In FY 1992, NREL modified the powerful ADAMS model to produce a comprehensive, realistic simulation of the interactions between the wind and a wind turbine. It allows turbine designers to rapidly simulate a design, evaluate individual components and subsystems, and optimize the entire system on the computer. Three industry subcontractors attended the training course and began using ADAMS to model their turbines. These turbines are under development as part of DOE's Wind Turbine Development Program. One of the subcontractors, R. Lynette & Associates, used the ADAMS model to redesign the AWT-26 blades to avoid unwanted vibrations.

NREL researchers also tested the ADAMS model's ability to predict the effects of wind turbulence on loads the turbine experiences during operation. They showed that blade loads predicted by the new software closely matched actual loads observed during field testing.

During FY 1993, researchers at the University of Utah adapted unsteady aerodynamics codes for ADAMS. The new codes enabled ADAMS to model both dynamic stall and the inflow to turbine blades.

In related efforts, NREL researchers improved the Force and Loads Analysis



Warren Gretz, NREL

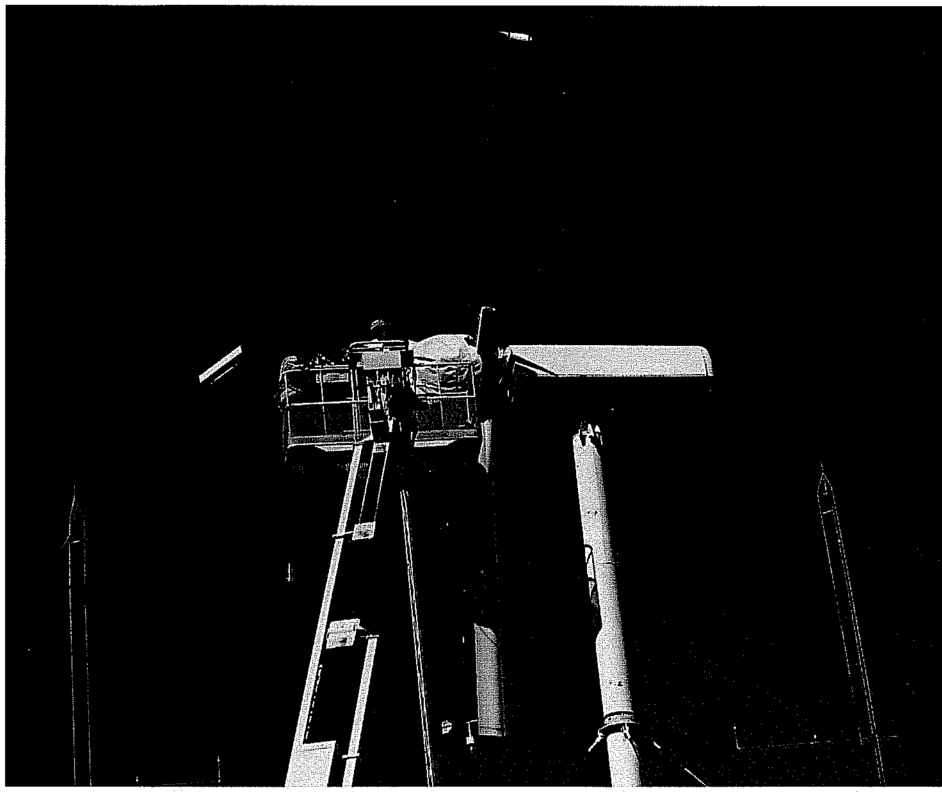
DOE places a high priority on developing sophisticated computer codes to assist the wind industry in developing advanced technologies.

'rogram (FLAP) code by including the .erodynamic properties of multiple .irfoils. The FLAP model is widely used y the wind industry to predict turbine oads.

During FY 1993, Sandia enhanced its .erodynamics codes for vertical-axis wind urbines and transferred them to FloWind Corporation. Sandia also worked with a 'loWind consultant to adapt structural odes developed at Sandia for use on the ompany's computers.

In July 1993, NREL and Sandia sponored a 1-day workshop entitled "Wind Turbine Design and Modeling Codes: A Iands-On Workshop," held in conjunction vith Windpower '93. The well-attended vorkshop provided an overview of the rincipal design codes currently available n Europe and the United States. NREL .nd Sandia researchers and subcontracors presented codes that model aerodyamics, blades, structural dynamics, .dvanced dynamics, turbulence, and atigue.

Following Windpower '93, Sandia sponored a short course to train wind turbine ngineers and university researchers on ising the LIFE2 and the Fatigue and Reliability of Wind Turbines (FAROW) odes. Sandia is developing FAROW to .llow turbine designers to focus on xtending the lifetimes of the most expenive turbine components. Industry already ises the LIFE2 code to predict wind turine service lifetimes and develop inspecion schedules for turbine components. 'articipants spent 2 days working with xample problems designed to teach them ow to apply the codes to typical wind urbine design analyses.



Warren Gretz, NREL

NREL's research into unsteady aerodynamics is part of an international research project to study the physics of wind/wind turbine interactions.

Aerodynamics Research Seeks to Explain Operation of Turbine Rotors

Since 1989, NREL has studied the complex interaction of turbine blades with the wind. Turbulent winds affect both turbine performance and loads in ways that are difficult to predict. Understanding these interactions will help researchers develop better aerodynamic models for wind turbine designers to use in building durable, low-cost wind turbines.

During FY 1993, researchers analyzed data gathered during the first phase of this research. They also built new sensors, instruments, and twisted-airfoil blades for use in the next phase of this research, scheduled to begin in FY 1994. The more complex blade shape will give researchers an insight into the forces that affect dynamic stall on standard turbine blades. Dynamic stall occurs when the air flow separates over part of a turbine blade, causing sudden changes in the aerodynamic forces on the blade. In FY 1993, the University of Colorado worked with NREL to develop a faster, more powerful method to analyze data from this research. For example, researchers developed a computerized video display that showed air pressure distributions on a turbine blade against a backdrop of a rotating blade.

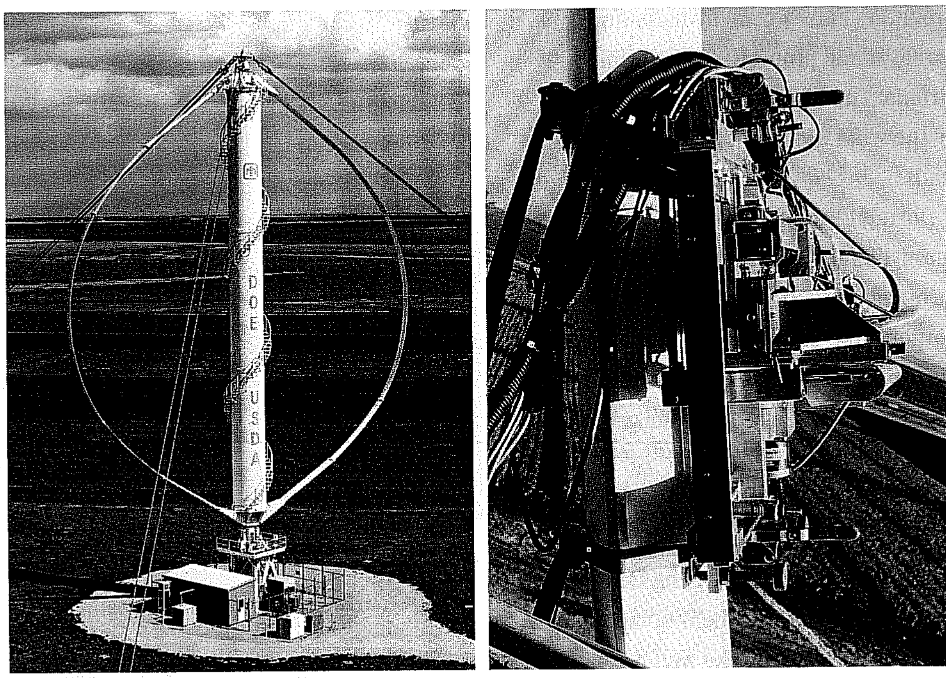
NREL's research into unsteady aerodynamics led to a 3-year international research project, which began in FY 1992. Under the International Energy Agency's (IEA) Annex 14, researchers from the United States, the Netherlands, Denmark, and the United Kingdom are conducting studies to elucidate the physics of wind/turbine interactions.

Sandia continued to develop a computer simulation of how lift and drag forces interact to control the rotating motion of a wind turbine. Researchers hope to better determine what happens to air flow when it separates from the blade during stall. In FY 1993, Sandia used the simulation, known as computational fluid dynamics, to study blade air flow patterns just as the point of stall is reached.

Sandia Targets Blade Surface Roughness Problem

In April 1993, Sandia and NREL met with industry representatives to discuss strategies for dealing with turbine blade surface roughness. During turbine operation, the accumulation of dirt and insects can cause the smooth leading edge of a turbine blade to become rough, which changes the shape of the airfoil. Blade surface roughness can reduce a turbine's energy capture by as much as 40%, particularly in stall-controlled turbines. Because decreased energy capture translates into decreased revenues, participants agreed it was crucial to find solutions to the problem.

During FY 1993, Sandia conducted tests of an innovative device that can accurately scan a wind turbine blade for surface irregularities. Known as a laser profilometer, this device uses a laser and a motion-control mechanism to measure the blade's surface profile. The profile is used to characterize roughness and can be used to assess manufacturing quality. Sandia used the device to scan small sections of the blades on the 34-m vertical-axis wind turbine test bed in Bushland, Texas. Sandia also tested the device in the wind tunnel at Ohio State University.



Sandia National Laboratories

USDA Agricultural Research Station

Sandia conducted field tests of its new laser profilometer (right) on the 34-m vertical-axis wind turbine test bed (left) in Bushland, Texas. The profilometer measures accumulations of dirt and bugs on a turbine blade.

Wind Turbulence Studies Hold Key to Understanding Turbine Damage

Since 1990, PNL has collaborated with the wind industry to better understand wind turbulence and its effect on power production. Turbulence can affect power output and damage turbine components. In 1993, PNL studied turbulence at four sites in California and one in Vermont.

PNL's studies showed that there are two kinds of turbulence that affect rotating turbines: engulfing gusts and rotating shear. Engulfing gusts consist of rotating eddies in the wind flow that are larger than the rotor. In contrast, eddies smaller than the rotor were responsible for fluctuating shear. After analyzing specific upwind terrain features, PNL researchers were able to detect eddies being shed from the ridge. They also detected a subtle difference in the terrain on a ridge in front of two different sites that caused the flow to separate at one site but not the other. These studies underscored the importance of studying local terrain features in siting wind turbines.

In related work, NREL developed a statistical method to evaluate the characteristics of the wind that are associated with severe damage to wind turbines. Researchers conducted the studies at the San Gorgonio, California, wind power plant. Turbines in the power plant suffer unusually high levels of fatigue damage, particularly at some locations inside the plant. The studies showed that most of the damage correlated to turbulent conditions, which vary with the time of day.

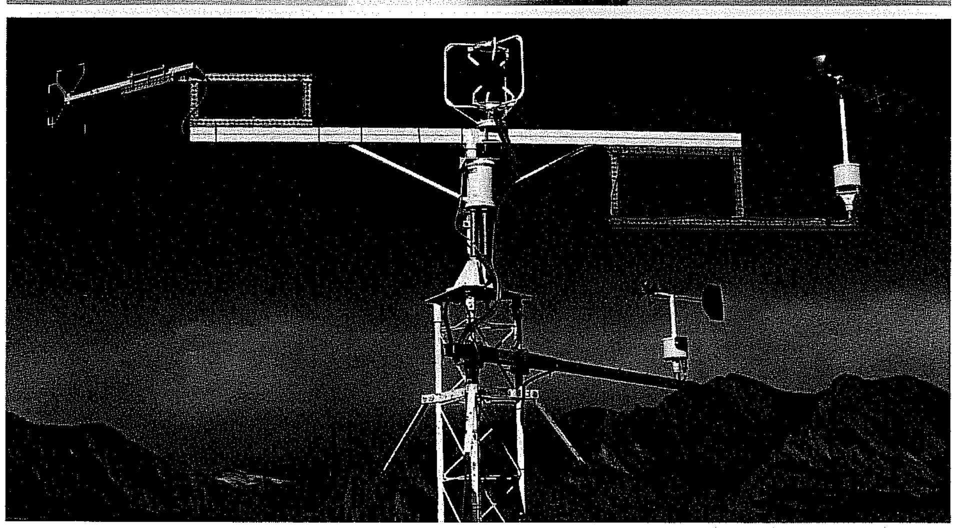
Researchers found that turbulent condi-
:ions were unlikely to develop during
daylight hours when the atmosphere just
above the earth's surface (where the wind
:urbines are located) is unstable. Nor were
:urbulent conditions likely to occur in the
early morning hours when the atmosphere
becomes very stable. The most damaging con-
litions occur during the transition from the
ınstable daytime conditions to the stable
ones at night. The severe turbulence that can
levelop under these conditions appears to be
enhanced within a multi-row wind park.

NREL researchers incorporated their find-
ngs into a turbulence simulation code called
SNLWIND-3D in FY 1993. They are now using
:his code as input to the ADAMS model to
observe the impact of atmospheric turbu-
ence on critical wind turbine components.

In another experiment to monitor wind
:onditions, PNL evaluated a new method for
ncreasing the sensitivity of wind-speed
neasurements made by a rugged, low-cost
:up anemometer. The goal of this research
was to help industry obtain information
about wind turbulence without resorting to
ısing an expensive sonic anemometer (a
sophisticated device that uses sound waves
:o measure three different components of
wind speed). A sonic anemometer can cost
ıp to $65,000, while a cup anemometer
:osts about $70.

In FY 1993, PNL developed a special fil-
ering technique to enhance the quality of
he data gathered by a cup anemometer.
Jsing this technique, PNL produced
preliminary measurements from a cup
ınemometer that were surprisingly close to
hose made by a nearby sonic anemometer.
PNL's discovery should significantly lower
he cost of measuring wind turbulence.

Warren Gretz, NREL



Warren Gretz, NREL

PNL has developed a special filtering technique to enhance data gathered by an inexpensive cup anemometer (top). With the technique, cup anemometer measurements are surprisingly close to those made with a costly and sophisticated sonic anemometer (bottom).

DOE Supports Research on Hybrid Power Systems

In late FY 1993, DOE and the USDA signed an agreement to develop and test innovative hybrid electrical generating systems. Unlike conventional hybrid systems that incorporate diesel generators, these systems will rely entirely on renewable resources such as wind, solar, and biofuels made from vegetable oils. USDA's Southern Plains Area Conservation and Production Research Laboratory in Bushland, Texas, will house the research project. The project will evaluate different hybrid system configurations, explore control strategies, investigate options for energy storage, and study component fatigue life. Researchers plan to use data from the project to validate computer models of innovative hybrid systems.

Researchers at NREL and the University of Massachusetts made progress in developing computer models of the energy performance of remote hybrid power systems during FY 1993. The university added a life-cycle cost analysis to its HYBRID-1 model, improved its user interface, and added a PV module to the computer model, which already included up to 20 wind turbines and three diesel generators. The university also began validating the model using laboratory apparatus that simulates a wind/diesel system.

NREL completed a survey of existing computer models of hybrid systems during FY 1993. The laboratory determined that no single software package provided a versatile, user-friendly, realistic, and fair evaluation of all the energy technologies that are required for widespread acceptance by hybrid system planners. The laboratory is considering developing software that will provide life-cycle cost analyses of hybrid power systems comprising any combination of wind turbines, PV arrays, diesel generators, biomass power facilities, hydroelectric generation, and batteries.

NREL, Sandia Stay Abreast of International Research

NREL hosted an IEA meeting of experts on the "Fatigue of Wind Turbines" in 1993. Experts from Germany, Sweden, Denmark, the United Kingdom, the Netherlands, and the United States met to discuss the philosophies and testing methods used in their respective countries. Because each country had a somewhat different approach to fatigue analysis, participants were able to gain new insights into their own work. NREL and Sandia both reviewed their work in fatigue testing and reliability.

During FY 1993, NREL also attended several international meetings and workshops held in conjunction with IEA's Annex XIII on large wind turbines. The annex, which has compiled a catalog of large wind machines around the world, will complete its work in 1994.

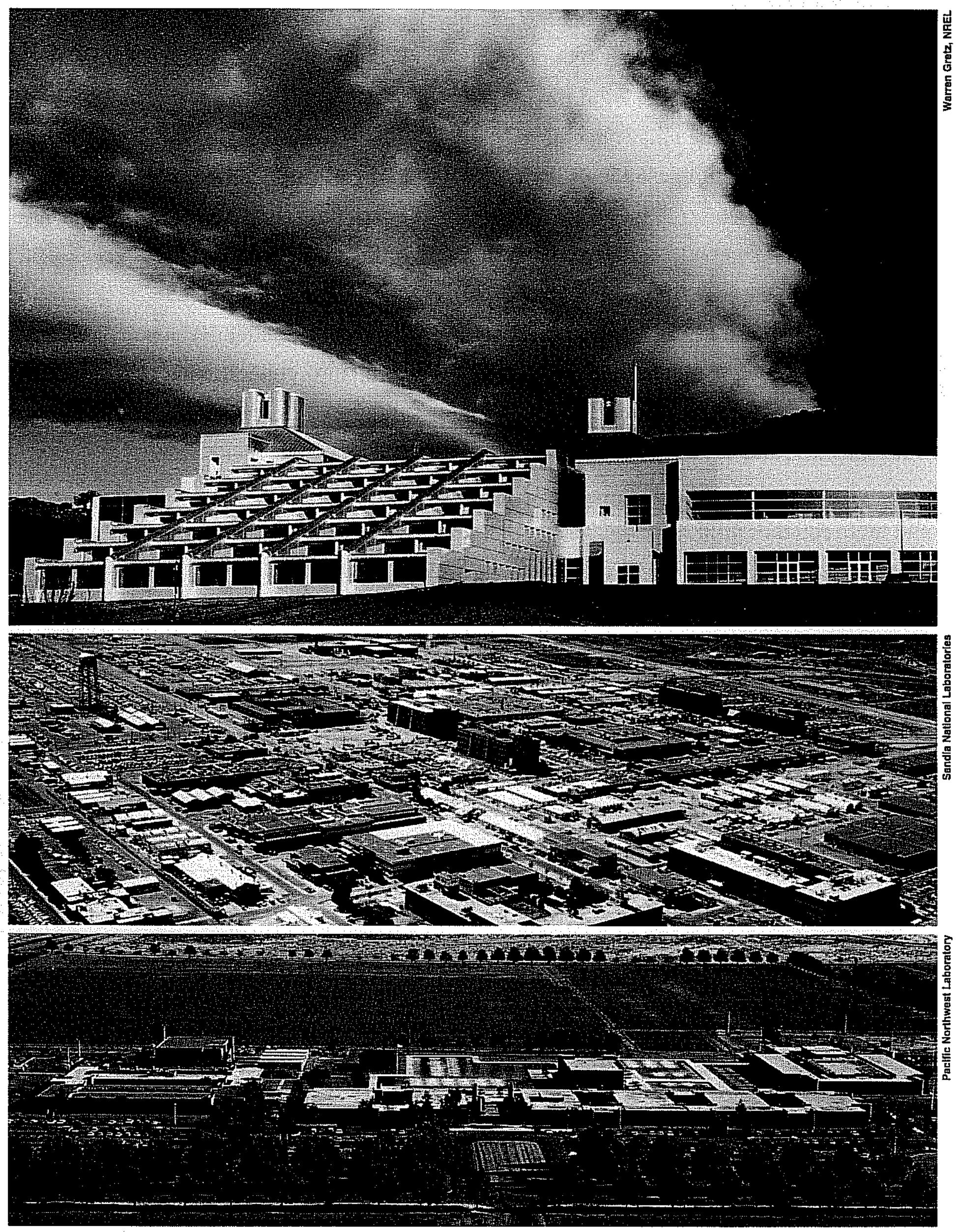
The Program Structure

As DOE's lead laboratory in wind technology development, NREL will operate the new National Wind Technology Center near Golden, Colorado.

The Wind/Hydro/Ocean Division of DOE's Office of Renewable Energy Conversion manages the national Wind Energy Program. The division is responsible for ensuring that program activities are consistent with national energy policy, priorities, and directives. DOE's field offices and national laboratories implement the program's technical activities, including numerous subcontracts with utilities, industry, and universities. The agreements with utilities and industry are designed to further the rapid commercialization of wind energy systems. University subcontracts help build the wind energy technology base.

The *National Renewable Energy Laboratory*, located in Golden, Colorado, is the world's largest scientific institution dedicated to developing renewable energy technologies. As the primary national laboratory for DOE's Wind Energy Program, NREL will manage the new National Wind Technology Center near Golden. NREL's Wind Technology Division manages DOE's cooperative government/industry programs, including the wind turbine development activities, utility programs, and industry programs. NREL also manages international and applied research programs. NREL conducts research in structures and fatigue testing, wind characterization, aerodynamics, and advanced components and systems.

Sandia National Laboratories, located in Albuquerque, New Mexico, conducts supporting research in computer modeling, structural dynamics, fatigue testing, reliability, aerodynamics, controls, and materials. Sandia works closely with NREL in structures and fatigue testing and in solving problems applicable to a broad range of wind turbine technologies.



Top to bottom: The National Renewable Energy Laboratory in Golden, Colorado; Sandia National Laboratories in Albuquerque, New Mexico; Pacific Northwest Laboratory in Richland, Washington.

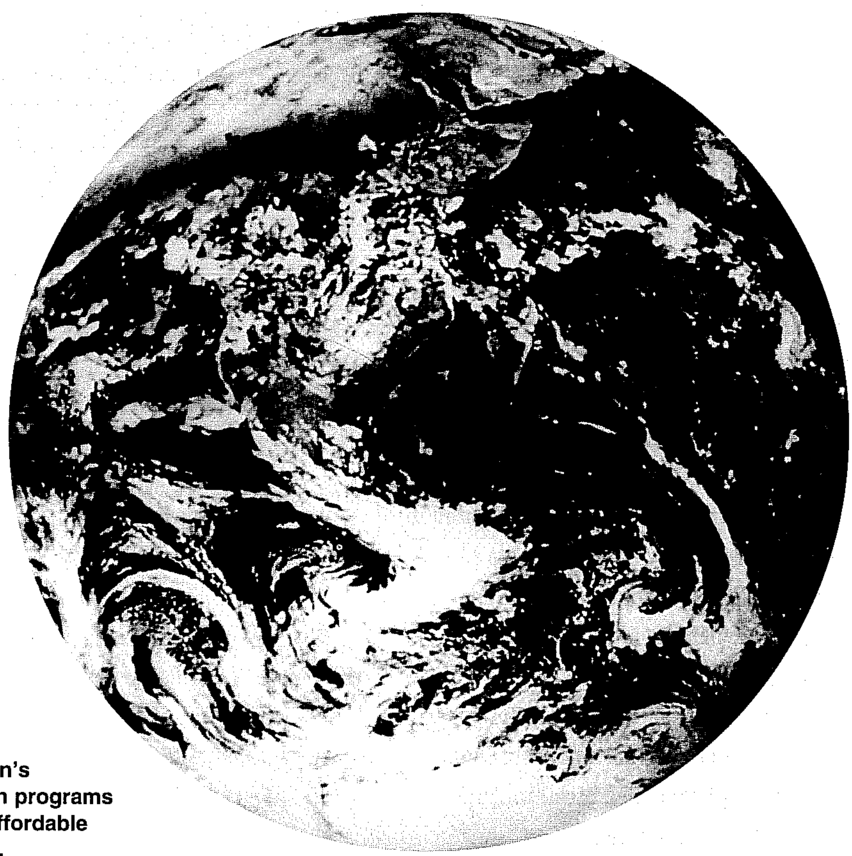
Pacific Northwest Laboratory, located in Richland, Washington, performs research and development on wind turbulence, atmospheric physics relating to wind turbines, tools for wind resource assessments, and site evaluations. The Laboratory provides wind measurement equipment to utilities and wind power plant operators for cooperative research.

A Look Toward Tomorrow

In FY 1994, DOE's Wind Energy Program will open the National Wind Technology Center, introducing a new era in the development and commercialization of wind energy systems.

In support of the Administration's Climate Change Action Plan and economic goals for the nation, the DOE Wind Energy Program will pursue the following objectives in FY 1994: (1) increase the utility use of wind energy systems; (2) increase the productivity and competitiveness of U.S. technology; (3) support the commercialization of advanced wind turbines developed in cooperation with industry; (4) launch the development of a new generation of wind turbines; and (5) further applied research concepts leading to lower cost and more reliable wind technologies. Here's what to expect in the coming years in wind technology development:

- Working with utilities and the wind industry, DOE will participate in a new market mobilization collaborative's efforts to further the adoption of wind technologies.
- EPRI and DOE will select new utility participants for the Utility Wind Turbine Verification Program.
- NREL will launch a development program for the next generation of advanced wind turbines.
- NREL will install a state-of-the-art research turbine at the National Wind Technology Center.
- With support from DOE, the wind industry will continue testing and refining advanced turbine prototypes.
- Federal researchers will launch turbulence studies at Midwest and Great Plains sites.
- NREL and Sandia will identify opportunities for utility-scale, village-power, and stand-alone wind energy systems throughout the world.
- Applied researchers at NREL and Sandia will continue to provide industry with improved design and analysis tools for developing the next generation of advanced wind turbines.



National Aeronautics and Space Administration

DOE supports the Administration's Climate Change Action Plan with programs to develop and commercialize affordable state-of-the-art wind technology.

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