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THE U.S. DOE WIND TURBINE DEVELOPMENT PROGRAM

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ABSTRACT

The development of technologically-advanced wind turbines continues to be a high priority of the U. S. wind industry. The United States Department of Energy (DOE) is sponsoring a range of projects that assist the wind industry to design, develop, and test new wind turbines. The overall goal is to develop turbines that can compete with conventional electric generation with a cost of energy (COE) of 5¢/kWh[1] at 5.8 m/s (13 mph sites) by the mid-1990s and with a cost of energy of 4¢/kWh or less at 5.8 m/s sites by the year 2000. These goals will be supported through the DOE Turbine Development Program. The Turbine Development Program uses a two-path approach. The first path assists U.S. industry to develop and integrate innovative technologies into utility-grade wind turbines for the near-term (mid-1990s). The second path assists industry to develop a new generation of turbines for the year 2000. This paper describes present and planned projects under the Turbine Development Program.

BACKGROUND

Today's market for electricity is driven by a complicated mix of direct and indirect costs, environmental concerns, tax incentives, financing, and regulations. Costs for electricity generated from the wind have been reduced since the first commercial turbines were installed in the late 1970s. By the late 1980s technology improvements and efficient operations had driven the cost of wind-generated electricity down to 5¢ to 7¢/kWh using the high winds available at California windfarms (Cohen, 1989). To increase wind energy's share of the U.S. electricity supply, additional improvements were required. Wind turbines were projected to be capable of producing electricity for less than 4¢/kWh at moderate (5.8 m/s-average) wind sites (Hock, 1990). To help industry attain the needed improvements, DOE implemented the Advanced Wind Turbine Program—now known as the Turbine Development Program. This program assists industry to use state-of-the-art technology and sound engineering practice to develop new, cost-competitive wind turbines.

Others have described this program (Laxson, 1993 and Thresher 1994) and some of the technological improvements being developed (Butterfield, 1993). This paper describes the present status of the program and the most recent projects underway.

ADVANCING TO THE FUTURE

The next 5 years are critical for the U.S. wind industry. Market opportunities are multiplying as utilities, state and local governments, the American public and the international community become aware of the potential for wind power. The wind industry must place itself in a position to take advantage of these opportunities. The Turbine Development Program was designed to assist industry efforts to meet these challenges. The Turbine Development Program features a two-path approach that follows directly from conceptual design studies completed in 1992 (Figure 1). The near-termp ath leads to improved wind turbines entering the marketplace around 1995. The Next-Generation Path leads to new wind turbines becoming available in the late 1990s. Projects in the near-term path are supported through two contract solicitations: Near-Term Product Development and Value Engineered Turbine. The next generation path includes projects supported by the Innovative Subsystems and the Turbine Development solicitations. The plans and progress made in each of these activities will be discussed below.

The DOE Wind/Hydro/Ocean Division supports the Turbine Development Program through the National Renewable Energy Laboratory (NREL) in Golden, Colorado, and Sandia National Laboratories in Albuquerque, New Mexico. NREL and Sandia administer contracts with the wind industry and provide technical oversight and assistance during the projects. Technical assistance

[1] COE is expressed in constant 1994 dollars and is based on utility financing.

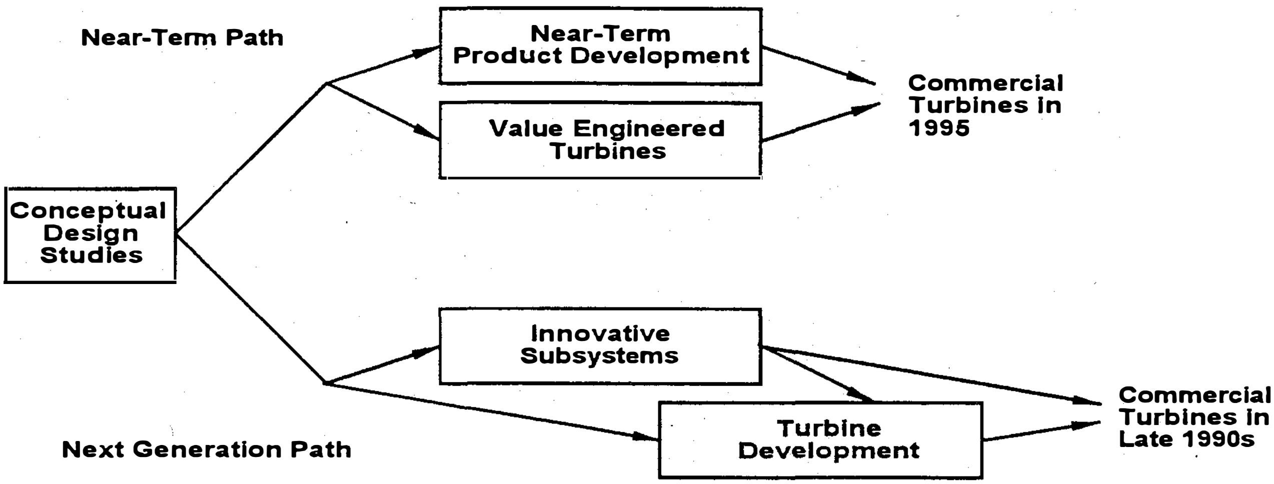

FIGURE 1 THE TWO-PATH APPROACH OF THE DOE TURBINE DEVELOPMENT PROGRAM

takes a variety of forms ranging from structural and aerodynamic analysis through structural testing of blades, modal surveys of turbines, and instrumentation for field testing, to application of new research findings. NREL and Sandia staff provide an important role in technical oversight by identifying potential problem areas and recommending alternatives.

DESCRIBING THE POSSIBILITIES

The Turbine Development Program began in 1990 with Conceptual Design Studies. Three companies assessed the state of wind energy technology and identified improvements that could be implemented in the near-term (by 1995) and advancements that could result in the next generation of machines for the market in 2000. These projections confirmed the potential for technology improvements to significantly reduce the cost of electricity generated from the wind (Atlantic Orient, 1994, Coleman, 1992, and Lynette, 1992).

ADDRESSING THE NEAR-TERM MARKET

The first solicitation in the near-term path, Near-Term Product Development, focuses on products for introduction to an expanded marketplace by 1995. The introduction of the federal 1.5¢/kWh tax incentive opened a wide range of possibilities for introduction of wind technology into still untapped wind resource areas. New machines that can produce electricity at 5¢/kWh or less are well suited to take advantage of both the tax credit for new capacity as well as the need to replace obsolete turbines in wind farms still covered under long-term, power-purchase agreements.

NREL awarded four contracts under this solicitation in 1992, with durations of 2 to 3 years. These contractors are developing prototype turbines that implement numerous improvements to baseline turbines currently running in a production environment.

R. Lynette and Associates

The first of these contracts was awarded to R. Lynette and Associates (RLA) of Seattle, Washington, to develop the AWT-26 (Figure 2). The AWT-26 is a 275-kW, downwind, stall-regulated machine incorporating a 26-m, two-bladed, teetered rotor. This turbine is based on the ESI-80, a turbine developed in the 1980s which had many promising features but never reached commercial maturity. The AWT-26's rotor features wood-composite blades molded to advanced, NREL-designed airfoil shapes. These airfoils improve energy capture by 20% to 30% depending upon wind speed and soiling from dirt and insects. Other features include a redesigned high-speed shaft brake and new, aerodynamic tip brakes, either of which are capable of stopping the turbine in an emergency. Electromagnetic latches hold the tip brakes in a streamlined position during normal operation. Upon control command or loss of power, the magnets release the brakes and allow them to rotate flatwise to the direction of rotor rotation. Their large drag area de-powers and slows the rotor without stressing the drivetrain.

FIGURE 2 R. LYNETTE AND ASSOCIATES' AWT-26 PROTOTYPE TURBINE IN TEHACHAPI, CALIFORNIA

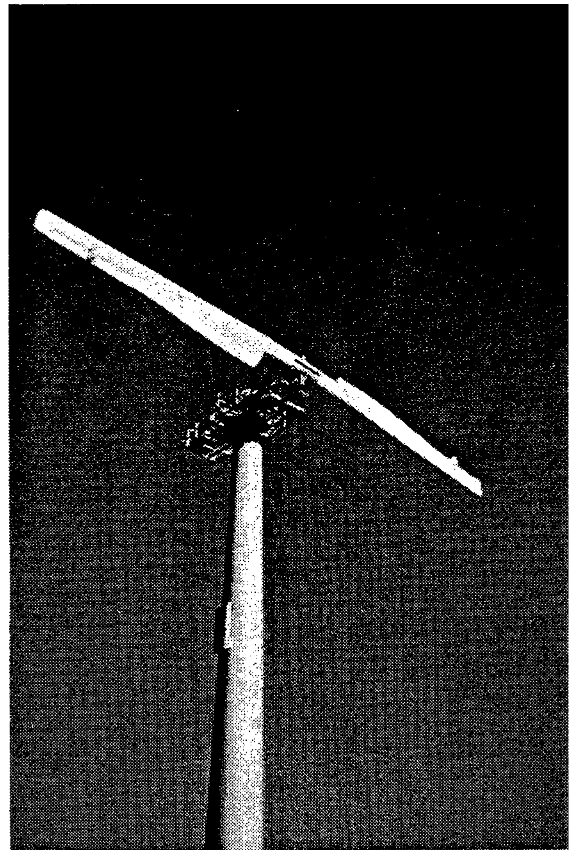

FIGURE 3 NORTHERN POWER SYSTEMS' NORTH WIND 250 PROOF OF CONCEPT TURBINE IN PALM SPRINGS, CALIFORNIA

The initial development project for the AWT-26 is presently nearing completion with the deployment and successful operation of two prototypes in a Tehachapi, California, wind farm. The first prototype was installed in February 1993 and featured a 24-m lattice tower. They mounted a second turbine on a 24-m tubular tower to evaluate the effect of the tower configuration on the rotor. Turbines with down-wind rotors are affected by the tower's obstruction of wind entering the plane of rotation. This "tower shadow" effect can result in subsonic acoustic emissions and blade fatigue. RLA has used aerodynamic treatments such as round cross-members on their lattice tower and spiral strakes on their tubular tower to significantly reduce the adverse effects of tower shadow.

RLA later mounted their second prototype turbine onto a new, 43-m tubular tower. This taller tower enables the turbine to capture stronger winds aloft and to avoid some of the atmospheric turbulence associated with ground-level obstructions.

RLA will continue development of the AWT-26 under new projects funded by DOE. In one project, discussed below, RLA is working with Electronic Power Conditioning, Inc., to test a variable-speed generator and power electronics package. In another project, RLA is investigating alternative aerodynamic devices for braking and improved energy capture. RLA has also installed a third prototype at NREL's National Wind Technology Center in Golden, Colorado. This turbine is operating in the harsh winds that are characteristic of this test site.

A consortium of public utilities called CARES (Conservation and Renewable Energy Systems) has selected the AWT-26 for a commercial, 25-megawatt power plant in Washington. This plant will begin providing power to the Bonneville Power Administration's network in 1996.

Northern Power Systems

DOE funding is supporting a second Near-Term project being conducted by Northern Power Systems of Moretown, Vermont, a subsidiary of New World Power Corporation. Northern Power's North Wind 250 is a 250 kW turbine derived from the North Wind 100. The North Wind 100, like the ESI-80, was developed in the 1980s, showed potential to achieve high performance, but did not achieve commercial success. In conjunction with NREL, Northern Power obtained a significant quantity of operational, performance, and loads data on the North Wind 100 which formed a solid foundation on which to develop the North Wind 250.

The North Wind 250 features a two-bladed, teetered, up-wind rotor that uses ailerons for braking and power modulation. Northern Power judged that ailerons, as investigated by the DOE wind program in the early 1980s, would be better suited for larger wind turbines than full-span pitch control. In addition to their smaller bearings and actuators, ailerons permit the use of a "flow-through" hub. The hub transmits

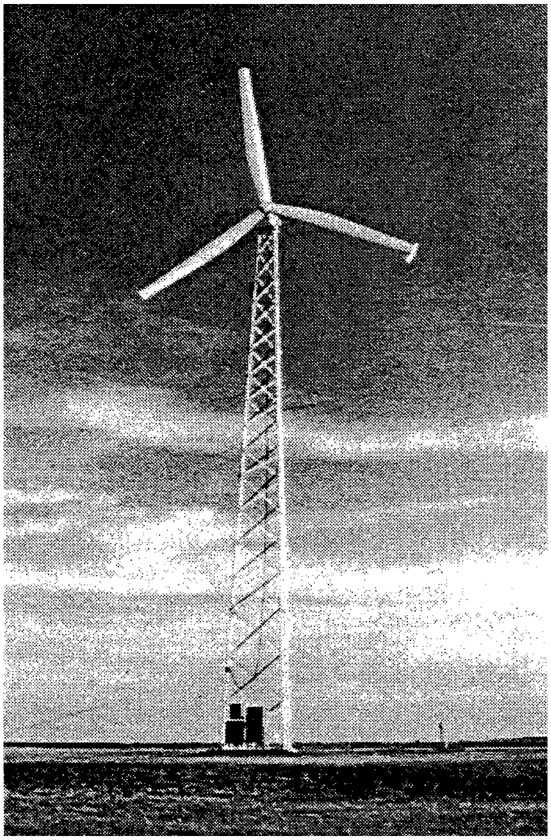

FIGURE 4 ATLANTIC ORIENT CORPORATION'S AOC 15/50 PROTOTYPE TURBINE IN BUSHLAND, TEXAS

out-of-plane bending loads and in-plane centrifugal loads from one blade to the other through a continuous, fiber-reinforced beam. Steel flow-through hubs were successfully used on the DOE-developed, 3.2-MW, MOD 5 wind turbine. Other features of the North Wind 250 include an innovative tower-head design in which loads are efficiently transmitted from the drive train to the tower, a teeter brake to prevent excessive teeter oscillations during start-ups and shut-downs, and elastomeric teeter bearings.

Northern Power has developed a considerable base of knowledge in aileron design and operation in this project through wind tunnel testing at Wichita State University, and installing and field testing ailerons on three wind turbines: a 65-kW Bonus, a North Wind 100, and a Proof-of-Concept version of the North Wind 250 (Figure 3). The aileron-fitted North Wind 100 has operated unattended since August 1994. Northern Power Systems is now using this experience to upgrade the Proof-of-Concept design to a prototype configuration. They plan to fabricate and test five prototype turbines in 1995.

Atlantic Orient Corporation

In the third project supported under Near-Term Product Development funding, Atlantic Orient Corporation of Norwich, Vermont, is developing the AOC 15/50 wind turbine (Figure 4). Atlantic Orient expects that this three-bladed, down-wind turbine will fill a niche market for moderate-size wind turbines: remote applications, small wind farms, and village power systems. The 15/50 is based on the successful Enertech 44/40 and 44/60 turbines, hundreds of which continue to operate today in California wind farms.

Atlantic Orient staff, already familiar with the Enertech turbines, conducted a rigorous investigation of those turbines' strong and weak points. They identified three needed improvements: 1) better airfoils—using the NREL-designed, S-series, 2) improved tip brakes—replacing the mechanical latching with electro-magnetic latching, and 3) stronger components—the hub, transmission, and tower-top designs are now more-fully integrated and stronger. Atlantic Orient's use of magnetic-latched tip brakes is similar to the scheme described above on the AWT-26 turbine. Atlantic Orient has added an innovative, rotary transformer to provide power to the electromagnets. This transformer eliminates the cost and maintenance associated with slip rings by transmitting electrical power from the transmission housing across a non-contacting interface to the rotor. Atlantic Orient's rotary transformer is configured to fit on the low-speed shaft between the transmission and the hub and can be removed without removing the rotor.

The Turbine Development program and other elements of the DOE/NREL program have assisted Atlantic Orient to fabricate and test a total of five prototype turbines. They installed their first prototype at Bushland, Texas, in June 1993. Since then they have installed turbines at the Atlantic Wind Test Site on Prince Edward Island, Canada, a SeaWest wind farm in San Gorgonio Pass, California, and NREL's National Wind Technology Center near Golden, Colorado. They are presently installing their fifth turbine in Burlington, Vermont. These field tests are providing the experience needed to ensure that the AOC 15/50 will be a robust, low-maintenance turbine.

Carter Wind Turbines

The fourth NREL contract supported Carter Wind Turbines, Incorporated (CWT) to improve the Carter 300 kW wind turbine. Variations on this very-promising design have been in operation since 1991. The improvements CWT investigated included improved NREL airfoils, an improved control system, and taller towers. Unfortunately, business issues have ended CWT's activities in the United States and, therefore, support from DOE.

ANOTHER PERSPECTIVE ON TURBINE DESIGN

Late in 1992, NREL offered a second solicitation in the near-term path specifically directed toward operators of wind farms in the United States. Over the past 10 years these wind plant operators have gained considerable knowledge and experience with the turbines in the California wind farms and have developed an understanding of the most dependable features in current designs. Many of these turbines have operated reliably, but their initial costs are higher than acceptable for future markets. The Value Engineered Turbine (VET) project is intended to help U.S. wind plant operators to develop their own turbines based on the best existing turbines. The approach of value engineering proven designs is intended to lower development costs, time, and risks.

Currently two contracts have been awarded. NREL expects to conclude negotiations leading to a third VET project by the end of 1994.

Zond

NREL awarded the first VET contract to Zond Systems Incorporated, of Tehachapi, California. Zond is using its extensive experience in operating wind power plants to develop the Z-40, a 500-kW turbine (Figure 5). The Z-40 features a 40-m, three-bladed, upwind rotor—a configuration that has been successfully used on a variety of wind turbines. The blades use NREL's advanced airfoils to minimize the need for cleaning without sacrificing optimum performance. Zond is investigating both full-span pitch control and ailerons to control power and to prevent overspeeding in high winds. In full-span pitch control, each blade is pivoted about a large bearing in the hub assembly. Aileron control is achieved by rotating the outboard portion of the blades' trailing edges to decrease lift and add drag in high winds. Zond is also comparing open-truss towers with tubular towers.

Zond fabricated and installed their first prototype in May 1994. They are presently conducting qualification tests on their gearbox and blades and installing their second prototype. They anticipate completing development of the Z-40 by early-1995.

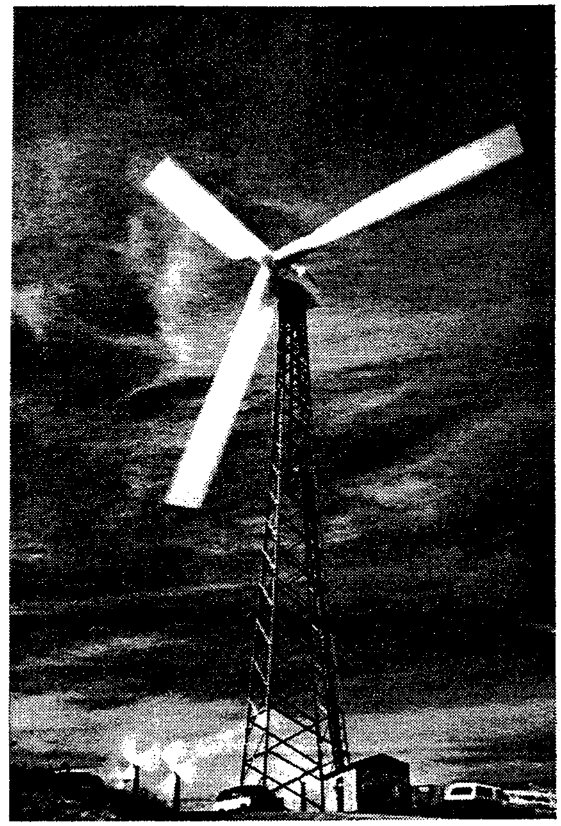

FIGURE 5 ZOND'S Z-40 PROTOTYPE TURBINE IN TEHACHAPI CALIFORNIA

New World Grid Power

In a second VET project, New World Grid Power (formerly Field Service and Maintenance) of Palm Springs, California, is developing the 500-XST, a 500-kW, three-bladed, upwind turbine. One of its most innovative features is a unique, highly-integrated drivetrain coupled to a variable-speed generator. New World Grid Power began this project in June 1994 and anticipates installation of their first prototype turbine in early 1996.

BOLD STEPS INTO THE NEXT GENERATION

The Turbine Development Program's Next-Generation path will help U.S. industry to explore new concepts and apply cutting-edge technology for utility-grade wind turbines entering the marketplace in the late 1990s. These innovative wind turbines are expected to produce electricity for the grid at 4¢/kWh or less at 5.8 m/s (13 mph) wind sites. Primary factors which must be addressed to reach this COE goal include reduced turbine capital cost, increased performance and reliability, and decreased operations and maintenance expense.

The development of advanced utility-grade turbines requires major innovation with considerable risk. In the Next-Generation path, participants will explore high-risk, high-reward components and configurations such as variable-speed generators, power-electronics topologies, direct-drive generators, very tall towers, and larger-capacity turbines. To maintain the risk within acceptable limits and to promote the rapid extension of technology, the Turbine Development Program is supporting two rounds of contracts. In the first, companies are developing new components and subsystems appropriate to the next generation of turbines. In the second, companies will integrate these and other innovations into full turbine systems.

INNOVATIVE COMPONENTS AND SUBSYSTEMS

The first round of contracts in the next generation path is termed Innovative Subsystems. NREL has awarded five contracts and is currently negotiating with a potential sixth participant. Contractors are 1) completing a detailed design of an innovative component or subsystem, 2) fabricating and testing the innovation in a shop environment, 3) testing the subsystem on an existing operating wind turbine, and 4) assessing the subsystem's performance and impact on COE.

Electronic Power Conditioning

Electronic Power Conditioning, of Corvallis, Oregon, is developing a variable-speed generation subsystem with the intention of improving performance, increasing reliability, and decreasing the cost-of-energy for a broad class of utility-scale wind turbines. Their unique approach is to control a portion of the power generated by a variable-speed turbine so as to keep the cost of the power electronics much lower than in conventional configurations. Their system can use a wound-rotor, induction generator which is expected to cost little more than the standard induction generators commonly used in fixed-speed turbines. They will fabricate and test a 300-kW system on the AWT-26 in 1995.

CERTEK

CERTEK Corporation of Bedford, Massachusetts, is developing a direct-drive generator that will eliminate the need for a gearbox. In the past, direct-drive generators have been limited to use in small wind turbines. Now CERTEK is using advanced technology to develop a permanent-magnet generator suitable for 100 kW and larger turbines.

They have teamed with Northern Power Systems to test their first generator on a North Wind 100 turbine. This size could be readily used in remote and cold environments. It is also scalable to the larger, 250 to 1,000 kW wind turbines being developed for the utility market.

Second Wind

Second Wind, in Somerville, Massachusetts, is developing a fatigue-based distributed control system for incorporation on utility-scale wind turbines and wind power plants. This system is an updated and improved version of a product that is widely used to monitor and control turbines in California wind farms. The new system will monitor the structural condition of turbines including vibration, power, and other key parameters. It will then use statistical methods to recommend or implement changes in turbine operations that will reduce fatigue damage while optimizing energy production. It will also provide operators with information needed to efficiently schedule maintenance, integrate wind power into the generation capacity of utilities, and lower the cost of wind-generated electricity.

PS Enterprises

PS Enterprises, of Palm Springs, California, has obtained funding from the California Energy Commission to develop a four-bladed, utility-scale wind turbine. This innovative turbine will use flexible blades that have a constant cross-section and can be pultruded. Pultrusion is a low-cost manufacturing technique that is commonly used for low-cost, fiber-reinforced components. DOE is supporting PS Enterprises to validate this concept and to compare the cost to that of rotors using blades with optimal twist and taper. If these studies show an overall advantage of pultruded blades, PS Enterprises will fabricate and test a scaled-down rotor on the PSE-52, an 80-kW turbine with a 16-m rotor.

R. Lynette and Associates

R. Lynette and Associates is investigating the advantages of an advanced rotor using trailing-edge aerodynamic brakes, vortex generators, and longer blades. They project that a larger rotor and vortex generators will produce more energy in low to moderate winds without significantly increasing loads on the turbine in high winds. Trailing-edge brakes should be less susceptible to icing than tip brakes and should help to reduce blade weight and cost. Their test bed for this rotor will be an AWT-26 wind turbine in Tehachapi, California.

BRINGING INNOVATION INTO THE NEXT GENERATION

The second element in the Next-Generation path is the Turbine Development Project. This two-stage project will support industry to design and test a new generation of wind turbines incorporating the most recent technology in all aspects of wind turbine operations. It will build on lessons learned from the Conceptual Design Studies, Near-Term Product, VET, and Innovative Subsystems projects. In the first stage, each contractor will define its development project including the turbine configuration, the development team, and the activities to be conducted in the second stage. This "start-up" stage will result in a detailed, Concept Definition Report that will double as a technical proposal for Stage 2.

Efforts leading to the first stage of this project have already started with the issuance of a Request for Proposals in May 1994. After selection of the best proposals, NREL began contract negotiations in October 1994 and expects to award up to nine Stage 1 contracts by the end of 1994.

Based on the proposals received and available funding, NREL will select up to three teams to continue on to the second stage of this development project. These selections are currently planned for July 1995. In Stage 2, participants will test critical components and design, fabricate and test three prototype turbines. DOE funds totalling $30 million will be available to augment the 30 to 50 percent private cost-sharing from the selected participants.

RELATED PROJECTS

DOE is supporting other projects closely related to the projects described above. In the Utility Wind Turbine Performance Verification Program, DOE is working jointly with the Electric Power Research Institute (EPRI) to deploy and evaluate newly-developed turbines in typical utility environments. This program provides a bridge between the projects conducted under the Turbine Development Program and commercial purchases by utilities. In 1993 and 1994, EPRI and DOE selected three utilities to support the installation of 20 megawatts of wind power. Central and South West Corp. will build a 6.6-megawatt plant in West Texas, Green Mountain Power will install a 6-8 megawatt plant in southern Vermont, and Niagara Mohawk Power Corp. will build a 6-megawatt plant in upstate New York.

A second activity, the Blade Manufacturing Project, being managed by Sandia, will help industry improve blade reliability and reduce blade costs by at least 30%. DOE envisions that these improvements will result from incorporating new materials, new manufacturing techniques, and new principles such as "agile manufacturing," and concurrent engineering into the process. Sandia has recently requested comments on the contractual arrangements they are planning for this project. The projects would consist of two phases similar to the two stages used in the Next-Generation Turbine Development Project. Total government funding could be on the order of $3.5 million for the project with industry cost-sharing of at least 10% in Phase I and at least 20% in Phase II. These funds would support 8-10 companies in Phase I and 2-3 companies in Phase II.

CONCLUSION

The DOE Turbine Development Program provides a multitude of opportunities for industry to develop competitive new products. The Program is supporting the development of wind turbines for near-term markets and both wind turbines and turbine components for the market at the end of the twentieth century. This program permits industry to select the turbine configuration and development path they judge to be compatible with their business strategy. The success of the program is evident from the products developed so far. Four companies have already negotiated sales of turbines developed under this program. Additional new turbines will enter the marketplace in the coming years.

REFERENCES

Atlantic Orient Corporation, 1994, "Advanced Wind Turbine

Design Studies, Advanced Conceptual Study, Final Report," TP-442-4740, National Renewable Energy Laboratory, Golden, CO.

Butterfield, C.P, B. Smith, A. Laxson, B. Thresher, P. Goldman, 1993, "DOE/NREL Advanced Wind Turbine Development Program," *Proceedings, European Community Wind Energy Conference*, H. S. Stephens and Assoc., Bedford, UK, pp. 260-264.

Cohen, J. M., T. C. Schweizer, S. M. Hock, J. B. Cadogan, 1989, "A Methodology for Computing Wind Turbine Cost of Electricity Using Utility Economic Assumptions," *Proceedings, Windpower '89*, SERI/TP-257-3628, National Renewable Energy Laboratory, Golden, CO, pp. 168-172.

Coleman, Clint, 1992, "Advanced Wind Turbine Design Studies, Final Report," Subcontract ZG-0-19090-2, Northern Power Systems, Moretown, VT (Draft).

Hock, S. M., R. W. Thresher, J. M. Cohen, 1990, "Performance and Cost Projections for Advanced Wind Turbines," SERI/TP-257-3795, *Proceedings, ASME Winter Annual Meeting*, American Society of Mechanical Engineers, New York, NY, pp. 211-212.

Laxson, A., D. Dodge, L. Flowers, R. Loose, P. Goldman, 1993, "An Overview of DOE's Wind Turbine Development Programs," NREL/TP-441-5761, National Renewable Energy Laboratory, Golden, CO.

Lynette, Robert, 1992, "Advanced Wind Turbine Conceptual Study," Final Report, Subcontract ZG-0-19090-3, R. Lynette & Associates, Redmond, WA, (Draft).

Thresher, R.W., S. Hock, R. Loose, P. Goldman 1994, "Wind Technology Development: Large and Small Turbines," NREL/TP-440-7224, National Renewable Energy Laboratory, Golden, CO.