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# Wind Technology Development: Large and Small Turbines

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## Abstract

Wind technology has been developing rapidly over the last decade. The experience gained in the wind farms of California is being used to design and develop advanced systems with improved performance, higher reliability, and lower costs. During the past several years, substantial gains have been made in wind turbine designs, lowering costs to an average of $0.05 per kilowatt-hour (kWh) for utility-scale applications at 13 mile-per-hour (mph) average annual wind speeds. Further technology development is expected to allow the cost of wind-generated electricity to drop below $0.04 per kilowatt-hour by 2000. As a result, wind is expected to be one of the least expensive forms of new electric generation in the next century. With global efforts already underway to curb energy-related emissions of carbon dioxide, the current availability of this low-cost technology means that the use of wind systems will likely increase worldwide throughout the 1990s for both utility-scale applications and remote, small-village applications. This paper will present the technology developments for both utility-scale wind turbines and remote, small-village wind turbines that are currently available or in development. The authors describe future technology improvements and likely wind turbine configurations in 2000.

Technology innovations are being adapted for remote and stand-alone power applications with smaller wind turbines. Hybrid power systems using smaller 1- to 50-kilowatt (kW) wind turbines are being developed for non-grid-connected electrical generation applications. These village power systems typically use wind energy, photovoltaics (PV), battery storage, and conventional diesel generators to supply power for remote small-village communities. In remote locations, transportation costs can make fuel-powered generating systems extremely expensive. Smaller wind turbines are also being explored for application as distributed generation sources on utility grids to supply power during periods of peak demand, avoiding costly upgrades in distribution equipment.

New turbine designs now account for turbulence-induced loads, unsteady aerodynamic stall effects, and complex fatigue loads, making use of new technology developments such as advanced airfoils tailored for wind turbine applications. These new airfoils increase the energy capture and improve the operating efficiency of turbine rotors by increasing the power for a given rotor thrust, and reducing the sensitivity of the airfoils to roughness which naturally accumulates during operation. Technology has been developed which uses power electronics to allow variable rotor speed operation to improve efficiency. Aerodynamic control devices, such as ailerons and flaps, are being explored to aerodynamically modulate power or stop the rotor in high-speed conditions. These technology trends and future turbine configurations are being explored through research and development activities sponsored by the U.S. Department of Energy's (DOE's) Wind Energy Program.

## Utility-Scale Systems

In the United States, utility-scale wind turbines are the primary focus of new technology development. By 1996, U.S. manufacturers will have introduced seven new turbines (with capacities ranging from 250 to 500 kW) for the utility market. Five of the turbines are being developed by members of the U.S. wind industry with direct funding support from DOE. Cannon Energy Corporation and Kenetech Windpower are each developing a utility-scale wind turbine independently. Two of the utility-scale wind turbines sponsored by DOE are commercially available: R. Lynette & Associates' AWT-26, and Zond Systems' Z-40. Northern Power Systems, New World Grid Power, and Flowind Corporation are expected to introduce their turbine designs within the next two years.

## *R. Lynette & Associates' AWT-26*

The 275-kW AWT-26 (Figure 1) is a downwind, stall-regulated, free-yaw machine incorporating an innovative two-bladed teetered rotor. The AWT-26 is based upon the ESI-80, a turbine developed in the United States during the mid-1980s which had many promising features, but never reached commercial maturity. The designers of the AWT-26 have taken advantage of the substantial operating history of its predecessor, retained components that were reliable, and improved the remainder.

The larger 26-meter (m) rotor incorporates aerodynamically efficient, wood-composite blades using National Renewable Energy Laboratory (NREL) designed airfoils. The new blades improve the turbine's energy capture from 20% to 70%, depending on wind speed and the degree of blade soiling from dirt and insects. The AWT-26 also features a redesigned high-speed shaft brake and new aerodynamic tip vanes. The tip vanes serve two important functions on this turbine: as a fail-safe (emergency) brake and as an active brake for normal shut-down operations. Mounted on a hinge at the tip of each blade, the vanes are held closed by electromagnets. The vanes are activated by control system command, which releases the electromagnets. A redundant caliper disk brake can also stop the machine under normal or emergency conditions.

The AWT-26 has been selected for a commercial 25-megawatt (MW) power plant to be installed in late 1995 in Washington state by a consortium of public utilities called CARES (Conservation and Renewable Energy Systems) as a project under the Bonneville Power Administration's Resource Supply Expansion Program (RSEP). The RSEP program was a competitive solicitation to add wind generation capacity to the Bonneville network.

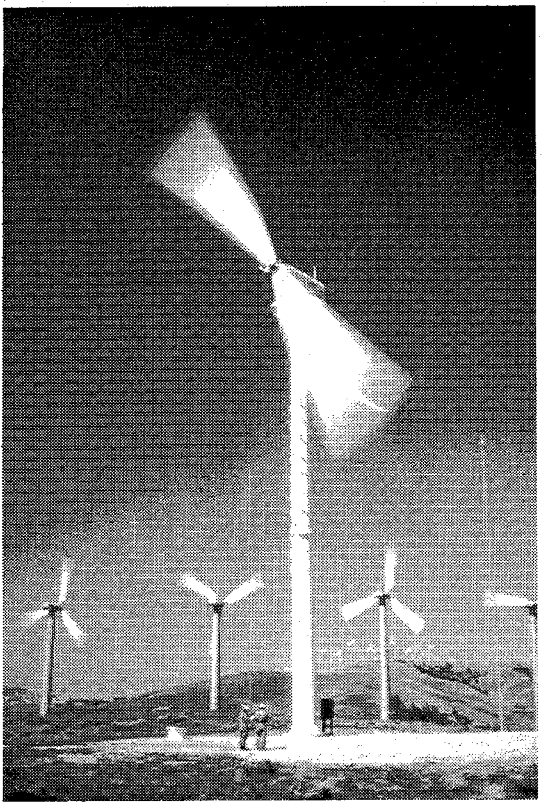


**Figure 1. R. Lynette & Associates' 275-kW AWT-26.**

## *Northern Power Systems' North Wind 250*

The 250-kW North Wind 250 (Figure 2) is a two-bladed, teetered, upwind machine that has been scaled up from the company's North Wind 100

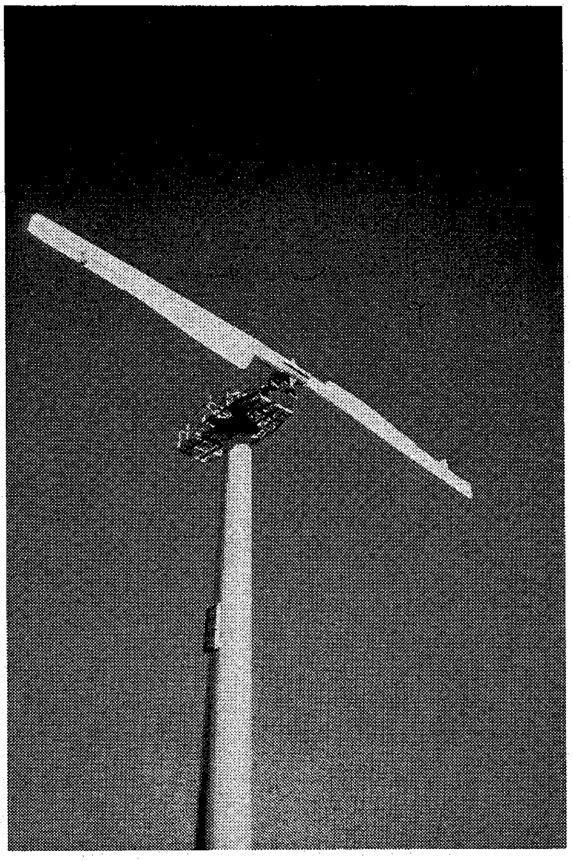


**Figure 2. Northern Power Systems' 250-kW North Wind 250.**

turbine. The new turbine features an integrated drive train, aileron controls, and an innovative rotor that is fabricated as a single unit. The "flow-through" rotor eliminates the blade root joints, which are expensive, complicated, and subject to high stress during turbine operation. The unique, flow-through, teetered-rotor design eliminates structural discontinuities at the blade/hub interface by fabricating the rotor as one continuous structural element. Fatigue tests were conducted on the full-scale rotor joint at NREL to qualify this element of the rotor for field testing and to provide information needed to improve its structural design.

The hub incorporates teeter dampers and an active teeter brake. The rotor is made of a hybrid composite material. The hub saddle captures the blade center section in a wrap-around elastomeric blanket. The new rotor also substitutes aileron control for the full-span pitch control system used in the earlier North Wind model.

Ailerons, which work like flaps on an airplane wing, are the most important development featured in the North Wind 250. When deflected in the downwind direction, they reduce lift and power output. When power modulation is needed, the ailerons can be deflected through small angles to either increase or decrease power. Upwind deflections increase lift, causing the power to increase. Wind tunnel tests at Wichita State University have confirmed the ability of ailerons to control power and prevent the rotor from over-speeding.

### *Zond Systems' Z-40*

The 500-kW Z-40 wind turbine (Figure 3) is being developed by Zond Systems, Inc., with support from NREL. Zond is building two versions of its prototype turbine, a three-bladed, upwind, rigid hub machine with active yaw drive. One turbine prototype employs a full-span pitch control system and sits atop a tube tower. The other turbine uses aileron controls to provide aerodynamic braking and peak power modulation and sits atop a low-cost, free-standing open truss tower. Zond plans to compare the two turbine control strategies during prototype testing.

Both designs capitalize on the company's extensive experience operating wind power plants using similarly-designed turbines. Each prototype incorporates NREL-designed airfoils and an integrated gearbox design that minimizes the number of parts and simplifies load paths. Based on blade structural and fatigue testing at NREL, design changes were made that will improve the final design of the blades.

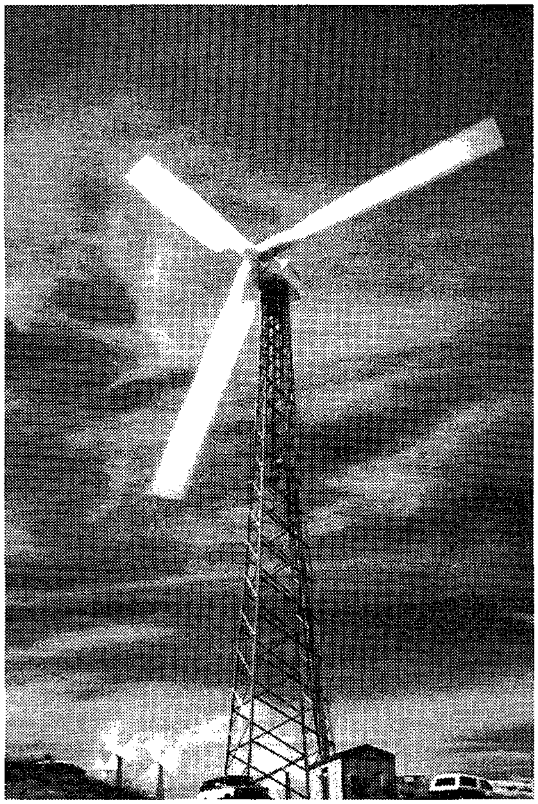


**Figure 3. Zond Systems' 500-kW Z-40.**

### *Flowind's EHD*

Unlike the other turbines discussed in this paper, Flowind's 300-kW EHD (**E**xtended **H**eight/**D**iameter ratio) is a Darrius (eggbeater-shaped) vertical-axis wind turbine. Its three blades spin about an axis perpendicular to the ground, capturing energy from winds blowing from all directions. The drive train and generator are located under the rotor near the ground for easy maintenance and inspection.

The EHD series will use tall, high-performance 17- to 21-m rotors incorporating advanced airfoils designed specifically for the series. Flowind's prototype turbine rotor, which has a height to diameter ratio of 2.78, is taller and thinner than the 19-m rotor on Flowind's existing vertical-axis turbines. The shape allows the larger rotor to be placed upon existing turbine bases, if desired. This design also makes it easier to bend the turbine blades into the desired shape and makes better (and more profitable) use of available sites in a wind power plant.

The EHD's low-cost blades are manufactured using a new, automated pultrusion technique, in which fiber-resin blades are pulled through a die. The blades incorporate natural laminar flow airfoils developed at Sandia National Laboratories to keep air flowing smoothly over the blades and increase energy capture. The rotor should effectively double the annual energy output of Flowind's current vertical-axis turbines which use aluminum blades and are about half as tall.

### *New World Grid Power's 500-XST*

New World Grid Power will develop the 500-XST (e**X**perimental **S**ynchronous **T**urbine) based on the company's experience operating European turbines of this size. The 500-kW, upwind, three-bladed 500-XST will include active yaw control, a full-span pitch control rotor and a free-standing tubular tower. One of its most innovative features is a unique integrated drivetrain system which uses variable-speed operation. Therefore, it can provide a unity power factor without requiring capacitors for reactive power control.

## Remote and Village Systems

Technology innovations are being adapted for remote and stand-alone power applications with smaller wind turbines. Hybrid power systems using smaller 1- to 50-kW wind turbines are being developed for non-grid connected electrical generation applications. These village power systems typically use wind energy, solar, photovoltaics (PV), battery storage, and a conventional diesel generator to supply power for remote, small-village communities. In areas without electric utility service and with good wind resources, a single wind turbine can provide electricity at lower cost than diesel generation for individual homes, schools, clinics, water pumping, or small industries. Larger "mini-grid" village power systems incorporating multiple wind turbines and other generation sources are often more economical than transmission line extension for communities in remote, but windy regions. Smaller wind turbines are also being explored for application as distributed generation sources on utility grids to supply power during periods of peak demand, avoiding costly upgrades in distribution equipment.

Hybrid systems comprised of wind turbines, PV, batteries, and diesel generators have been used successfully to meet direct-current electric loads in remote international telecommunications markets.

These systems are now an emerging technology for generating alternating-current electric power for remote communities. Assisting the U.S. industry in developing and demonstrating hybrid systems, NREL has embarked on a program of collaborative technology development and technical assistance in the area of hybrid systems for village-power applications (Flowers, *et al*, 1994).

### *Atlantic Orient Corporation's AOC 15/50*

The 50-kW AOC 15/50 (Figure 4) is an improved and simplified version of the Enertech 44/60 wind turbine developed in the United States in the early 1980s. The downwind, stall-regulated, three-bladed turbine features passive yaw control, wood epoxy composite blades incorporating NREL-designed airfoils, aerodynamic tip brakes, an electrodynamic brake, and an integrated drivetrain. Blade-fatigue testing was conducted at NREL. This turbine is well-suited for remote, stand-alone applications, village power systems, and small wind power plants.

The AOC 15/50's integrated drivetrain eliminates many critical bolted joints found in conventional turbine designs and creates an efficient load path from the rotor to the tower top. A cast-steel, tower-top plate further improves the efficiency of the load path. The new drivetrain design weighs less than conventional drivetrains and eliminates maintenance-prone couplings between the gearbox and the generator. Other design features include tip brakes and an optional yaw damper. The optional yaw damper, a passive hydraulic system that limits yaw rates (and gyroscopic loads), is available for turbulent wind sites.

### *Bergey Windpower Company's BWC Excel*

Bergey Windpower Company (BWC) turbines use passive controls, fiberglass blades, direct-drive permanent-magnet alternators, and integrated structures to provide mechanically simple turbines between 0.85 and 10 kW. The Bergey BWC Excel (Figure 5) is a 10-kW, three-bladed, direct drive, upwind wind turbine with passive blade-pitch control. To achieve overspeed protection, the rotor yaws out of the wind. The rotor diameter is 7 m. The BWC Excel wind turbine is designed to supply most of the electricity for an average all-electric home in areas with an average wind speed of 12 mph. In remote locations, it can charge batteries for stand-alone applications or pump water electrically without the need for batteries. More than 1400 BWC wind turbines have been installed in a total of more than 60 countries. BWC, under subcontract to NREL, is developing a 15-kW high-frequency link, full-digital-control inverter to provide high reliability at low cost for its stand-alone AC systems.

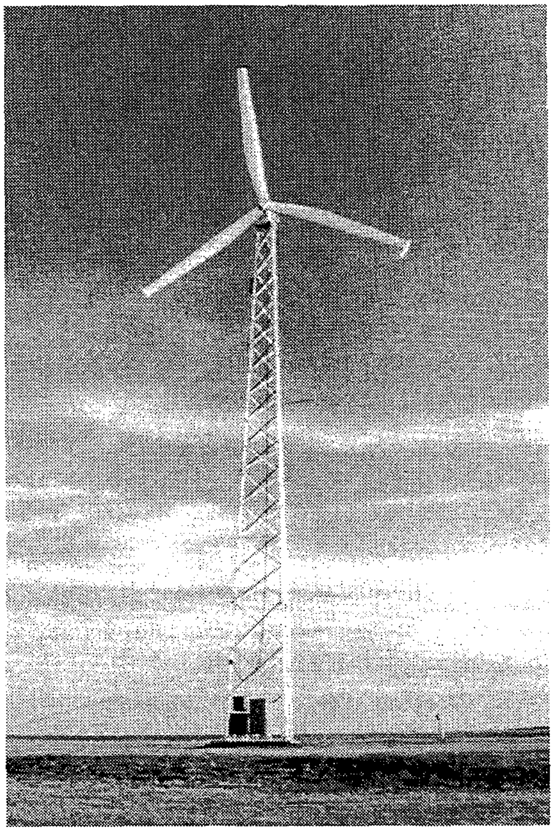


**Figure 4. Atlantic Orient Corporation's 50-kW AOC 15/50.**

In 1992, a Bergey system was installed in Xcalac, Mexico, with funding and technical

Kenetech Windpower 56/100 and 33-M/VS, the AOC 15/50, the NPS North Wind 250 (Musial, *et al,* 1994), and the Zond Z-40.

### Power electronics

New technology has been developed which uses power electronics to allow variable-rotor-speed operation to improve efficiency, control structural loads, and improve power quality. Today variable-speed operation is estimated to increase energy capture by up to 15%, which is about the same level as the cost increase (Lucas, *et al*, 1989). However, it is thought that variable-rotor-speed operation can reduce the cost of wind-generated electricity by reducing structural loads (allowing a lightweight, low-cost configuration), and improving power quality.

### Aerodynamic control devices

Aerodynamic control devices provide two benefits: they are used for overspeed control and power modulation. Significant damage to the turbine can occur as a result of high wind or loss of generator load unless control of the rotor is maintained. In addition, natural wind-speed variations, insect-impact accumulations, or minor blade damage can result in off-optimum rotor rotation speeds and less-than-desired power output. Incorporated into turbine blades, aerodynamic control devices (also called trailing-edge control devices) can adjust the rotor aerodynamic driving forces and thus optimize energy capture, control loads, and control rotor speed. These aerodynamic controls are often compared to the ailerons used on aircraft. Various trailing-edge control devices have been incorporated in wind turbines that are in development or commercially available. NREL is working with subcontractors and wind industry representatives to further study improved trailing-edge control devices. These trailing-edge control devices are thought to offer some cost and control advantages over pitch control and tip controls which are typically used on existing designs, although these advantages are yet to be proven.

### National Wind Technology Center Hybrid Power Test Facility

A wind hybrid test facility is planned for NREL's National Wind Technology Center that will allow researchers to study hybrid power systems, developed by the U. S. industry, that combine wind turbines, photovoltaic arrays, backup generators, and storage systems (Thresher, *et al*, 1994). The key function for the hybrid test facility will be to test small wind and hybrid power systems that are nearly market ready and provide a system development user's facility for U.S. industry.

### Hybrid System Modeling

NREL is currently developing computer simulation codes to allow modeling of the full range of hybrid power technologies being considered for village power in the 1900s. Building on existing wind/diesel models, a new advanced hybrid systems simulation model is being developed which will accommodate a wider array of technologies and system architectures now being considered for hybrid village power systems.

### Renewable-Hybrid Configurations

In 1994, DOE initiated a 5-year, cost-shared research collaboration with the U.S. Department of Agriculture to investigate a range of wind/diesel system configurations. The goal of this collaboration is to develop systems powered entirely from renewable sources (e.g. wind power, solar power, and use of vegetable oils in place of diesel fuel) that would be reliable and cost competitive. The experimental study will focus on performance and stability for various system configurations and will identify necessary controls. This research will be performed in a wind/diesel test facility at the U.S. Department of Agriculture research laboratory at Bushland, Texas.

### *Future Technological Improvements*

The advancement of wind turbine technology is leading to next-generation wind turbines which promise significant improvements in performance, reliability, and cost. Figure 6 illustrates three possible configurations that may be competing for the market in 2000. In general, each of these competing turbine designs will probably incorporate many of the following advanced features.

- *Advanced airfoils.* For 2000, structurally tailored blades made of soft, flexible materials may also be possible. Such blades would change shape in response to wind conditions, increasing energy capture and reducing loads as wind speed controls blade shape.

- *Aerodynamic controls.* Ailerons, spoiler flaps, and double-split-flaps (deployed from both sides of a blade's trailing edge) are being examined for future use as effective rotor-speed brakes.

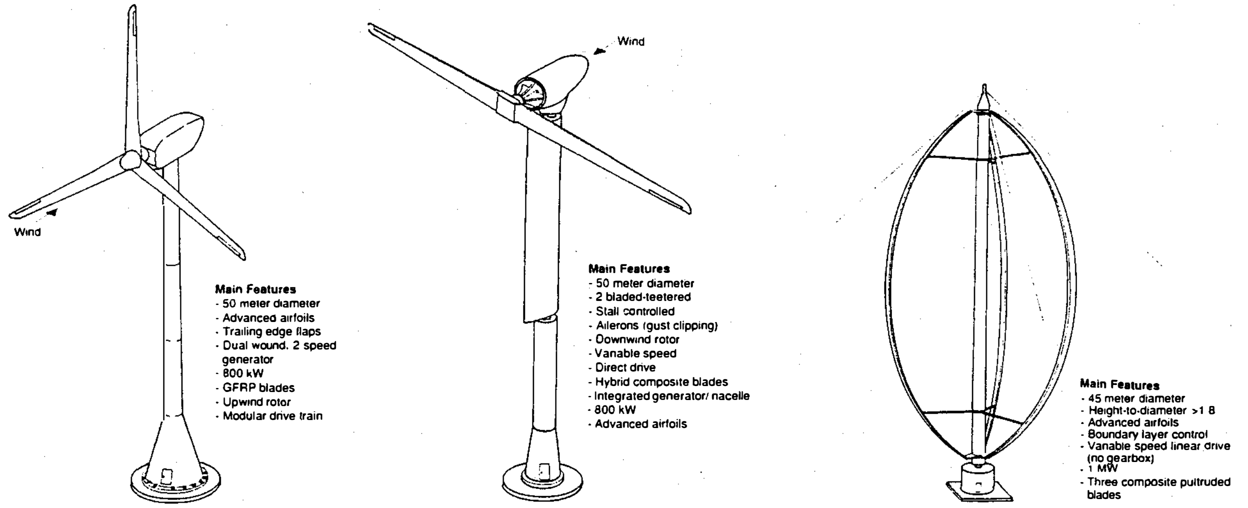
- *Advanced generators.* Using low-speed, direct-drive generators could eliminate the need for the gearbox, thereby reducing turbine weight and costs. This generator is likely to be used in combination with variable-speed operation to take advantage of the benefits of power electronics.

- *Advanced control systems.* Advanced, expert control systems capable of controlling a single wind turbine, an array of turbines, or an entire power plant should be commonplace in the future. Smart systems can detect wind-speed changes and adjust individual turbines throughout a power plant.

### *Advanced Wind Turbine Configurations*

Figure 5 (A and B) illustrates two likely configurations for advanced HAWT designs. These configurations were first suggested in the configuration study by Swift, Hock, and Thresher (1992). The first configuration, shown as A, represents a low-risk design path incorporating the more conventional three-bladed rotor. Innovations include a larger rotor diameter using advanced airfoils and trailing-edge flaps for overspeed control. This design is rated at 800 kW, which is twice the size of current machines.

The second machine, shown as B, incorporates higher-risk design options, including a 50-m-diameter, two-bladed, teetered downwind rotor. The stall-controlled rotor also has actively controlled ailerons for power clipping in response to gusts. The use of a variable-speed generator will allow increased energy capture over a broad range of wind speeds. While this design philosophy is perceived as high risk because of its innovations, it offers high potential for reduced weight and therefore cost.



**A) Advanced three-bladed turbine** **b) Lightweight teetered turbine** **C) Lightweight vertical axis wind turbine**

**Figure 6. Three possible advanced wind turbine configurations.**

## *Vertical-Axis Wind Turbine (VAWT) Configuration*

For 2000, the hypothesized VAWT (C) will almost certainly retain one aspect of its current strengt simplicity. The key to future success with this configuration, however, will be cost-effectiv manufacturing techniques (primarily for blade production) that will produce significantly les expensive blades, based on cost per unit length (Dodd, 1990). VAWT blades are not geometricall complex (e.g. no twist or taper), thus making manufacturing processes such as extrusion an pultrusion viable candidates to reduce costs. In addition, the inherent advantage of the VAW configuration, having all drivetrain and generator parts at ground level, creates opportunities fo using components with high weight or large physical size. Of recent interest in this regard is th direct- or linear-drive generator, which eliminates the need for a gearbox and provides th advantages of variable-speed operation at a very competitive price.

## Summary

Significant progress has been made in wind energy technology over the last decade. Today advanced systems offer improved performance, higher reliability, and lower costs. Turbine design now make use of new technical developments such as advanced airfoils, information fro structural blade testing, variable rotor speed operation, and aerodynamic controls. Thes developments have been incorporated into wind turbines that are, or will soon be, commerciall available at a cost of energy at, or below $0.05/kWh. Further cost reductions are expected as th technology evolves and moves toward larger scales, and mass production.

Technology innovations are being adapted for remote and stand-alone power applications with smaller wind turbines. Village power systems using wind energy, photovoltaics, battery storage, and a conventional diesel generator are successfully providing power in remote locations. These systems can compete economically due to the high cost of either utility grid extension, or the cost of delivered fuel and maintenance for a diesel unit alone.

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