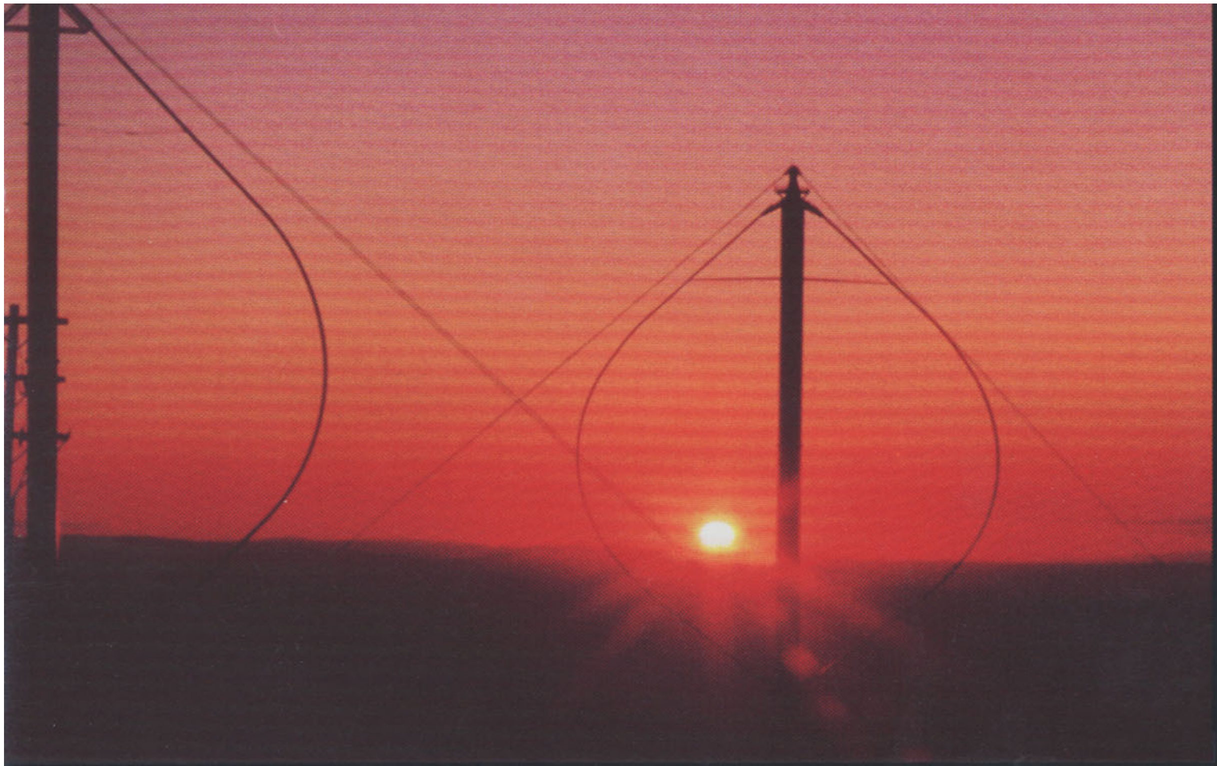
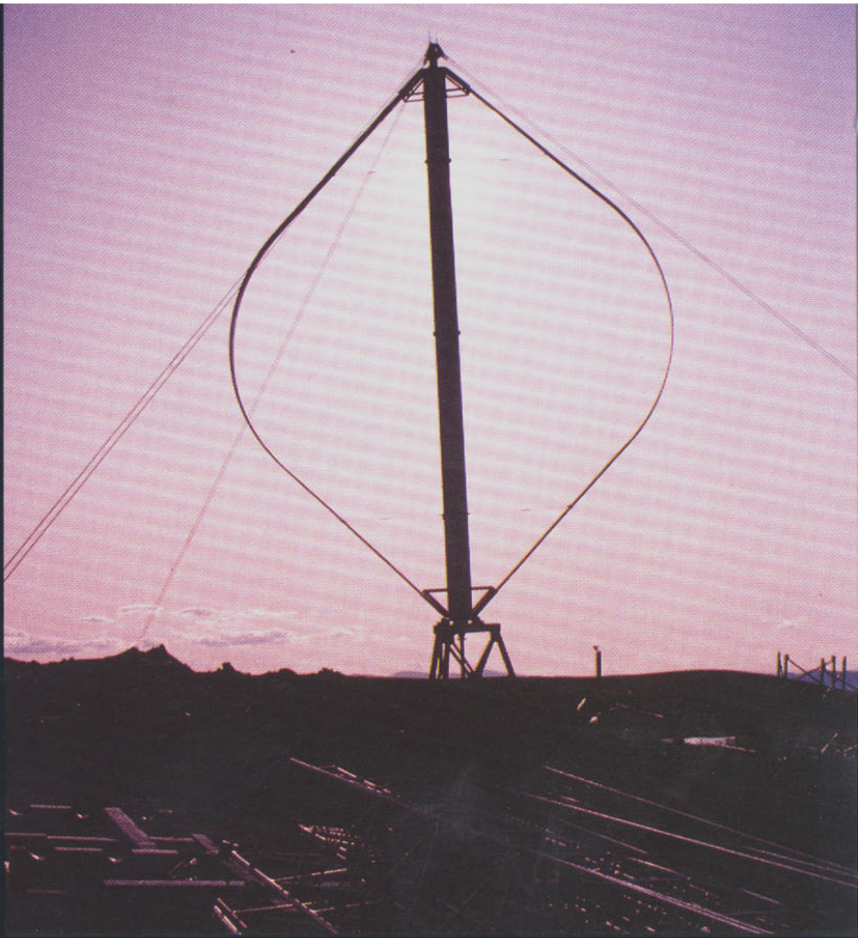




Vertical Axis Wind Turbines

The History of the DOE Program

This document was produced through a cooperative effort
by the U.S. Department of Energy, Sandia National Laboratories,
and the American Wind Energy Association.

Visitors to windy Altamont Pass in northern California or Cameron Ridge in central California's Tehachapi Mountains are intrigued by what looks like a testing ground for huge egg-beaters. Appearances to the contrary, the machines are vertical axis wind turbines—VAWTs— whose curved, slender blades catch the wind and convert its energy into electricity. The Department of Energy has sponsored VAWT research and development for 15 years, research that has resulted in commercializing the technology.

The wind farms in California are fairly new, having been built in the 1980s. On a wind farm, numerous turbines generate enough electricity to power a small city. But mankind has been using the wind for power since about 200 B.C., when the Persians developed wind-powered grist mills. These very early wind machines were of the vertical axis type, using bundles of reeds tied to a frame that rotated as the wind blew. Later, the more familiar horizontal axis wind mills became the standard, particularly in Holland where they are legendary.

Futuristic VAWTs provide bus passengers with something to write home about.

The modern VAWT, the machine with an egg-beater appearance, wasn't developed until after the first World War. This publication outlines the history of VAWTs in the United States and describes some of the turbine's innovative features.

Development of the modern vertical axis wind turbine

Re-inventing the turbine

French inventor Georges Jean Marie Darrieus filed the first patent for a modern type of vertical axis wind turbine (VAWT) in France in 1925, then in the United States in 1931. His idea received little attention at that time, so little in fact that two Canadian researchers re-invented his concept in the late 1960s for the National Aeronautics Establishment of Canada without knowing of Darrieus's patent. They later learned of the French inventor, and today's VAWT is known as a Darrieus-type wind turbine.

International events in the 1970s focused attention in the United States on alternative sources of energy, because the 1973 Arab oil embargo forced the nation to take a sobering look at its reliance on foreign energy sources. The federal government began to support research into domestic energy sources, and a great deal of interest turned to those technologies using time-honored sources of energy—the sun and the wind.

In 1973, the Atomic Energy Commission, a predecessor to the current Department of Energy (DOE), asked Sandia National Laboratories, a national laboratory devoted to engineering research and development, to investigate and develop alternative energy sources. Using their extensive experience in aerodynamics and structural dynamics from years of work with delivery systems for weapons, Sandia's engineers began to look into the feasibility of developing an efficient wind turbine that industry could manufacture. During this time, the Canadians shared their re-invention with Sandia, and interest in the VAWT concept began in earnest.

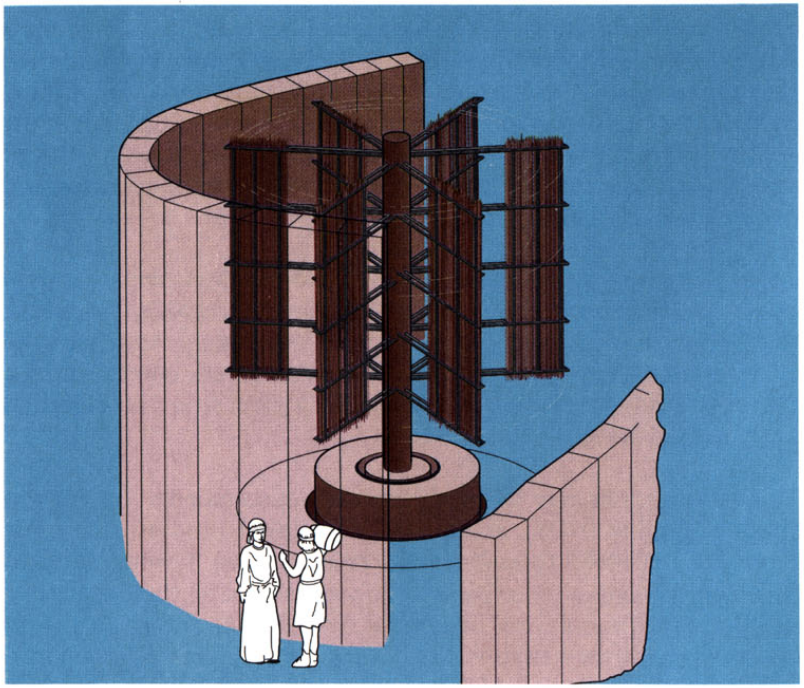
From desktop to rooftop

The first Darrieus-type VAWT in America was actually only 12 inches tall and was constructed on top of an engineer's desk. To demonstrate that the VAWT concept worked, Sandia's engineers used a fan to create wind for the miniature turbine and a blackboard to perform their calculations—using these simple means, they converted non-believers.

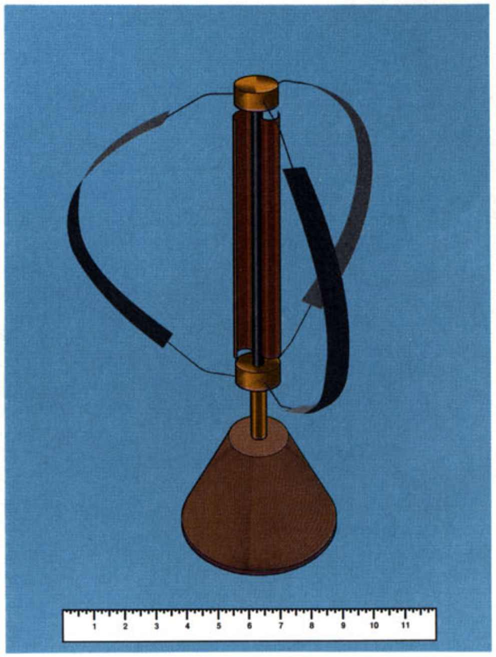
Darrieus's concept appeals to engineers because it works on the principle of aerodynamic lift. Lift is what keeps an airplane in the sky—the wind actually pulls the blades along. In contrast, the traditional Holland-type windmill operates on the principle of drag, meaning the wind has to push a manmade barrier, such as a blade. Modern vertical- and horizontal-axis wind machines both use lift, which makes them more efficient compared with traditional windmills.

Sandia's original model VAWT combined Darrieus's design with another concept for a wind turbine, called Savonius after its inventor, a Swede. Because the Darrieus VAWT could not start itself, some researchers thought it might be at a disadvantage. The turbine Savonius designed used some lift, but its theoretical advantage was in using cups or vanes to trap the wind—employing the principle of drag—and so it was able to catch the wind and start itself in motion. However, the Savonius element was soon abandoned because of the blade size required for it to work; instead engineers opted to start up the turbine manually and to use the Darrieus design.

To test the aerodynamics of the turbine, a larger working model was built on the rooftop of the main administration building at Sandia. This model measured 5 meters across the outer edges of the two bowed blades, each



In 200 B.C., the ancient Persians constructed a gristmill by fastening bundles of reeds to a frame that rotated as the wind blew.



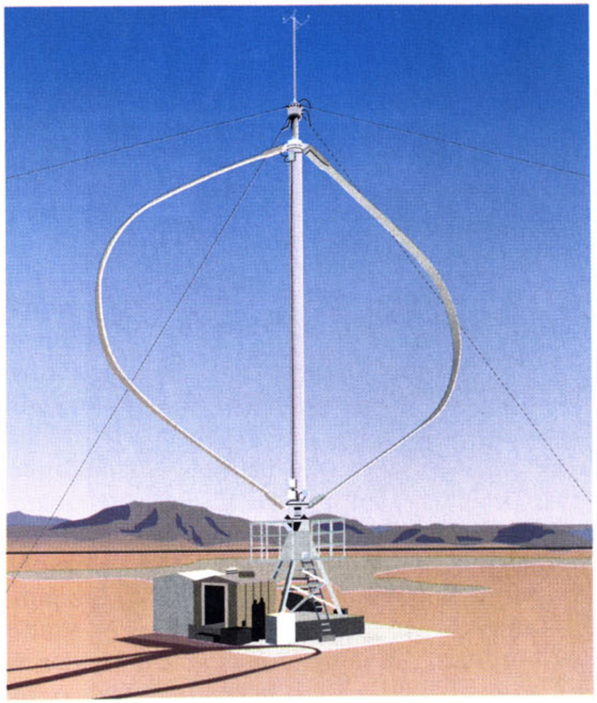
The first Sandia VAWT utilized Darrieus and Savonius concepts in a desktop model that was only 12 inches tall.

constructed out of a shank of steel covered by foam and fiberglass, then molded into the characteristic teardrop airfoil shape commonly used in the aircraft industry.

Putting the test turbine in motion was no easy feat—researchers patiently waited for the wind to begin to blow, strapped themselves onto the roof of the building and spun the blades by hand. Whenever a thunderstorm, with its accompanying high winds, would blow into Albuquerque—night or day—the engineers rushed to the laboratory, climbed to the roof, and began turning the blades.

Starting the blades was not the only problem, however. To sustain their rotation, the blades had to be turning at least two to four times faster than the wind so that lift could work properly. At this early stage in the turbine's development, the blades required certain wind conditions, which did not occur on a daily basis. In the spring of 1974, however, the winds cooperated, the VAWT blades rotated smoothly on their own, and the demonstration phase began.

Another factor engineers had to consider was that under certain conditions, wind turbines can literally spin apart; they go into what is known as a runaway condition. Researchers knew that if their VAWT had a load to power—a generator for example—the load would act as a brake against runaway, but at that time, there was no load in the test system. For this reason, they built a disc brake into the system, similar to that used in automobiles. The test brake consisted of a commercially available automobile disk caliper clamped onto a machined disk. To apply the brake, one pulled on a handle originally used in a pre-1940 pickup truck.



For about one year, Sandia's 17-meter machine, built in 1975, was the largest VAWT in existence.

Sunrise on windfarm in northern California.

Moving to industry

Some two years after constructing the rooftop model, Sandia built a second, larger wind turbine—this one on the ground. With a blade span of 17 meters, the turbine's main purpose was to show that it could compete in cost with the more traditional horizontal-axis machines. An economic study from 1976 supported the research: vertical and horizontal axis wind turbines, or HAWTs, should indeed be comparable in performance and price if some improvements were made to the VAWT's design.

The 1976-study suggested these improvements. First, two blades would be better—the earliest design had three. Next, slimming down the shape of the turbine would improve its design, and the turbine's efficiency could be improved with better airfoil shapes. And finally, the study found that a blade span of at least 17 meters was best. During its first year of operation, 1976, this experimental machine was the largest VAWT in existence, and its performance compared favorably with that of a horizontal-axis machine.

The first VAWT blades were expensive because they were made of aluminum, fiberglass, and a man-made, honeycomb-like material, all of which had to be carefully fitted together. Alcoa Industries was interested in reducing manufacturing costs of VAWT blades and in the mid-1970s developed an extrusion process in which partially molten bars of aluminum are forced into a die cut into the shape of an airfoil. The aluminum is under such pressure that it melts and flows through the die, where it cools and resolidifies. The result is a uniformly manufactured airfoil in the required shape. The process dramatically reduces the cost to manufacture VAWT blades, and it continues to be used today.

Alcoa won a DOE contract a few years later, in 1979, to construct four low-cost VAWTs, each to have a 17-meter blade span and to deliver 100 kilowatts of electricity. Construction lasted from January 1980 until March 1981; however, because of DOE budget constraints, only three of the units were installed. Each of the sites was chosen for a specific application: Bushland, Texas, to demonstrate an agricultural application, Rocky Flats, Colorado, to confirm structural and performance tests, and Martha's Vineyard, Massachusetts, to demonstrate the VAWT's applicability to the utility grid.

Their successful operation—more than 10,000 hours for the Bushland machine—convinced two companies to commercialize this design.

Steel die used to form aluminum into airfoil shape (inset).

VAWTPOWER and FloWind each manufactured VAWTs for use in California, where weather conditions favor using the wind's power for electricity. The result was that more than 500 VAWTs were operating in California and producing electricity by the mid-1980s.

Further developments in vertical axis wind turbine technology

Beginning in the mid-1980s, the DOE has focused its VAWT research efforts at Sandia on additional reductions in cost and improvements in the reliability of VAWTs. To this end, research is concentrated in four areas: aerodynamics, structural dynamics, fatigue and reliability, and systems engineering.

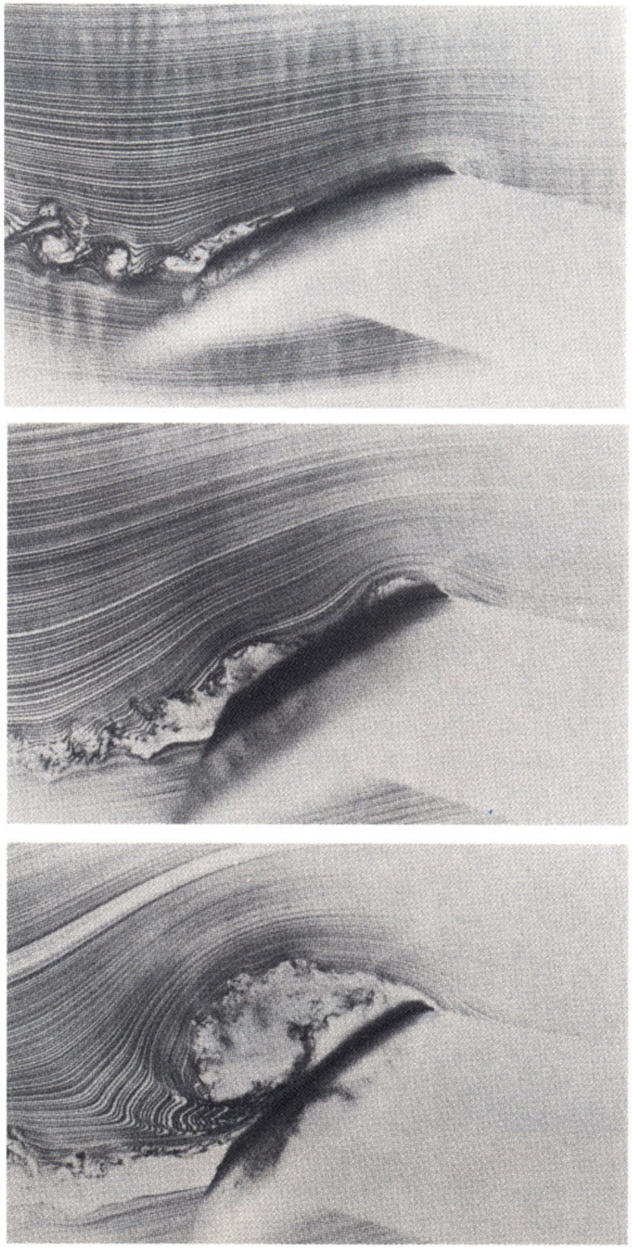
Aerodynamics

Each time the blade of a VAWT makes a 360-degree rotation around its central tower, the angle at which it meets the wind varies. Technically, this angle is known as its angle of attack. Because the VAWT's angle of attack changes so rapidly and so widely, engineers face a complicated aerodynamic problem in trying to determine the best shape for the turbine's blades.

The blades are shaped not only to enhance lift, but also to create a situation known as stall—the opposite of lift. For a wind turbine powering an electric generator, stall moderates lift so that constant power is achieved in high winds. This ability to regulate power output in high winds helps to control the cost of the system.

Sandia researchers patented an early attempt to tailor the VAWT's performance by creating the condition of stall. This condition is called 'pumped spoiling' and involves drilling small holes along the blade to create stall. However, engineers also found that by modifying the traditional teardrop shape of the blade, they could also regulate the power. Redesigning the blade shape proved to be much more practical; it was a real breakthrough, because it achieved the goal of regulating output in a less expensive, simpler, and more reliable manner.

Engineers put years of effort at Sandia into developing airfoils that can regulate power through stall. This was one of the most difficult aspects of



Air flowing past an airfoil changes from smooth (top) through turbulent (middle) to stall (bottom) as the airfoil's angle of attack changes.

advanced VAWT technology, but it was a major step in making this kind of wind turbine more economical in producing electricity. Under DOE funding, in 1980 researchers at The Ohio State University originated the concept of natural laminar flow airfoils. These specialized components were first used—or 'flown'—on the 5-meter VAWT in 1982 and then on Sandia's 17-meter VAWT in 1984.

Structural dynamics

Studying the structural dynamics of a VAWT gives research engineers clues to making them succeed. Using these studies, they can predict the natural frequencies of vibration, as well as stresses caused by gravity, centrifugal force, and wind-induced forces affecting the machine while it is at rest or in motion. They can also avoid most disasters, such as operating in a resonance condition (a dangerous condition in which the machine's natural frequency coincides with its operating speed, causing the turbine to shake apart quickly). Analysis also allows engineers to estimate the machine's fatigue life.

Analyzing the natural frequency of a turbine requires computer modeling that must be validated with actual data. This has been true since the outset of VAWT development. To obtain the data, accelerometers (electronic measuring devices) are strategically mounted on the VAWT before testing takes place. The natural frequencies of the turbines are measured during what is called 'modal testing' by attaching cables to the turbine's structure, tightening the cables, then quickly releasing them, causing the structure to be stressed. The accelerometers pick up the frequencies and send the data to computers. Once the data are analyzed, they are compared with computer simulations, and the model is adjusted to reflect the data. In this way, researchers have been able to design accurate computer simulations of many conditions that a working VAWT might experience. The modal testing capability Sandia designed for the VAWT is recognized throughout the world and is also used by researchers interested in HAWTs.

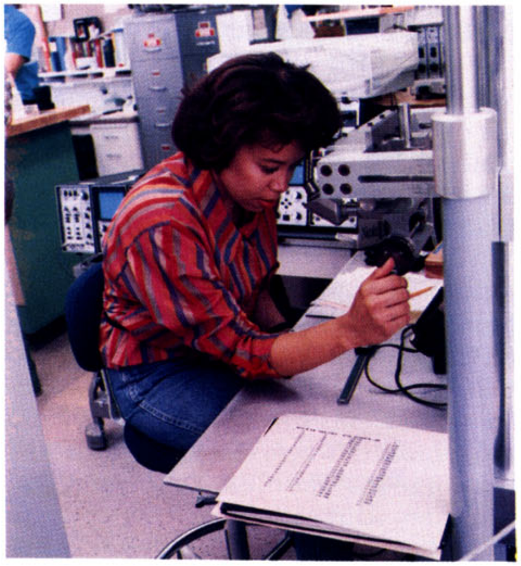
Release of cable by worker causes VAWT structure to vibrate. Instrumentation mounted on structure record these motions and send data to computer for analysis.

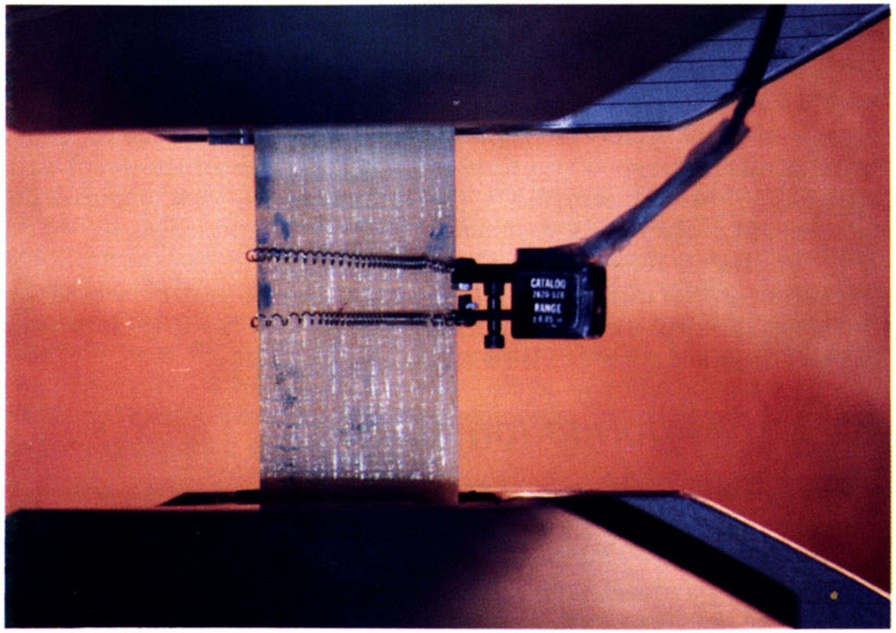
Fatigue and reliability

Engineers have long been interested in the reliability and fatigue of a VAWT system, or how loads caused by the wind affect its expected lifetime. Air turbulence, for example, can substantially increase the wind loads on a wind turbine, and computer modeling can determine the effects it may have on loads and stress levels. A computer code Sandia developed called LIFE2 permits data, such as loading-stress cycles, wind-speed distribution, and materials properties, to be combined to estimate the operating time before fatigue will begin to cause cracks in the blades. This analysis permits designers of wind turbines to determine the adequacy of each component's design. In addition, LIFE2 can predict problems such as the growth of small cracks, which ultimately result in blade fractures.

Materials now used in high-performance wind turbine applications have been taken from low-cost uses such as aluminum extrusions typically used in window frames and fiberglass composites borrowed from boat hull applications. Laboratory fatigue-test programs seek to characterize the durability of these materials more thoroughly than ever attempted before. Aluminum stress tests determine how long and at what load levels minute cracks will begin to form in the material. Crack growth testing then determines how fast the cracks will grow under typical wind turbine loadings. Fiberglass fatigue tests determine the relative durability to be gained (or lost) by using any of the myriad of options for glass fiber orientation and lay-up design. As with all materials, there is significant variability in the time it takes different pieces of the material to break, even under identical loadings. Reliability methods are being used to help the designer determine when sufficient material durability has been achieved to meet performance goals. Engineering researchers are improving their capability to predict a system's reliability, thereby increasing their ability to modify the appropriate design factors to improve the lifespan of wind turbines.

Researcher examining aluminum bar for cracks. This type of testing determines how long cracks take to form and at what rate they grow.





The durability of composite materials such as fiberglass is tested to ascertain their viability for blade construction.

Systems engineering

Systems studies are designed to minimize the cost of energy over the design life of the turbine. This requires a trade-off in energy capture and use of materials. For example, these studies look at the implications of operating the system at variable speeds, an ability that permits the VAWT to respond more gently to shifting wind gusts and to starts and stops.

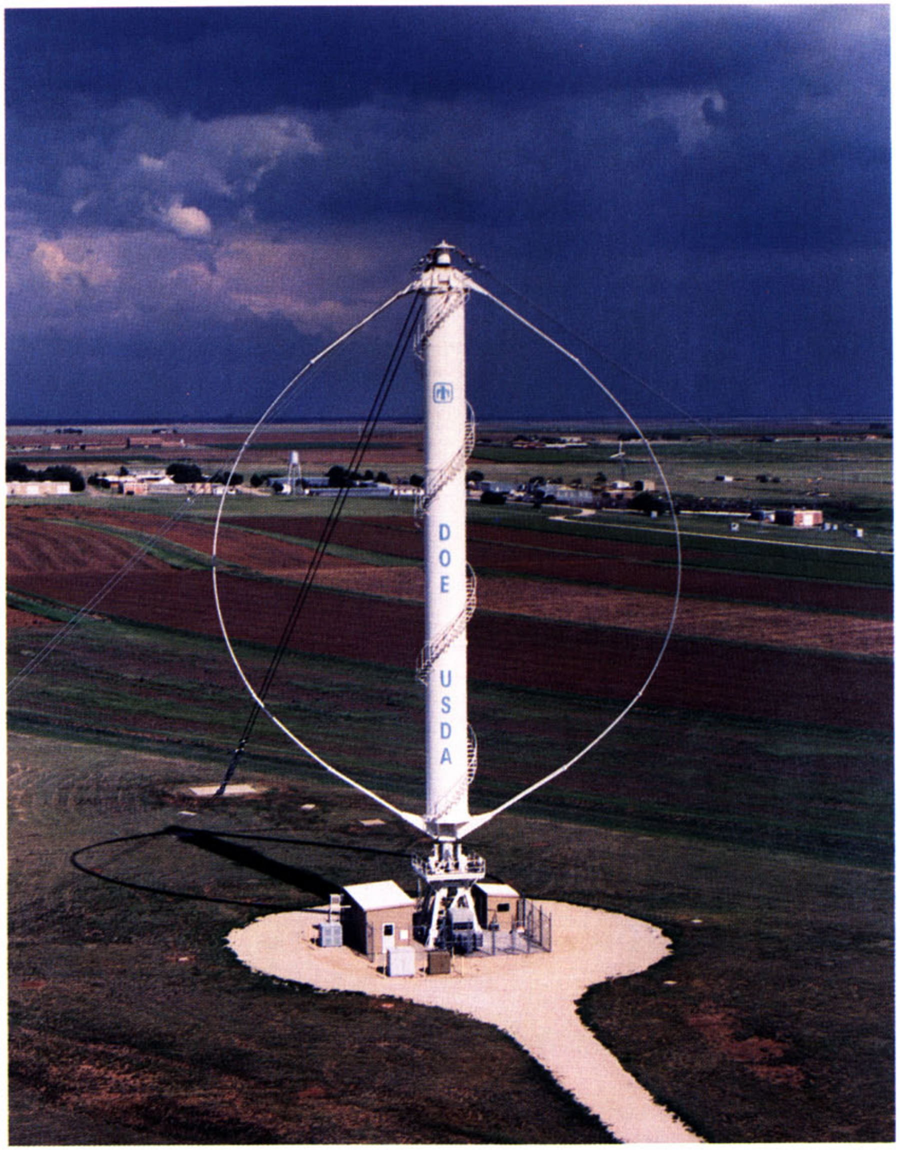
A team approach is vital to a systems study, because any alteration in a complex machine such as a VAWT affects the other components and/or their operation. The DOE's 34-meter Test Bed at Bushland, Texas, is a good example of systems engineering at work; when this test VAWT was built, major trade-offs involved structure and aerodynamics. The blades were made broader where the foils attach to the tower and narrower at their equator so that the turbine's structure and the aerodynamics of the blades would not fight each other.

Typical design choices for a VAWT illustrate the trade-offs that continually have to be made. For example, the blade size influences the amount of energy that can be output, but it also affects the structure needed to hold the blades. These two factors in turn affect cost. A team approach to include only these two factors would thus involve integrating the peak output desired and the cost of the infrastructure to support the turbine. The details of the structural enhancements lead to a calculation of how these enhancements—such as struts or guy wires—might degrade the aerodynamic performance of the blades.

The bottom line for all of these systems studies is whether the trade-offs are economically worth the compromise—or enhancement—in performance. This give-and-take approach is central to a team effort.

Using the information for a new, larger machine

Because the 17-meter VAWTs showed such success, the DOE Wind Program directed Sandia to develop an expanded research machine. System studies indicated 34 meters was a good size for the blade diameter to test the new airfoils, and the size made economic sense. In cooperation with the Department of Agriculture, a 34-meter turbine was completed in 1988 at Bushland, Texas, the culmination of planning that began in 1984.



Sandia's 34-meter Test Bed can produce more than half the electricity needed to power the local community, but it is a research and development tool only.

Called simply the 34-meter Test Bed, this VAWT is a research tool for testing and developing advanced concepts. It can produce 500 kilowatts of electricity, more than half of the local community's normal power needs, but its purpose is research, not power production. For this reason, instruments are strategically mounted on the VAWT to measure its parameters, especially stress on the blades. Weather conditions that affect the VAWT's performance are also recorded, including wind direction and speed, ambient temperature, and barometric pressure.

A special feature of the Test Bed is that it can run over a continuously variable range of rotor speeds, from 25 to 40 rpm, whereas most wind turbines are designed to turn at a constant speed. The large, bowed aluminum blades are made of sections of specially designed airfoils that are bolted together; three different sizes and designs increase efficiency and regulate power through stall.

The work at Sandia and its Test Bed includes validating computer models, testing airfoil designs, and developing various control strategies. The work is part of improving the first-generation design, which has been commercialized in California, as well as developing technology that can be used by industry in developing next-generation VAWTs. Transferring technology from its national laboratories to the commercial sector is a major goal of the DOE, and Sandia's development of the VAWT and its subsequent adoption by industry is a good example of such a program.

The future of VAWT research

Within the DOE's Office of Renewable Energy Conversion is the Wind/Hydro/Ocean Division, which oversees the current federal wind energy program, including wind research and development, formed by the national laboratories. The DOE supports Sandia's efforts to develop VAWT technology, which serves as the basis for private industry to develop new generations of VAWTs with greater efficiency and longer life expectancy than any machine produced in the past. To this end, the Department supports its laboratories' forming cooperative research agreements with commercial firms to improve wind turbine designs.

The DOE's program with the vertical axis wind turbine has come a long way since Sandia built its 30-centimeter-tall desktop version, and plans are for the wind program to continue its work, but focused along two main paths. Just as they have done in the past, engineers will continue core research into VAWT systems to develop fundamental design tools for industry to use. They will continue to look at aerodynamics, examining whether the shape of the airfoil can be further improved from the natural laminar flow design now specific to the VAWT. They will look at the materials from which the blades are made to see whether extruded aluminum is still the best, or whether to use some other materials such as fiberglass or wood.

Sandia and industry engineers will research the control strategies for running VAWTs, and the optimum conditions for these machines. They will investigate whether they can further reduce the cost of components by designing what are called 'soft structures,' entailing such details as scaling down the diameter of the tower and reducing the thickness of the guy lines and the blades so the structure can flex with the wind.

In addition, Sandia will use its computer model, the VAWT Structural Dynamics Simulator, to calculate stresses caused by various operating conditions. Stress on these wind turbines is still a major concern for VAWT designers; it affects almost every aspect of the machine when it operates. The code improves researchers' abilities to simulate aeroelastic effects and to study how they affect the blade's performance. Using this model, researchers can also simulate a wide range of other effects—how the machine works when variable-speed generators, or soft rotors, or different control systems are used, for example.

Wind energy today . . .

Today's wind systems are meeting today's energy needs. Wind farms located in California have been supplying utility-scale power since 1983. This displaces the use of additional fuel and its related emissions. The wind farms in California offset at least 10 million pounds of air pollutants and 2 billion pounds of greenhouse gases per year. They also replace the energy requirements of almost 4 million barrels of oil per year.

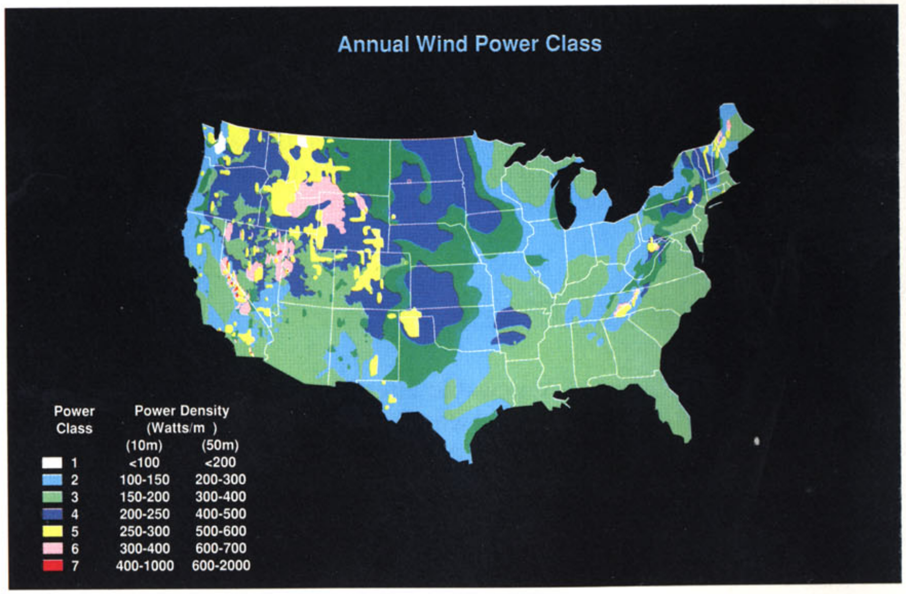
Emerging as perhaps the most important reason for using renewables for some of the nation's energy supply is the real cost to produce electricity. Regulations adopted by several public utility commissions now ensure that the cost of pollution emitted by power plants will be accounted for. These commissions look beyond traditional costs of power generation, such as fuel and operations and maintenance, and include expenses not usually calculated into the total cost of proposed power plants, for example, the cost of pollution.

But renewable energy stands on its own merit. Wind energy is a valuable contributor to utility-scale electricity production in some areas today. Modularity is one important system design feature. Systems, such as the wind farms, can be scaled from small to large capacity depending on the needed increase in electrical capacity, all within a relatively short period of time. When compared to the total cost of larger, more traditional power plants, the cost of wind energy becomes quite competitive. And in the most energetic sites, the cost of electricity produced with wind is already competitive with traditional energy sources.

. . . And tomorrow

As the national laboratories work more closely with industry, concerns—such as quality control for the equipment, fatigue, materials, and reliability—related to manufacturing and manufacturability of the VAWT are becoming more important than in the past. The DOE's wind energy program is looking into using VAWT as well as HAWT technology to contribute to the nation's electricity production, because promoting renewable energy use is an important part of the DOE mission.

Both vertical and horizontal axis types of wind machines will figure in the mix of renewable energy technologies that the nation is predicted to use within the near future. Each kind of wind turbine is best suited to certain conditions, and each will take its place where it can be used most economically and reliably. Researchers predict that within the next five years, wind energy will be more economical than traditional fossil-fuel-fired energy. With heightened technology transfer from our national laboratories to our nation's wind energy industry, and the prospect of more states investigating renewable energy, the future of wind energy in supplying our nation's electricity needs grows stronger. Renewable, economical, and clean—wind energy is for today and tomorrow.

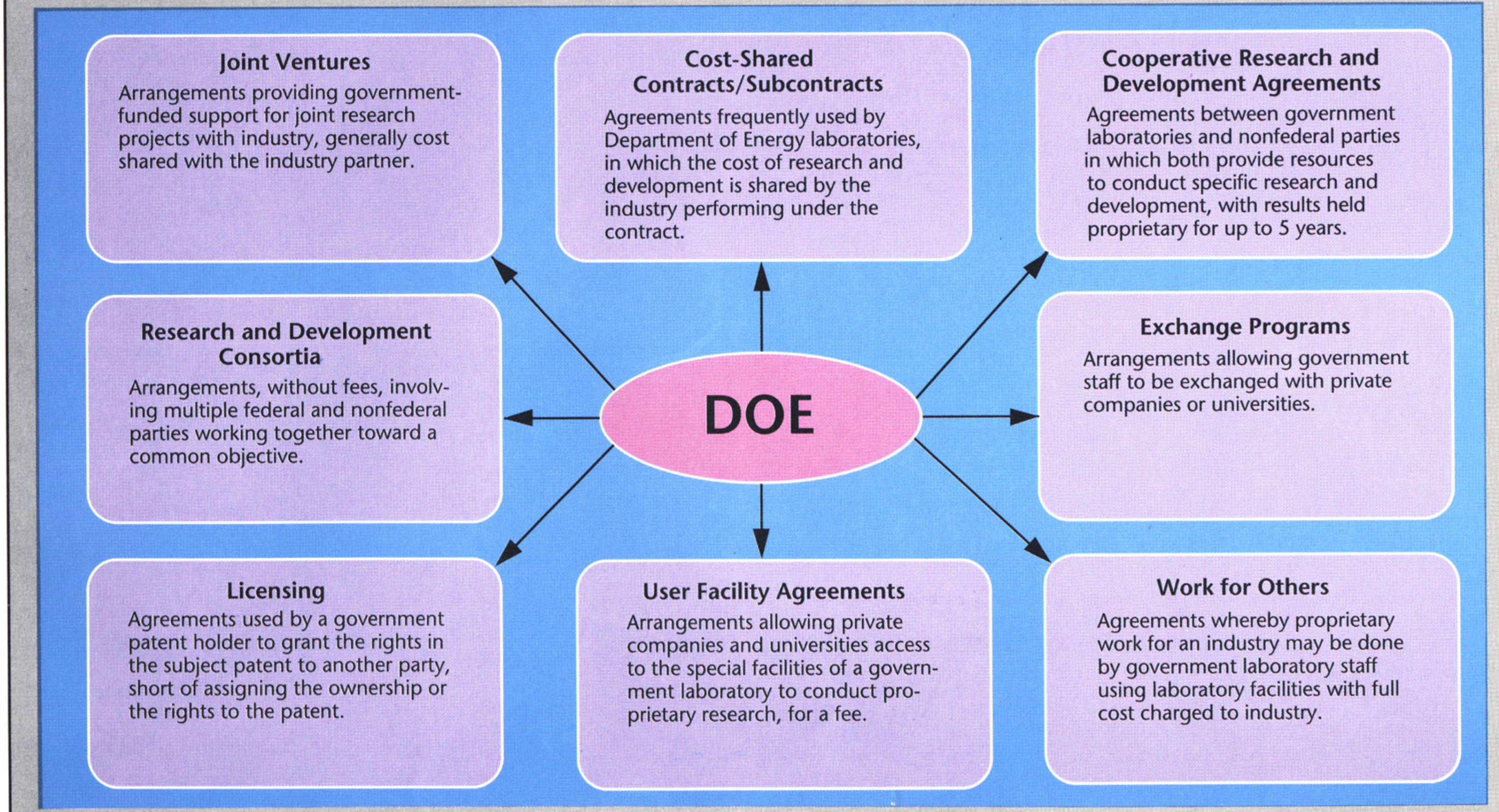


Computerized map of the United States showing wind energy potential. Properly harnessed, winds could supply twice the electricity needs of this country. Power densities are given for 10 and 50 meters above ground.

The Department of Energy and technology transfer

Research in the national laboratories is under the guidance and sponsorship of the Department of Energy, and it is done in the national interest. For this reason, a primary mission of the Department is to transfer the results of this research to industry, so that technical advances can benefit the nation and the competitiveness of American commerce.

Some of the mechanisms by which technology can be transferred to industry include:



Joint Ventures
Arrangements providing government-funded support for joint research projects with industry, generally cost shared with the industry partner.

Cost-Shared Contracts/Subcontracts
Agreements frequently used by Department of Energy laboratories, in which the cost of research and development is shared by the industry performing under the contract.

Cooperative Research and Development Agreements
Agreements between government laboratories and nonfederal parties in which both provide resources to conduct specific research and development, with results held proprietary for up to 5 years.

Research and Development Consortia
Arrangements, without fees, involving multiple federal and nonfederal parties working together toward a common objective.

Exchange Programs
Arrangements allowing government staff to be exchanged with private companies or universities.

Licensing
Agreements used by a government patent holder to grant the rights in the subject patent to another party, short of assigning the ownership or the rights to the patent.

User Facility Agreements
Arrangements allowing private companies and universities access to the special facilities of a government laboratory to conduct proprietary research, for a fee.

Work for Others
Agreements whereby proprietary work for an industry may be done by government laboratory staff using laboratory facilities with full cost charged to industry.

A cooperative venture to improve vertical axis wind turbines

The wind farms near Tehachapi, California with their several kinds of wind machines, some of them VAWTs, encompass acres of land. The winds are high here; gusts frequently reach 80 miles an hour and sometimes get as high as 120. Damage to the machines is not unusual. This area is perhaps the most demanding in California on wind turbines, and companies have installed both vertical and horizontal axis wind turbines. The VAWT wind farm here, as well as the one in Altamont Pass, uses first-generation VAWTs, which in the ten years since they were built have provided researchers with ample opportunity to study issues relating to fatigue, turbulence, and aerodynamics.

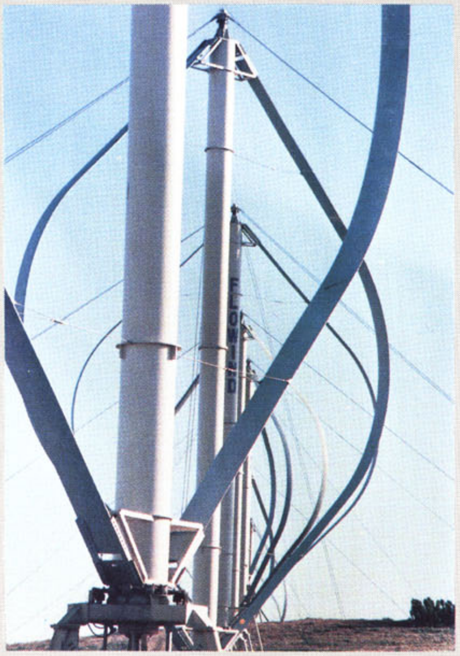
Analyzing data in those areas shows that there is room for improvement in the first-generation VAWT design. Sandia is working with private industry to build on the knowledge and experience learned from the first-generation VAWTs and hopes to develop more efficient machines with next-generation designs and materials.

Because of its long-time research and development work with VAWTs, and the extensive experience with larger machines derived from its 34-meter Test Bed, Sandia National Laboratories is a natural partner for a company involved with VAWTs at these sites to improve the performance of its fleet of first-generation wind turbines.

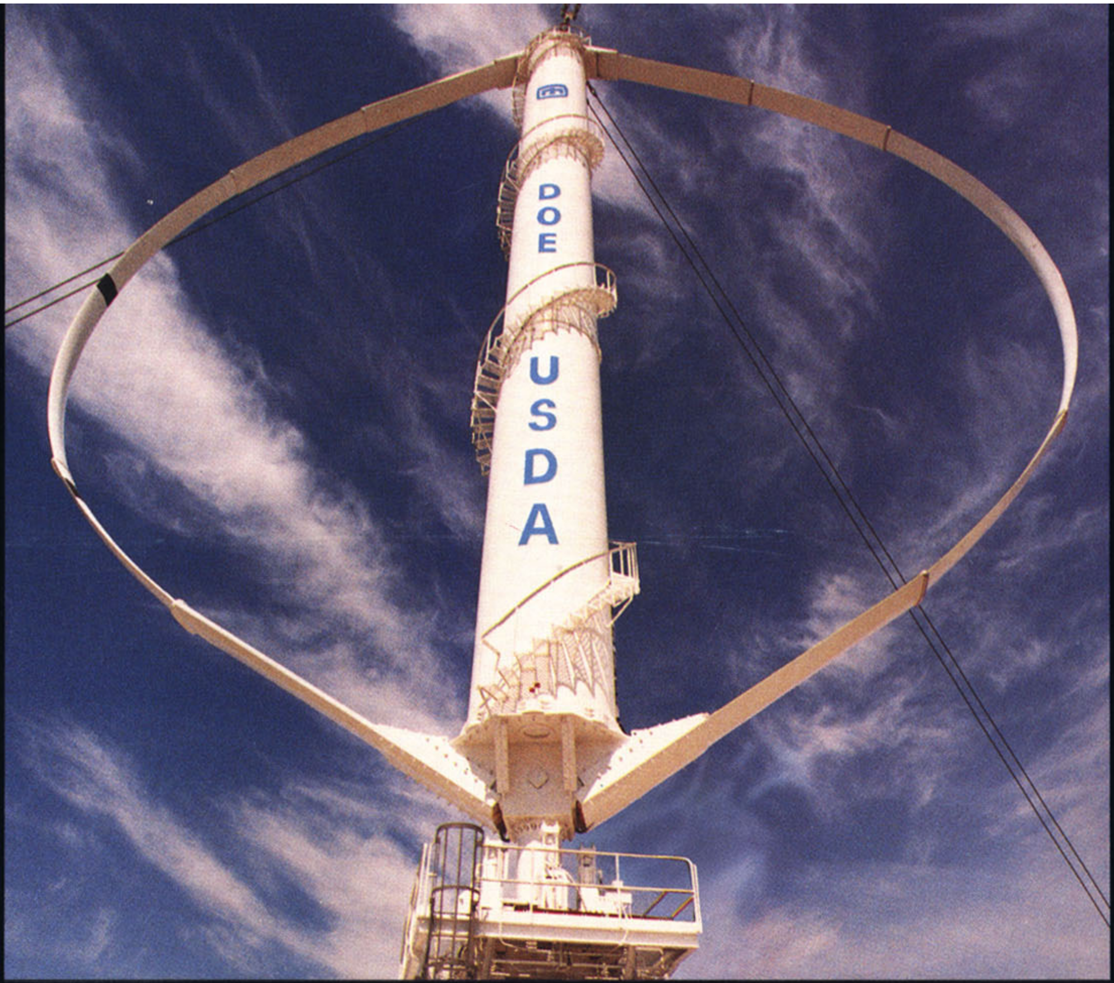
Sandia established a cooperative activity with FloWind Corporation to help improve the performance and durability of the company's more than 500 VAWTs. Retrofitting machines with Sandia's natural laminar flow blades is one of several options for increasing the blades' ability to capture the wind's energy. Various blade repairs to minimize the cost of replacing the large blades are tested, and ways to reduce drag on the blades are being found.

Sandia's engineers work with the company to reduce the cost of energy produced by modern VAWTs and to improve the company's prototype commercial machines. The agreement extends the DOE's mission to transfer technologies developed in its national laboratories.

FloWind Corporation's VAWTs aligned along windy passes in California compose this wind farm.



Storms provide high-energy winds for these VAWTs.



Writing/Project Coordination:
Energy/Waste Management Publications Department
Tech Reps., Inc., Albuquerque, NM, in collaboration with
Wind Energy Technology Department
Sandia National Laboratories, Albuquerque, NM

Design:
Publications staff, Illustration Department
Tech Reps., Inc., Albuquerque, NM

Photo credits:
Tyler Solt, FloWind Corporation, San Rafael, CA
Sandia National Laboratories, Albuquerque, NM
Michael Calcote Photography, Amarillo, TX