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WIND ENERGY - A REVITALIZED PURSUIT*

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An estimate of the wind energy available in the Great Plains area has been determined, and it was concluded that this energy is large in comparison to the 1973 U. S. electrical energy consumption. The status of the Darrieus-type vertical-axis wind turbine being investigated by Sandia Laboratories is reviewed.

INTRODUCTION

Despite the 1974 release of mid-Eastern oil to the U. S., the energy crunch is continuing and should be a source of concern. For the technically advanced countries, a favorable balance of payments has always depended heavily on the exported products of their technologies. Unfortunately, the heavy manufacturing industry, which supplies these products for the U. S., uses an inordinate quantity of energy. It has been reported that 29.4 percent¹ of the total energy consumption in this country is by the industrial sector.

Heavy use of fossil fuels with the accompanying degradation of the quality of the air we breathe, excessive damming of our rivers for hydroelectric power production, thermal pollution, and supposed risks of nuclear/electric plants—all have come under attack by environmentalists and other concerned groups and individuals. Consequently, the use of such "clean" natural energy sources as solar, geothermal, ocean thermal, and tidal and wind is being thoroughly evaluated.

It has been demonstrated that the "standard-of-living" of a country is directly related to the per capita energy consumption. The U. S., for example, with only 6 percent of the world population uses about a third of the world's energy production. To maintain its high standard of living, the U. S. must develop promising energy sources that are (1) vast, (2) environmentally acceptable, and (3) economically competitive.

Wind-energy conversion has always fulfilled the first two of these requirements. It is shown here that there is an immense reservoir of untapped wind energy available to the U. S.; for example, in the Great Plains area. The ecological harmony of wind-energy systems has been proclaimed by many, ranging from high government officials to contributors to the Mother Earth News.

Recent sharp increases in the costs of fossil fuels, especially oil from foreign sources at \$11 per barrel, are making wind-generated electricity more attractive. Spending our dollars at home is

*This work was supported by ERDA.

more important to us, because energy dollars spent on our own soil multiply many times with a resultant favorable pyramiding effect on the national economy. Thus, our present state of economic affairs should amplify the importance of Project Independence² and the urgency of the immediate and aggressive implementation of this proposal.

There has been an astonishing widespread grass-roots interest in the efforts toward advancing wind-energy technology. The efforts of NASA³ toward establishing a large, working state-of-the-art propeller generator system are being eagerly observed. Investigators of the more unconventional designs, such as the Darrieus wind turbine described later, are being besieged with requests for the latest information. Also, observers are intent on the latest developments in the formulation of the new national energy research body and how the policies of this Energy Research and Development Administration (ERDA) may affect their favored projects.

It is shown here that wind energy has already proved itself technically feasible and, when conditions are appropriate, economically capable of matching the competition in the business of producing useful energy. That the economic goals can be achieved is tantamount to success of large-scale wind-energy production.

Many observers, aware of several past efforts around the U. S. and elsewhere to harness the energy of the wind, are understandably skeptical. A history of similar efforts⁴ in the past century or so yields the one significant reality that these efforts have all been short-lived; there has been no sustained effort toward perfecting the techniques and hardware involved. These critics pointedly ask, "What's different today?"

What is different today is that the world in general and we in the U. S. in particular have come to the realization that we cannot continue to function as a "use up" or "throw away" society. Concerns about

our environment and the wasting of what we have left are not occasional ethereal musings. These hard-fact reckonings will continue to influence our societal decisions from now on.

The purpose of this paper is to assess the 1975 state of wind-energy conversion efforts, especially concerning those areas of available U. S. wind energy and conventional and unconventional wind turbine development. The Darrieus-type vertical-axis turbine is given special emphasis. Also, economic, environmental, and political conditions that will influence these efforts are discussed.

WIND-ENERGY POTENTIAL

Although the wind has been used as an energy source for many centuries, one must ask, "What potential does wind energy have in today's world?" Before addressing this question, we must first characterize the power available in a wind stream. The kinetic energy per unit mass of a moving air parcel is $\left(\frac{1}{2} V^2\right)$, and the mass rate of flow through a streamtube of cross-sectional area A is (ρAV) . The product of these two terms is the power available in this streamtube:

$$\begin{aligned} P &= \left(\frac{1}{2} V^2\right) (\rho AV) \\ &= \frac{1}{2} \rho V^3 A \end{aligned} \quad (1)$$

The variables that influence the power availability in the wind are density of the air, velocity of the air, and streamtube area. Seasonal density variation may vary about 20 percent. The streamtube area, which is directly proportional to the wind turbine frontal area, will be increased by increasing the size of the turbine. Windspeed is the primary variable that influences the available power because of the cubic relationship. For example, a 10-m/s wind contains 8 times the power of a 5-m/s wind. This cubic relationship makes turbine siting extremely important.

Since any size turbine can (theoretically) be located at a given turbine site, it is convenient for meteorological purposes to look at the power per unit area (power flux). From Eq. (1), the power flux is

$$\frac{P}{A} = \frac{1}{2} \rho V^3. \quad (2)$$

A wind turbine responds to V^3 ; therefore, mean windspeed data are not adequate for estimating power availability. Instead, one must use the mean of V^3 , which is always greater than the cube of the mean windspeed for actual turbine sites. In order to determine the geographical areas with high wind-power potential, 5- to 10-year wind data measurements from 600 individual U. S. weather stations were analyzed.⁵ Annual average power flux was computed for each station from long-term velocity-frequency data. The geographical locations of these stations, along with lines of constant power flux, are shown in Fig. 1.

Considerable smoothing was necessary in the preparation of this map, with subjective adjustment being applied to give pattern conformity to major orographic features. For comparison purposes, the constant windspeed corresponding to several power flux values is also shown in Fig. 1.

The most striking feature of this map is that the largest geographical area of high power flux is a north-south band through the Great Plains, stretching from the Texas Panhandle to the Canadian border. Within this large area, small regions of very high power flux are located in southern Wyoming and in the Texas-Oklahoma Panhandle. Regions along both the northeast and northwest coast lines have high power potential but, because of the off-shore locations, would be more difficult to utilize for both economical and technical reasons.

The geographical location of the major high power flux areas has been determined. Let us now investigate the amount of energy that can be produced by fields of wind turbines at selected sites.

Fig. 1. Available Wind Power - Annual Average

The annual energy production from a field of wind turbines can be estimated as follows:

$$E = [\text{system efficiency}] [\text{annual average power/unit area}] [\text{total turbine area}] [\text{hours in year}]$$

$$= [\epsilon] \left[\frac{1}{2} \rho \bar{V}^3 \right] [A_t] \left[8760 \frac{\text{hr}}{\text{year}} \right]. \quad (3)$$

It is convenient to introduce the total land area (A_L) occupied by the wind turbine field into Eq. (3):

$$E = [\epsilon] \left[\frac{1}{2} \rho \bar{V}^3 \right] \left[\frac{A_t}{A_L} \right] [A_L] \left[8760 \frac{\text{hr}}{\text{year}} \right]. \quad (4)$$

The ratio of turbine area to the land area used depends on the turbine spacing necessary to eliminate mutual interference problems and on the detailed geometry of the turbine field. For this analysis, let us assume that the turbines are located at the corners of a square grid and separated by a distance of MD , where D is the turbine diameter and M is a scaling constant. For propeller-type wind turbines, this area ratio can be expressed as

$$\frac{A_t}{A_L} = \frac{\pi D^2/4}{(MD)^2}$$

$$= \frac{\pi}{4M^2}. \quad (5)$$

Note that this area ratio is independent of the turbine size and varies inversely with the square of the relative spacing.*

*This quantity would be increased by a factor $2\sqrt{3}/3$ for a hexagonal spacing and would be an increase of approximately 16 percent.

Let us assume a total system conversion efficiency of 14 percent which comes from component efficiencies of 80, 60, and 30 percent for the generator/gear train, turbine site, and turbine, respectively. These efficiencies are generally conservative estimates.

In order to properly evaluate Eq. (4), the variation in power flux with geographical location should be accounted for by integration. As a simple approximation, let the geographical regions of interest be divided into regions of constant power flux. Specifically, let us consider the Great Plains area of Fig. 1 where the power flux is greater than or equal to 150 W/m^2 . These ranges and their corresponding land area are tabulated in Table I.

TABLE I

Power Flux and Associated Land Area for Great Plains Wind Turbine Fields

Power Flux Range (W/m^2)	$\frac{1}{2} \rho \bar{V}^3$ (W/m^2)	A_L (km^2)	$\frac{1}{2} \rho \bar{V}^3 \cdot A_L$ (W/m^2)(km^2)
150-200	175	1.0×10^6	175×10^6
200-300	250	1.1×10^6	275×10^6
300-400	350	1.2×10^5	42×10^6
> 400	450	1.9×10^4	8.6×10^6
		2.24×10^6 *	500×10^6

*Land area of continental U. S. is $9.36 \times 10^6 \text{ km}^2$.

Substituting the results from Table I and Eq. (5) into Eq. (4) yields

$$E = (0.14) \left(\frac{\pi}{4M^2} \right) (500 \times 10^9) (8760)$$

$$= \frac{4.8 \times 10^{14}}{M^2} \text{ kW-hr/annum}. \quad (6)$$

The turbine spacing parameter (M) was intentionally retained as a variable because it is projected with the least amount of certainty. A spacing of 10 turbine diameters is probably reasonable. For this 10-diameter spacing, the annual energy output from a wind turbine field covering the entire Great Plains would be 4.8×10^{12} kW-hr. For comparison purposes, the 1973 United States electrical energy consumption was 1.849×10^{12} kW-hr, or 40 percent of the estimated wind energy available from the Great Plains.

The installed turbine systems will not always be able to produce electricity at their rated capacity because of the variability of the wind source. Typically, for a wind turbine in the Great Plains area, 2500 kW-hr/yr of electrical energy can be produced for each kW of installed capacity. This results in a load factor of only 29 percent of the full use at the maximum generating capacity. Therefore, the energy production of 4.8×10^{12} kW-hr would require an installed generating capacity of 1.9×10^6 MW. Large turbines of up to 100 m in diameter are being considered, and these systems would be rated at a capacity of over 1 MW. Consequently, it would take more than a million 1 MW-rated turbines to capture the wind energy available in the Great Plains. The United States generating capacity as of December 31, 1973, was 457,879 MW, which averages about 4000 kW-hr per installed kW. This higher load factor (46 percent) is a direct consequence of more nearly full use of the installed generating capacity of conventional power-production systems.

The wind-energy value of 4.8×10^{12} kW-hr represents a realistic upper limit, but will certainly never be fully utilized for several practical reasons. First, the land currently occupied by cities, farms, and natural obstacles will preclude 100-percent utilization of the land area in the Great Plains. Even a 10-percent land utilization, however, would still

produce a very large quantity of wind energy. Second, the demand for electrical energy will not always correspond to times when the wind blows. Consequently, if wind energy is used strictly as a fuel saver, not all of the available wind energy can be utilized (unless an energy storage scheme proves practical). Even if the wind-energy systems of today were more economical than fossil fuel or nuclear plants, the availability of capital for new plants would impose a limitation on the rate at which wind-energy systems could be installed. For example, if one assumed that the electrical generating capacity is growing by 4 percent annually and the installation costs are \$350/kW (coal-fired), the electrical utility industry would spend approximately \$6 billion annually on increasing generating capacity. For the potential Great Plains wind-generating capacity of 1.9×10^6 MW at a projected cost of \$500/kW, the total wind system cost would be \$950 billion. If construction costs were limited to \$6 billion annually, it would take 158 years to build windpower systems with a total installed capacity of 1.9×10^6 MW, which is somewhat unrealistic.

Let us look at the problem from a slightly different point of view. Assume that 25 percent of the \$6 billion annually goes for constructing wind turbine systems. This \$1.5 billion would purchase 3000 MW of wind turbine generating capacity annually and by the year 2000, a total of 75,000 MW of windpower generating capacity would be installed.

It appears that a more-than-adequate supply of windpower is available, but that the rate at which wind energy will be utilized is strongly dependent on the available capital for constructing wind-energy systems. As wind turbine systems become operational, the rate of implementation could be accelerated if fuel savings were utilized to install additional windpower generating capacity.

U. S. EFFORTS

Wind energy has provided an important service to the people of the U. S. in years past, especially in rural areas. Scores of local companies across the country produced their own versions of what is now universally known as the American windmill. For example, the 1922 Farm Light and Power Year Book lists 54 manufacturers of "windmill" pumps and wind-driven electric plants. The success of these devices is evidenced by the fact that 6.5-million wind-driven water pumps were manufactured to supply water for remote farms and ranches. Several suppliers have survived the waning sales of the past 40 or so years, and these companies have experienced an unexpected resurgence in their sales. New Mexico State University has recently offered a "windmill" course designed to reacquaint users of wind-pumping machines with the operation and maintenance of these devices.

The rural areas also provide the market for an estimated 50,000 wind/electric generators.⁴ These were self-contained (mainly DC) systems of modest generating capacities ranging from 200 to 3000 watts of output. Only one model, and the smallest (Win-charger 200 W) at that, has survived the slumping sales of recent years. Today, sales are increasing for both this device and those imported from other countries. (Several suppliers distribute wind/electric systems manufactured in Australia, France, and Switzerland.) There is usually a waiting time—sometimes almost a year—before the larger systems can be acquired.

There is general accord in the scientific community that harnessing of the wind is technically attainable. This has been demonstrated many times. In the western mountains of Vermont the largest wind turbine ever built was constructed in the early 1940's.⁶ A visionary named Palmer Putnam convinced the S. Morgan Smith Company (now a branch of Allis Chalmers) to finance the venture. The

completed colossus had a two-bladed stainless steel propeller 175 feet in diameter. Rated at 1.25 MW, it fed power into an existing AC power grid system of the Central Vermont Public Service Co. There were some technical problems—material and component shortages due to WW II, an over-estimate of the average windpower in the area, fabrication and analysis techniques that were (for that time) the limit of the state of the art—but the essential historical fact was that the system worked and worked well. The technical problems that beset the Smith-Putnam venture can be resolved by this era's scientific community. The major unanswered question in the minds of many is, "For what price?"

Recently, there has been an obvious resurgence in the efforts toward harnessing the energy in the wind. Many universities, various smaller profit- and nonprofit-oriented research organizations, and private individuals—together with such large aerospace companies as Lockheed, Grumman, Kaman, and Boeing—have entered the wind-conversion-technology arena. Others will surely follow. However, relatively few research groups in this hemisphere have much wind-turbine experience. Two exceptions are Oklahoma State University,⁷ which has had an active program in this area since 1960, and the Brace Research Institute of McGill University in Montreal, which has been a leader in developing and encouraging the use of small wind turbine systems, many of which could be produced by a home craftsman. Recently, however, there has evolved a profusion of university-sponsored organizations that pledge an attack on energy and/or environmental problems. Many newly formed private groups with similar goals are also striving for recognition.

Perhaps the "pump-primer" in this development has been the awareness that government financial sponsorship of energy-related research is sharply

expanding. The primary government arm concerned with fostering the wind-energy research efforts has been the National Science Foundation (NSF). Its funds for supporting wind-related research have climbed over the past 3 years from \$200,000 (FY 73) to \$1.5 million (FY 74) to \$7 million (FY 75).² The ambitious goals of Project Independence indicate that a much more intense level of federal support is imminent.

Initially, a major portion of the NSF wind-energy research funding has gone to the NASA Lewis Research Center for the design, fabrication, and testing of a 125-foot-diameter, two-bladed, variable-pitch, propeller system which will be mounted atop a 100-foot tower at the Plum Brook test area at Sandusky, Ohio.³ The purpose of this program is to establish a data base concerning the fabrication, performance, operating, and economic characteristics of propeller-type wind turbine systems. The main thrust of the NASA effort is toward furnishing power in commercial quantities; i. e., to the existing AC power grid.

Because of the alarming recent energy shortage and its subsequent effect on our internal economy and the turbulence displayed in international politics, the Congress has directed that a new national commission be formed. The Energy Research and Development Administration (ERDA) will assume some of the tasks now being undertaken by NSF, and the research and development efforts—especially concerning operational prototype systems—will be intensified. Because of the present uncertainties concerning the direction and support of wind-energy efforts from the national level, it is difficult to project a chronology of events. Once ERDA has been shaped and the division of efforts between it and NSF has been specified, the direction of such efforts will be more positive. The recently developed NSF plan is, however, sound and it is anticipated that the primary features of this plan (if not the timescale) will be retained.

The NSF/NASA efforts toward establishing a "baseline" design of a large propeller system will undoubtedly continue. Other "alternate concept" systems will probably be funded, and the support of the most promising ideas will be increased. An intense "wind prospecting" effort will continue and will progressively "zero in" on the best available wind turbine locations available to us.

Some advocates of wind turbines maintain that a nonconventional system that emphasizes lower cost (even while possibly sacrificing some operational efficiency) may replace the conventional propeller wind generator. Ironically, a similar argument led, in the 1920's, to replacement of the "Dutch-type" windmill by the thin propeller systems.

An example of the "new-technology" wind machines is the Chalk⁸ turbine, which appears at first glance to be a revival of the creaky but reliable "American windmill." At closer inspection, however, it is noted that the blades are not flat sheet-metal panels but are airfoil-shaped blades. This characteristic puts the Chalk turbines into the realm of the high-tip-speed devices; such association correlates with their being more efficient wind-energy converters. Material costs of wind turbines are critical because of the typically large sizes of such machines. For economic considerations, it is important that the turbine be fabricated as an extremely lightweight structure. The Chalk turbine resembles a huge bicycle wheel, with a thin sheet-metal airfoil placed over the "spokes" at the proper angle. The 15-foot-diameter prototype turbine "wheel" weighed only 70 pounds.

Another recent entry into the list of contenders against the propeller system is the high-speed Darrieus-type vertical-axis wind turbine.⁹ This system, resurrected from the technology of the 1920's, was studied first by the National Research Council (NRC)^{10,11} of Ottawa, Canada, and later by Sandia Laboratories and NASA-Langley. Further Darrieus turbine history is presented in Table II.

TABLE II
Darrieus Turbine History

PATENT

- APPLIED FOR IN FRANCE, 1925
- APPLIED FOR IN U.S., 1926
- GRANTED U.S. No. 1,835,018, 1931

PROTOTYPE FABRICATION

- NATIONAL RESEARCH COUNCIL, OTTAWA, CANADA, 1970
- NASA, LANGLEY, VA, 1973
- SANDIA, ALBUQUERQUE, NM, 1974
- TEXAS TECH, LUBBOCK, TX, 1975
- RESEARCH AND DESIGN INSTITUTE, PROVIDENCE, RI, 1975

DARRIEUS-TYPE VERTICAL-AXIS
WIND TURBINE

The vertical-axis wind turbine (VAWT) as proposed by Sandia Laboratories is actually a synthesis of two inventions of the 1920's: (1) the Darrieus⁹ wind turbine, with blades of symmetric airfoil cross section bowed outward at their mid-point and attached at both ends to a rotational axis perpendicular to the airstream (in this case, vertical) and (2) the Savonius¹² rotor or S-rotor, the two arcs of the "S" disjointed at their middle and overlapped, allowing air to flow through the passage. Again, the rotational axis is vertical. The S-rotors are located top and bottom on the vertical shaft to minimize air flow interference with the Darrieus blades; this is illustrated in Fig. 2, a photograph of the Sandia 15-foot-diameter test bed.

The Darrieus turbine is the primary power-producing device but, like other fixed-pitch high-performance systems, is not self-starting;¹³ the blades drive into the wind as a result of the high lift from the airfoil-shaped blades. The S-rotor is a self-starting device which is used primarily to drive the Darrieus airfoils up to the starting rotational speed, where the blade tip speed is about

3 times the wind speed. By controlling the relative sizes of the two rotors, it is practical to use the S-rotor to "start" the primary rotor and to provide driving torque (power) at the design maximum power production rotational speed.¹⁴

Fig. 2. Photograph of the Sandia 15-Foot-Diameter Test Bed

Although the wind-energy conversion efficiency of the Darrieus rotor is about the same as that of a high-performance horizontal-axis propeller system,¹⁰ the potential advantages of the VAWT are lower fabrication costs and functional simplicity.¹¹ The most significant indication of comparative cost is from NRC of Canada, whose research showed that its Darrieus turbine weighed from

4 to 10 times less than typical horizontal-axis systems equivalent in size. NRC estimates that the installed cost of a VAWT may be as low as one-sixth that of a conventional horizontal-axis system.¹¹ Current cost estimates of large horizontal-axis systems are approximately \$1000/kW, with \$500/kW as the design goal. This estimate is compared (Table III) with previous wind turbine project economic data as well as present installed costs for coal and nuclear generating plants.

TABLE III
Wind Generator Economics*

INSTALLED COSTS OF GENERATING PLANTS				
•	COAL	\$350/kW	1974	
•	NUCLEAR	\$500-\$700	1974	
•	WIND			
•	SMITH-PUTNAM	\$190/kW	1941-45	(1.25 MW)
•	JACOBS	\$400/kW	1957	(3 kW)
•	NSF GOALS	\$1000/kW	1975	(100 kW)
		\$500/kW	1980	
COSTS OF DELIVERED ELECTRICAL ENERGY				
•	1.7¢/kWh	INDUSTRY	1974	
•	2.5¢/kWh	RESIDENTIAL & COMMERCIAL	1974	
COSTS OF SUPPLYING WIND ENERGY				
•	SMITH-PUTNAM	175 FT DIA	0.7¢/kWh	1941-1945
•	NRC	15-FT-DIAM VAWT	1¢-3¢/kWh	1974

* ALL COSTS SHOWN ARE IN DOLLARS FOR THE YEAR LISTED.

The cost-effective weight savings is a direct result of the simplicity of the system. The VAWT, which can accept wind equally well from any direction, needs no costly "heading-into-the-wind" mechanism. The VAWT tower costs are minimized, as the tower need be only a low and small structure which also contains the generator. Having the generator on the ground yields two substantial advantages: (1) ease of erecting and maintaining the system; (2) less weight aloft (precluding the greater expense of a rigid, heavy tower structure, usually required to minimize the vibrational loads). The VAWT side-wind loads can

be accommodated by guy cables attached to the upper bearing fixture.

Blade costs can represent up to 40-50 percent of the total cost of a large, conventional high-performance prototype propeller system. For production quantities, this cost may be reduced somewhat. The VAWT power blades should be significantly lower in cost because of their unique loading. The bending stresses are eliminated, and the primary loads are centrifugal forces resulting in tension along the major blade axis. With the crippling bending loads eliminated, a much lighter structure can be designed. Blade fabrication costs can be further reduced by the usually expensive compound curve fabrication being minimized. There is no twist in the airfoil from end to end and also no taper.

The shape to which the Darrieus airfoils should conform was examined by Darrieus, as well as by present-day researchers. The Darrieus patent statement⁸ indicates that each blade should "have a stream-line outline curved in the form of a skipping rope." This "skipping rope" shape, described mathematically by Blackwell and Reis,¹⁵ has been given the name troposkien (from the Greek: τροπος, turning, and σχολιον, rope). Another result disclosed by this study is that the troposkien shape is independent of rotational speed. If the blades are curved in the troposkien shape during fabrication, rotation will not cause the blades to deform as a result of bending loads and thus the stresses will be pure tension.

Primarily because of the unique blade loading, it appears that the vertical-axis wind turbine will be relatively easy to scale up structurally. The blades are not cantilevered; they have two attachment points rather than one. Because of the tension-only loading, it will be possible to "tailor"

the natural vibration frequency of the blade in a manner to promote longevity of operation.

Note from Fig. 2 that each of the blades of the Sandia prototype turbine is made in three sections. The two end sections are straight and are formed into a low-drag cross section from sheet metal; the center curved section is a NACA 0012 airfoil, which produces the majority of the driving torque. Although this zone occupies only 55 percent of the total height of the turbine, it produces over 90 percent of the turbine torque. Sectioning the blade in this way minimizes the exacting manufacturing requirements for the airfoil blade portion.

The tensile-only stresses in the blade permit a wide variety of manufacturing methods to be considered. The method selected for the Sandia prototype is shown in Fig. 3. First, the center load-carrying steel strap was rolled to the desired arc and the end fixture was attached. Next, foam halves, machined to the airfoil contour, were bonded to this strap. A skin of fiberglass (three layers of cloth) was applied to the finished airfoil shape. The cured structure was smoothed and finish coated with several layers of abrasion-resistant polyurethane paint.

Fig. 3. Photograph of Darrieus Blade Cross Section

Because of the uniqueness of the VAWT, specifically the Darrieus turbine, a brief explanation of its functioning is intriguing to most. Consider

that a vertical section (at a maximum turbine diameter) of the blade has achieved a "running" condition; i.e., the blade speed ($R\omega$) to wind-speed (V) ratio is 3 or greater. Figure 4 is a pictorial representation of this condition (with the rotational position of the blade frozen at position θ for an instant).

The flow the airfoil "sees" is a combination of the windspeed (V), and its own rotational speed (direction reversed) ($-R\omega$). The addition of these two vectors is the relative wind vector (W), which is at an angle (α) with respect to the chord line (the centerline of the airfoil) for this particular rotational position (θ). Angle α is termed the angle of attack and is important in describing aerodynamic behavior of wings or airfoils.

Fig. 4. Aerodynamic Forces Acting on a Rotating Airfoil

When a fluid flows over an airfoil, forces are exerted on the airfoil. These forces are generally resolved into lift and drag components; the drag force is colinear with the relative wind vector (W) and the lift force is perpendicular to W . A general characteristic of airfoil behavior is that the lift-to-drag (L/D) ratio increases with increasing angle of attack up to the point where the fluid flow begins to separate from the airfoil. (Flow separation from the airfoil is termed stall.) Once the angle of attack is sufficiently large to cause stall, the lift-to-drag ratio decreases with increasing angle of attack. For optimum aerodynamic performance, the stalled condition must be avoided.

The forces that cause rotation are determined by projecting onto the chord line the lift force (L) and the drag force (D). For a well-designed airfoil, the lift-to-drag ratio can be as high as 20 to 1. The chordwise component of the lift force tends to cause rotation in the counterclockwise sense, and the chordwise component of the drag force opposes this motion. As long as the chordwise lift force is greater than the chordwise drag force, the driving torque will be positive. The condition described is constantly changing as the airfoil traverses a complete revolution about its rotation axis. This is because the angle of attack (α) depends on the relative magnitude of the tip speed versus the windspeed and on the blade position angle (θ). This is shown in Figure 5. If it is assumed that the windspeed and tip speed remain constant, the angle of attack is dependent solely on the blade position angle (θ). If the tip-speed ratio is sufficiently high, the angle of attack is sufficiently small to completely avoid stall during a revolution.

Figure 6 presents the normalized torque developed by a single blade traversing one complete revolution and operating at an optimum $R\omega/V$ ratio. Note that the torque is constantly changing, being maximum when the blades are broadside to the wind vector (V) on both the upwind side as well as on the

downwind side of each revolution. The torque also becomes slightly negative in the two positions where the blade is driving directly into or away from the true wind direction (V). Having a variable torque is considered a disadvantage of the VAWT, but this effect can be minimized by incorporating three blades into the design.

Fig. 5. Angle-of-Attack Variation for Vertical Axis Wind Turbine Blade (Symmetry)

Fig. 6. Variation of Torque with Rotational Angle for a Darrieus Wind Turbine with Various Numbers of Blades

The torque variation for a three-bladed rotor can be obtained by superimposing three torque curves for single blades, but with each curve displaced 120° from its neighbor. The resulting shaft torque variation for a three-bladed rotor (Fig. 5) is only of the order of 2 percent. This torque variation will cause a negligible variation in rotor speed because of the inertia of the rotor. The smoothing of the torque curve by use of three blades is analogous to the three-phasing of electrical power to smooth out power pulsations.

The aerodynamic performance is poor at the high angles of attack common to low rotational speeds because of the airfoil stall phenomenon. The performance is also poor at high relative rotational speeds, but for an entirely different reason. As $R\omega/V$ increases, the angle of attack (α) decreases. As can be seen from Fig. 4, if α becomes very small, the chordwise component of the lift also becomes small whereas the drag component may increase. In addition, the lift goes to zero at zero angle of attack for a symmetrical airfoil.

From the above discussion, a composite picture of the Darrieus turbine performance can be envisioned: Poor performance occurs at both low and high relative rotational speeds; the best performance occurs at intermediate values of $R\omega/V$ because the angle of attack is sufficiently large to develop significant chordwise lift, but not large enough to cause stall.

Figure 7 illustrates the above behavior in graphical form. The efficiency of a Darrieus turbine is comparable to that of a conventional (propeller) wind turbine; i.e., about 40 percent of the available wind stream energy can be converted to useful torque. The Darrieus turbine efficiency is greater than that of the starter system used in the compound VAWT; however, the starter must be used to accelerate the Darrieus blades through the stall zone characteristic of low tip speed ratios. The starter can be radially

sized so that it and the Darrieus blades can achieve their maximum efficiency simultaneously. This allows the starter buckets to be permanently attached (no clutch-type disengagement is required) to the same shaft as the Darrieus blades. The starter buckets will then continue to provide useful torque after starting the Darrieus blades.

Fig. 7. Performance Characteristics of Darrieus and Savonius Rotors

Future Sandia plans include performance evaluation of the existing 15-foot test bed and wind tunnel tests of various Darrieus and Savonius rotors. The next step will be to design and fabricate a larger (35 feet in diameter) vertical-axis turbine.

SUMMARY

The present state of wind-energy development work has been reviewed. [This work is currently being funded by NSF, but it appears that the majority of this responsibility will be transferred to the newly formed ERDA.] An estimate of the wind-energy availability in the Great Plains area of the U. S. was presented. It was shown that the usable

wind energy available is greater than the 1973 total U. S. electrical energy consumption and that a probable factor limiting wind-energy utilization will be availability of capital for new equipment. As a result of the detailed research of Sandia and others involving the Darrieus-type vertical-axis wind turbine, it is believed that the reduced weight and unique blade loading for this turbine appear to offer considerable potential economic advantages over propeller systems.

The U. S. possesses the technical wherewithal to establish wind-energy conversion systems as significant contributors to our future energy needs. The results of wind-energy conversion are probably nearer to massive utilization than any other "clean" methods now being promoted. Present and projected economic considerations indicate that wind energy can play a substantial role in achieving the goals of Project Independence and should receive significant and sustained government support.

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