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UNDERSTANDING WIND ENERGY

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PREFACE

This paper is one of a series published by Volunteers in Technical Assistance to provide an introduction to specific state-of-the-art technologies of interest to people in developing countries. The papers are intended to be used as guidelines to help people choose technologies that are suitable to their situations. They are not intended to provide construction or implementation details. People are urged to contact VITA or a similar organization for further information and technical assistance if they find that a particular technology seems to meet their needs.

The papers in the series were written, reviewed, and illustrated almost entirely by VITA Volunteer technical experts on a purely voluntary basis. Some 500 volunteers were involved in the production of the first 100 titles issued, contributing approximately 5,000 hours of their time. VITA staff included Leslie Gottschalk and Maria Giannuzzi as editors, Julie Berman handling typesetting and layout, and Margaret Crouch as project manager.

The authors of this paper, Dr. James F. Manwell and Dr. Duane E. Cromack, are professors with the Department of Mechanical Engineering at the University of Massachusetts. Dr. Manwell also has background in solar energy, hydropower, thermodynamics, and electrical and computer engineering. Dr. Cromack has consulted for the U.S. Government and private industries in wind energy. Christopher Schmidt is a professional illustrator in the fine arts, technical, and medical areas, and attends the Pacific Northwest College of Art. He illustrated VITA's Renewable Energy Dictionary. Theodore Alt, P.E., is a mechanical engineer who has been in the energy field since 1942. He has worked with the energy research and development group of the Arizona Public Service Company and the Government of Mexico's electric commission. Christopher Turner monitors and disseminates information about appropriate technology, and has worked with wind energy in North Carolina. Christopher Weaver is an engineer with Energy and Resource Consultants, Inc. in Colorado. He has written two technical papers for VITA on hydroelectric generation.

VITA is a private, nonprofit organization that supports people working on technical problems in developing countries. VITA offers information and assistance aimed at helping individuals and groups to select and implement technologies appropriate to their situations. VITA maintains an international Inquiry Service, a specialized documentation center, and a computerized roster of volunteer technical consultants; manages long-term field projects; and publishes a variety of technical manuals and papers.

UNDERSTANDING WIND ENERGY

By VITA Volunteers James F. Manwell and Duane E. Cromack

I. INTRODUCTION

The sun is the original source of wind energy. Sunlight warms the sea, land, and mountains at different rates. This creates inequalities in the temperature of the earth's atmosphere. These thermal imbalances produce air in motion--or wind. Wind machines capture the energy of the wind and convert this energy into mechanical motion or electricity.

The typical wind machine consists of a rotor or turbine, which are usually mounted upon a tower. The wind rotates the turbine or rotor, which turns the shaft of an electrical generator or a mechanical device. If the wind system produces electricity, the electrical power may be used immediately or stored in batteries for later use.

THE HISTORY OF WIND POWER

The use of wind power is almost as old as recorded history. The Egyptians used sails to power their boats on the Nile River over 5,000 years ago. The Chinese are thought to have been the first to use windmills, and the Persians are known to have built windmills in 200 B.C. The Persian vertical shaft windmill, or "panemone," was used to power grain-grinding stones. Medieval Europeans used windmills for a wide range of activities, including pumping water, sawing wood, grinding grain, and pressing oil--in fact virtually any process that required mechanical energy. The traditional windmill was developed to its greatest extent by the Dutch, who used windmills by the thousands (Figure 1).

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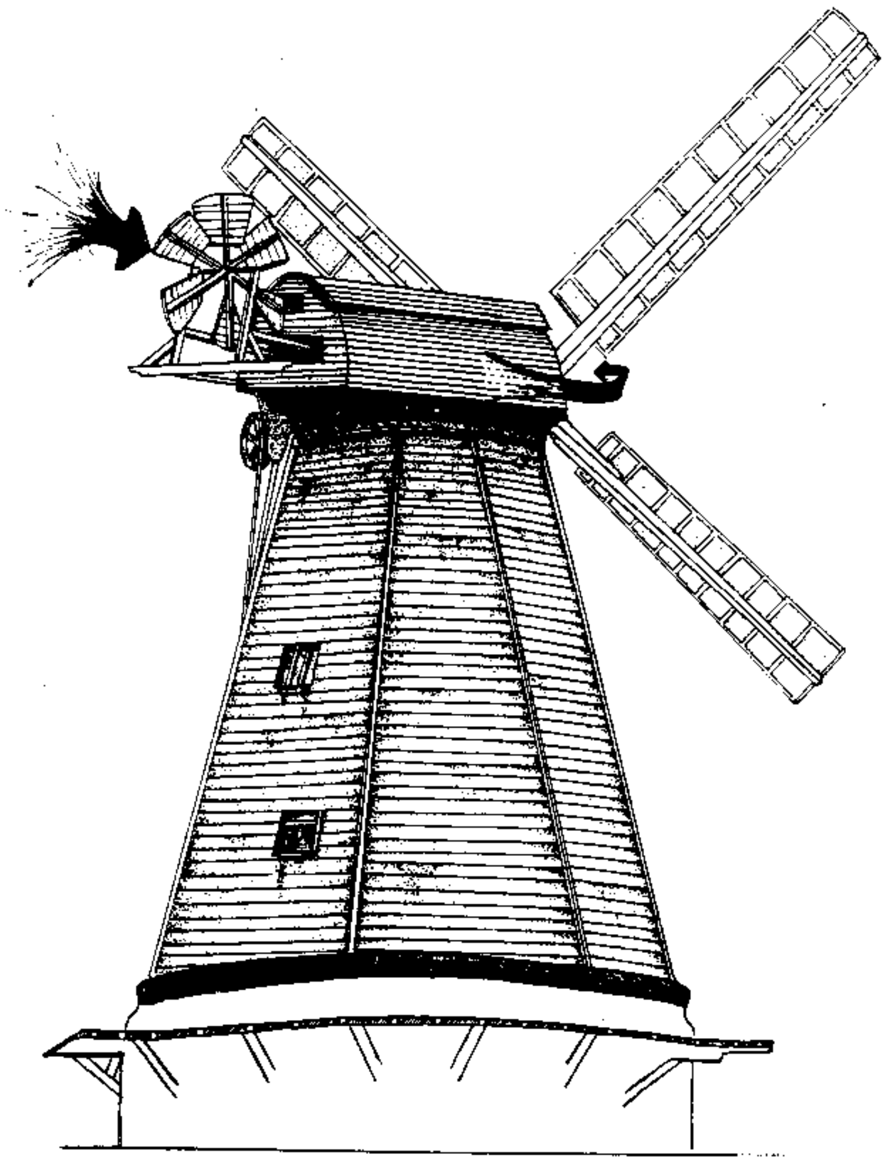

Figure 1. A Dutch Windmill

Early European windmills were of the "post mill" type (Figure 2).

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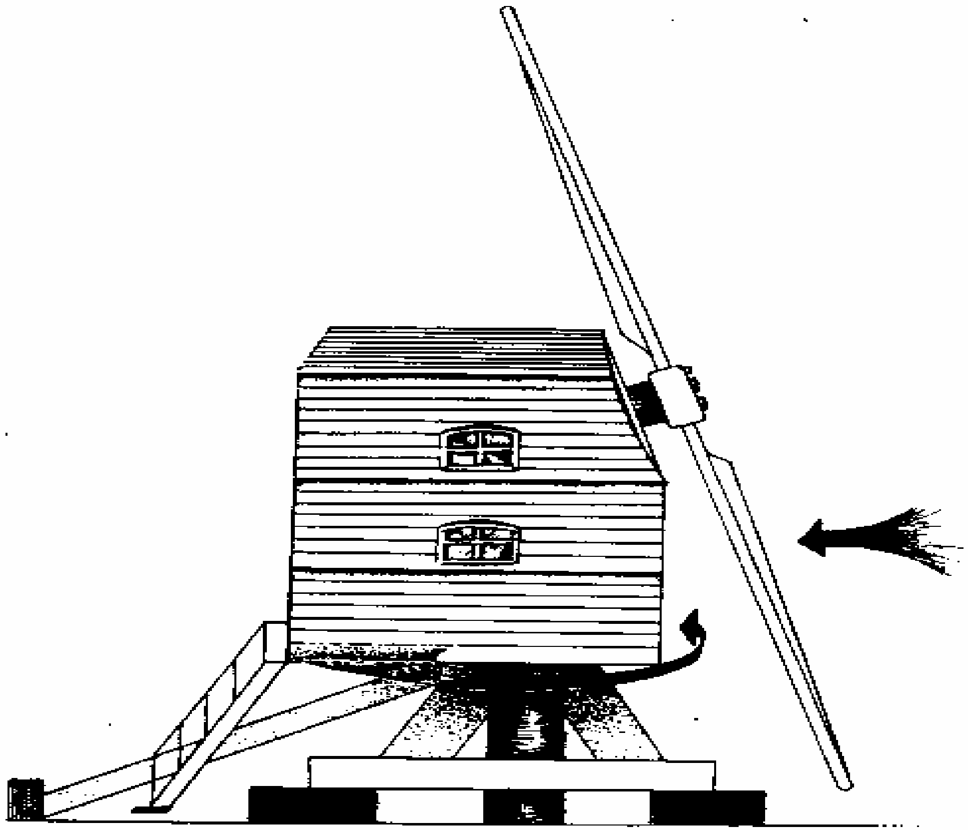

Figure 2. A European Post Mill

The entire machine was mounted on a post, and the mill itself was built around the post. The post, supported on the ground, served as a pivot for turning the mill so that it could be faced into the wind, or "yawed." Subsequent mills were of the "cap design."

In this case only the top, or cap, of the mill, which held the blades, was turned to face the wind. Until the 1750s, millers had to turn the machine by hand to face the wind. After that period, the invention of the fantail--a small windmill mounted at right angles to the main blades--allowed the machines to be yawed automatically (Figure 3).

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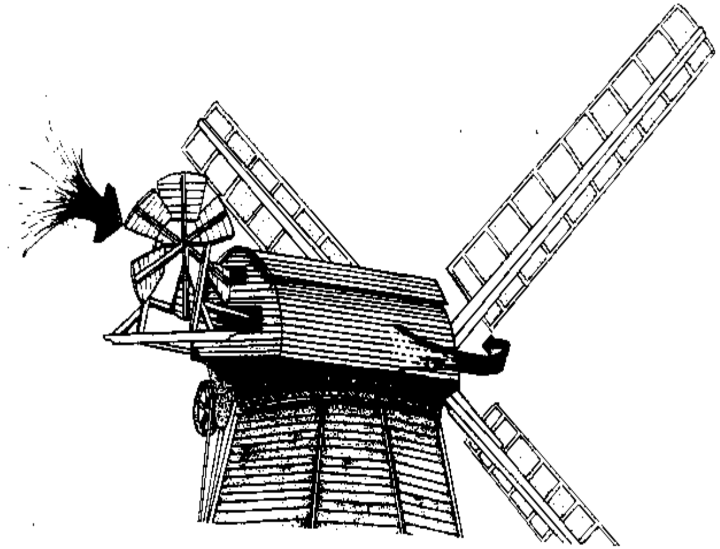

Figure 3. A Dutch Windmill with Fantail

A new era for windmills began in the late 1800s in the United States. The settling of the semi-arid western United States required the use of water, which had to be pumped out of the ground. The American multibladed farm windmill (Figure 4) was

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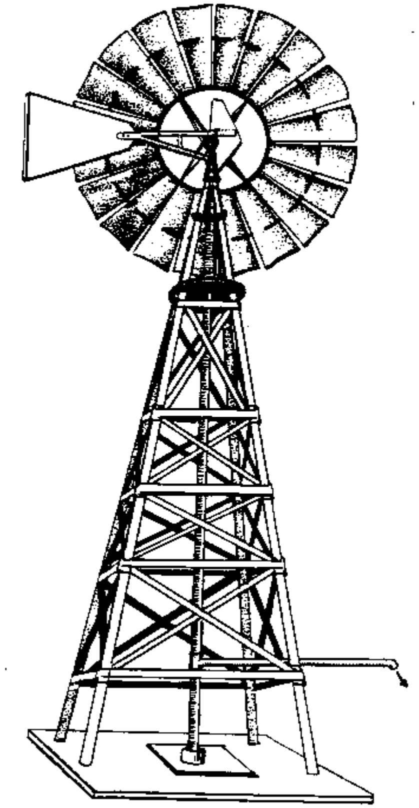

Figure 4. An American Farm Windmill

developed around that time to provide pumping power. At one time, hundreds of thousands of these machines were in use. They have been largely replaced today, but in many parts of the world they are still used.

Near the beginning of the 20th century, the Danes first used wind power to generate electricity (Figure 5). The new wind generators

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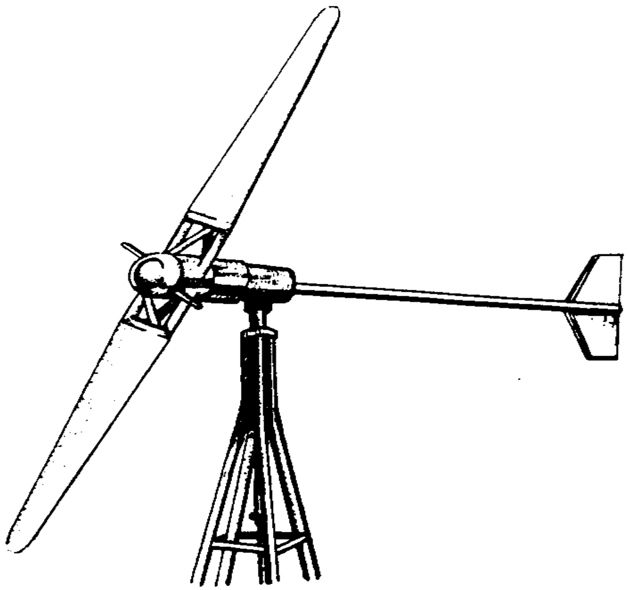

Figure 5. An Electric Generator

found an active market in the American Great Plains, which already had its wind-driven water pumpers in place. The new machines usually had an electrical output of less than 1,000 watts, which was adequate to provide lighting and power for small appliances. After the major U.S. rural electrification program had begun in the 1930s, these wind machines could not compete with cheap, reliable utility power and most of them were abandoned.

Nevertheless, some development in wind power continued into the 1950s, mostly on machines capable of much larger electrical output. The Danes, Russians, British, French, and Americans all experimented with wind machines that could produce 100 kilowatts (kW) or more. By the early 1960s, however, interest in wind power as a viable source of power production had waned, because other energy sources appeared to make it obsolete. During the 1970s many people realized that fossil fuels were not renewable and were subject to interruption and that nuclear power was not as reliable and inexpensive as some people had imagined. People once again turned to wind power as an alternative to some of those unexpected problems.

Since the mid-1970s a number of countries have begun major programs to develop modern wind systems. Some of the programs have focused on large-scale power generation, others on medium-scale systems for commercial use, and still others on improved "intermediate technology" devices, most suitable to Third world applications.

WIND POWER: NEEDS IT SERVES

Wind power provides for two basic types of needs: (1) For remote applications, where an electricity grid (supply) is not available or the need is for mechanical power such as water pumping, wind can serve the function quite well, provided an adequate wind source is available. (2) In other areas, where electricity grids are available, wind power can serve as an alternative to conventional forms of power generation. It can help to decrease the amount of purchased fuel and replace some of the conventional generating capacity.

Where surface water is scarce and there is adequate wind, wind machines are a reliable and economical way to pump water from deep or shallow wells for isolated ranches, villages, and farms.

Wind power can provide water for irrigation, drinking supplies, livestock, and other uses. Wind power can also be harnessed to provide power for grinding grain and sawmill operations.

For sites not connected to an electric grid, wind machines can generate electricity for pumping water, grinding grain, heating homes, running appliances, and lighting. In those areas where utility service is already available, wind power can contribute to the operation of lights, electric stoves, air conditioners, and other appliances. In some applications, wind power may also provide heat for warming homes and water.

II. BASIC WINDMILL THEORY

POWER IN THE WIND

Wind is air in motion. As such, it possesses energy. A windmill operates by slowing down the wind and capturing some of its energy in the process. Consider an area A([m.sup.2]) perpendicular to the wind direction. If the wind, with density p (kg/[m.sup.3]), flows through it with a velocity V(m/s), the power (watts) in the wind is given by:

P = 1/2p[AV.sup.3]

This equation summarizes the following key facts:

(1) The power varies directly as does the density. It should also be noted that the density decreases with

increasing temperature and decreasing atmospheric pressure (e.g., caused by increasing altitude). At sea level and 15 [degrees] C, p = 1.225 kg/[m.sup.3]. Under other conditions, the density is given by p = .464 P(mm Hg)/ (T([degrees] C) + 273).

(2) For a horizontal axis windmill of radius R, the power is proportional to A = [pi] [R.sup.2].

(3) The power varies with the cube of the wind speed. This means that the power increases by a factor of eight when the wind speed doubles.

ACTUAL POWER

A windmill cannot extract all the power in the wind. Theoretically, a wind machine rotor can extract at most 59.3 percent of the power. Other factors contribute to even greater decreases in efficiency. Typical rotor efficiencies, called power coefficients, or Cp, range from 20 to 40 percent.

BASIC WIND MACHINE DESIGN

Most wind machines operate through the use of sails, blades, or buckets connected to a central shaft. The extracted wind energy causes the shaft to rotate. This rotating shaft can be used to drive a pump, power a generator or compressor, or do other work.

Two aerodynamic principles come into play in wind-machine operation:

lift and drag. The wind can rotate the rotor of a wind machine by pushing against it (drag) or by lifting the blades (aerodynamic lift). Wind drag is the force you feel when you turn the palm of your hand into a strong wind. Drag is the primary motive force in some slow-speed machines such as the Savonius rotor (Figure 6).

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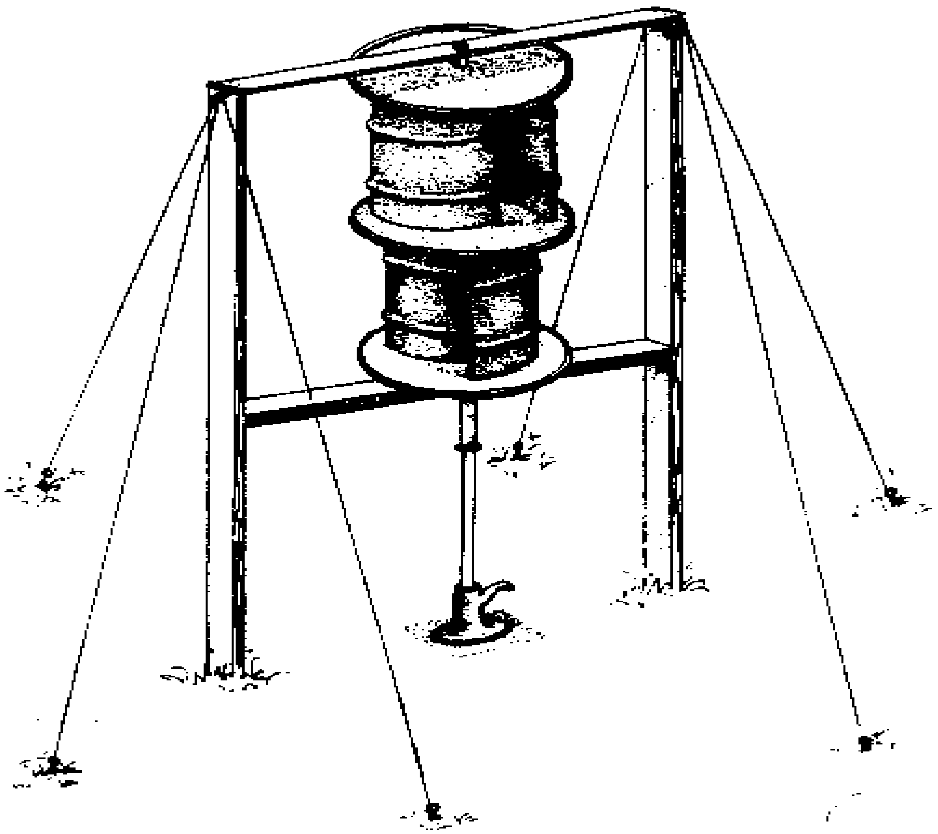

Figure 6. A Savonius Rotor

A common example of aerodynamic lift is the force that acts on the wings of an airplane. Airplane wings have a special shape called an airfoil (Figure 7). The airfoil produces a low pressure

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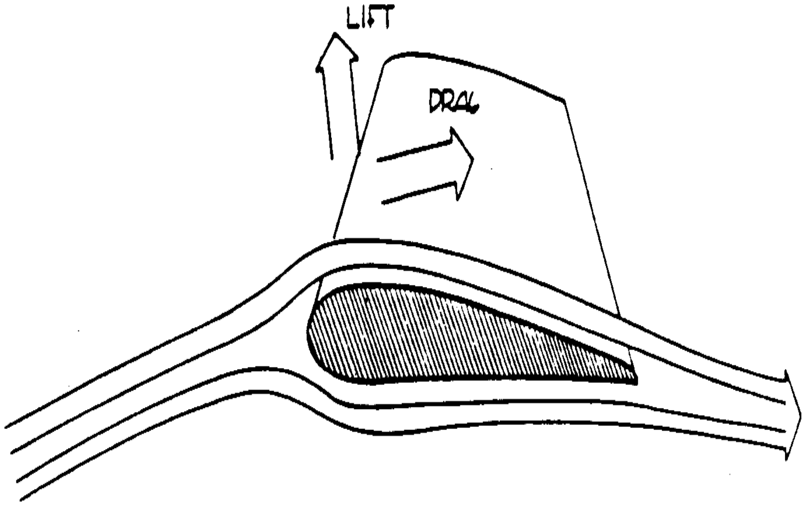

Figure 7. An Airfoil

Source: Jack Park and Dick Schwind, Wind Power for Farms, Homes and Small Industry, (Mountain View, California: Nielsen Engineering & Research Inc., 1977), p. 9.

area above the wing and a high pressure area beneath it as the airplane flies. The difference in pressure between the top and bottom of the wing actually lifts the plane and keeps it in the air.

Lift force is used on most wind machines today, whether they are the relatively slow, multibladed water pumpers, or the high-speed two- or three-bladed electric generators.

The blades of most present day wind generators are, in effect, airfoils. When the wind hits these blades the pressure difference lifts the blade and allows it to move with great speed and

efficiency. Any drag force on the blades decreases power production. The relationship of the blade speed (measured at the tip) to the wind speed is the tip speed ratio. If the blades are moving five times faster than the wind, the tip speed ratio is 5:1. Tip speed ratios are typically in the range of one to six. Drag machines always have a tip speed ratio of less than one.

The higher the design tip speed ratio, the lower is the required ratio of total blade area to swept area (called solidity). For electric power generation, the trend is toward higher tip speed ratios, both because high rotational speeds are required at the generator and because fewer blades are needed so relative costs are less. In addition, higher power coefficients are obtainable at the higher tip speed ratios.

A high tip speed ratio is not always desirable, however. Power is the product of torque ("twisting force") and rotational speed. Thus, low-speed machines have relatively high torque compared with high-speed machines. In particular, fast machines have very poor starting torque characteristics.

For many mechanical applications, such as water pumping, high torque is of primary importance. Thus, machines used for those purposes tend to be slower, higher-solidity machines. Although these machines do require a relatively greater blade area, because of their lower speed the blade shapes can be simpler. For example, slower machines can use sails or curved flat plates effectively, whereas faster machines need more streamlined blade shapes to minimize the adverse effects of drag.

An important consideration in any wind machine design is structural integrity. The forces that give rise to the torque and hence power also have components parallel to the wind direction. These forces contribute to the bending of the blades and a thrust that tends to push the machines over. The thrust force is given by:

[F.sub.T] = [C.sub.T]1/2p[AV.sup.2]

Under ideal conditions, [C.sub.T] = 8/9. The machine and tower are usually designed to withstand at least four times the force that would be produced when the machine is operated at its greatest output. The thrust force is distributed equally over the blades, and for blade design purposes can be assumed to act at two thirds of the way out on the blade from the hub.

WIND CHARACTERISTICS

The essential characteristic of the wind is its variability. The power output of a wind machine will vary accordingly. Average wind speeds vary from place to place. They also vary with the time of day and with the seasons. The average wind speed normally increases with height above the ground. For example, each time the height above ground is doubled (e.g., from 10 m to 20 m), the wind speed increases by at least 10 percent, which increases the available power by 30 percent.

The most important measure of a site's potential for wind power

is the annual average wind speed. For example, sites with mean wind speeds less than 3 m/s are seldom good sites. Those with averages above 3 to 4 m/s may be feasible, depending on the application and the cost of other forms of energy. Sites with averages in the range of 6.5 to 8 m/s or higher are excellent candidates for wind power development. At any prospective site, however, it is important to consider the seasonal and diurnal (time of day) wind speed variations and ensure that they are compatible with the load.

Nearby weather stations can provide data on wind speed. In flat terrain, readings from the three or four closest stations will provide a rough estimate of average wind speed. In mountainous areas the wind speed is more site-specific and requires more detailed analysis.

To determine the wind resourse at a proposed site, the following information should be obtained: monthly mean wind speed; frequency distribution of wind speed (the percent of time the wind speed blows at a given strength); and daily variation of wind speed. The monthly mean wind speed will indicate if power will be available when most needed. It will also help determine the kind of turbine that is needed. The frequency distribution of wind speed and direction will provide an estimate of potential power and help to identify the best location for a wind system. The daily variation of wind speed will tell the likelihood that power will be available at those times during the day when it is most needed.

If these data are available, an anemometer, or wind sensor, should be used to obtain readings on or near the proposed site. The hand-held type is the least expensive and is usually available in outdoor and aircraft supply stores. Although it does not average the wind speed, it will give a rough idea of the wind resource. A cup anemometer can be set up and left alone to measure wind speed (See Figure 8).

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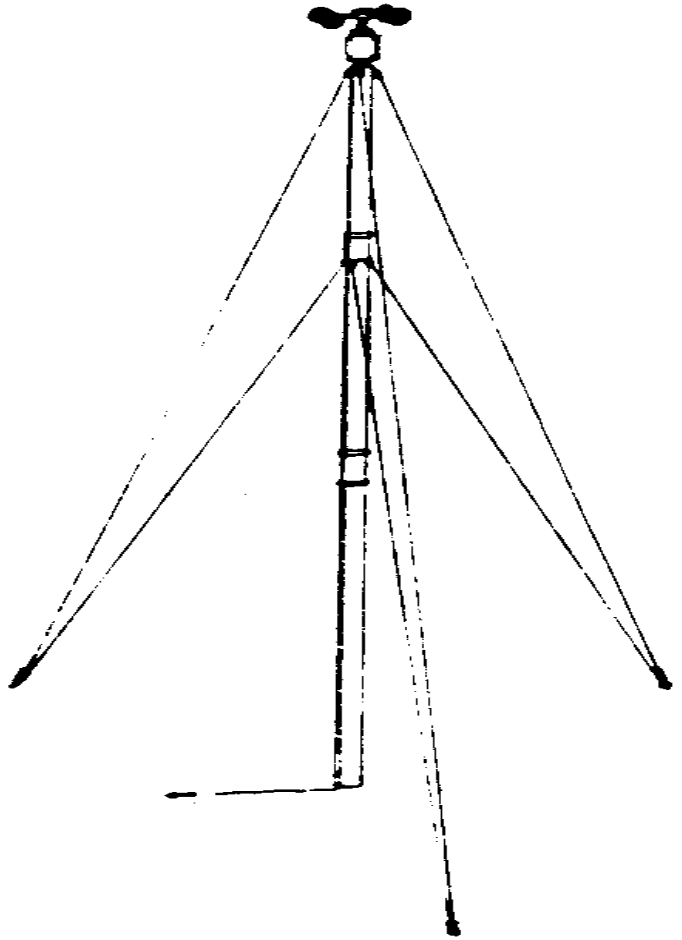

Figure 8. A Cup Anemometer

Wind characteristics are best analyzed by taking hourly wind speed data at a site for at least 12 months. When that is not possible, data may be taken for a shorter period, and then compared with data from another, nearby site, such as an airport, for which long-term data are available. When complete data are available these are often summarized in velocity and power duration curves, which can then be used in estimating energy production for various wind machine designs. If only summary data are available, such as mean wind speeds, a variety of statistical techniques have been developed that make it easier to determine the amount of wind resources available.

Often, no data are available for a particular site. In this case, the shapes of bushes and trees can give an indication of the wind resource at a given site. Bushes will generally be shorter in locations with strong winds. Trees will have off-center crowns and trunks, and branches will be swept leeward.
Other environmental indicators of strong winds may include sand scours and crescent-shaped sand dunes. These indicators will be particularly prevalent if the wind direction is relatively constant.

WIND MACHINE OPERATING CHARACTERISTICS

The operation of a wind machine as well as its power output depends on the wind speed. There are four important wind speed ranges to consider. In the first range, when the wind is less than the cut-in speed, no power is produced. The wind machine may rotate at these low speeds, but it would not be performing useful work. In the second range, between the cut-in speed and the rated wind speed, useful power will be produced. The amount of power will depend on the wind speed. In a machine optimally matched to wind speed variations, the power output will vary directly as the available power in the wind, i.e., as the cube of the wind speed. For most machines, however, the relation is usually less than cubic. In the third range, where the wind is above the rated speed, but less than the cut-out wind speed, power output is usually constant, at rated power. Partially furling the blades (pitching them out of the wind) or moving the rotor out of the wind prevents more power from being produced. Above the cut-out speed, the machine is totally shut down and remains so until the wind speed decreases back to the normal operating range. The operating characteristics are usually summarized in a power versus wind speed curve.

III. DESIGN VARIATIONS OF WIND ENERGY SYSTEMS

PHYSICAL CHARACTERISTICS

Wind energy systems include the following major components: rotor, hub assembly, main shaft, main frame, transmission, yaw mechanism, overspeed protection, electric generator, nacelle, power conditioning equipment, and tower.

Rotor

High-speed wind machine rotors usually have blades with a cross section like that of an airplane wing (airfoil). The blades are usually made of wood (solid or laminated), fiber glass, or metal. Slower machines usually use flat or curved metal plates or sails mounted on a spar (See Figures 9, 10, and 11).

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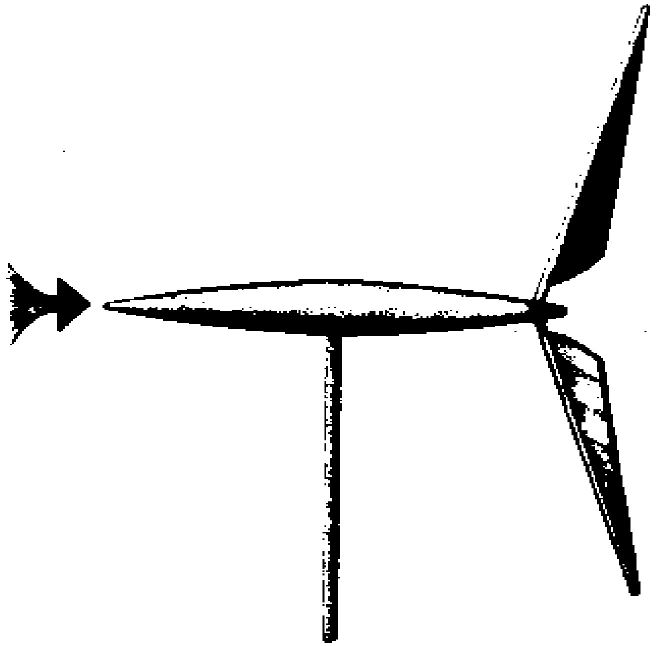

Figure 9. Rotor Placed Downwind

Hub Assembly and Main Shaft

The blades are attached by a hub assembly to a main shaft. The main shaft rotates in bearings supported in the main frame. If the blades are designed to rotate (pitch control), the hub can be fairly intricate. With fixed pitch, attachment is relatively simple.

Main Frame with Support Bearings

The main frame of the wind machine serves as the point of attachment for various components, such as the main shaft, transmission, generator, and nacelle. It usually contains a yaw bearing assembly as well.

Transmission Mechanism

A transmission assembly (gear box, chain drive, or the like) is required to properly match the rotational speed to the desired speed of a water pump, electric generator, or air compressor because the rotational speed of the wind wheel (rotor) does not match that of the pump or generator to which it is to be connected.

Yaw Mechanism

Horizontal axis machines must be oriented to face the wind by a process called yawing. Upwind machines (those with blades upwind of the tower) usually incorporate a tail vane, small yaw rotors (fantails), or a servo mechanism to ensure that the machine always faces upwind. Downwind machines (blades downwind of the tower) often have the blades tilted slightly downwind (coned) so that they also act as a tail; this angle ensures proper orientation. Vertical axis machines accept wind from any direction; thus, they do not need a yaw control (See Figure 12).

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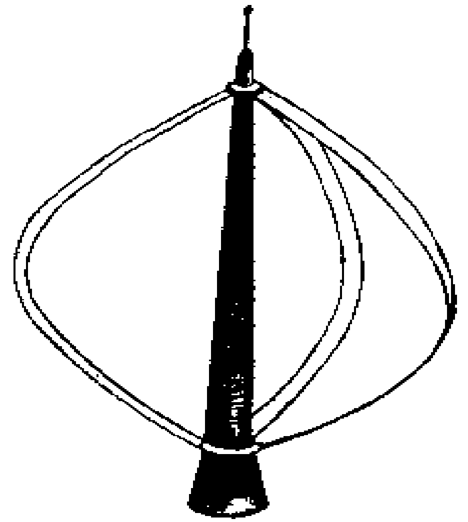

Figure 12. A Darrieus Rotor

Overspeed Protection

All wind machines must be protected from high winds. A number of different methods are used. In some machines, the blades can be turned around their long axis (pitch control) and aligned so that they do not produce any lift, hence no power. Blades with fixed pitch often use brakes to slow the machine. The brakes are either aerodynamic (e.g., tip brakes) or mechanical (e.g., disc brakes on the main shaft). Other machines use various mechanical means to turn the rotor out of the wind.

Electric Generator

The electric generator is attached to the main support frame and coupled to the high-speed end of the transmission shaft. Alternating current generators often run at 1,800 rpm in the United States or 1,500 rpm in much of the world to maintain system frequencies of 60 Hz and 50 Hz, respectively.

The most popular types are:

1. For small independent wind systems, direct current (DC) generator alternators with built-in rectifier diodes are often used to change AC to DC.

2. For larger independent systems, or those that may be run in conjunction with a small diesel electric grid, synchronous generators are common. These machines produce alternating current (AC) and must be able to be regulated precisely, to ensure proper frequency control and matching.

3. Wind machines connected to a utility grid may have induction generators. These induction machines produce AC current, but are electrically much simpler to connect to a grid than a synchronous generator. They normally require a utility connection to maintain the proper frequency and cannot operate independently without special equipment.

Electric Power Conditioning Equipment

The need for electrical equipment in addition to the generator will depend primarily on the type of generator. For small DC systems, at least a voltage regulator is needed. Battery storage is often used to provide energy in times of low winds. Sometimes, an inverter (to convert DC to AC) is used if some of the load requires alternating current. For grid-connected systems, a control panel is needed that will typically include circuit breakers, voltage relays, and reverse power relays. Synchronous machines require special synchronizing equipment and frequency relays.

Nacelle

The nacelle is the housing that protects the main frame and the components attached to it. This enclosure is particularly important for wind electric systems, but is often left out in water pumpers.

Tower

A tower or other support structure is needed to get the wind machine up into the air, away from the slower and more turbulent winds near the ground. A wind machine should be at least 10 m higher than any obstructions in the surroundings, such as trees. Towers are typically of truss design or of poles supported by guy wires. Guy wires are cables attached to the tower and anchored in the ground so that the tower will not move or shake from the force of the wind. Towers must be designed to resist the full thrust produced by an operating windmill or a stationary wind machine in a storm. Special concern must be given to the possibility

of destructive vibrations caused by a mismatch of wind machine and tower (See Figure 13).

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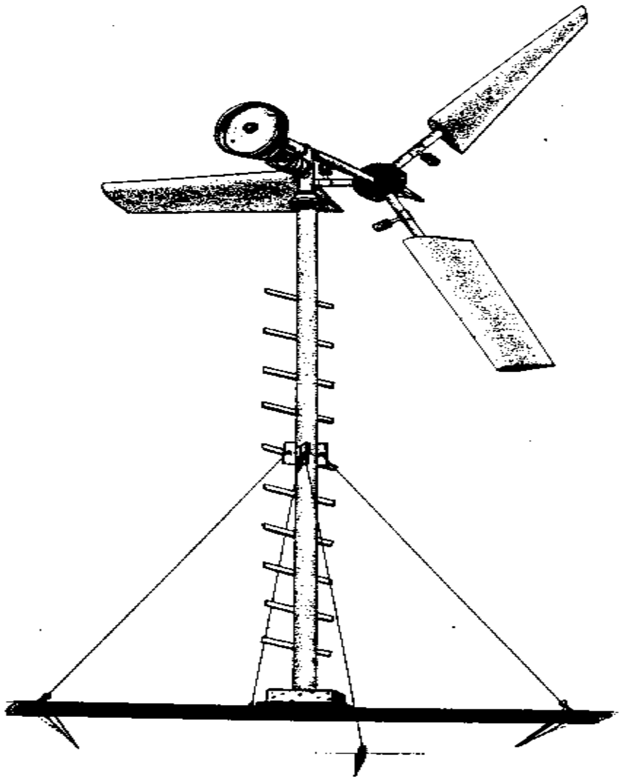

Figure 13. Tower Supported by Guy Wires with Anchors

APPLICATIONS OF WIND POWER

Wind power has two major uses today: mechanical power and electric power production. By far, the most important use of mechanical power is in water pumping, although wind power is sometimes used directly for aeration of ponds or other mechanical loads.

Within the electric power production category, there are two main applications: (1) power for remote applications, and (2) utility-connected machines. Wind electric generating machines (WEGM) or wind electric conversion systems (WECS) used in remote applications, separate and distant from any utility grid, are typically connected to storage batteries. When supplemented by another electric generator such as fossil fuel or hydro, the WEGM or WECS is termed a hybrid system. Large machines (100-2,500 [kw.sub.E]) are being developed to be operated by the utility companies, much the same an they would operate any other power plant. An application that is becoming more common in industrial countries is the development of wind farms. This involves private groups who form consortia to purchase wind machines, and sell power to utilities as small power producers.

Small machines (1.5-50 [kw.sub.E]) are being used by individuals, farmers, and small businesses in remote locations to augment their power supply and decrease the power purchased from electric companies.

A minor and frequently inefficient use of wind power is in heating applications. This is carried out either through electrical generation, the power from which is dissipated in resistors, or mechanically by using a water brake or churn.

EQUIPMENT, MATERIALS, AND RESOURCES

The equipment, materials, and resources needed to construct and

operate a wind system depend largely on the type of system being planned. Wind systems are divided into three categories: (1) simple technology, (2) intermediate technology, and (3) complex technology.

The simple technology systems include those that can be built easily using locally available components. They are typically small machines with low power output, operating at low rotational speeds for water pumping. Savonius rotors, made of recycled drums and erected on wooden truss towers, fall into this category, as do sailwing machines patterned after traditional designs. Although such machines can be built using locally available wood and cloth materials, most of them could be improved substantially by incorporating a few imported, manufactured components, especially bearings.

The intermediate-technology wind machines are more sophisticated than those in the first category. These WECS include deep well water pumpers of modern design plus small wind electric machines. They are made primarily of steel, which should be available in the form of sheet stock, rods, bars, and structural forms (angle iron). The blades themselves are likely to be made of curved steel plates (slow-speed machines) or carved wood, either solid or laminated (high-speed machines). Most of the components can be made at a local machine shop or blacksmith shop. In addition to conventional hand tools, such equipment as drill presses, sheet metal cutters, lathes, milling machines, arc welders, and gas torches should be locally available. Specialty components, such as bearings, gears, chains, sprockets, and electrical equipment (when applicable) might need to be purchased elsewhere.

The high-technology, complex WECS represent the third category of machines. This category includes the high-speed wind electric systems of high power output (200-2,500 [kw.sub.E]). These machines require special equipment, as well as materials more exotic than steel or wood. Many of the components, such as gearboxes, generators, control system electronics, and electrical switchgear, are likely to be produced by separate suppliers. The blades are likely to be made of fiber glass, constructed either in the manner of fiber glass boats or with a filament winding technique such as is used in the helicopter industry. The nacelle also is likely to be of fiber glass. Special materials and equipment might also be used in building such items as brakes, pitch control systems, yaw controls, or electrical slip rings. The main frame could be built at a standard machine shop. The tower must be designed specifically for the machine; it probably has to be constructed by a firm familiar with support structures.

SKILLS NEEDED TO PRODUCE AND OPERATE A WIND ELECTRIC SYSTEM

Construction of simple-technology WEC machines requires a journeyman skill level. Builders should be familiar with basic hand tools, and be able to read construction plans. For example, a literate farmer, capable of making, maintaining, and using simple implements such as plows or animal-operated irrigation pumps, should be able, with some instruction, to construct and operate a simple wind machine.

To build intermediate-technology machines requires a higher skill level. The designs could certainly be produced elsewhere, but a good understanding of the principles behind the design is desirable. Builders must have the skills of a competent machinist or blacksmith, and must be able to operate the simple tools described earlier. They also must have some special skills in order to handle certain aspects of the construction, such as making blades or hooking up the electrical equipment. A person familiar with rigging should supervise the installation of the machine. The design of the machine should be such that normal operation and repair could be carried out by the owner.

The production of high-technology machines requires the highest skill level. An engineer familiar with the design should oversee the construction and testing of at least the first few machines. Persons, with a variety of skills, such as welders, machinists, electricians, sheet metal workers, and fiber glass workers are required. Much of the work also requires precision, and familiarity with the latest building techniques and materials. The various subcontractors should have their own work force to ensure the proper design and construction of the individual components.

COST/ECONOMICS

Although the energy in the wind is free, the wind system that extracts the work is not. System-installed cost is often associated with the rated output, e.g., dollars per kilowatt or dollars per horsepower. To evaluate the economics of a system accurately, one must consider at what wind speed the machine is

rated or how much total energy should be produced in a given wind regime. Despite this caveat, the costs of wind machines usually fall within specific ranges. For example, water pumpers usually cost from $4,000 to $8,000 per horsepower (hp) for units less than one hp. In sizes of 5 to 15 hp, they usually cost between $1,000 and $2,000/hp. Simple designs that can be built locally and that produce mechanical shaft power can cost in the range of $1,000 to $1,500/hp, but they also could involve higher labor, maintenance, and operational requirements.

Complete wind electric systems typically cost from $1,500 to $3,500/kW for machines in the range of 5 kW and from $1,000 to $2,500/kW for machines in the range of 30 kW.

Evaluating the economics of a wind system requires a knowledge of the system's useful energy output and its value, as well as the cost of the machine. Complete analyses usually consider other factors as well, such as maintenance costs, loan interest rates, and discount rates. One useful indicator of economic viability is the payback period, which can be calculated easily. The payback period, in years, is determined simply by dividing the system cost by the annual value of energy produced. The payback period, then, is the number of years it takes to pay back the original cost. The following example illustrates a simple economic analysis:

Wind Machine: Rated power = 10 kW at 10 m/s

Cost = $1,500/kW or $15,000 installed

Wind Resource: Annual average wind speed = 6.5 m/s

Annual Productivity of Machine = 35,000 kilowatt hours (kWh) (assuming a typical wind regime)

Value of Power = $.15/kWh

Payback Period = Cost/value of annual productivity = 15,000/(.15) (35,000) = 6.67 years.

EFFICIENCY

As discussed earlier in this paper, wind machine rotors have power coefficients in the range of .2 to .35 for slow machines and .35 to .45 for fast machines. In addition, transmissions, generators, and pumps all have efficiencies associated with them. Transmissions can have efficiencies in the range of 90 to 97 percent, depending on the type. Generators can have efficiencies as high as 95 percent, but small generators often have lower efficiencies. In addition, the efficiency can drop off substantially, when the generator is operated at less than 25 to 50 percent of its rated output. The overall efficiency of the gearing and pump of a water-pumping windmill can be about 60 percent. When all the losses are considered, the overall maximum efficiency of a high-speed machine can be in the range of 25 to 38 percent. For slow machines, overall efficiencies can be in the range of 12 to 21 percent. It is important to note that efficiencies

can fall off substantially at wind speeds other than those corresponding to the maximum; due to the inherent mismatch between piston pumps and windmills, the overall efficiencies of water pumpers drop off sharply at higher wind speeds. The ultimate performance of the machine, as a function of wind speed, including all the inefficiencies, is summarized in the power curve described earlier in this paper.

MAINTENANCE REQUIREMENTS

Windmills are rotary machines that require maintenance at regular intervals to keep them operating smoothly. Close attention to proper design and construction will ensure that the machines have a long service life with minimum repair. Normal maintenance includes lubrication of moving parts, and regular inspection of all the equipment for signs of fatigue, wear, or damage. The brushes used in direct-current electrical generators must be checked periodically, and replaced when necessary. All electrical connections should be fastened tightly to make sure that the vibrations do not loosen connections when the WECS is operating. All electrical connections must be clean and free of dirt to ensure that electric operations are done without arcing of connection surfaces.

The metal towers must be painted as needed to minimize rusting. Some machines have manual reset after shutdown due to such causes as vibration or overspeed. Since the main body of the wind machine is high above the ground, access to it must be provided for any repairs or maintenance. Access can be as simple as a tall ladder for low machines. Other machines can be lowered readily to the ground. Still others are equipped with a built-in ladder to reach a work platform at the top of the tower.

ENERGY STORAGE REQUIREMENTS

The energy storage requirements for wind systems vary, depending on the type of wind machine and how it is used. Water-pumping windmills can use ponds or elevated tanks to store water and to help match the wind requirements with the water requirements. Typically, a storage volume of at least three days' demand is desirable. However, the desired storage volume will depend on the wind characteristics (duration per day and velocity) at the site.

Stand-alone wind electric systems require storage (usually in the form of batteries) because wind energy varies hour by hour over a wide range of velocities. The total storage requirement for these systems is typically three to five days, depending on the wind conditions and the load requirements. Wind electric systems connected to large utility grids usually do not need storage if the electric utility purchases excess power. If the utility does not purchase the power, some storage is advisable. Wind machines coupled to a small isolated grid, such as an isolated grid powered by diesel generators, may require storage--in terms of a few hours--to smooth the system output and suppress electrical transients (sudden changes of load, voltage, or current). Wind heating systems use thermal storage, usually water. The storage is usually sized for two or three days of the maximum heating requirement.

Some wind electric systems use only a portion of their output for normal AC loads. The remaining output is used for heating, and augments the thermal storage.

IV. COMPARING POWER-PRODUCING ALTERNATIVES

Depending on load requirements, climatic conditions, degree of development of the area, and proximity to power lines, there are a number of alternatives to wind power. In any comparison, the identified wind resource must be adequate for wind power to be considered.

For electric power load requirements, the usual alternative is utility electric service. Whether or not to use a wind system depends on the relative cost. Reliability will be higher with the utility. Smaller grids that use diesel generators are also reliable, but the power is expensive. Wind power may be highly competitive here.

In mountains or hilly terrain with ample rainfall, hydroelectric power is an alternative to wind power. Habitation tends to be clustered more in valleys (where the rivers are) rather than at mountain peaks, thus transmitting hydroelectric power should be easier than wind power. Hydropower is more controllable than wind power, and a pond is much cheaper than batteries. Otherwise, system costs for hydropower and wind systems are roughly comparable, except where major civil work (e.g., a dam) is required.

For remote areas in regions with good solar energy potential,

photovoltaic (PV) cells are an alternative to wind power. At present, PV cells are much more expensive than wind systems; so, if the region has a good wind source, PV cells will probably not be economically competitive. Where the wind resource varies greatly over the year, a hybrid system comprising both solar cells and wind power could prove advantageous.

For water pumping, the main alternatives to wind power are animal power, gasoline or diesel pumps, photovoltaic cells, and utility electric power. Animal power, the oldest of the alternatives, is slow and may involve an inefficient use of resources. Fossil fuel pumps are convenient, but their operating costs are very high. Photovoltaic cells, as mentioned before, are very expensive. On the other hand, a complete water-pump system using a PV panel coupled with a submersible electrically driven pump is easy to install, compared with a wind system. It would have many fewer moving parts and could prove more reliable in the long run. Utility power is only an option in regions where a grid is already in existence. Even in those areas, the cost of bringing a separate power line to the site of the water may render this option more expensive than others.

For heating applications, there are also a number of alternatives available: fossil fuels, wood, and solar energy. Fossil fuels (e.g., oil, natural gas) burned in a furnace are very convenient sources of heat, and the technology of furnaces is well developed and relatively simple. The disadvantage of these fuels is their high cost and inaccessibility. Coal is another fossil fuel that has been commonly used for heating, but it can produce substantial

amounts of pollutants, especially when burned in a small furnace.

Wood is a very competitive source of heat in many areas of the world. It is much cleaner than coal and often readily available. In other areas, however, wood usage has outstripped the regenerative capability of the forests; thus, obtaining wood for fuel may be difficult.

Direct use of sunlight for heating is another alternative. The technology for use of solar energy is developing rapidly. Active solar systems, using collectors separated from the load, are used for space heating, domestic hot water, process applications, crop drying, etc. Passive solar systems, where the collectors are incorporated into the load, are excellent choices for many applications, such as heating residential buildings. The disadvantage of solar energy is that at the time when it is most needed for heating--in the middle of winter--solar radiation is scarcest. The wind resource, however, is strongest in the winter in many locations; for that reason, the use of wind power may be more cost effective than the use of direct solar energy. In addition, obtaining high temperatures with wind power, using electric resistance heaters, is simpler than obtaining it through the conversion of sunlight.

GENERAL CONSIDERATIONS

One of the main advantages of wind power and other forms of solar-derived energy is that all involve clean renewable sources of energy. All are relatively safe, and the "fuel" is not subject

to arbitrary interruption. Because wind power provides power in the form of a rotating shaft, the power is of the highest grade--it can be used to perform work as well as to provide heat.

On the other hand, there are also land use questions and environmental issues that must be considered with wind power development. The wind is a relatively diffuse source of energy. Wind machine rotors must sweep a large area, and many machines must be made available to supply an amount of energy comparable to that supplied by fossil fuels. The competing options in the choice of technology, as well as use of the prospective site, must be examined carefully.

V. CHOOSING THE RIGHT TECHNOLOGY

In deciding whether to use wind power in a region, a number of questions must be addressed:

1. Is there a sufficient wind resource available?

2. Can reliable, maintainable machines be built or obtained at a resonable cost?

3. Is the infrastructure in place to ensure that the machine can be operated over its economic lifetime? Will parts and the people to service it be available?

4. Is wind power a better choice than the other alternatives available? Should the system chosen incorporate

other technologies as well?

5. Will wind power meet with public acceptance? Is there anything about the society in the region where it is to be introduced that might cause it to reject the use of wind power? If so, how can the concerns of the society be met and still allow the technology to be introduced?

6. Are the economics such that the wind system is truly desirable? Will the system be built largely with local materials and resources and thus help the local economy, or will it involve only imported machinery that may be as much of an economic drain as would the Purchase of oil?

All of the above questions must be answered before the development of a wind system can begin. Given the right situation, the wind is undoubtedly an excellent source of producing power for today's world.

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