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EGYPTIAN RENEWABLE ENERGY FIELD TESTING PROJECT

WIND ENERGY

TECHNOLOGY REFERENCE NOTEBOOK

Prepared for

EGYPTIAN ELECTRICITY AUTHORITY

Cairo, Egypt

and

U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT

USAID Mission: Cairo, Egypt

Submitted to

LOUIS BERGER INTERNATIONAL, INC.

Washington, D.C.

Prepared by

MERIDIAN CORPORATION

Falls Church, VA

U.S.A.

JUNE 1985

RENEWABLE ENERGY RESOURCES FIELD TEST PROJECT

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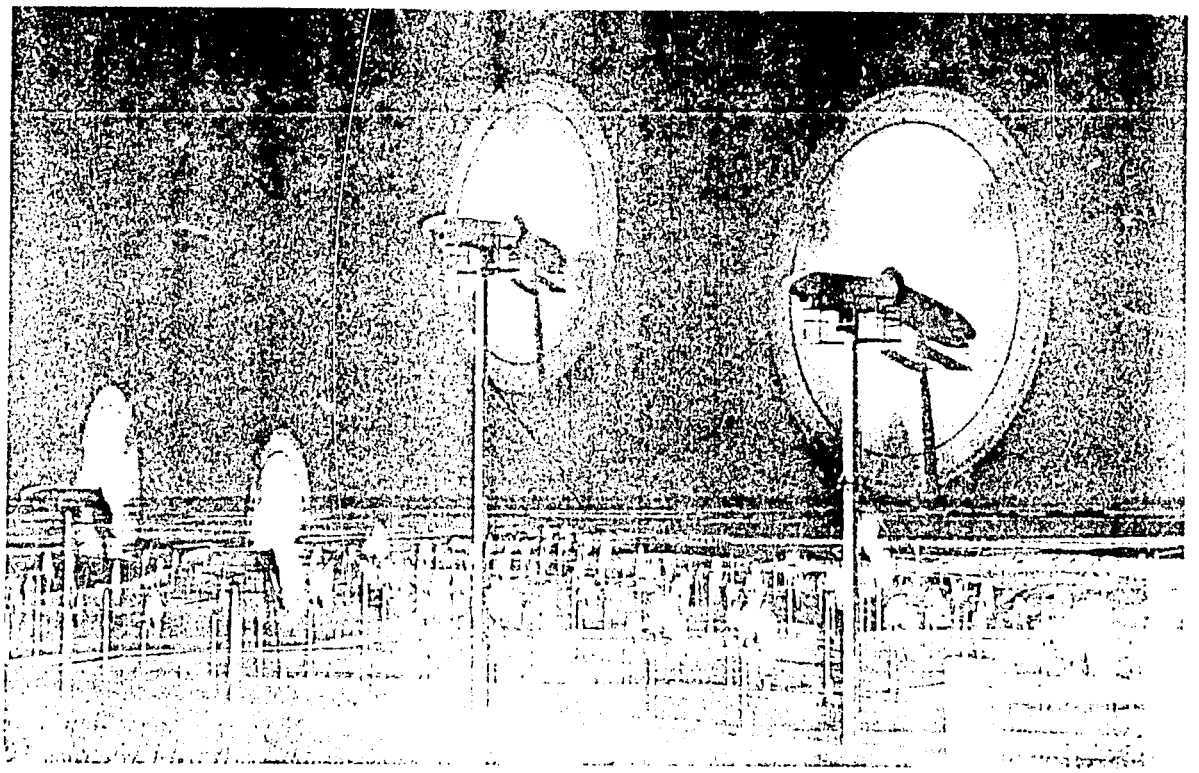

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1.0 INTRODUCTION

This document is one of a series of Technology Reference Notebooks developed for the Renewable Energy Resources Field Testing (REFT) Project sponsored by USAID and the Government of Egypt. The series includes individual notebooks on the following energy technologies:

- Active and Passive Solar
- Biomass
- Geothermal
- Photovoltaics
- Solar Thermal
- Wind

The objective of this series is to provide the most current information on renewable energy technologies in an easily updated and easily retrievable format.

This particular document is the Wind Energy Technology Reference Notebook. Operating principles, component descriptions, design considerations, installation and performance criteria, and applications of wind energy conversion systems (WECS) are addressed. Also included are special considerations of the Egyptian environment, extensive literature on commercially available products from major manufacturers involved in wind, and a Wind Projects Site Visit Book, providing information on specific projects that have been installed worldwide.

2.0 OPERATING PRINCIPLES AND DEFINITIONS

The purpose of this chapter is to introduce the reader to the concepts and terminology involved with wind energy conversion. The reader will be exposed to the physical principles governing wind energy conversion, the nature of wind resources, and the operating principles of the various types of wind systems.

2.1 PHYSICAL-TECHNICAL BASIS FOR POWER FROM THE WIND

Wind energy conversion systems (WECS) convert the kinetic energy of wind to usable mechanical energy. According to the laws of physics, the energy of motion (kinetic energy) of a pirticle increases with the square of its velocity. Wind, in effect, is a large number of individually moving particles (masses) of air, and hence, the kinetic energy in a given amount of wind varies proportionally with the square of the average wind velocity.

WECS convert the kinetic energy available in the wind to mechanical energy by reducing the momentum of the particles of moving air. The momentum reduction realized by the moving air particles results in an increase in the momentum of the WECS's turbine blades - i.e. conservation of momentum. This increased momentum is converted to useful mechanical energy through a wind machine hub and output shafr.

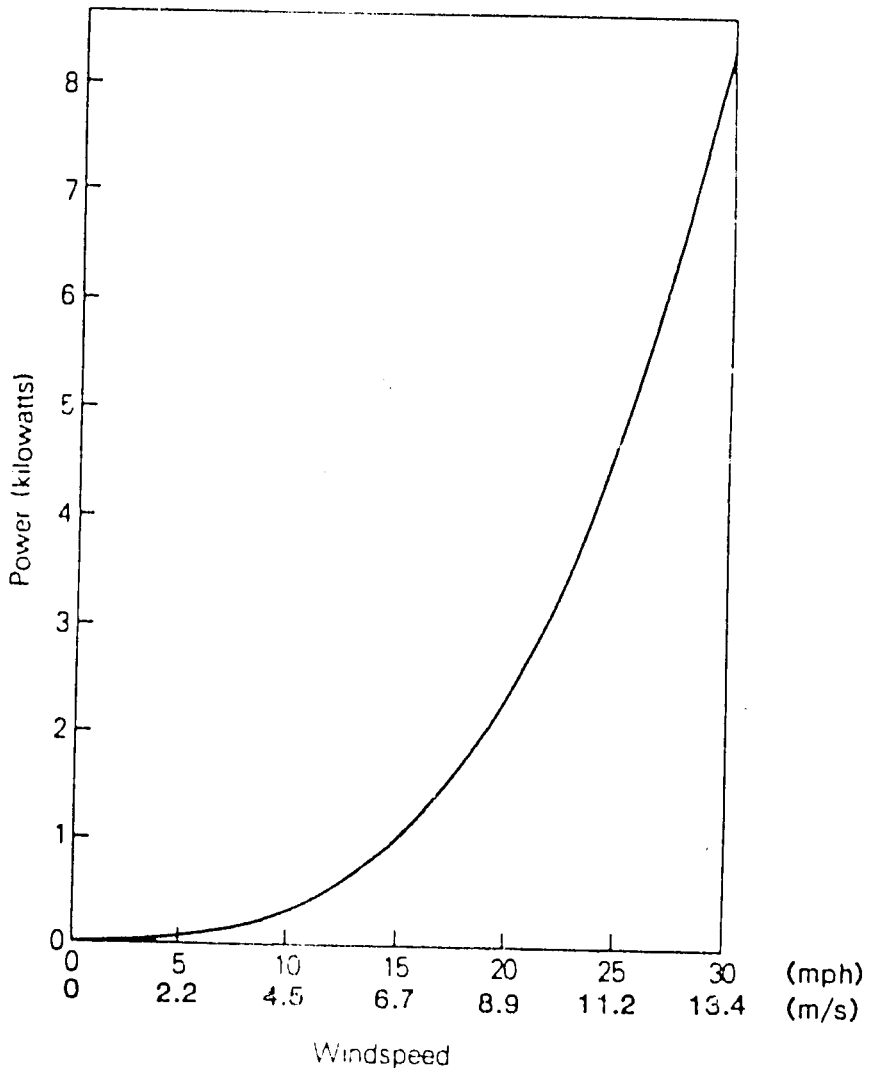
As mentioned above, kinetic energy is measured in units of mass and velocity squared. Since the mass-flow-rate of wind is also proportional to velocity, the final power flux is proportional to the wind velocity cubed. The general formula for wind power is:

$$P=1/2(\rho AV^3) \quad \text{Eq. 2.1}$$

where P is the power available, ρ is the density of the air (which varies but is approximately 1.2 kg/m^3 at sea level), A is the cross-sectional area of the air flow under consideration and V is the freestream velocity.

Exhibit 2.1

AVAILABLE WIND POWER AS A FUNCTION OF WINDSPEED



An ideal efficiency of 59.3 percent has been assumed for a rotor with frontal area of 100 square feet.

The variation of wind power with wind speed is presented in Exhibit 2.1. At a wind speed of 13 mph (5.8 m/s) approximately 10 watts of power are contained in each square foot (.09m^2) of wind area (where area is taken perpendicular to the wind direction). This represents the theoretical power available. The laws of nature limit the power transmission of ideal propellers to 59.3 percent (see Appendix B for details). Because of losses associated with real propellers, gearing and generators, the power that can actually be obtained from 1 square foot (.09 m^2) of this 13 mph (5.8 m/s) wind is 3 to 3.5 watts.

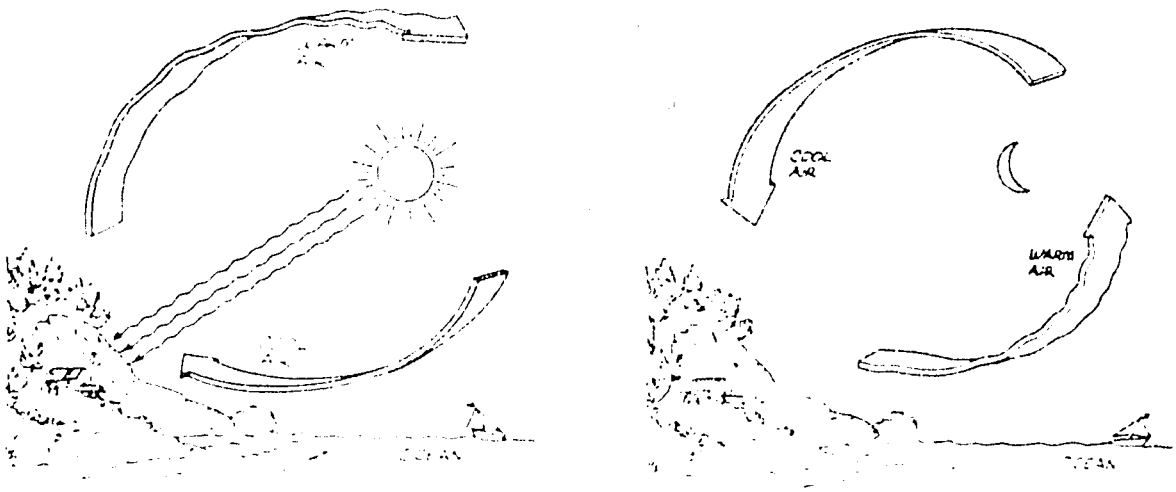
2.2 WIND RESOURCE

The wind resources required to operate a wind machine result from uneven solar heating of the earth's atmosphere. This uneven heating causes large pressure gradients across short distances. Winds result when large air masses move to alleviate such atmospheric pressure differences. For example, during the day an ocean will heat up more slowly than the adjacent land, since the water has a higher heat capacity than the land. The heated air over land expands, becomes lighter and rises. The cooler, heavier air over the water moves in to replace it. In this way, local breezes on a shoreline are created (see Exhibit 2.2a). During the night, these local seashore breezes reverse themselves since the land, and the air above it, cools more rapidly than the water. The cool air blows seaward to replace the warm air that rises from the surface of the water (Exhibit 2.2a). Similar local breezes occur on mountainsides during the day as heated air rises along the warm (south-facing) slopes heated by the sun (Exhibit 2.2b). During the night, the relatively cool heavy air on the slopes flows down into the valleys.

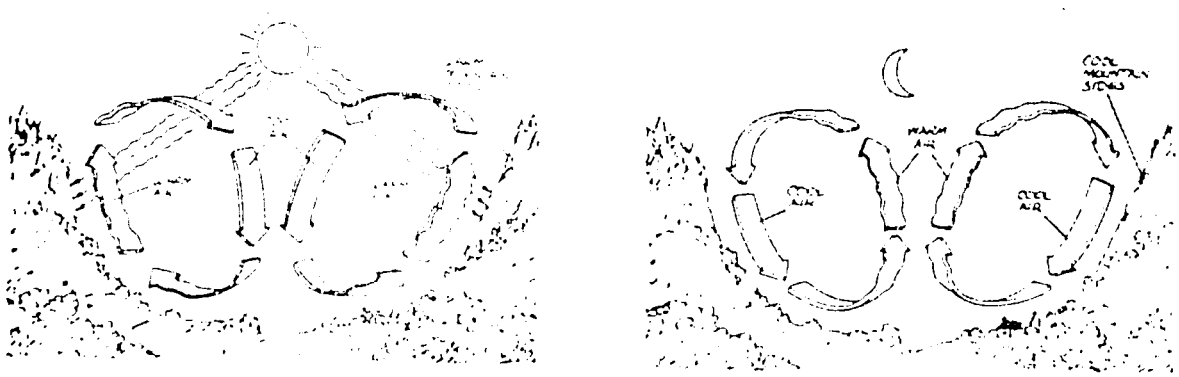
These local breezes are reinforced by large-scale winds caused by the greater heating of the earth's surface near the equator than near the poles. Inertial effects caused by the earth's rotation result in global wind circulation patterns known as the "trade winds," prevailing westerlies," and "polar easterlies."

Exhibit 2.2

HOW SEA-LAND AND MOUNTAIN-VALLEY BREEZES ARE CAUSED



Sea-land winds occur because adjacent land and ocean masses have different rates of heating and cooling. On-shore breezes occur during the day and off-shore breezes at night.



Mountain-valley winds. The [illegible] breezes occur because the air over high mountain slopes warms up faster [illegible]

Winds at virtually all sites have some remarkably uniform characteristics. At any given site, there will be a length of time when there is absolutely no wind. For another length of time, the wind will blow at an average speed, and for another period - perhaps only a few minutes over a entire year - the wind will blow at its maximum speed.

Wind records indicate that wind direction and speed are constantly varying. Local winds are influenced by pressure and temperature differences across a few miles of land. These local atmospheric influences in combination with those of hills, trees, and other topographical features, cause wind to shift directions frequently. At any particular site, however, one general wind direction will usually prevail.

The wind speed at a site increases dramatically with height. This effect is called wind shear, a term derived from the shearing or sliding effect of fast-moving air molecules slipping over the slower ones. Friction between faster and slower air leads to lower wind speeds and much less wind energy available near the ground. Equations have been developed which allow the calculation of wind speeds at varying heights based on surface condition. Different surfaces have different effects on surface winds, which in turn affect winds at higher elevations as a result of aerodynamic friction forces. The equation is:

$$V_B/V_A = (h_B/h_A)^a \quad \text{Eq. 2.2}$$

where V_A=the windspeed measured at height h_A,
V_B=the windspeed estimated at height h_B,
a =the surface friction coefficient (see Exhibit 2.3).

This equation is most commonly referred to as the 1/7th power law, where the exponent (a) takes on the value of 1/7. The 1/7th power law equation is used more often than its general form (Eq. 2.2) since most wind turbines are installed on moderately rough surfaces (i.e., surface friction coefficient = 1/7).

Exhibit 2.3

VALUES OF SURFACE FRICTION COEFFICIENT (A) FOR DIFFERENT ROUGHNESS AT GROUND LEVEL

Terrain Type	a
Smooth (sea, sand, snow)	0.10-0.13
Moderately rough (short grass, grass crops, rural areas)	0.13-0.20
Rough (woods, suburbs)	0.20-0.27
Very rough (urban areas, tall buildings)	0.27-0.40

2.3 WIND SYSTEM OPERATING PRINCIPLES

Energy extracted from the wind is initially energy in the form of rotary, oscillatory or translational mechanical energy. This mechanical motion can be used to do work directly, such as grind grain or pump water in a stand-alone application, or it can be converted to electrical power for both stand-alone and grid-connected applications.

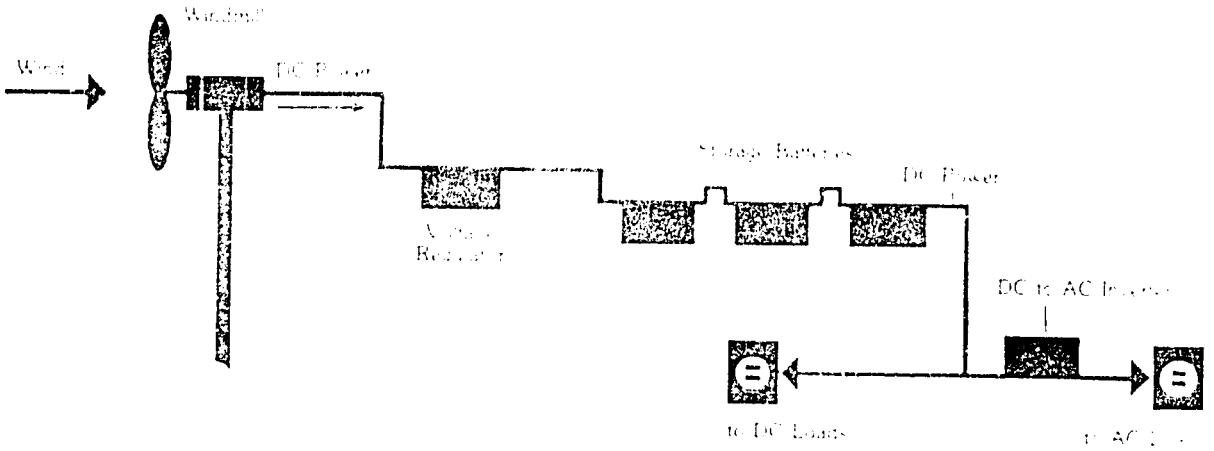
Unlike WECS for mechanical applications, which require only a gearbox and a shaft to transmit power to the required load, wind machines generating electricity require additional equipment to generate, condition and store energy (Exhibit 2.4).

Wind machines may be classified by the manner in which they transfer kinetic energy from the wind to WECS blades. The first type uses drag forces while the second operates as a result of lift forces. Lift forces act perpendicular to the local wind direction, while drag forces act parallel to it.

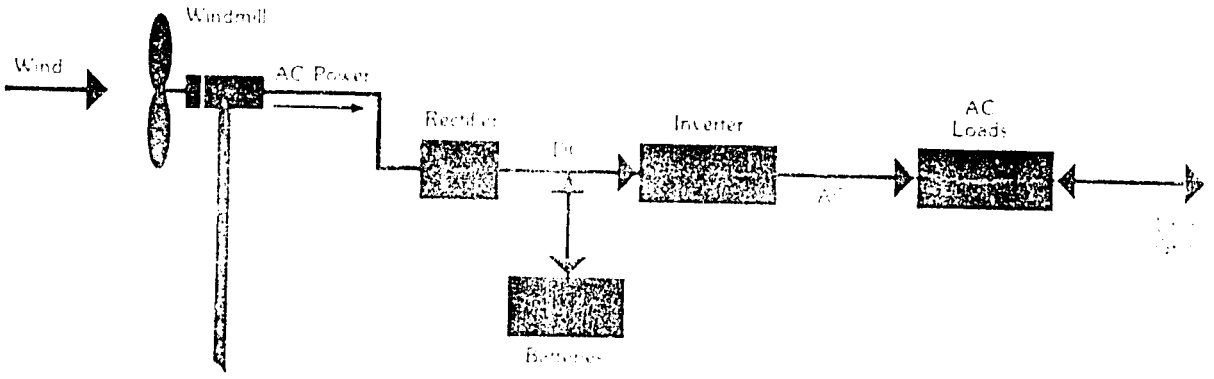
In a drag-type machine, kinetic energy is converted to mechanical energy in a vertical rotating shaft. As shown in Exhibit 2.5 one vane (blade) is pushed along by the wind while the opposite vane moves against the wind around a circular path. The drag force on the latter vane must be overcome by the force on the first vane for continuous rotation.

Exhibit 2.4

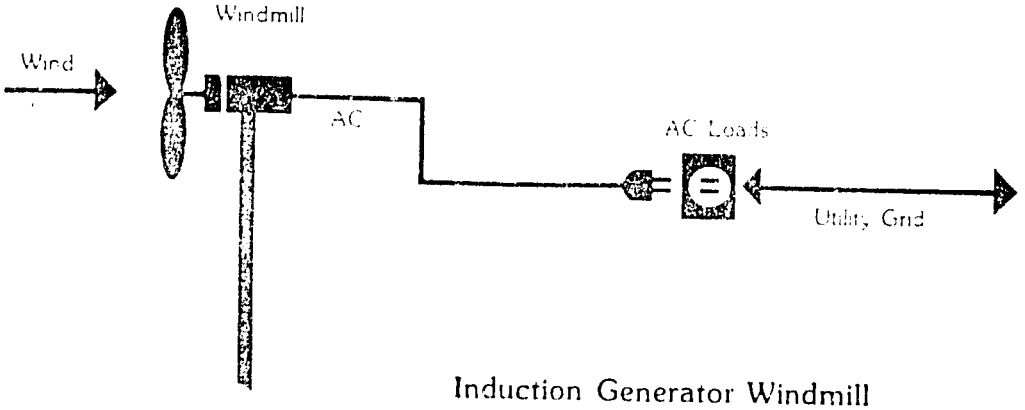
POSSIBLE WIND ENERGY SYSTEM CONFIGURATIONS



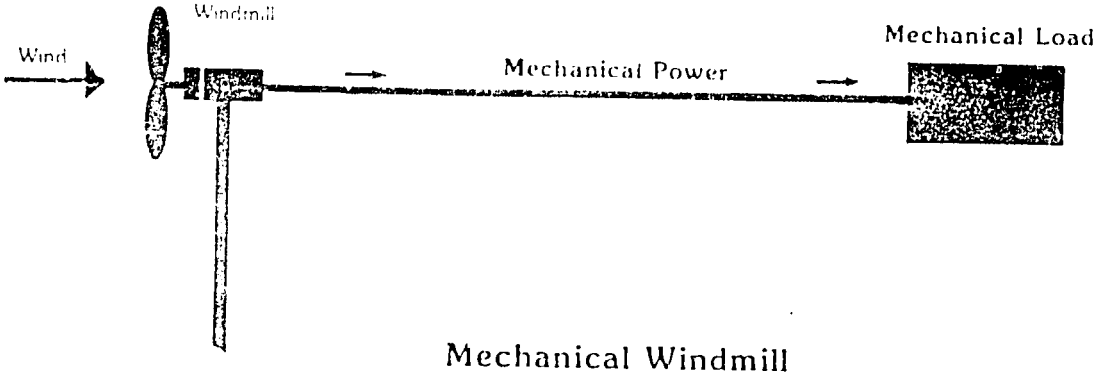
DC Generator Windmill



Variable Frequency AC Generator Windmill

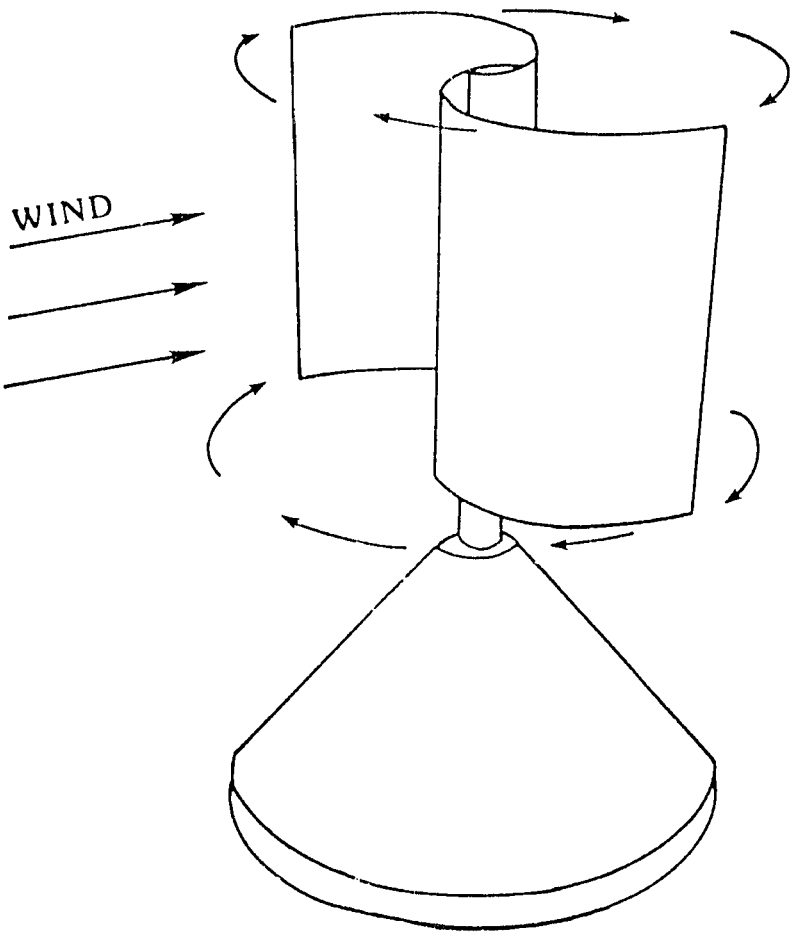


Induction Generator Windmill



Mechanical Windmill

Exhibit 2.5
SIMPLE DRAG-TYPE WIND MACHINE



Wind pressure on the high-drag, concave surface turns the rotor about its vertical axis.

Lift-type machines use aerodynamic forces generated by wind flowing over an airfoil shaped rotor. When wind flows past a blade, lift forces are generated perpendicular to the wind while a small drag penalty results that is parallel to the wind. Fortunately, the lift force is usually 10 to 50 times as strong as drag on the airfoil and the resultant aerodynamic force causes the blades to rotate (Exhibit 2.6). A surface operating on drag principles is constrained by aerodynamic friction forces and cannot rotate faster than the wind speed. A lift-type surface, however, is not constrained as such. Thus, for a given wind speed a lifting surface will rotate faster than the wind speed and, hence, produce a higher output torque than a comparable drag-type machine.

Most modern wind machines operate on the lift principle.

2.4 TYPES OF WIND ENERGY COLLECTORS

Many types of wind energy collectors have been devised for WECS. Almost any physical configuration which produces an asymetric force in the wind can be made to rotate, translate, or oscillate, and power can be extracted. Machines using rotors as wind energy collectors may be classified in terms of the orientation of their axis of rotation relative to the windstream, i.e.:

horizontal-axis rotor -- for which the axis of rotation is parallel to the direction of the windstream; and

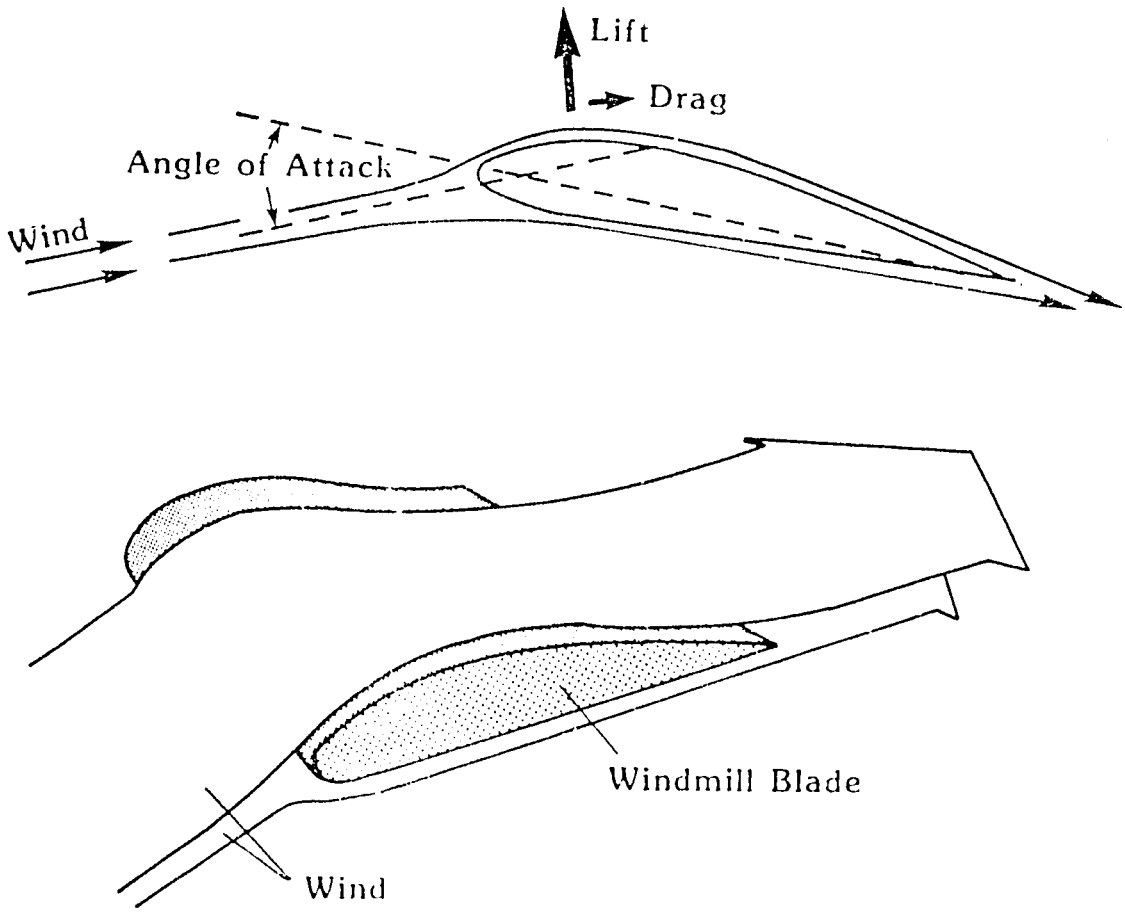
vertical-axis rotors -- for which the axis of rotation is perpendicular to both the surface of the earth and the windstream.

2.4.1 Horizontal-Axis Rotors

Horizontal-axis rotors are normally designed to maximize lift forces, although some machines have been designed which operate on drag principles. In order to obtain maximum power output from a horizontal-axis wind machine,

Exhibit 2.6

LIFTING TYPE MACHINES AND AERODYNAMIC FORCES



THE FLOW OF WIND ABOUT A WINDMILL BLADE. Lift forces act perpendicular to the local wind direction, while drag forces act parallel to it.

it is essential to have the plane of rotation of the blades perpendicular to the wind direction. Since wind direction at any site is constantly changing, some type of control mechanism is required so that the wind machines can track the changing direction of the winds. Small wind machines usually use a tail vane to accomplish this, while larger systems require a complicated servo operated system. This control mechanism is referred to as "yaw" control.

In addition to a turbine orientation control system, horizontal-axis rotors require controls to limit turbine propeller rotational speed in high winds. These control systems consist of feathering of the blades, or flaps rotating with the blades, as well as devices that turn the propeller sideways to the wind. Such high-speed cut out controls are required to prevent turbine damage or catastrophic failure.

Some horizontal-axis machines are designed with blades that rotate in front of the tower, with respect to the wind direction, and are called "up-wind" machines. Rotors that are designed with the blades rotating in back of the tower are called "down-wind" machines.

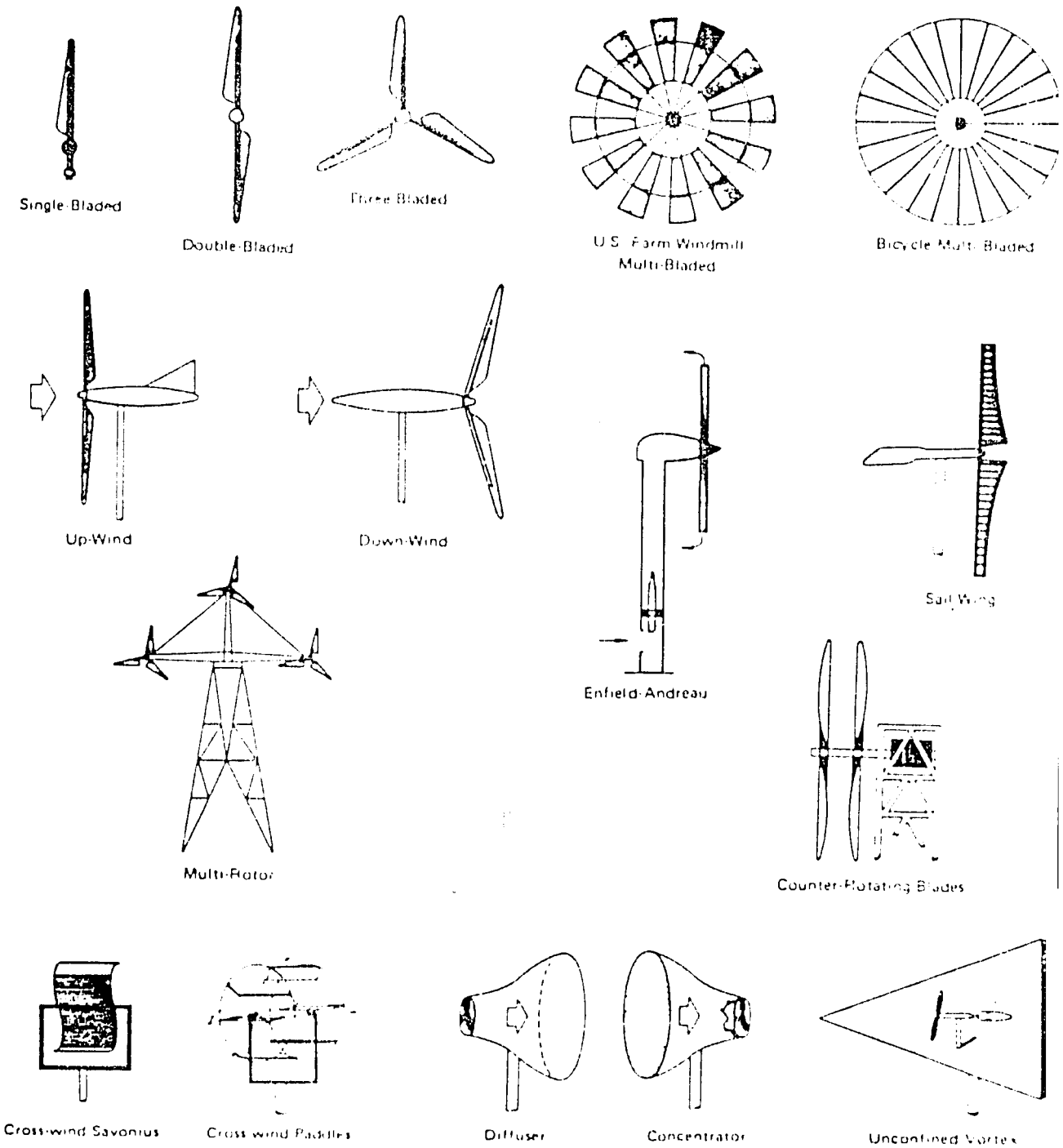
Exhibit 2.7 presents a taxonomy of conventional horizontal-axis machines as well as some experimental concepts.

2.4.2 Vertical-Axis Rotors

Vertical-axis machines have an advantage over horizontal-axis rotors in that they do not have to be turned into the wind as the direction of the windstream varies, i.e. they need no yaw control system. Various types of vertical-axis devices have been developed that use drag forces to turn rotors of different shapes. These include systems using plates or cups as the drag device, as well as the Savonius S-shaped cross-section rotors. The latter usually provides some lift force but is still predominantly a drag device. Darrieus-type rotors are lift devices characterized by curved blades with

Exhibit 2.7

TAXONOMY OF HORIZONTAL-AXIS WIND TURBINES



airfoil cross-sections. They have relatively low starting torques and, as a result, require an external power source for start-up. Since they are lift devices, they have relatively high power outputs in comparison to comparably sized drag-type vertical-axis machines.

Exhibit 2.8 presents a taxonomy of conventional vertical-axis wind turbines as well as some proposed concepts.

2.5 SYSTEM COMPONENTS

2.5.1 Turbine Assembly

The purpose of the turbine assembly is to capture and convert wind energy to useable mechanical or electrical energy. The capture function, as mentioned, is accomplished by means of aerodynamic lift or drag forces acting on a set of blades attached to a hub (horizontal-axis) or central rotating tower (vertical-axis). After the kinetic energy has been captured and converted to rotating mechanical shaft power, a drive train is required to synchronize the rotation of the output shaft, as well as transmit torque, to a load. The drive train usually includes a gear box or speed increaser, couplings, diagnostic sensors, and a braking/control system. Typical loads are devices producing useful mechanical work, or generators producing electricity.

A wind machine used for electricity production includes all of the above items, as well as a generator and associated controls. In horizontal-axis machines the rotor, shaft, gear box, generator and controls are housed on top of a support tower in the nacelle (Exhibit 2.9). In a vertical-axis machine the gearbox, generators and controls are located on the ground, below the turbine and the central shaft (Exhibit 2.10).

Generators used in WECS are one of three standard types: a synchronous generator, commonly referred to as an alternator; an induction generator; or a dc generator. Each of these will be explained in more detail in Chapter 3.

Exhibit 2.8

TAXONOMY OF VERTICAL-AXIS WIND TURBINES

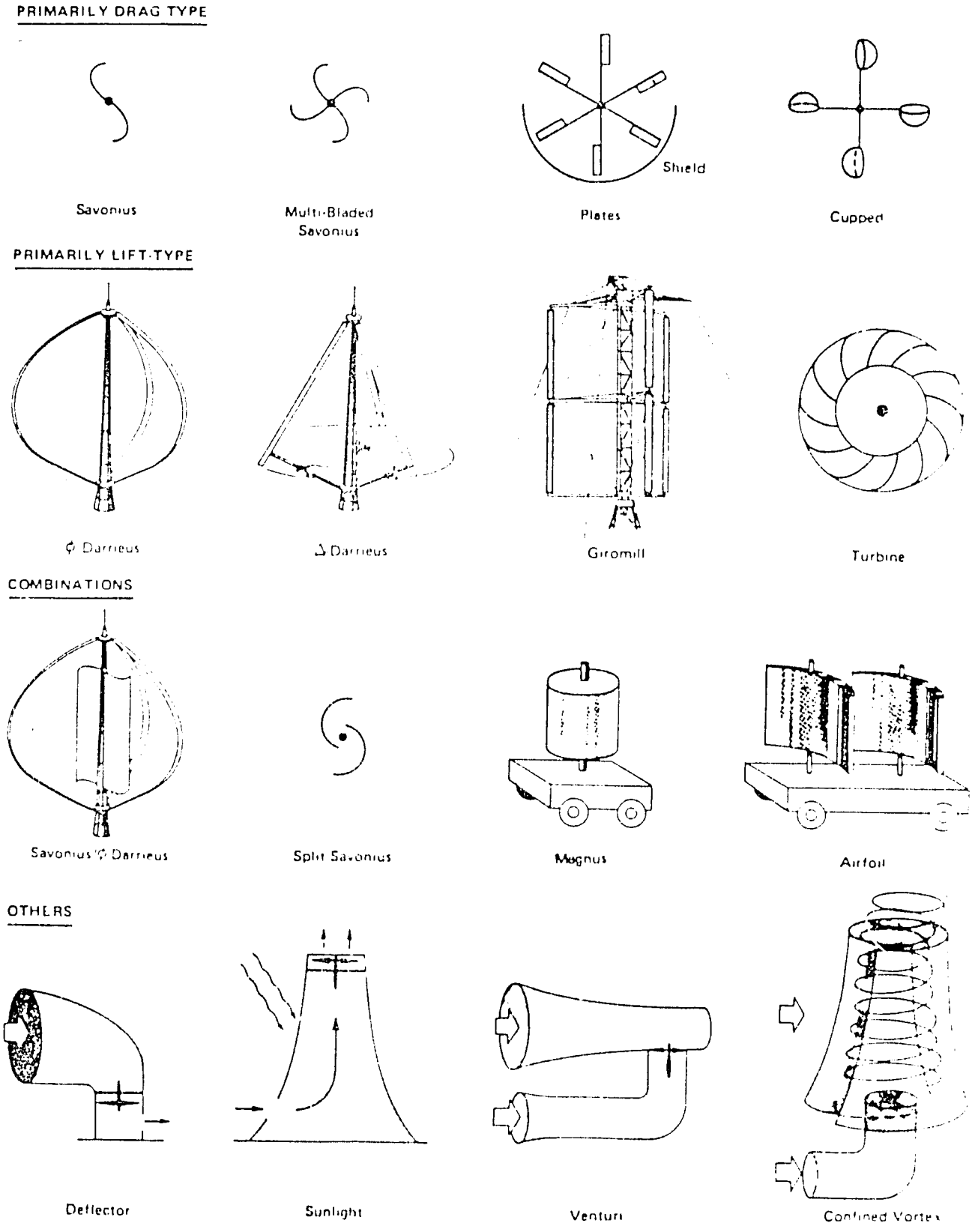


Exhibit 2.9
HORIZONTAL-AXIS TURBINE NACELLE

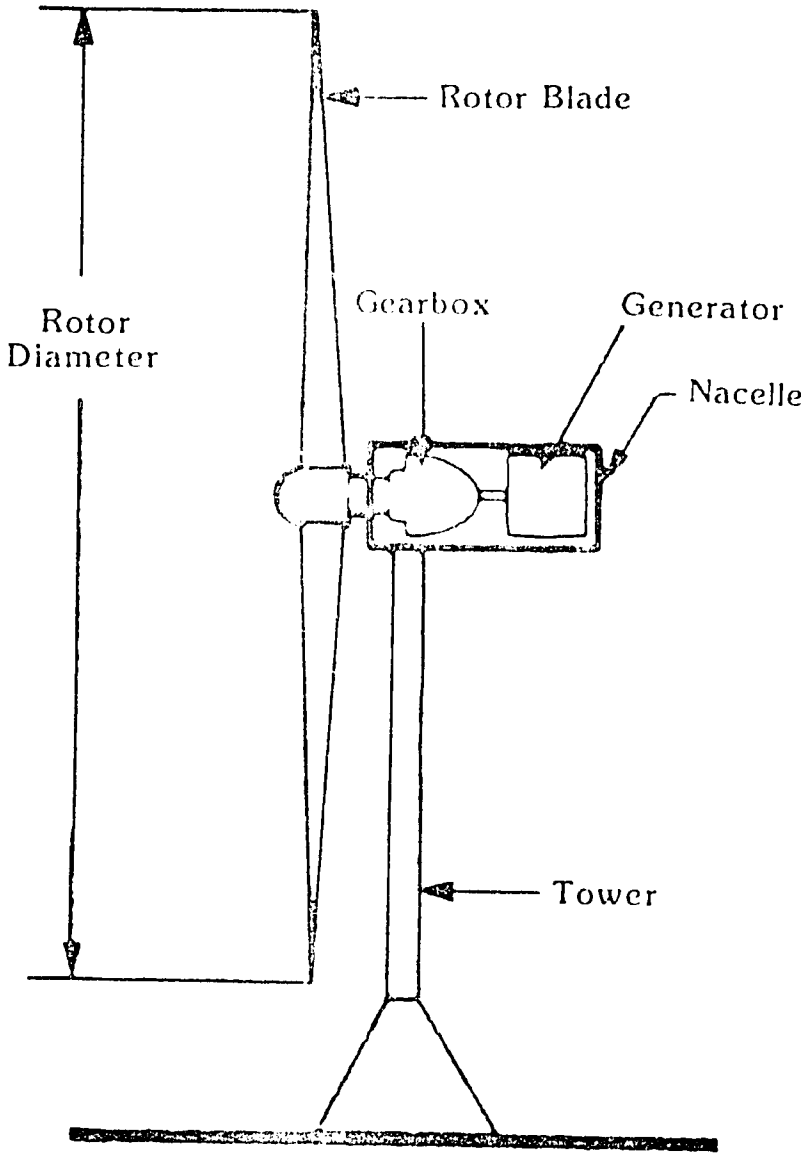
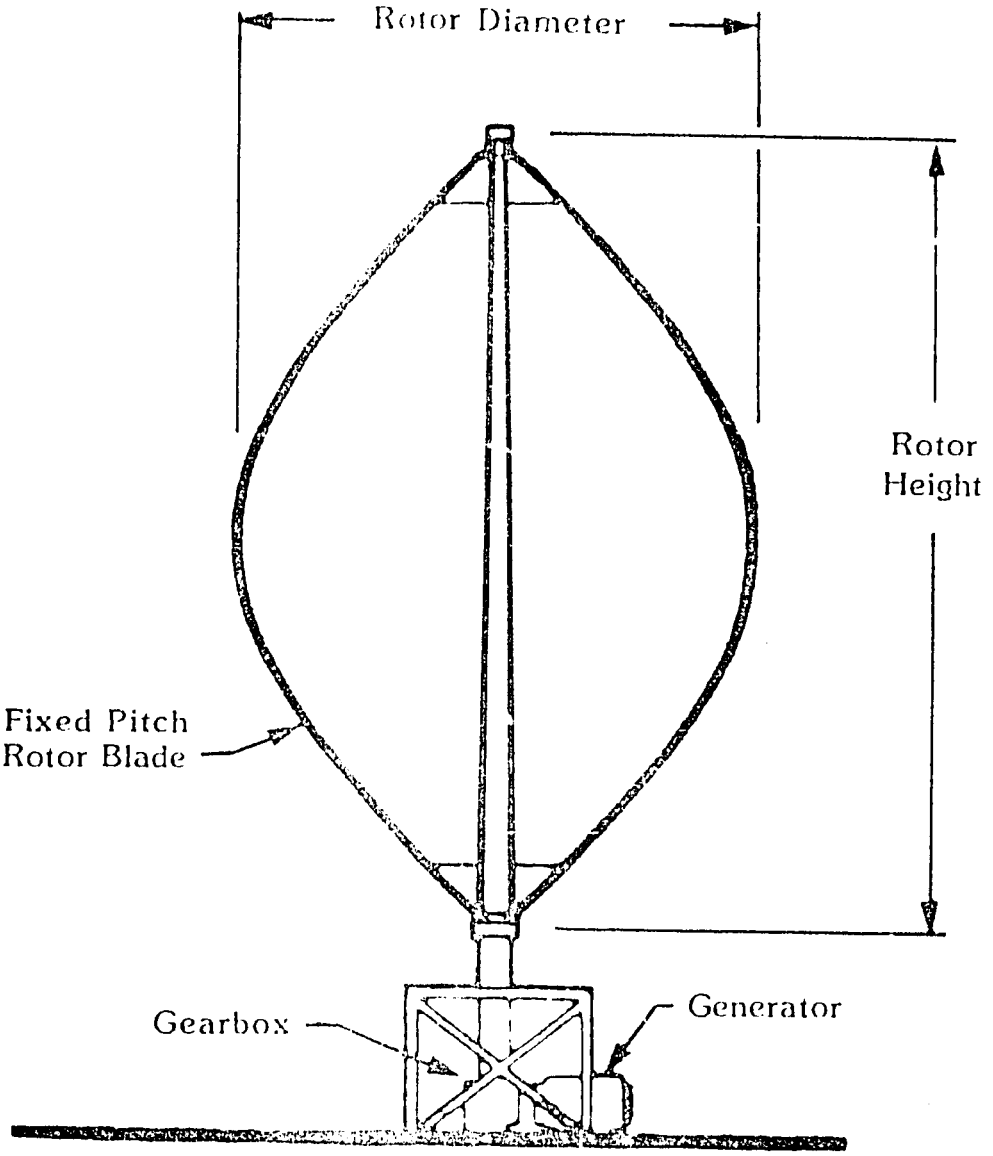


Exhibit 2.10
VERTICAL-AXIS TURBINE ARRANGEMENT



2.5.2 Power Conditioning and Safety Control For Electrical WECS

Wind machines generating electricity require additional equipment to control and regulate power output. This is accomplished through a device called a converter. The modern converter is a solid state apparatus without moving parts, which converts alternating current (ac) to direct current (dc), dc to ac, or ac to ac at another voltage and frequency. The converter is usually referred to as a rectifier when used only for ac to dc conversion, or as an inverter when used for dc to ac conversion. The converter or inverter performs an important function in matching a variable frequency or dc source to the load requirements, and by regulating power flow. The term "synchronous inverter" is applied to converters which synchronize WECS output frequency with the frequency of the load in grid-connected applications.

When a WECS is interconnected with the local utility grid, additional controls are required to isolate the WECS output. Special circuitry is required to cause wind machine shut down, or shunt power to ground, in situations where a section of the utility grid being fed by the WECS is shut off for emergency or maintenance purposes. Such controls prevent the WECS from feeding electricity into the grid and causing unacceptable hazards.

2.5.3 Energy Storage

Wind power is an intermittent energy source. For stand-alone applications, where the time of energy production does not coincide with the time of energy demand, a storage system should be employed. Of the many possible energy storage systems available, many have the disadvantage of high initial costs and energy storage capability mismatch (many can store much more energy than is required and are only economical on a large scale). Pumped hydroelectric, compressed air, thermal or hydrogen storage, super conducting magnets, and flywheel storage fall into this category. Chemical storage of electrical energy via batteries proves to be the most effective method of storing energy in con-

junction with WECS. In this sense, batteries act as a load to the WECS system and as a source to other loads. However, battery storage is expensive and can therefore be used only in limited quantity.

2.5.4 Towers

In order to capture the winds with higher energy availability, wind machines should be installed on a tower, above any obstructions such as buildings and trees. Towers are made in two basic configurations: guy-wire supported and free-standing. In addition to being guy-wired or free-standing, towers are made as single column structures, such as poles and pipes, or as a lattice framework of pipes or boards. Nominal tower height most frequently used with WECS are 60, 80, and 100 ft. (18.3, 24.4, and 30.5 meters).

3.0 DESCRIPTION OF WECS TECHNOLOGY

3.1 MECHANICAL OUTPUT WIND MACHINES

Mechanical power can be used for a number of activities, from grinding grain to pumping water. However, the only widely used mechanical application for windmills is water pumping. There are three basic categories of mechanical windpumps commercially available, each of which is explained in detail below:

A) Traditional multi-bladed farm pumps

B) Modern, light-weight farm windpumps

C) Low cost windpumps

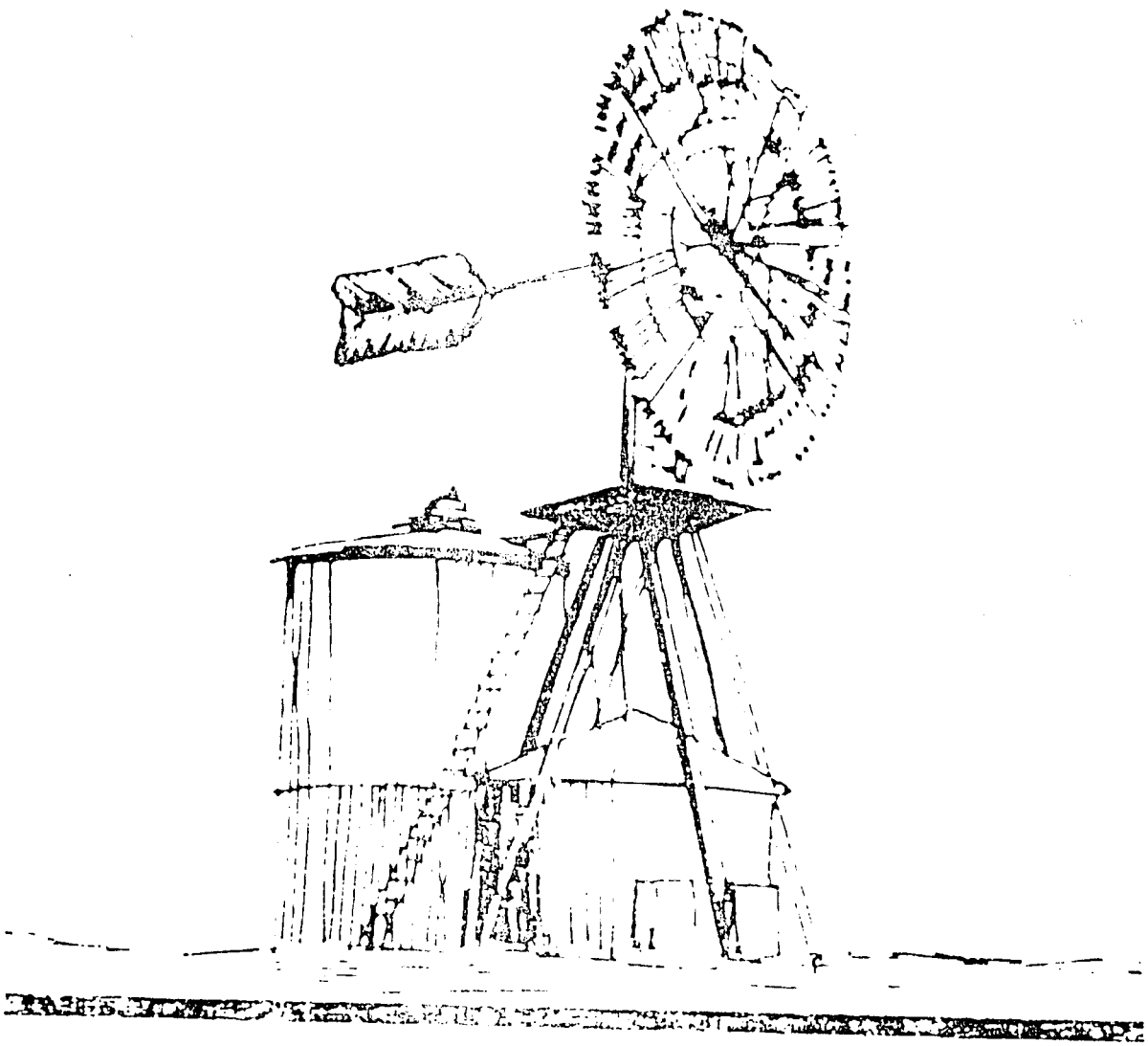
In addition, electric wind pumping systems are included in this section. Although they are primarily electricity producing wind mills connected to motor-pump sub-systems, they are covered here since their purpose is pumping water.

3.1.1 Traditional Multi-Bladed Farm Windpumps

This basic type of design was developed during the period from 1880 to about 1930 and has since changed little (Exhibit 3.1). These machines either transfer rotary motion of the windmill rotor to a pump, or convert the rotary motion to reciprocating before transferring it. Smaller sized machines (i.e. rotors of 5m (16 ft) or less), are generally "back geared"; i.e. they are geared down so that the pump speed is less than the rotor speed.

Larger machines tend to be direct-driven by a crank, because the rotor speed is naturally low enough to suit most pumps. Construction is from galvanized rolled-steel sections bolted together, with the transmission built up from large castings or forgings and oil-bath lubricated. Machines of this kind are inherently very heavy, and therefore material-intensive (in all except the smallest sizes), and complicated to assemble, but they are also very reliable, robust and need very little maintenance (usually annual change of lubricant).

Exhibit 3.1
TRADITIONAL MULTI-BLADED FARM WINDPUMPS



3.1.2 Modern Light-Weight Farm Windpumps

These involve a similar design concept to the traditional farm windpump, but using modern manufacturing techniques that permit use of such features as welded modular sub-assemblies, construction tube rather than rolled sections, rolling element bearings (i.e. ball or roller bearings) and grease lubrication.

Larger machines, i.e. of over 5m (16 ft) rotor diameter, are very similar conceptually to traditional large farm windmills, but are much lighter and simpler to assemble and erect. They are generally composed of prefabricated welded sections with a much lighter transmission unit at the top of a tower. Nevertheless they have comparable, and potentially better performance than the traditional designs. The relative structural simplicity resulting from modular welded construction is clearly evident from Exhibit 3.2, as is the aerodynamically "cleaner" rotor of the modern design, which should give it a better performance.

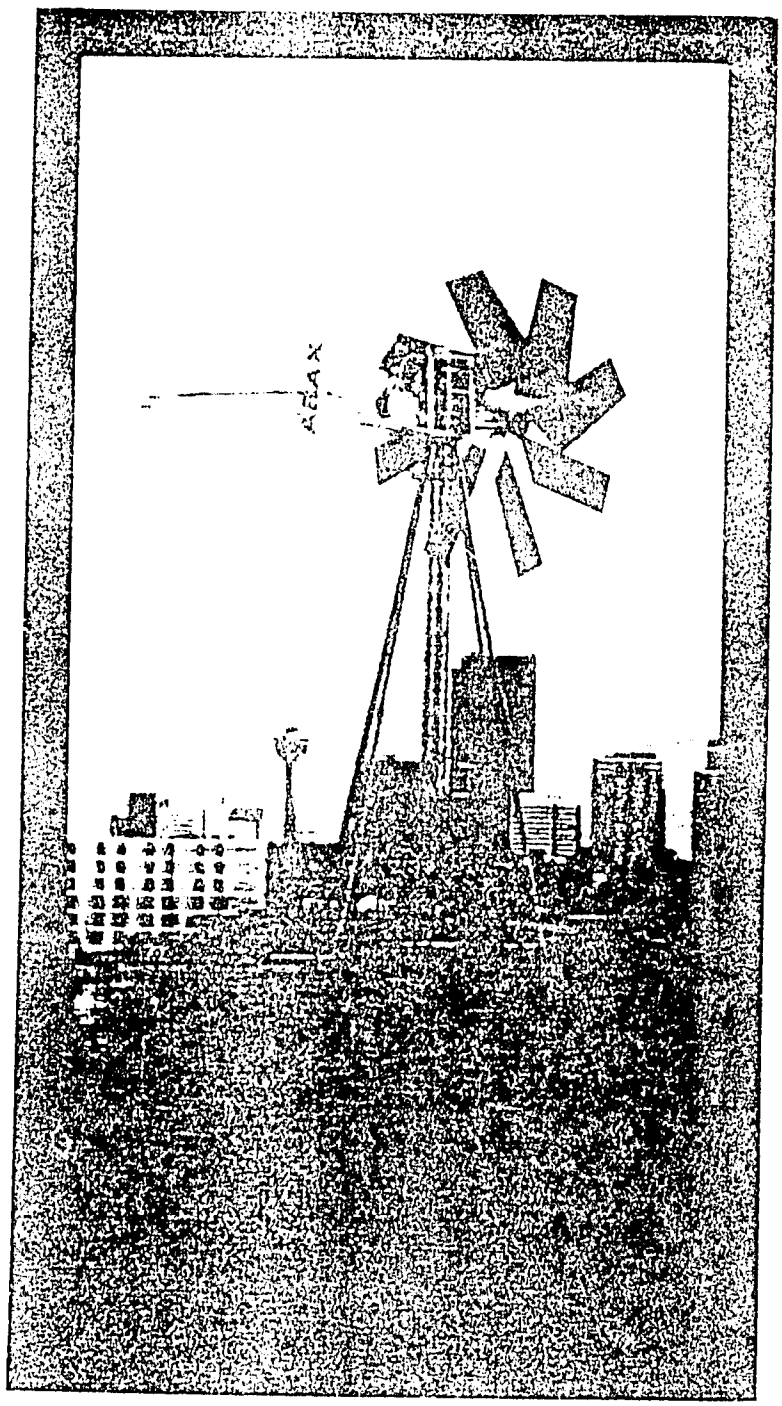
A number of smaller direct-drive welded steel windpumps are also available: these are generally light and simple to manufacture and assemble, but are not suitable for such heavy duties as the back-geared traditional smaller farm windpumps as they tend to run at rather high speed and have less pump rod pull. The smaller direct-drive units are generally manufactured in Europe (particularly France) where winds are relatively good, pumping heads are relatively small and the output requirement is modest (i.e. to fill a cattle trough).

3.1.3 Low Cost Windpumps

All manufacturers aim to produce a low cost windpump, but it is possible to reduce the costs dramatically if the windpump is built "on-site" on a self-help basis, using as far as possible cheap locally available materials.

Many thousands of windpumps built on this basis were used in the USA in the late nineteenth century and in China. Today, several thousand "self built" machines are in use by farmers in Crete, Peru and Thailand. Most of these machines are made of wood or basic steel structural components: cloth or wooden sails are

Exhibit 3.2
MODERN WINDPUMP DESIGN



often used to capture the wind. The efficiency is quite poor (half that of a farm windpump) and relatively frequent oiling and adjustment is needed.

3.1.4 Wind-Electric Pumping Systems

In addition to the three mechanical water pumping categories outlined above, there are commercially available wind-electric pumping systems. These systems are described in this section since they are packaged water pumping systems; i.e., their final output is mechanical shaft power from a motor.

Any wind generator can be made to power an electric motor pump subsystem. In practice the correct matching of components is essential. For someone not in the business, this would be very difficult. Some manufacturers of wind generators offer a complete wind electric pumping system as part of their services.

Wind electric pumpers tend to be higher technology than mechanical windpumps and data on their operational performance are very limited. Therefore their reliability and system life are as yet unproven. However, they have numerous advantages, the main one being that the wind turbine can be located remote from the water source, for example on a hill top, overcoming the condition where the location of the wind resource is not the same as the water source.

Wind-electric systems are potentially more efficient than wind-mechanical systems. They also are more flexible in offering the possibility of multi-purpose use such as charging batteries with excess power generated. Wind-electric systems are likely to be particularly competitive with mechanical systems where large outputs of water are required at low to medium pumping heads, particularly when the application is to pump surface water to higher ground.

3.1.5 Operational Characteristics of Mechanical Water Pumping Systems

Most multi-bladed windmills are designed for pumping water by direct mechanical connection to positive displacement pumps. These systems are typically rated in terms of their stroke per unit time or their delivery rate of water

for a given cylinder size and well depth. Pumping rates of approximately 160 gallons/hr (.17 litres/sec) from depths of 580 ft (177 meters) in 15 mph (6.7 m/s) winds can be achieved. The "rate x depth" factor is approximately a constant decreasing slightly with increasing depth due to pipe friction effects on the water flow. Because of the multi-bladed rotors used for this type of system, the windmill will pump water at low wind speeds if the cylinder size is appropriate for the well depth. The windmill pumping system is a positive displacement action and must have an open discharge at all times. The windmill should not be used for pumping into pressurized tanks.

Windmills can be used with or without water storage depending on the application. If storage is required, water can be pumped into an elevated storage tank for later distribution. Water storage is always recommended in order to take maximum advantage of the wind's sporadic nature.

Typical mechanical waterpumpers do not pump from offset locations and should be installed directly over the well or water supply. For good energy conversion, the rotor should be located at least 15 ft (4.6m) above obstructions such as buildings and trees and be in an area with a free flow of air from all directions for about 400 ft (122 m).

3.1.6 System Costs

Typical system costs for the range of available mechanical windpumpers is shown in Exhibit 3.3. Presented are ranges of machine costs, additional costs (towers, mechanical linkages pumps, foundation and installation), and total system costs for standard size machines. The wide cost ranges shown result from different country labor rates as well as the varying degrees of technical sophistication and structural complexity of the many available systems.

Exhibit 3.3

RANGES OF SYSTEM COSTS FOR MECHANICAL WIND PUMPERS (1982 $)

Type	Rotor Diameter (Meters)	Machine Cost (US $, FOB)	Other Costs* (US $, FOB)	Total System Cost (US $, FOB)
6 ft	1.83	370-860	300-1,300	670-2,160
8 ft	2.44	510-1,250	300-1,300	810-2,550
10 ft	3.05	760-2,200	300-1,400	1,060-3,600
12 ft	3.66	1,020-3,700	500-1,800	1,520-4,500
14 ft	4.27	1,250-5,970	1,300-2,180	2,550-8,150
16 ft	4.88	3,750-8,210	2,000-2,800	5,750-10,010

Reference: Wind Technology Assessment Study, Intermediate Technologies Power Ltd, Reading, Berks. RG7 3PG, UK, World Bank Project GLO/80/003, February, 1983.

* Other costs include tower, mechanical linkages, pump, foundation and installation.

3.2 ELECTRICAL OUTPUT MACHINES

3.2.1 Small Wind Energy Systems for Electrical Output

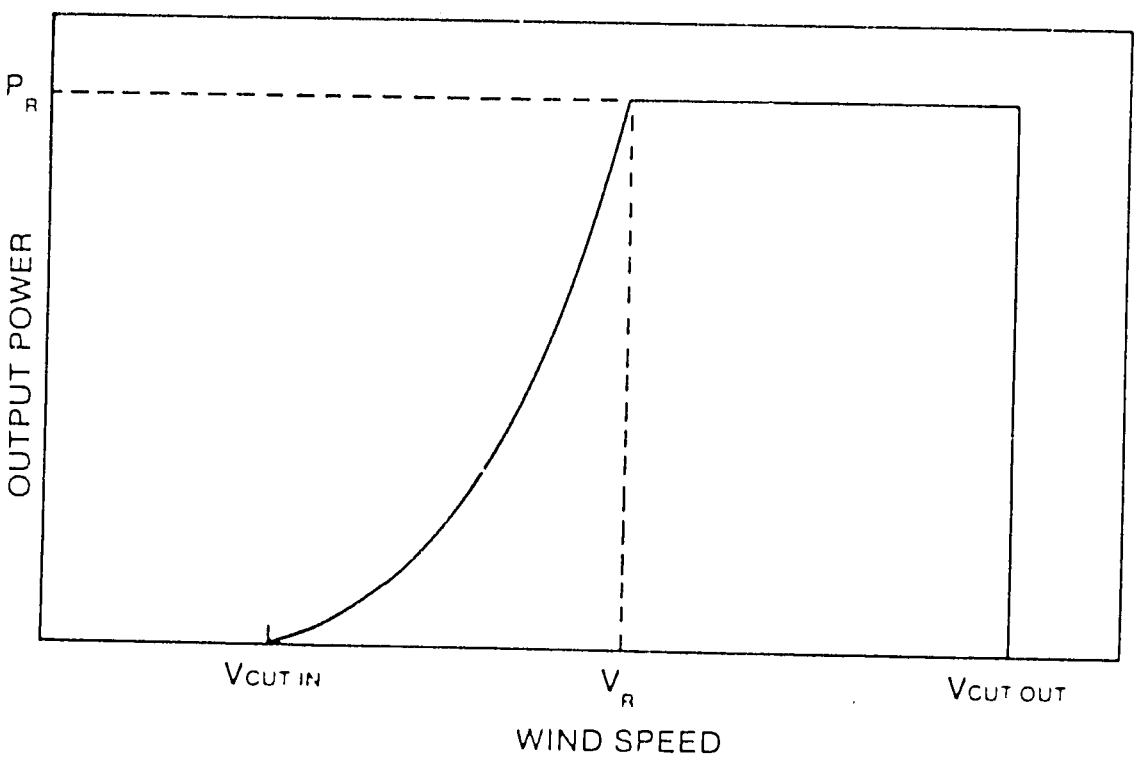
Small wind energy systems vary in size from a few watts up to 100 kW. Rotor sizes for these systems range from 10 ft (3 m) diameter for 1 kW machines to 125 ft (39 m) diameter for the larger machines. Currently, there are manufacturers producing both horizontal and vertical axis machines in this category.

Small wind generators can produce either ac or dc power and can be used as stand alone systems or interconnected with a utility network. The propeller type machines have low torque and high rotational speeds and operate best in moderate to high wind speeds. Power transmission for this type is nearly always in the form of gears, although pulley belts, crankshafts and direct-drive systems have also been used.

3.2.1.1 Performance Characteristics

Wind electric systems extract power from the wind according to a exponential curve. Below a "cut-in" speed (the wind speed at which the turbine rotor begins spinning) no power is generated. Above this speed, the power produced is theoretically proportional to the cube of the windspeed. This equation holds until the "rated speed" (sometimes referred to as reference wind speed) of the machine is reached, when the power output (the turbine's rated or reference power) remains constant for increasing windspeed. At some higher windspeed the machine will shut down to eliminate the possibility of damage, i.e., cut-out or shut down wind speed (Exhibit 3.4). A high rated speed implies a system which extracts energy from the powerful but relatively infrequent high windspeeds. The resultant output consists of bursts of high power at irregular intervals. If a low rated windspeed is chosen, then the rated output of the machine is lower but energy is extracted from the more frequent low wind speed bands giving a steadier power output and possibly a greater total output over a given time period.

Exhibit 3.4
WIND TURBINE PERFORMANCE CURVE



Generic Power Curve. V_R and P_R are rated wind speed and power, respectively.

The operating wind speed for electrical systems ranges from 5-12 mph (2.2-5.4 m/s) for cut-in wind speed to 40-60 mph (17.9-26.8 m/s) for cut-out wind speed. The efficiency of most commercial machines is limited by the design of the rotor and control system.

Tower height is an important consideration in small wind systems performance. Because wind speed normally increases with height above the ground, energy output increases as tower height is increased. Current standard tower heights are 20, 40, 60, 80 and 100 ft (6, 12, 18, 24, 30 meters).

3.2.1.2 System Costs and Availability

Typical system costs for a number of commercially available small WECS are presented in Exhibit 3.5. Presented are ranges of installed costs for systems with different rated outputs. The wide cost ranges shown result from different country labor rates as well as the varying degrees of technical sophistication of the many available systems. The majority of the installed cost is for hardware associated with the rotors, tower and generation, (approximately 42% of the system cost). Installation costs may account for as much as 20%. Limited production volume also contributes to such high machine cost. In addition, small lot fabrication forces manufacturers to use off-the-shelf components not specifically designed for their application, which leads to an inefficient and less reliable design.

3.2.2 Large Wind Energy Systems for Electrical Output

Large wind energy systems are defined as any system with a rated output of over 100 kW. To date relatively few manufacturers have developed such models. Currently, U.S. manufacturers are developing machines with rated outputs of 1 to 2 megawatts.

3.2.2.1 Performance Characteristics

Both horizontal and vertical axis machines are available in this size

Exhibit 3.5

RANGES OF SYSTEM COSTS FOR SMALL WECS (1982 $)

RATED OUTPUT (kW)	TOTAL SYSTEM COST (FOB, USA $)
.5	1,000-3,100
1.0	2,300-5,000
2.0	5,300-7,000
6.0	9,000-15,000
10.0	12,000-20,000
20.0	15,000-25,000
25.0	26,000-30,000
30.0	21,000-47,000
50.0	26,000-35,000
60.0	35,000-40,000
100.0	70,000-120,000

Reference: Wind Technology Assessment Study, Intermediate Technology Power Ltd., Reading Books. RG7 3PG UK, World Bank Project GLO/80/003, February, 1983.

range. The largest vertical axis machine available is a 500 kW Darrieus. The larger (over 1 MW) machines are all horizontal axis machines. Cut-in wind speeds are higher than those of the smaller machines (under 100 kW) and are usually between 12 and 14 mph (5.4 and 6.3 m/s). This is true for the vertical axis machines as well. The rated wind speed for these machines is also higher than those of the smaller machines (under 100 kW) and are usually between 25 and 30 mph (11.2 and 13.4 m/s). Horizontal-axis machines are generally of the propeller type with two or three airfoil blades.

System performance of these machines has been impressive. While failures have occurred in components of several systems, overall performance has equalled or exceeded most manufacturer's expectations. Power coefficients of 0.4 have been achieved (compared to a theoretical maximum of 0.59). Capacity of (ratio of actual power produced to rated power) 30-40 percent have been achieved, and availability is projected to be at least 90 percent.

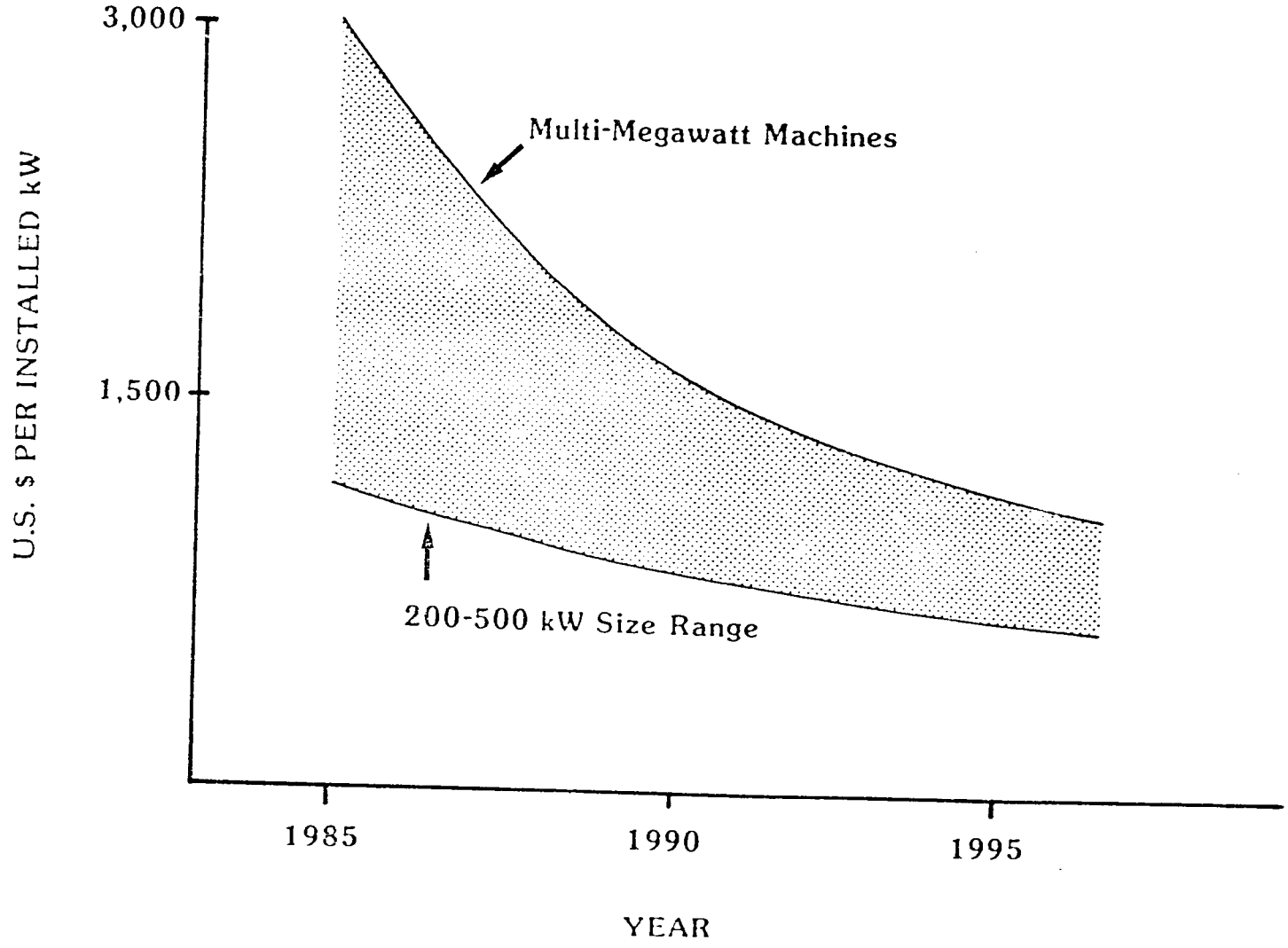
Much is still being learned about the operation and maintenance of such large machines. Improvements in system and component design are expected as a result of several years of operating experience.

3.2.2.2 System Costs

Capital costs of machines in this size range vary greatly because of the large size difference, the different levels of technology and management skills of the manufacturer and because the machines are only prototypes. With the present designs, the dominant cost factor for this size category is the production volume and order size. Exhibit 3.6 presents cost projections for large WECS. As seen in the exhibit, the multi-megawatt machines are considerably more expensive at present because there are only a few prototype models in operation. Significant cost reductions will be realized as a result of mass production and technological advances in system components.

Exhibit 3.6

COST PROJECTIONS FOR LARGE WECS



3.3 SYSTEM COMPONENTS

3.3.1 Wind Turbine Rotor

Major performance variations in wind machines generally will involve blade design. The diagrams and discussion that follow apply to both horizontal-axis and vertical-axis machines.

One popular blade material is wood, either laminated or solid, with or without fiber glass coatings (Exhibit 3.7). Uncoated wooden blades usually have a copper or other metal leading edge cover for protection against erosion by sand, rain, and other environmental factors.

The extruded hollow aluminum blade first was installed on a WECS in the early 1950's. This blade construction is being used again, especially for the Darrieus machines.

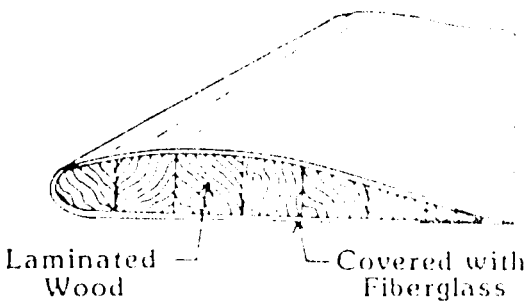
Built-up fiberglass blades with honeycomb or foam cores, or hollow cores (except for a tubular structural spar), are also being used, as are built-up sheet aluminum blades. All these methods of construction have a history of service life in WECS applications as well as in many aerospace applications.

It is important to understand the various methods of rotor speed control. Blades are designed to withstand a certain centrifugal force and a certain wind load. The centrifugal force tends to exert a pull on the blades, whereas wind loads tend to bend the blades (Exhibit 3.8). A control is needed to prevent over-stressing the blades in high winds. Obviously, one could design a wind turbine strong enough to withstand the highest possible wind, but this would be an expensive installation compared to a more fragile unit having a good control system.

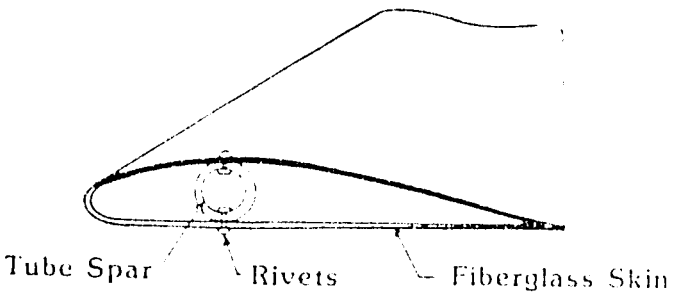
Two primary methods exist for controlling a wind turbine: 1) tilting the windwheel out of excessive winds and 2) changing the blade angles (feathering) to lower their loads. Exhibit 3.9 illustrates these two methods.

Exhibit 3.10 illustrates a simple mechanical mechanism used to control

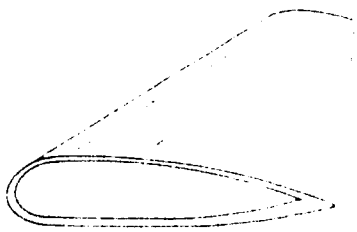
Exhibit 3.7
DIFFERENT BLADE CONSTRUCTION METHODS



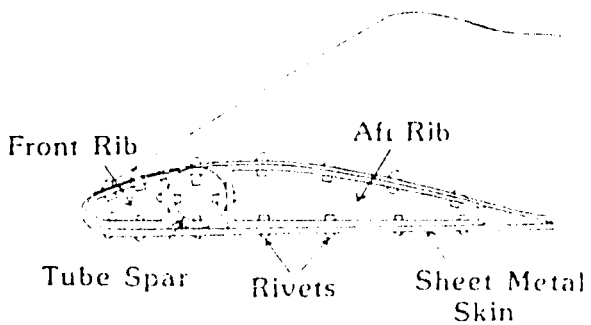
SOLID WOOD BLADE



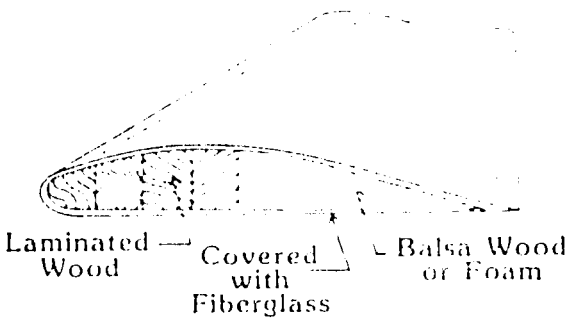
TUBULAR SPAR, WITH MOLDED FIBERGLASS SKIN



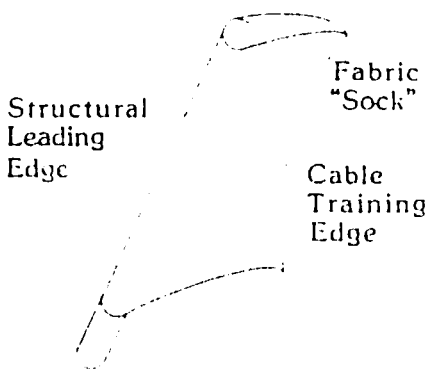
EXTRUDED HOLLOW METAL BLADES



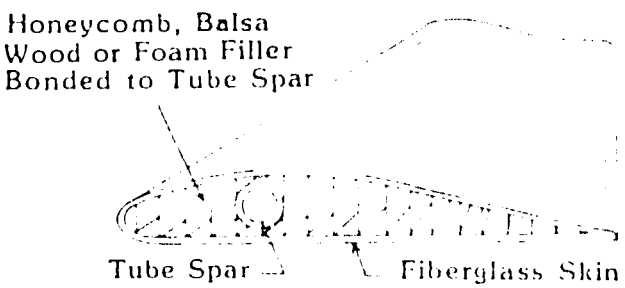
TUBULAR SPAR, WITH METAL RIBS AND SKIN



PARTIALLY SOLID BLADE



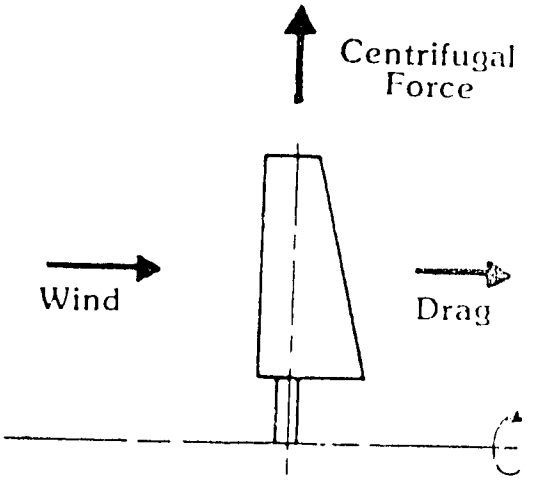
SAILWING CONSTRUCTION



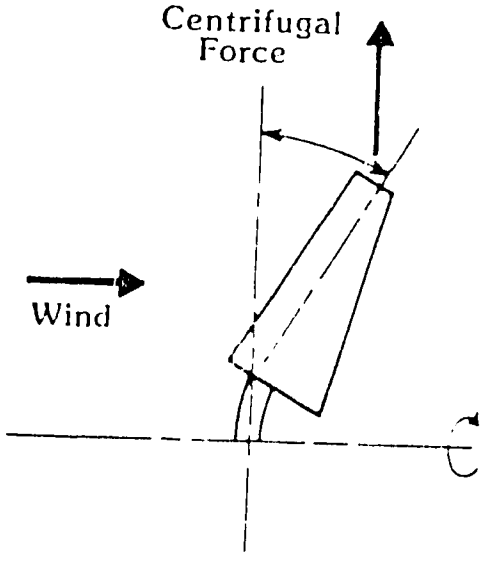
COMPOSITE BLADE CONSTRUCTION

SOURCE: PARK, Jack and Schwind, Dick. Wind Power for Farms, Homes, and Small Industry. Nielsen Engineering & Research, Inc., Mountain View, CA., Department of Energy Contract E(04-3)-1270, September, 1978.

Exhibit 3.8
LOADS ON A WIND TURBINE BLADE



BLADE WITHOUT BENDING DEFLECTION



BLADE WITH BENDING DEFLECTION

Exhibit 3.9

TWO METHODS OF WIND TURBINE CONTROL BY TILTING THE ROTOR

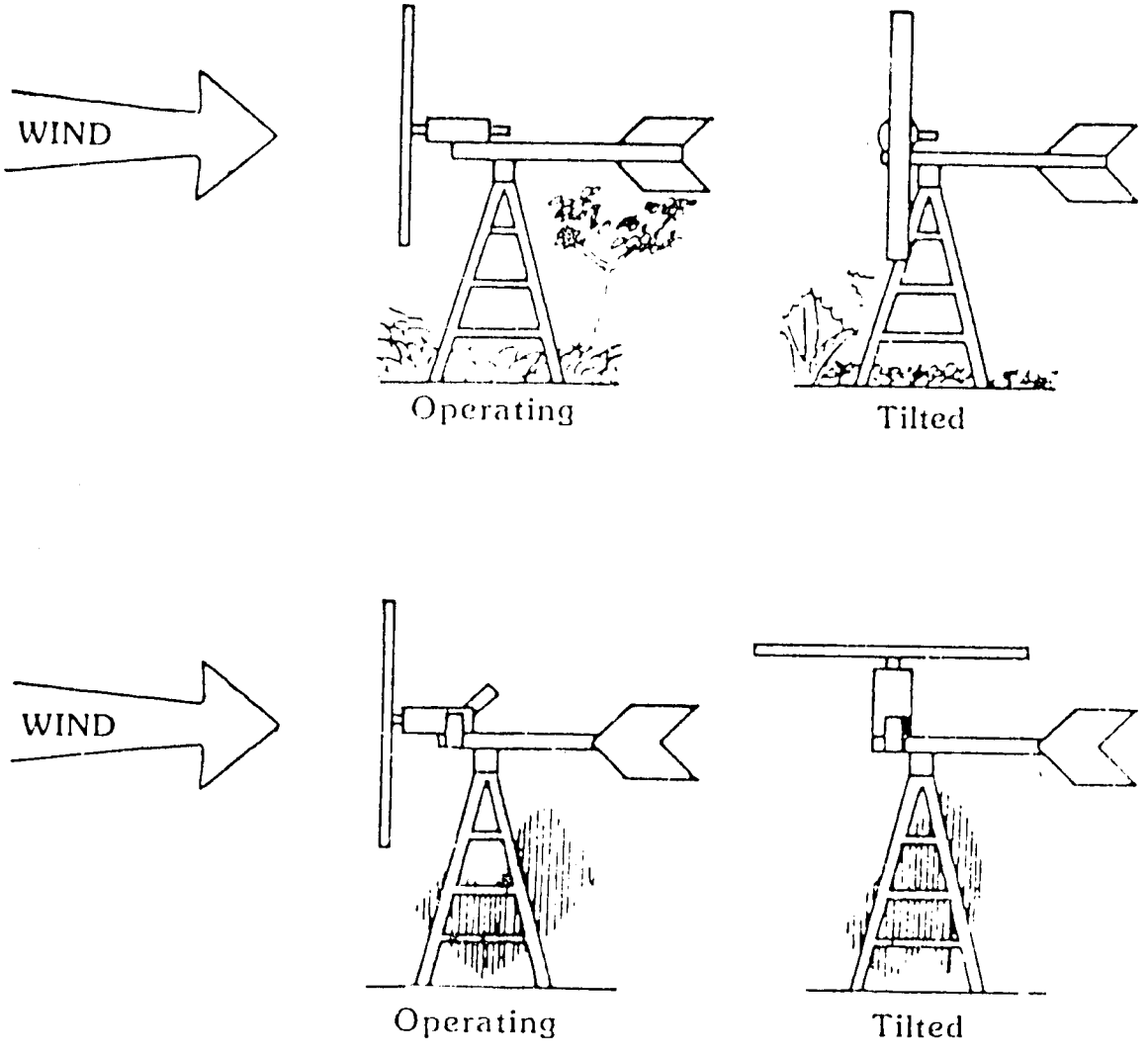
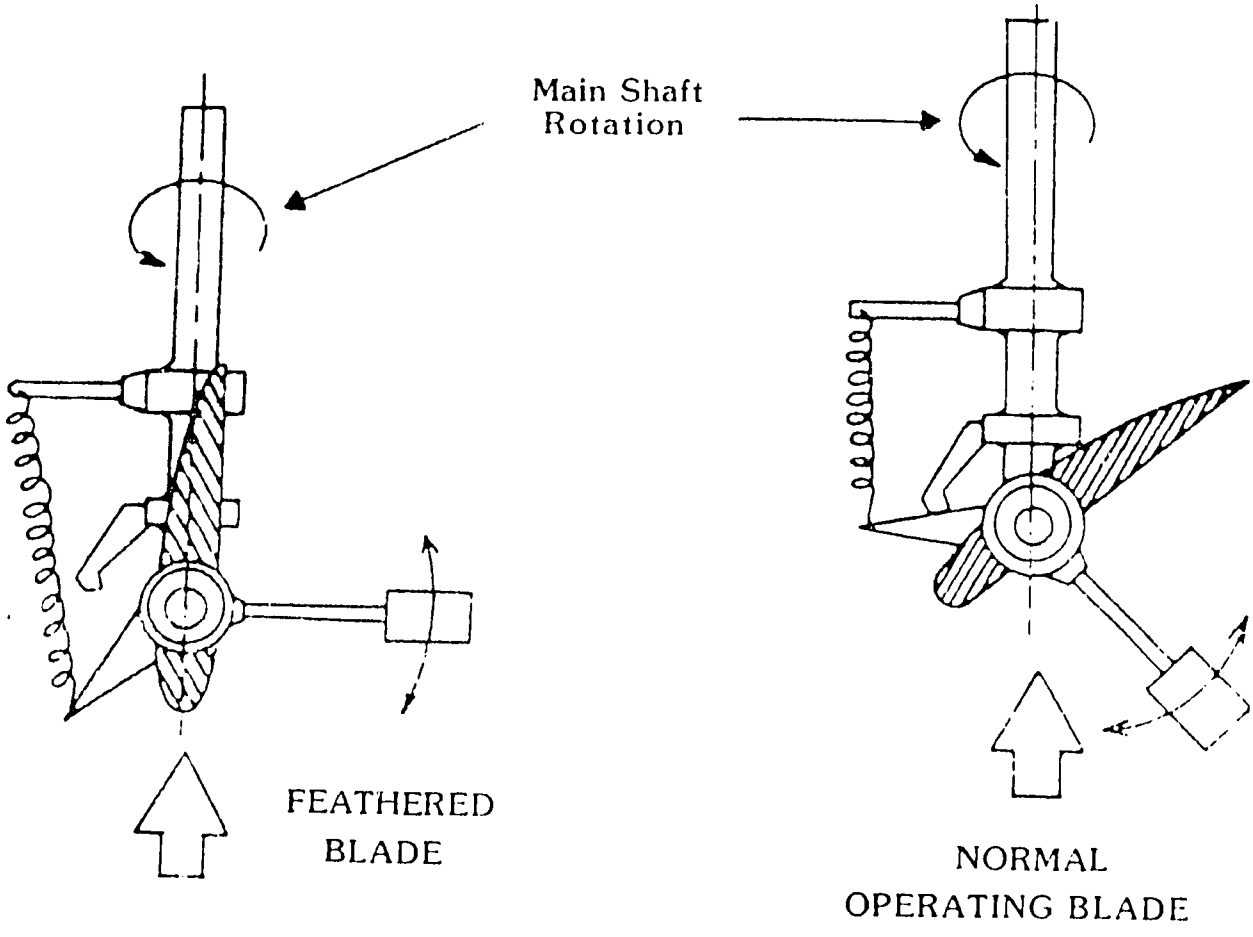


Exhibit 3.10

BLADE FEATHERING CONTROL



blade angle (sometimes called blade pitch angle) for feathering the blades. Notice that the leading edge of the blade in its normal position is at an angle suitable to cause blade motion in the direction indicated. As blade rpm increases, centrifugal forces on the flyweight cause the weight, which is connected to the blade, to move around the blade center pivot shaft and cause the blade to pitch toward the feathered position. The feathered position pulls the leading edge of the blade into the wind to reduce or eliminate its driving force.

The Darrieus rotor (Exhibit 3.11), which is commercially available in the "egg beater" shape (this shape has been given the name troposkein), can be controlled using any one of two main methods:

1. A unique aerodynamic characteristic of the Darrieus rotor permits the blades to stall; that is, quit lifting or pulling, which slows them down.

2. Drag spoilers mounted either on the blades or the support structure can be mechanically or electronically actuated to slow the speed.

Darrieus rotors designed with straight blades (Exhibit 3.11) use variable blade pitch, in addition to these methods, to control rotational speed.

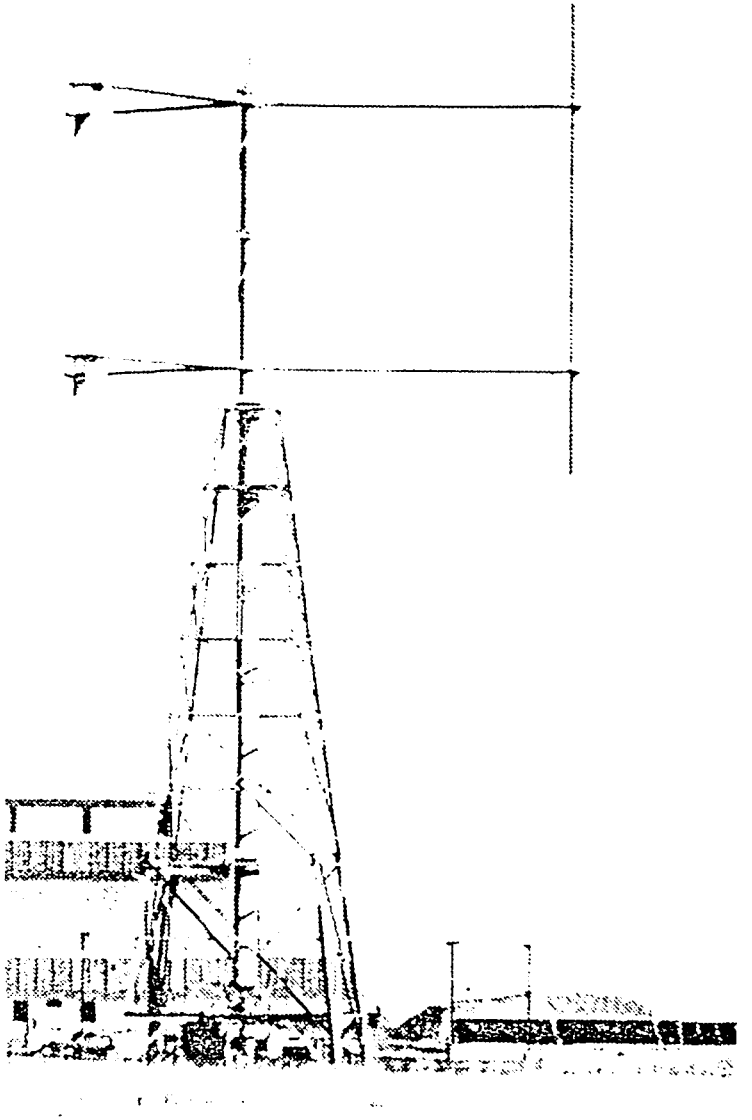
Turbine blade characteristics which are important in selecting a turbine are briefly discussed below.

Turbine blade solidity is the ratio of turbine blade(s) surface area to rotor swept area. The more turbine blades connected to a hub, the larger the turbine blade solidity.

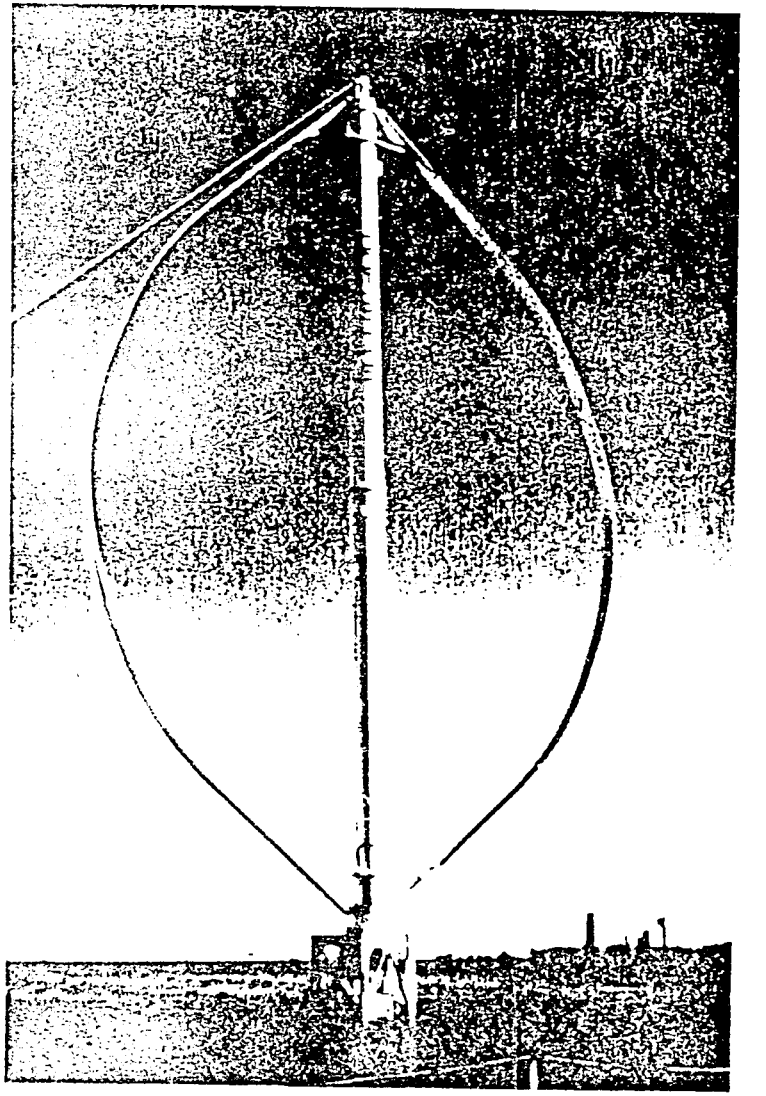
Tip speed ratio is the speed at which the windwheel perimeter is moving divided by the windspeed. If the wind is blowing at, say, 20 mph (9 m/s), and a windwheel is turning so that the outer tip of the blade is travelling at 20 mph (9 m/s) around a circular path, its tip speed ratio equals 1.0.

Exhibit 3.12 shows how the relative torque of various wind machines decreases with increasing tip speed ratio. As shown, high torque rotors require a

Exhibit 3.11
DARRIEUS ROTOR DESIGNS

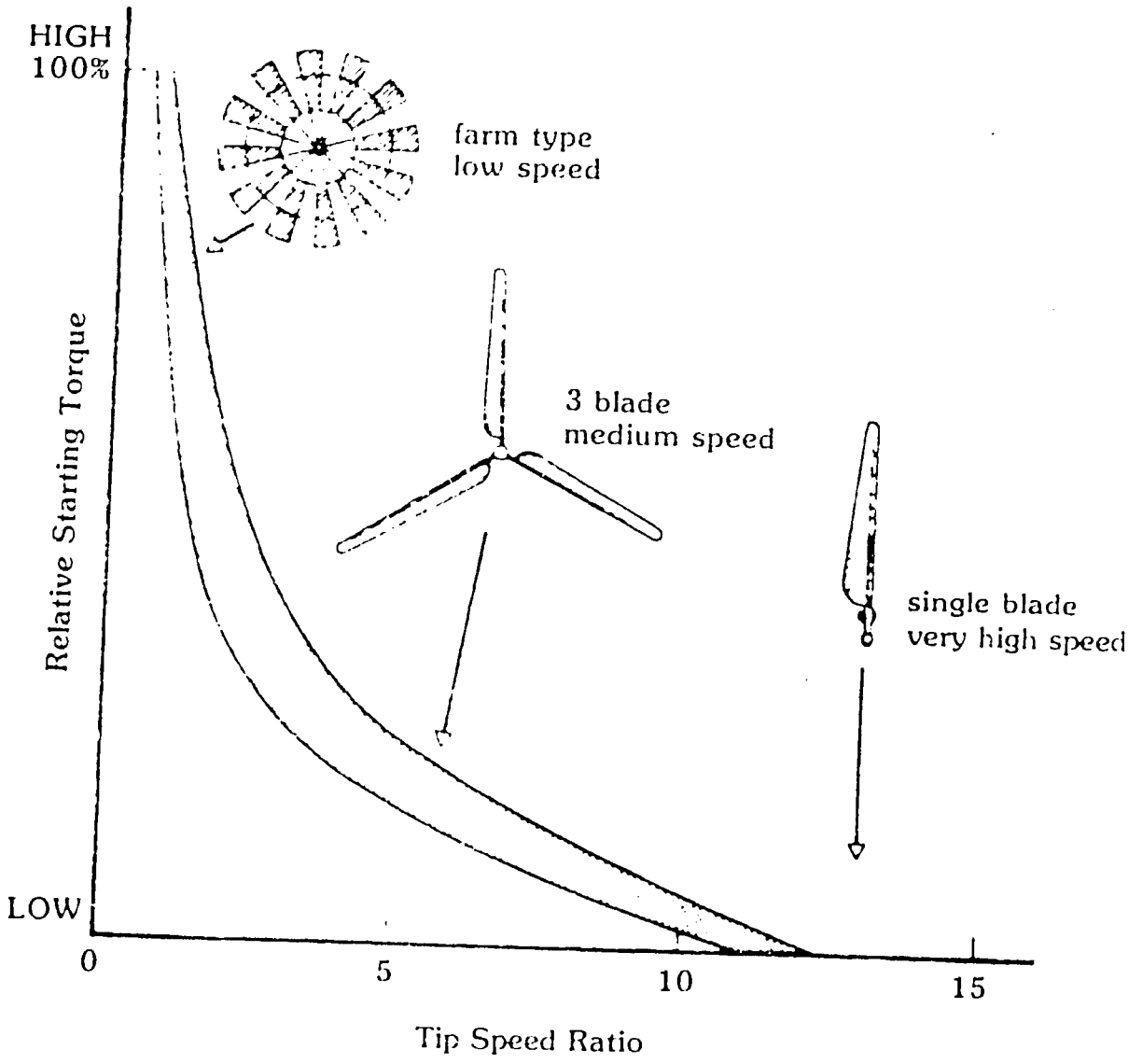


DARRIEUS ROTOR WITH STRAIGHT BLADE



DARRIEUS ROTOR WITH CURVED BLADES

Exhibit 3.12
RELATIVE STARTING TORQUE



SOURCE: PARK, Jack and Schwind, Dick. Wind Power for Farms, Homes, and Small Industry. Nielsen Engineering & Research, Inc., Mountain View, CA., Department of Energy Contract E(04-3)-1270, September, 1978.

high solidity (required for mechanical application), and that type of turbine works best at low tip speed ratios. Exhibit 3.13 shows how the best operating tip speed ratios change with solidity.

The relative efficiencies of commercially available wind machine designs is compared with an ideal machine (with a maximum efficiency of 59.3%) in Exhibit 3.14. Notice that the efficiency is also related to tip speed ratio, as is starting torque.

System Power Coefficient (Cp) is defined as the ratio of wind system power output to the power available in the wind. Cp includes rotor, drive train and generator efficiencies (for wind generators), as follows:

$$\text{System Cp} = \text{Rotor Efficiency} \times \text{Drive Train Efficiency} \times \text{Generator Efficiency} \qquad \text{Eq. 3.1}$$

Drive train and generator efficiencies are most commonly about 90%. Thus, the only variable which significantly affects Cp is Rotor Efficiency, which is dependent on turbine blade type (lift vs. drag) and aerodynamic profile.

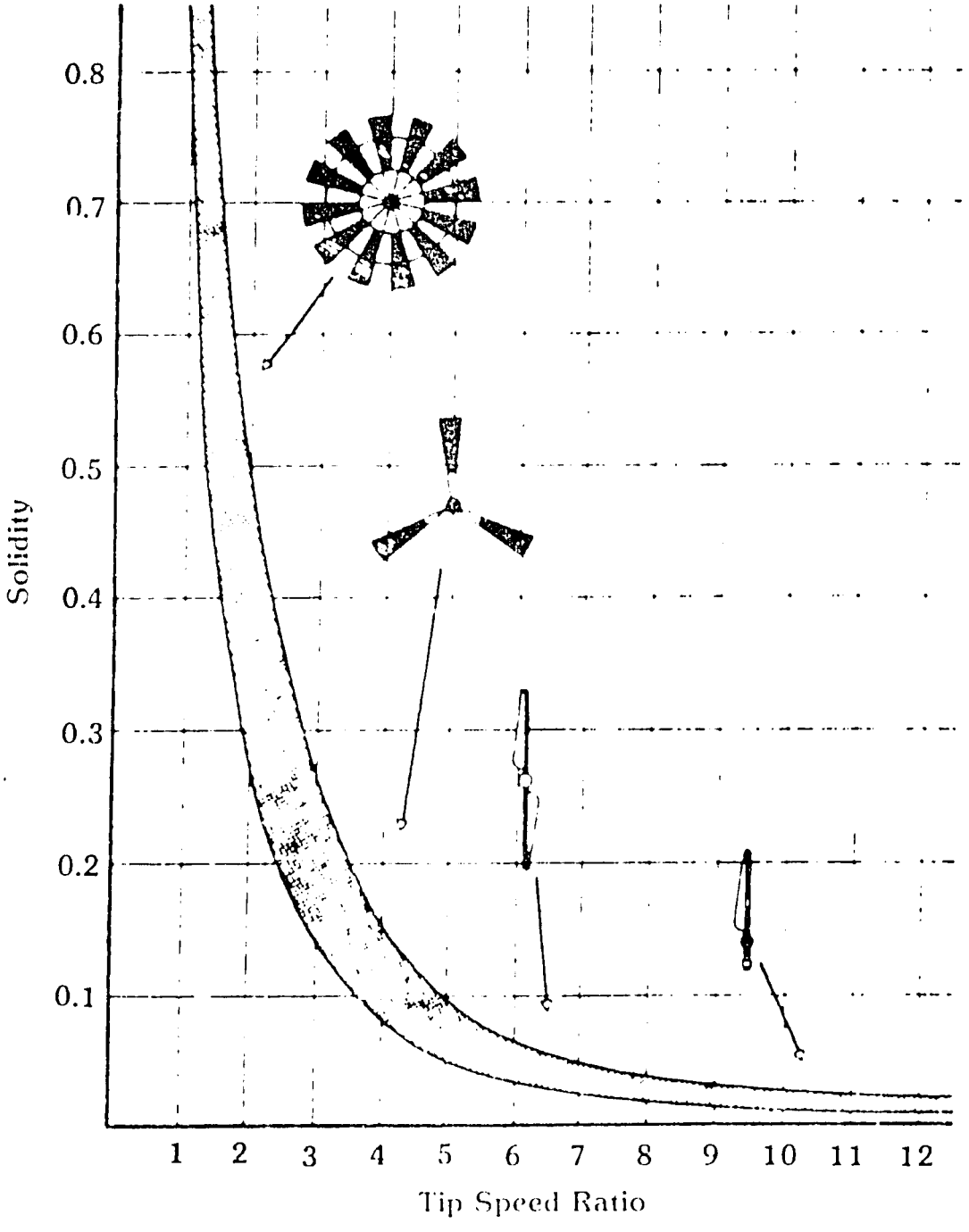
3.3.2 Generators For Electrical WECS

Generators used in electrical WECS are one of three standard types: a synchronous generator, commonly referred to as an alternator; an induction generator; or a dc generator. The first two produce alternating current.

An induction generator is like an induction motor, operated as a generator by being driven above synchronous speed. Induction generators are self-regulating in adjusting to varying torques and load conditions, and can act as motors for starting. Most small WECS (less than 100 kw) use induction generators.

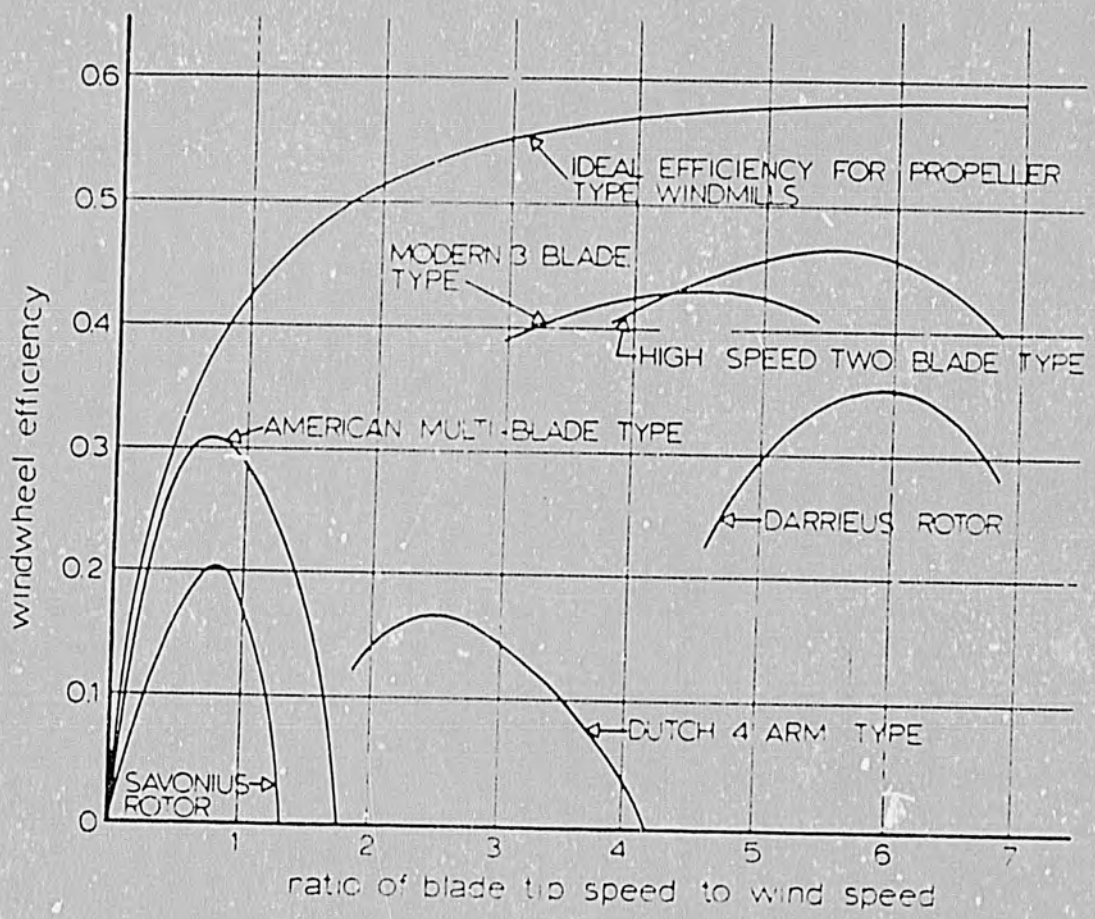
Synchronous generators (alternators) must run, like electrical clock motors, precisely in step with the frequency of the load. An alternator therefore requires special circuitry and controls for synchronizing before it connects to the load. Most large WECS, and those currently under development, employ alternators.

Exhibit 3.13
SOLIDITY OF SEVERAL WIND MACHINES



SOURCE: PARK, Jack and Schwind, Dick. Wind Power for Farms, Homes, and Small Industry. Nielsen Engineering & Research, Inc., Mountain View, CA., Department of Energy Contract E(04-3)-1270, September, 1978.

Exhibit 3.14
TYPICAL PERFORMANCE OF SEVERAL WIND MACHINES



SOURCE: PARK, Jack and Schwind, Dick. Wind Power for Farms, Homes, and Small Industry. Nielsen Engineering & Research, Inc., Mountain View, CA., Department of Energy Contract E(04-3)-1270, September, 1978.

Induction generators have advantages over alternators in simplicity of control and start-up, and in some situations, in their ability to re-establish normal operation after electrical and mechanical transients. Also, induction generators automatically cease generating when the load is removed (unless capacitors are connected), thus reducing the possibility of hazardous voltages being produced by an isolated generator.

Generation of dc usually involves generation of ac inside the generator, then conversion of the ac to dc by means of brushes and a commutator. This has been the common design for dc generators until recently. A method more commonly used now, because of improvements in diode technology, is to rectify the ac output of the alternator to dc.

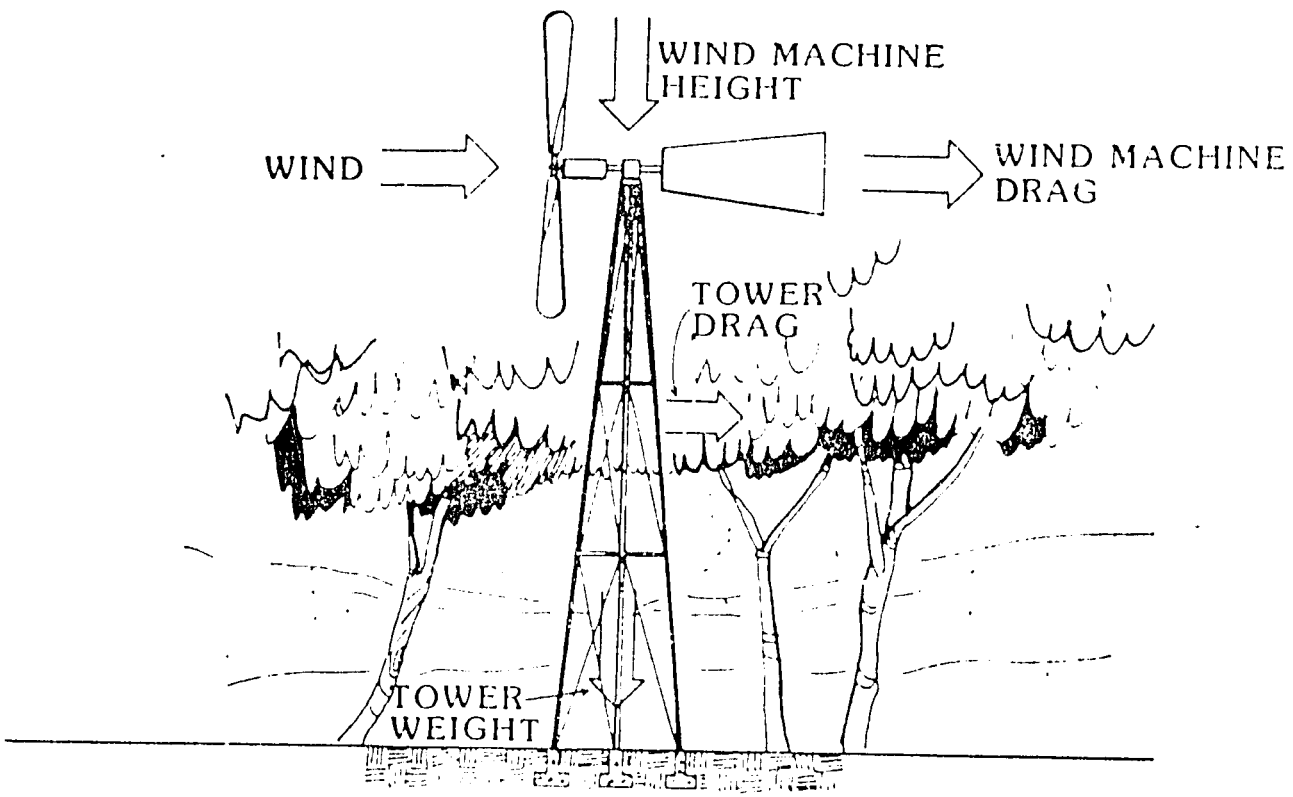
Generators and alternators are selected or designed by WECS manufacturers according to their own criteria, which includes cost, weight, performance, and availability. Thus, in the selection of a suitable wind turbine, units with specially made generators, as well as units with truck, automotive, and industrial alternators are found. There can be a problem regarding availability of spare parts for custom, as well as industrial equipment. In some cases, the WECS manufacturer designs his own generator as a means of improving overall system performance.

3.3.3 Wind System Towers

It is essential to support your wind system, be it vertical-axis or horizontal-axis, to capture the higher winds above the ground and to be well above the nearest trees. Supporting a wind turbine that weighs several hundred pounds is no simple task and requires a rigid structure of some sort. Towers are subjected to two types of loads, as illustrated in Exhibit 3.15: weight, which compresses the tower downward, and drag, which tries to bend the tower downwind.

Towers are made in two basic configurations: guy-wire supported, and

Exhibit 3.15
TOWER LOADS



cantilever or unsupported (sometimes called freestanding) (Exhibit 3.16). Also, given these two basic structural support configurations, towers are made with telephone poles, pipes, or other single column structures (Exhibit 3.17) as well as lattice frameworks of pipe or wooden boards.

Regardless of which tower design is selected, the overriding consideration is the selection of a tower that can support the wind turbine in the highest wind possible at a particular site. The load that causes many towers to fail is a combination of wind turbine and tower drag.

3.3.4 Energy Storage

There are three potentially attractive forms of energy storage which can be employed with a WECS system. These are batteries, pumped hydro and flywheel. At present, battery storage appears the most economical. Presented below is a description of each storage option.

3.3.4.1 Battery Storage

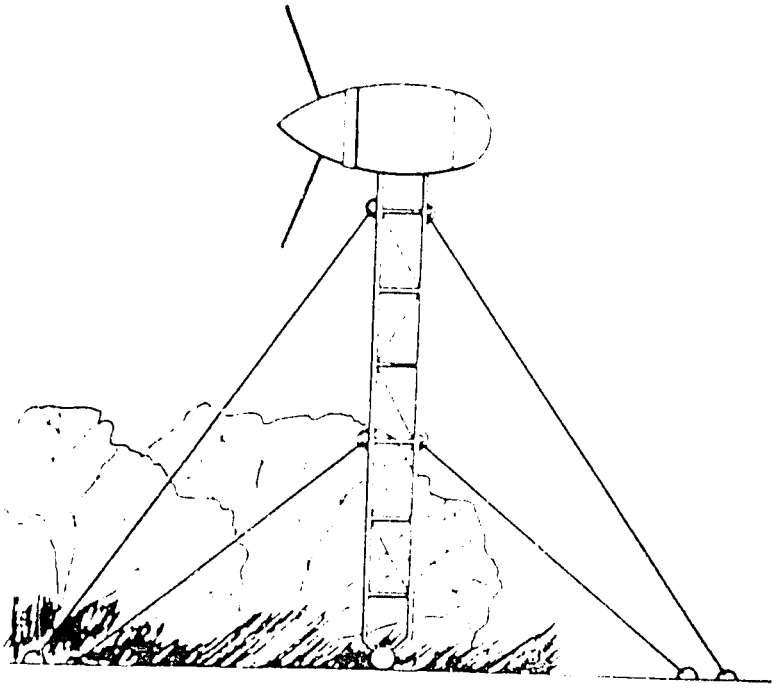
Batteries are storage devices that store dc electric energy in the form of a chemical potential, and release dc electric energy when needed via a chemical reaction.

The basic building block of a battery is a cell. Battery cells can be connected in series or parallel to form battery banks. The voltages of cells in series are additive, while the current through each is the same. In parallel cells, the voltage across each is the same, while the currents are additive.

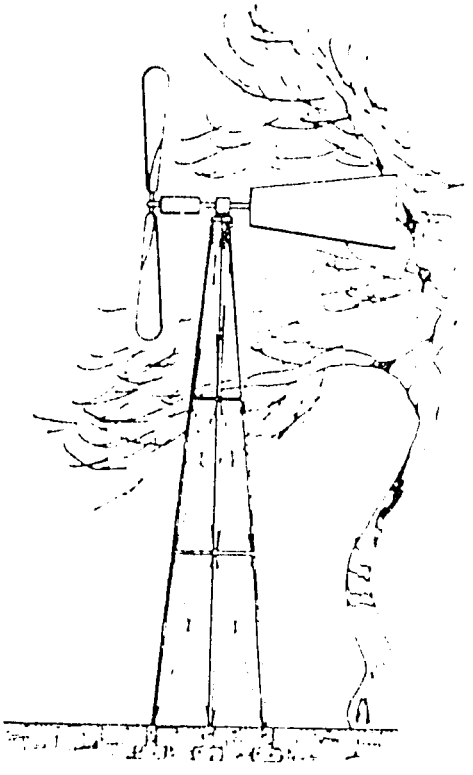
Cells are composed of three basic components: (1) the negative electrode that supplies electrons to the external circuit as it is oxidized during the discharge reaction; (2) the positive electrode which accepts electrons from the external circuit when it is reduced during discharge; and (3) the electrolyte that completes the circuit by furnishing the ions (i.e., electrically charged atoms) needed for conductance between the two electrodes.

Batteries are normally classified as either primary or secondary.

Exhibit 3.16
TWO TYPES OF TOWERS

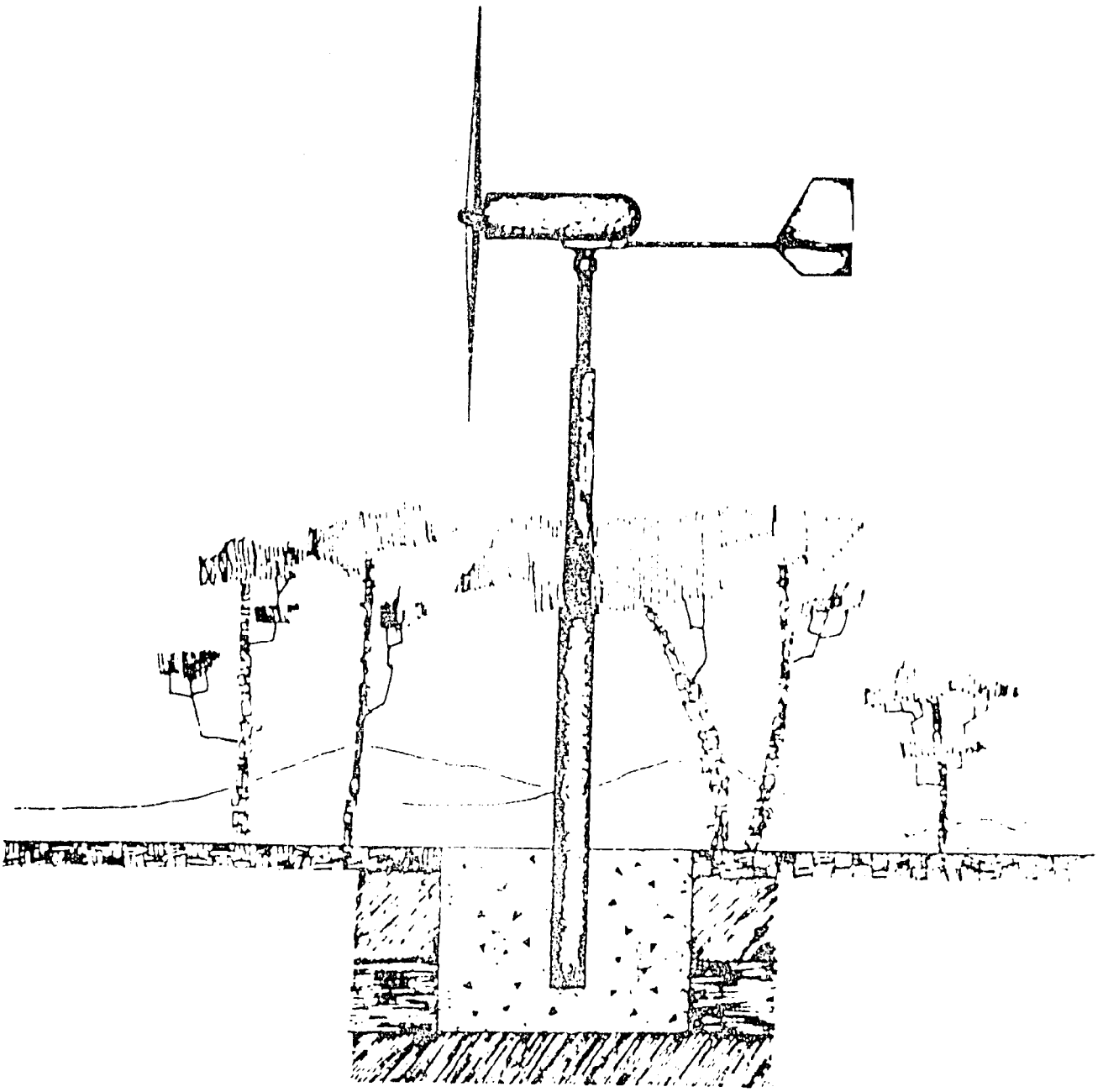


GUY WIRE SUPPORTED



FREE STANDING

Exhibit 3.17
FREE-STANDING PIPE TOWER



Primary batteries use active chemicals. After they are discharged, they can only be reused if new chemicals are added (e.g. fuel cells). Secondary batteries are designed to be used repeatedly by recharging. Charging and discharging occur through a change in the direction of current. The two most common secondary batteries for WECS applications are lead-acid and nickel-cadmium. Lead-acid batteries are the more frequently used, primarily due to their lower cost.

Lead-acid batteries are sometimes referred to by the type of electrode used (for example, lead-antimony, pure lead, or lead-calcium). Nickel-cadmium cells are constructed in two types, each having slightly different operating characteristics -- sintered plate and pocket plate construction.

Batteries are rated as having a certain storage capacity, that is, the amount of energy they can store. There is a limit to the amount of usable battery capacity, which is less than the rated capacity. Discharging the battery beyond this limit can result in permanent damage to the battery. This limit is referred to as the allowable depth of discharge. As temperatures decrease, the allowable depth of discharge also decreases.

3.3.4.2 Pumped Hydro Storage

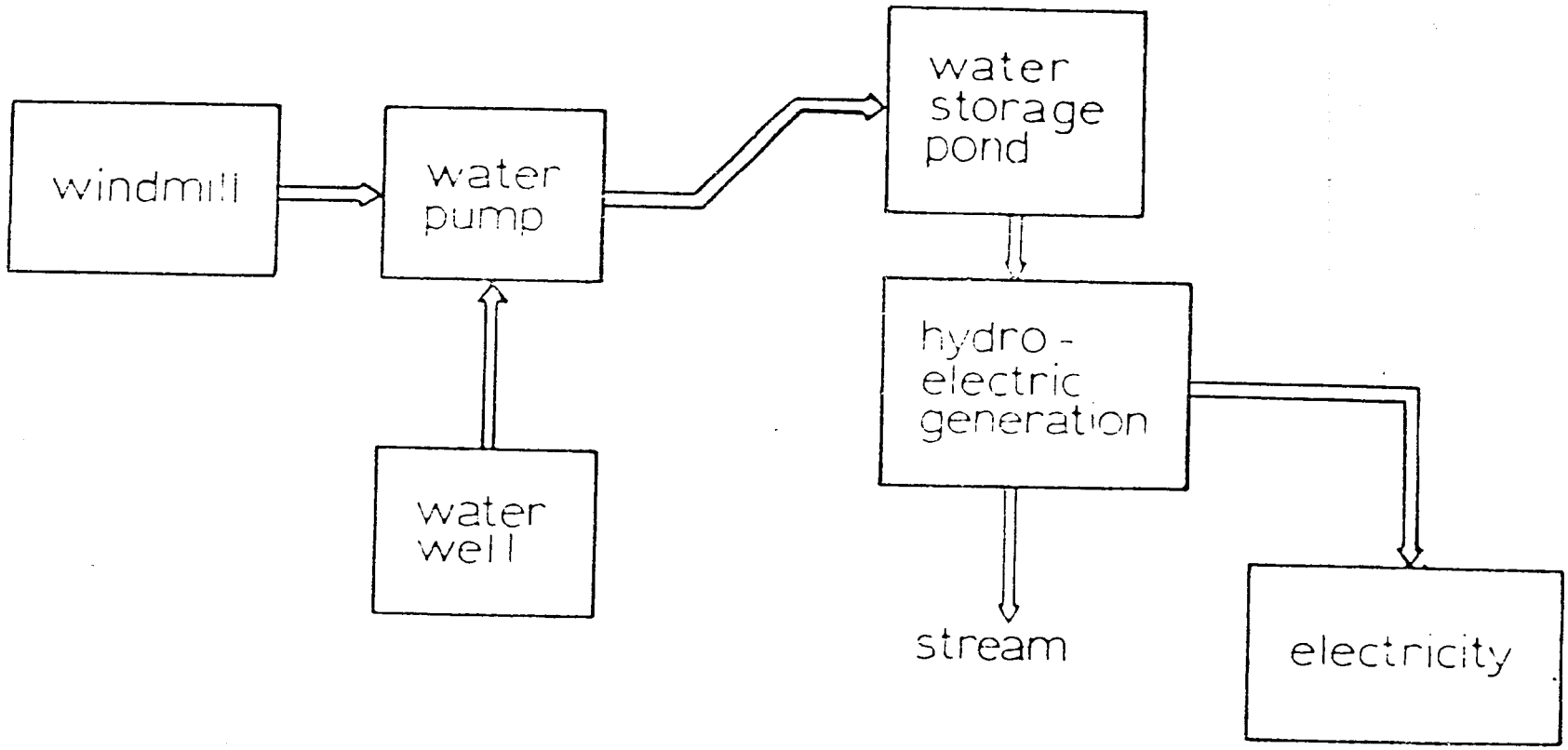
It may be that one wishes to simply store enough water for domestic uses. On the other hand, it may be that one prefers an electric system where wind power pumps water up a hill to a small lake. The lake then supplies this stored water to operate a small hydroelectric system which can recover the potential energy available in the lake, as illustrated in Exhibit 3.18.

The decision to use pumped water storage must be based on availability of land and such factors as: would the required amount of land be better used for something else; cost (bulldozing a lake can be expensive); and the end use of the pumped water.

3.3.4.3 Flywheels

Flywheels are devices which store energy in the form of rotational

Exhibit 3.18
WATER STORAGE FOR ELECTRICITY



mechanical energy. Old flywheel designs consisted of large, heavy-rimmed wheels, while contemporary flywheels are spoke-rimmed wheels made from lightweight materials.

Recent literature discusses an improved flywheel energy storage device, the super flywheel. The super flywheel is different from the traditional spoked-rim flywheel, which propelled mine cars and elevators. The older gyros were large, heavy-rimmed wheels, like a tractor tire filled with water, while super flywheels are thin and tapered and spin at a high rpm (Exhibit 3.19).

Various design studies illustrate that a small advanced flywheel energy storage unit should be cost-competitive with an equivalent battery system in the future, and will most probably weigh less. Thus, this storage unit should see great potential in future WECS applications.

3.3.5 Power Conditioning System

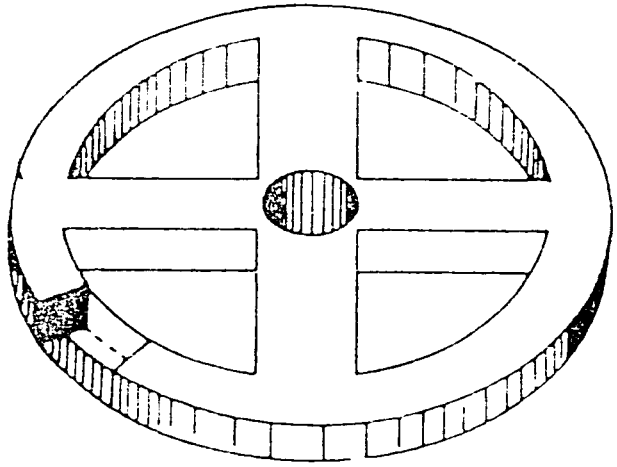
3.3.5.1 Controllers and Regulators

WECS producing ac power normally contain all of the equipment to control and regulate output in the turbine assembly. DC wind generators, on the other hand, require external systems to control and regulate power output.

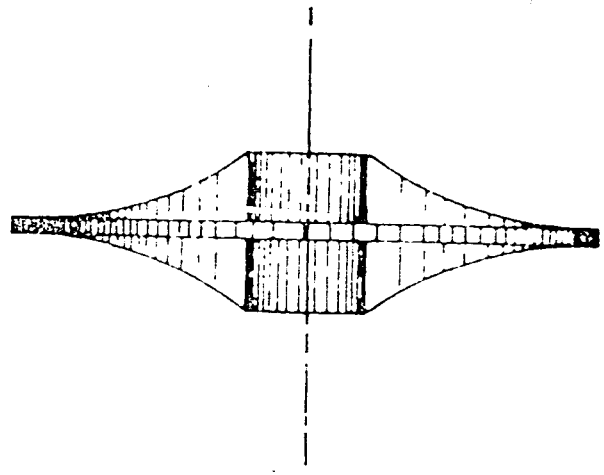
Regulators are used to limit WECS output in order to prevent battery overcharge and maintain constant voltage to the loads. Regulators can be characterized by their method of power dissipation--series or shunt.

Shunt-type regulators use zener diodes, transistors, contactors or solid-state relays to shunt excess current to ground. Series-type regulators use transistors, contactors or solid-state relay elements to switch off or reduce the flow of current from the WECS to the battery. Series regulators consume power at all times, whereas shunt regulators dissipate only that power not required by the loads. Shunting power to ground is not recommended with a WECS. It is much more economical to use a series regulator to control current flow to the batteries and a "dummy load" when the batteries are fully charged,

Exhibit 3.19
FLYWHEEL DIAGRAMS



CONVENTIONAL FLYWHEEL



SUPER FLYWHEEL

the series regulatory can transfer excess energy to a dummy load -- such as an ice maker, air compressor, etc. -- to perform useful work, instead of wasting the energy by shunting to ground.

The simplest type of regulator involves a passive method of controlling the regulation function, using a zener diode. Zener diodes can accommodate power and voltage from a few watts to 50 watts and up to 200 volts. Passive control results in a relatively wide voltage cutoff band. For larger systems and/or more accurate regulation, it is necessary to use active control systems.

Regulators with active control systems are more commonly referred to as controllers. They are more sophisticated, providing for more precise voltage regulation, proportional current control, and often for the adjustment of voltage control to compensate for changes in battery temperature.

3.3.5.2 Inverters

An inverter is used to convert dc power to ac power such that it can interact with a utility grid or ac loads. The precision of this conversion dictates the cost of the equipment. The precision required by the system is determined by the loads.

The primary indication of the quality of the output is its wave form. Perfect ac is in the form of a sine wave. Inverters can be purchased that produce square wave, near-sine wave and sine wave ac. The selection of one type of another depends on the loads. For resistive elements and some motors, simple square wave ac is acceptable. For precision equipment, however, sine-wave or near-sine wave ac is necessary. In cases where the user wants to link to a utility grid, only sine-wave quality ac is acceptable. Because the prices associated with the inverters that produce these wave forms vary significantly, it is important for purchasers to recognize the minimum acceptable quality of power for their loads.

Another important characteristic of an inverter is its efficiency.

Efficiency varies somewhat with the type of inverter. Inverters can be classified into two major types--solid-state and rotary. Solid-state inverters have higher efficiencies--in the range of 70-95 percent. Rotary inverters have efficiencies of less than 85 percent. However, despite the lower efficiencies, rotary inverters can be more effective in motor start-ups. In general, inverter efficiency decreases with decreasing load.

Manufacturers often offer specialized circuits and switches for their inverters. For example, some offer circuits designed for motor start-ups. Others offer automatic on/off switches which eliminate power consumption when not in use.

There are three basic types of inverters: line-commutated, self-commutated and stand-alone. In a line-commutated inverter, switches are triggered by the timing on the utility lines. The switches of a self-commutating inverter are triggered by an internal clock in the inverter. Self-commutated inverters are more expensive due to the additional circuitry; however, some are capable of operating in a stand-alone mode. Stand-alone inverters can operate only in stand-alone mode.

3.3.5.3 DC-to-DC Converters

A dc-to-dc converter is used to step dc voltage up or down. For example, if the WECS produces 240 volts dc but one of the attached loads require 48 volts dc, then a dc-to-dc converter is necessary. In general, a WECS used to power a single dc electrical load can be designed such that a dc-to-dc converter is not necessary. In such cases, the use of the converter is discouraged since it adds to system cost and detracts from efficiency.

3.3.6 Instrumentation and Controls

Identification of instruments and controls for a WECS must be examined in the context of the purpose of the instrumentation. That is to say, is the instrumentation being used to operate, monitor or evaluate the design of a WECS? For example, an unattended system designed for cathodic protection does not

require any instrumentation. On the other hand, an agricultural processing system in an educational setting used to evaluate optimum system design justifies a highly instrumented system.

Aside from the purpose of the instrumentation, other factors to consider are the necessary sophistication required to achieve that purpose and the distance the system is from institutional support. These factors are interrelated, in that the farther the installation is from the monitoring institution or repair facility, the less elaborate the instrumentation should be. For example, take the case of measuring the discharge flow rate of a pump. Four options are available:

(1) A bucket of a specific volume and a stopwatch will determine an instantaneous flow rate.

(2) A basic in-line flow meter with float also shows an instantaneous flow rate.

(3) A stripchart recorder measures and records the flow rate continuously.

(4) A flow meter with solid-state magnetic pickup and automatic data transfer provides continuous, long-term monitoring.

Exact knowledge of the flow rate will not improve system operation or reliability. However, in terms of evaluating the design, flow rate can be very important. A second point to be made from this example is related to the cost involved with the increase in sophistication. If only an instantaneous reading is needed, it is best to use the simplest and least costly option--option one. The third option would undoubtedly fail in a very remote site as soon as the special paper and ink pens were exhausted.

For attended systems, the minimum instrumentation and controls for continued operation of given type systems are as follows:

<u>Applications with Battery Storage</u>

- a voltmeter on the control panel
- low voltage disconnect control (battery protection)
- circuit breaker/fuse protection between all loads and the batteries

Pumping

- low water level protection for the pump (especially in situations of low well-yield rates with respect to draw)

Refrigeration

- low-high temperature alarm with manual reset
- thermometer
- run-time meter

Agricultural Processing

- ammeters on all motors

One level above minimum instrumentation involves training an operator to perform simple and safe system/component trouble-shooting and repair. In this situation, the following additional instruments are recommended: a portable voltmeter, portable ammeter and run-time meters.

Moving to a higher level of instrumentation and control is recommended only for systems that are being used for R&D and are located near test/educational centers. The number of features that could be added to an instrumentation package is too large to enumerate here. Even in the case of a given instrument (like the flow meter discussed earlier), there can be numerous alternatives, varying in their levels of sophistication. The costs associated with various options for instrumentation and control vary significantly. Therefore, the following basic rules of thumb are recommended:

(1) If the instrument is not necessary, given the purpose of the system do not include it.

(2) If an instrument is necessary, use the simplest alternative to meeting the need.

(3) The complexity of the instrumentation and control should be inversely proportional to the distance between the system and technical expertise.

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4.0 SYSTEM DESIGN CONSIDERATIONS

4.1 OVERVIEW

In designing any type of system, be it a WECS or not, there are a few basic principles to keep in mind:

(1) Keep the system as simple as possible.

(2) Use local labor and materials whenever possible.

(3) To the degree possible, involve the ultimate users in the conceptualization, design, installation, start-up and testing of the system.

These items may seem almost too obvious to state, yet it is surprising how many times these rules have been violated.

Designing involves a series of tradeoffs, all of which eventually boil down to cost. Exhibit 4.1 identifies steps in the system design process. These steps are discussed in the following sections.

4.2 LOAD CHARACTERISTICS

4.2.1 Application

Your demands will establish whether the windwheel (rotor) will drive mechanical devices, such as pumps, compressors, or grinding wheels; or electrical devices, such as generators or alternators. Exhibit 4.2 can be used to focus your thinking on the steps required to accomplish a rational selection of the most appropriate WECS. To visualize some of the many ways a windmill can be used as part of a complete system, study Exhibit 4.3. You can follow any path on this diagram that leads from top to bottom, from wind turbine to wind user. A bold line connects the components in the most common wind systems designs. Although most of the possible systems shown in the exhibit are not economically practical, one can begin to appreciate the versatility of a WECS.

For stand alone applications, accurate determination of system loads is essential for system design and component selection. For a wind farm, (grid

Exl t 4.1

SYSTEM DESIGN PROCESS

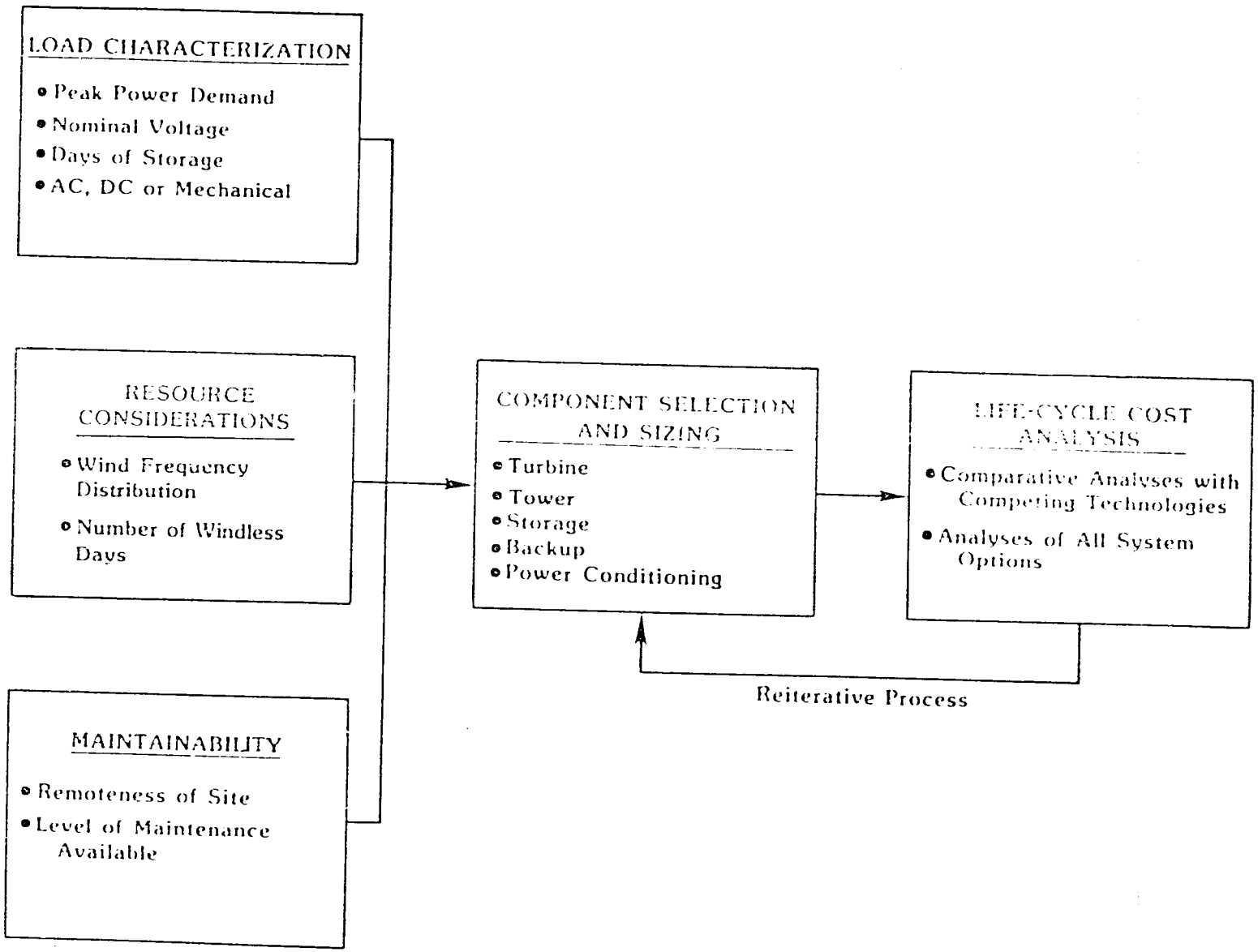


Exhibit 4.2
SYSTEM DESIGN STEPS

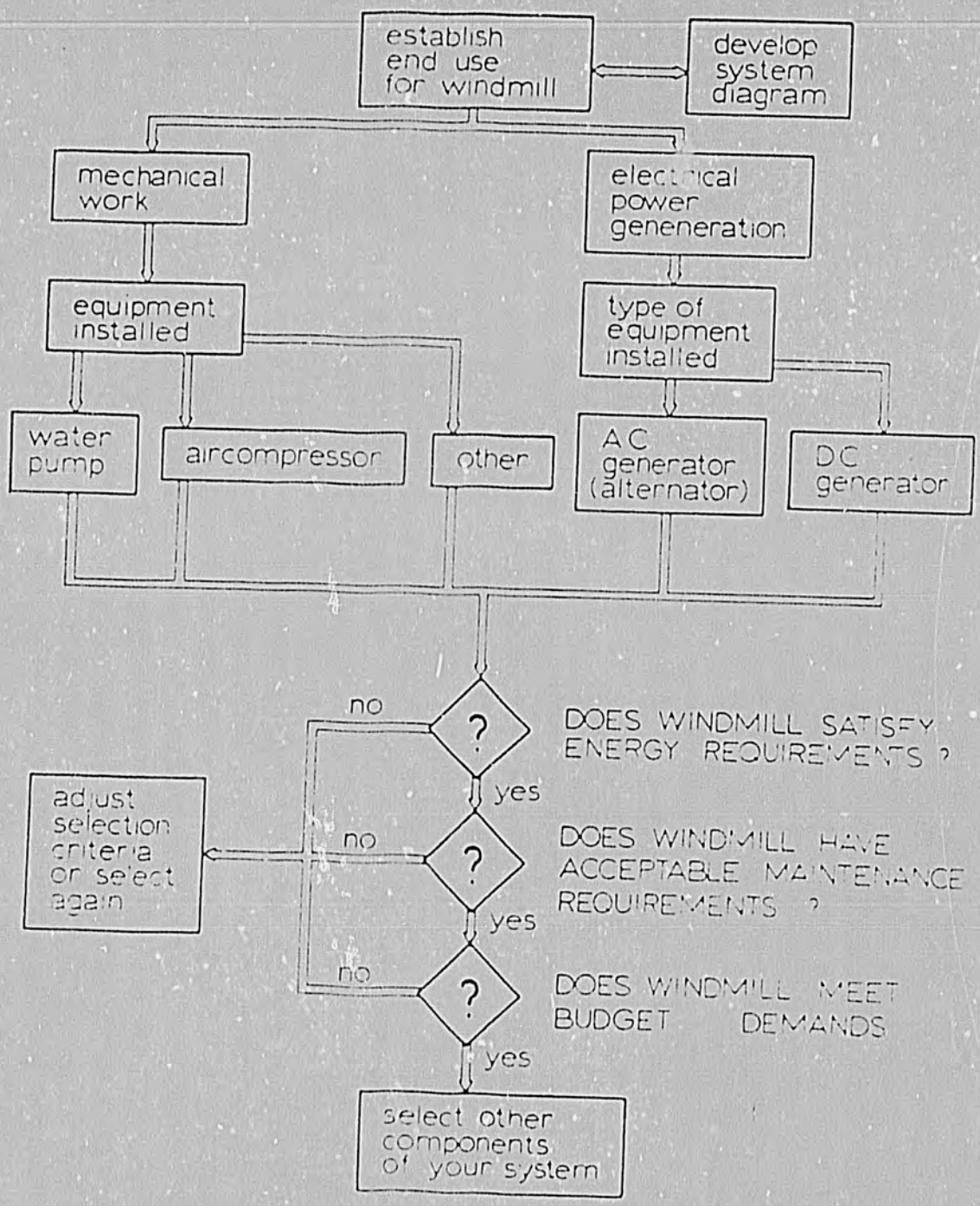
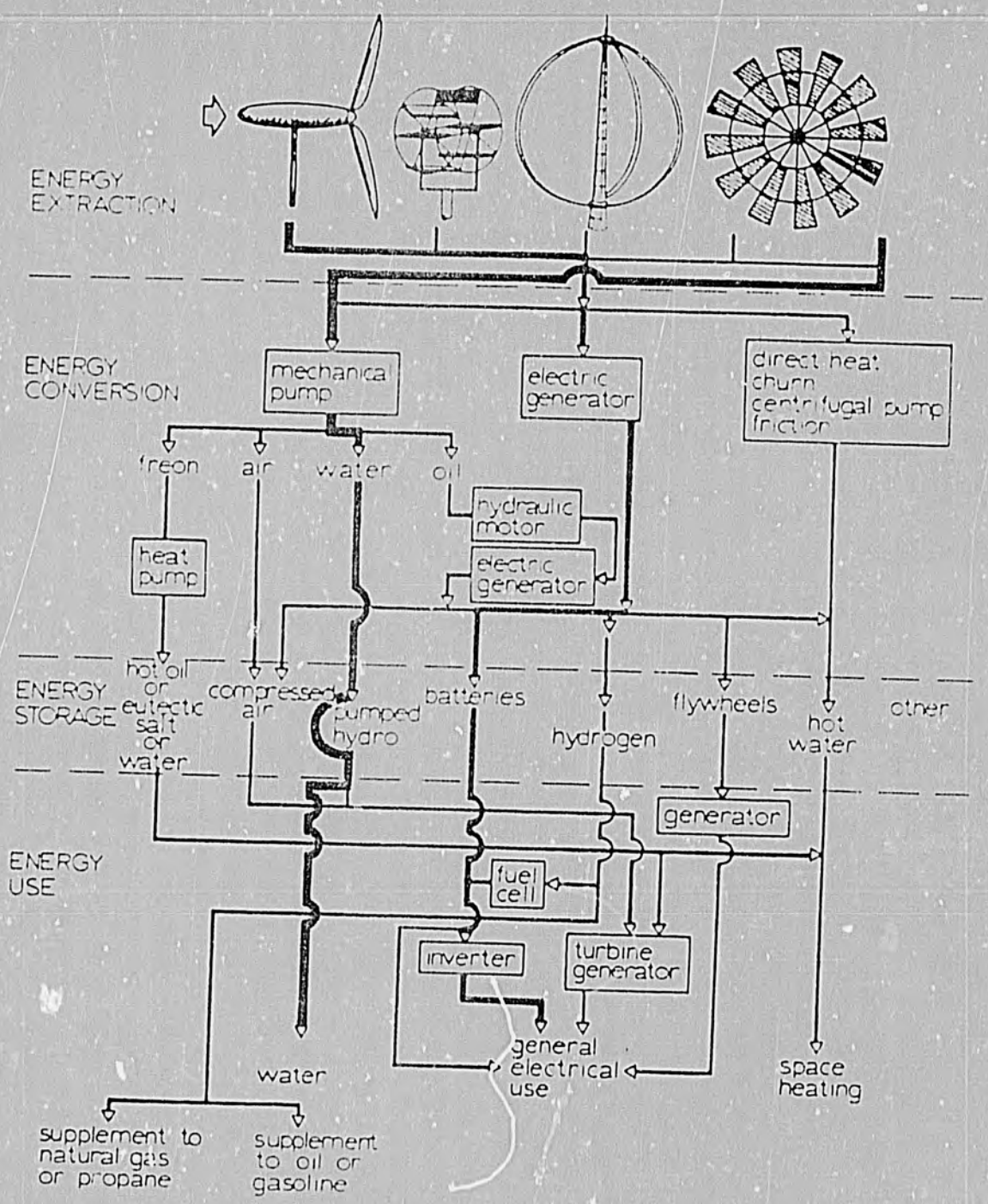


Exhibit 4.3
WECS CHOICES



connected) application, accurate load determination is not essential, since the wind generators are supplying as much electricity to the grid as is economically viable.

4.2.2 Required Reliability

It is important to know how critical it is that loads be supplied with power at a given time. For example, a telecommunications system may have to operate twenty-four hours a day -- no excuses. In this case, a WECS and a large storage system (to supply the load during a series of windless days) and possibly even a backup system may be considered. On the other hand, maybe battery storage or backup may not be needed in an electric pumping system where it is sufficient to pump only during times when it is windy (the pumped water can be stored in a tank).

If several loads are powered by a given WECS, load priorities should be set. In the case where WECS output on a given day is low and/or the batteries are at a low state-of-charge, loads should be disconnected in the order of reverse priority. This load-shedding can be done manually by an operator or automatically if designed for in the power conditioning system.

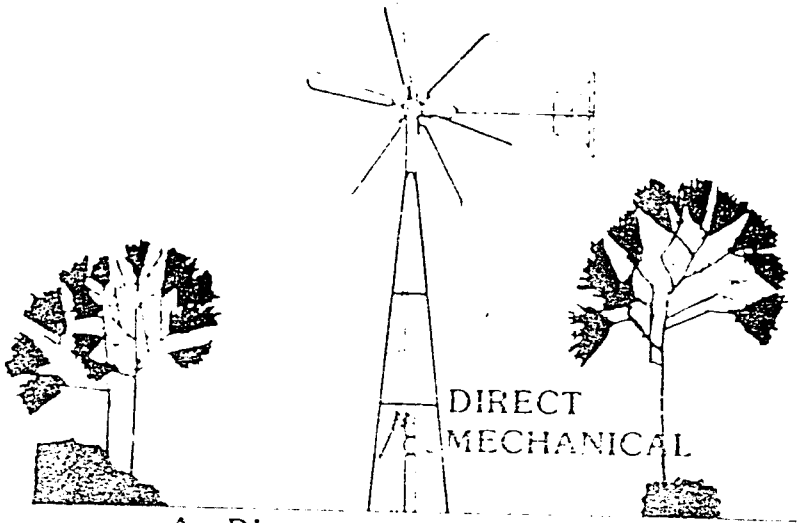
4.2.3 Load Estimation

4.2.3.1 Mechanical Applications

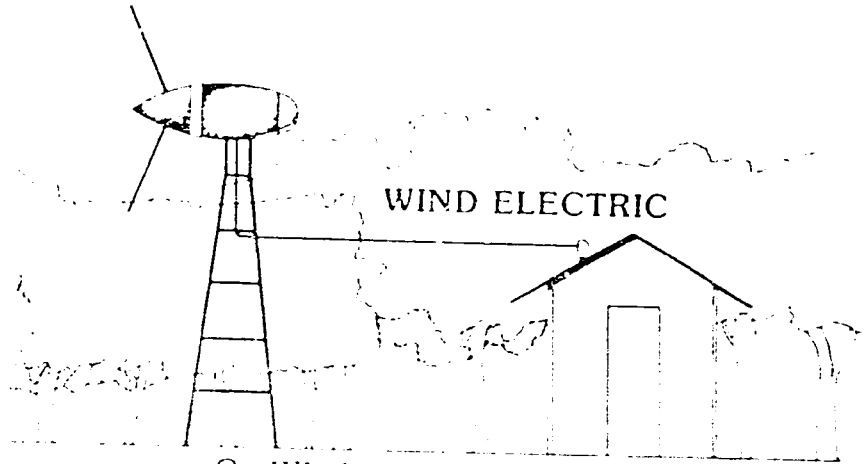
Estimation of mechanical load may be as simple as reading the data plate on the device you expect to drive mechanically, and can be as complex as calculating the power required to pump water through pipes. In addition, friction losses associated with fluid flow in pipes must be estimated for pumping applications.

Since water pumping is the most common mechanical WECS application, a few things are worth mentioning. There are a number of practical system designs, as shown in Exhibit 4.4 (including electric wind pumpers), each of which has advantages and disadvantages. These advantages and disadvantages are detailed in

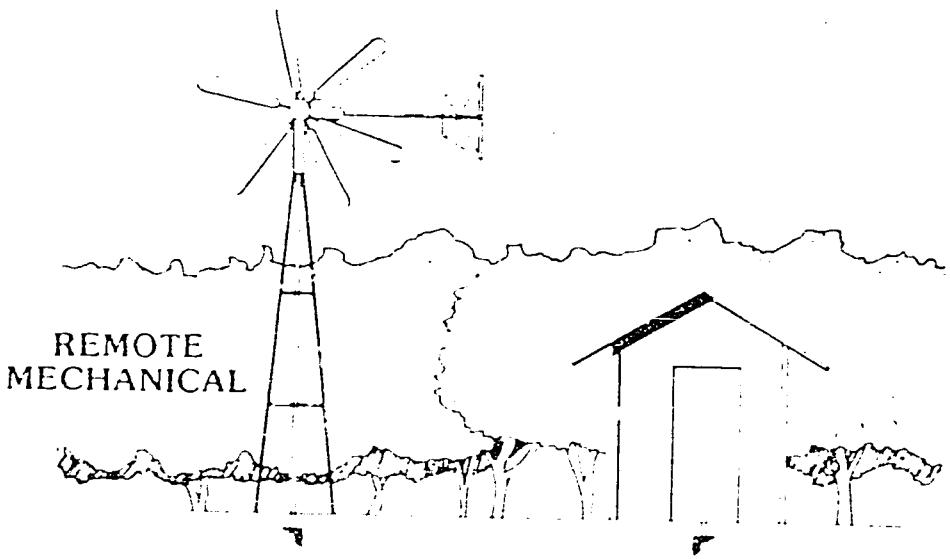
Exhibit 4.4
WATER PUMPING OPTIONS



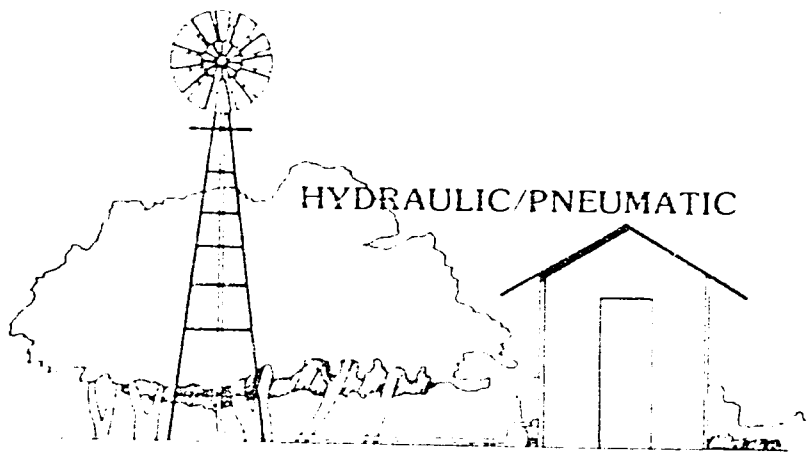
A. Direct mechanical system



C. Wind electric system



B. Remote mechanical system



D. Hydraulic/pneumatic system

Exhibit 4.5. Some water pumping applications may benefit by choosing one option over another. For other applications there may be only one choice. Whatever the application, however, the system designer should weigh the relative advantages and disadvantages of the various system designs (Exhibit 4.5) and compare with the application requirements.

Appendix C presents a detailed step-by-step procedure for estimated loads for mechanical water pumping applications. Design curves are provided for estimating pumping power requirements and pipe friction losses.

4.2.3.2 Stand-Alone Electrical Applications

In order to design a WECS for stand-alone electric applications, accurate information on connected electrical loads must be obtained. In order to arrive at such information, three things must be determined:

1) What electrical devices will be connected to the WECS, and what are their power requirements?

2) How long will each device operate, say, in hours per month?

3) At what time of day does each device operate?

In most situations, a given electrical load has a certain kilowatt or watt rating which can be obtained from the nameplate. This figure is the power requirement for that particular piece of equipment. To obtain energy requirements, multiply the power rating by the approximate number of hours of operation. Exhibit 4.6 details the methodology required for estimating electrical loads.

The steps outlined in Exhibit 4.6 must be performed for each piece of electrical equipment connected to the wind generator. Steps 1 through 4 in the flow chart are fairly straight-forward, but will only give the load on the WECS when all connected equipment is operating, i.e., a worst case scenario. Sizing a WECS to meet this worst case scenario is both inefficient and impractical. To accurately determine the load profile which the WECS should be designed for, one must estimate the time of day which each piece of electrical equipment will

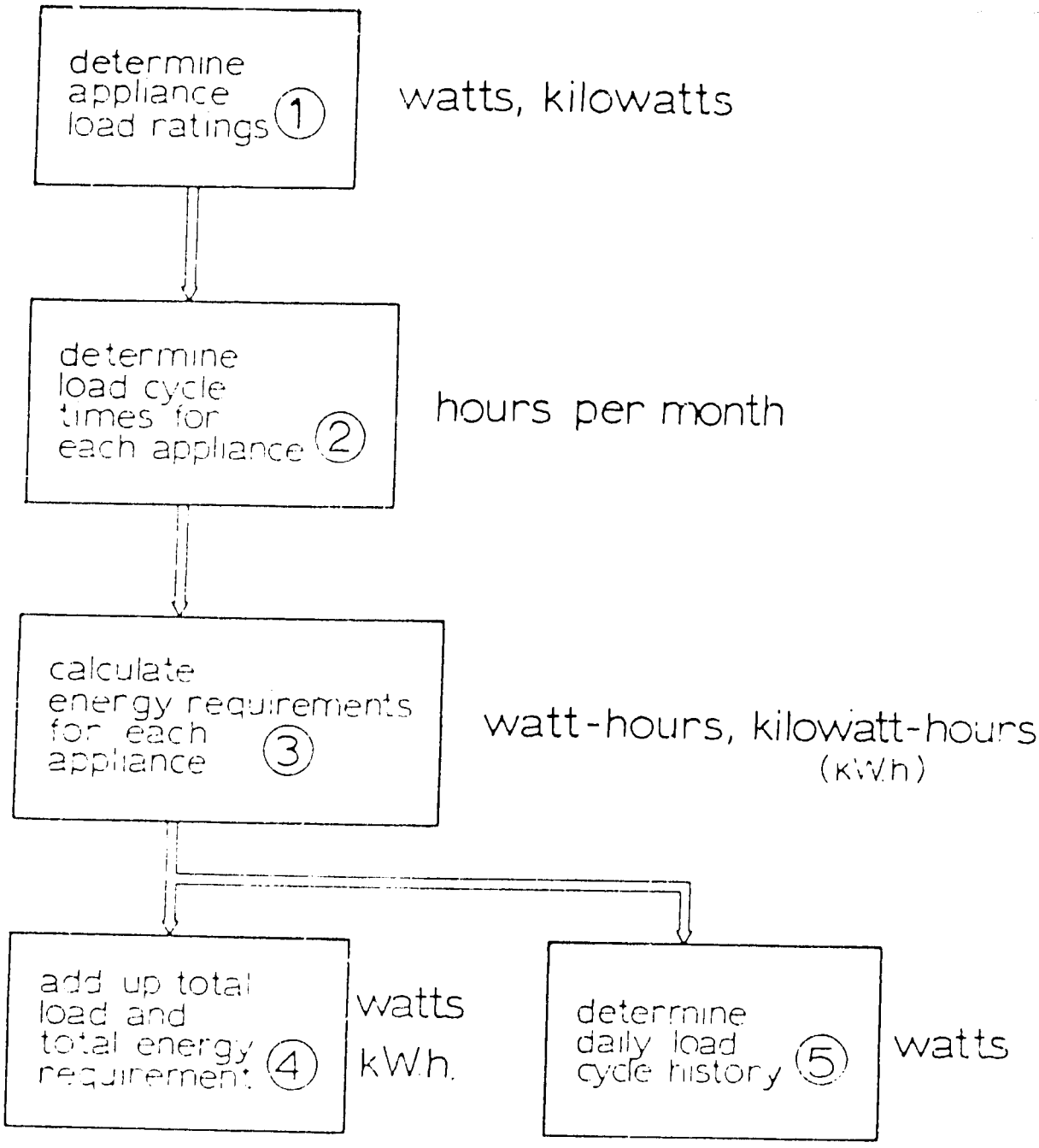
Exhibit 4.5

FACTORS TO CONSIDER IN SELECTING A WIND PUMPING SYSTEM

	METHOD	ADVANTAGES	DISADVANTAGES
A.	Windmill direct over well driving pump at well with drive shaft or push rod	Simple. Possibly relatively low cost. Equipment has long history of availability	Well site may not be a good wind site.
B.	Drive shaft to remote well site	Allows some flexibility in WECS siting. Allows power take off for other requirements	Safety hazard of drive shaft. Relatively high cost of drive components.
C.	Wind generator electric pump	Allows energy storage (in batteries, etc). Electricity for other requirements. Relatively high efficiency. Equipment has long history of availability. Allows best flexibility in WECS siting.	Energy loss in long wire runs. Relatively high cost. Safety requirements of electric wire runs.
D.	Windmill - hydraulic/ pneumatic system. Water can be pumped directly by bubbled air, or by pneumatic pump.	Allows greater flexibility of WECS WECS siting than B. Hydraulic power or compressed air available for other requirements.	Energy loss in long fluid pipes. Safety considerations of compressed fluids or air. Relatively high cost.

Exhibit 4.6

ESTIMATING ENERGY REQUIREMENTS FOR STAND - ALONE ELECTRICAL APPLICATIONS



collected include wind speed, direction and duration at each speed.

The process of siting wind turbines may be divided into two broad steps: site selection, and site evaluation. Site selection is the process of locating windy sites while site evaluation is the process of determining the potential wind resources at this site.

4.3.1 Site Selection

The main meteorological problem in WECS siting is the variability of the wind resource. The variation in magnitude of the wind from one place to another makes site selection difficult. The variation of wind with time at a particular location complicates site evaluation. Wind characteristics such as average wind speed, turbulence intensity, and seasonal and diurnal variations can be significantly different over seemingly short distances. This means that there is only limited value in direct application of existing wind data collected at historical stations --stations that were probably established without wind energy applications in mind, such as airports or thermal power plants.

Since the wind resource variability is so great and the cost of onsite measurements can be large, there is great interest in techniques for estimating the wind energy potential of an area or site without having to initiate wind measurements everywhere. Numerous techniques for doing this exist or have been proposed. These techniques can be applied over large land areas to identify smaller high wind potential areas or they can be used to estimate wind behavior at a particular site. Among these techniques are:

- analysis of existing and supplementary wind data
- topographic indicators
- ecological indicators
- geographical indicators

Each of these techniques is explained in detial in Appendix E.

4.3.2 Site Evaluation

If accurate wind resource data is not available for the chosen site, on-site wind measurement is required. Two steps are needed to assess the energy potential at a given site; 1) data collection, and 2) data analysis.

4.3.2.1 Data Collection

The type of wind sensor one should select depends upon the problem. Wind measuring instruments commonly used for site evaluation are:

- Cup Anemometers
- Wind Vanes
- Propeller Anemometers
- Tethered Balloon Instrument Systems
- Kites and Kite Anemometers

The cup anemometer is the most popular for wind surveys. It measures wind velocity but not direction. To measure direction, a wind vane is required. Both pieces of data can be obtained with the third sensor, the propeller anemometer. Accurate data can only be obtained with these sensors if they are mounted on a pole high enough and far enough away from buildings and trees to have a clear sweep of the land. Ideally they should be mounted at the same height as the turbine, and not less than 25 to 50 feet (7.6 to 15.2 meters) above ground.

If mounting the sensor at a reasonable height is a problem, tethered balloon systems can be employed. Additionally, if a number of measurements are to be taken at various sites, moving pole mounted sensors can be a problem. By using sensors attached to a tethered balloon the above problems can be alleviated.

Kites can serve as wind indicators in two ways. First, they can provide a visual indication of the wind direction and of the steadiness of wind at

their level of flight. The second application of kites uses the tension on the line as an indicator of wind speed.

All the above sensors need to be interfaced with meters which can interpret signals from the sensors and record the necessary data. Recorders can be digital or stripchart instruments. It is recommended that recorders with large data storage capabilities be used to minimize the time and effort required to read meters on a periodic basis.

4.3.2.2 Data Analysis

In order to select a turbine for a given application, as well as analyze its performance, the wind data obtained during site evaluation should be plotted in the form of a wind frequency distribution curve, as shown in Exhibit 4.7, or recorded in a tabular form, as shown in Exhibit 4.8.

If wind data is recorded for at least a year, wind frequency distribution curves can be plotted for a typical day in each month. This will reveal diurnal, as well as seasonal, variations in wind speeds (Exhibit 4.9).

As mentioned in Chapter 2, the power available in the wind is proportional to the windspeed cubed:

$$P = 1/2\ (\rho A V^3) \qquad \text{Eq. 2.1}$$

From this and the wind frequency distribution curve, a wind energy availability curve can be plotted to determine daily and seasonal variations in wind energy availability (energy = power x duration). Such curves are important for estimating required energy storage.

If accurate wind resource data is not available, a technique known as the Rayleigh Distribution can be used to determine a wind frequency distribution curve. A Rayleigh distribution takes the form of the curves shown in Exhibit 4.10.

The equation used to develop the curves is:

$$\text{HOURS} = \text{PERIOD} \times \pi/2 \times V/\bar{V}^2 \times e^{-k} \qquad \text{Eq. 4.1}$$

Exhibit 4.7
EXAMPLE WIND DURATION CURVE

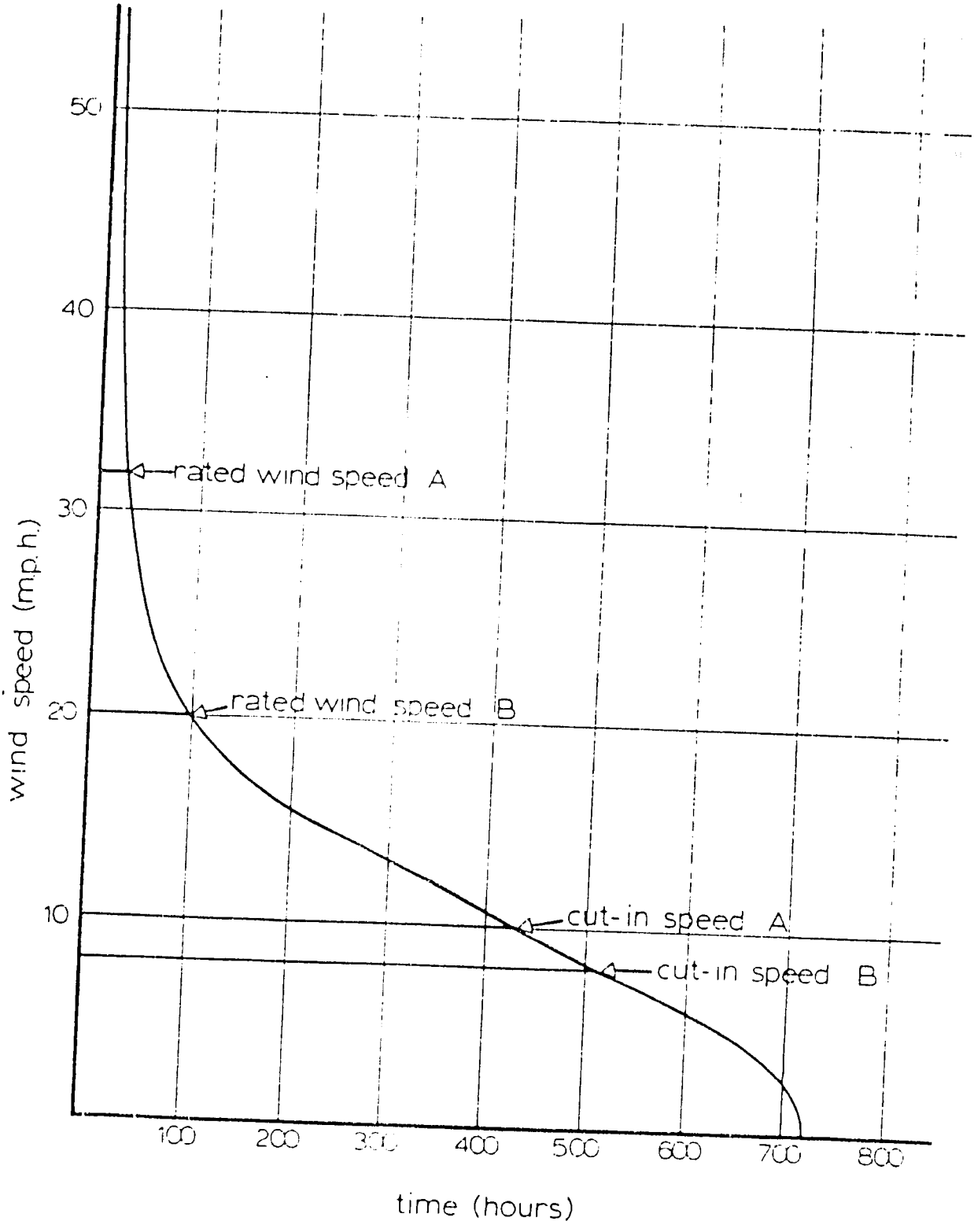


Exhibit 4.8

SAMPLE OF WIND DATA COLLECTION FORM

DATA PROCESSING DIVISION
ETAC, USAF
ASHEVILLE, N. C. 28801

SURFACE WINDS

PERCENTAGE FREQUENCY OF WIND
DIRECTION AND SPEED
(FROM HOURLY OBSERVATIONS)

45702 (STATION) AMCHITKA ISLAND ALEUTIAN IS (STATION NAME) 44-50 (YEARS) JAN (MONTH)

ALL WEATHER (CLASS) ALL (HOURS (L.S.T.))

(CONDITION)

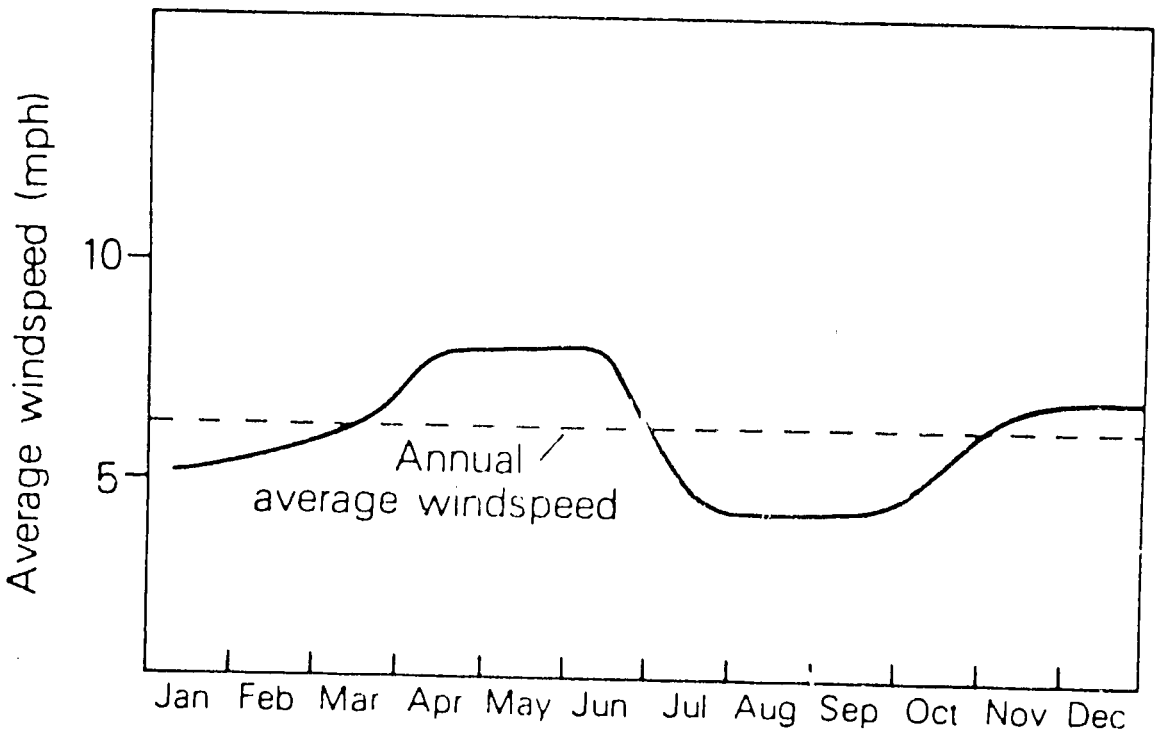
SPEED KNOTS DIR	1-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	41-47	48-55	≥56	%	MEAN WIND SPEED
N	.1	.3	1.3	1.1	1.0	.5	.2	.1	.0	.0	.1	4.8	15.8
NNE	.2	.1	.5	.7	.9	.8	.6	.1		.0	.0	3.8	19.8
NE	.2	.1	.6	.8	1.2	.8	.7	.1	.0	.1		4.5	19.4
ENE	.1	.1	.3	.8	1.3	1.5	1.2	1.0	.3	.2	.9	7.7	30.0
E	.2	.4	1.1	1.9	1.5	1.0	.9	1.0	1.0	.8	.2	9.5	23.7
ESE	.1	.1	.5	1.0	1.3	1.3	1.1	.8	.8	.7	.1	7.9	27.4
SE	.1	.3	.6	.7	1.1	1.6	1.3	.9	.4	.3	.1	7.6	25.1
SSE	.0	.2	.3	.2	.3	.4	.4	.7	.5	.6	.3	3.9	32.1
S	.3	.3	.6	.9	1.0	.7	.7	.8	.5	.4	.2	6.4	24.9
SSW	.1	.1	.5	.6	.4	.7	.7	.3	.0	.2	.2	3.7	24.9
SW	.1	.2	.6	1.2	.9	1.1	.9	.5	.3	.2	.2	6.3	23.9
WSW	.0	.2	.8	.9	1.1	1.1	.9	.6	.3	.2	.0	6.1	23.0
W	.2	.3	.7	.9	1.3	1.4	.9	.4	.1	.1		6.3	20.7
WNW	.2	.3	.5	1.1	1.0	1.1	.7	.6	.2	.1		6.0	21.3
NW	.3	.4	1.7	1.9	1.4	1.4	.7	.6	.2	.0		8.7	18.1
NNW	.0	.2	.8	1.7	1.5	1.1	.4	.2	.0	.1		6.0	18.6
VRB												.9	
	2.3	3.7	11.4	16.4	17.3	16.6	12.2	8.7	4.8	3.7	2.1	100.0	22.9

TOTAL NUMBER OF OBSERVATIONS 5146

SOURCE: PARK, Jack and Schwind, Dick. Wind Power for Farms, Homes, and Small Industry. Nielsen Engineering & Research, Inc., Mountain View, CA., Department of Energy Contract E(04-3)-1270, September, 1978.

Exhibit 4.9

MONTHLY VARIATION OF WINDSPEED AT A HYPOTHETICAL SITE



where HOURS = the number of hours the wind blows at velocity V during the specified PERIOD

PERIOD = period of interest in hours (hours per year, hours per month, or hours per day)

$\overline{V}$ = measured average windspeed

π = 3.416

e = 2.718

$k = \pi/4 \times (V/\overline{V})^2$

The graph shown in Exhibit 4.10 gives the percent of time the wind is blowing at each wind speed (horizontal axis) for various average wind speeds. Appendix F presents Exhibit 4.10 in a tabular form, with the PERIOD being 1 year (8,760 hours). By knowing the average windspeed it is easy to determine the number of hours the wind is blowing at different speeds throughout the year.

Although Appendix F presents the Rayleigh distribution with total annual hours as the period, the table can be of greater benefit by converting the figures to a percent-of-time basis by dividing all numbers by 8,760 hours per year. This will allow the determination of daily and monthly (or any other period of interest) wind distribution and available energy curves by knowing the mean wind speeds in the period of interest.

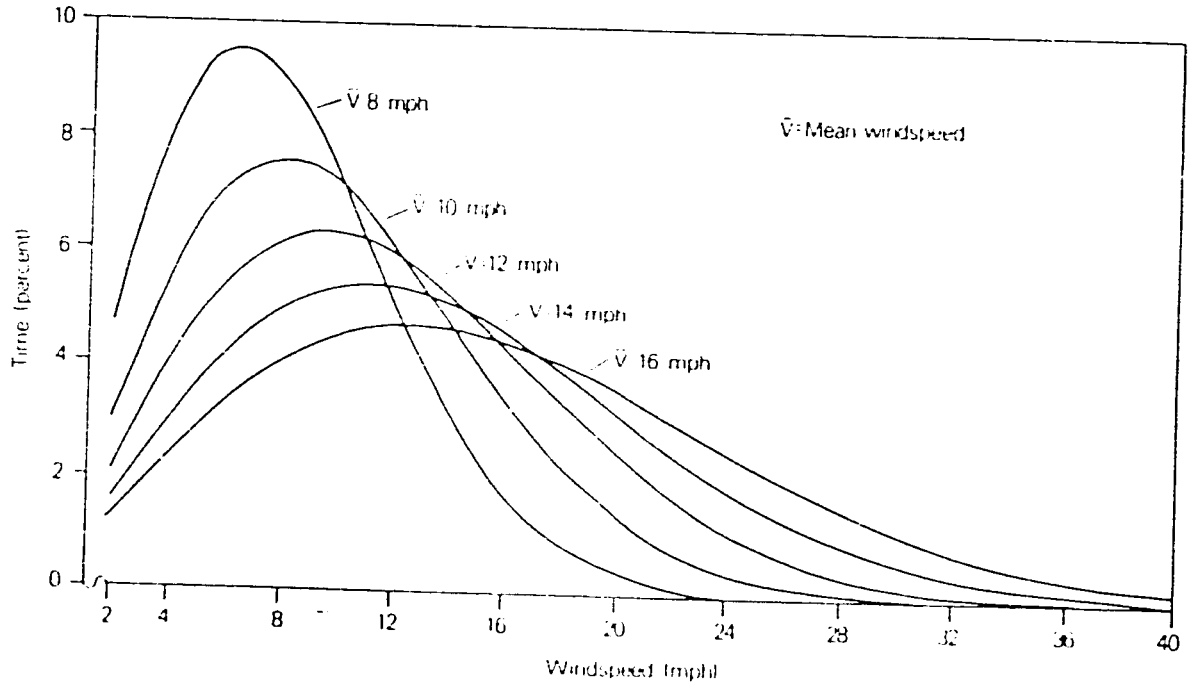
Rayleigh calculations should only be used if actual wind distribution data is not available. At average wind speeds below 10 mph (4.5 m/s), the Rayleigh distribution has low reliability; it should not be used at all at sites with mean wind speeds below 8 mph (3.6 m/s).

4.4 COMPONENT SELECTION

Once load requirements (for a stand-alone application) and wind resource characteristics have been determined, a preliminary system design can be developed. Wind energy conversion systems are primarily characterized by the intermittent nature of the wind, and by the fact that their output varies with both the swept

Exhibit 4.10

RAYLEIGH DISTRIBUTION VERSUS WINDSPEED FOR SITES WITH WINDSPEEDS BETWEEN 8 AND 16 MPH



area of their rotors and the cube of the wind velocity. Sizing of wind systems for a particular application is complicated due to the interrelationships among energy output, wind speed, system efficiencies, and rotor size. The problem of calculating WECS energy production is further compounded by the variety of possible rotor designs, system control schemes, and wind regimes.

Furthermore, there are limitations on the size and power output of WECS because of limitations on strength of materials, which in turn limit the size of blades, bearings, tower height, and other critical system components. As a result, if a larger capacity is needed for a particular application than can be supplied by commercially available WECS, a number of wind machines will have to be interconnected or a backup system must be used.

In general, WECS applications can be categorized in terms of type and amount of output power required (taking into account power conditioning system efficiencies, if applicable) and the requirements of the user for an uninterruptable supply of power. In many applications the power supply can be interrupted for short periods of time without disrupting the process utilizing the power, e.g. grid-connected, grinding grain or other materials, and pumping water to a holding tank.

If an uninterrupted source of power is required for stand-alone applications, diurnal storage, as well as a back up power source, may be required.

4.4.1 Turbine Selection

In selecting a turbine for a particular application, tradeoffs must be made among; 1) meeting all of the connected load with the wind turbine vs. providing a portion with wind power and the remainder with a back-up generator; 2) daily, monthly and annual energy production and storage requirements vs. load requirements; 3) WECS availability vs. efficiency; and 4) turbine cut-in, cut-out and rated wind speed vs. wind frequency distribution at site.

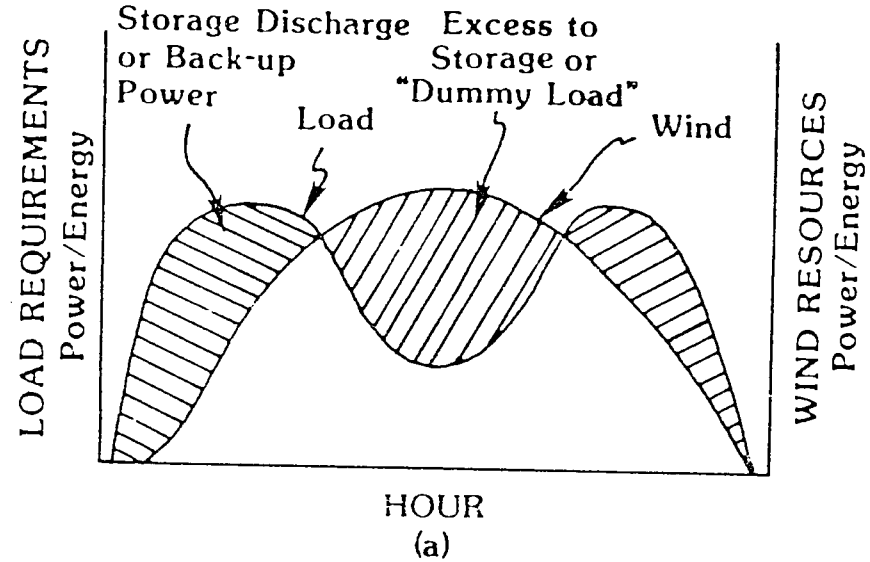
To size a WECS to meet peak loads is an inefficient design since a lot

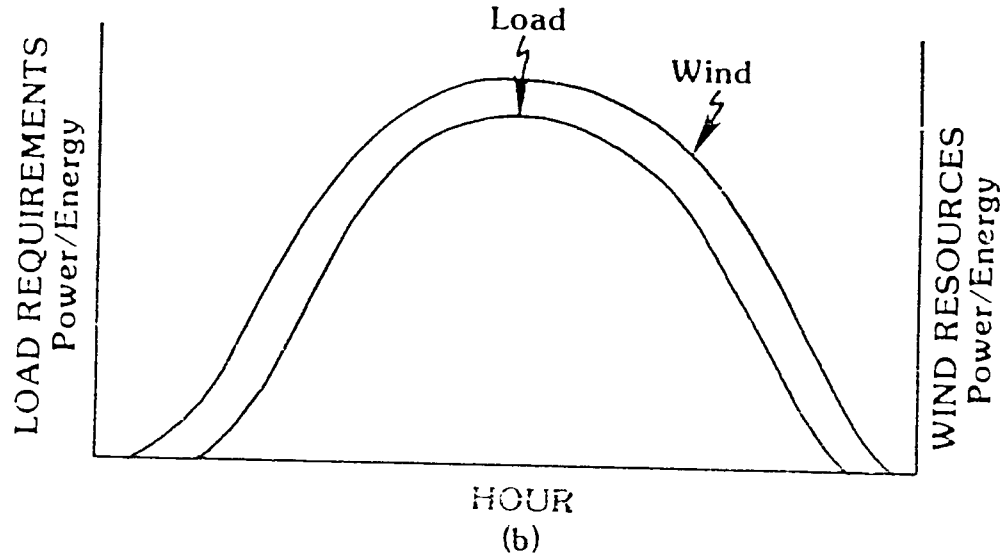
of capacity would be wasted most of the time. Rather, a WECS system consisting of a diesel generator back-up would be more economical. If a very low mean wind speed characterizes the site then a turbine with low cut-in and rated wind speed should be selected to maximize energy production. If, on the other hand, a site has very high average wind speeds, cut-in velocity is not a major concern. Rather a turbine with a fairly high rated windspeed and cut out velocity should be selected to maximize energy production. If turbine availability is critical, a turbine with a low cut-in wind speed and a rated wind speed lower than the site average should be selected. In addition, the system designer must decide whether the turbine and storage system should be sized to meet daily, monthly or annual energy requirements.

The above examples outline some of the considerations required to meet a particular load, in addition to satisfying any user demands. In short, the selection of a turbine which will perform as required is very difficult and sometimes impossible (in which case some of the operational constraints must be reformulated or removed). In all applications, however, a designer should use all energy produced from a WECS, i.e., power the load, charge a battery storage system (wind generators), or power a "dummy load" (ice making, water pumping, etc.). The term dummy load is used since the "additional load" is not part of the original load for which the system was designed, but rather something which consumes excess power/energy in a useful manner if no battery storage is used. In no wind generator application should excess power/energy be shunted to ground. It is much more economical and practical to power a dummy load.

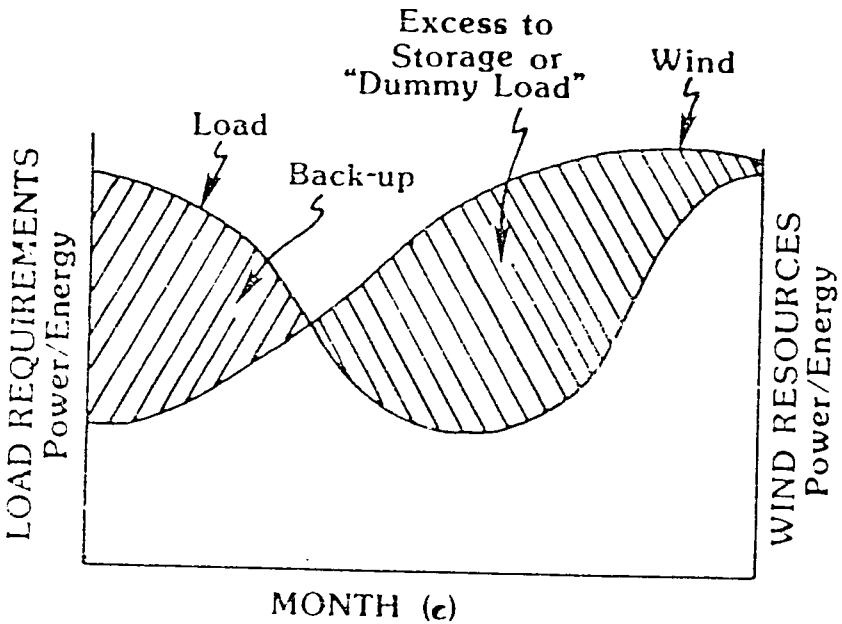
By comparing load requirement and resource availability (both energy and power) for daily, monthly and annual periods, one can begin to see the requirements for storage capacity and back-up generation (Exhibit 4.11). Such curves should be constructed and examined for an average, minimum and maximum resource availability day in each month to determine relative sized for wind machine and

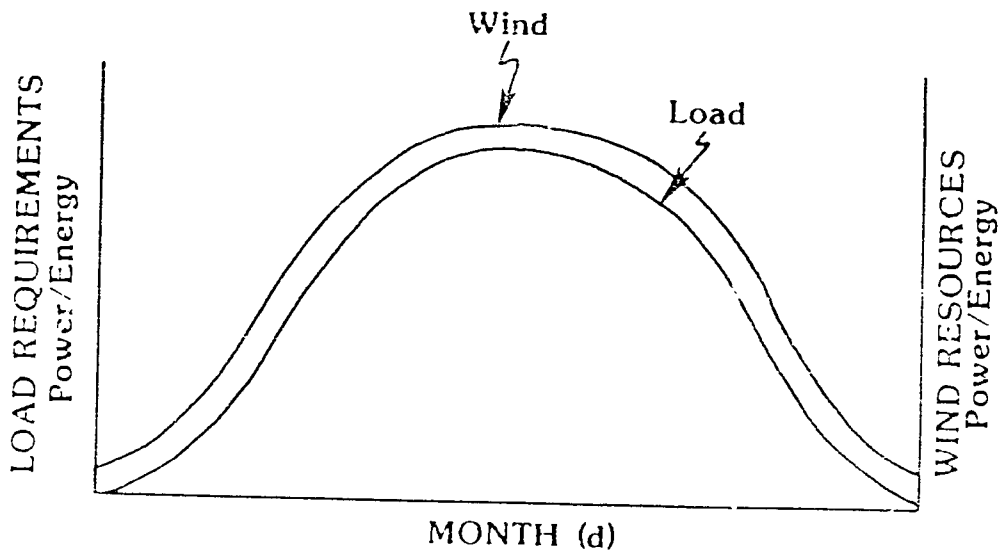
Exhibit 4.11
LOAD REQUIREMENTS AND RESOURCE AVAILABILITY PROFILES





DAILY LOAD AND RESOURCE AVAILABILITY CURVES





ANNUAL LOAD AND RESOURCE AVAILABILITY CURVES

storage. It should be noted that wind energy and power availability will initially have to be calculated on a "per square foot of swept rotor area" basis, and converted to an absolute value by choosing a rotor diameter large enough to provide the power and energy required by the load.

The wind resource availability curves only give an indication of the match between resource profiles and load profiles. Since they do not take into account system performances coefficients (Cp), they only give an indication of when, during the day or year, storage capacity or back-up power is required (Exhibit 4.11 a and c). If the load curve and the resource availability curve have the same profile than storage is probably not required, i.e., the wind availability is well matched to load requirements (Exhibit 4.11 b and d).

Wind turbine energy production, is a function of turbine rated power, rated wind speed, rotor diameter, performance coefficient, cut-in and cutout windspeeds, as well as resource availability. Ultimately, the system designer should maximize WECS energy production for a given application. Energy production from a WECS is easily calculated, knowing turbine characteristic and wind speed data at a site. By combining wind speed duration data with the manufacturers' turbine performance characteristics one can determine the wind machine energy production at each windspeed. The sum of these energy outputs over the spectrum of wind speeds at the site is the total energy production for a particular WECS. If only data on mean wind speed is available for the site, one can assume the Rayleigh distribution to determine a wind duration curve. In order to select a turbine that performs as required, a designer must repeat the above procedure until a product is found which meets load requirements. Such a process is very time consuming.

Turbine rotor diameter is the design parameter which has the greatest effect on wind machine power and energy output. Wind turbine power and energy output vary directly with rotor size. Therefore, selecting a wind machine with a

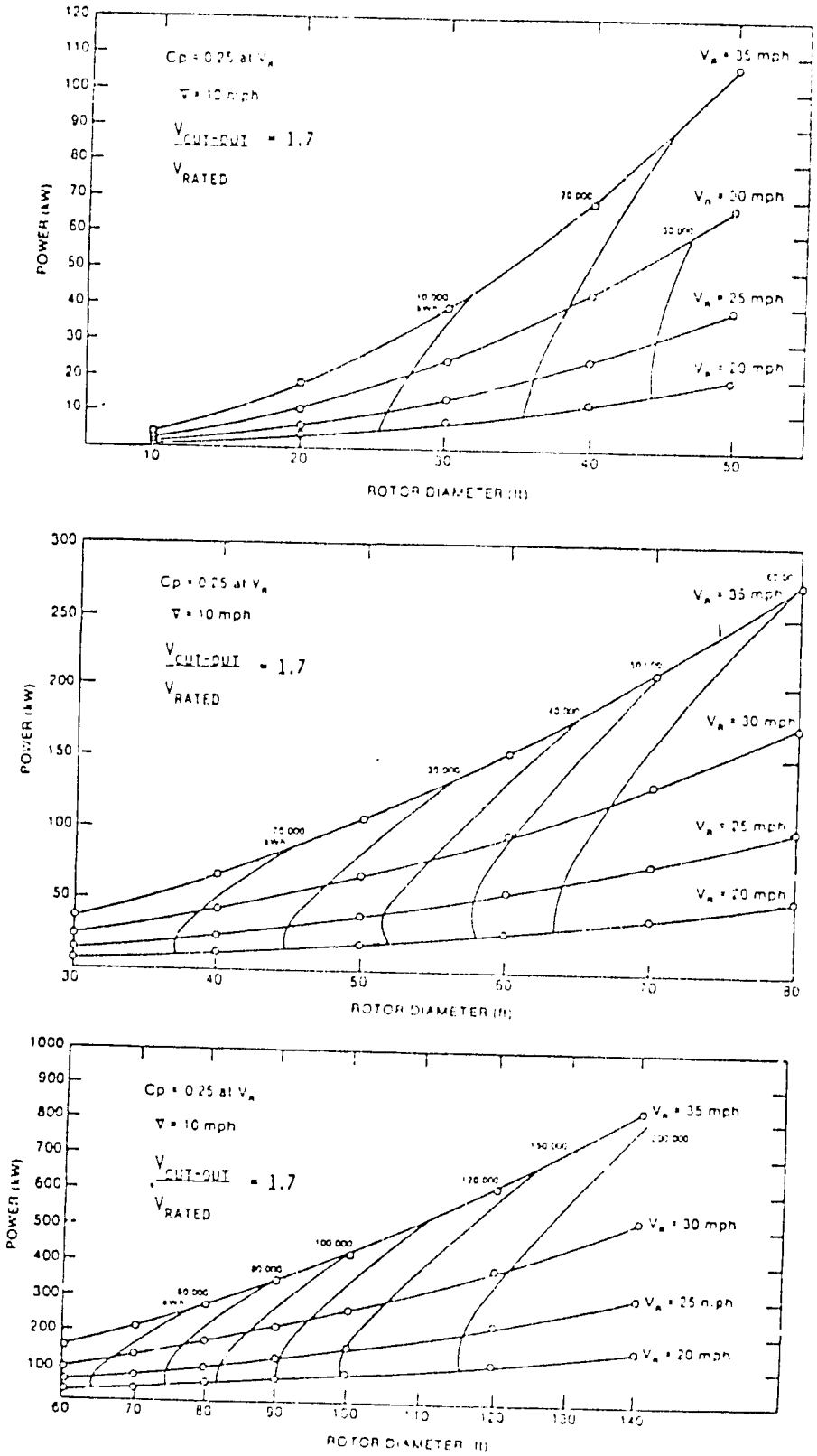
large enough rotor can be difficult and time consuming, especially if one has to repeatedly analyze performance of commercially available machines on a "one-at-a time" basis.

Exhibit 4.12 presents curves relating rated power output, rated wind speed (V_R), and annual energy production to rotor diameter. These curves can shorten the turbine selection process by eleminating from further consideration those machines with rotor diameters not large enough to meet power and energy requirements. The curves were derived for a turbine with Cp of .25 at V_R, a ratio of cut-out to rated wind speed of 1.7, at a site with a mean wind speed ($\bar{V}$) of 10 mph (4.5 m/s). The curve assumes a Rayleigh wind speed distribution with 8760 hours (1 year) as the period. As an example (top graph), a turbine with a Cp of .25 at V_R = 20 mph, Vcut-out/ Vrated = 1.7, V = 10 mph (4.5 m/s), and a rotor diameter of 30 ft (9.1 m) will produce approximately 15,000 kWh per year. If the WECS load requirements are approximately 15,000 kwh per year, then a turbine with a rotor diameter close to 30 ft (9.1 m) is needed. Curves similar to Exhibit 4.12 allow a WECS designer to compare the annual energy production for a number of different turbines quickly and easily. The annual energy production figures can be prorated to give energy production for any daily or monthly period, if required. Exhibit 4.12 can be used as a design tool to eliminate many turbines from further consideration, but a more detailed economic anlaysis should be performed, using manufacturers' specifications, before making a final decision on turbine selection.

Appendix G presents similar curves for various turbines characteristics and mean wind speeds. Curves are presented for Cp's of .25, .30, and .35 and $\bar{V}$'s of 10, 12, 14, 16, and 18 mph (4.5, 5.4, 6.3. 7.2, and 8.0 m/s), since these are most common. In addition, all plots assume a cut-in velocity below 18 mph (8 m/s). Cut-in velocities less than this have negligible effects, except in areas with extremely low mean wind speeds. Also, plots in Appendix G assume Vcut-out/Vrated

Exhibit 4.12

CURVES RELATING TURBINE POWER OUTPUT, ROTOR DIAMETER AND ANNUAL ENERGY PRODUCTION



Set of curves rated power, rated wind speed and annual energy production to rotor diameter. System Cp = 0.25 at V_R; V = 10 mph; a Rayleigh distribution is assumed.

SOURCE: Moment, R.L. Performance and Size Estimating for Wind Systems. Rockwell International Corp., Golden, CO., Department of Energy Contract DE-AC04-76DP03533, February, 1983

= 1.7, since this is most often the case with commerically available WECS.

It is important to stress that these plots allow only an estimation of energy production capability from a given rotor size. Several qualifications must be made. As noted previously, the power curve shape with constant output from V_R to $V_{cut-out}$ is not always the case with wind systems, as numerous factors contribute to reducing the output at wind speeds above V_R. First, use of this idealized curve would tend to overestimate annual energy production. Second, values for $V_{cut-out}$ relative to V_R giving ratios other than 1.7 will change the results by a degree dependent on the value of V/V_R. Third as Exhibit 4.12 was developed only to provide a rough estimate of average wind turbine output, calculated energy production using data read from the plot will similarly be only approximate, and should be used only in preliminary turbine selection. Nevertheless, such plots allow reasonable estimates of performance for a given rotor size, probably towards the high side owing to the favorable shape of the power curve used. Finally, the reader is reminded that the plots presented are for system C_p values of 0.25, 0.30, and 0.35 at V_R. For other values additional plots must be prepared, or plots in Appendix G must be interpolated.

Individuals needing to judge adequacy of particular wind systems for specific applications usually have data on the power curve, rated output, wind speed, and rotor diameter to work from. The curves presented here would be used in the following manner to rough-check the machine size against power/energy needs. For the known rotor diameter and rated wind speed, the expected power is read from the appropriate V_R curve. This should be checked on plots made using all three values of C_p, and the rated power so determined should be close to the machine's listed rated output. An estimate of system C_p at V_R results from that associated with the plot giving the best P_R agreement. Next, the set of plots corresponding V of the proposed site are used to arrive at an estimate of the

annual energy production for the given rotor size. The information arrived at by this process can be used to screen possible WECS candidates for those reasonably capable of meeting the user's performance criteria.

Accurate calculations of performance require knowing details of machine design, performance, and wind regime characteristics. However, such data are not always readily available. A significant increase in performance prediction accuracy can be realized if good power curve data are available for combining with the Rayleigh wind distribution. The resulting annual energy production value would then be as good as one could reasonably expect to obtain.

Wind turbines are relatively efficient energy converters when properly loaded. Optimum aerodynamic efficiencies of .3 to .45 are not uncommon. After conversion of turbine shaft power to useful output power, optimum overall system power coefficients of .2 to .4 are common. However, long-term average system efficiencies are usually much lower, commonly only half of peak system efficiency in electric systems and one-fifth to one-tenth of peak system efficiency in water pumping mills. Even in a well-designed WECS, three factors reduce average efficiency below peak efficiency:

1) Maximum power must be governed in high winds to prevent destruction of system components and, particularly, to avoid overloading the generator, pump, etc., that converts turbine shaft power to useful output power.

2) Most shaft power conversion devices lose efficiency outside a limited operating power range, corresponding to a limited windspeed range.

3) For most turbine-shaft power conversion devices, the variation of shaft torque with rotation speed does not match the turbine's optimum square-law characteristics, so that turbine rotation speed is optimum relative to windspeed at only one windspeed.

WECS's are normally designed to operate only up to a design-maximum turbine power and to sacrifice turbine efficiency at higher windspeeds to avoid damage to the turbine, structure, and the shaft power conversion device -- most commonly a generator or pump. The efficient range of operation of the shaft

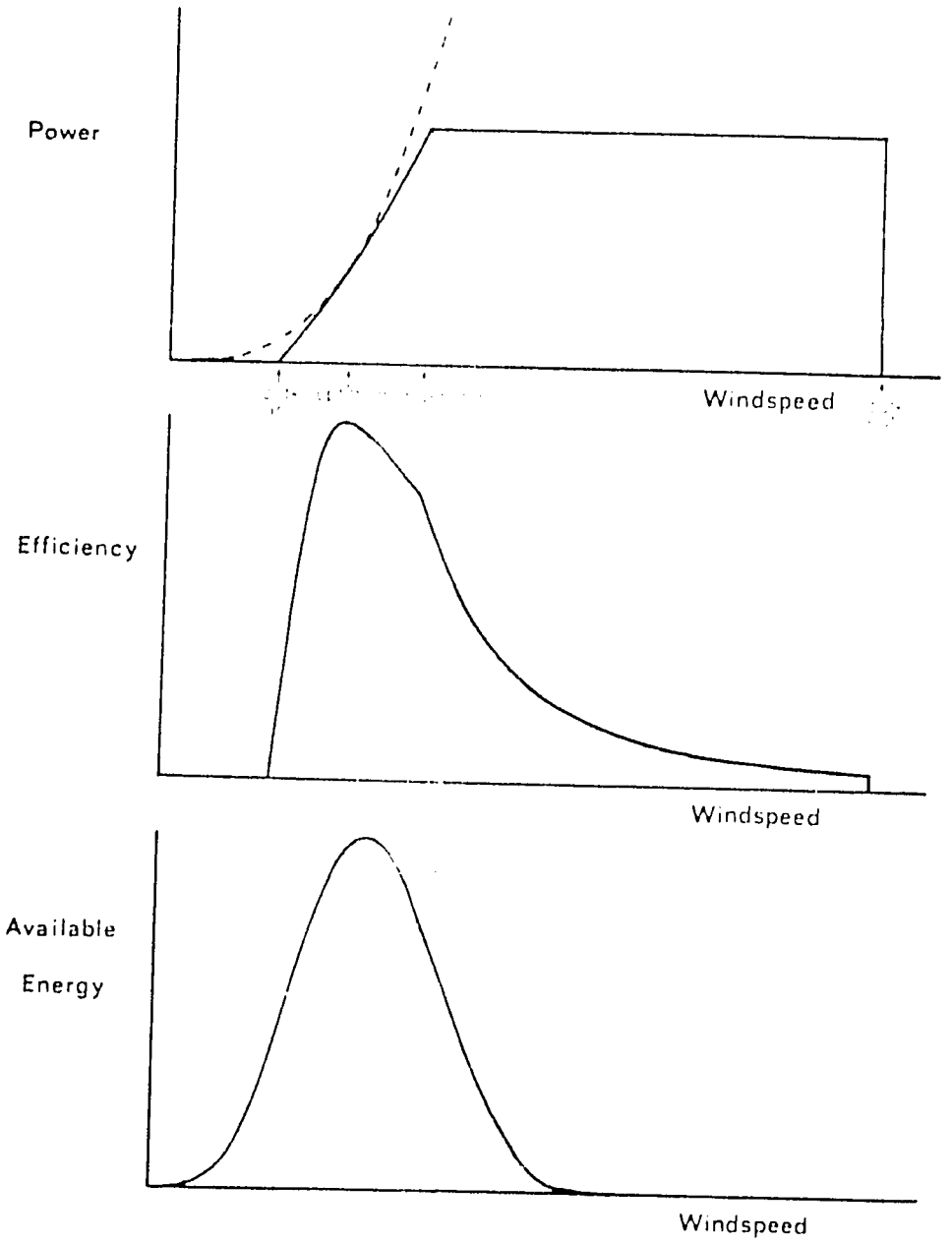
power conversion device is usually limited and usually tied to its maximum power-handling ability. Thus, a generator capable of handling very large power levels is usually less efficient at a given low power level than a smaller generator at the same low power level. Turbine efficiency is similarly limited to a restricted range of windspeeds for which shaft load torque is approximately correct in relation to the turbine's optimum characteristics. As Exhibit 4.13 illustrates, a WECS normally achieves a maximum system efficiency at one windspeed and drops in efficiency on either side. At optimum efficiency, the WECS power curve will be tangent to an optimum-efficiency cubic curve, i.e., power available in the wind vs. wind speed, (top graph, Exhibit 4.13). On the low-wind side of optimum, efficiency goes to zero at cut-in windspeed. On the high-wind side, efficiency drops rapidly above the governing windspeed and eventually goes to zero at the cut-out windspeed. Improving efficiency at high power levels entails increasing the power-handling capacity of the shaft power conversion device, gearing for optimum turbine loading at a higher windspeed, and adjusting the governing power upwards to the new maximum rated power. This results in an increased governing windspeed, but almost inevitably this process makes the turbine and the shaft power conversion device less efficient in low winds. As a result, system cut-in windspeed tends to increase in proportion to the governing windspeed.

Designing a WECS with a given turbine size for optimum average power entails centering the range of optimum system efficiency with respect to the curve of available energy in winds at an anticipated site (compare center and bottom graphs, Exhibit 4.13). This requires a proper rated-capacity choice for the shaft power conversion device, a proper gear ratio to achieve a favorable turbine/load match in the correct winds, and a proper adjustment of any governing mechanism.

Commerically available wind turbines are characterized by their cut-in, cut-out and rated (reference) wind speeds, as well as their rated power

Exhibit 4.13

LIMITATIONS IN RANGE OF WECS PERFORMANCE



output. As seen in Exhibit 4.14, turbine reference power and windspeed are greater than the optimum power point on the curve.

4.4.1.1 Generators

Most wind generators come complete with an ac or dc generator. For stand-alone applications, a choice between ac or dc power must be made. (Grid-connected systems are always ac.) The choice is dependent on the types of loads being powered and availability of dc power equipment.

Actually, though, it is not all that difficult to decide. If your power needs are small and you require only a limited number of electrical appliances as in a small home, a dc system may be appropriate. On the other hand, if you are a moderate, average, or heavy user of electricity your system should provide primarily ac, with dc used, if at all, for small loads such as lights and communication equipment.

As a rule of thumb, load size determines whether ac or dc should be generated. If the total load on the independent power system is frequently expected to equal or exceed 1,000 watts, the system should be designed to provide ac electricity to the major loads. But if the total load is rarely above 1,000 watts and dc equipment of the type required is available, the system should be designed to provide dc electricity.

4.4.2 Storage

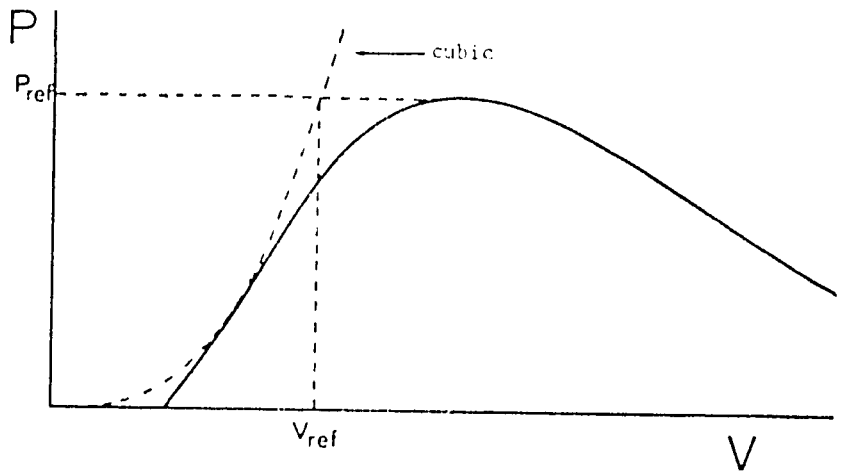
4.4.2.1 Battery Storage

Depending on the match between the load and the wind resource, a battery storage system may be required for electrical applications. The storage system is sized based on differences between daily load requirements and wind availability.

Storage batteries are rated on the basis of their energy storage capability (amp hour capacity or watt hour capacity), cycle life (the number of

Exhibit 4.14
DETERMINATION OF REFERENCE WINDSPEED

Illustration for two very different WECS's: A cubic curve is drawn tangent to turbine power curve at point of optimum power coefficient. Intersection of this cubic with horizontal line from maximum power point determines reference windspeed.



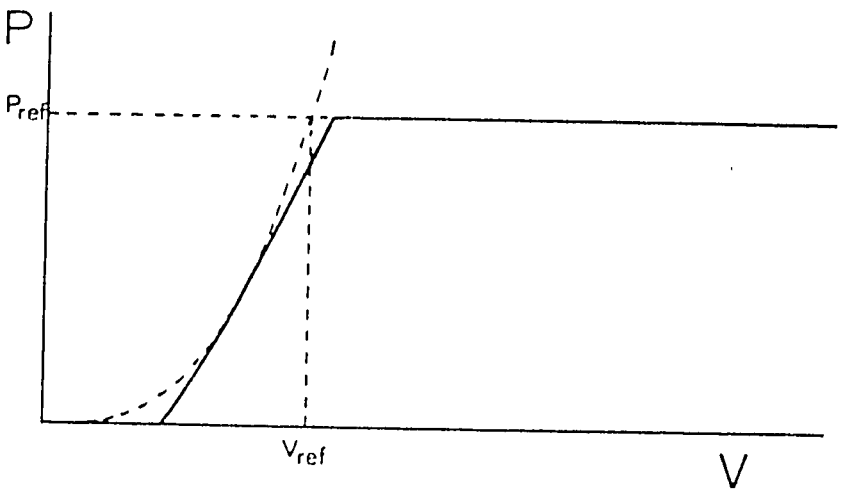
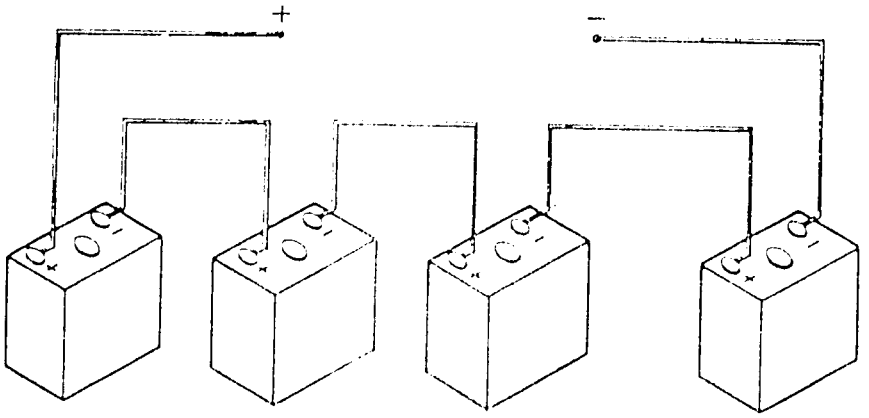
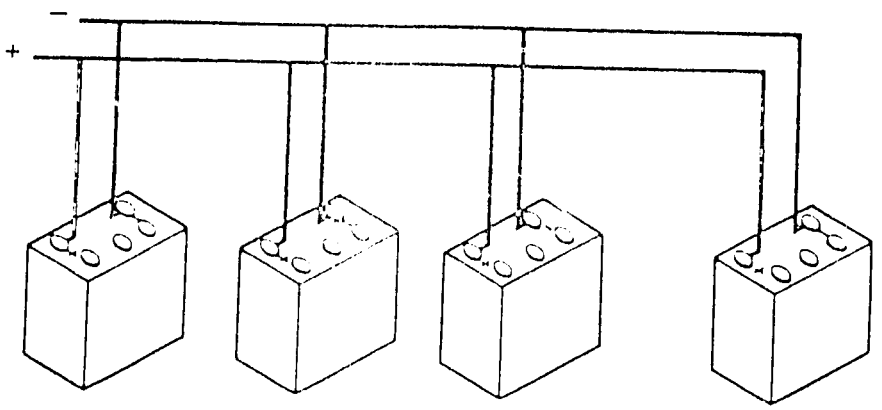


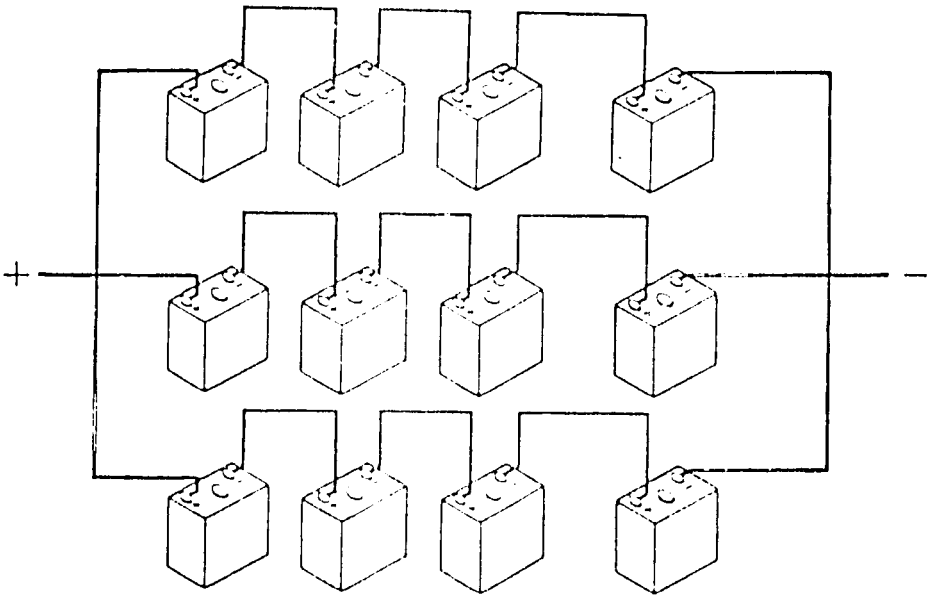
Exhibit 4.15
BATTERY ARRANGEMENTS



(a) Series Arrangement



(b) Parallel Arrangement



(c) Series-Parallel Arrangement

For example, consider a 6-volt battery, rated at 200 amp-hrs. It is important to know that the amp-hour rating is based on a certain discharge rate. If 200 amp-hours were discharged over a period of 20 hours, the discharge rate would be 10 amps/hour (200/20 = 10 amps). Greater discharge rates will result in a slightly reduced amp-hour capacity. You can get performance curves from battery manufacturers that illustrate this fact. You can convert the amp-hour and voltage ratings into watt-hours by simply multiplying the two. For example, 6 volts x 200 amp-hours = 1200 watt hours, or 1.2 kWh. With this, you can determine the number of batteries required for the given load requirements and resource availability.

Connecting batteries in series increases the voltage of the battery bank while the amp-hour rating of the bank remains the same as that of the smallest amp-hour rated battery in the bank (Exhibit 4.15a).

Connecting batteries in parallel increases the amp-hour rating of the entire battery bank (simply add up the total amp-hours available from each battery), while the output voltage remains the same as that of an individual battery (Exhibit 4.15b). All batteries in a system must have the same voltage rating. An advantage to this arrangement is that any number of batteries can be taken away or added at any time to adjust your storage capacity to your needs.

Connecting batteries in a series-parallel arrangement, as shown in Exhibit 4.15c allows the user to match current and volatage storage requirements to most any load.

Many approaches have been suggested for selecting a battery storage system. Criteria such as load voltage requirements, maximum battery current drain capacity and battery energy density can be used, the choice of which depends on the loads' critical requirements.

Battery characterics which must be examined when selecting a storage system are:

1) Nominal and minimum voltage

2) Current drain and schedule of proposed operation

3) Desired service, at expected temperature -- ampere-hour capacity

4) Limitation of size and weight -- consideration of premium for small size with high output capacity

Storage sizing is dependent on user requirements. Most battery systems are sized based on the number of windless days. However, the user may require a seasonal energy storage system large enough to provide supplementary power during the low wind resource season.

An optimally sized battery storage system can best be achieved by meeting critical loads and subordinating other characteristics. Thus, it is essential to prioritize each piece of electrical equipment based on nominal and minimal voltage, as well as maximum current requirements and operating schedule.

4.4.2.2 Water Storage for Water Pumping Systems

Water pumping systems can maximize wind resource utilization by using a holding tank to store water when the wind blows and there is no demand. To calculate energy storage requirements you need to know the maximum number of days for which you must store water. These data come from your wind site survey where one month data on maximum number of windless days in a period (usually 7) can be obtained. To obtain the storage requirements (gallons or liters) simply multiply the daily water requirements (gal/day or liters/day) times the number of windless days.

4.4.3 Power Conditioning System

Power conditioning equipment is selected based on its rated output power and current (and, hence, voltage). Components integrated into system design should be rated at or above the system components to which they connect.

The static inverter is probably the most widely used power conditioning subsystem in a WECS design. When selecting static inverters for stand-alone

applications, a number of factors must be kept in mind. First, the inverter must be sized to handle peak hour, minute, and second loads, as well as leaving room for expansion. Selecting an inverter which is oversized with respect to the loads will operate less efficiently than a properly sized unit. Second, one must be sure the input voltage of an inverter matches the voltage of the connected source, whether that source be a battery or dc turbine. In addition, the inverter must be able to surge well, have good voltage regulation, and have low harmonic distortion, for the following reasons:

1) To start an induction motor requires 5 to 6 times as much power as required during steady state operation. An inverter with poor surge characteristics must be larger (and the investment larger), in order to handle the same load as an inverter with good surge characteristics.

2) Too little or too much voltage can burn out motors. What's good voltage regulation? Plus or minus 10% variation is usually adequate.

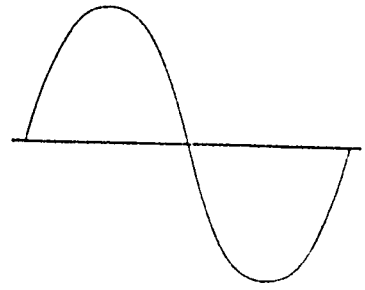
3) If harmonic distortion approaches 40% (which is the case with square wave output inverters) the heat rise in a connected ac motor becomes unacceptable. Harmonic distortion up to 20% results in small heat rise differences when compared to an inverter with a near-perfect sine wave (Exhibit 4.16).

4) If an inverter with a large harmonic distortion is used in conjunction with an ac motor, the motor must be oversized to compensate for the efficiency loss that results in a large heat rise in the motor windings. An inverter with a high harmonic distortion will tend to produce a lot of unuseable energy in the form of heat, while inverters with low distortion provide more useable energy to a motor.

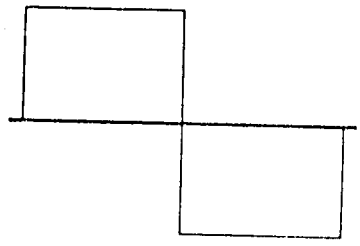
If the inverter has good surge characteristics and voltage regulation, and low harmonic distortion what you look for next is reliability. Something that contributes to reliability is of course, simplicity of design, which means among other things a minimum of components, it is a truism that electronic components inevitably fail and so the fewer the components the fewer the failures. Serviceability is next on the list of things to look for in an inverter. Inverters are heavy. They are difficult to ship around. The ability to repair them in the loop systems. This makes them difficult to troubleshoot. Inverters that are

Exhibit 4.16

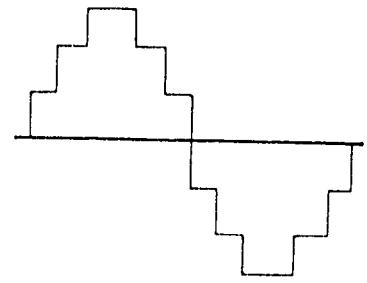
WAVE SHAPE COMPARISON



SINUSOIDAL WAVE
(No Distortion)



SQUARE WAVE
(40% Distortion)



STEPWAVE
(10% Distortion)

loop systems. This makes them difficult to troubleshoot. Inverters that are designed to allow for modular replacement of components are ideally suited for field installation.

The next thing to look for in an inverter is efficiency. That is, how efficient is it in converting dc electricity to ac. There are two things to consider here. One is idling losses, and the second is efficiency under load. The efficiency curve shown in Exhibit 4.17 illustrates these two items. Even in an unloaded condition the inverter uses electricity. This is called idling loss or no-load loss. (As load is added, overall efficiency improves.) Idling losses among inverters vary tremendously, for instance, from 50 watts to 500 watts on a 2 kilowatt inverter. Also, inverter efficiency in a loaded condition varies greatly, from 60% to 90%. Compare both types of inverter efficiencies among the brands of inverters you are considering before you make a purchase.

4.4.4 Tower

Once a turbine has been selected, the type of support structure can be chosen. A tower should be selected based on the following requirements:

1) Turbine must be easily attached to tower.

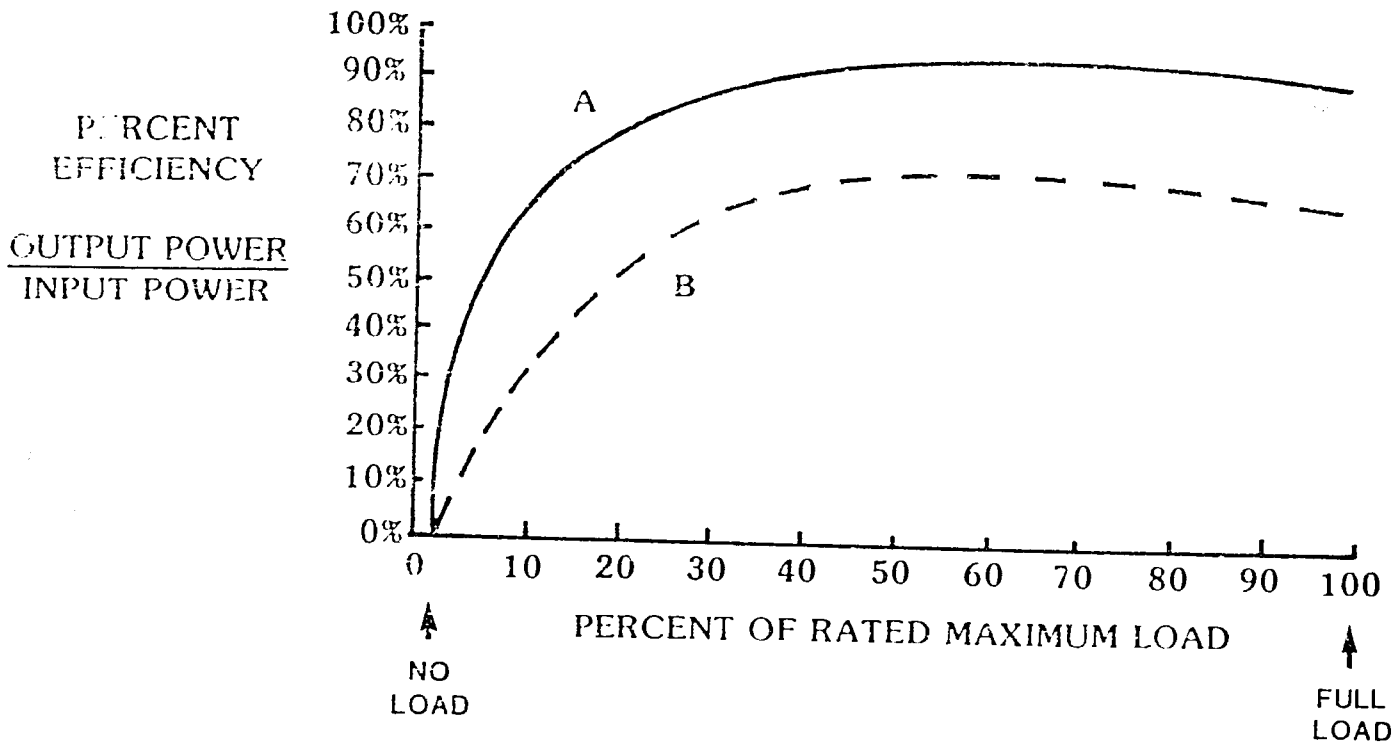
2) Turbine weight plus dynamic loading caused by high winds and gusts must be supported.

3) Tower should be modular for shipping ease. Modular towers must be easily assembled on site.

Since the tower's function is to support the wind machine weight in the worst conditions, the primary turbine selection criteria should be number 2 above. The load that causes many towers to fail is a combination of wind turbine and tower drag. A pair of skinny windmill blades may not look like they could cause much drag, but when extracting full power at rated speed they create nearly the drag of a solid disk the diameter of the rotor.

Exhibit 4.17

INVERTER EFFICIENCY CURVE



The ways in which towers typically fail are:

1) Freestanding towers buckle due to higher-than-design wind drag load from the windwheel.

2) A footing that anchors the tower to the ground becomes uprooted.

3) A bolt somewhere along the tower fails due to improper tightening, resulting in a tower weak point that eventually fails.

4) Guy-wire braced towers often buckle from improper spacing of the wires supporting the tower. In such a situation, a tower that requires, say, three sets of cables spaced evenly along the length of the tower, gets only two sets, resulting in intercable spans greater than design specifications.

5) Guy wires fail from improper wire size, improper tension fasteners, or damage.

6) Guy-wire anchors uproot from the ground or come away from the structure to which they are attached.

Most WECS can be purchased with towers that have been tested by the turbine manufacturer. If a tower other than that recommended by the turbine manufacturer must be selected, several things should be considered. When selecting a tower, you must know something about the tower structure and about the ground supporting it. A detailed soil analysis should be performed to determine proper foundation design for a specific turbine installation.

Building codes will detail the basis for foundation design, and the wind turbine/tower dealer or manufacturer should have drag data for the product you select. A professional structural engineer can perform any calculations necessary to ensure that a particular tower installation will support your windmill. The cost of professional services in the area of tower selection and design should be considered cheap insurance for a sound installation. Vibratory loads induced by the wind or wind machine also should be considered and professional advice may be required.

4.4.5 Backup Systems

The key question that arises in evaluating the need for and type of backup system is: is the occasional loss of power critical? If the loss is not

critical, there is no need to add the complexity of a backup system; however, if it is critical, a contingency plan is necessary.

The primary causes of power loss are as follows:

Design

- More load than expected
- Less wind than expected
- Maintenance shutdown

Hardware Failures

- End-use device failure
- Electronic failures (power conditioning)
- Turbine failures
- Battery failures (rare)

Natural

- Lightning
- Consecutive windless days
- Cold weather effect on batteries

4.4.5.1 Potential Backup Systems

The potential choices for backup are the following:

- o None (e.g., visit on demand, carry spare parts)
- o Manual (e.g., pumping, pedaling)
- o Engine/Generator
- o Primary Battery
- o Emergency Wind-Rechargeable Battery
- o Emergency Fossil-Rechargeable Battery
- o Utility grid

The best backup is spare parts combined with responsive technical expertise. Where remoteness or lack of infrastructure prevents this, manual backups are a viable, low-cost alternative. Hand pumping can be used for village water on an emergency basis, although provisions must be made in the initial design for hand pumping. Centrifugal pumps cannot be manually operated, but positive-displacement pumps can. For small radio systems, pedal-powered generators can be used in emergencies.

For larger pumping operations or large-power operations, an engine can be justified for the backup system. If an engine is rarely used, it should be

started regularly to prevent problems. The maintenance costs associated with the weekly operation must be factored into any economic analysis.

Battery backups can be the most desirable. Primary batteries can be used in some circumstances. Once discharged, they must be manually replaced, so the maintenance costs could be high. If stand-by rechargeable batteries are used, battery replacement can be avoided. For example, lead-acid batteries could be used that have their charge maintained by the WECS, but are not connected to the main battery-storage system (which is used for non-emergency energy storage). The advantage of the wind-recharged battery is that it can recover from an emergency condition without separate servicing by a mechanic. The batteries might also be recharged by a portable generator. The portable generator would be especially useful as a backup in the rare circumstance of extremely low wind conditions for many days.

Utility backup is as reliable as the utility. In the U.S., for example, utility power is probably the most reliable source of energy; however, in developing countries, utility grids are often unreliable and are therefore the reason for using a wind system.

The advantages and disadvantages of the various backup systems are outlined in Exhibit 4.18.

4.4.5.2 Appropriateness of Various Backup Systems

The appropriateness of various backup systems depends on the application, whether loss of power is critical, and whether the system is attended. Exhibit 4.19 indicates the appropriateness of backup system according to these considerations.

4.4.5.3 Integration of Backup into WECS

Once the type of backup has been selected, it must be integrated with the WECS. This can be done through means such as a manual transfer switch, a remote manual transfer switch, or an automatic transfer switch.

A manual transfer switch is clean, direct, and involves no energy

Exhibit 4.18

ADVANTAGES & DISADVANTAGES OF VARIOUS BACKUP SYSTEMS

BACKUP SYSTEM	ADVANTAGES	DISADVANTAGES
None	Simple	Noncritical Applications Only
Manual	Simple Reliable	Require Attendance
Engine	High Power	Frequently Won't Start High Maintenance
Primary Battery	Can be Remote Reliable	One Time Use Only
Wind Recharged Battery	Can be Remote Reliable	Cannot Recover without Wind
Fossil-fueled Recharged Battery	Can be Remote Reliable	Fuel & Engine Transport
Utility Grid	Can be the Most Reliable	Cannot be Remote Requires Sophisticated Power Conditioning

APPROPRIATENESS OF VARIOUS BACKUP SYSTEMS

APPLICATION	UNATTENDED		ATTENDED	
	CRITICAL	NONCRITICAL	CRITICAL	NONCRITICAL
Radio	Battery, Alarm	None	Battery, Pedal	None
Lighting	Battery, Alarm	None	Engine	None
Pump	Battery, Alarm	None, Alarm	Engine	None
Refrigerator	Battery, Alarm	None, Alarm	Engine	None, Alarm
TV	Battery, Alarm	None	Battery, Pedal	None
Cathodic Protection	Battery, Alarm	None, Alarm	Battery, Alarm	None, Alarm
Field Instruments	Battery, Alarm	None, Alarm	Engine, Battery, Alarm	None, Alarm
Grid-Connected	None	None	None	None

Exhibit 4.19

loss; however, it requires detection and then on-site correction.

A remote manual transfer switch can be used for remote sites--especially those with a telemetry system that transmits when the system is not performing properly. A second communication link can be supplied (i.e., two-way telemetry) such that a person at a central station can radio the site for the backup to come on. This type of switching requires an activator and human monitoring, but there are no energy losses in the process.

Automatic switchover is also possible. The sensing and controlling function results in a continuous power drain through the power conditioning system. It is possible to arrange the system so that power drain occurs only during periods when the backup is on, so the total energy loss would be less.

4.5 GRID-CONNECTED WECS

Sizing of a grid-connected WECS system is dependent on the local utility requirements. Grid-connected applications (wind farms) are not sized based on any particular load but, rather, on the following utility criteria:

1) The effect of a wind farm on a utility's operating reserve requirements.

2) Utility capacity expansion plans.

A utility maintains an operating reserve for several reasons. One is to serve as a backup for the sudden loss of a generating source. Another is to correct for any errors in the load forecast, used to commit units available for a particular day. Still another reason to maintain an operating reserve is to handle minute-to-minute fluctuations in load. Because average wind speeds across the WECS array may be quite variable, and change significantly within short periods of time, WECS power may also be quite variable. To accomodate this variability may require additional operating reserves over and above those normally required by the utility. Thus it is essential to determine the additional operating reserves the utility may require in order to accommodate expected fluctuations in

wind system output.

As electric consumption continues to grow, utilities continue to face the same problem. This is one of adding enough new sources of generation to enable them to meet these increasing loads. A major objective of these generation expansion programs is to provide energy to the consumer at the lowest possible cost, consistent with established levels of reliability of supply. But not all generation sources have the same costs, or even the same cost structures. In fact, over the range of alternative sources, the relationship between fixed and variable costs varies substantially. Fixed costs are incurred by the mere ownership of generation capacity and remain fixed regardless of the amount of energy produced with that capacity. Variable costs, on the other hand, are specifically related to the production of energy and are, therefore, a function of the amount of energy produced. As a rule, a generating unit with a low incremental cost (it may burn coal instead of oil), and thus one economically attractive for long hours of use, has a higher fixed cost than a unit with a high incremental cost. The reason that that unit has a higher fixed cost is that it costs more to get the greater efficiency necessary to use less expensive fuels. Once a utility acquires a certain set of generating units, that set of units is loaded or set for dispatch in such a way that units with the lowest incremental costs, such as a coal-fired unit, are dispatched first. This step results in a gain in overall system economy and yields, for the utility, the lowest total cost of generation. When a utility selects capacity to add to its current generation mix, it must first identify the proper generation mix. This is one that will reliably satisfy a projected load profile at the lowest total cost of generation. If we add wind generation to the utility equipment mix, the utility system becomes more reliable, as it will with the addition of any other generating source. As a result, the addition of WECS to the mix makes it possible for the utility to reduce its projected requirements of conventional source capacity and still maintain its

target reliability.

Determining an optimal size for a wind farm is a very complicated procedure. Models have been developed which perform such analyses, taking into account the above criteria as well as utility financial parameters such as cost of capital, tax rate structures, and insurance requirements.

4.6 ENVIRONMENTAL ISSUES

4.6.1 Design Considerations

WECS have been proven reliable under a wide variety of environmental conditions. They have operated successfully in snow-covered regions, deserts and oceans. The temperature and humidity in which a system operates does not directly affect turbine output and reliability. However, battery capacity and life, and electronic equipment performance are reduced in such environments.

Battery performance is a strong function of temperature. As temperature decreases, battery capacity is substantially reduced. At high temperatures, although capacity is near maximum, battery life decreases. Also, in particularly low-humidity environments, battery maintenance in terms of water addition will be affected.

Electronic circuitry is most reliable at lower temperatures and low humidity.

System experience has indicated that it is best to house batteries and power conditioning equipment in an enclosed area to minimize exposure to extremes in environmental conditions.

4.6.2 Ecological Effects

Impact on flora occur where the ground cover is disturbed during WECS installation process. These impacts are similar to those caused by the construction and maintenance of transmission line towers and are site-specific. For example, land-clearing in mountainous terrain can produce significant impacts. Additional

ecological effects during installation are: production of fugitive dust, added motor vehicle emissions and heavy equipment noise, and possible soil erosion and siltation of surface waters.

The impacts on fauna do not appear to be serious. The only probable impact to animal populations which is significant is nighttime kills of birds at wind turbine towers. The probability of such collisions under normal operating conditions is approximately 8 percent.

4.6.3 Electromagnetic Interference

Rotating blades reflect electromagnetic signals in such a way as to cause periodically constructive and destructive interference between the reflected and transmitted signals. Poor siting of wind turbines could cause unacceptable interference with television, radio, VOR and DVOR navigational systems, microwave links, and other radio frequency equipment. Metallic blades can produce more severe effects than those composed of fiberglass, wood, or composite materials.

The effect associated with TV reception can be alleviated through the use of a directional (fringe) antenna, local TV repeater, cable reception, or circularly polarized transmission.

Effects on AM reception are minimal. Due to the higher broadcast frequencies, FM reception is more subject to interference. However, interference with FM reception will be negligible except within tens of meters of the wind turbine.

EMI effects may be minimized by the proper siting of large wind turbines.

4.7 MAINTAINABILITY

WECS require periodic maintenance. The extent of such maintenance should be considered when selecting system components. Factors which should be considered before final selection of a WECS are:

- Maintenance history of WECS components

- Can routine maintenance be easily performed up on a tower, or must the machine be lowered?
- Frequency of expected routine maintenance
- Nature of monthly, or yearly, expected routine maintenance: lubrication, component replacement, and inspection
- Number of different tools required to perform maintenance tasks
- Availability and cost of spare parts
- Completeness of owner's manual/maintenance documentation
- Relative safety: can machine be shut off, is there sufficient blade clearance from maintenance personnel, and are there exposed shafts, wires, and potential hazards?
- Is a factory-trained, experienced installation/maintenance organization available?

Answers to many of these questions are available directly from dealers and other users. Some questions will never have answers, but are subject to your best estimate during product evaluation. Manufacturers usually provide information on inspection procedures and timetables. In any event, maintenance should always be scheduled following any extreme wind or storms.

4.7.1 Turbine and Tower

The air flowing past your wind machine is full of dust and grit, which, over a long period of time, gets into the various components, including bearings, transmissions, and generators. Changing the oil, greasing the bearings, inspecting generators or pumps is one way to monitor the system and prevent rapid wear from such environmental conditions. Evidence of rust, loose wires, worn bushings, and so on should be on an inspection list, which is used each time the wind turbine is inspected.

Blades or vanes which are exposed to the wind are subject to impact from hail, rain, ice, and rocks. Any inspection should include examination of these blades. Wooden blades might need fresh paint; fiberglass and metal blades might also need similar service.

Vibrations in the wind turbine can cause bolts and nuts to loosen on towers and machine parts to fatigue and fail, wires to break, and so on. This is another area for thorough examination. Properly bolted joints will not fatigue. These are items that should be inspected as a routine, preventative procedure.

Once a year is a usual interval for performing this type of maintenance.

4.7.2 Battery Types

Battery selection is a function of available maintenance. Sealed batteries require little maintenance (perhaps cleaning of battery terminals). Vented batteries, on the other hand, also require the addition of water (approximately every 3-6 months in average humidity environments). Battery caps with catalysts that recombine hydrogen and oxygen to form water are available. These caps reduce water loss.

4.7.3 Other Equipment

Power conditioning equipment requires routine cleaning and terminal inspection. Water pumps need to be checked for leaks.

4.8 SAFETY

System design and operating procedures must be adequate to prevent injury to people and to prevent or minimize damage to the equipment. The following protective measures should be taken:

Structure Grounding--the WECS structure and power control panel frame should be connected to buried metallic counterpoise. Connections to the WECS structure should be made at several locations to ensure reliability.

Disconnects--disconnects (in the form of switch gear and circuit breakers) should be included in the design to allow for isolation of portions of the systeml prior to maintenance and for shorting of the power mains in emergency situations.

Utility Power Disconnect--automatically disconnects the WECS from the grid in the event of a utility failure.

Fuses/Circuit Breakers--these should be provided between all major components to protect the equipment from overload.

Grid Isolation--a transformer is used to protect the WECS from ac feeoback and the grid from the injection of dc.

Lightning Protection--in regions of high thunderstorm activity, it may be advisable to install grounded lighting rods. Varistors (electrical "release valves") should also be installed to protect circuitry against large current surges.

Battery Enclosure--it is recommended that the batteries be housed in a structure. If using vented batteries, it is important that this structure have adequate ventilation to prevent the explosion of hydrogen liberated during battery charging. Within this battery area, a supply of fresh water should be kept if vented batteries are used. This is to flush a person's eyes and skin if splashed with electrolyte (acid and water mixture).

Load Enclosures--equipment that turns on automatically (such as a pump that starts when water in a storage tank drops to a pre-determined level) should be enclosed to prevent injury to bystanders.

Turbine location--High speed, low solidity turbine blades can fail due to excessive wind force, blade feathering controls which fail to operate, or poor mounting to the turbine hub. If such failures occur, blades can be thrown anywhere from 300-500 meters, and cause serious damage to both person and property. If possible, wind generaters should be located a sufficient distance from populated areas in case of such blade failure.

4.9 ECONOMIC CONSIDERATIONS

The analysis of economic factors can be as complex or as simple as you wish to make it. For a simple analysis you need to know the following:

1. Total installed cost (dollars)
2. Expected system life (years)
3. Total energy yield over the entire system life (kWh, hp-hr, etc.)
4. Annual maintenance and repair costs (dollars)
5. Other annual costs and savings (dollars)
6. Expected resale value at end of service life (dollars)
7. Other user defined requirements

4.9.1 Total Installed Cost

Generally, the bigger a WECS system is, the less it will cost per unit of rated output. The installed costs of WECS, measured in dollars per kilowatt rated power, tend to decrease with increasing rated power (Exhibit 4.20).

This total cost is broken down into component costs (Exhibit 4.21). These pie charts show the relative costs by the size of the pie slice. For the wind electric system, batteries may cost as much as the wind turbine, as illustrated. The pie slices may not acutually reflect the system you are planning, but it is a good idea to look at the relative costs.

Costs normally include everything you must purchase and install to

Exhibit 4.20

COSTS OF COMPLETE WIND ELECTRIC SYSTEMS IN THE 1970'S

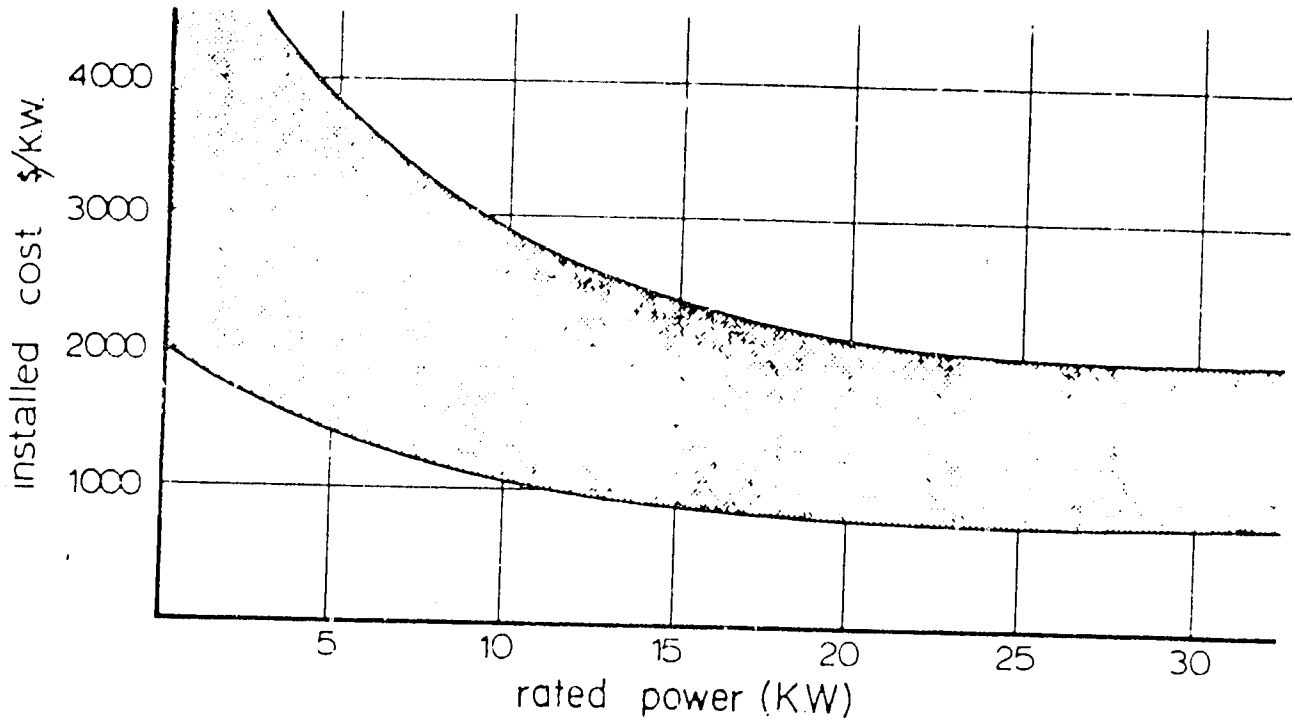
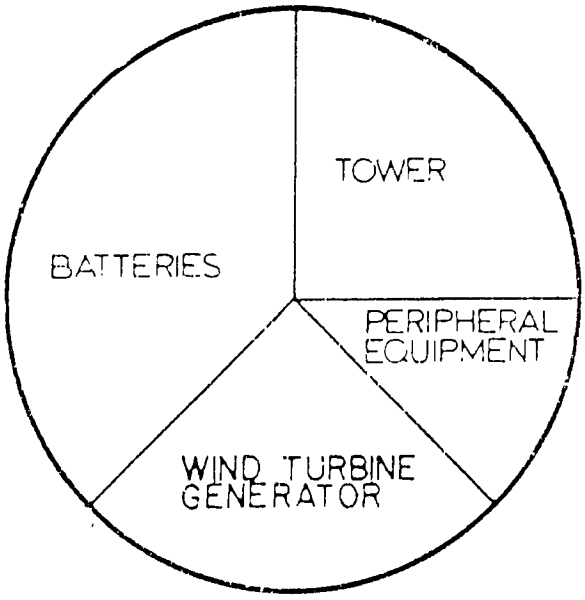
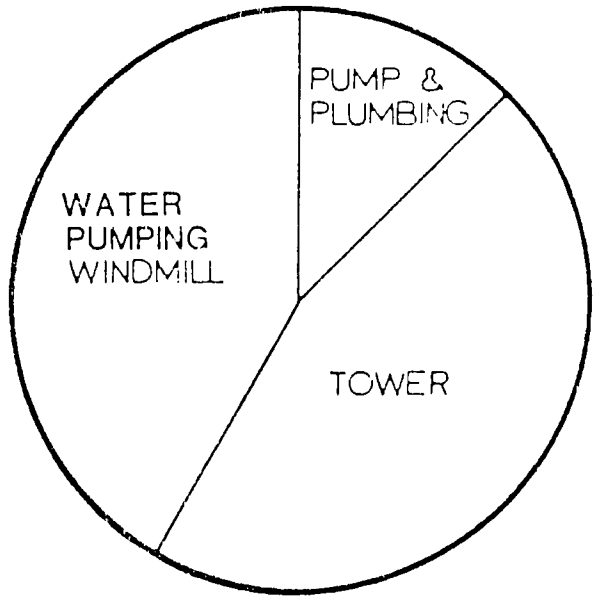


Exhibit 4.21

TYPICAL RELATIVE COSTS FOR SMALL WECS





provide normal or desired operation of the system. This would include:

1. Wind turbine
2. Tower, footing, guy wires, etc.
3. Batteries, power conditioning equipment
4. Pumps
5. Storage sheds for batteries or other equipment
6. Storage tanks
7. Wires

8. Plumbing
9. All installation costs such as delivery, plumbing, electrical, and building permits.

4.9.2 Expected System Life

Wind turbines have been installed at the South Pole and performed for more than 20 years. Wind turbines have been installed in mountainous regions and have been destroyed, or damaged, in just a few months. Both locations are windy and subject to severe weather conditions. In trying to analyze the expected life of your system, you are confronted with several problems. No 20-year rating of wind turbines by any consumer-oriented organization is available. It would be nice to simply assume that the manufacturer's or dealer's statements (if any) concerning expected life are valid for your site. To do so will require intuition and an unemotional, scientific guess of the relative credibility of such statements. Most manufacturers tend to shy away from making claims on the life of their units.

Wind system designers, however, tend to design their equipment for useful lifetimes of much longer than 20 years. Bearings, belts, and some parts may have to be replaced during such a time span, but the basic machinery--if well designed--should last.

4.9.3 Total Energy Yield

This value, expressed in kWh, or horsepower-hour (hp-hr) is the result of the energy resource study and site analysis outlined earlier in this chapter. Total energy yield represents the work of your entire system planning process.

You will likely estimate or calculate energy requirements on a monthly basis. Simply add these together for all the months of a year, and multiply the

annual total by the expected life. This results in the total energy yield you expect from your system.

4.9.4 Annual Maintenance and Repair Costs

It is possible to purchase a maintenance contract from some WECS dealers. Depending on the terms of such a contract it might be possible to use the costs of the contract, plus a small contingency cost for replacement of broken parts, as the annual maintenance cost.

If a service contract is not an available option, maintenance and repair costs can be estimated based on performance information provided by equipment manufacturer, as well as other users of similar systems.

4.9.5 Other Annual Costs and Savings

Listed below are other costs associated with the purchase of WECS. All factors may not be applicable for every situation.

1) Bank interest on money borrowed to purchase a WECS, or interest lost on capital used to purchase WECS.

2) Cost for insuring the WECS

3) Property tax

4.9.6 Expected Resale Value

The resale price of old machines has risen rapidly in recent years. Greatly increased demand, coupled with the availability of old machines at reasonable cost has contributed to the resale value trend. Introduction of new wind turbines from more manufacturers could soften the resale price structure, but this depends upon the ability of the WECS industry to satisfy the demand. It seems reasonable to expect some resale value.

4.10 SPECIFICATIONS IN THE RFP

Within the technical section of RFP, certain information must be provided by the purchaser such that the responder can design the system as well as submit a responsive bid. These two steps that the responder must perform

require different levels of input as discussed in the sections that follow.

4.10.1 Input to System Design

The more detail that is provided by purchasers, the better the responder will understand the nature of the request and thus the closer the system can be designed to the purchaser's expectations (technical and financial). Any doubts in the designer's mind will result in an elevated bid.

First of all, adequate background about the desired system should be given:

- What is the purpose of the system (e.g., demonstration, training, R&D, commercial)?
- Where is the system going to be installed (e.g., distance to technical expertise, accessibility)?

Information on the equipment desired, the climate and available resources, and maintainability should be included as indicated below.

Equipment Detail

- Preferences on equipment supplied (e.g., generator (ac vs. dc), sealed versus vented batteries)
- Technical specifications for existing/required loads
- Indication of demand (e.g., required hours of operations, electric load profiles, amount of water pumped to what head)
- Required reliability of each load (consequences of system downtime)
- Specifications for instrumentation desired (e.g., telemetry)
- Specifications for system protection and safety equipment (e.g., enclosures, alarms)
- Upper and lower system size limits
- Rated wind speed
- Minimum cut-in wind speed
- Cut-out wind speed
- Required availability
- Control system requirements
- Design tolerances

Resource and Climate Data

- o Wind and, in the case of water pumping, water resource data
- o Frequency of extreme, unique, or performance-limiting conditions (e.g., dust storms, high winds, hail, fog, earthquakes, wind turbulence)
- o Consecutive number of windless days

Maintainability

- o Available maintenance for the system (e.g., none; regularly scheduled visits by what skill level of person; trained system operator of what skill level)
- o Available enclosures (e.g., battery room of what size)

Whenever possible, diagrams, maps and site layouts should be provided. Any known dimensions or distances should be identified. An important note to remember, however, is that while detailed specifications are encouraged, they may not allow for a creative bid.

4.10.2 Input to Development of Bid

The items discussed in the previous section addressed that information required by the bidder to design the system; however, additional items must be specified by the purchaser in order for the bidder to submit an uninflated quote. They are as follows:

- o Clear indiciation of what the responder is expected to provide (and thus include in the bid) and what the purchaser will provide.
- o Points of responsibility in the transfer of equipment (e.g., Does the bidder just have to ship equipment to a given port, and then the purchaser is responsible for transfer to the site?)
- o Proof of performance (What is the limit of the contractor's responsibility for technical performance?)
- o Required equipment warranty
- o Turnkey system, or in conjunction with in-country organization or local people
- o Labor support (Provided by the purchaser? If no, what are approximate local labor rates?)

- Type of manuals, if any, to be provided with the system (e.g., startup and testing, operation and maintenance, in what language)
- Spare parts (Are they to be included with the system?)
- Continued technical support (To be provided by the contractor?)
- Local availability of materials (e.g., cement, water, lumber, iron)

5.0 SYSTEM IMPLEMENTATION AND OPERATION

5.1 INSTALLATION REQUIREMENTS

5.1.1 Factory Assembly

For all field installations, it is advisable that as much system assembly as possible be performed at the factory. Nacelles, regulators, inverters, controls, instrument board and so forth can be assembled and inspected prior to shipment to the installation site. Modular turbine towers can be easily assembled on-site, provided adequate instructions, tools and expertise are available.

5.1.2 On-Site Installation

Installation requirements at the site can be categorized as either construction or electrical. Construction tasks are as follows:

- Prepare the site by removing all brush, performing minor leveling, and providing drainage
- Construct buildings and enclosures for instrumentation, controls, switchgear, batteries, and loads, as required
- Construct foundation and erect tower based on manufacturers specifications
- Trench and lay control lines from turbine and loads to the control panel
- Physically install turbine, loads and power conditioning system

Electrical tasks include:

- Wire the turbine generators
- Wire the loads
- Connect power conditioning subsystem, instrumentation and protection circuits

5.1.2.1 Installing Wind Turbine and Tower

To install a tower, you can either assemble it on the ground and tilt it up or assemble it standing up. The first method requires assembly of all components, guy wires, and as much of the wind turbine equipment as possible on

the ground. The base of the tower is then fixed to a pivot to prevent the tower from sliding along the ground and a rope is tied from the tower, over a gin pole (Exhibit. 5.1) to a car, truck or winch. Moving the car/truck pulls the tower up. The gin pole serves in the initial stages to improve the angle at which the rope pulls on the tower.

In the case of the tower being pulled up by a rope tied to a car/-truck bumper, it might be well to pull with the car/truck backing up so the driver maintains a clear view of the action. Also, an effective, foolproof communications link must be established and maintained between the driver and the person who is directing the operation. If not, towers pulled over center, bent, broken cables, and a host of other crises are likely to beset the tower crew.

Tower-raising techniques such as this are usually described in the owner's manual or installation instructions that come with the tower. Since each tower has a different load rating and different installation requirements, it is not possible to discuss the details of tower raising.

Many towers, such as a free-standing octahedron module tower can be erected in place. This is usually done by assembling the first few bays on the ground, standing these up, then assembling the remaining bays while standing on each successive lower bay.

To raise a wind machine, you can: hoist a completely assembled machine up an already erected tower; hoist a partially assembled machine up an already erected tower (Exhibit 5.2), completing the assembly aloft; or tilt the tower up, with the wind machine already installed. The first two methods rate the title "traditional"; the last, in many cases, is not possible or safe. Tilting up a tower with the wind machine already installed (Exhibit 5.3), imposes additional loads on the tower. The compressive load at the base pivot and the bending loads where the rope is attached will be much greater, with the

Exhibit 5.1
TOWER RAISING WITH A GIN POLE

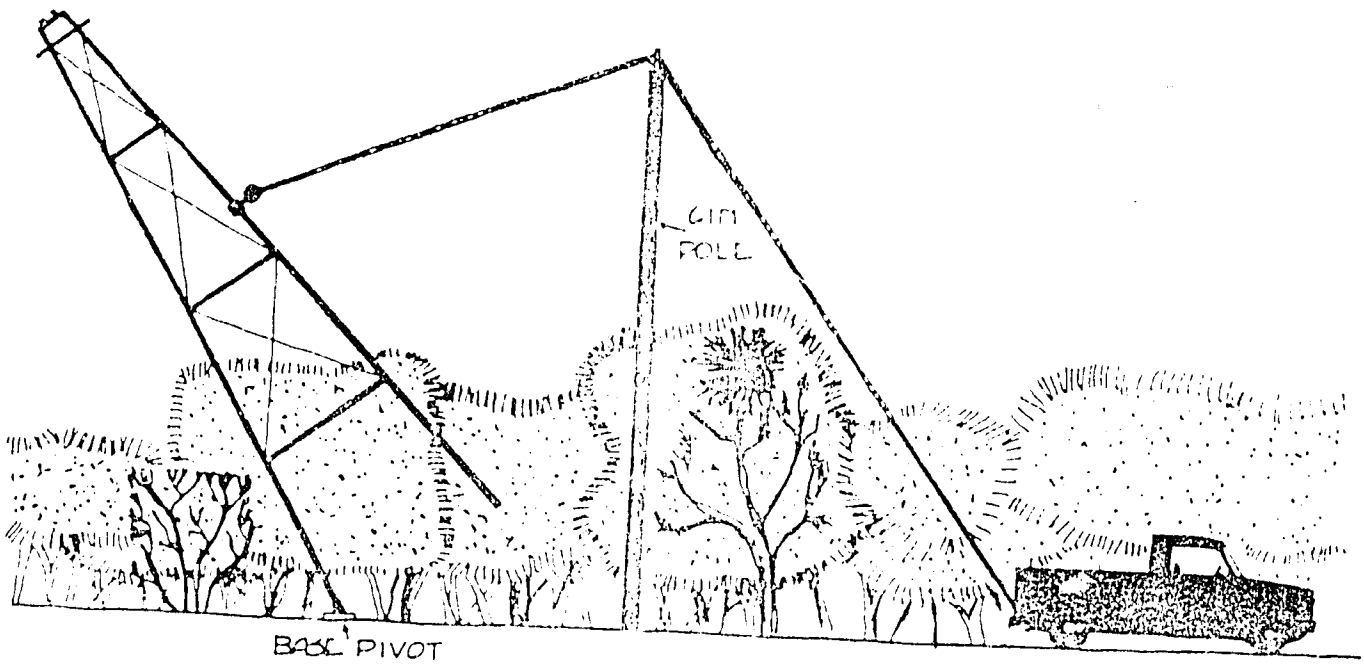


Exhibit 5.2

HOISTING A WIND MACHINE UP THE TOWER

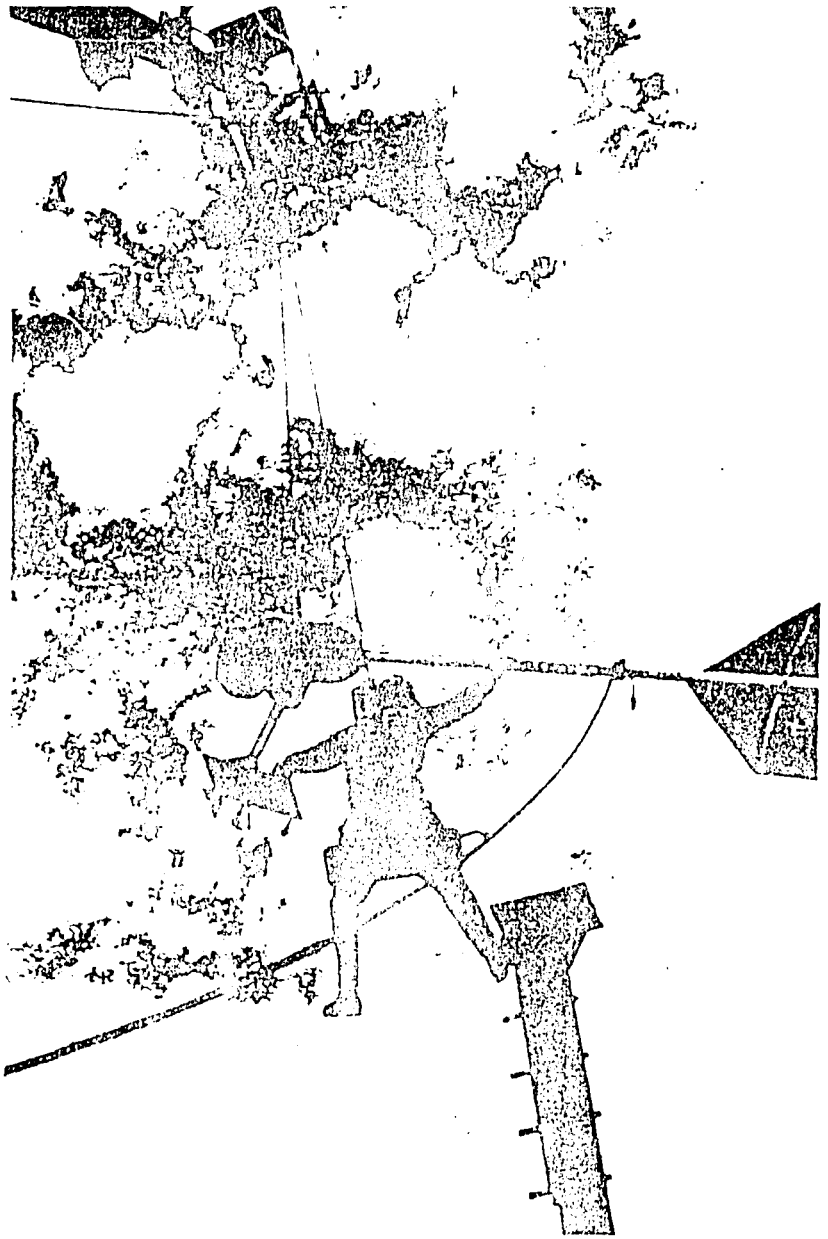
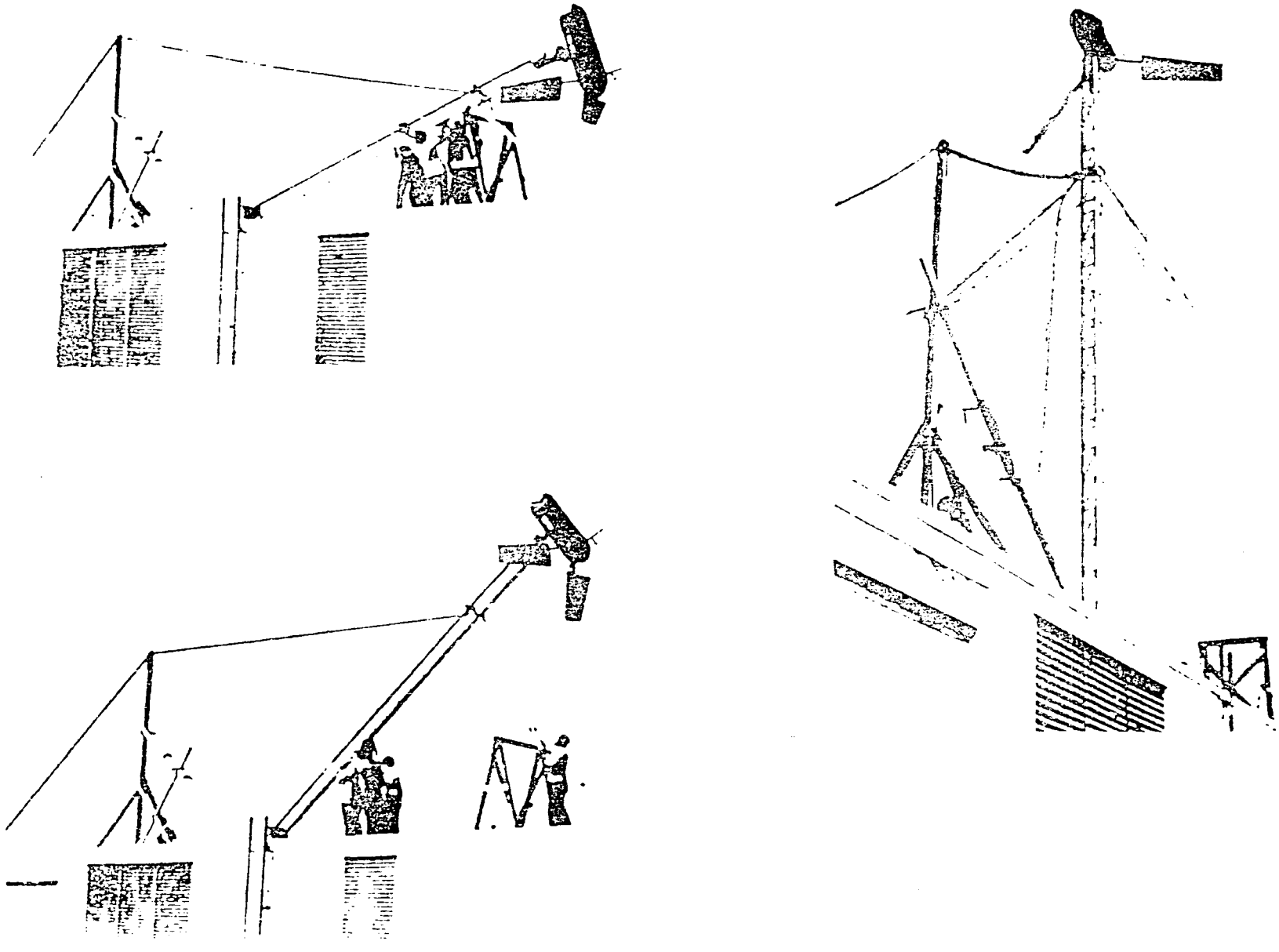


Exhibit 5.3

TILTING UP A WIND SYSTEM AND TOWER USING A GIN POLE



turbine attached. Most likely, you will have to provide extra bracing, but in any case you should consult the manufacturer about these loads or rely on a competent installation crew.

Consider also that if anything goes wrong, you stand to lose the entire tower and wind machine. Risks go up rapidly as tower height and wind machine weight increase. This is not to say, however, that this method will not work; it does, but the individual installation will dictate the method. For sturdy towers of 20 to 40 feet (6.1 to 12.2 meters) experience has shown that tilting the whole works aloft can work.

For taller towers, you can expect to hoist the wind turbine up an already erected tower. This will require a block-and-tackle supported aloft and an extra rope to the wind machine. The block-and-tackle is used to lift, while the rope is tugged at from the ground to keep the wind machine from banging into the tower as it journeys upward.

Consider that with a hand-operated block-and-tackle, you can feel what is happening. Tail vanes snagged on a guy wire may not be detected until damage has occurred if you use a winch or auto-pulled hoist. The support structure that holds the block-and-tackle to the tower top must not bend or otherwise yield to the loads of the wind turbine. You can test it by hoisting up the wind machine with a volunteer adding extra weight. Remember that you must depend on this hoist to suspend the machine over its mount while it is bolted down, maybe 80 to 100 feet (24.4 to 30.5 meters) in the air.

Points to remember while doing any wind turbine installation:

1. Hard hats are required, as tools, bolts, and other objects seem to be routinely dropped from aloft.

2. Climbing safety belts must always be used.

3. Make provision for preventing the wind turbine from operating until it is fully installed. Feather the blades, tie them with a rope, or otherwise lock them. One of Murphy's laws says that whatever can go wrong, will. While you may not detect a breeze

on the ground, there may be enough wind aloft to create an unpleasant surprise about halfway into the installation process.

4. Perform installations when no wind is expected, and start early. Installations always take longer than expected; bolting a wind turbine aloft after dark is to be avoided.

5. Plan and practice the entire installation process very carefully. The process should cover such details as who has which bolt in which pocket, when said bolt is to be installed with what tool, and by whom.

6. Create an alternative plan. This plan is designed to be used as a contingency if something goes wrong (e.g., the main bolt gets dropped and the wind is coming up).

7. Tools and parts can best be carried aloft in a carpenter's tool belt.

8. Pay close attention to the strength of ropes, pulleys, or other auxiliary equipment you may use in hoisting equipment aloft. For example, if you use standard 7/16-inch (1.1 cm) climbing rope for hoisting, a nylon rope will withstand about 3900 pounds (1773 kg) (wet strength), while a manilla rope is rated at 2600 pounds (1182 kg). If you tie a knot in the rope, you will reduce its strength to about 60 percent of the original, and if you pull it around a tight radius - like a bolt - you reduce the strength of the rope to 80 percent of its rating. Naturally, smaller ropes have lower load ratings. If you are hoisting aloft a 400-pound (182 kg) machine, and you want a factor of safety of about 4 (a minimum you should plan for), you are going to need a rope and other equipment capable of hoisting 4 x 400 = 1600 pounds (4 x 182 = 728 kg). If you have a manila rope rated at 2600 pounds (1182 kg) and you tie a knot at its attachment, the rope is really good for 0.6 x 2600 = 1560 pounds (0.6 x 1182 = 709 kg) This rope is the minimum strength to consider for the job.

5.1.2.2 System Wiring for Electrical WECS

Wire size, wire routing, and lightning protection are important considerations for wind generators. Wire size is determined by current requirements and length of wire. In general, wire sizes should be selected so as to limit line voltage losses to about 1%.

Wire routing, except for any deviations necessary for lightning protection, is a matter of direct routing, adequate support to prevent wind or mechanical damage to the wind turbine or wire insulator and adequate separation for prevention of electrical short circuits. Wires that are routed down the

tower should be tied to the tower every few feet or fed through a conduit to preclude wind damage.

5.1.2.3 Labor

Construction tasks can be performed by local unskilled labor under the direction of an experienced individual. Electrical tasks require a skilled electrician; however, where repetitive procedures are involved, local people can be trained under the supervision of an electrician.

5.1.2.4 System Checkout

The final step in the installation procedure is a total system checkout. Construction and electrical connections should be both sound and correct to ensure the safety of operators as well as bystanders and livestock. This checkout is performed prior to system start-up and testing procedure.

5.2 SYSTEM START-UP

It is essential, from both operator and equipment safety standpoints, to follow a systematic start-up procedure. A few points to keep in mind follow:

- Components should be tested independently of one another to the extent possible.
- Initial switching-on of the turbine should be done in low wind speeds (In case power conditioning components have not been properly "burned in" by the manufacturer, they should not be subjected suddenly to full power--likewise with pumps.)
- In systems with battery storage, the batteries should never be turned off prior to the turbine. Similarly, the turbine should never be turned on prior to the batteries.

5.3 PERFORMANCE MONITORING

The ultimate purpose of performance monitoring is to improve/modify designs of systems and components to fit new applications. It is therefore recommended only in the context of an R&D center. The basic questions that must be answered are:

(1) Is the system producing as much energy as predicted?

(2) Are the loads consuming as much energy as predicted?

The energy flows throughout the system can be measured using an anemometer, amp-hour (A-h) meters, dynamometer and run-time meters as indicated below.

Wind Resource Verification: Using an anemometer, wind speed and duration can be monitored and then compared to data used in designing the system.

Wind Turbine Performance Verification: A-h measured coming out of the turbine during a certain period of time divided by A-h predicted coming out of the turbine during the same period should be completed. For mechnical applications, a device which can measure shaft output, such as a dynamometer, can be used to verify wind turbine performance.

Battery State-of-Charge Estimate: The current into the battery divided by the current out of the battery both over a given period of time, starting at full charge should be measured. This can be done with an instrument that continuously records amperehours in and out of the battery.

Load Profile Verification: A load profile verification is only necessary for stand-alone electrical WECS applications.

-- A-h measured into the loads over a period of time divided by A-h predicted into the loads over the same period

-- Load run time measured over a period of time divided by run time predicted over the same period

Overall System Performance: A-h measured out of wind generator during given time period minus the A-h measured to the loads over the same time equals A-h surplus or deficit. If there is a sustained surplus, the turbine was oversized or the loads are underutilized. If there is a sustained deficit, battery life is threatened.

Whether the data acquisition system is automatic or manual, it should be performed only where technical expertise is readily available. This statements is based on the following two points:

(1) the accuracy and amount of data is inversely proportional to distance from technical expertise

(2) accuracy is not proportional to cost (for example, digital recording A-h meters are costly, while their accuracy is difficult to maintain).

6.0 SPECIAL CONSIDERATIONS IN EGYPTIAN ENVIRONMENT

6.1 DUST STORMS

WECS gearboxes and generators, whether they are located in a nacelle atop a tower (horizontal-axis) or ground mounted (vertical-axis), require extensive cooling for proper performance. This cooling is caused by airflow through the nacelle or other generator/gear box housing structure. Dust storms can result in accumulation of dust (as well as other debris) on gearboxes and generators, causing them to overheat. In addition, dust can find its way into bearings, causing further turbine complications. Engineering adaptations of manufacturer's designs may be required to obtain better sealing of operating gears and other parts. Also, coating or annual recoating of blades may be necessary to maintain aerodynamic efficiency.

Dust storms also result in dust accumulation on batteries, power conditioning equipment and electrical contacts. These should be cleaned as often as necessary to insure optimum system performance.

6.2 TEMPERATURE & HUMIDITY

The high temperatures encountered in Egypt reduces electrical equipment reliability and decreases battery life. Low humidity also increases evaporation of water from vented batteries, thus increasing the frequency of maintenance. Batteries should be sheltered in such a way as to optimize passive cooling.

6.3 WIND RESOURCE

At least two regions in Egypt have sufficient average daily and annual wind speeds considered high enough for the application of wind power. Available data demonstrates that the Mediterranean Sea coast has an average annual wind speed of about 12.4 mph (5.6 m/s), and the Red Sea coast approximately 13.6 mph (6.1 m/s). Useable electric energy output in these areas is

estimated to be 650 kWh per square meter of windmill swept area.

Available data on wind resources in Egypt is presented in Appendix H.

7.0 CURRENT R&D THRUSTS

Current WECS R&D thrusts are aimed at increasing system reliability and availability, producing larger (megawatt) size machines (average turbine size in 1984 was 78kW), increasing the range of windspeeds in which a given turbine can operate (increasing the energy output), and developing lightweight materials. Projections showing the cost of energy produced by WECS are shown in Exhibit 7.1 for smaller machines (50-60kW).

Specific technical thrusts of the current WECS research programs are outlined below.

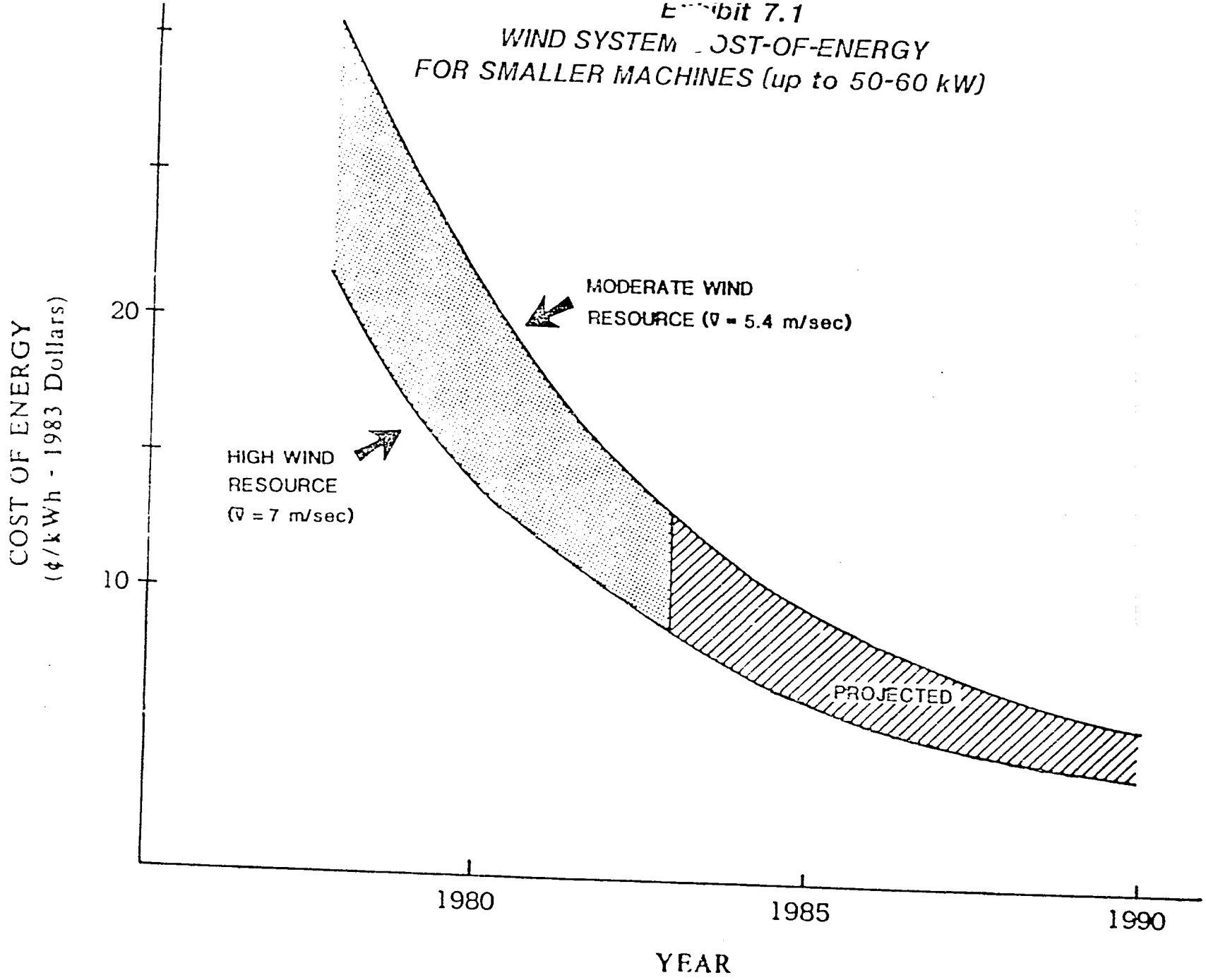
7.1 AERODYNAMICS

Several approaches are being taken to improve and gain a better understanding of the aerodynamics of the rotor. Recently, research to reduce draft of airplane wings has discovered that small surfaces attached to the wing tip, called winglets, reduce the drag of the wing. Similar devices on the wind turbine rotor blades may result in improved rotor performance.

Up to this point, wind turbine rotor blades have been designed and built from airfoil shapes intended for airplane wings. These shapes are not necessarily the most optimum design for the range of operating conditions experienced by the wind turbine rotor. Large wind turbine rotor airfoils should be thicker than the conventional thin wings on airplanes. Well-established methods for designing airfoils will be extended to include airfoils having their maximum thickness up to 30 percent of their width. To validate these advanced designs, models will be built and tested in a wind tunnel. Later, a set of thick blades will be built and tested on a full-scale rotor.

Detailed experiments will be conducted to determine the effects on rotor chraracteristics of several airfoil control surface methods. Objectives of this research will be to investigate and obtain a data base on the performance of

Exhibit 7.1
WIND SYSTEM COST-OF-ENERGY
FOR SMALLER MACHINES (up to 50-60 kW)



rotors with full- and partial-span pitch control, trailing-edge control surfaces, and fixed pitch blades.

7.2 STRUCTURAL DYNAMICS

Both experimental and analytical research is being undertaken to gain a better understanding of the structural dynamics of wind turbine systems and to improve operation by controlling and preventing, where possible, undesirable dynamic effects. Sources of rotor dynamic loads and deflections include, for example, the effect of wind shear on the rotor during rotation. For most wind turbine sites the wind speed increases with altitude above ground level. As a result, each rotor blade experiences higher wind speeds and resulting higher loads at the top of its travel than at the bottom, or lowest position above ground. Air turbulence caused by the tower, and occurring downwind of the tower, causes dynamic blade loads and deflections as each blade passes through the turbulent region. The wind itself can be very turbulent and is a primary source for rotor loads and deflections. Variability of the wind is felt not only by the blades as they rotate but also by the drivetrain and tower since the loads from the rotor are transmitted into these components.

As mentioned previously, changing wind speeds are not only felt by the rotor but are also transmitted into the drivetrain. Drivetrain loads can exceed design allowables if the frequency of the transmitted load oscillations is at or near the resonant frequency of the drivetrain structure. It is predicted that the variable-speed generator will be effective in smoothing out those cyclic loads in the drivetrain. Research is currently being conducted with a variable-speed generator configuration to determine how variable-speed generators respond to drivetrain load oscillations induced by the rotor.

7.3 COMPOSITE MATERIALS

Low cost and highly durable rotor blades are goals of current research efforts. Both wood and fiberglass composite materials have been

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identified, through development and testing projects, as the most promising materials to meet these goals. However, additional research is needed to improve these materials and to develop extensive and comprehensive properties data. Basic materials properties tests will be conducted to determine the effects of such variables as wood grade, moisture content, construction procedures, and temperature and humidity exposure.

Prestressed concrete was studied and rejected as a blade material because of excessive weight. A new technique of reinforcing concrete by using glass or graphite fibers could possibly change the outlook of using concrete for blades. A conceptual design will be made to determine if blade weight and cost would be reasonable if fiber-reinforced concrete were used.

High-strength graphite filaments can also improve the strength of both wood and fiberglass composite blades. Because the wood blades are of laminated construction, a laminated reinforcement using high-strength materials can be readily incorporated into the fabrication procedure. Blade test articles will be built and tested to acquire strength data and to develop the ability to apply this technology to full-size rotor blades.

For economic wind turbine operation, rotor blades should have an operating life expectancy of about 30 years under widely varying environmental conditions such as salt-laden, humid air and high and low temperatures. Research is required to determine the effect of such extreme environmental conditions on rotor blade structures and will provide the technology needed for environmental protection. Data will be acquired by environmental and time-accelerated testing methods and by actual real-time exposure to various environmental conditions.

7.4 DIFFUSER-AUGMENTED WIND TURBINE

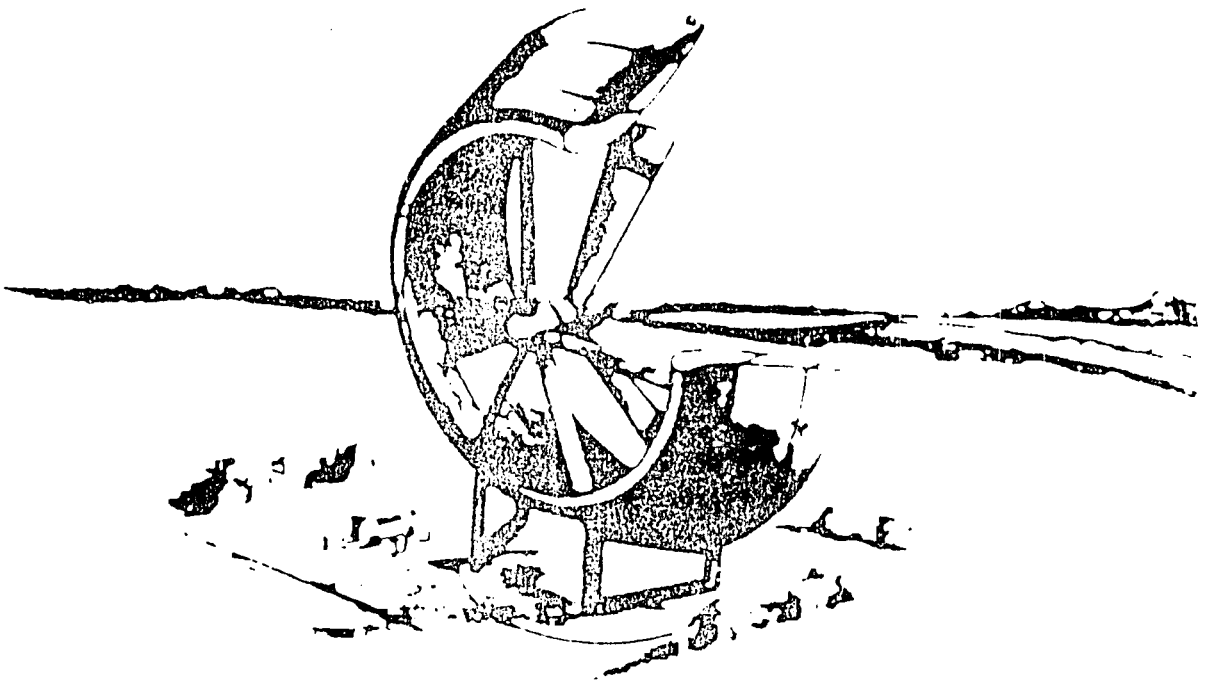
The Diffuser-Augmented Wind Turbine (DAWT) is one of the advanced concepts being investigated to improve the economics of wind energy conversion. The project is aimed at increasing the output and reducing the cost, the off-duty

time, and the technical risk of wind energy conversion systems.

In the DAWT concept, the turbine rotor is enclosed in a diverging duct called a diffuser (Exhibit 7.2). By recovering exhaust kinetic energy, the diffuser produces a greatly reduced pressure behind the turbine with at least as much pressure drop across the turbine. Because the wind power available to the turbine is the product of flow rate and pressure drop, much greater power output is possible than for a conventional WECS at the same turbine size and free wind speed. The DAWT also has additional operational and reliability advantages that arise from the diffuser's large nonrotating structure.

Exhibit 7.2

ARTIST CONCEPTION OF A DIFFUSER AUGMENTED WIND TURBINE



8.0 WECS APPLICATIONS

Wind is a practical energy source for many applications requiring electrical or mechanical power. Its suitability for a specific application at a given location will depend on many factors, both economical and logistical. Wind energy has proven economically and technically successful in water pumping and stand-alone electrification applications, as well as in supplementing a utility's generating capacity. This chapter presents information on such applications which are currently operational or being tested worldwide. Descriptions of representative WECS applications are shown in Appendix I - Wind Project Site Visit Book.

8.1 AGRICULTURAL APPLICATIONS

In a majority of developing countries, the agricultural sector is probably the most important and productive sector of the economy, encompassing such activities as livestock, food and non-food crops, fisheries, poultry and dairy. Applications for wind systems include a variety of uses such as irrigation, feed preparation, refrigeration, and ventilation for livestock and produce storage.

8.1.1 Crop and Livestock Production

The major production activities in which wind energy systems could play a significant role are irrigation and livestock watering. To illustrate the attractiveness of wind in such applications consider the following example. In a location with a mean wind speed of 15 mph (6.7 m/s) and a pumping requirement of 100 vertical feet (30.5 m) total pumping head, a mechanical wind turbine with a 6 ft. (1.8 m) diameter rotor can supply approximately 677,000 gallons (2.6 million litres) of water per year, while a machine with a 14 ft (4.3 m) diameter rotor will supply about 4.6 million gallons (17.4 million litres) per year. If the mean wind speed was only 12.5 mph (5.6 m/s), the above machines would supply 540 thousand and 3.6 million gallons (2.0 million

and 13.6 million litres) of water, respectively. With either windspeed, the smaller machine could supply enough water to irrigate 0.15 hectares of land or water about 77 cattle annually. The larger machine could irrigate 0.8 hectares of land or water over 500 cattle annually.

8.1.2 Crop Processing

Major crop processing activities include: cutting, grinding, milling, hulling, scarifying, polishing and decortication. These activities occur in most countries of the world. The extend of the operation depends greatly on the type of crop, staple diet and cultural practices. Often, peak power demands occur just after harvest, requiring mills to operate 12-15 hours/day. However, there is also a year-round demand requiring 4-8 hours/day of operation. Energy requirements are characterized by capacity, power required per unit of material processed, size and shape of product. Energy requirements vary significantly, ranging from 1.5 kWh/metric ton (MT) for winnowing to 40 kWh/MT for fine grinding of cereal grains. Wind energy could be economical in many locations, depending on local wind resources, but is is unlikely to economically meet 100% of the loads as a result of the seasonal demand of the application.

8.1.3 Refrigeration, Ventilation and Crop Drying

A critical need in rural areas of developing countries is storage and refrigeration facilities for agricultural produce. Losses up to 40% have been reported due to a lack of such facilities. Energy requirements of storage and refrigeration vary depending on type of product and climate condition.

Inadequate drying is a major cause of losses. As a result, many of the cereal growing countries are beginning to introduce mechanical driers. These units require power to operate the blower.

Wind machines could be a suitable power source for such applications. Power requirements could vary between 20-40 kWh/MT for low temperature drying.

Ventilation for grain, fruit and vegetable storage could range from about 0.05 to 0.5 kWh/MT/day. If cooling, refrigeration or freezing is required, then the energy demands are much higher. Typical sizes of rural storage facilities range from about 25 MT to above 1,000 MT.

8.2 INDUSTRIAL APPLICATIONS

Industry is a major consumer of commercial energy in developing countries, accounting for 20 to 66% depending on the specific country. Most of this usage, however, can be attributed to the production of energy intensive products such as steel, cement, ammonia, pulp and paper, fertilizers, and refined petroleum products. The more appropriate applications potential for wind energy in these countries is in the cottage industry category where power requirements are more dispersed, grid power is not available and the availability of local generator systems is limited.

8.3 RESIDENTIAL/COMMERCIAL APPLICATIONS

In the residential and commercial sector electric energy is used for a wide variety of domestic and productive purposes. These could range from a few hundred kilowatt hours annually for a basic household purposes to thousands of kilowatt hours for a larger commercial business. Rural areas receive electricity from (1) stand-alone generators serving single consumers; (2) a local network serving several consumers and; (3) the main grid system of a utility.

8.4 OTHER REMOTE AND SPECIAL APPLICATIONS

There are a myriad of other wind machine applications that do not easily fall into the above categories. These include telecommunications, highway applications, lighthouses, battery charging, power for outposts, clinics and schools, and desalination. Exhibit 8.1 summarizes these applications, their general energy requirements, and the competitive position of wind machines when compared to diesel power. In general wind systems are competitive with conventional diesel and gasoline generators in most remote and special applications. For the

Ex. Bit 8.1

COMPARISON OF POWER SOURCES FOR
REMOTE AND SPECIAL APPLICATIONS

Application	Energy Requirement (kWh/year)	Wind Energy System Size Range	Conventional System to Wind System Cost Ratio*	
			1981-1985	1986-1990
Repeater Station	22,400	10-25kW	1.30	1.65
Private Micro-wave	2,400	2-5kW	2.34	3.45
UHF/VHF	800	≤ 1kW	1.15	1.76
Radio Transceiver	500	≤ 1kW	1.27	1.98
Highway Rest Stop	2,000	1-5kW	.67	1.01
Cathodic Protection	250	≤ 1kW	1.21	1.95
Lighthouse	10,000	5-10kW	.92	1.29
Small School	10,000	5-10kW	.92	1.29
Battery Charger	600	≤ 1kW	1.20	1.87
Outpost	300	≤ 1kW	.38	.61
Health Center	4,000	2-5kW	1.01	1.49
Desalination (Small)	17,000	10-25kW	1.07	1.41
Desalination (Large)	33,000	15-40kW	.70	.89

*Ratio is based on: cost of energy from wind energy systems with 12.5 mph (5.6 m/s) mean annual wind speed; fuel cost of $1.50/gal for highway rest stop; battery charger and desalination applications; fuel cost of $3.00/gal for all other applications; 12% real discount rate.

Source: Prospects for Foreign Applications of Wind energy Systems - Preliminary Report. Department of Energy Report DOE/NBM-1005, November 1981.

smaller applications (e.g. 250-800 kWh/year), a closer match between wind system size and energy requirements would further improve the cost comparisons in favor of wind systems.

9.0 PRODUCTS

The U.S. wind industry offers a wide variety of equipment to choose from: small, medium and large scale wind generator systems, both ac and dc; mechanical systems; packaged systems for specific applications; towers; rotors; controllers, inverters and converters; and mechanical and electrical end-use equipment. Individual WECS components can be obtained from respective manufacturers, or their distributors; turn-key systems can be purchased through systems integrators and some turbine manufacturers. Several of the major manufacturers also supply packaged systems for certain applications.

This chapter organizes U.S. manufacturers' products. Information is presented in matrix format by component, as follows:

- Wind Turbines (Exhibit 9.1)
- Packaged Systems (Exhibit 9.2)
- Towers (Exhibit 9.3)
- Batteries (Exhibit 9.4)
- Regulators/Controllers (Exhibit 9.5)
- Power Conditioning-Inverters (Exhibit 9.6)
- Miscellaneous Equipment (Exhibit 9.7)

The information presented is based on product literature obtained through a mailing to U.S. manufactures. Only those manufacturers who responded are included on the matrices. As such, the information in this chapter is representative of U.S. wind products but not all inclusive. The actual product literature received from the mailing are filed by components in the REFT Project Library.

At the end of this chapter are the names and addresses of all the manufacturers identifies in the matrices.

FEATURE / MANUFACTURER	RATED OUTPUT (kW)							RATED WIND SPEED (meters/second)						CUT-IN WIND SPEED (m/s)		CUT-OUT WIND SPEED (m/s)			ELECTRICAL OUTPUT	
	≤10	11-20	21-35	36-50	50-100	101-200	>200	<10	10-12	13-14	15-16	17	>18	2-3	4-5	17-19	20-23	>23	AC	DC
ADVANCED ENERGY		●							●						●				●	
ASTRAL WILCON INC.		●									●				●				●	
BERGEY WINDPOWER	●								●					●		←	none	→	●	
CARTER WIND SYSTEMS			●				●		●				●	●	●	←	none	→	●	
EARTH ENERGY SYSTEMS	●	●						●	●					●			●		●	
ESI INC.					●				●						●				●	
ENERTECH		●	●	●				●	●	●					●		●	●	●	
FLOWIND					●	●						●			●		●		●	
INTERNATIONAL DYNERGY								●	●	●					●		●	●	●	
KW CONTROL SYSTEMS			●						●						●	●			●	
LAKESTATE SYSTEMS*															●		●		●	
NORTH WIND POWER	●	●				●		●				●		●				●		●
PRODUCT DEVELOMENT	●								●						●		●		●	
VAWTPOWER					●						●				●		●		●	
WHIRLWIND POWER	●								●					●		●			●	
WINDPOWER					●							●			●			●	●	
WINPOWER	●								●						●	←	none	→	●	
WINDTECH					●						●				●				●	
WIND TECHNOLOGIES		●							●						●	←	none	→	●	

* Annual output listed in product literature

Exhibit 9.1 WIND TURBINES

MANUFACTURER \ FEATURES	BATTERY CHARGING	AIR COMPRESSOR SYSTEM	REFRIGERATION	WATER PURIFICATION	MECHANICAL WATER PUMPERS	ELECTRIC WATER PUMPERS
ADVANCED ENERGY	●					
BERGEY	●			●		●
DYTEK	●					
DEMPSTER					●	
ENERTECH						●
NORTH WIND	●		●			●
VALLEY PUMP GROUP					●	
WHIRLWIND	●					
WIND BARON		●		●	●	●

Exhibit 9.2 PACKAGED SYSTEMS

FEATURES / MANUFACTURER	TYPE		TOWER SUPPORT		HEIGHT						
	POLE	LATTICED	GUYED	FREE-STANDING	<15 METERS	15-17 METERS	18-23 METERS	24-29 METERS	30-35 METERS	35 METERS	>35 METERS
BERGEY WINDPOWER	●		●					●	●	●	
CARTER WIND SYSTEMS	●		●				●	●			●
EARTH ENERGY SYSTEMS		●		●			●	●	●	●	●
ENERTECH		●		●				●			
ESI INC.		●		●				●			
INTERNATIONAL DYNERGY	●		●	●		●	●				●
KW CONTROL SYSTEMS	●		●				●				
LAKE STATE SYSTEMS	●	●		●				●	●		
NORTH WIND POWER		●	●	●	●	●					
PRODUCT DEVELOPMENT					●		●	●	●		
ROHN *		●	●	●	●	●	●	●	●	●	●
WHIRLWIND	●	●	●	●	●	●	●	●	●		
WIND POWER SYSTEMS		●		●			●				
WINDTECH	●			●		●					

*Towers not part of total wind system

Exhibit 9.3 TOWERS

MANU-FACTURER \ FEATURE	Lead-Antimony (Lead-Acid)	Lead-Calcium (Lead-Acid)	Pure Lead (Lead-Acid)	Nickel-Cadmium	Sealed	Vented
C&D		●			●	●
CHLORIDE			●		●	
DELCO		●			●	
EXIDE			●			●
GNB	●	●			●	
GLOBE			●		●	
NIFE				●		●
SURRETTE	●					●
TIDELAND			●			●

Exhibit 9.4 BATTERIES

Exhibit 9.5
REGULATORS/CONTROLLERS

MANUFACTURER \ FEATURE	Characteristics			Nominal Voltage Input (Volts)						
	Shunt Regulation	Series Regulation	Maximum Power Tracking	6	12	24	36	48	120	240
ADVANCED ENERGY	●								●	
BOSS	●	●		●	●	●	●	●	●	
HELIOTROPE GENERAL	●	●			●	●				
NORTH WIND POWER CO.					●	●		●	●	
SPECIALTY CONCEPTS	●	●		●	●	●	●	●	●	
T DELAND						●				
WIND TECHNOLOGIES									●	

FEATURE / MANUFACTURER	Available Components						Inverter Characteristics								Inverter Power Output (kVA)			
	Inverter	Frequency Converter	Uninterruptable Power Supply	DC DC Converter	Rectifier (AC DC Converter)	AC Regulator	Line-Commutated	Self-commutated	Stand-Alone Only	Maximum Power Tracking	Single-Phase	Three-Phase	Quasi-Sine Wave Output	Sine Wave Output	<1	1-15	15*-75	>75
ABACUS	●	●	●	●				●		●	●	●		●	●	●	●	
ACHEVAL	●						●				●	●	●			●	●	
ADVANCED ENERGY	●					●								●		●		
AMERICAN POWER CONVERSION	●						●			●	●			●		●		
BOSS				●														
BEST	●		●						●		●		●	●	●	●		
GNB					●													
HEART INTERFACE	●								●		●		●		●	●		
HELIONETICS	●	●					●	●		●	●	●		●	●	●	●	●
NOVA ELECTRIC	●	●	●					●			●	●		●	●	●	●	
POWERMARK	●	●	●			●			●				●	●	●	●		
TESLACO	●									●				●		●		
TRIPPLITE	●								●		●		●		●	●		
WINDWORKS	●						●			●	●	●	●			●	●	●
BERGEY WINDPOWER	●				●							●						
WHIRLWIND	●			●										●		●		
DYTEK	●					●							●					

Exhibit 9.6 POWER CONDITIONING-INVERTERS

MANUFACTURER \ FEATURE	PUMPS	GENERATORS	TURBINE ROTORS	GEAR BOXES	COMPRESSORS	ALTERNATORS	ENGINE (Back-up power)	ANEMOMETERS	WIND RECORDERS
DEMPSTER	●								
HERMANN ROTOR			●						
GRUNDFOS	●								
NATURAL POWER						●		●	●
SANTA ROSA POWER			●						
SECOND WIND									●
VALLEY PUMP	●								
WINCO		●							

* Partial list, awaiting more product literature

*Exhibit 9.7 MISCELLANEOUS EQUIPMENT**

U.S. WIND ENERGY PRODUCT MANUFACTURERS

Abacus Controls, Inc.
P.O. Box 893
Somerville, New Jersey 08876
Phone (201) 526-6010
Telex 888186

Acheval Wind Electronics Company
361 Aiken Street
Lowell, Massachusetts 01803-4115
Phone (617) 453-0874

Advanced Energy Corporation
14933 Calvert Street
Van Nuys, California 91411
Phone (213) 782-2191

American Power Conversion Corporation
89 Cambridge Street
Burlington, Massachusetts
Phone (617) 273-1570

Astral Wilcon, Inc. (AWI)
P.O. Box 291
127 West Main Street
Millbury, Massachusetts 01527
Phone (617) 865-9570

Balance of Systems Specialists, Inc. (BOSS)
7745 E. Redfield Road
Scottsdale, Arizona 85260
Phone (602) 948-9809
Telex 6835043

Bergey Windpower
2001 Priestley Avenue
Norman, Oklahoma 73069
Phone (405) 364-4212

Best Power Technology, Inc.
P.O. Box 280
Necedah, Wisconsin 54646
Phone (608) 565-7200
Telex 701934

Carter Wind Systems, Inc.
Route 1 - Box 405 A
Burkbunett, Texas 76354
Phone (817) 569-2238

C&D Power Systems
(Allied Corporation)
3043 Walton Road
Plymouth Meeting, Pennsylvania 19462
Phone (215) 828-9000
Telex 681059 CD BAT UW

Chloride
P.O. Box 12936
Tallahassee, Florida 32308
Phone (904) 385-5686

Delco Electronics
Division of General Motors
2401 Columbus Avenue
Anderson, Indiana 46011
Phone (317) 646-7821

Dempster, Inc.
P.O. Box 848
Beatrice, Nebraska 68310
Phone (402) 223-4026

Dytek Laboratories, Inc.
Airport International Plaza
40 Orville Drive
Bohemia, New York 11716
Phone (516) 567-8500

Earth Energy Systems, Inc.
250 Prairie Center Dirve
Eden Prairie, Minnesota 55344
Phone (612) 830-7200
Telex 29-0753 EESI EP

Enertech Corporation
P.O. Box 420
Norwich, Vermont 05055
Phone (802) 649-1145
Telex 706433

ESI, Inc.
500 Valley Way
Milpitas, California 95035
Phone (408) 945-9922

Exide, Inc.
101 Gilbrator Road
Horsham, Pennsylvania 19044
Phone (215) 674-9500

U.S. WIND ENERGY PRODUCT MANUFACTURERS
(Continued)

FloWind Corporation
21249 72nd Avenue, South
Kent, Washington 98032
Phone (206) 872-7080
TWX 9104472762

Globe Battery
5757 N. Green Bay Avenue
Milwaukee, Wisconsin 53209
Phone (414) 228-1200
Telex 26650

GNB Batteries, Inc.
P.O. Box 43140
St. Paul, Minnesota 55164
Phone (612) 681-5000
Telex 297036

Grundfos
P.O. Box 549
2555 Clovis Avenue
Clovis, California 93613
Phone (209) 299-9741

Heart Interface Corporation
1626 S. 341st Place
Federal Way, Washington 98003
Phone (206) 838-4295
Telex 16053

Helionetics
17312 Easton Street
Irvine, California 92714
Phone (714) 261-8313
TWX 9105952829

Heliotrope General
3733 Kenora Drive
Spring Valley, California 92077
Phone (619) 460-3930

Hermann Rotor Company
208 La Salle Street, Suite 1283
Chicago, Illinois 60604
Phone (312) 346-5033

International Dynergy, Inc.
777 E. Tahquitz-McCallum Way
Suite 233
Palm Springs, California 92262
Phone (619) 322-0400
Telex 881743

ISTA Energy Systems Corporation
407 Hope Avenue
P.O. Box 618
Roselle, New Jersey 07203
Phone (201) 241-8880
TWX 7109965818

KW Control Systems, Inc.
South Plank Road
Middletown, New York 10940
Phone (914) 355-6741
Telex 6711599

Lakestate Systems, Inc.
Box 181
Kennedy, Minnesota 56733
Phone (218) 674-4105

Natural Power, Inc.
New Boston, New Hampshire 03030
Phone (603) 487-5512
Telex 845233

NIFE, Inc.
George Washington Highway
P.O. Box 100
Lincoln, Rhode Island 02865
Phone (401) 333-1179

North Wind Power Company
Box 556
Moretown, Vermont 05660
Phone (802) 496-2955
Telex 957034

Nova Electric Manufacturing Co., Inc.
263 Hillside Avenue
Nutley, New Jersey 07110
Phone (201) 661-3434

Product Development Institute
4445 Talmadge Road
Toledo, Ohio 43623
Phone (419) 472-2136

Rohn
6718 West Plank Road
P.O. Box 2000
Peoria, Illinois 61656
Phone (309) 697-4400
TWX 9106520646

U.S. WIND ENERGY PRODUCT MANUFACTURERS
(Continued)

Santa Rosa Machined Props, Inc.
127 Airport Blvd.
Santa Rosa, California 95401
Phone (707) 545-1108

Second Wind, Inc.
7 Davis Square
Somerville, Massachusetts 02144
Phone (617) 776-8520

Surrette Storage Battery Co., Inc.
P.O. Box 3027
Salem, Massachusetts 01970

Teslaco
490 South Rosemead Blvd.
Suite 6
Pasadena, California 91107
Phone (213) 795-1699

Tideland Signal Corporation
4310 Director's Row
P.O. Box 52430
Houston, Texas 77052
Phone (713) 681-6101
Telex 762 327 or 762 356

Tripp Lite
500 No. Orleans
Chicago, Illinois 60610
Phone (312) 329-1777

Valley Pump Group
Commerce & Exchange Streets
Conway, Arkansas 72032
Phone (501) 329-9811

Vawtpower, Inc.
134 Rio Rancho Drive
Rio Rancho, New Mexico 87124
Phone (505) 892-9463

WhirlWind Power Company
207 1/2 East Superior Street
Duluth, Minnesota 55802
Phone (218) 722-1492
Telex 910 561 0052

Winco
7850 Metro Parkway
Minneapolis, Minnesota 55420-1985
Phone (612) 853-8400
Telex 2907543

Wind Baron Corporation
3702 West Lower Buckeye Road
Phoenix, Arizona 85009
Phone (602) 269-6900
Telex 6835005

Wind Power Systems, Inc.
9279 Cabot Drive
San Diego, California 92126
Phone (619) 566-1806
Telex 383187

WindTech
P.O. Box 837
Glastonbury, Connecticut 06003
Phone (203) 659-3786

Wind Technologies
1190 Brooks Avenue
Rochester, New York 14624
Phone (716) 235-8500

Windworks, Inc.
Box 44A, Route 3
Muckwonago, Wisconsin 53149
Phone (414) 363-4088

Winpower Wind Systems, Inc.
Newton, Iowa
Phone (515) 792-1301

APPENDIX A

CONVERSION FACTORS

Conversion factors

Length	1 cm = 0.3937 in = 10^4 m
	1 in = 2.540 cm
	1 ft = 30.48 cm
Mass	1 lb_m = 453.59 g_m = 7000 grains
	1 kg_m = 2.2005 lb_m
Force	1 lb_f = 32.174 $lb_m \cdot ft/s^2$
	1 dyne = 1 $g_m \cdot cm/s^2$
	1 N = 1 $kg_m \cdot m/s^2$
	1 lb_f = 444,800 dyn = 4.448N
Pressure	1 lb_f/in^2 = 2.036 in Hg at 32°F
	1 in Hg = 33,864 dyn/cm^2 = 0.0334 atm = 0.491 lb_f/in^2
	1 atm = 14.696 lb_f/in^2 = 760 mm Hg at 32 F
	= 29.92 in Hg at 32°F
	1 bar = 0.9869 atm = 10^5 N/m^2 = 100 kPa
	1 torr = 1 mm Hg at 0°C = 10^3 m
	= 1.933 x 10^{-2} psi
Volume	1 l = 0.0353 ft^3 = 0.2642 gal = 61.025 in^3
	1 ft^3 = 28.316 l = 7.4805 gal = 0.02832 m^3
	1 in^3 = 16.387 cm^3
Density	1 lb_m/ft^3 = 0.01602 g_m/cm^3
Energy	1 Btu = 778.16 $ft \cdot lb_f$ = 252.16 cal = 1055 J
	1 Btu/lb = 2.32 kJ/kg
	1 J = 1 N·m = 1 V·C
	1 eV = 1.602 x 10^{-19} J
Power	1 W = 1 J/s = 860.42 cal/h = 3.413 Btu/h
	1 hp = 746 W = 550 $ft \cdot lb_f/s$ = 2545 Btu/h
Velocity	1 m/h = 0.447 m/s

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APPENDIX B

THEORY OF THE IDEAL EFFICIENCY OF WIND TURBINES

(Excerpt From: DeRenzo, D.J. editor, Wind Power--Recent Developments. New Jersey: Noyes Data Corporations, 1979)

WIND POWER

The power, P, that can be extracted from a windstream by an unshrouded wind turbine is equal to the efficiency, η, of the system used to extract the power, times the wind's volumetric flow rate at the turbine, $V_T A_T$, times the sum of the change in pressure energy, Δp, plus the change in kinetic energy, ΔQ, of a unit volume of air that passes through the turbine:

$$P = \eta V_T A_T [\Delta p + \Delta Q]$$

For a conventional wind turbine, operating under optimum steady state conditions in an initially free-flowing windstream of constant initial velocity, V_o, the velocity of a unit volume of air will decrease monotonically as it approaches the turbine, passes through it and recedes from it. As the air receives kinetic energy from the surrounding winds, its velocity will increase until it again reaches its initial velocity, V_o.

The sum of the change in pressure energy and the change in kinetic energy of the unit volume of air will be constant as it approaches the turbine upstream. The pressure energy will increase, and the kinetic energy will decrease, until the pressure reaches a maximum at the interface with the turbine. As the air passes through the turbine, its pressure will rise until it again reaches atmospheric pressure. After passing the turbine, its kinetic energy will continue to decrease until its pressure again reaches atmospheric pressure.

The cross-sectional area of the windstream that passes through the system will be inversely proportional to its velocity. Its streamlines will expand as it approaches the turbine, passes through it, and recedes from it. As the disturbed flow receives kinetic energy from the surrounding winds, the effects of the turbine will diminish through the dispersal of the disturbance in the windstream.

The power coefficient, C_p, of such a system is defined as the

power delivered by the system divided by the total power available in the cross-sectional area of the windstream subtended by the wind turbine.

It can be shown from momentum theory that the maximum amount of energy that can be extracted by a wind turbine from a windstream in the process described above, is eight-ninths of the kinetic energy of the windstream passing through it. Under these conditions, the maximum loss in wind speed will be two-thirds of the initial velocity of the windstream, V_o.

For a system of 100% efficiency, the maximum power density that can be extracted by the turbine from the windstream in the above process will, therefore be:

$$\frac{P_{max}}{A} = \frac{2}{3} V_o \left[\frac{8}{9} \frac{(\rho V_o^2)}{2} \right] = 0.593 \frac{\rho V_o^3}{2}$$

where, $\frac{\rho V_o^3}{2}$ = the ambient power density of a unit volume of the windstream

The factor 0.593 is known as the Betz coefficient (from the name of the man who first derived it). It is the maximum fraction of the power in a windstream that can be extracted by a turbine in the windstream.

APPENDIX C

LOAD ESTIMATION FOR MECHANICAL WATER PUMPING SYSTEMS

Accurate load estimation is extremely important in order to properly size a mechanical water pumping system Presented below is a step by step procedure, with example problems and design charts, for estimating required pumping power and energy.

Exhibit C.1 illustrates a complete water pump and storage system. In any water pumping application, two parameters must be determined for sizing system components. These are pump depth (depth of aquifer) and storage tank height. Together, these figures determine total water head - the maximum height to which the pump must lift water (assuming the storage tank is not pressurized - for a pressurized tank add 2.31 feet of head for each psi (.102 meters for each kPa));

Total Water Head = Pump Depth + Storage Tank Height Eq. C.1

where Total Water Head is measured in feet, Pump Depth is measured in feet from ground level and Tank Height is measured in feet from ground level to the top of the water outlet as shown in Exhibit C.1.

Pressure drop (head loss) resulting from water flow through pipes will increase the amount of load on the pump. Head loss is accounted for with a head loss factor. The factor is the feet of head loss per hundred feet of pipe run. Thus, the total length of pipe required for system operation, pipe diameter and maximum flow rate of the pump are required to deteremine total power requirements. Exhibit C.2 is a table used for determining head loss.

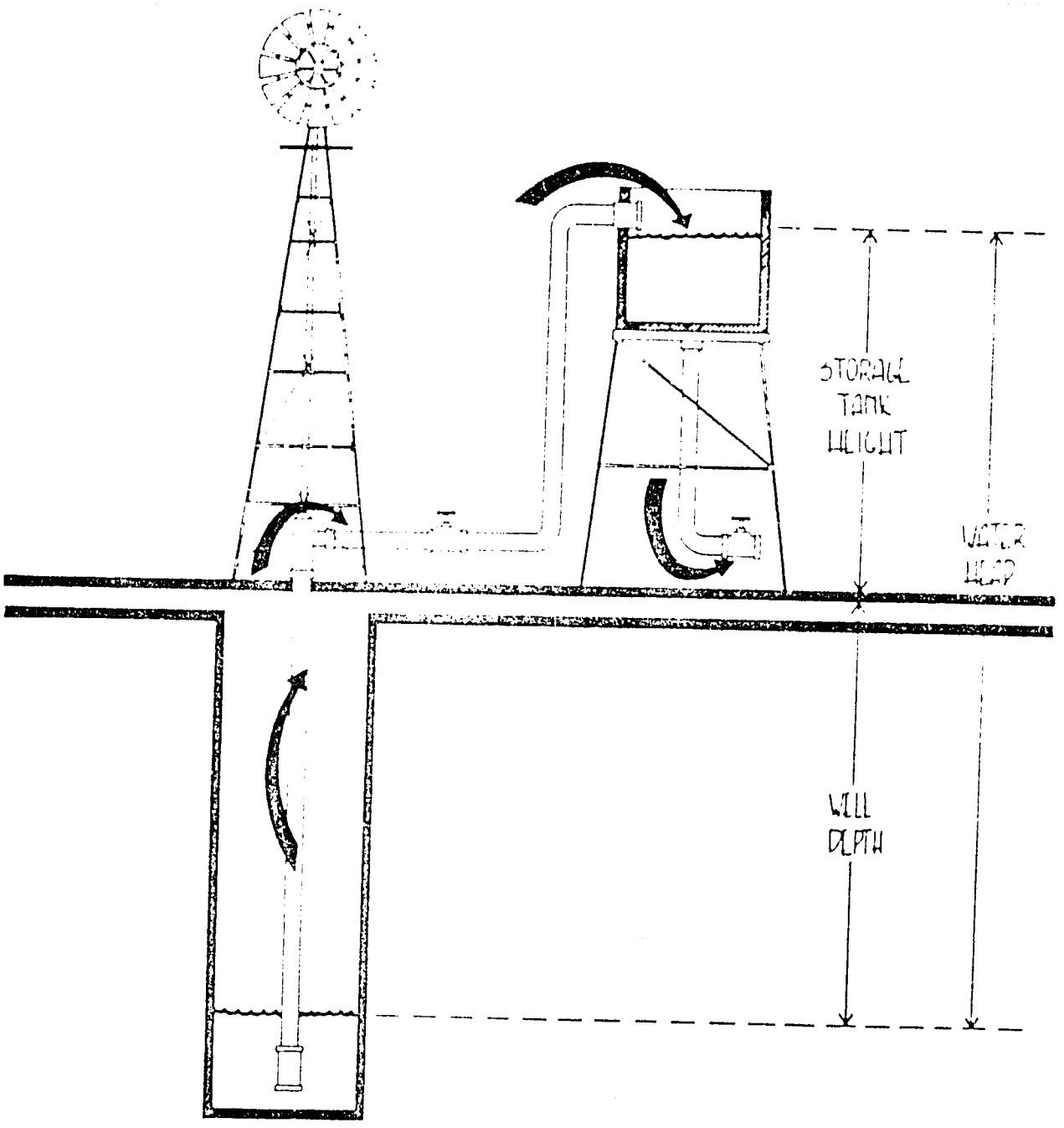
The head loss factor determined from Exhibit C.2 is converted to Head Loss by the following equation:

Head Loss = head loss x pipe run ÷ by 100 Eq. C.2

where pipe run is measured in feet (meters).

Exhibit C.1

WATER PUMPING SYSTEM DIAGRAM



(Note: Exhibit C.2 does not account for valve and fitting losses. To account for such losses it is easiest to determine a new pipe "length" as follows. Count up the number of tees and and elbows. For 1-inch pipe (2.5 cm) add 3 feet (.91 m) of "length" for each fitting, add none for a gate valve, 12 feet (3.66 m) for an angle, and 30 feet (9.14 m) for a globe valve (the usual spigot-type valve). This is then the equivalent pipe length to be used for determining Head Loss. For other pipe sizes, proportion these values to the pipe diameter (i.e., twice these values for a 2-inch [5 cm] pipe). For smooth plastic pipe reduce the head loss factor by 40%).

Having determined Head Loss, Total Pumping Head is calculated as follows:

Total Pumping Head = Total Water Head + Head Loss Eq. C.3

Total Pumping Head is the actual load presented to the pump.

Example: Maximum pump capacity - 5 gpm (.32 litres/rec)
Pipe run - 250 feet (76.2 m)
Water head - 250 feet (76.2 m)
Pipe diameter - 3/4 inch (1.9 cm)
Two 90° elbow fittings installed

From Exhibit C.2, find 5-gpm (.32 litres/sec) flow rate on the horizontal (bottom) line. From this point, go straight up to the 3/4-inch (1.9 cm) pipe curve line. From there, look straight to the left to read head loss factor = 6.0 on the vertical scale. This is 6 feet (cm) per 100 feet (cm) of pipe run. Then total head loss factor = 6 x 250 divided by 100 = 15 feet (4.6 m) For the two elbow fittings add 2.3 feet (.7 m) (3 x .75 feet or .91 x .75 meters) each. Then head loss = 15 + 4.6 = 19.6 feet (4.6 + 1.4 = 6.0 meters). From here, we calculate TOTAL PUMPING HEAD.

TOTAL HEAD = WATER HEAD + HEAD LOSS
(Where all factors are measured in feet or meters.)

Continuing the example, total head loss = 250 + 19.6 = 269.6 feet, or 270 feet (76.2 + 6.0 = 82.2 meters).

Because of head loss, the pump is loaded as if it has to pump water 19.6 feet (6.0 meters) higher than it really does.

Now we can calculate horsepower required by the pump and supplied by the wind turbine. From Exhibit C.3, you can read the theoretical power (no losses) knowing the total head and flow rate. Continuing our example, for total head = 270 feet (82.2 m) and 5 gpm (.32 l/s)

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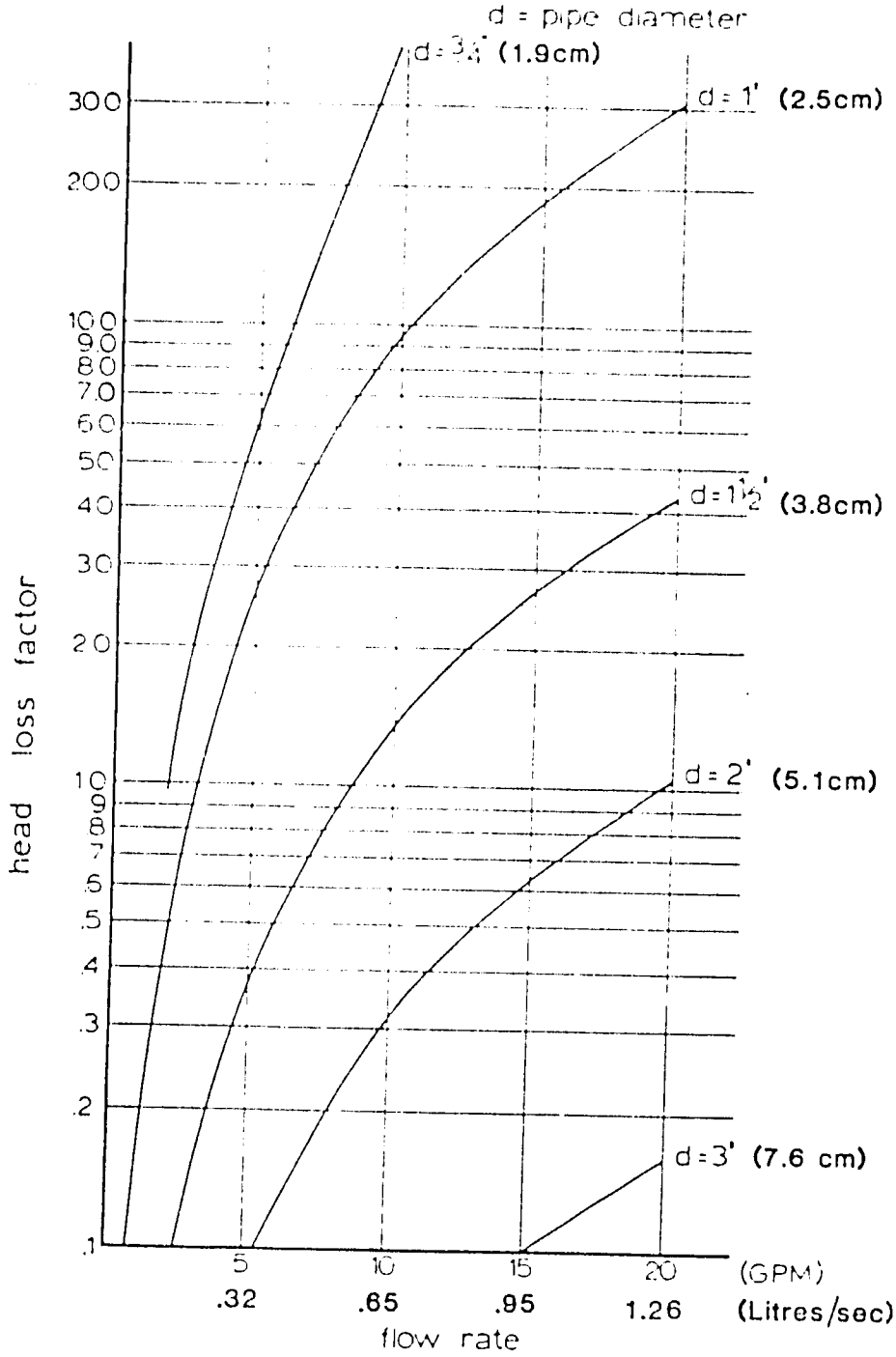
Exhibit C.2
HEAD LOSS FACTOR



NOTE: Exhibit assumes standard ("schedule 40") steel pipe. For other diameters than those listed, the head loss at the same flow rate is proportional to the fifth power of the ratio of the pipe diameters. Pipe diameter is approximately the internal diameter.

Exhibit C.3
THEORETICAL PUMP POWER

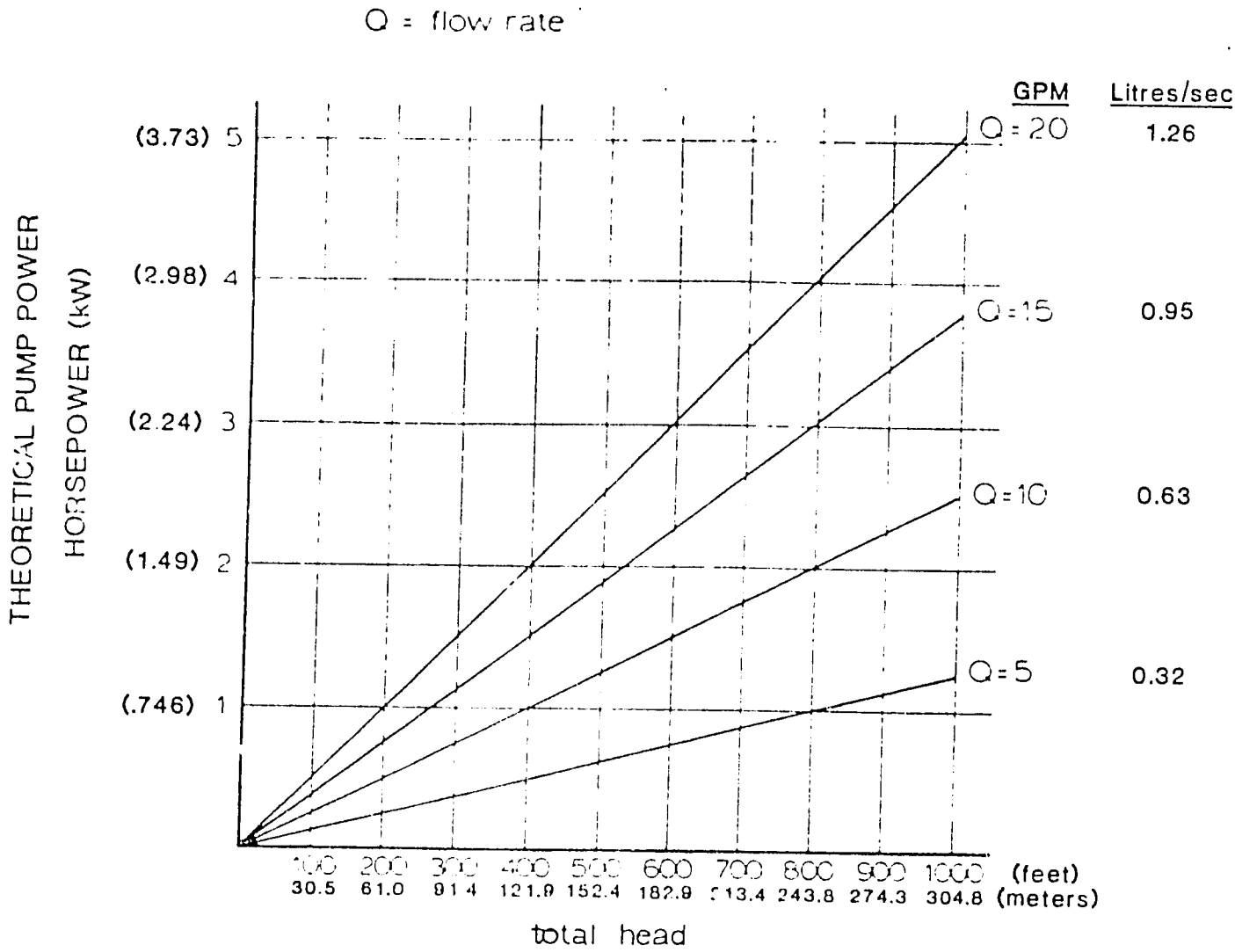


Exhibit C.4
WATER REQUIREMENTS

Water Consumption of Pigs
(Pounds of Water per Day)

Conditions	
Body Weight = 30 lbs	5-10
Body Weight = 60-80 lbs	7
Body Weight = 75-125 lbs	16
Body Weight = 200-380 lbs	12-30
Pregnant Sows	30-38
Lactating Sows	40-50

Water Consumption of Chickens
(Gallons per 100 Birds per Day)

Conditions	
1-3 weeks of age	0.4-2.0
3-6 weeks of age	1.4-3.0
6-10 weeks of age	3.0-4.0
9-13 weeks of age	4.0-5.0
Pullets	3.0-5.0
Nonlaying Hens	5.0
Laying Hens (moderate temperatures)	5.0-7.5
Laying Hens (temperature 90°F)	9.0

Water Consumption of Sheep
(Pounds of Water per Day)

On range or dry pasture	5-13
On range (salty feeds)	17
On rations of hay and grain or hay, roots and grain	0.3-6
On good pasture	Very little (if any)

Water Consumption of Growing Turkeys
(Gallons per 100 Birds per Day)

Conditions	
1-3 weeks of age	8-18
4-7 weeks of age	26-59
9-13 weeks of age	62-100
15-19 weeks of age	117-118
21-26 weeks of age	95-105

Water Consumption of People
Average Person: 75 gallons per day

Lawn: 0-200 gallons per 1000 square feet, every other day.

Water Consumption of Cattle

Class of Cattle	Conditions	Water Consumption (Pounds per Day)
Holstein calves (liquid milk or dried milk and water supplied)	4 weeks of age	10-12
	8 weeks of age	13
	12 weeks of age	18-20
	16 weeks of age	25-28
	20 weeks of age	32-36
	6 weeks of age	33-48
Dairy Heifers	Pregnant	60-70
Steers	Maintenance ration	35
	Fattening ration	70
Range Cattle		35-70
Jersey Cows	Milk Production 5-30 lbs/day	60-102
Holstein Cows	Milk Production 20-50 lbs/day	65-182
	Milk Production 80 lbs/day	190
	Dry	90

NOTE: The numbers in this exhibit were developed based on experience in the United States. They should be modified based on Egyptian experience.

SOURCE: Water, Yearbook of Agriculture, 1955. U.S. Department of Agriculture.

APPENDIX D

LOAD ESTIMATION FOR STAND-ALONE ELECTRICAL APPLICATIONS

The following pages present a step-by-step methodology for estimating electrical loads for stand-alone WECS applications. The examples presented are only for illustration and are by no means indicative of a typical stand-alone electrical application, especially in Egypt.

1. Determine the load ratings, expressed in watts, or kilowatts.

   Example: Brand C electric motor is a one-horsepower (746 Watt) motor. Its electrical load when operating is 860 watts, and when starting, 1400 watts for one second. These data are found: on the appliance data plate, by writing to the manufacturer, by testing an appliance yourself, or from Exhibit D.1. You can easily test the appliance if you presently have electric service provided by the electric company. Watch your electric utility meter, which measures energy usage. Usually it contains a slowly spinning disc, and some number of revolutions of it indicates that one kWh has been consumed. Ask your power company what each revolution means. Turn off all other appliances so the meter stops. Then turn on the appliance you wish to rate and time the spinning disc.

2. Determine the load cycle time and the number of hours the load will operate on a monthly basis.

   Example: Brand D refrigerator will operate an average of 15 hours per month. Note that this information depends on how well insulated the refrigerator is, the number of times the door is opened, how much bulk will be stored, and the room temperature.

3. Determine the appliance's monthly energy requirement. This is calculated by multiplying together the data from 1 and 2 above. The result is in watt-hours, or kilowatt-hours.

   Example: A color television is determined in step 1 to require 350 watts. You know that it will be used for 150 hours per month, so:

   350 watts times 150 hours equals 52,500 watt-hours. To get kilowatt-hours: 52,500 - 1000 = 52.5 kilowatt-hours (kWh)

4. Determine maximum load. This calculation will result in your maximum power demand, expressed as kilowatts (kW), which would occur if all of your appliances were operating at the same time.

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EXHIBIT D.1
Power and Energy Requirements of Appliances and Farm Equipment

Item	Watts	Hrs/Mo	KWHRS/Mo
Air conditioner, central			620*
Air conditioner, window	1566	74	116*
Battery charger			1*
Blanket	190	80	15
Blanket	50-200		15
Blender	350	3	1
Bottle sterilizer	500		15
Bottle warmer	500	6	3
Broiler	1436	6	8.5
Clock	1-10		1.4*
Clothes drier	4600	20	92*†
Clothes drier, electric heat	4856	18	86*†
Clothes drier, gas heat	325	18	6*†
Clothes washer			8.5*
Clothes washer, automatic	250	12	3*
Clothes washer, conventional	200	12	2*†
Clothes washer, automatic	512	17.3	9*
Clothes washer, ringer	275	15	4*†
Clippers	40-60		½
Coffee maker	800	15	12
Coffee maker, twice a day			8
Coffee percolator	300-600		3-10
Coffee pot	894	10	9
Cooling, attic fan	1/6-3/4HP		60-90*†
Cooling, refrigeration	3/4-1½ ton		200-500*
Corn popper	460-650		1
Curling iron	10-20		½
Dehumidifier	300-500		50*
Dishwasher	1200	30	36*
Dishwasher	1200	25	30*
Disposer	375	2	1*
Dryer	445	6	3*
[illegible]	250	7	5
Electric baseboard heat	10,000	160	1600
[illegible]	5,250		1*
[illegible]	3000-7000		100*
[illegible]	370	65	24*†
[illegible]	250	30	8**
[illegible]	35-210		4-10*†
[illegible]	200-300		½
[illegible]	350	20	7
[illegible]	50-100		1
[illegible]	250-400		1
[illegible]	300-800		30-125*
[illegible]	6-35		½
[illegible]	350	90	32*
[illegible]	440	330	145*
[illegible]			140*
Freezer, frost free	440	180	57*
[illegible]	1000-1500		5
[illegible]	150*	4	6
[illegible]	1196	12	15
[illegible]	10-30		10*
[illegible]	100-300		25-40*
[illegible]	500-700		25-100**
[illegible]	250-800		3-60**
[illegible]			32*†
Garbage disposal equipment			
[illegible]	1/4-1/3 HP		¾*
Grinder	450-1000		5
[illegible]	650-1300		5
[illegible]	250-1200		½-6*
[illegible]	400	5	2*
[illegible]	125-250		2
[illegible]	1320	30	40
[illegible]	660-2000		15-30
[illegible]	25-150		1
[illegible]	65	10	1
[illegible]	25	10	3
[illegible]			9*
[illegible]	500-1650		7-30
[illegible]	8000-11,000		1000-2500
[illegible]	500		5-15*
[illegible]	1100	12	13
[illegible]			12
[illegible]			13
[illegible]	1500	12	18
[illegible]	120		½*
Lawnmower	1000	8	8*†
Lighting	5,300		10-60
Lights, Groom house in winter			60
Light bulb, 75	75	120	9
Light bulb, 40	40	120	4.8
Mixer	125	6	1
Mixer, foot	50-200		1
Movie projector	300-1000		
Oil burner	500	100	50*
Oil burner			50*
Oil burner 1/8 HP	250	84	18*
Pasteurizer ½ gal	1500		10-40
Polisher	350	6	2
Post light, dusk to dawn		–	35
Power tools			3
Projector	500	4	2*
Pump, water	450	44	20*†
Pump, well			20*†
Radio			8
Radio, console	100-300		5-15*
Radio, table	40-100		5-10*
Range	8500-16,000		100-150
Range, 4 person family			100
Record player	75-100		1-5
Record player, transistor	60	50	3*
Record player, tube	150	50	7.5*
Recorder, tape	100	10	1*
Refrigerator	200-300		25-30*
Refrigerator, conventional			83*
Refrigerator, freezer	200	150	30*
Refrigerator, freezer, 14 cu ft	326	290	95*
Refrigerator, freezer, frost free	360	500	180*
Roaster	1320	30	40
Rotisserie	1400	30	42*
Sauce pan	300-1400		2-10
Sewing machine	30-100		½-2
Sewing machine	100	10	1
Shaver	12		1/10
Skillet	1000-1350		5-20
Skil Saw	1000	6	6
Sunlamp	400	10	4
Sunlamp	2[illegible]	5-4	1.5
Television	20[illegible]45		15-30*
TV, BW	200	120	24*
TV, BW	23[illegible]	110	25*
TV, color	350	120	42*
TV, color			100*
Toaster	1150	4	5
Typewriter	30	15	5*
Vacuum cleaner	600	10	6
Vacuum cleaner, 1 hr/wk			4
Vaporizer	200-500		2-5
Waffle iron	550-1300		1-2
Washing machine, 12 hrs/mo			9*
Washer, auto	300-700		3-8*
Washer, conventional	100-400		2-4*
Water heater	3416	89	400
Water heater	2[illegible]0-7000		200-300
Water pump (shallow	[illegible]		5-20*†
Water pump (deep)	[illegible] HP		10-60*†
AT THE BARN			
Name	Capacity HP or watts		Est. KWHR
Barn cleaner	2.5 HP		120/yr*
Clipping	fractional		1/10 per hr
Corn ear crushing	1.5 HP		5 per ton*
Corn ear shelling	½-2		1 per ton*†
Electric fence	7-10 watts		7 per mo*†
Ensilage blowing	3-5		1 per ton
Feed grinding	1-7½		½-1½ per 100 lbs*†
Feed mixing	½-1		1 per ton*†
Grain cleaning	¼-½		1 per 100 bu*†
Grain drying	1-7½		5-7 per ton*†
Grain elevating	¼-5		4 per 1000 bu*†
Hay cubing	3-7½		60 per ton*
Hay hoisting	½-1		1/3 per ton*†
Milking, portable	¼-[illegible]		1½ per cow/mo*†
Milking, pipeline	[illegible]		2½ per cow/mo*†
Sheep shearing	fractional		1½ per 100 sheep
Silo unloader	2-5 HP		4-8 per ton*
Silage conveyor	1-3 HP		1-4 per ton*
Stock tank heater	200-1500 watts		varies widely
Yard lights	100-500 watts		10 per mo
Ventilation	1/6-1/3 HP		2-6 per day*† per 20 cows
IN THE MILKHOUSE			
Milk cooling	½-5 HP		1 per 100 lbs milk*
Space heater	1000-3000		800 per year
Ventilating fan	fractional		10-25 per mo*†
Water heater	1000-5000		1 per 4 gal
FOR POULTRY			
Automatic feeder	¼-½ HP		10-30 KWHR/mo*†
Brooder	200-1000 watts		½-1½ per chick per season
Burglar alarm	10-60 watts		2 per mo*
Debeaker	200-500 watts		1 per 3 hrs
Egg cleaning or washing	fractional HP		1 per 2000 eggs*†
Egg cooling	1/6-1 HP		1½ per case*
Night lighting	40-60 watts		10 per mo per 100 birds
Ventilating fan	50-300 watts		1-1½ per day*† per 1000 birds
Water warming	50-700 watts		varies widely
FOR HOGS			
Brooding	100-300 watts		35 per brooding period/litter
Ventilating fan	50-300 watts		½-1½ per day*†
Water warming	50-1000 watts		30 per brooding period/litter
FARM SHOP			
Air compressor	¼-½ HP		1 per 3 hr*
Arc welding	37½ amp		100 per year
Battery charging	600-750 watts		2 per battery charge*
Concrete mixing	¼-2 HP		1 per cu yd*†
Drill press	1/6-1 HP		½ per hr*†
Fan, 10"	35-55 watts		1 per 20 hr*†
Grinding, emery, wheel	1/4-1/3 HP		1 per 3 hr*†
Heater, portable	1000-3000 watts		10 per hr
Heater, electric	100-300 watts		1 per 5 hr
Lighting	50-250 watts		4 per hr
Lathe, metal	¼-1 HP		1 per 3 hr
Lathe, wood	¼-1 HP		1 per 3 hr
Sawing, circular 8"-10"	1/3-1/2 HP		1/2 per hr
Sawing, jig	1/4-1/3 HP		1 per 3 hr
Soldering iron	60-500 watts		1 per 5 hr
MISCELLANEOUS			
Farm chore motors	½-5		1 per HP per hr
Insect trap	25-40 watt		1/3 per night
Irrigating	1 HP up		1 per HP per hr
Snow melting, sidewalk and steps, heating-cable imbedded in concrete	25 watts per sq ft		2.5 per 100 sq ft per hr
Soil heating, hotbed	400 watts		1 per day per season
Wood sawing	1-5 HP		2 per cord

Symbol Explanation
*AC power required
†Normally AC but convertible to DC
Notes: Lighting in this table is assumed to be incandescent—if fluorescent the wattage listed consume the same power but the service life is longer. Light—fluorescent bulbs also require AC but can be converted to DC
These figures can be cut by 50% [illegible] conservation of electricity

Source: Park, Jack and Schwind, Dick. Wind Power For Farms, Homes and Small Industry. Nielsen Engineering & Research, Inc., Mountain View, CA., Department of Energy Contract E(04-3)-1270, September, 1978.

Example:

Item	Power (watts)
TV	200
Coffee pot	894
Dishwasher	1200
Refrigerator	300
Water heater	6000
Maximum Load	8594 watts = 8.59 kW

5. Determine your total monthly energy requirement. Total energy is expressed in kilowatt-hours (kWh). This is the energy you must supply each month, or pay for when supplied by your electric company.

Example:

Item	Energy (kWh)
TV	24
Coffee pot	9
Dishwasher	36
Refrigerator	30
Water heater	300
Total Energy Requirement	399 kWh per month

(Note: The above examples are selected at random from Exhibit D.1 and do not necessarily represent a typical WECS stand-alone application).

The next step in determining load characteristics is to develop your daily load cycle history. This calculation will given you a much better estimate of your actual electric load demand. Simply adding up all of the loads, as in the above example, assumes that all appliances will be on the same time and gives a worst case figure, but does not reflect a real case. To arrive at a load cycle history, you must make estimates of the time of day your devices will be on and for how long.

This estimate may be as accurate or as rough as necessary. How accurate you decide to be in making estimates will depend entirely on your assessment of the importance of this calculation. For an accurate estimation, it will be necessary to actually monitor any items that operate on a cyclic basis, such as refrigerators. For less accuracy, it may be reasonable to assume such loads "on" continuously. As a first example (not representative,

but illustrative of the thinking here), we shall separate items by their nature: those which you control, and those which operate automatically. For this example, items that operate automatically shall be assumed to operate continuously. The other loads will require estimation of operating cycles. This is illustrated in the following example.

Automatic Items	Load (watts)	Time
Refrigerator	300	Continuous
Water heater	6000	Continuous

For a second example, let us be more realistic. The assumption that all automatic items are continuous loads should be adjusted. Since the data were originally extracted from Exhibit D.1, let us look at that chart again.

Notice that the refrigerator is listed as 200-300 watts, for 25 to 30 kWh per month. Using 300 watts and 30 kWh (or 30,000 watt-hours) per month, we can calculate the hours per month this device operates:

30,000 watt-hours per month ÷ 300 watts = 100 hours per month

Now, assuming a 30-day month, 100 hours per month ÷ 30 days = 3.3 hours per day. This is the estimated number of hours per day this refrigerator will operate. Now we must guess when, and for how long during each cycle it operates. A safe guess is that it cycles most during mealtimes.

For the water heater, a similar calculation should be made: 300,000 watts-hour per month - 6000 watts - 30 days = 1.6 hours per day.

Automatic Items	Load	Time
Refrigerator	300	3.3 hours per day: 1.1 hours each 7 am, noon, 5 pm.
Water heater	6000	1.6 hours per day: 0.8 hours each 8 am, 6 pm.

With use-controlled items similar to the first example, results from the new graph (Exhibit D.2) will be somewhat closer to reality.

Performing the type of analysis in Exhibit D.2 may not actually be necessary for your energy requirement estimates, but it is a good way to understand the nature and characteristics of the electric load you may expect.

A previous example illustrated how a monthly energy requirement of 399 kWh was established. This could have been any month. For some months, a heavy demand for heating may raise electrical consumption, while in others, air conditioning will prevail. Thus, you must complete a demand analysis for each month of the year. A graph plotted from your totals would look like Exhibit D.3.

User-controlled Items

TV	200	4 hours per day as follows: 1 hour: 8 am - 9 am 3 hours: 6 pm - 9 pm
Coffee pot	894	20 minutes per day 7:30 - 7:50 am
Dishwasher	1200	1 hour per day: 5 pm - 6 pm

From this example, we can see a base load, that is, a continuous load equal to 6300 watts, with peak loads going as much as 1200 watts higher. Again, this is not a representative example. If we made a simple graph of this load, it would look something like Exhibit D.4.

The preceding discussion details the steps required to estimate power and energy consumption of the connected WECS load. In order to determine turbine power and energy output requirements, efficiencies of any power conditioning equipment must be considered. (Line losses in stand-alone applications, where the wind turbine is located close to the loads, can be neglected).

Exhibit D.2
GRAPH OF EXAMPLE LOAD HISTORY

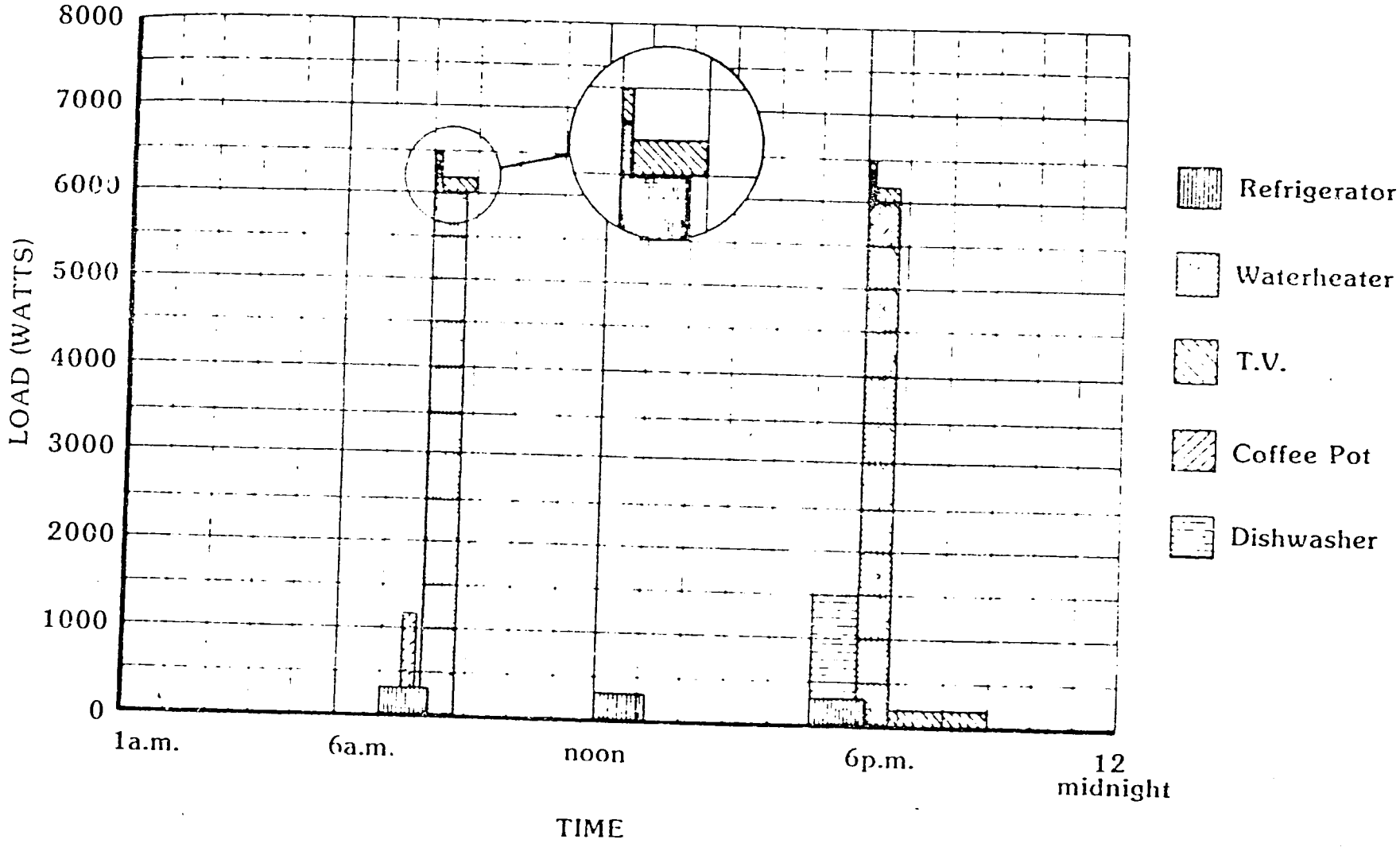


Exhibit D.3
TYPICAL MONTHLY ENERGY DEMAND

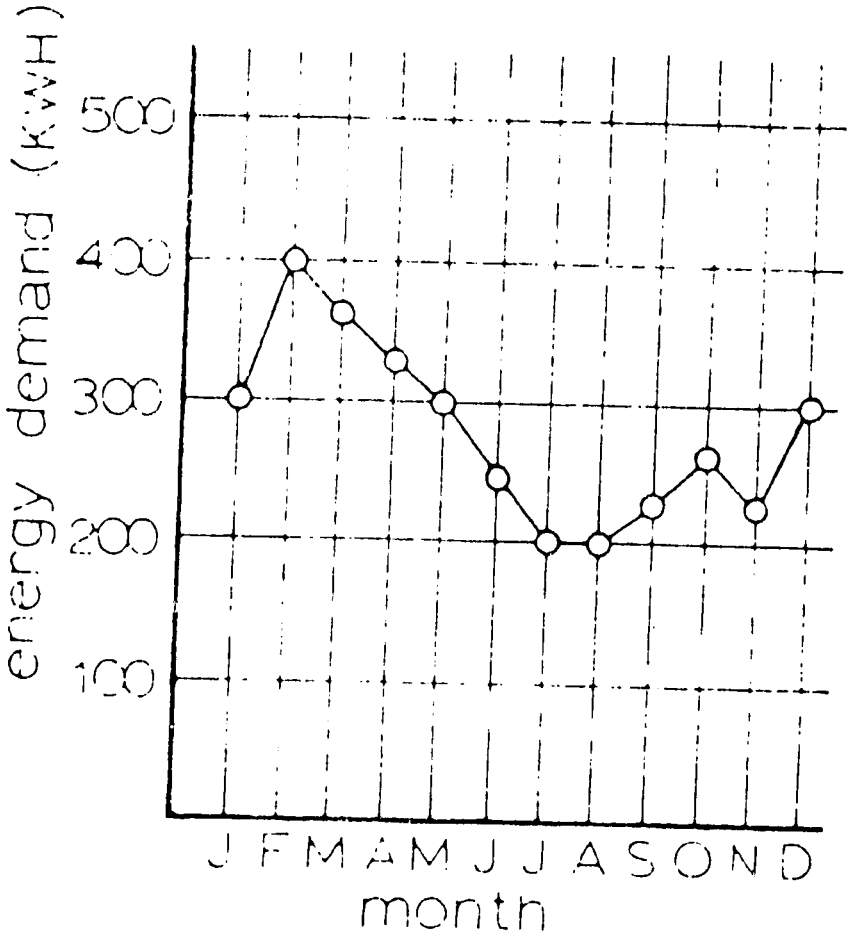
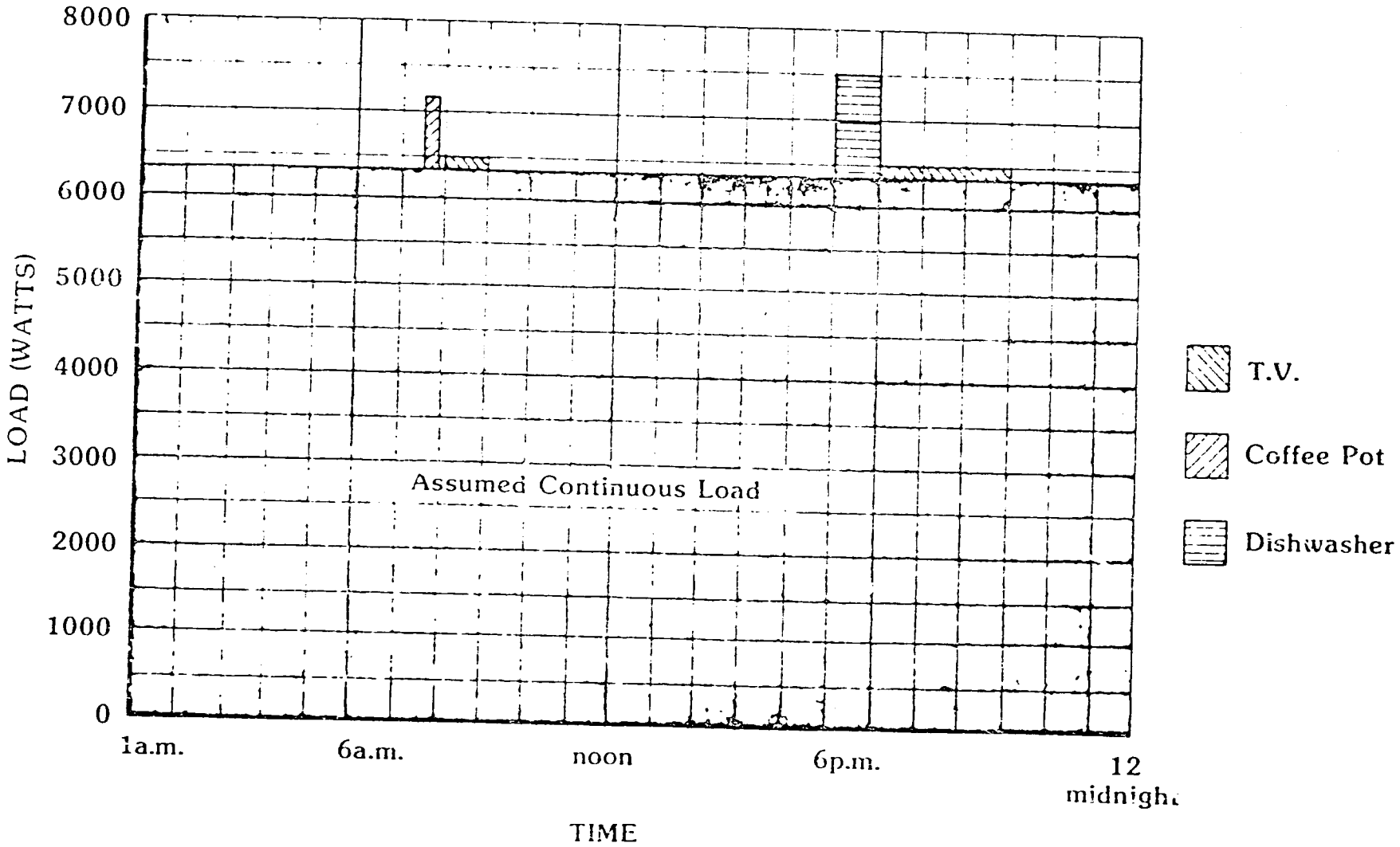


Exhibit D.4

GRAPH OF EXAMPLE LOAD HISTORY



APPENDIX E

SITE SELECTION TECHNIQUES

EXHIBIT E.1

TYPICAL FREQUENCY DISTRIBUTION PRODUCTS
AND THEIR POTENTIAL APPLICATIONS

Dimensions of Frequency Distribution	Usefulness of Characterization of Wind Behavior or Analysis of Wind Potential
Wind Speed	Estimating energy production.
Wind Direction	Assessing local or regional effects of topography.
Wind Speed - Wind Duration	Determining principal directions of wind power. Necessary for turbine cluster design.
Wind Speed - Time of Day	Determining diurnal load match. Caution is required, however, for vertical extrapolation of diurnal behavior.
Wind Speed - Month of Year Wind Direction - Time of Day - Month of Year	Determine seasonal load match. Assessing local or regional thermally driven wind systems, such as sea breeze or mountain-valley winds.
Duration of Wind Speed Persistence in Specified Speed Interval - Month of Year	Assessing probability of continuously available wind power. Determining partitioning of available wind energy between large-scale migrating storms and regional or local thermally driven wind systems. Determining optimum times for scheduled wind turbine maintenance.

TOPOGRAPHICAL INDICATORS

Historically, wind machines have been sited by applying topographical indicators, which are empirical guidelines describing the general effects of terrain or surface obstacles on the wind. Topographical guidelines are based on a physical understanding of how topography affects flow and on experience gained through observation.

A number of topographical features are recognized as indicators of high wind energy potential. One group includes gaps, passes, and gorges in areas of frequent strong pressure gradients. These strong pressure gradients occur when large temperture gradients form across a mountain barrier. For example,

coastal mountains separate a nearly uniform temperature marine air mass from continental air masses. The inland air can become hot in summer or daytime, or cold in winter or at night, thereby causing seasonal and diurnal fluctuations in the pressure gradient across passes. Pressure gradients also form across mountain ranges when strong winds, as from a storm, blow up against the mountain barrier. If the flow has insufficient kinetic energy to cross the potential energy barrier that the mountains represent, the gaps, passes, and gorges are the relief points for the winds driven by the storm.

Long valleys extending parallel to prevailing wind directions are often good wind energy regions also. The wind stream is channelled by the valley walls. At narrow points along a broad valley, mass conservation causes winds to accelerate through the constriction. In the opposite way the river of air spreads out and slows down where the valley widens.

Summits of ridges and mountains usually provide enhanced wind resource areas. Over small-scale hills and ridges (less than 984 ft. (300 m) high), the air accelerates over the crest. This is also due to mass conservation, a stream of air is vertically compressed as it flows over the hill and so must move faster in the constricted region. This is not necesarily so for the flow over large-scale mountains. The winds at summit elevation of a high mountain may actually slow down near the summit because of the drag that the mountain exerts on the flow. However, mountains and ridges are still usually good resource areas because they are like tall towers that intercept the flow at higher levels where winds are usually stronger.

Some features that indicate low wind energy potential are basins and valleys that are perpendicular to the prevailing wind. These features can be low wind areas because the flow spreads out over them, opposite to the effect of flow acceleration over ridges, or because they collect cold, heavy air that stagnates at potential energy minima.

Proper use of topographical indicators requires an experienced boundary layer meteorologist because the issue of when and how to use them, and how far to trust them, are complex. Consider the complexity of flow over a small isolated hill. Wind speeds at a given height above the terrain surface usually are higher over the summit of a hill than over surrounding lowlands.

Topographical indicators provide only qualitative information. Generic flow guidelines have been developed from theory, from numerical and physical simulations of flow over model terrain, and from actual measurements of flow around full-scale features. Succinct generalizations drawn from these studies are useful; however, reliance upon them must be tempered. Topographical indicators should therefore be used as guidelines to:

- understand flow-terrain interactions;
- indicate where to look for, or when to use, other indicators;
- indicate where to make measurements; and
- interpret measurements already made.

In short, the following topographical features are indicative of high mean wind speeds:

- Gaps, passes, and gorges in areas of frequent strong pressure gradients;
- Long valleys extending down from mountain ranges;
- High elevation plains and plateaus;
- Plains and valleys with persitent strong downslope winds associated with strong pressure gradients;
- Exposed ridges and mountain summits;
- Exposed coastal sites.

Features that signal low mean windspeeds are listed as:

- Valleys perpendicular to the prevailing winds;
- Sheltered basins;
- Short or narrow valleys and canyons;

- Areas of high surface roughness, such as forested hilly terrain.

ECOLOGICAL INDICATORS

Vegetation deformed by high average winds can be used both to estimate the average speed (thus power) and to compare candidate sites. This technique works best in three regions; 1) along coasts, 2) in river valleys and gorges exhibiting strong channeling of the wind, and 3) in mountainous terrain. Ecological indicators are especially useful in remote mountainous terrain not only because there are little wind data, but also because the winds are often highly variable over small areas and difficult to characterize. The most easily observed deformities of trees (illustrated in Exhibit E.2) are listed and defined below:

- Brushing - Branches and twigs bend downwind like the hair of a pelt that has been brushed in one direction only. This deformity can be observed in deciduous trees after their leaves have fallen. It is the most sensitive indicator of light winds.

- Flagging - Branches stream downwind, and the upwind branches are short or have been stripped away.

- Throwing - A tree is wind thrown when the main trunk and the branches bend away from the prevailing wind.

- Carpeting - This deformity occurs because the winds are so strong that every twig reaching more than several inches above the ground is killed, allowing the carpet to extend far downwind.

Exhibit E.2 is one of the best guides to ranking tree deformities by wind speed. Both a top view and a side view of the tree are shown to demonstrate the brushing of individual twigs and branches and the shape of the tree trunk and crown. The figure uses the "Griggs-Putnam" (Exhibit E.4) classification of tree deformities described by indices from 0 to VII. When WECS sites are ranked by this scheme, only like species of trees should be compared, because different types of trees may not be deformed to the same degree.

Another good indicator of relative wind speeds is the deformation ratio. It also measures how much the tree crown has been flagged and thrown.

Exhibit E.2
THE GRIGGS-PUTNAM INDEX

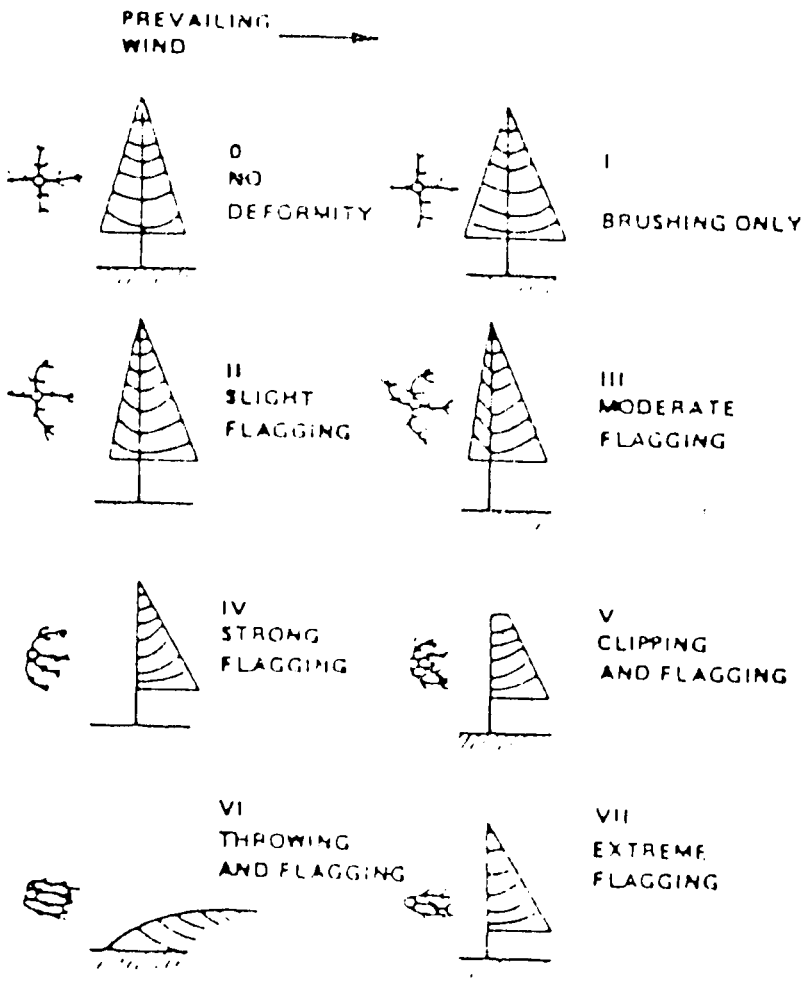


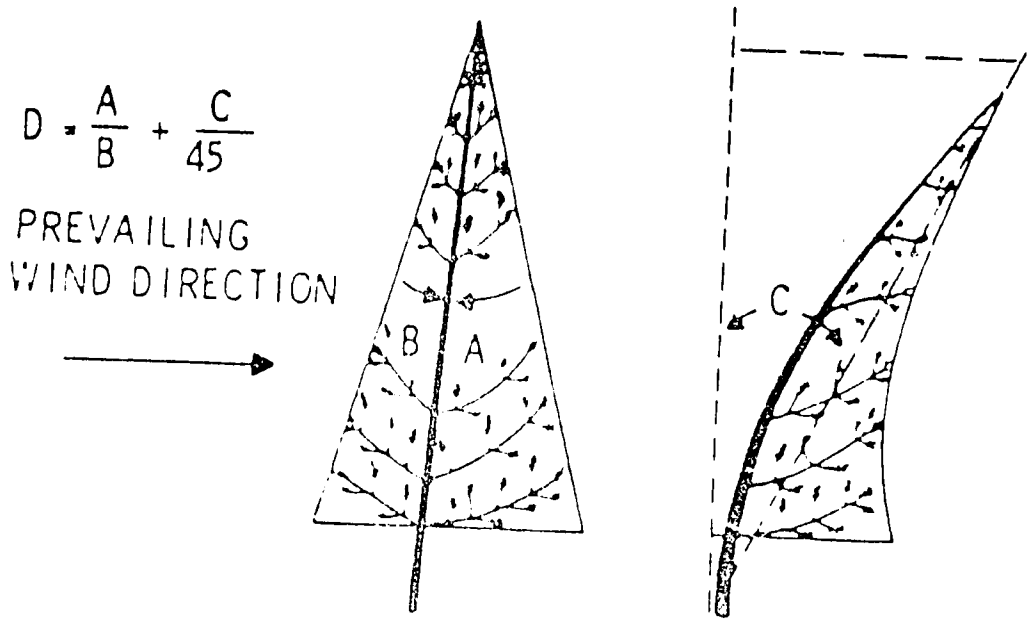
Exhibit E.3 shows the three angles, A, B, and C, that must be measured to compute the deformation ratio "D". To measure these angles, the trees can either be photographed or sketched to scale.

To compute D, the three angles shown in the figure (A on the downwind side, B on the upwind side and C, the angle of deflection) should be measured in degrees using a protractor. The larger the value of D, the stronger the average wind speed.

Estimates of mean annual wind speed using vegetation can be improved if several trees in a siting area are sampled, using the Griggs-Putnam Index and the deformation ratio. The results of all the sampling should then be averaged. However, ecological indicators should be used primarily to identify possible high wind areas, to locate candidate sites, and to estimate roughly the annual average wind speed. Selection of a WECS should not be based solely on ecological indicators. WECS economics and performance analysis should include either a wind measurement program or available wind data in addition to ecological indicators.

Though the presence of one type of deformity (or a combination) may indicate an area of high average winds and the degree of deformity may give estimates of the relative strengths of the winds, there are still pitfalls to rating sites according to tree deformity. Because past or present growing conditions can greatly affect the size and shape of trees, only isolated trees appearing to have grown under similar conditions should be compared. For example, a tree in or near a dense stand of timber should not be compared to an isolated tree. In addition, trees being compared should be of nearly the same height (preferably 30 ft (9.1 m) or more). Another fact to be aware of is: limbs are stripped from trees not only by strong flagging. They can be damaged by man, disease, other trees that once grew nearby, or possibly ice storms. Misinterpreting such signs could lead to the wrong assumptions about the prevailing wind direction and the average speed. Common sense, however, should reveal whether or not all

Exhibit E.3
DEFORMATION RATIO



DEFORMATION RATIO COMPUTED AS A MEASURE OF THE DEGREE OF FLAGGING AND THAWING

Exhibit E.4

MEAN ANNUAL WIND SPEED VERSUS THE GRIGGS-PUTNAM INDEX AND THE DEFORMATION RATIO

MEAN ANNUAL WIND SPEED VERSUS THE GRIGGS-PUTNAM INDEX

Griggs-Putnam Index	I	II	III	IV	V	VI
Probable Mean Annual Wind Speed Range (mph)	7-9	9-11	11-13	13-16	15-18	16-21
(m/s)	3.1-4.0	4.0-4.9	4.9-5.8	5.8-7.2	6.7-8.0	7.2-9.4

MEAN ANNUAL WIND SPEED VERSUS THE DEFORMATION RATIO

Deformation Ratio	I	II	III	IV	V	VI
Probable Mean Annual Wind Speed Range (mph)	5-9	8-11	10-13	12-16	14-18	15-21
(m/s)	2.2-4.0	3.6-4.9	4.5-5.8	5.4-7.2	6.3-8.0	6.7-9.4

the deformities observed in an area fit together into a consistent pattern.

The following guidelines summarize this section and suggest how to use ecological indicators effectively:

1) detect ecological indicators of strong wind;

2) compare isolated trees of the same species and height within the strong wind areas to select candidate sites; and

3) Consider flow patterns over barriers, terrain features, and surface roughness in the final selection.

GEOMORPHOLOGICAL INDICATORS

When winds interact with and alter the earth's surface, the geomorphological features that result are called eolian landforms. Especially in arid regions where vegetation is sparse, winds can erode the surface, transport sand and dust, and deposit sediment. The erosional and depositional eolian landforms and the characteristics of the transported sediments are indicators of the history of the winds that caused these landforms.

Geomorphological interpretative techniques can be applied for three purposes:

- to indicate that a relatively good wind resource exists where eolian landforms are present
- to determine crude estimates of mean wind speeds from observed sand dune migration rates, sand size particle distributions, and sand ripple formation
- to indicate prevailing wind directions.

The principal difficulty with estimating wind speeds using these techniques is that substantial prior knowledge of the wind climatology is required. For example, how much of the total dune migration is cancelled by winds of opposite directions, or how frequently are winds strong enough to cause the sands of a certain size to move? If these answers are in hand prior to eolian feature analysis, why carry out the analysis?

Information gained from the use of geomorphological indicators is

sometimes helpful in forming an integrated picture of the wind regime in a data-sparse area. However, the effort expended should be compared with the great uncertainty of the technique. Aerial photographs may be obtained during the early stages of the siting process for purposes other than for examining eolian landforms. If eolian indicators are found in the photographs, interpret the the photographs as quickly as possible and use geomorphological indicator techniques only as part of site visits that include other activities, e.g., setting out anemometers or inspecting terrain feasibility.

ADDITIONAL INDICATORS

In addition to the four techniques presented above for site selection, a fifth method, the Beaufort wind scale, is mentioned here for educational purposes. The Beaufort scale of windspeeds (Exhibit E.5), developed in 1806 for use at sea and later extended to use on land, can serve as a convenient reference point. The scale indicates approximate windspeeds which cause the effects (visual evidence) indicated in Exhibit E.5.

Exhibit E.5
MODIFIED BEAUFORT SCALE OF WIND SPEEDS

BEAUFORT NUMBER	APPROXIMATE WIND SPEED				DESCRIPTIVE TERM		VISUAL EVIDENCE
	MPH	M/S	KM/H	KNOTS	SEAMAN'S	WMO (1964)**	
0	<1	<0.3	<1	<1	calm	calm	Calm, smoke rises vertically.
1	1-3	0.3-1.5	1-5	1-3	light air	light air	Smoke drift indicates wind direction; vanes do not move
2	4-7	1.6-3.3	6-11	4-6	light breeze	light breeze	Wind felt on face, leaves rustle; vanes begin to move
3	8-12	3.4-5.4	12-19	7-10	gentle breeze	gentle breeze	Leaves, small twigs in constant motion; light flags extend, hair is disturbed, clothing flaps
4*	13-18	5.5-7.9	20-28	11-16	mod. breeze	mod. breeze	Dust, leaves & loose paper raised up; small branches move, hair disarranged.
5*	19-24	8.0-10.7	29-38	17-21	fresh breeze	fresh breeze	Small trees in leaf begin to sway; force of wind felt on body
6*	25-31	10-13.8	39-49	22-27	strong breeze	strong breeze	Larger branches of trees in motion; whistling heard in wires; some inconvenience in walking.
7*	32-38	13.9-17.1	50-61	28-33	mod. gale	near gale	Whole trees in motion; resistance felt in walking against wind.
8*	39-46	17.2-20.7	62-74	34-40	fresh gale	gale	Twigs & small branches broken off; trees; walking generally impeded.
9	47-54	20.8-24.4	75-88	41-47	strong gale	strong gale	Some damage occurs; slate blown from roofs; danger of being blown over.
10	55-63	24.5-28.4	89-102	48-55	whole gale	storm	Trees broken or uprooted; considerable damage occurs
11	64-72	28.5-32.6	103-117	56-63	storm	violent storm	Very rarely experienced on land; usually accompanied by widespread damage.
12-17	73-136	32.7-61.2	118-220	64-118	hurricane	hurricane	

*Within general operating range of most WECS. Conditions above Beaufort number 8 are considered dangerous and are more costly than helpful to WECS installations. Conditions represented by Beaufort numbers below 4 don't contain enough power to be of use.
**World Meteorological Organization. Since 1966, knots have replaced Beaufort numbers as weather map symbols.

Rayleigh Windspeed Distribution

The Rayleigh distribution is a one-parameter equation that can be used to estimate the number of hours the wind blows at any particular windspeed. The single parameter in the equation is the annual average windspeed (the mean windspeed) at the site in question. The accompanying table presents values of the Rayleigh distribution for mean windspeeds ranging from 8 to 17 mph. Along each horizontal line in this table are the numbers of hours one would expect the wind to blow at each value of the windspeed listed in the leftmost column.

For example, suppose your site had a mean windspeed of 14 mph, and you wanted to estimate how often the wind blew at 23 mph. Just read down the column marked "14" at the top until you reach the horizontal line marked "23" at the left. You get the result "194", which means that the wind will blow at 23 mph approximately 194 hours per year at this site.

To get the result in terms of the percent of time each windspeed occurrs, divide the table entry by 8760 - the number of hours in a year. Thus, the wind blows at 23 mph for 194/8760, or 2.2 percent of the time.

RAYLEIGH DISTRIBUTION FOR VARIOUS MEAN WINDSPEEDS										
Windspeed mph	Mean Windspeed, mph									
	8	9	10	11	12	13	14	15	16	17
8	784	731	666	601	539	484	435	391	353	320
9	716	697	656	605	553	503	457	415	377	344
10	630	644	627	594	554	512	470	431	395	363
11	535	578	585	570	543	510	476	441	408	377
12	441	504	533	536	523	500	473	443	415	386
13	351	429	474	494	494	483	464	441	416	391
14	272	356	413	446	459	458	448	432	412	391
15	204	288	353	396	420	429	427	418	404	387
16	149	227	295	345	378	396	403	400	392	380
17	105	175	242	296	336	361	375	379	377	369
18	73	132	194	250	294	325	345	355	358	355
19	49	97	153	207	253	289	314	330	337	339
20	32	70	119	170	216	254	283	303	315	321
21	20	50	90	136	181	220	252	275	291	302
22	12	34	68	108	150	189	222	248	268	281
23	7	23	50	84	123	160	194	222	244	260
24	4	15	36	65	99	134	168	197	220	239
25	3	10	25	49	79	111	143	173	198	218
26	1	6	18	37	62	91	122	150	176	197

RAYLEIGH DISTRIBUTION FOR VARIOUS MEAN WINDSPEEDS										
Windspeed mph	Mean Windspeed, mph									
	8	9	10	11	12	13	14	15	16	17
27	.8	4	12	27	48	74	102	130	155	177
28	.4	2	8	20	37	60	85	111	136	158
29	.2	1	5	14	28	47	70	94	118	140
30	.1	.8	4	10	21	37	57	79	102	124
31	0	.5	2	7	16	29	46	66	87	108
32	0	.3	1	5	11	22	37	55	74	94
33	0	.1	.9	3	8	17	29	45	63	81
34	0	0	.5	2	6	13	23	37	53	70
35	0	0	.3	1	4	10	18	30	44	60
36	0	0	.2	.9	3	7	14	24	36	51
37	0	0	.1	.6	2	5	11	19	30	43
38	0	0	0	.4	1	4	8	15	24	36
39	0	0	0	.2	.9	3	6	12	20	30
40	0	0	0	.1	.6	2	5	9	16	25
41	0	0	0	0	.4	1	3	7	13	20
42	0	0	0	0	.3	.9	3	5	10	17
43	0	0	0	0	.2	.6	2	4	8	13
44	0	0	0	0	.1	.4	1	3	6	11

APPENDIX F

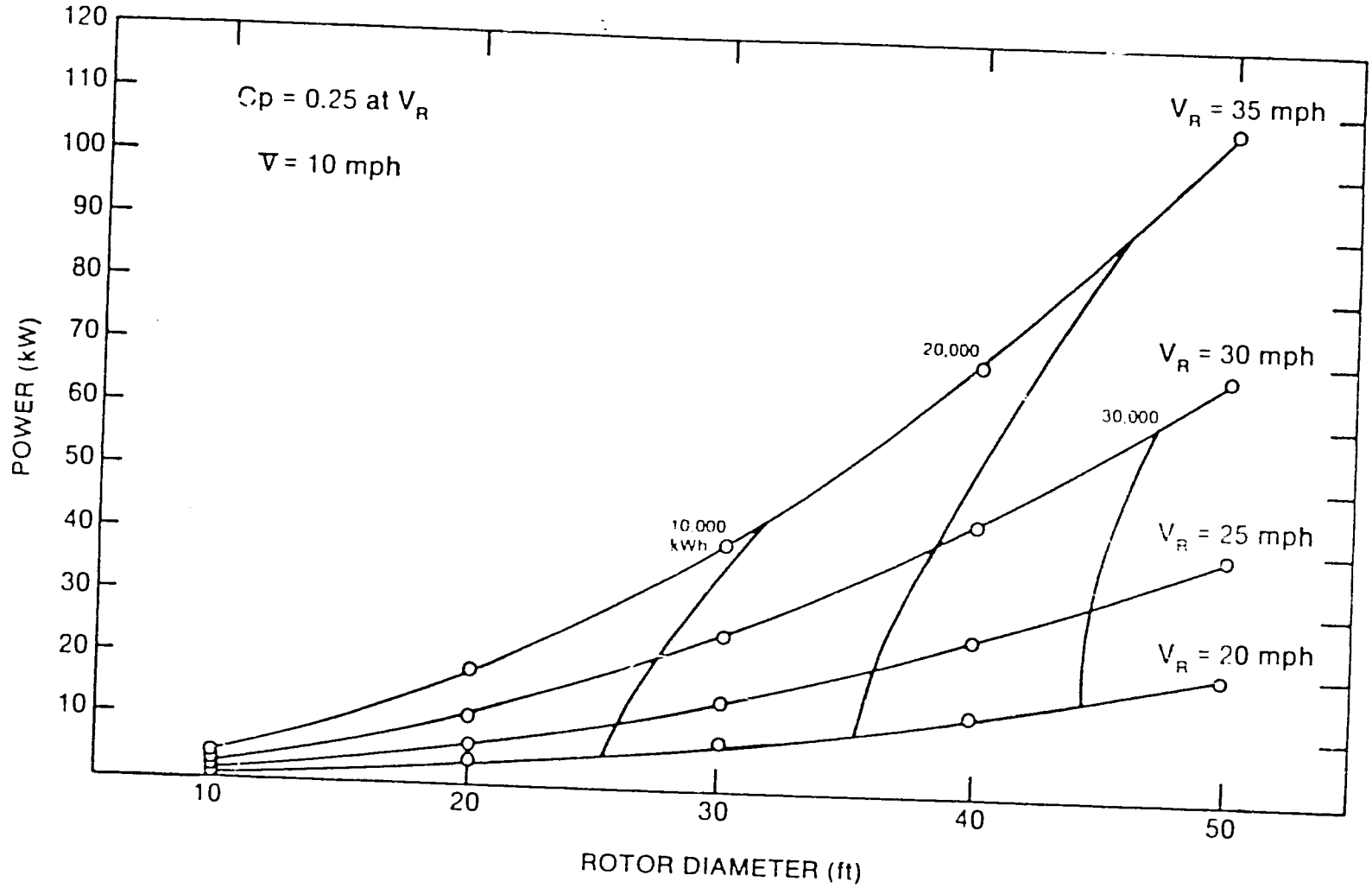
RAYLEIGH WINDSPEED DISTRIBUTION

(Excerpt from: The Wind Power Book, Parr, Jack, Cheshire Books, Palo Alto, California, 1981)

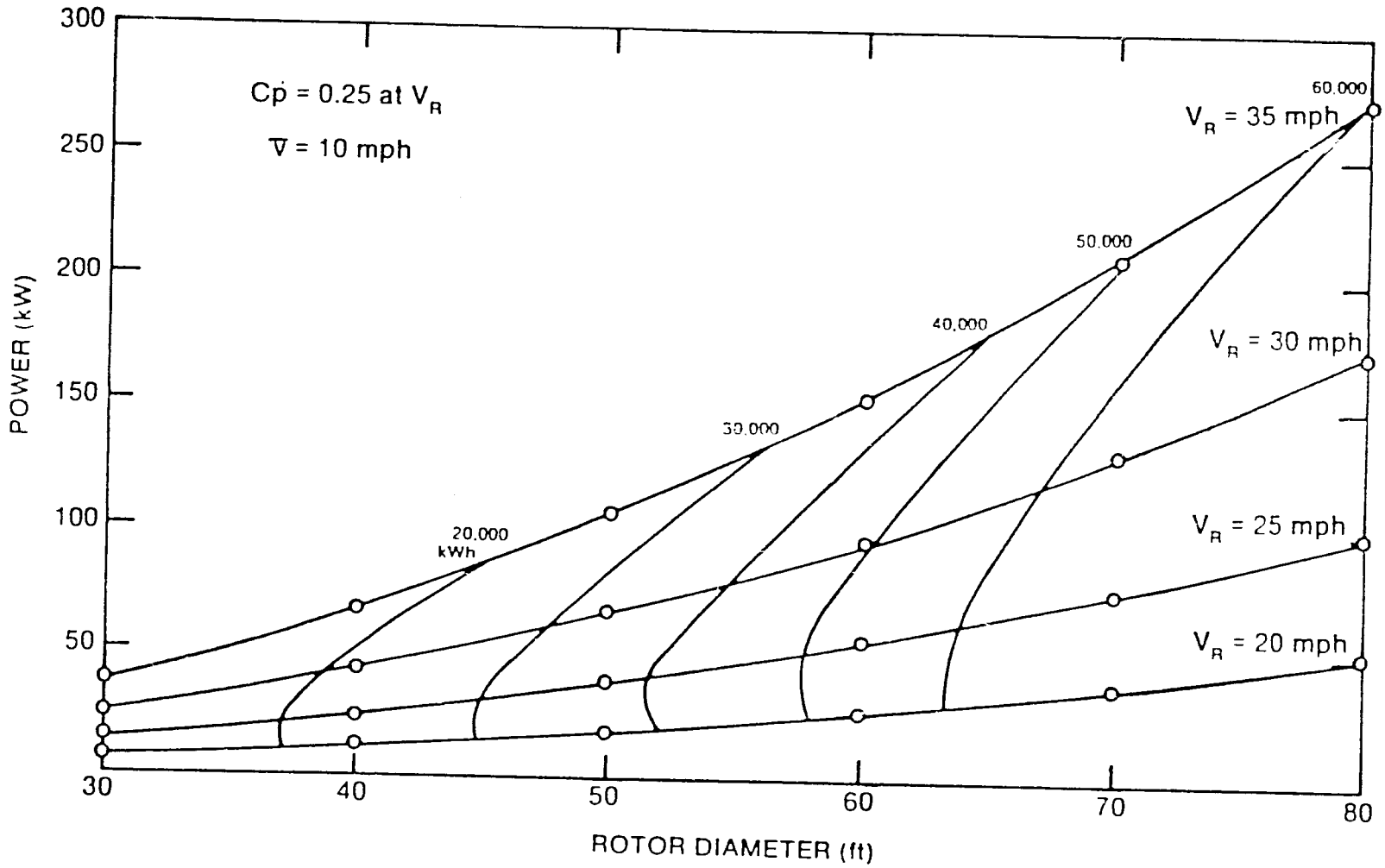
APPENDIX G

GRAPHS FOR RELATING TURBINE RATED OUTPUT, ANNUAL ENERGY PRODUCTION, AND ROTOR DIAMETER

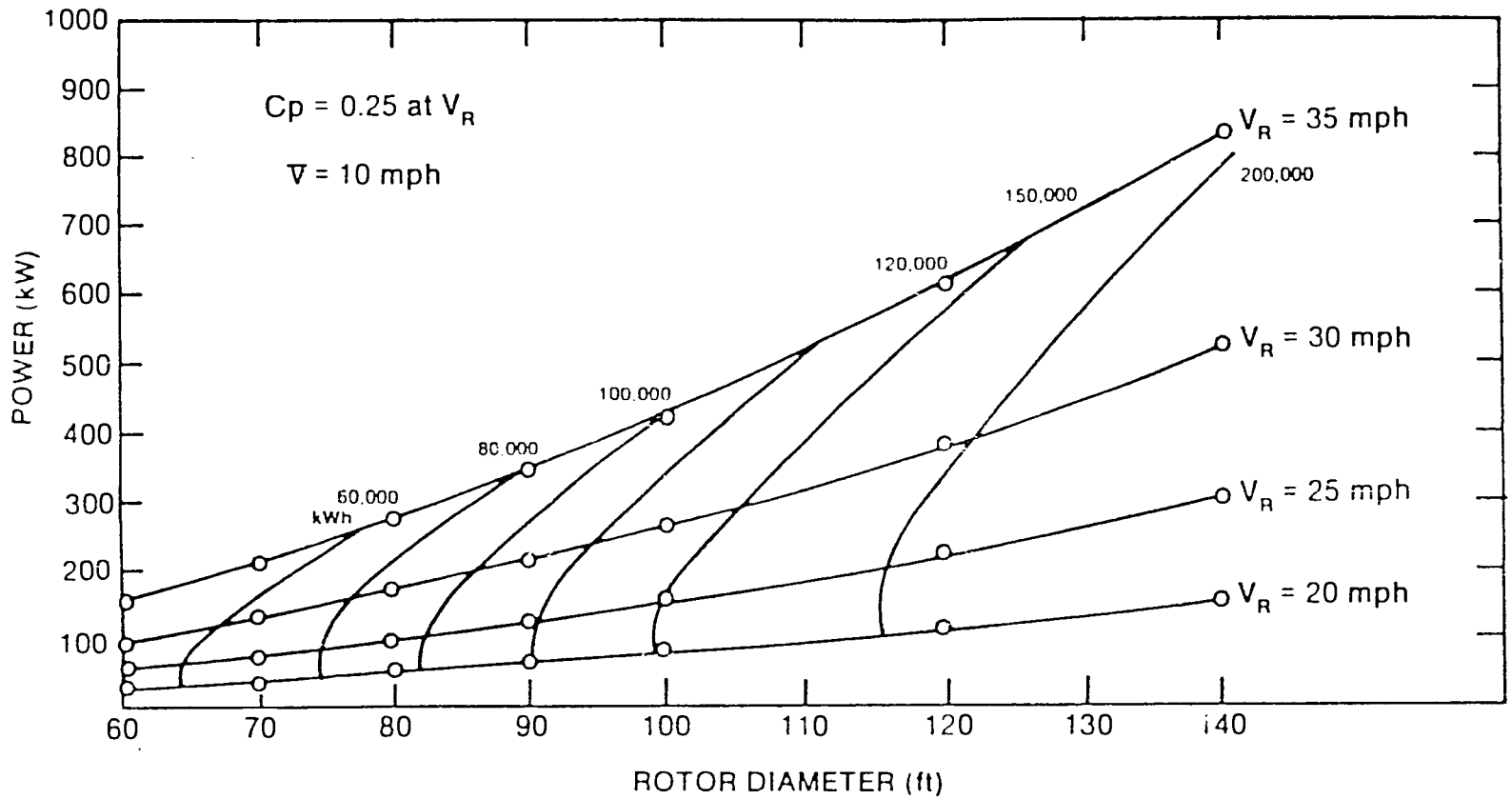
(Excerpt From: Performance and Size Estimating for Wind Systems, U.S. DOE, Feburary, 1983).



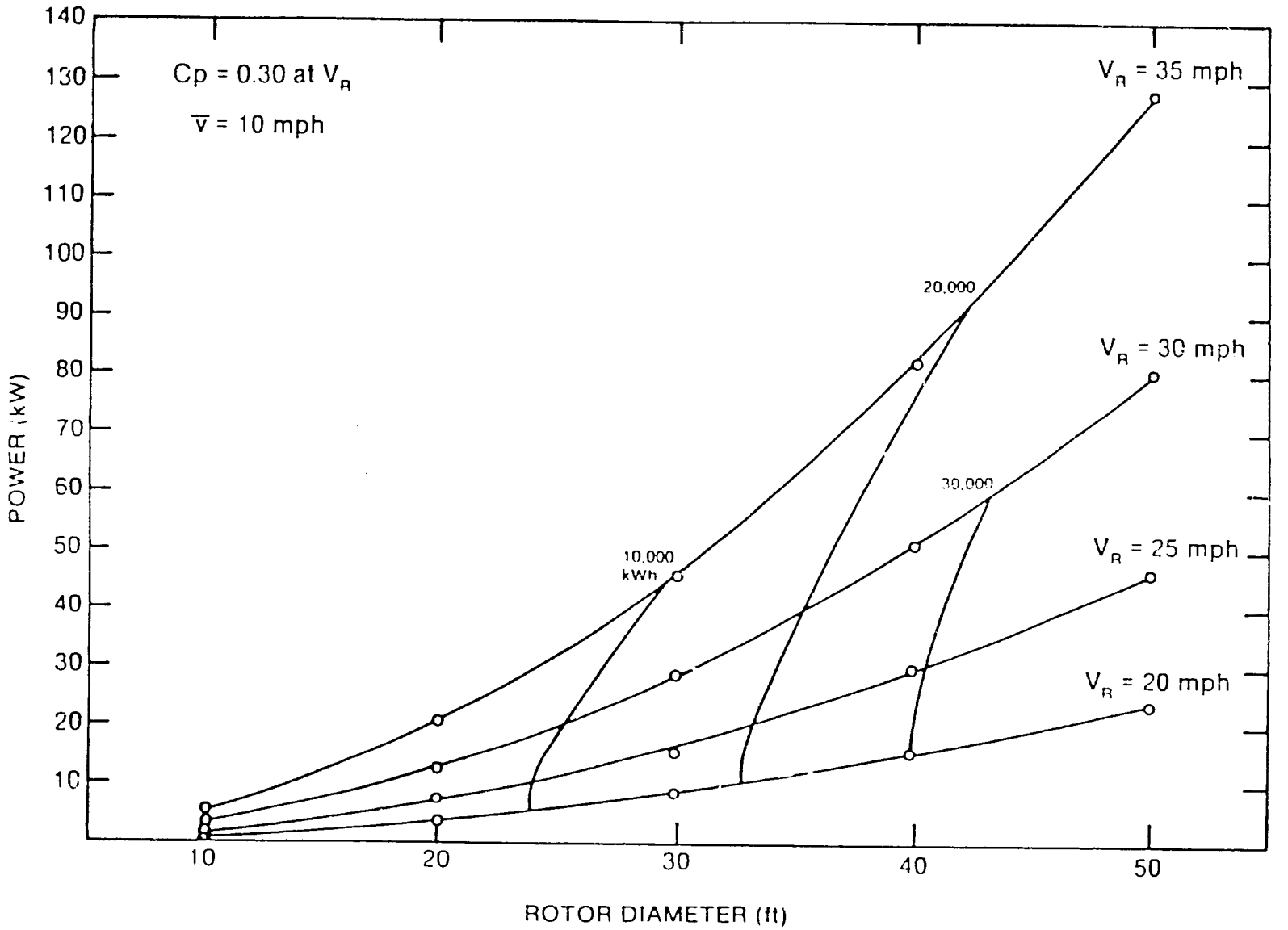
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



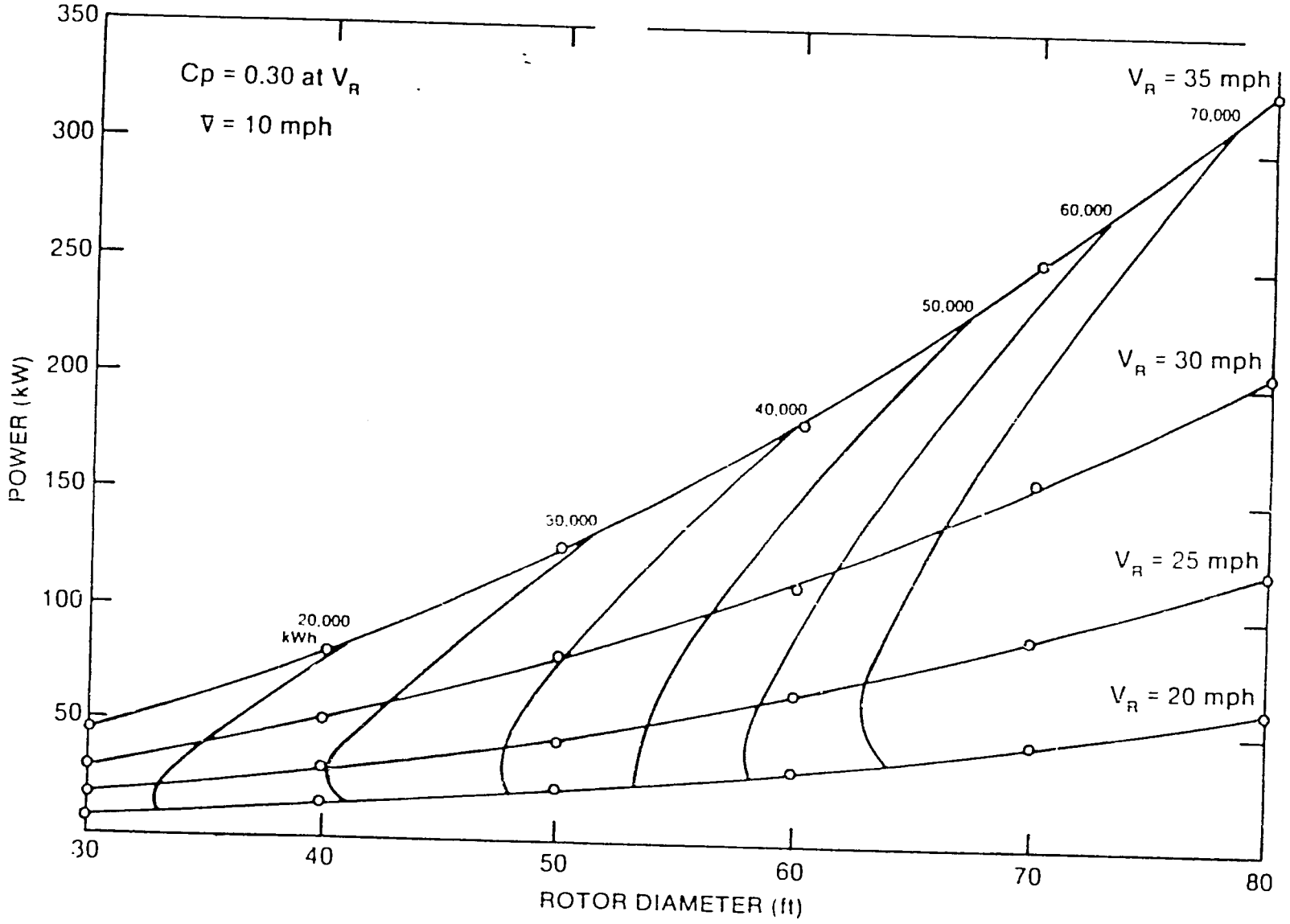
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



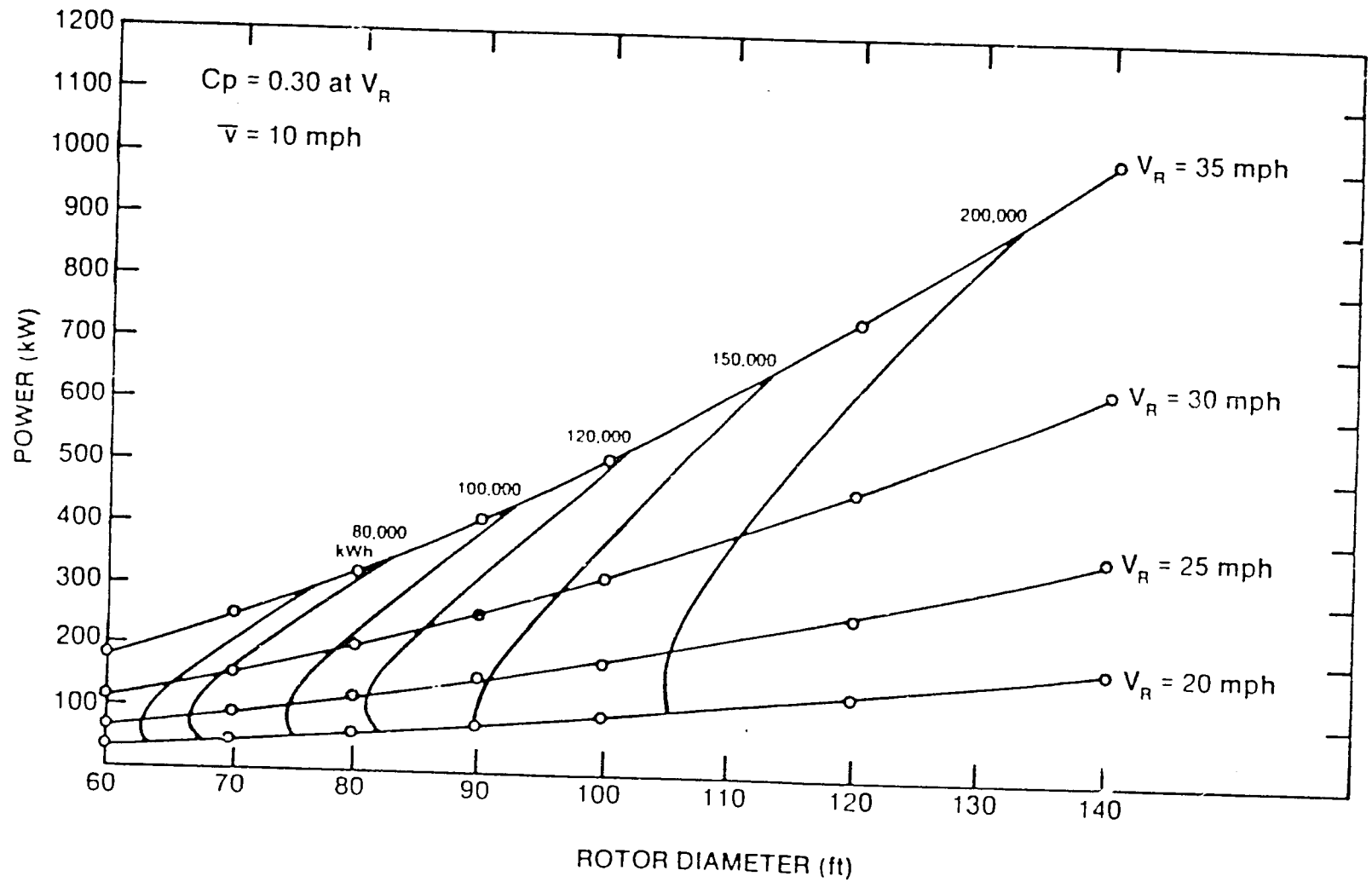
Power (kW) and Energy (kWh) vs. 60-140 ft. Rotor Diameter



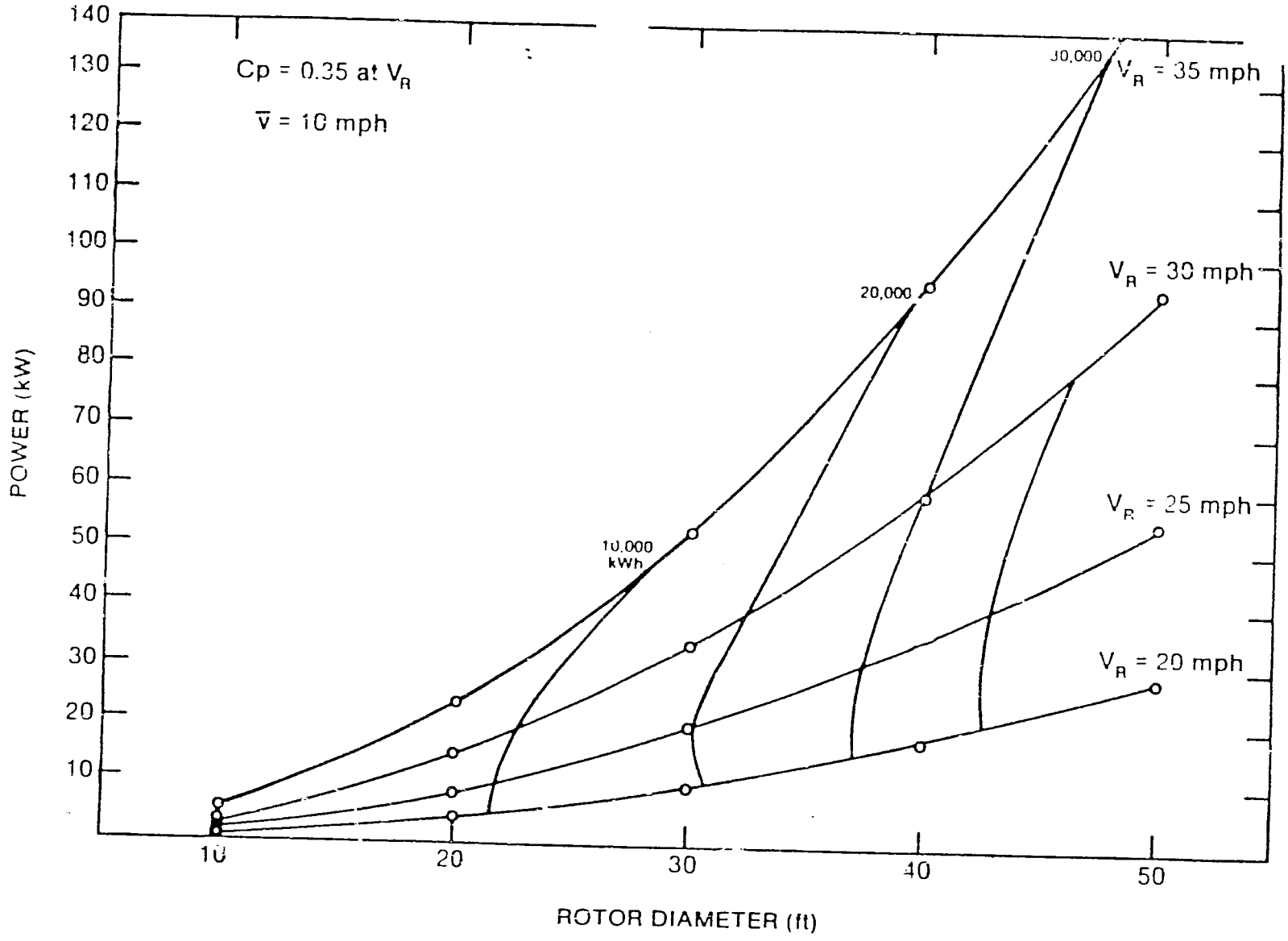
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



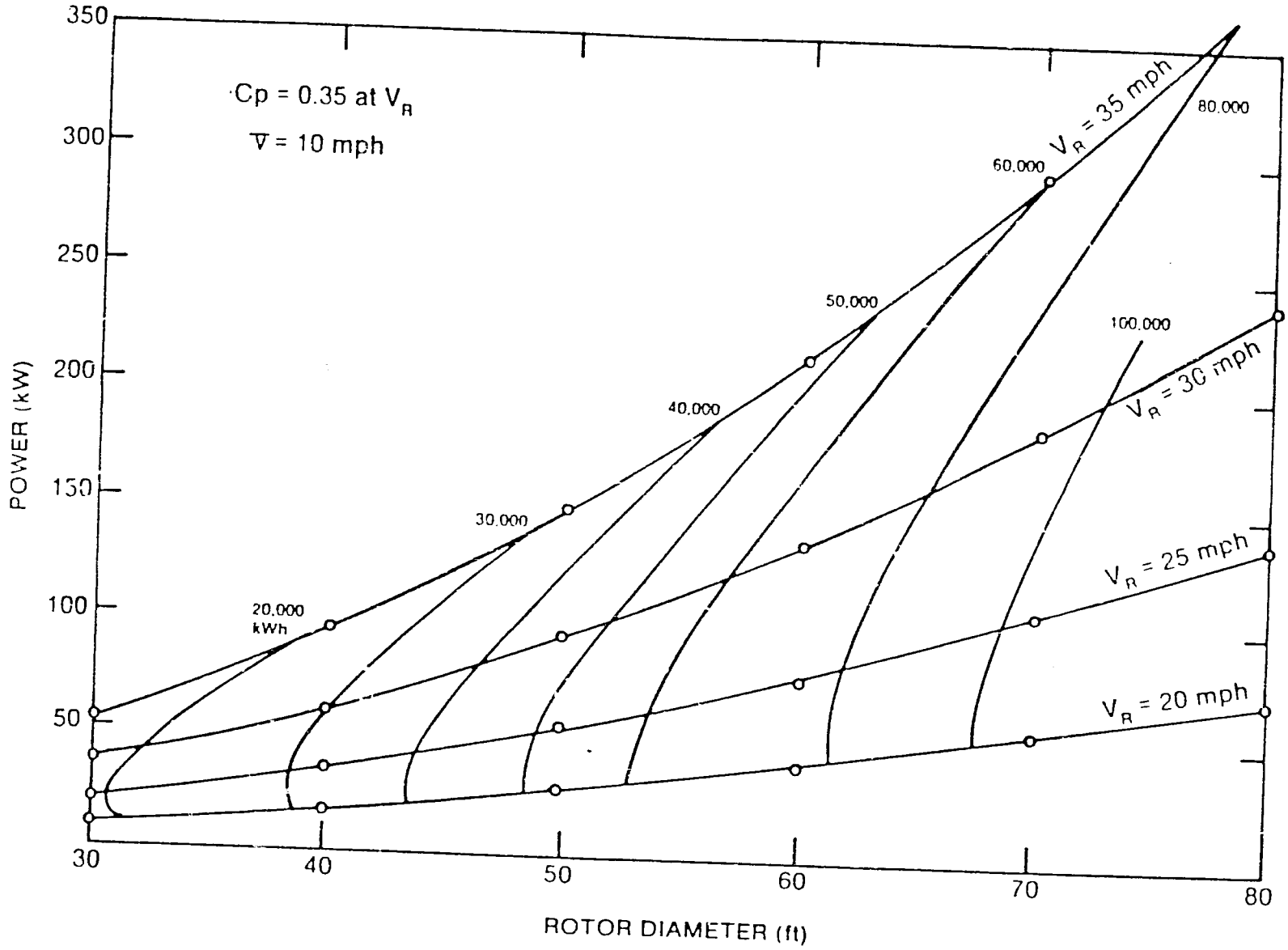
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



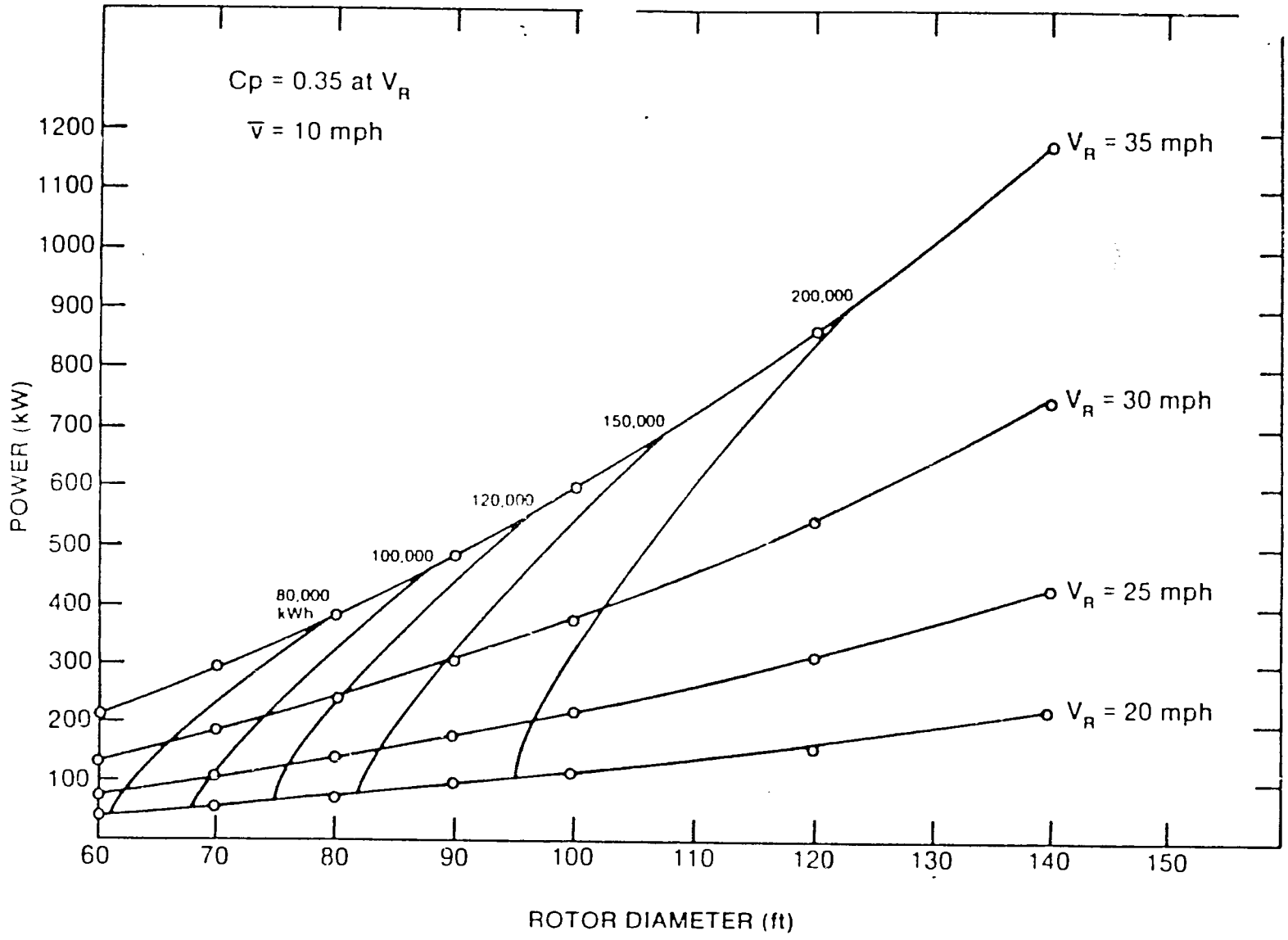
Power (kW) and Energy (kWh) vs. 60-140 ft. Rotor Diameter



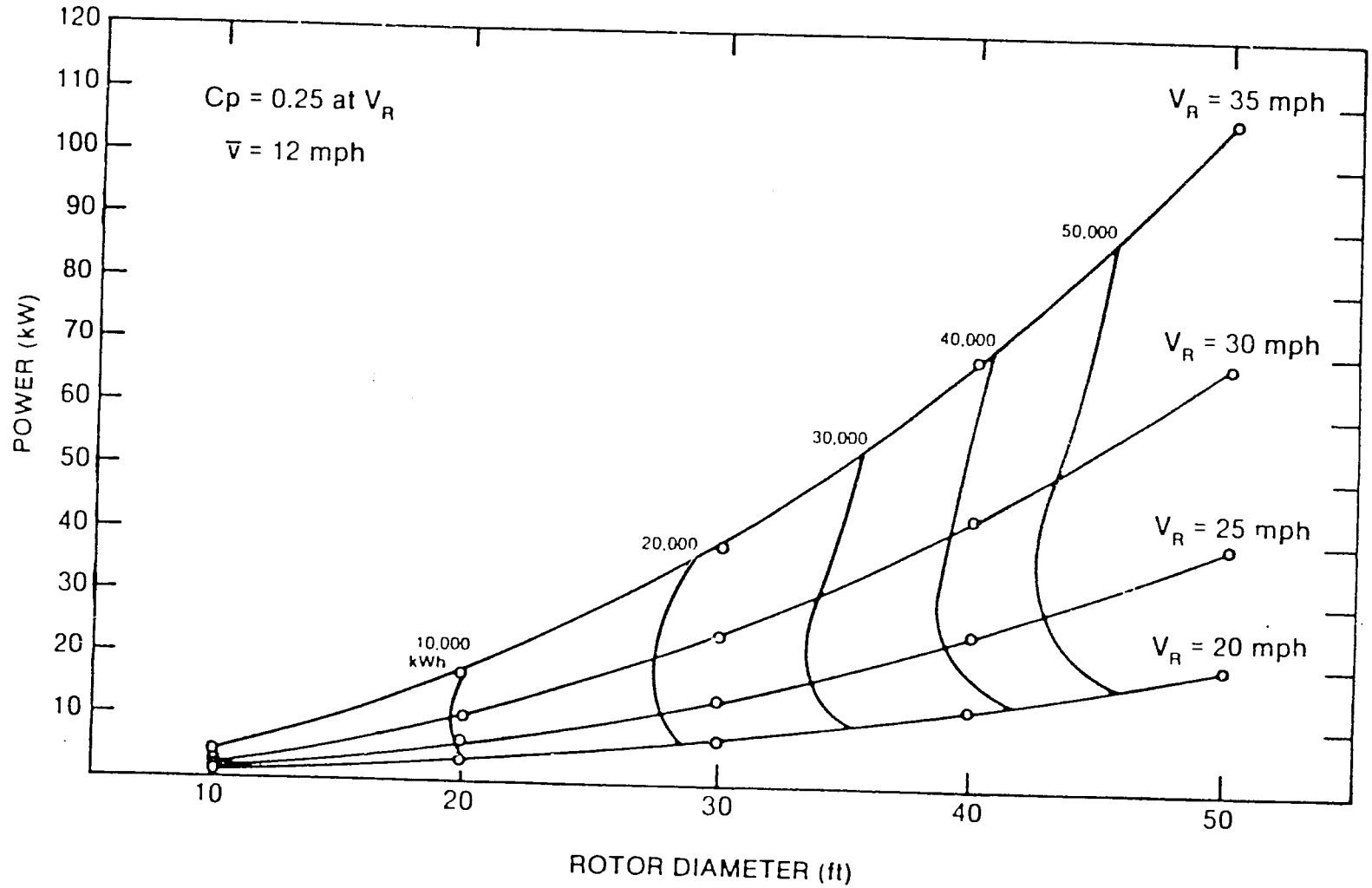
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



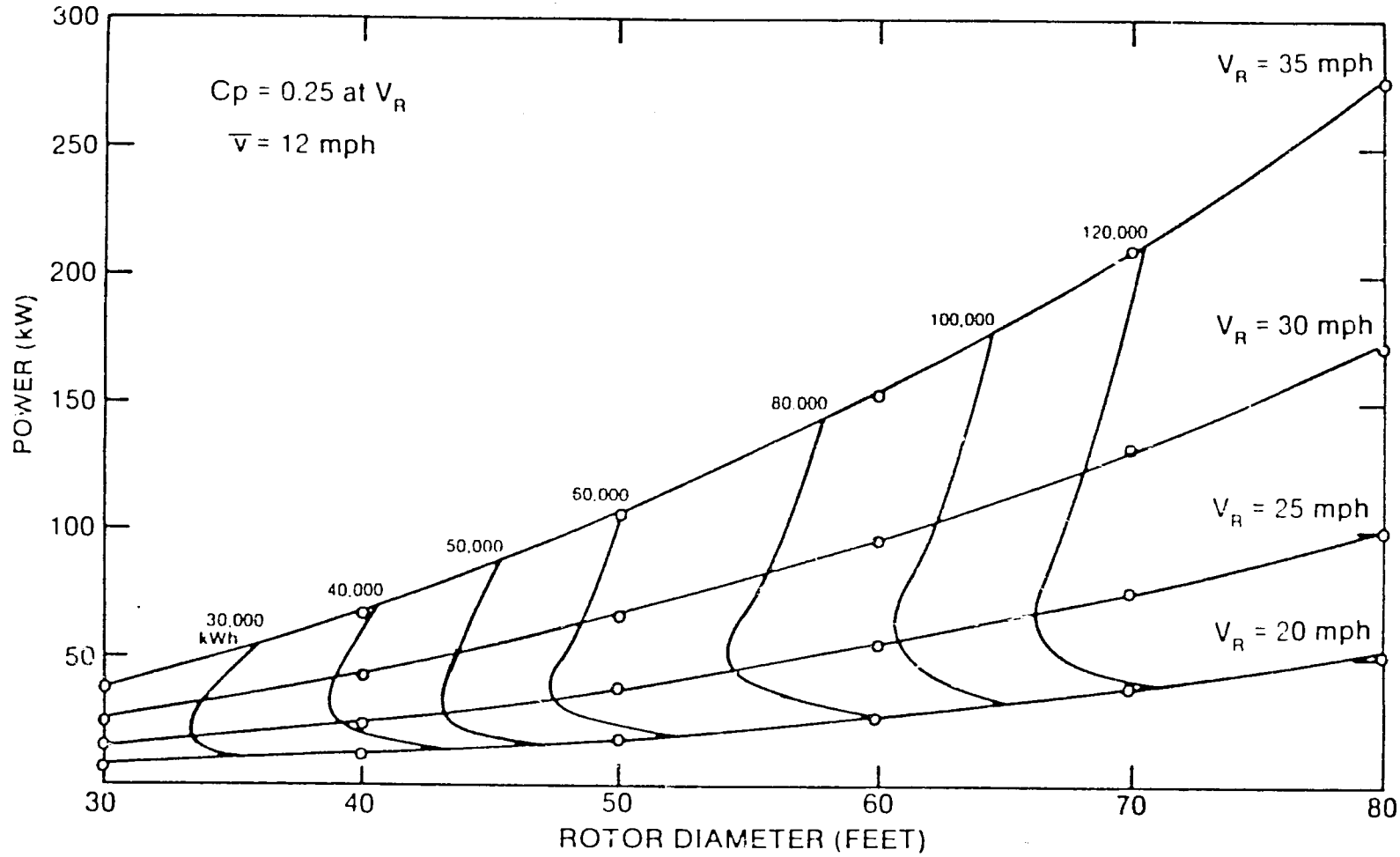
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



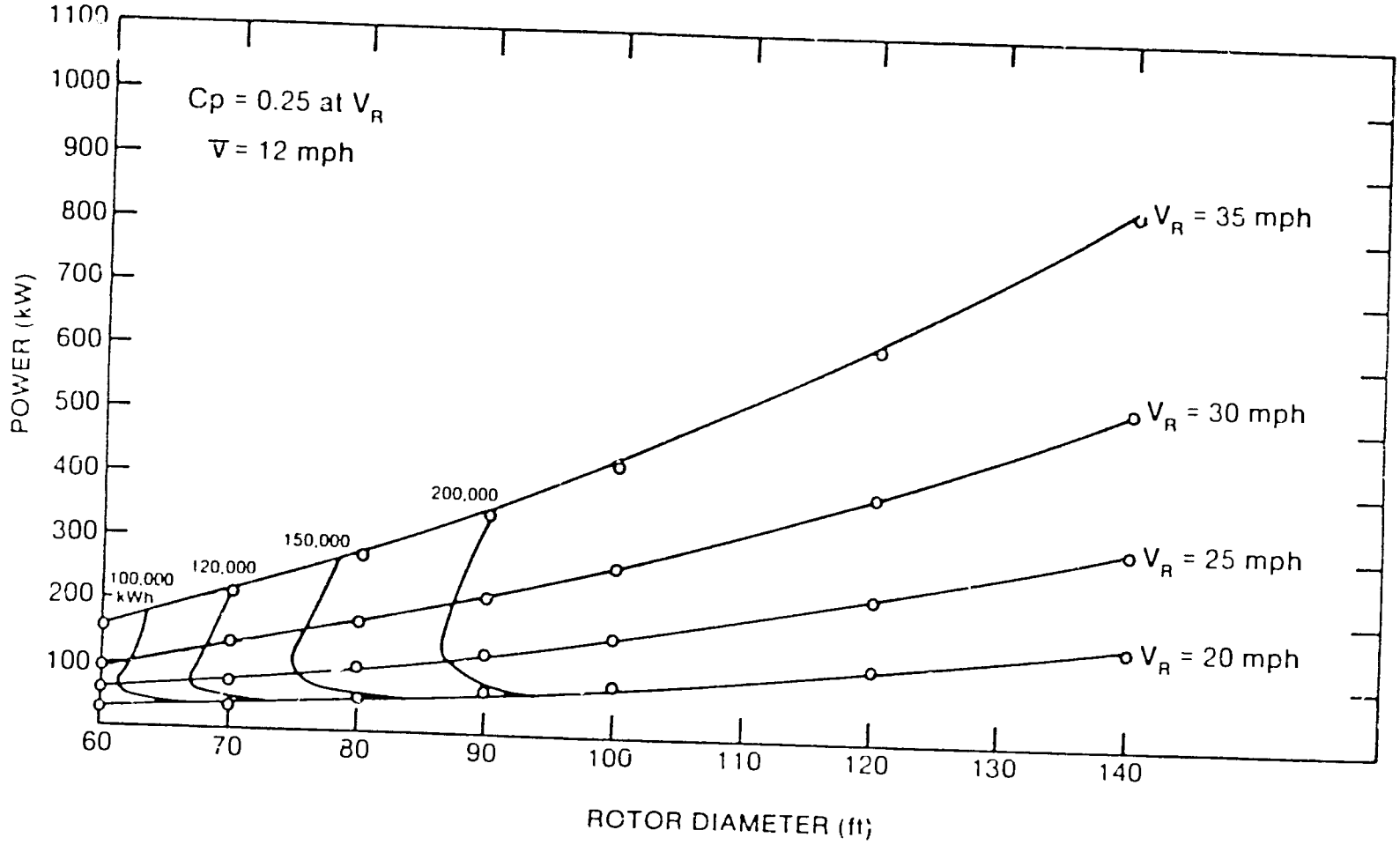
Power (kW) and Energy (kWh) vs. 60-140 ft. Rotor Diameter



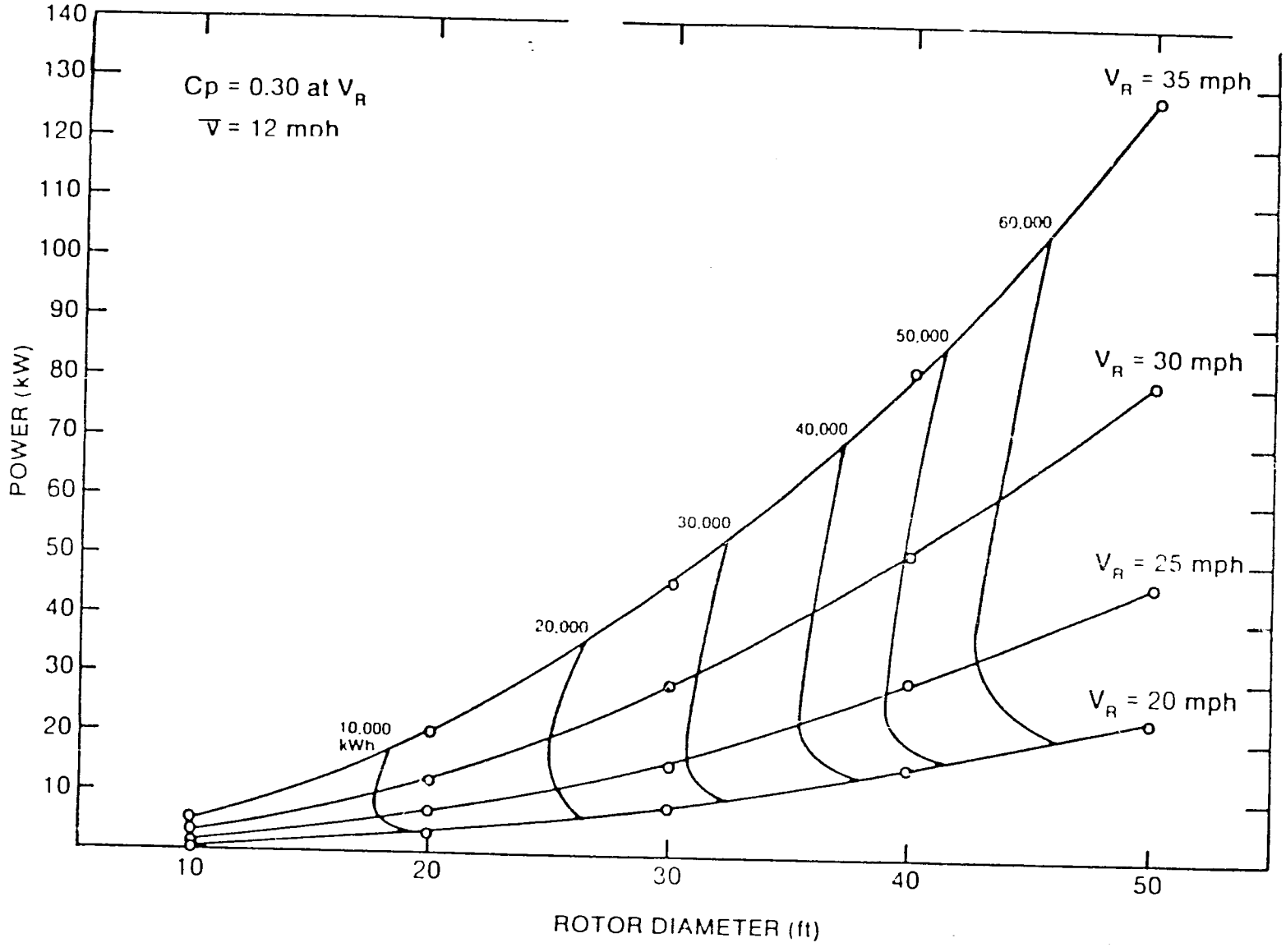
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



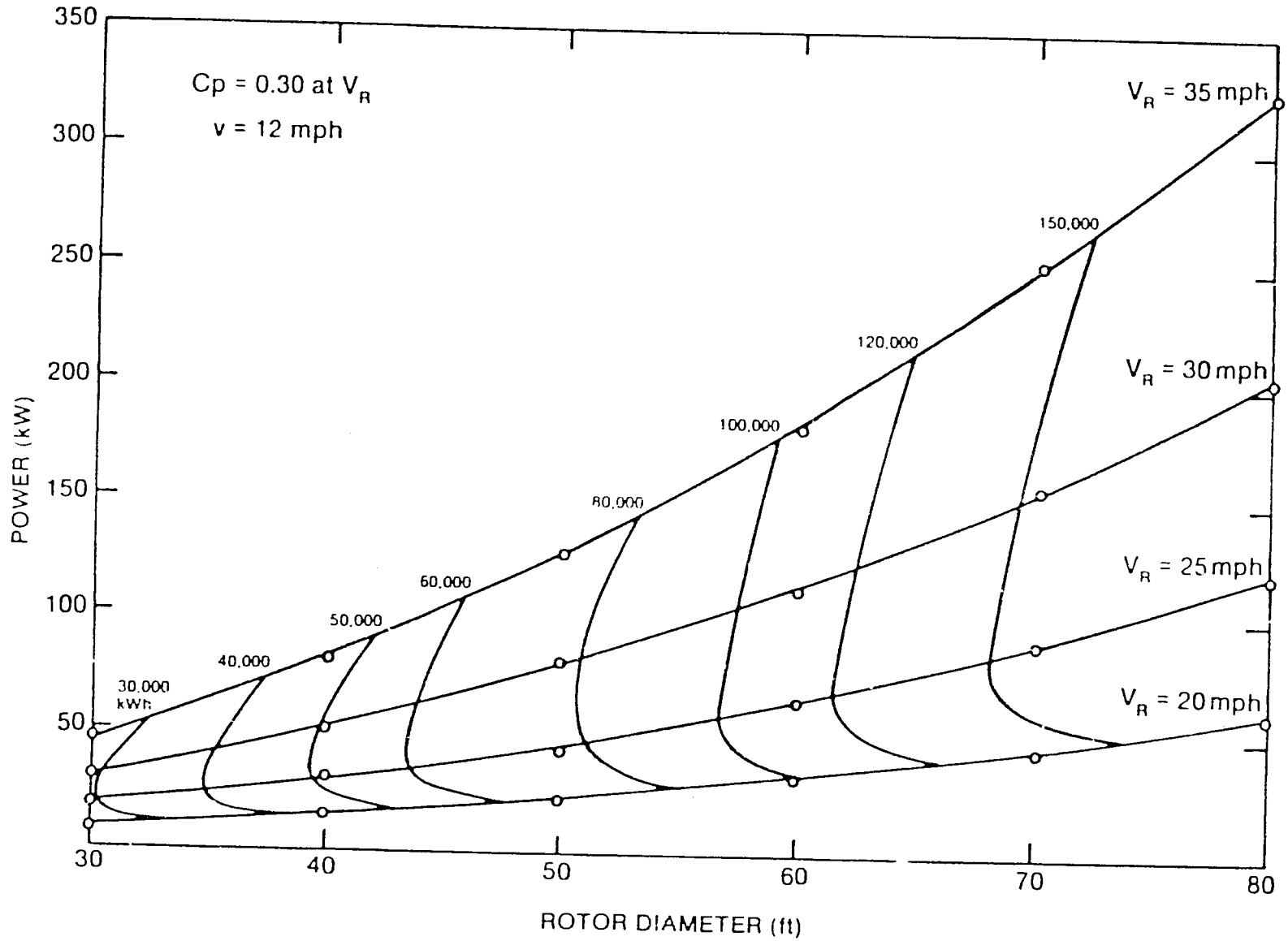
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



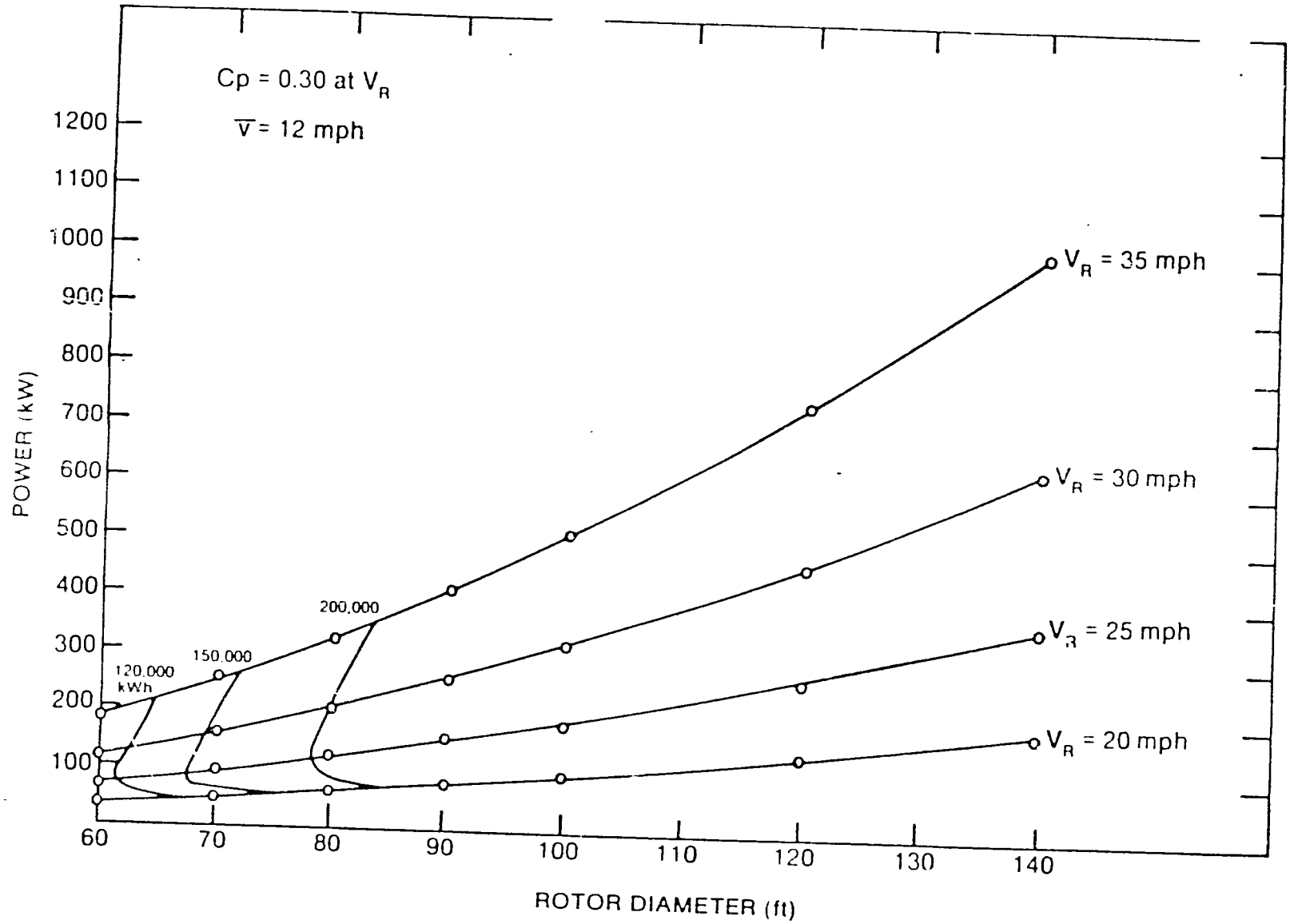
Power (kW) and Energy (kWh) vs. 60-140 ft. Rotor Diameter



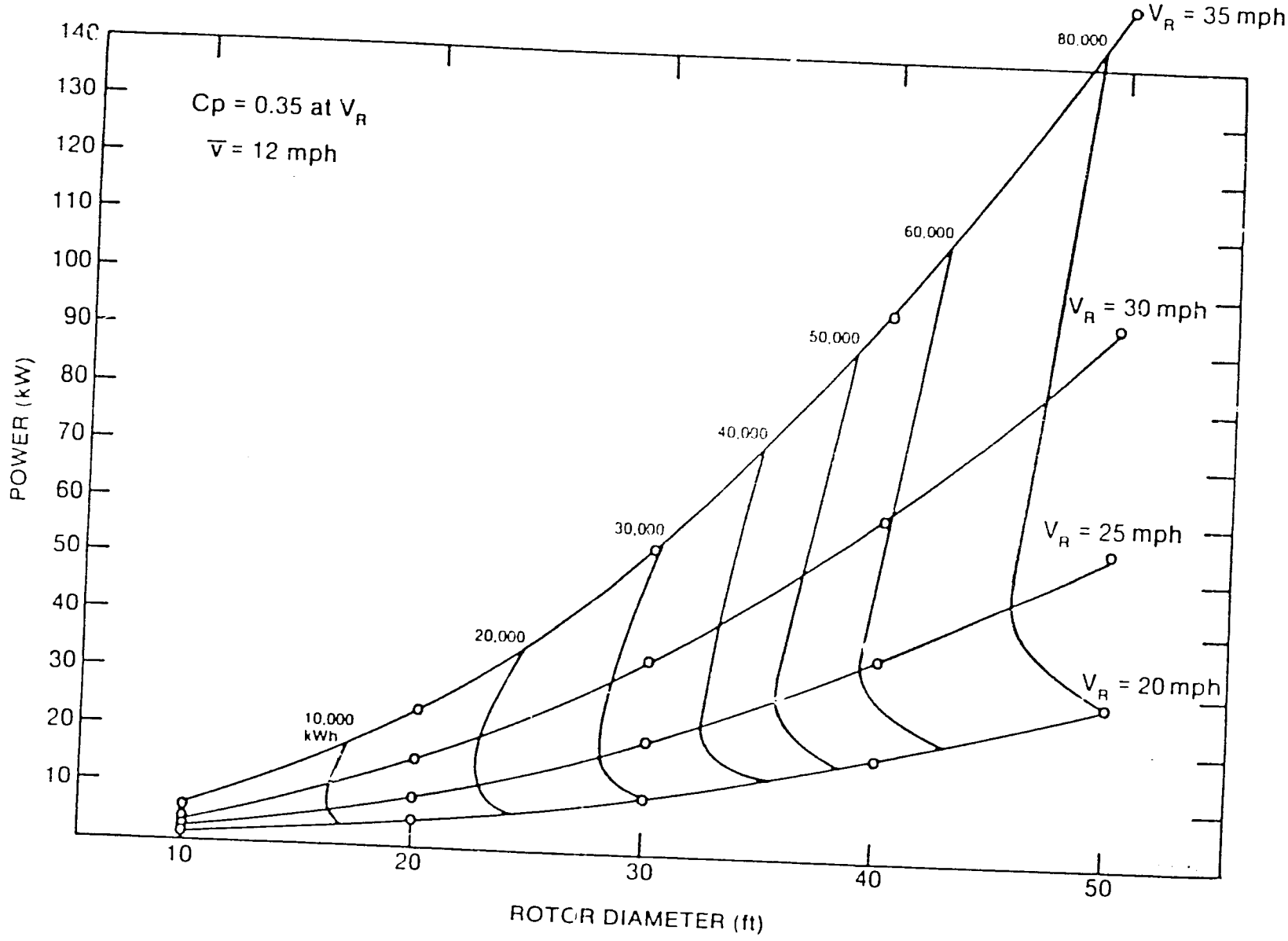
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



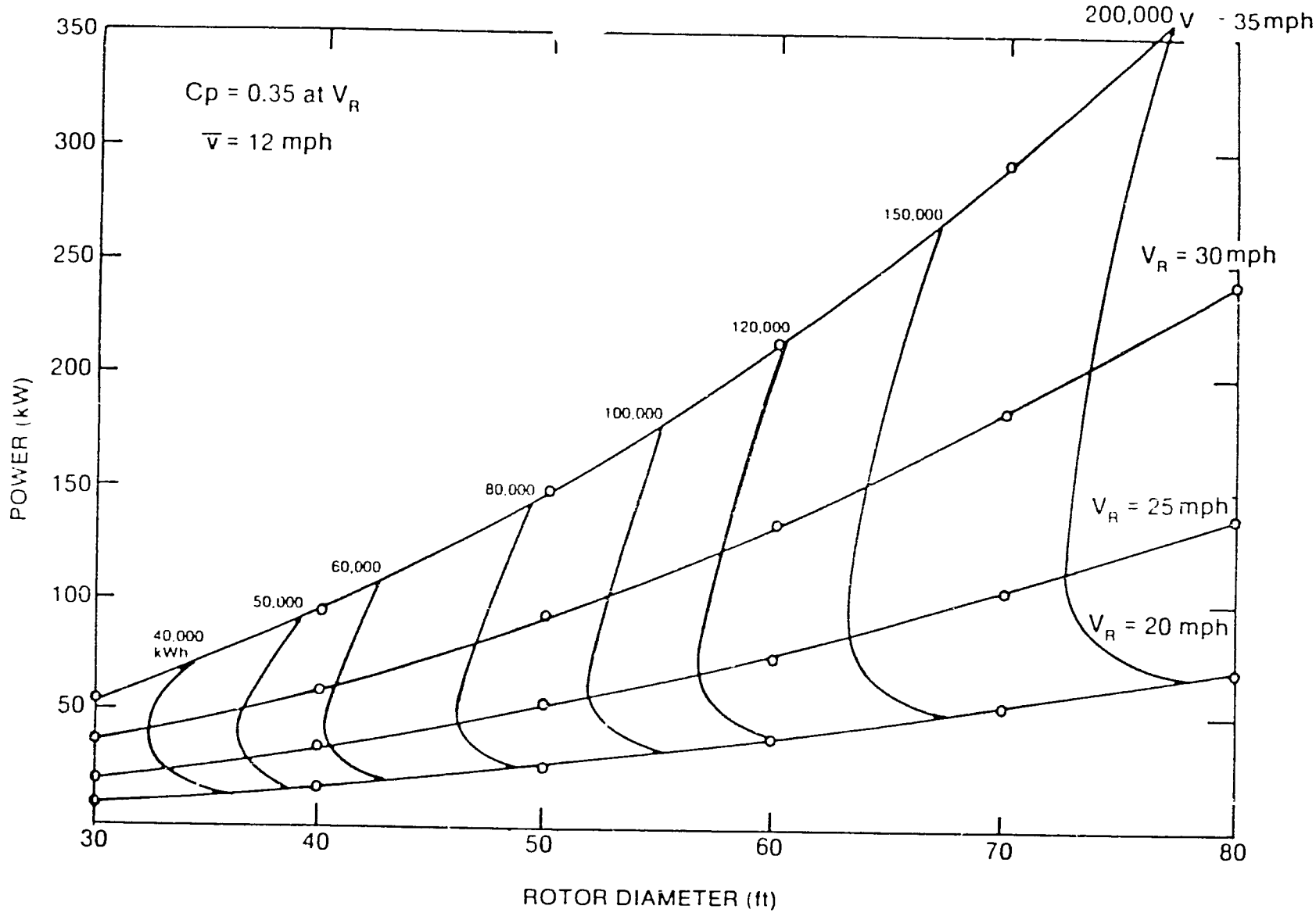
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



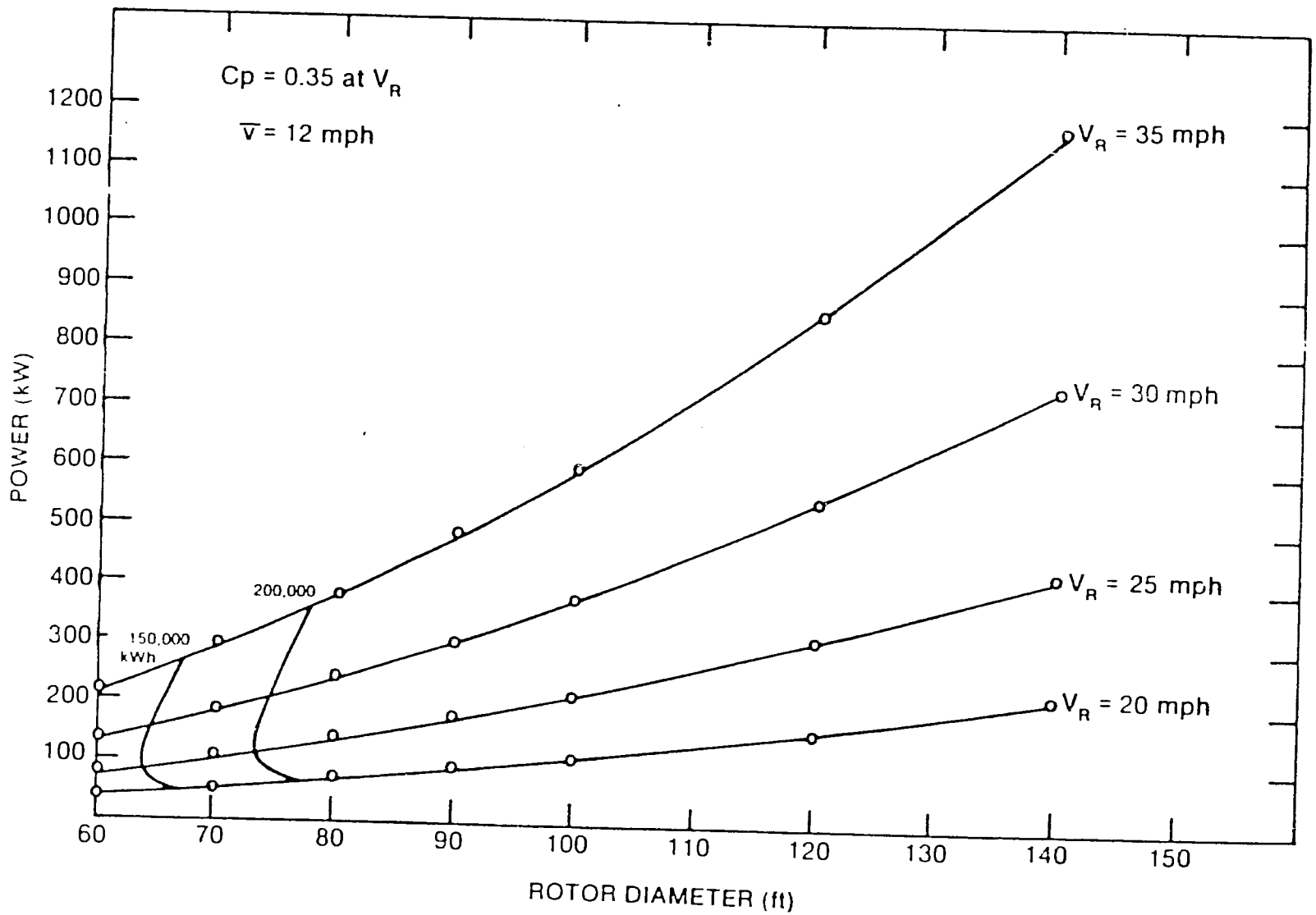
Power (kW) and Energy (kWh) vs. 60-140 ft. Rotor Diameter



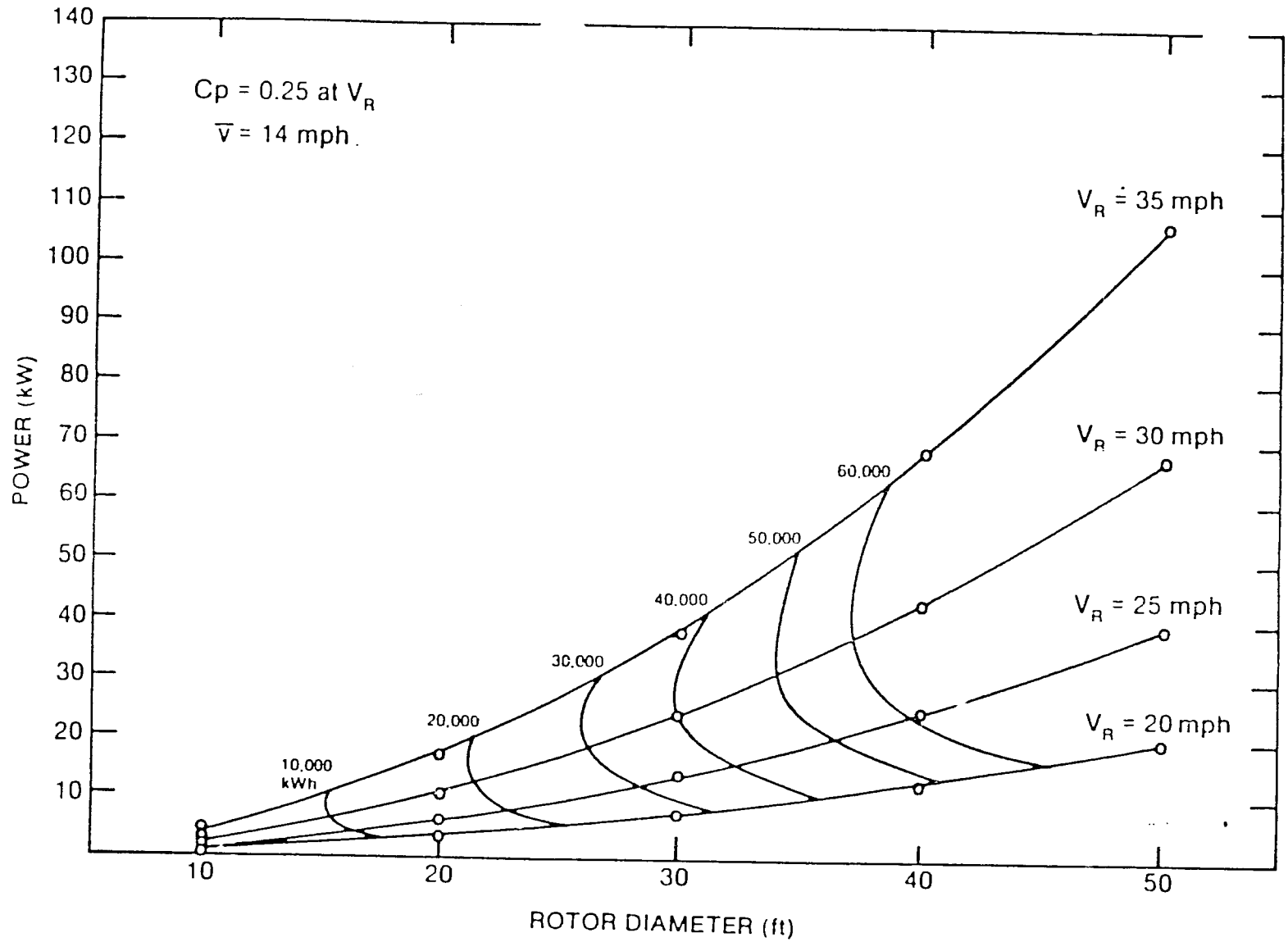
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameters



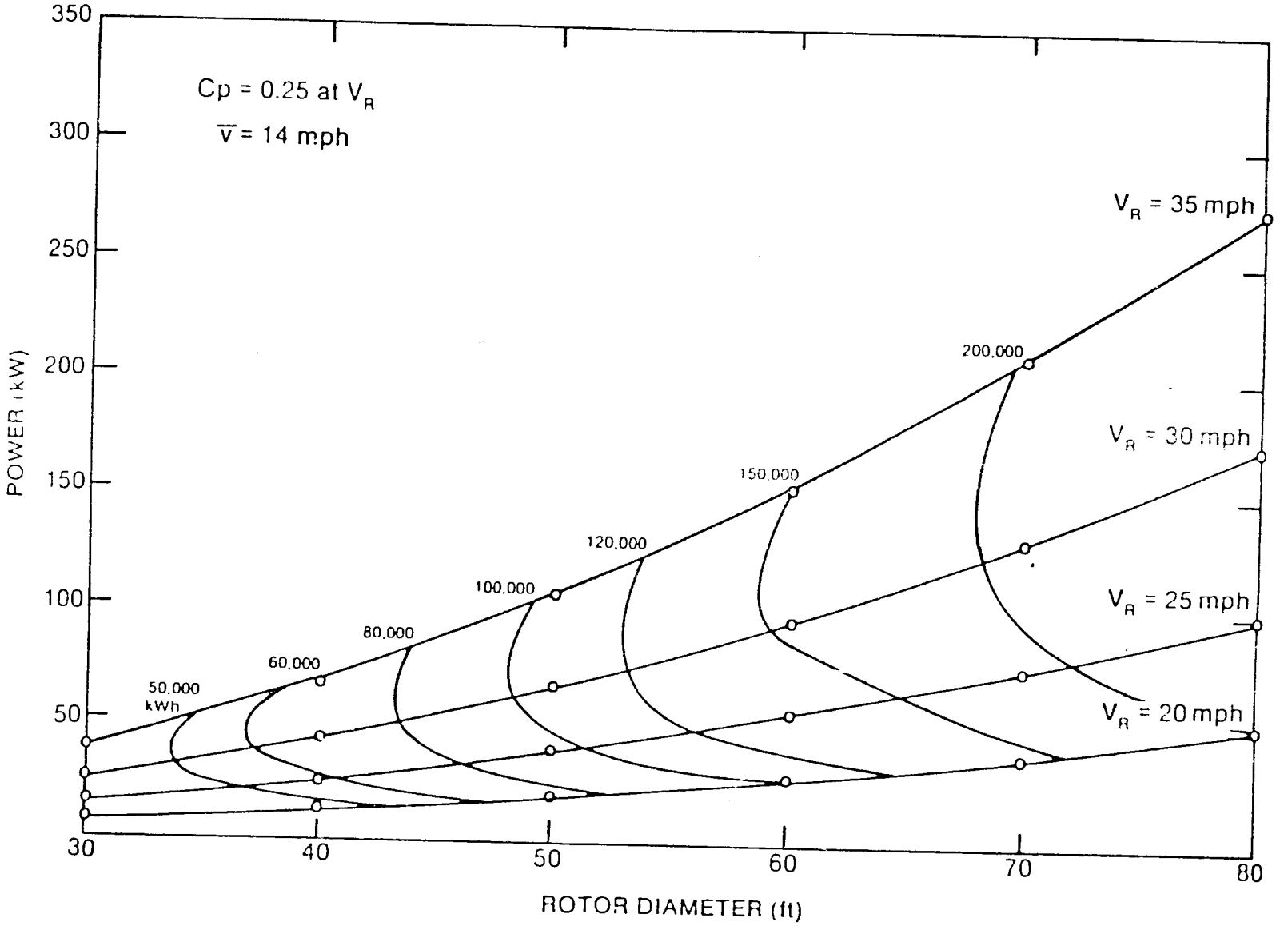
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



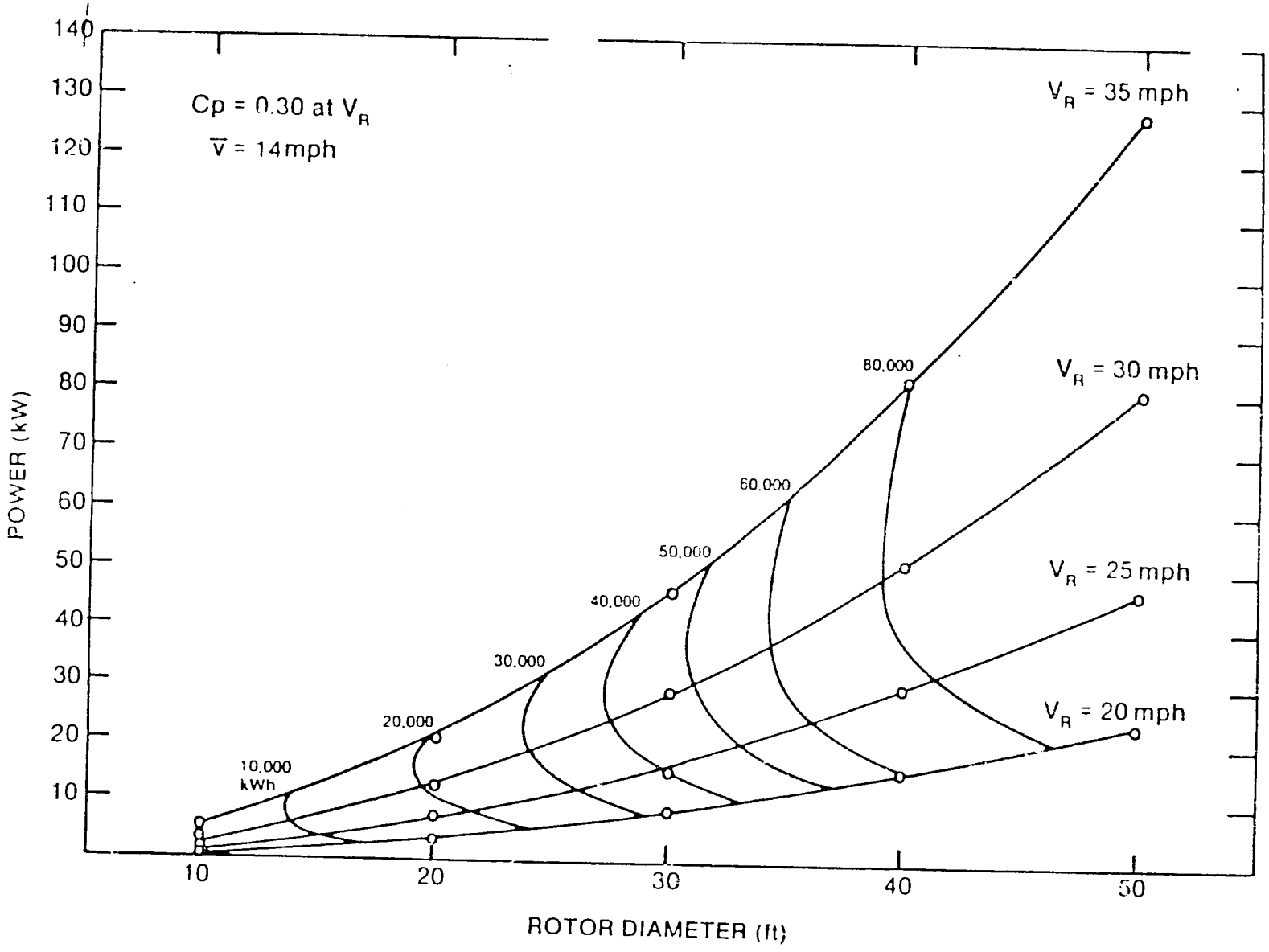
Power (kW) and Energy (kWh) vs. 60-140 ft. Rotor Diameter



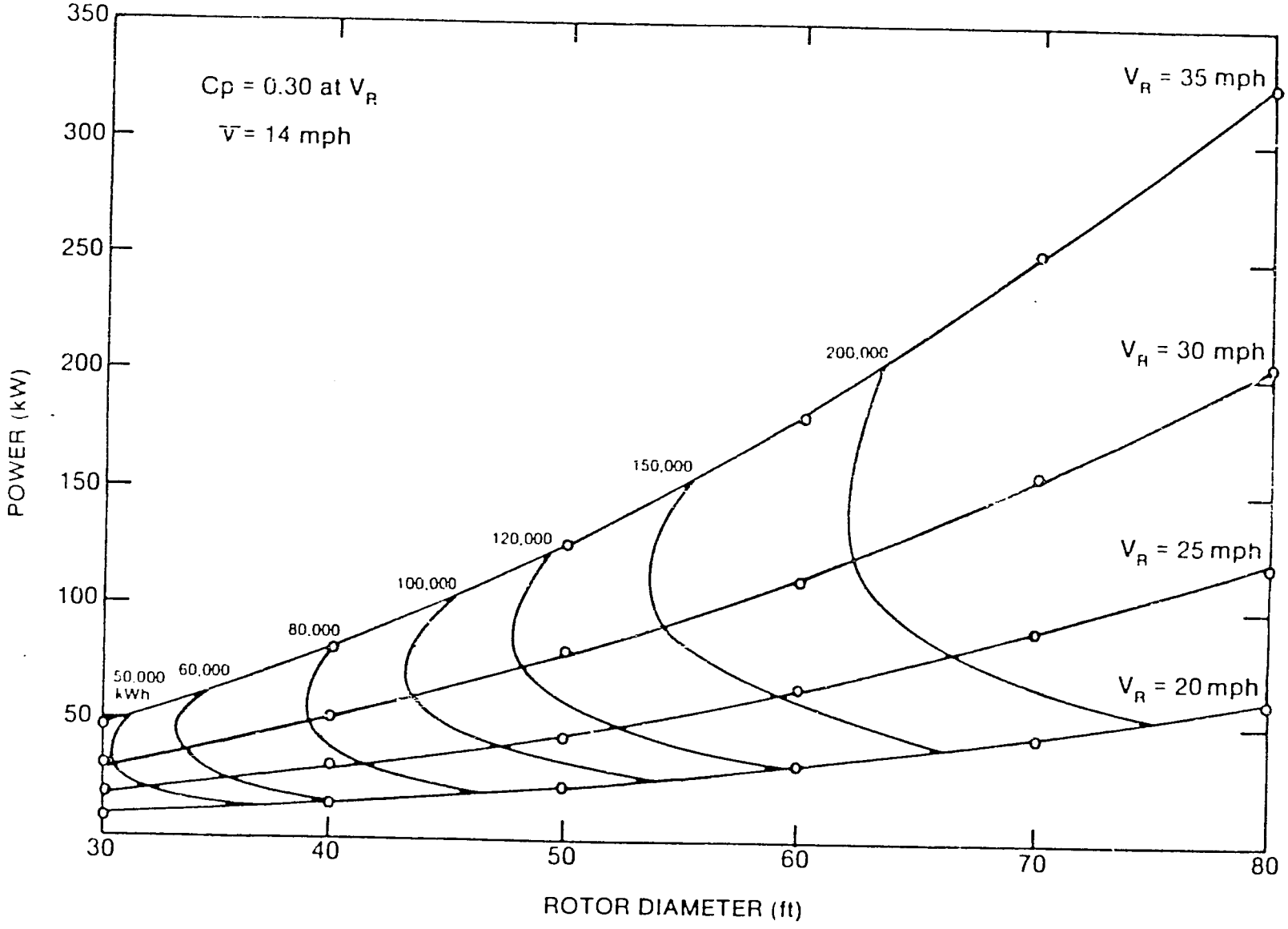
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



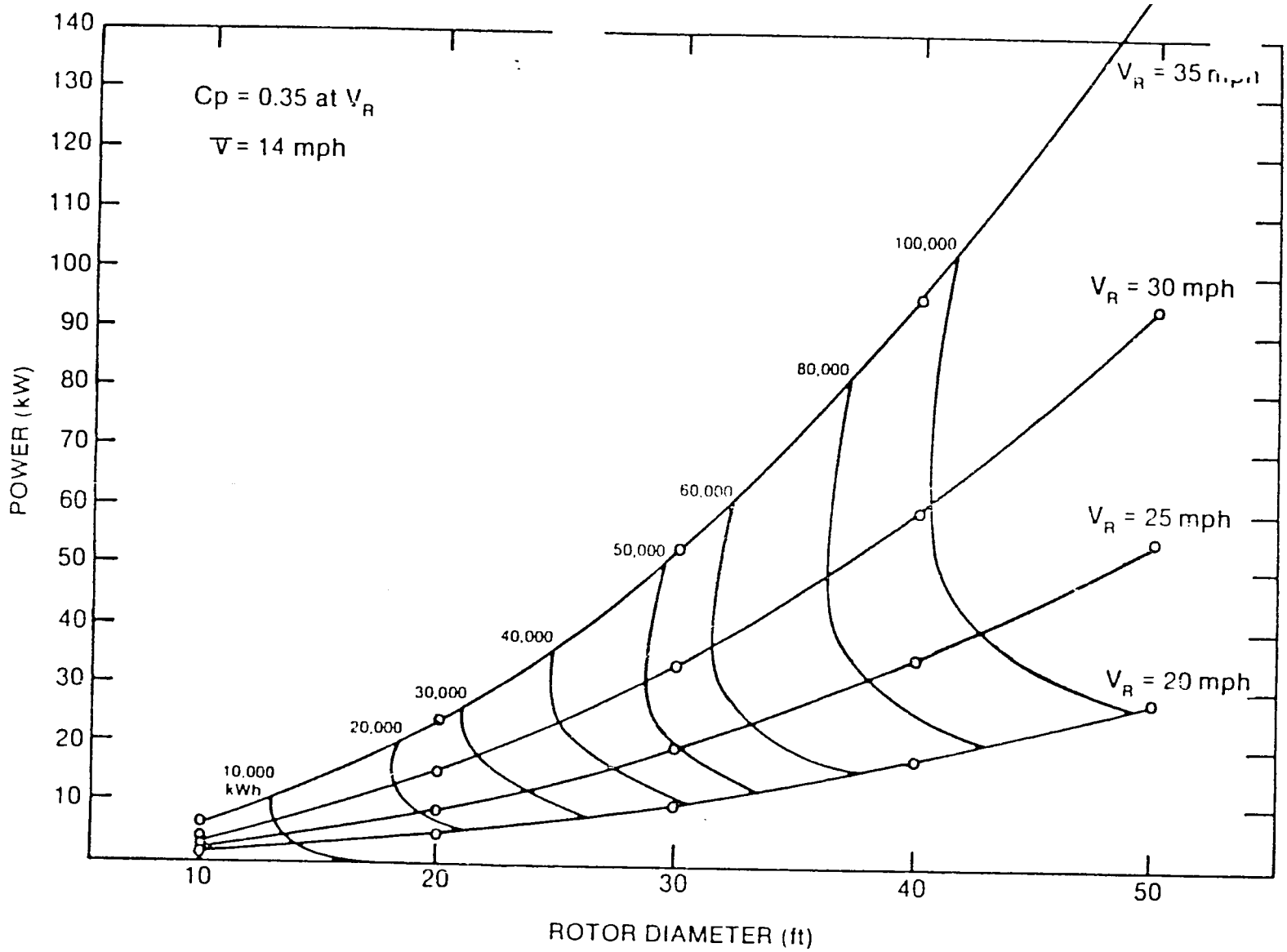
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



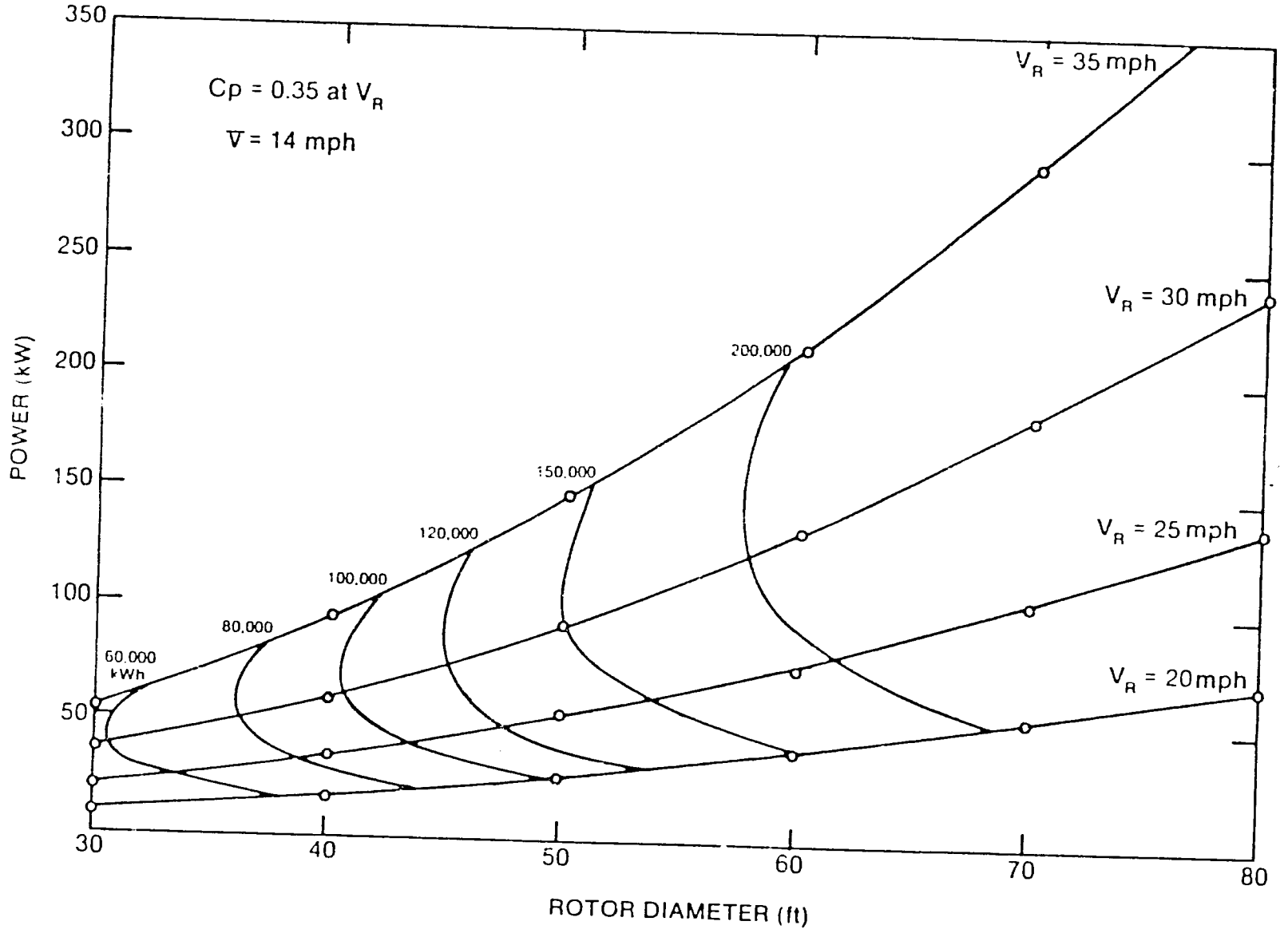
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



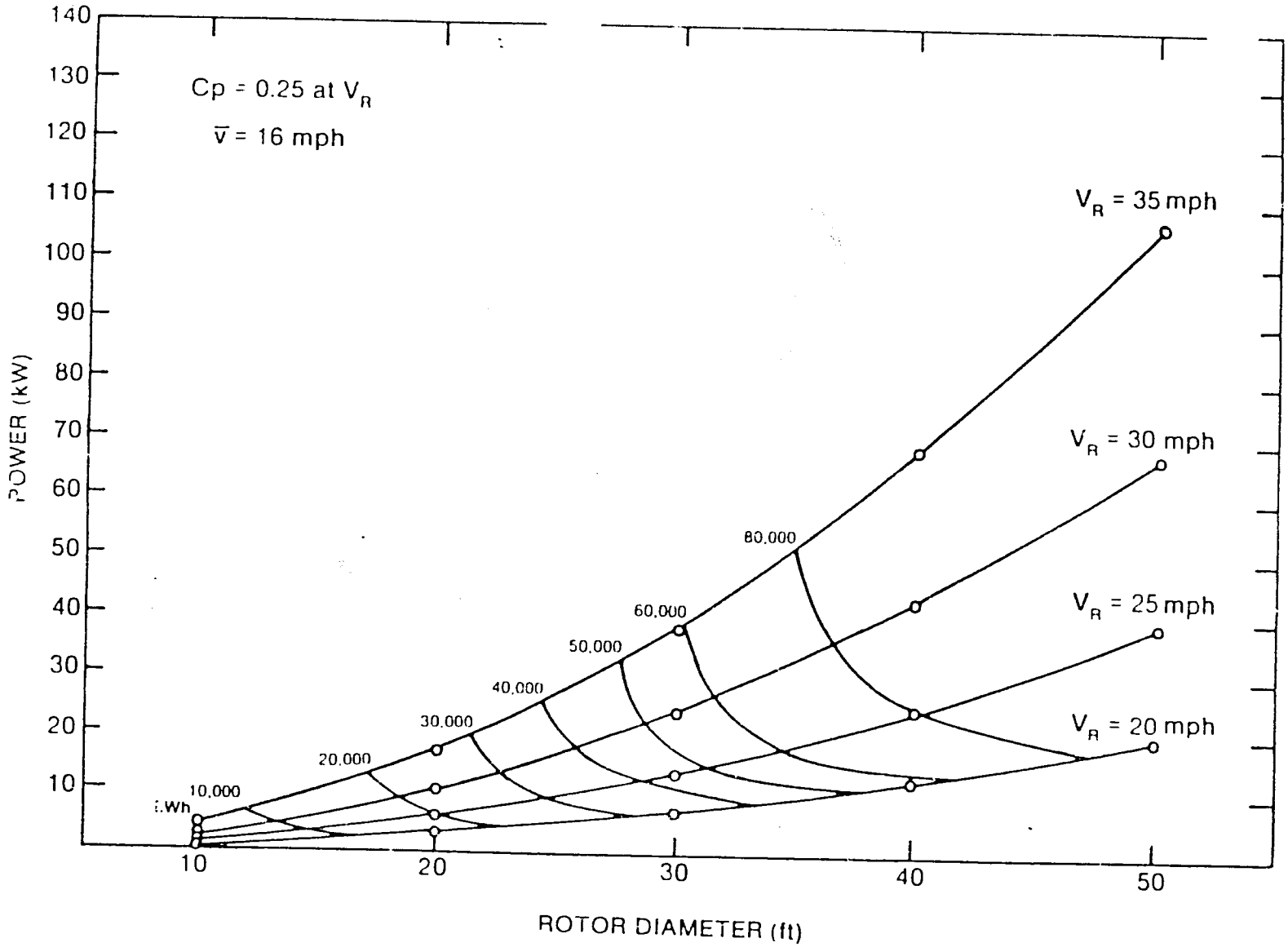
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



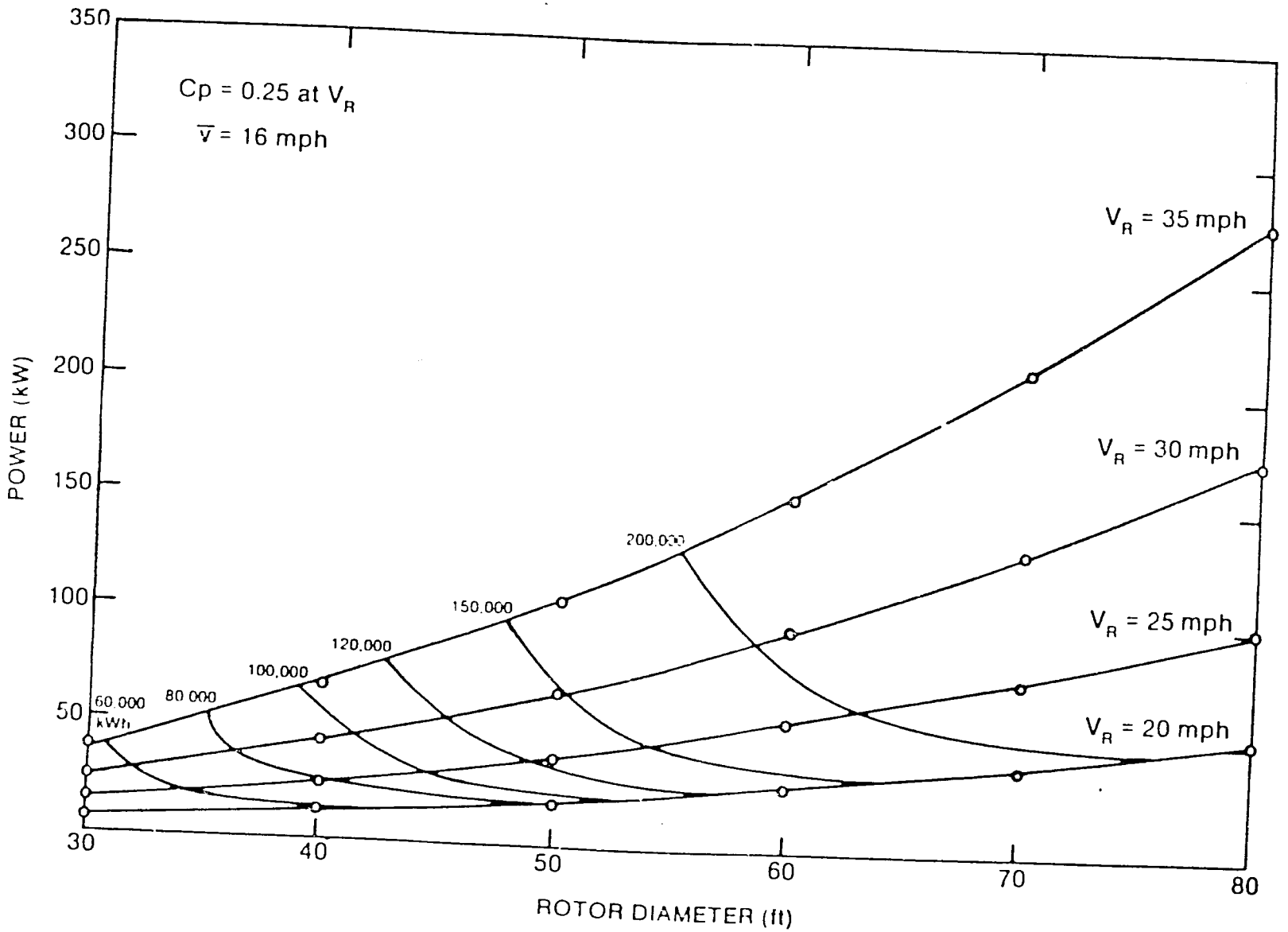
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameters



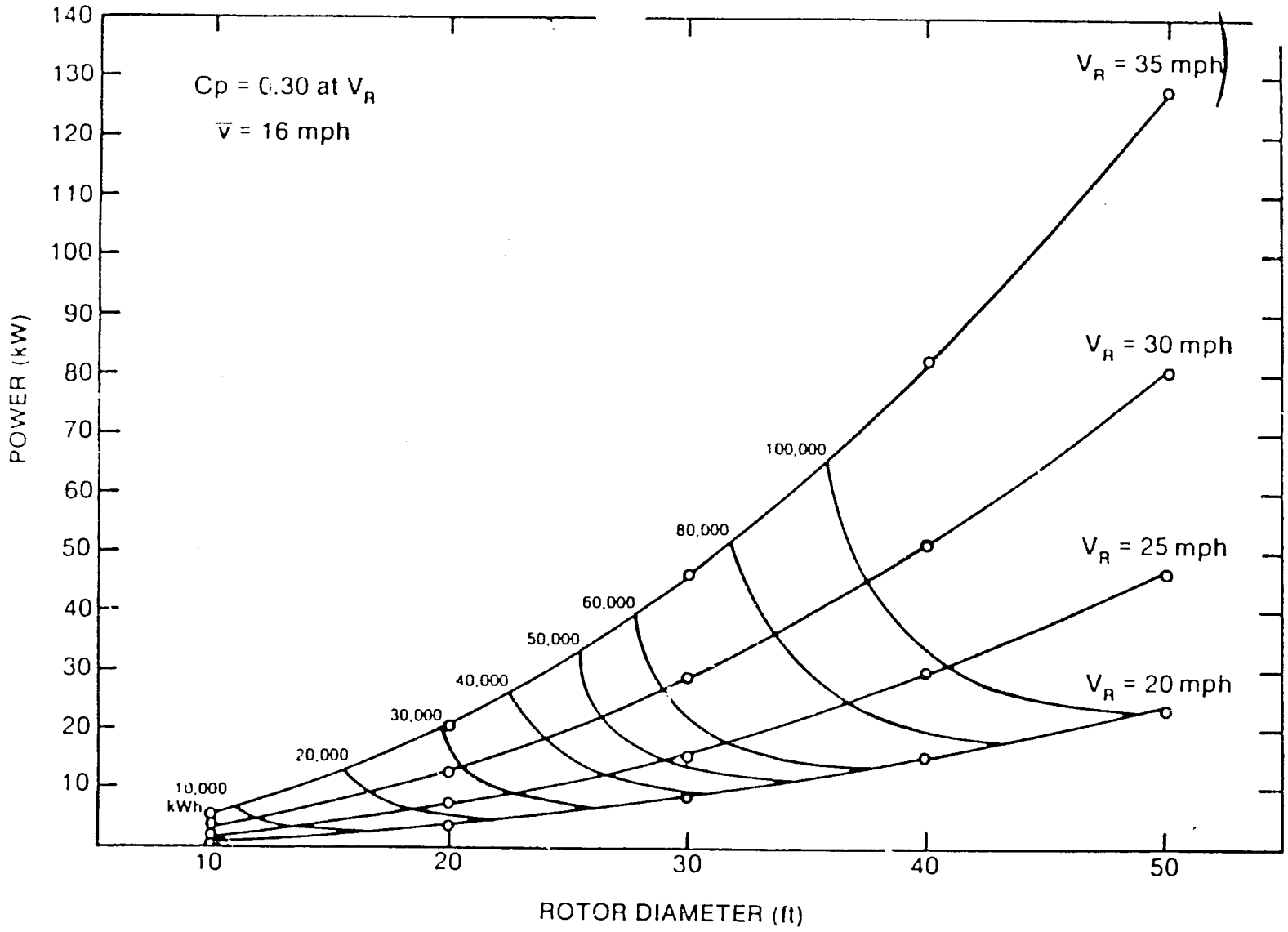
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



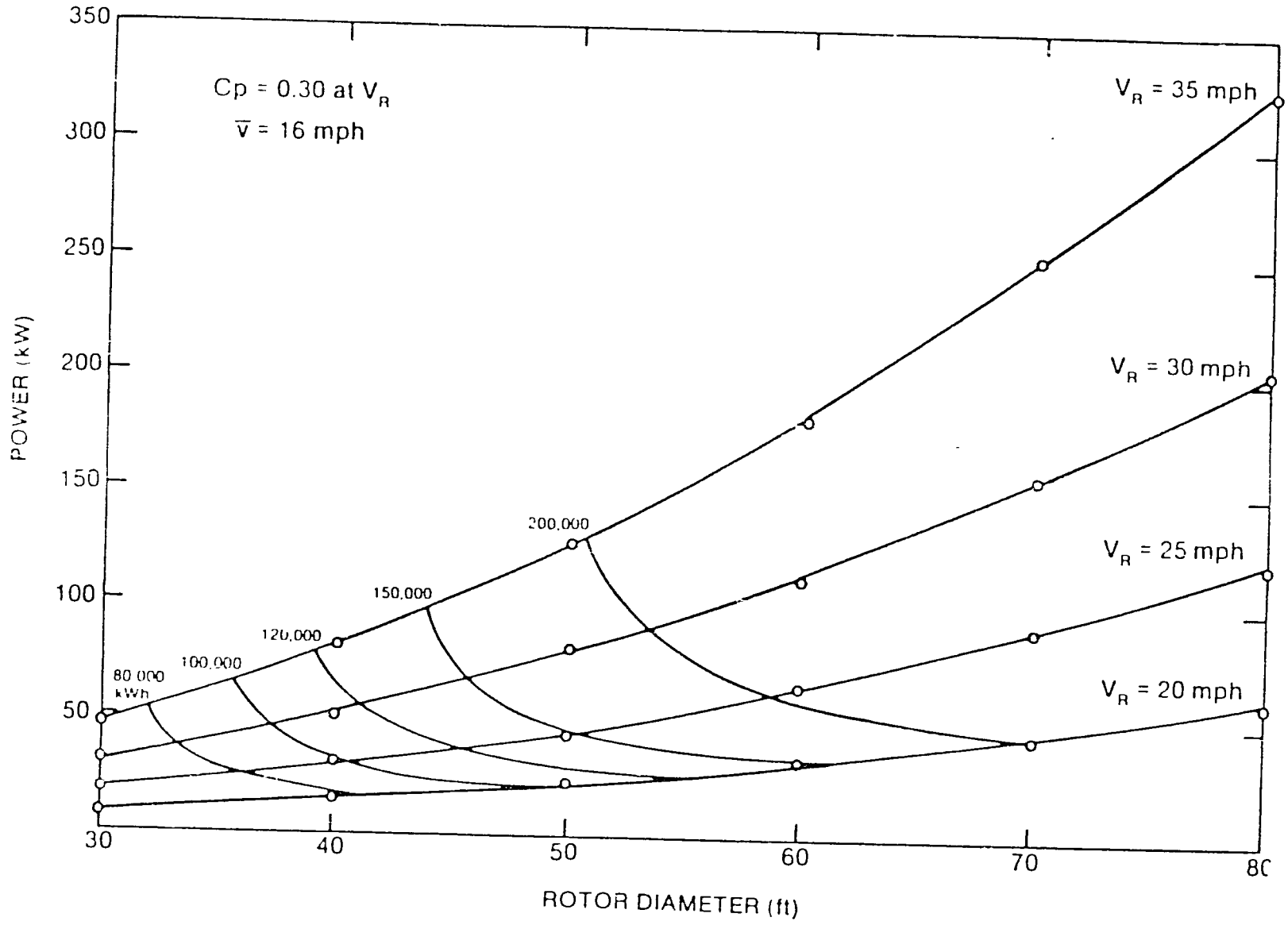
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



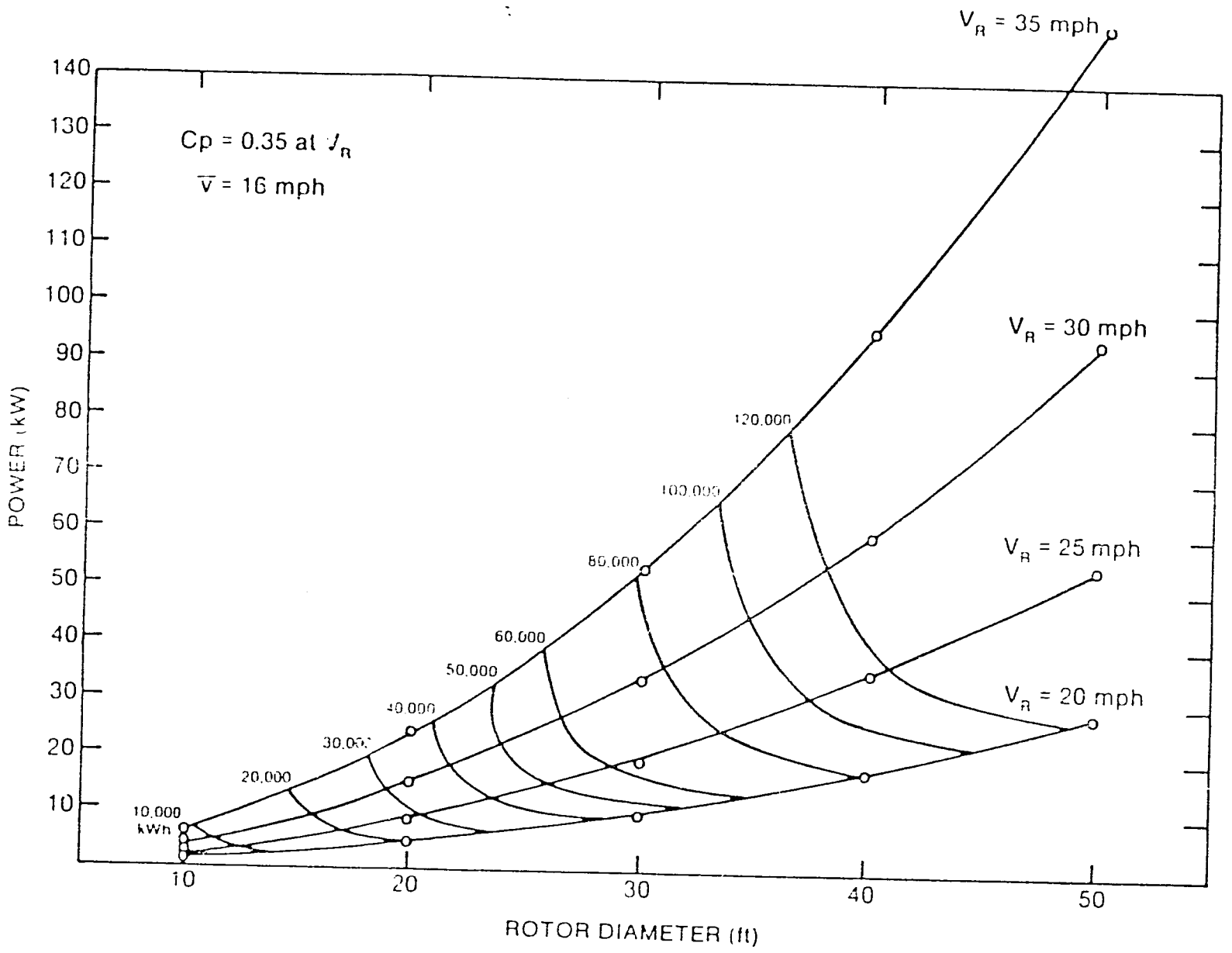
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



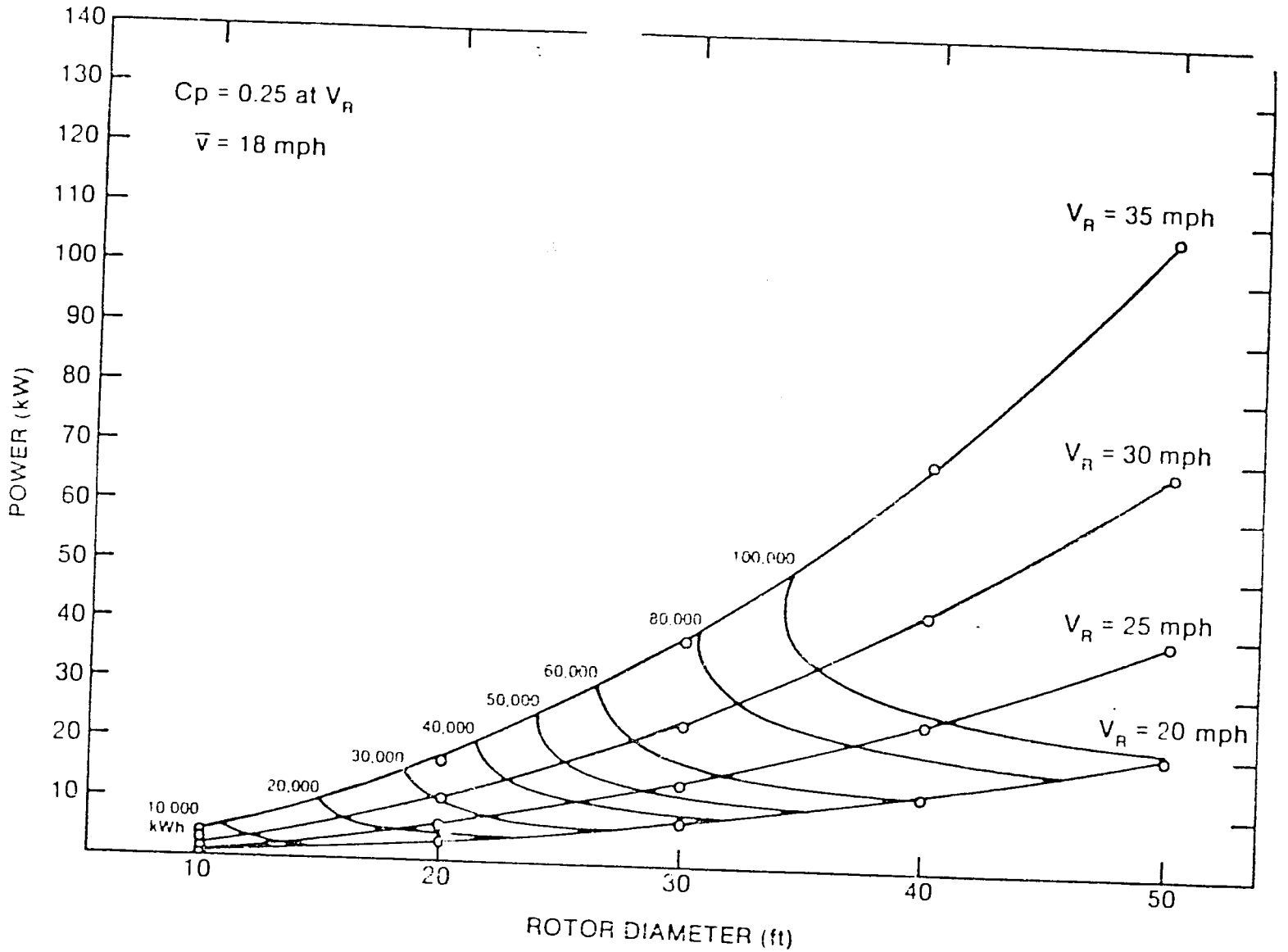
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



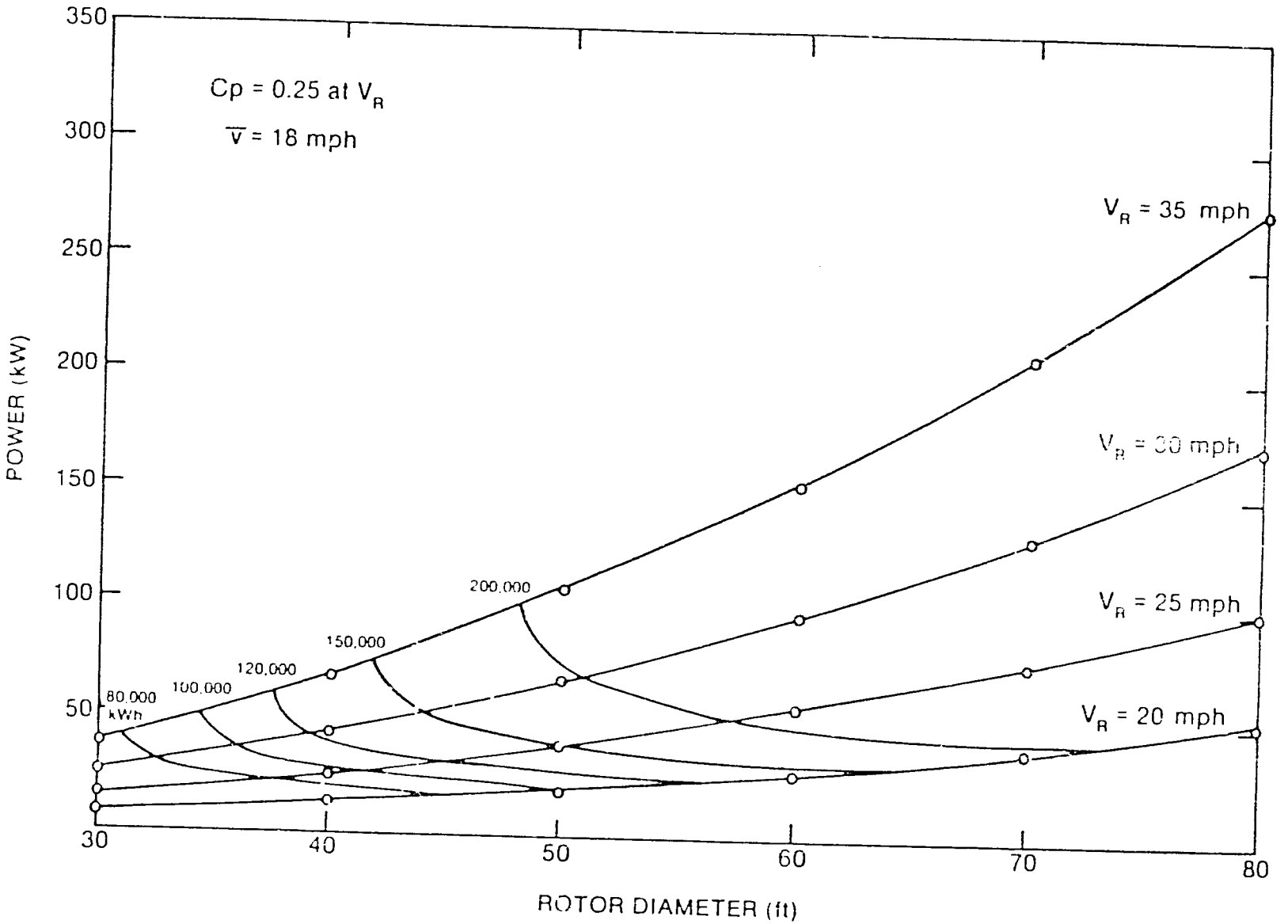
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



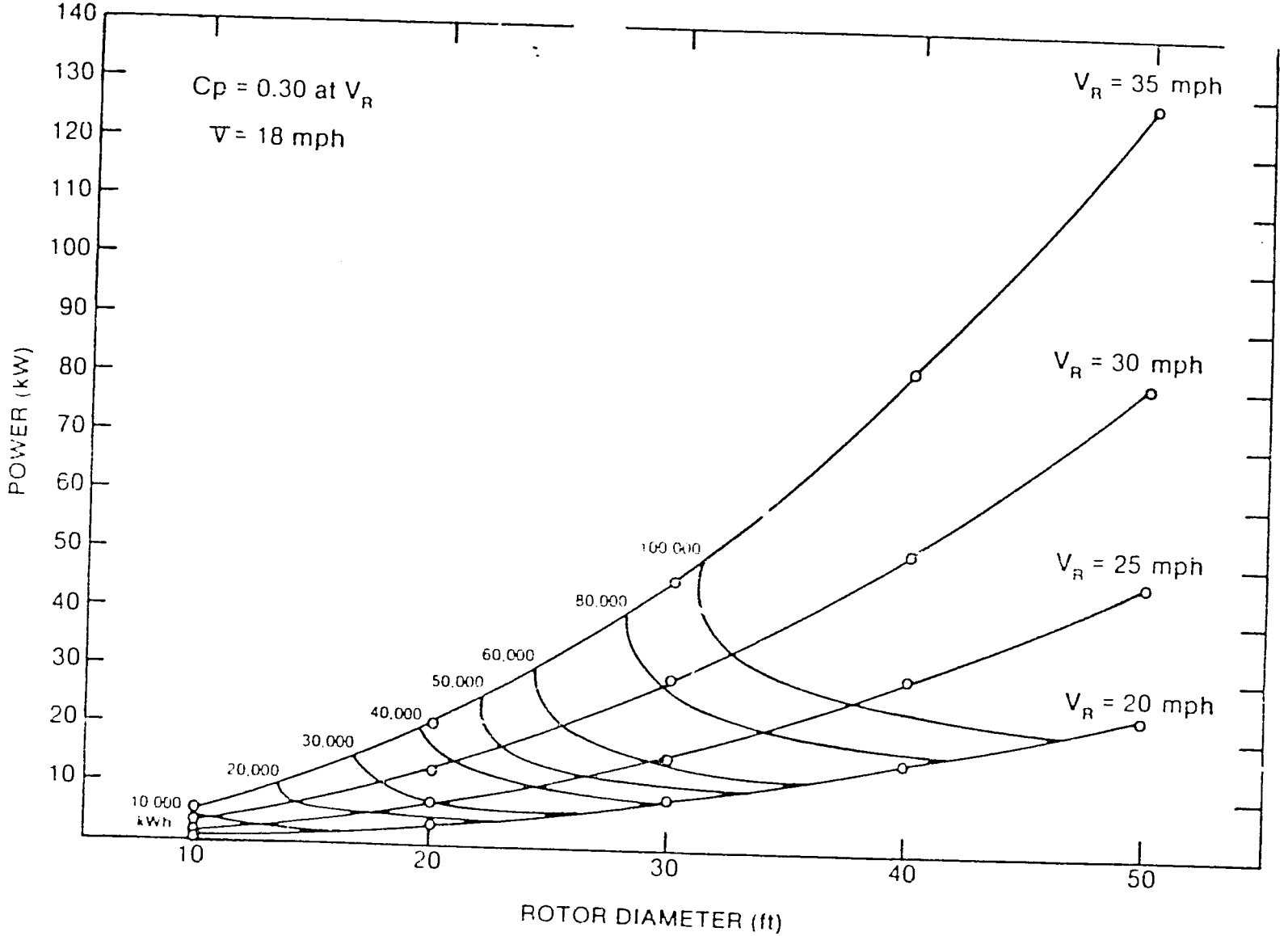
Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter

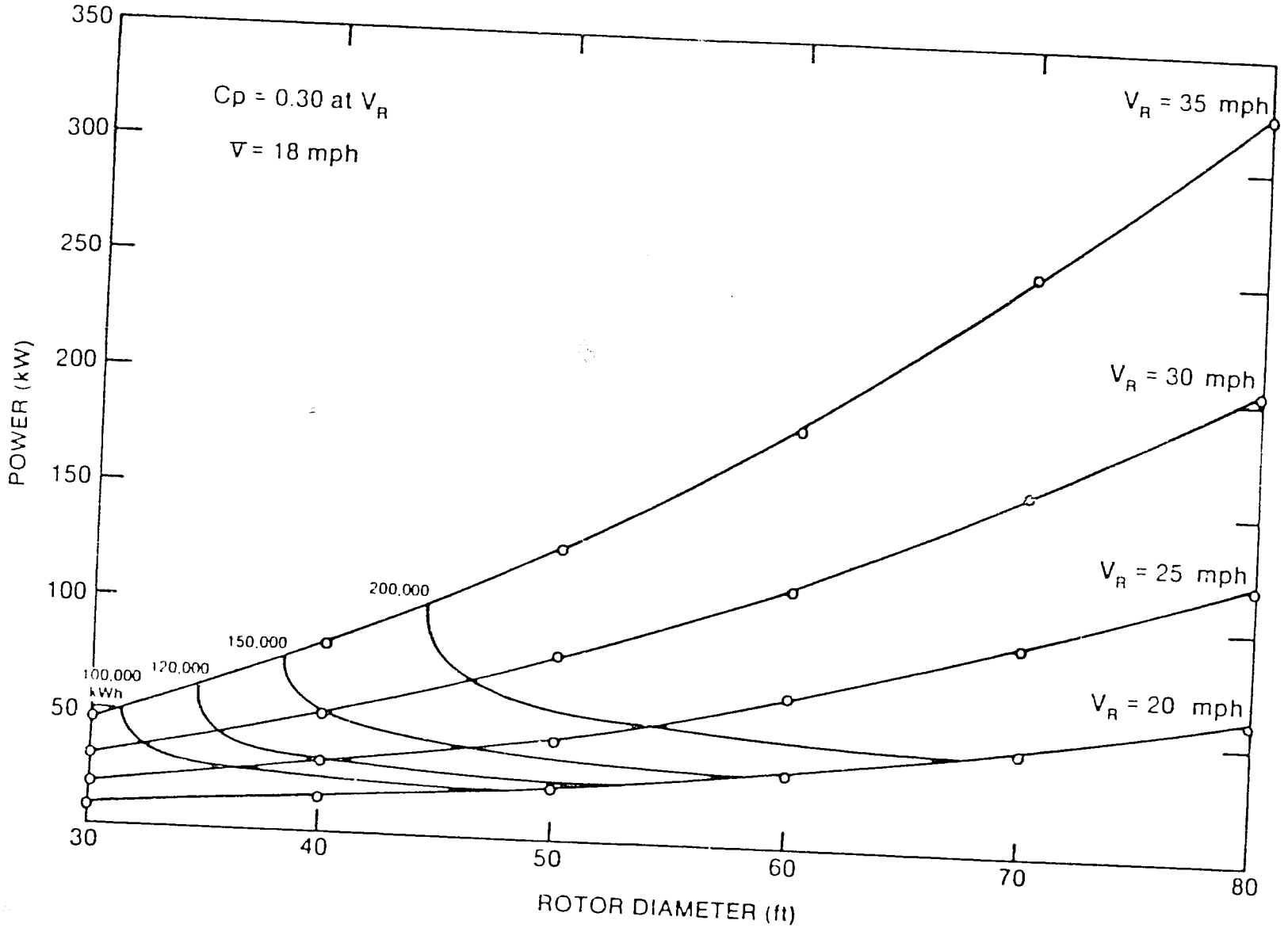
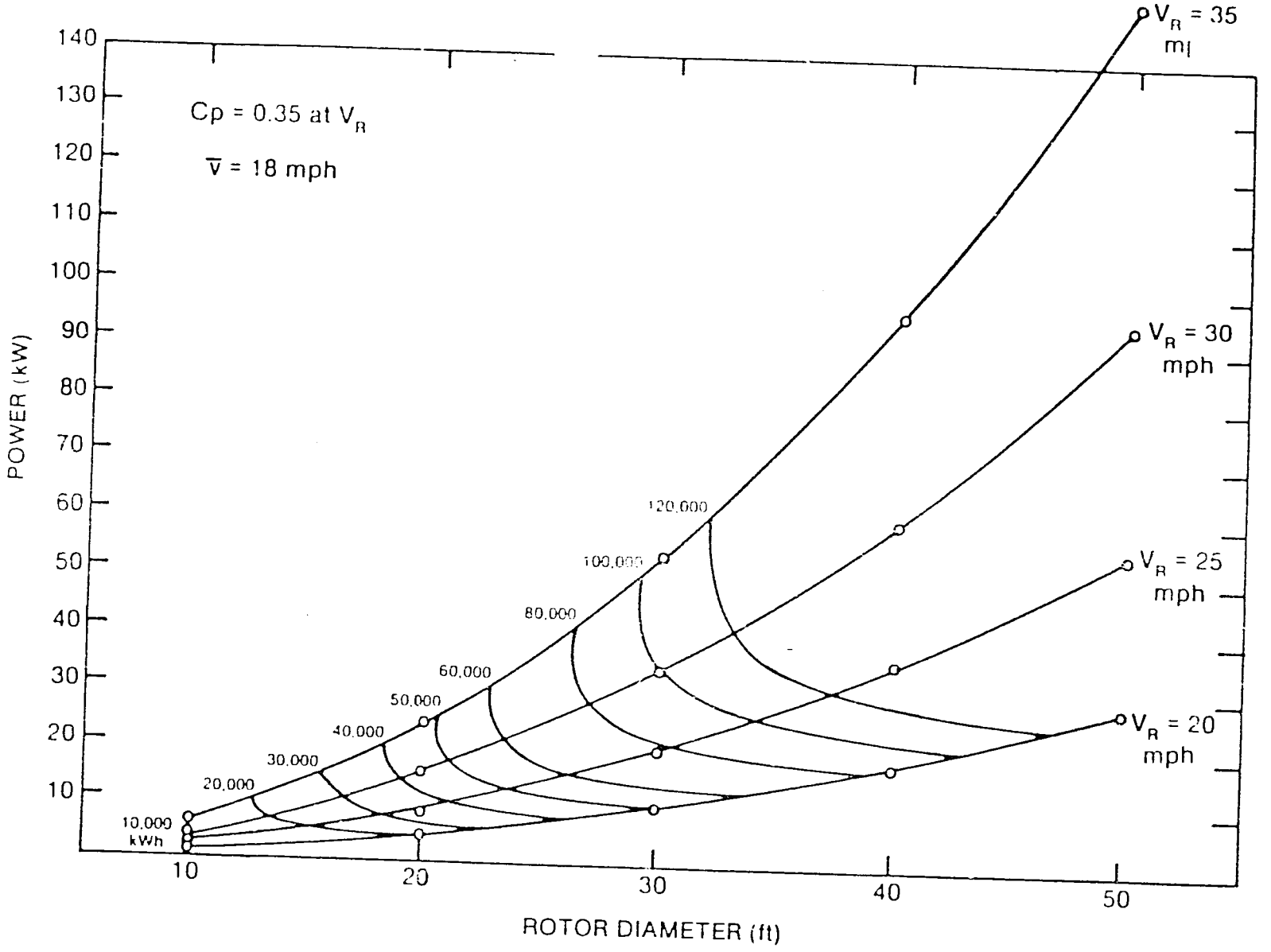
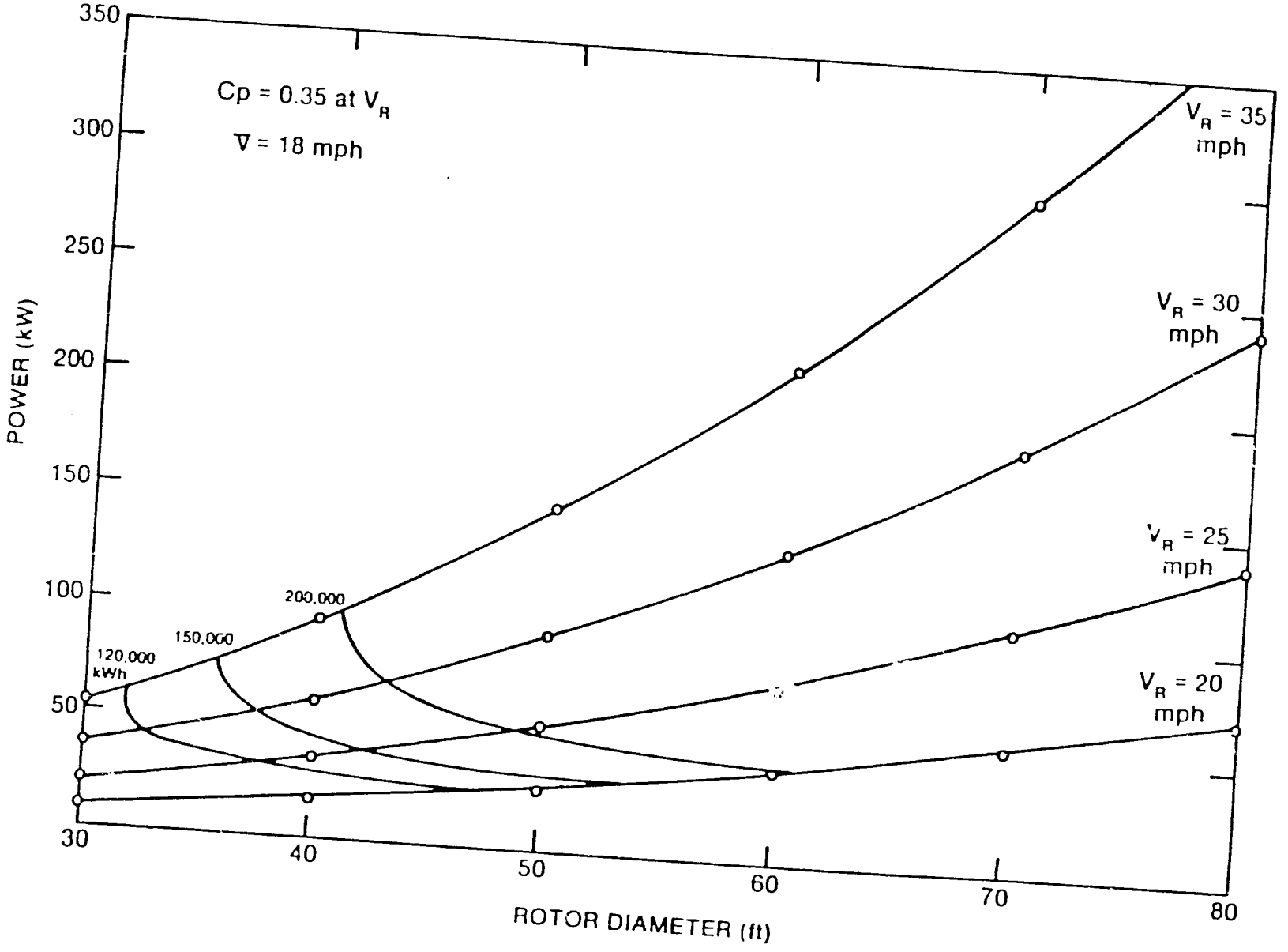


Figure A.34
Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter



Power (kW) and Energy (kWh) vs. 10-50 ft. Rotor Diameter



Power (kW) and Energy (kWh) vs. 30-80 ft. Rotor Diameter

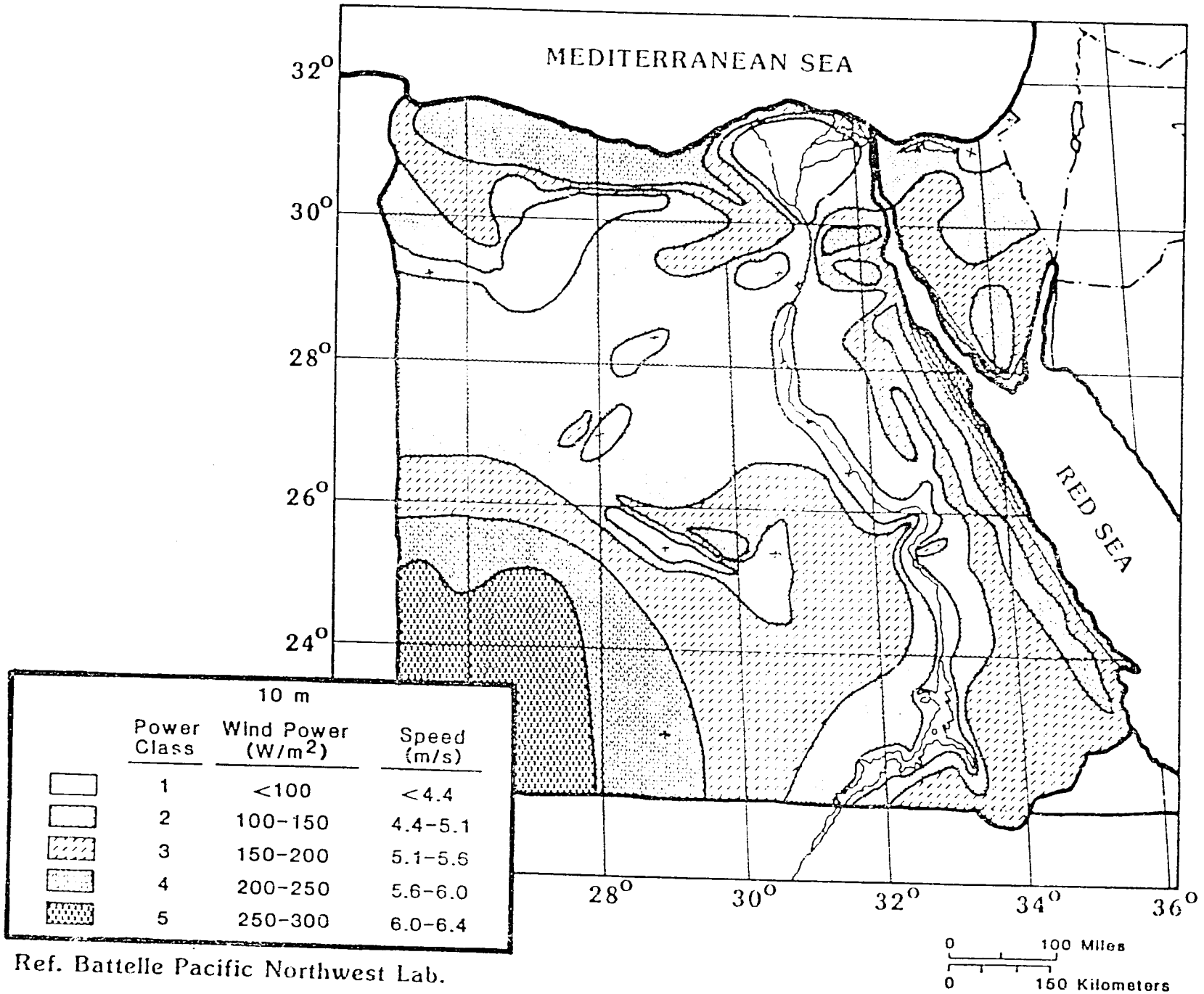
APPENDIX H

WIND RESOURCE DATA FOR EGYPT

(Excerpt From: Joint Egypt/United States Report on Egypt/United States Cooperative Energy Assessment. Volume 4, Annexes 6-10, U.S. Department of Energy Report DOE/IA-0002/04, April, 1979.

This appendix contains data on wind energy resources in Egypt. The first figure, the Wind Power Density Map, presents an overview of the average wind power and mean wind speeds throughout Egypt. This is followed by charts and curves from the referenced report.

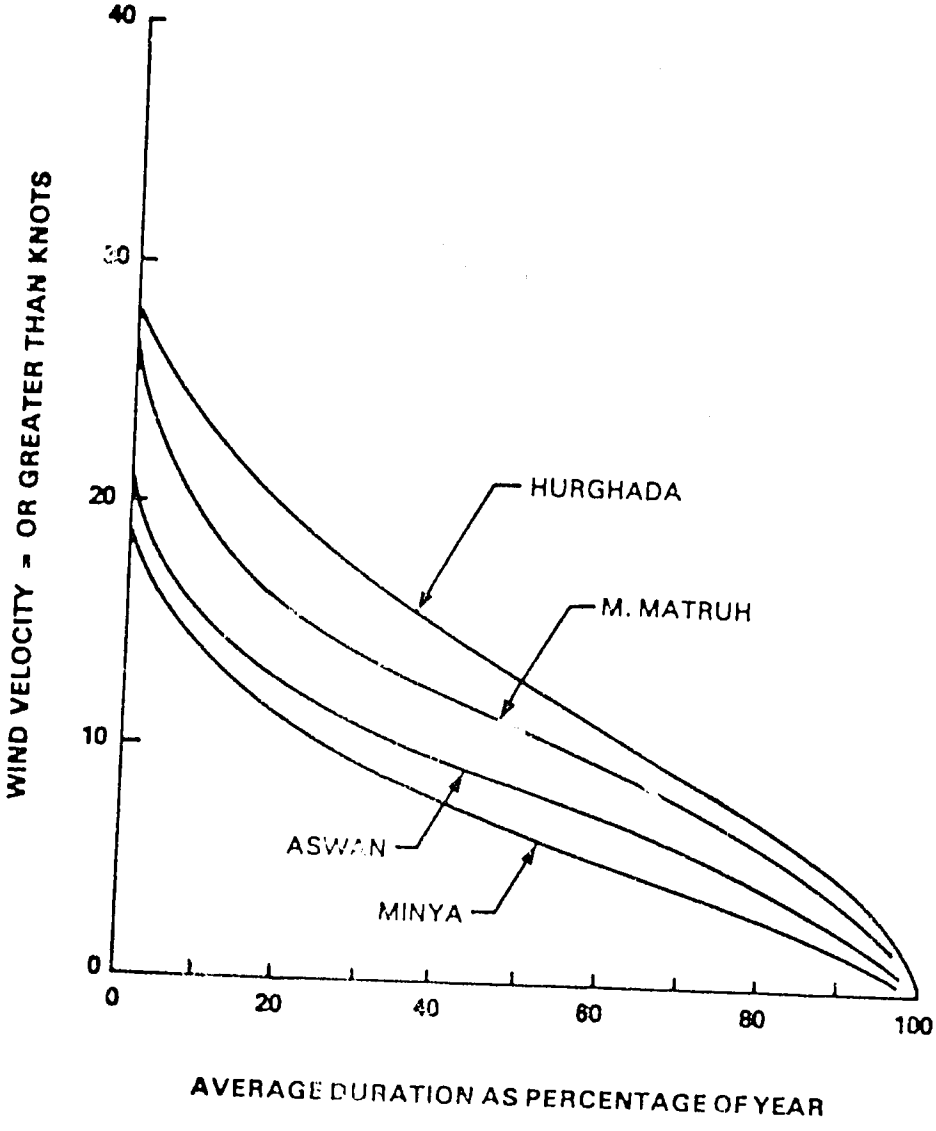
CLASSES OF WIND POWER DENSITY IN EGYPT



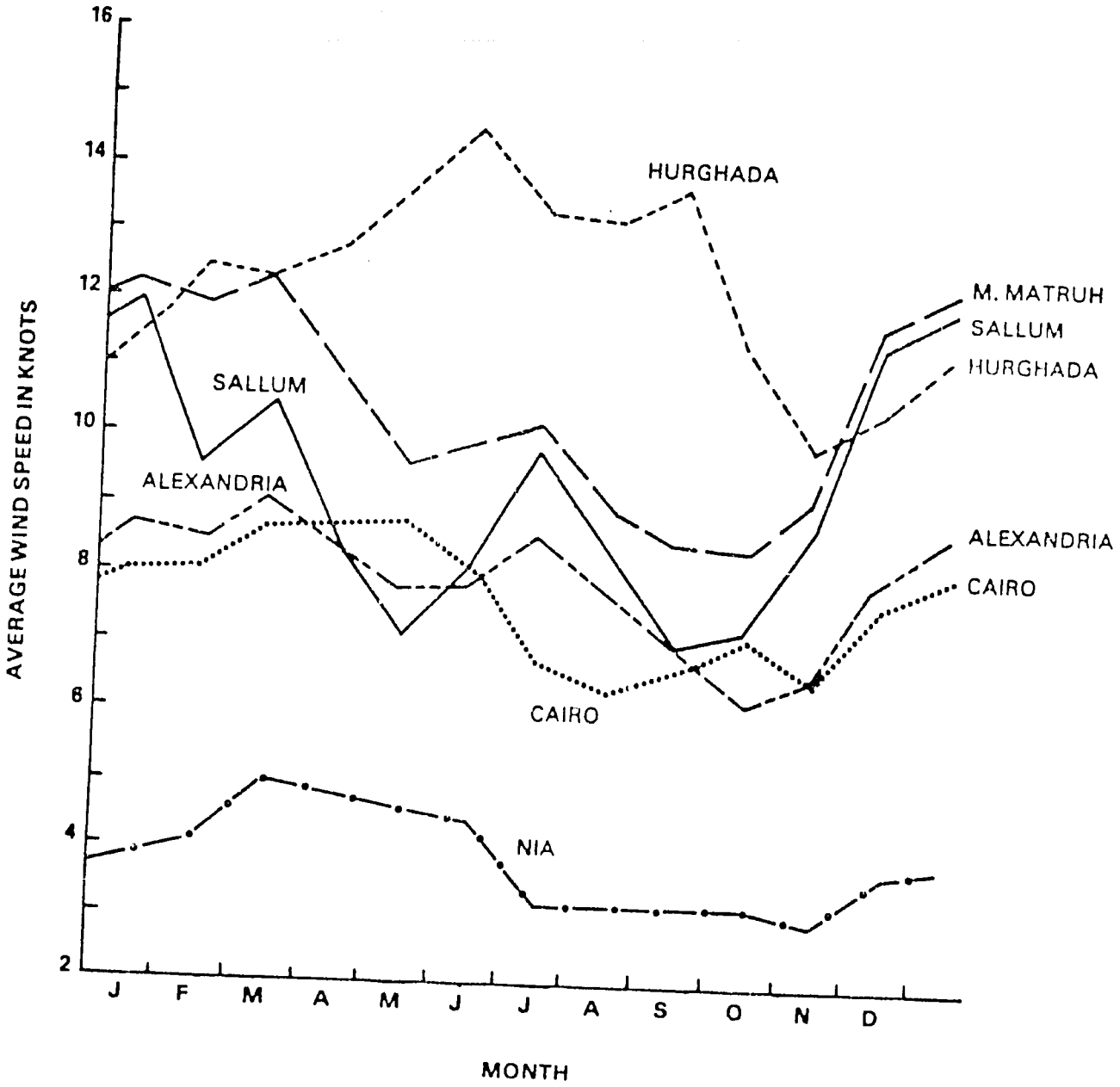
Ref. Battelle Pacific Northwest Lab.

MONTHLY AND AVERAGE WINDS (KNOTS) AT SELECTED STATIONS FROM 1952-1970

STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVERAGE
Sallum	12.0	9.5	10.5	8.4	7.1	8.0	9.8	8.5	7.0	7.2	8.7	11.4	9.0
Sidi Barrani	11.0	10.8	11.5	10.6	9.1	8.6	9.9	8.5	7.2	7.8	8.8	11.0	9.6
Mersa Matruh	12.2	11.9	12.3	11.0	9.6	9.9	10.2	9.0	8.5	8.4	9.2	11.8	11.2
Dabaa	11.0	11.2	12.4	11.3	9.9	11.6	12.1	10.6	9.0	7.8	8.4	10.6	10.5
Alexandria	8.7	8.5	9.1	8.4	9.8	7.9	8.6	7.8	7.0	6.2	6.5	8.0	7.9
Rosetta	5.8	5.3	6.4	5.6	4.9	5.3	5.9	4.6	4.1	3.9	4.2	5.0	5.1
Damietta	6.2	6.1	8.4	7.5	6.8	6.4	5.6	4.9	4.1	5.0	4.6	5.4	5.9
Port Said	9.5	10.3	11.6	10.7	9.6	9.0	8.6	7.6	7.5	8.0	8.5	8.4	9.1
Duanhour	4.7	4.1	5.4	5.1	5.0	4.7	4.0	3.7	3.5	3.7	4.0	4.5	4.4
Tahrir	6.0	6.0	7.1	6.3	5.9	5.5	5.0	4.3	4.0	3.8	4.1	5.0	5.3
Tanta	3.8	4.1	5.0	4.8	4.6	4.4	3.2	3.2	3.2	3.2	3.0	3.6	3.8
Cairo	8.0	8.1	8.7	8.7	8.8	8.1	6.7	6.4	6.6	7.1	6.5	7.6	7.6
Abbassiya	4.0	4.3	4.9	4.9	4.5	4.1	3.5	3.5	4.0	3.9	3.5	3.7	4.1
Helwan	5.6	7.1	8.6	9.5	9.3	9.8	8.5	8.0	8.5	8.5	7.9	6.2	8.1
Fayoum	3.5	4.0	5.0	4.7	5.4	5.5	5.1	4.9	5.1	4.3	4.4	3.6	4.6
Minya	4.8	5.8	6.5	7.6	8.4	9.0	7.7	6.4	7.2	6.2	5.6	4.4	6.6
Asyout	6.6	7.1	8.2	8.0	7.9	7.5	7.0	6.4	8.2	7.2	6.6	6.0	7.2
Luxor	3.5	4.0	4.8	5.1	4.6	4.3	4.0	3.7	3.3	3.0	3.3	3.5	3.9
Aswan	7.5	8.0	8.8	9.2	8.6	9.0	8.1	8.0	8.3	8.1	8.0	7.5	8.3
Siwa	5.8	6.5	7.8	7.8	7.0	6.5	6.0	5.4	4.6	4.2	4.0	5.2	5.9
Dakhla	3.6	4.4	4.9	5.0	5.9	6.3	5.4	4.8	5.4	4.8	4.1	3.2	4.8
Kharga	6.2	7.7	8.4	8.6	9.6	11.5	9.1	8.3	9.4	9.2	7.4	6.0	8.4
Hurghada	11.4	12.5	12.3	12.7	13.6	14.5	13.3	13.2	13.6	11.3	9.9	10.5	12.4
Quseir	9.4	9.2	9.4	8.8	9.6	9.8	7.7	7.6	9.0	8.7	9.4	9.4	9.0



Velocity duration curve

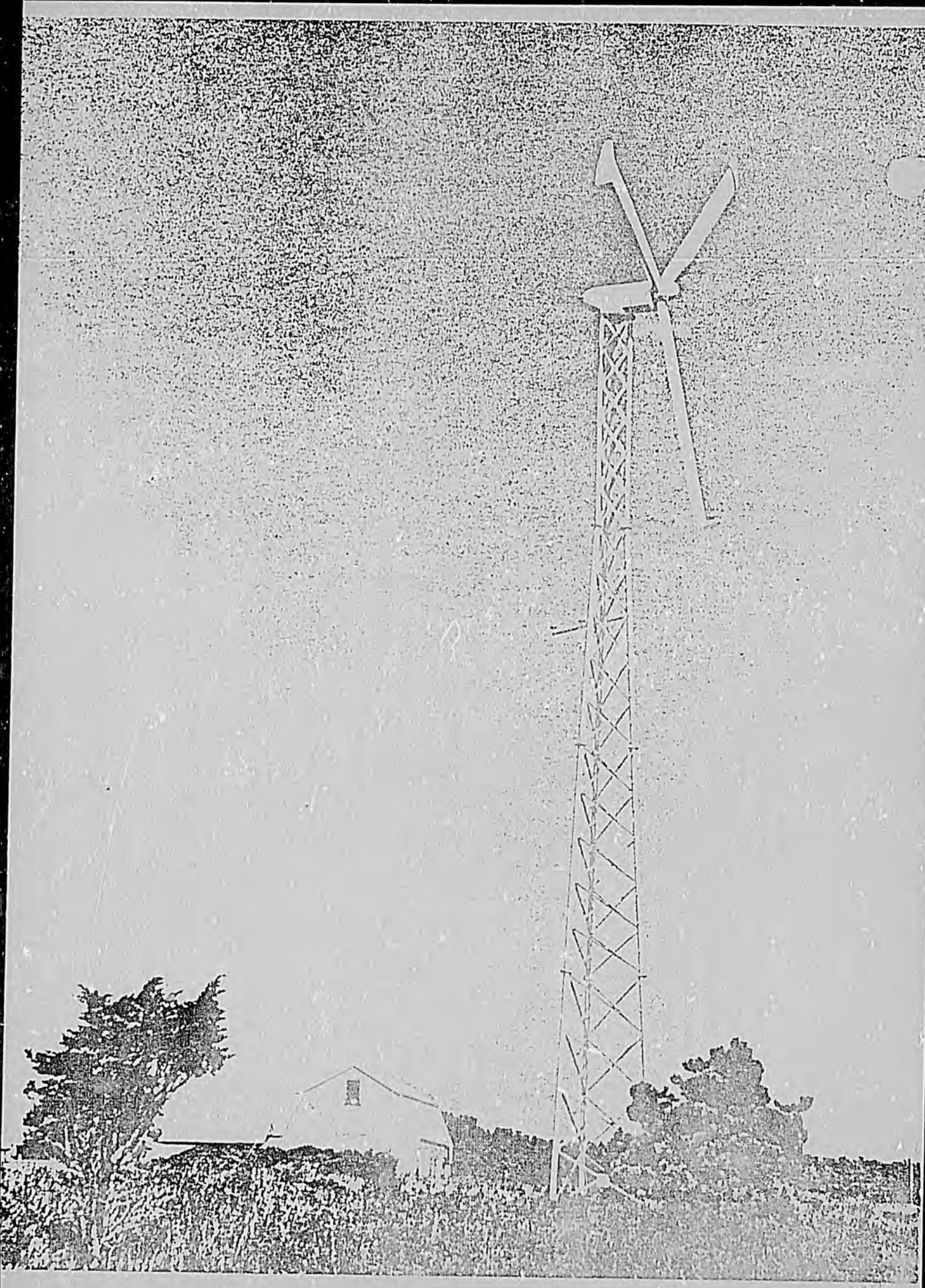


Average monthly wind speeds for some localities

APPENDIX I

WIND PROJECTS SITE VISIT BOOK

THIS APPENDIX CONTAINS SUMMARIES AND PHOTOGRAPHS OF A VARIETY OF WIND SYSTEMS THAT ARE OPERATING TODAY. THEY ARE REPRESENTATIVE OF THE RANGE OF APPLICATIONS THAT ARE BEING POWERED BY WIND SYSTEMS THROUGHOUT THE WORLD.



PROJECT INFORMATION

TECHNOLOGY AREA: Wind Energy

PROJECT TITLE: USDA Agriculture Research Service

LOCATION: Bushland, Texas

OBJECTIVE: Supply electrical energy for irrigation pumping and other agricultural purposes.

SYSTEM: Grid connected wind turbine with 25 kW induction generator providing 240 V, 60 hz, single-phase electrical power.

DESCRIPTION:

A wind turbine was installed on May 26, 1982 at the U.S. Department of Agriculture Conservation and Production Research Laboratory in Bushland, Texas. The objective of the project was to supply electrical energy to meet the laboratory's irrigation needs. The installed system was designed to provide high power production in low to moderate wind areas. During a 16 month period from July 1982 through October 1983, the system operated over 7,700 hr and produced over 80,000 kWh of energy in an average windspeed of [illegible] m/sec. It operated 64 percent of the time, with an availability of 9[illegible] percent. From April 1, 1985 to June 20, 1985, the wind-powered pumping system produced 596,200 cubic meters of water. The wind turbine meets 90 percent of the facility's irrigation needs, except during the month of August when the irrigation demand is the highest.

PROJECT CONTACT:

R. Noland Clark
Agriculture Engineer
USDA Agriculture Research Center
Conservation and Production
Research Laboratory
P.O. Drawer 10
Bushland, TX 79012
(806) 378-5752

PROJECT INFORMATION

TECHNOLOGY AREA: Wind Energy

PROJECT TITLE: Rodrigues Island Village Water Supply

LOCATION: Anse Quitor, Rodrigues Island, Mauritius

OBJECTIVE: Supply water to the village of Anse Quitor and provide electrical power to 20 neighborhood homes.

SYSTEM: 2 kW wind turbine and a 2.25 kW DC motor coupled to a pump and 19 kWh of battery storage.

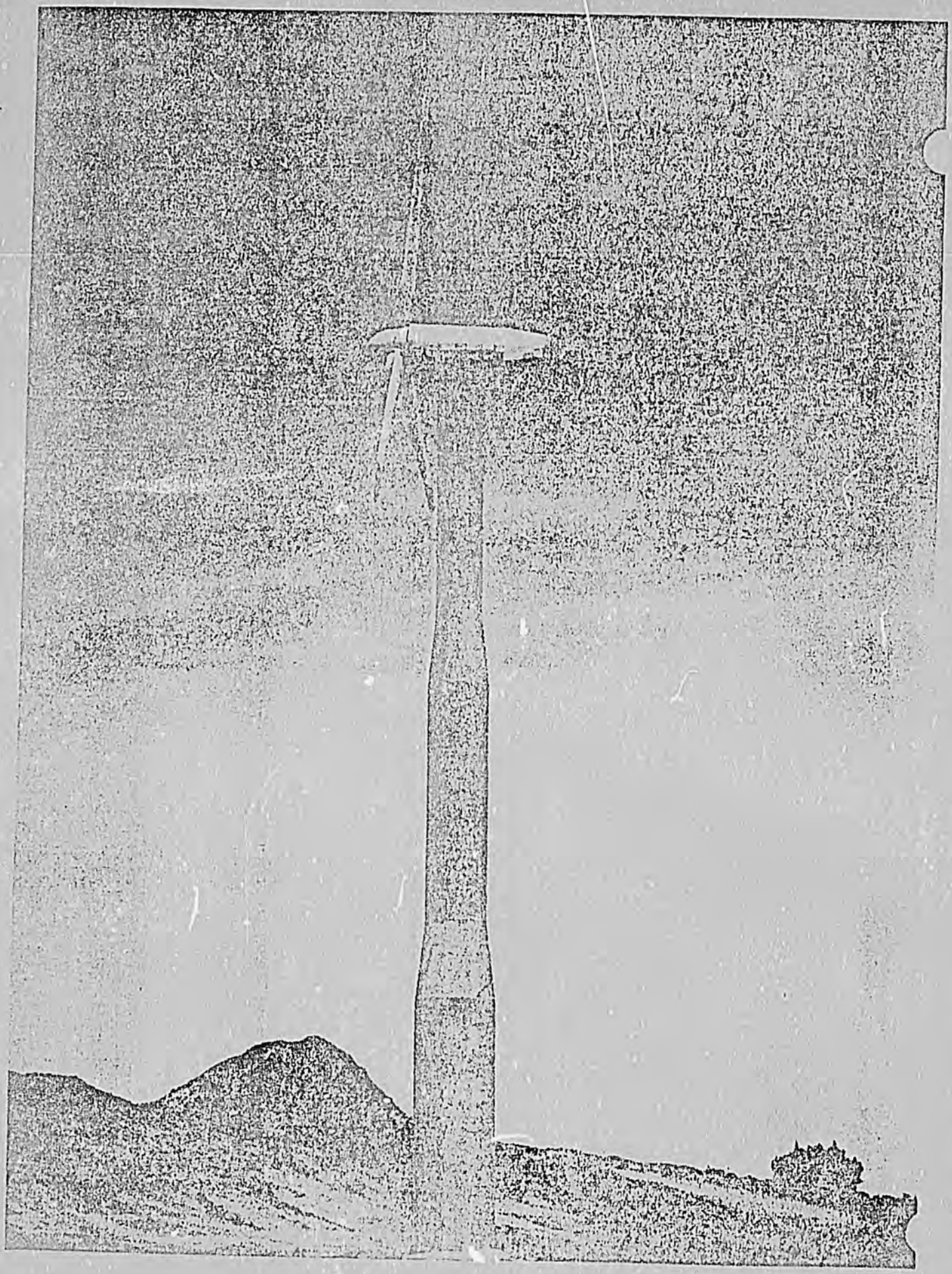
DESCRIPTION:

In 1983, the United Nations financed a wind powered pumping system for the village of Anse Quitor, located in the southwest of Rodrigues Island. Since its installation in early 1983, the system has been maintained and closely monitored by the Central Electricity Board under the supervision of the UN resident officer. The total pumping system output from the date of commissioning until the end of April 1984 (the only period for which data is currently available) was approximately 1.7 million gallons of water pumped over a period of 1,788 hours of operation.

It is estimated that on the basis of the favorable wind regime at Anse Quitor that the average daily electric generation of the 2 kW wind turbine is approximately 27 kWh. The average daily pump requirement is on the order of 16.5 kWh. This provides an average daily surplus of about 10.5 kWh which is used to supply electrical power to approximately 20 houses in the neighborhood of the pumping station.

PROJECT CONTACT:

Derek Lovejoy
United Nations
Department of Technical
Cooperation for Development
New York, New York
(212) 754-8597



PROJECT INFORMATION

TECHNOLOGY AREA: Wind Energy

PROJECT TITLE: Bagenkop Cooperative

LOCATION: Bagenkop near Langeland, in southeast Denmark

OBJECTIVE: Supply electricity to a 23 family cooperative

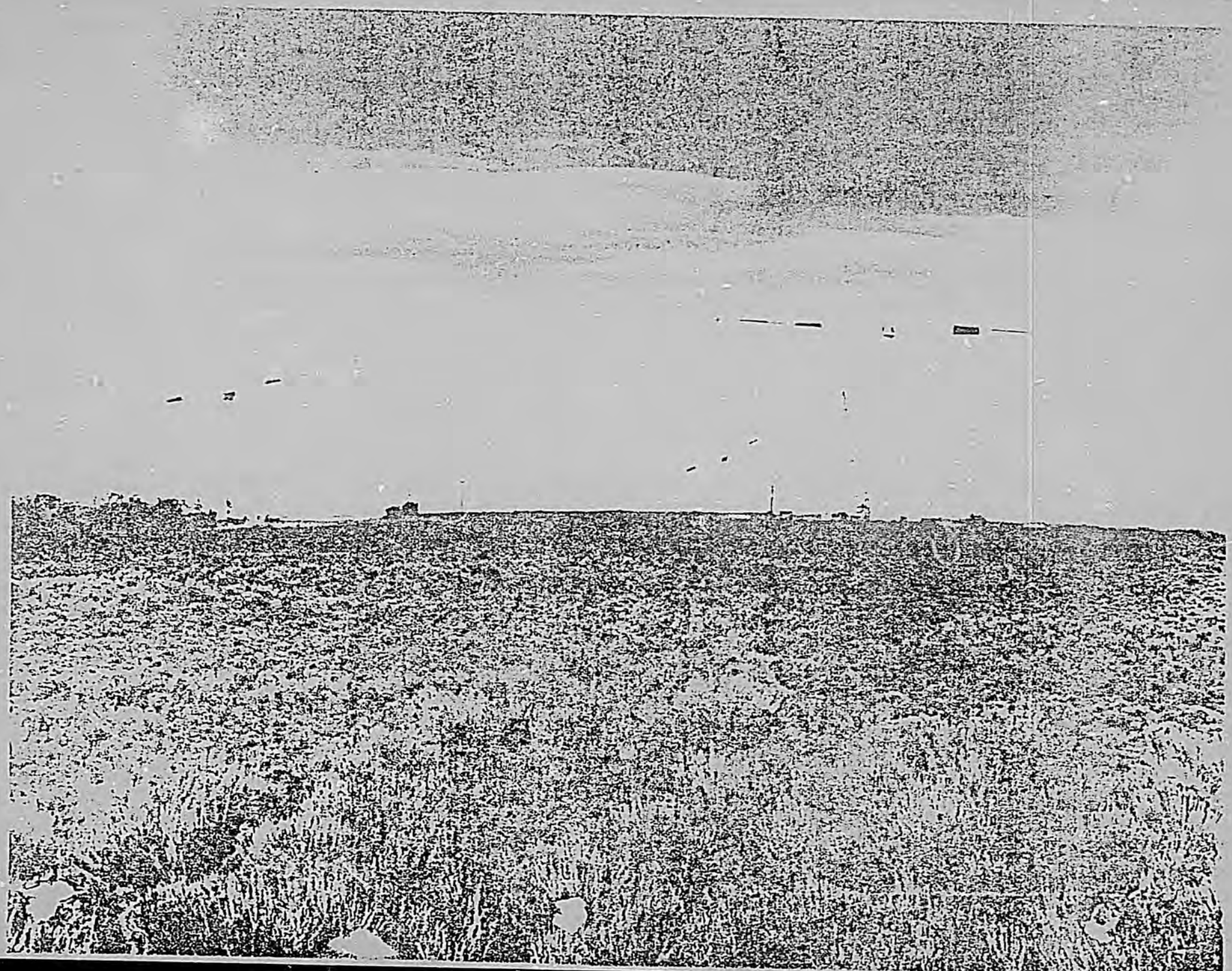
SYSTEM: 55 kW electrical wind turbine system

DESCRIPTION:

On January 23, 1983, the Bagenkop Cooperative, a wind turbine partnership of 23 families, erected a 55 kW wind turbine system to supply the electricity needs of the cooperative. Regardless of weather conditions, the wind turbine has continued to operate without problems. Bagenkop has experienced winds with gale force over 30 m/sec but these do not interrupt the turbine's operation. The power production of the turbine from January 12, 1983 to January 12, 1984 was 201,370 kWh with an availability of 86.7 percent. This breaks down to an average hourly output of 26.2 hr.

PROJECT CONTACT:

Hans Ivan Didrikson
Kloveraenget 18
5935 Bagenkop
Denmark



PROJECT INFORMATION

TECHNOLOGY AREA: Wind Energy Systems

PROJECT TITLE: Mod-2, Large Wind Systems

LOCATION: Goodnoe Hills, Washington (212 miles from Seattle, or 110 miles from Portland, OR overlooking the Columbia River)

OBJECTIVE: Supply electrical power for public utility company.

SYSTEM: Horizontal axis wind machine generating 2.5 MW of electricity.

DESCRIPTION:

The Mod-2 is the world's first large wind turbine cluster of three experimental machines, each with two blades having an overall diameter of 300 ft. The cluster is providing power to the northwest power grid served by the Bonneville Power Administration. The Mod-2 is a horizontal axis machine and is designed to generate 2.5 MW of electricity in a 27.5 mph wind. It uses blade tip control instead of full blade control and has a teetering hub. The first turbine was rotated in November 1980.

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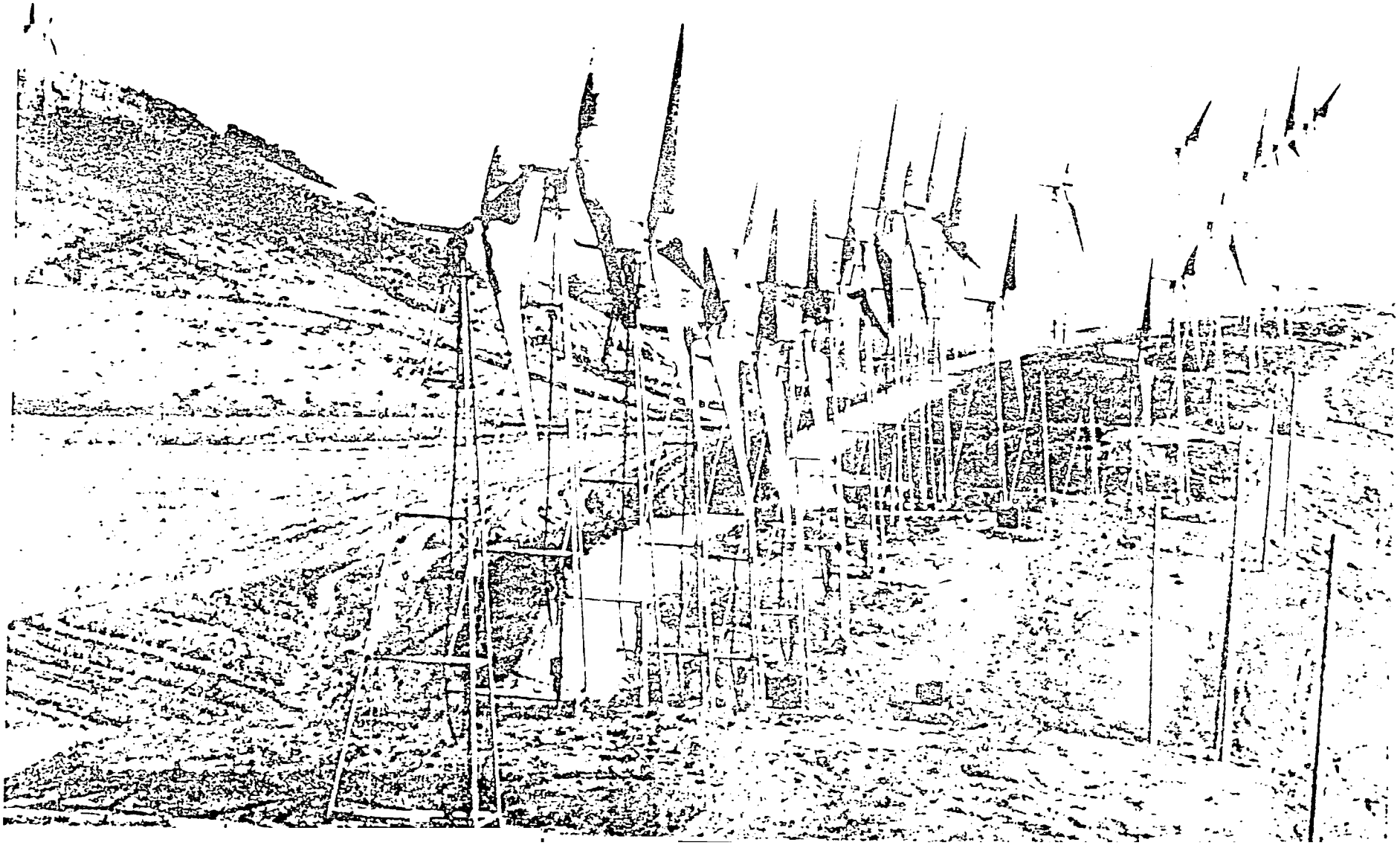

PROJECT INFORMATION

TECHNOLOGY AREA: Wind Energy Technology

PROJECT TITLE: California Wind Farms

LOCATION: Solano County, California (30 miles northeast of San Francisco)

OBJECTIVE: Supply electrical power for public utilities.

SYSTEM: N/A

DESCRIPTION:

The development of wind farms in the U.S. has grown significantly in the past few years as a result of research and development activities, rising fuel costs, and the establishment of federal and state investment and renewable tax credits. By the end of 1983, thousands of wind turbines had been installed at wind farm projects, a significant increase over 1982. Typical projects in northern California include both large and small wind turbines. For example, the Pacific Gas and Electric Company has purchased a 2.5 megawatt Mod-2 wind turbine and installed it in Solano County, 30 miles northeast of San Francisco. The installation is part of a company funded R&D program to evaluate the potential of wind generated electricity in their service area. The Mod-2 was designed and built under contract to the DOE Wind Energy Program. PG&E estimates that the Mod-2 will generate approximately 10 million kilowatt-hours of electricity annually for their customers. In Altamont Pass, 30 miles east of San Francisco, about 800 50-kilowatt wind turbines have generated millions of kilowatt-hours of electricity as of mid-summer 1983. There are plans to install several hundred additional wind turbines over the next two years in projects that will generate millions of kilowatt-hours per year. The chart on the following page illustrates the installed capacity of U.S. wind farms.

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or

Mr. Jerry Alderson
U.S. Wind Power Inc.
500 Sansome - Suite 205
San Francisco, CA 94111
(415) 398-3825

SUMMARY OF U.S. WIND FARMS

(END OF 1983)

LOCATION	NO. OF UNITS	INSTALLED CAPACITY (MW)
o CALIFORNIA		
ALTAMONT PASS	2053-2087	140-158
TEHACHAPI MTS	905-1166	60-74
SAN GORGONIO	225-284	11-14
PACHECO PASS	97-119	5-6
BOULEBARD	41	1.64
SALINAS VALLEY	8	.6
EL CAJON	13	.5
MONTEREY COUNTY	4-65	.16-2.6
SO. SOLANO COUNTY	2-5	.15-.38
MOJAVE	1-10	.1-.2
TOTAL	3349-3798	219-258
o OREGON		
COOS BAY	25	1.25
o NEW YORK		
ELLENVILLE	4	.18
BUFFALO	1	.6
o HAWAII		
KAHUA RANCH	18 (180 By Early 1984)	.32 (3.15 By Early 1984)

LOCATION	NO. OF UNITS	INSTALLED CAPACITY (MW)
o NEW HAMPSHIRE		
CROTCHED MT.	20	.6
o VERMONT		
MANCHESTER	4	.8
o MONTANA		
LIVINGSTON	5	.17
ULM	5	.13
o MASSACHUSETTS		
PRINCETON	8 (By mid 1984)	.32 (By mid-1984)
o OKLAHOMA		
MAGNUM	4	.1
o ALASKA		
GAMBEL	4	.04
o RHODE ISLAND		
NANTUCKET IS.	3 (10 Planned)	.012 (.04 Planned)
o TOTAL U.S.	3450-4068	224-265

REF: Estimates are from Solar Age (Feb. 1984), Renewable Energy News (Feb. 1984), or Alternative Sources of Energy (Sept./Oct. 1983).

BIBLIOGRAPHY

A Siting Handbook for Small Wind Energy Conversion System. Pacific Northwest Laboratory, Richland, WA, Department of Energy Contract DE-AC06-76 RL01830, December 1983.

DeRenzo, D.J., editor. Wind Power - Recent Developments. New Jersey: Noyes Data Corporation, 1979.

Eldridge, Frank R. Wind Machines. New York: Van Nostrand Reinhold Company, 1980.

Gordon, Larry H., Andrews, John S. and Zimmerman, Donald K. Mod-2 Wind Turbine Development. Department of Energy Report DOE/NASA/20305-9, June, 1983.

Hiester, T.R. Wind Turbine Siting: A Summary of the State of the Art. Pacific Northwest Laboratory, Richland, WA, Department of Energy Contract DE-AC06-76RLO 1830, August 1981.

Inglis, D.R. Wind Power and Other Energy Options. Ann Arbor, MI: The University of Michigan Press, 1978.

Koeppl, Gerald W. Putnam's Power from the Wind. New York: Van Nostrand Reinhold Company, 1982.

Le Gourieres, D. Wind Power Plants - Theory and Design. New York: Permagon Press, 1982.

Linscott, Bradford S., Perkins, Porter and Dennett, Joann T. Large, Horizontal-Axis Wind Turbines. Department of Energy Report DOE/NASA/20320-58, March, 1984.

Methodology for Determining the Value of Wind Energy Conversion Systems for Specific Utility Systems. JBF Scientific Corp, Department of Energy Contract EG-77-C-01-4042, September, 1981.

Moment, R.L. Performance and Size Estimating for Wind Systems. Rockwell International Corp., Golden, CO, Department of Energy Contract DE-AC04-76DP03533, February, 1983.

Park, Jack. The Wind Power Book. California: Cheshire Books, 1981.

Park, Jack and Schwind, Dick. Wind Power for Farms, Homes, and Small Industry. Nielsen Engineering and Research, Inc., Mountain View, CA, Department of Energy Contract E(04-3)-1270, September, 1978.

Paul, Terrance D. How to Design an Independent Power System. Necedak, WI: Best Energy Systems for Tomorrow, Inc., 1981.

Prospects for Foreign Applications of Wind Energy Systems - Preliminary Report. Department of Energy Report DOE/NBM-1005, November, 1981.

Seale, Joseph B. Matching Wind Turbine Rotors and Loads. The New Alchemy Institute, East Falmouth, MA, Department of Energy Contract DE-AC04-76DP03533, April, 1983.

Vosburgh, Paul N. Commercial Applications of Wind Power. New York: Van Nostrand Reinhold Company, Inc., 1983.

Wind Technology Assessment Study. Intermediate Technology Power Ltd, Reading, Berks. RG7 3PG, UK, World Bank Project GLO/80/003, February, 1983.