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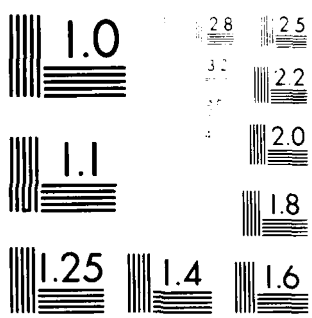

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This report presents general information covering site wind potential and characteristics, specific design, system design, and siting requirements for utilization of wind energy conversion systems (WECS) at Navy installations. The objective of this report is also to provide a method for performing economic analysis to plan and justify a WECS in a particular Navy application. The information presented here is sufficient to enable an engineer

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CONTENTS

Chapter 1

INTRODUCTION

1.1 SCOPE

This report presents general information covering site wind potential and characteristics, specific design, system design, and siting requirements for utilization of wind energy conversion systems (WECS) at Navy installations. The objective of this report is also to provide a method for performing economic analysis to plan and justify a WECS in a particular Navy application. The information presented here is considered to be sufficient to enable an engineer to prepare a system's design, or to conduct a feasibility study for a given application of WECS.

Most Navy applications of wind power will involve generation of electricity using small wind turbine generators (less than 60 kW size), with or without storage, located at remote Navy sites. Larger (over 100 kW size) WECS will, generally, be integrated with a base grid located on remote overseas or CONUS bases. This report, however, deals only with guidance for applying small WECS at Navy installations. The subject matter is divided into five parts dealing respectively with wind behavior and its determination with wind-driven turbines, power conditioning requirements, siting requirements, and the economics of wind power under different conditions. Three examples are given to demonstrate use of these sections in developing the required feasibility or design information for a given application.

1.2 BACKGROUND

WECS have been used since the early Chinese and Persian civilizations in the form of water-pumping windmills and wind-propelled ships (Ref 1.1). During the centuries, the windmill was improved slowly; greatest improvements in size, power output, and efficiency occurred from the late 1800s through the 1950s as capabilities in aerodynamics, electrical power generation, and structural design gradually increased.

During that period, such countries as Germany, England, France, Denmark, Russia, and the United States (Ref 1.2,1.3,1.4) showed great interest in developing large-scale wind turbine generators. Many WECS were built and successfully operated, but none were cost competitive with the energy supplied by coal- and oil-fired steam plants and hydroelectric stations. Apparently no sustained effort was made to develop wind turbine generators that were cost effective.

The oil embargo of 1973 created a new energy scenario, however, and wind turbines were reconsidered. Subsequent interest in renewable energy sources has shown that WECS have the promise of providing a significant portion of the United States' electrical energy supply in a cost-effective manner.

The Navy recognized the potential of wind power in 1974 when the Civil Engineering Laboratory (CEL), Port Hueneme, Calif., implemented a monitoring and evaluation program to reduce nonrenewable energy consumption within the Naval Shore Establishment (Ref 1.5 and 1.6). This policy was in keeping with a Navy instruction (OPNAVINST 4100.5A) that not only stressed energy conservation and management, but also stressed energy substitutions "when economically practical, alternative, more abundant or renewable energy sources where petroleum and natural gas are now used."

The total Navy energy plan includes aircraft and ships, as well as shore facilities; but, planes and the fleet are dependent upon liquid hydrocarbon fuel for the foreseeable future. Only the shore facilities (buildings, shipyards, airfields, real estate, etc.) can take advantage of an alternative energy source such as the wind.

Through its Wind Energy Program the Navy ultimately will examine for suitability all types of WECS being developed by the Department of Energy and by private industry. The goal is to provide maximum use of wind power within the Navy wherever a life cycle basis makes it economical. Approximately 180 Navy bases in the United States, including Hawaii, Alaska, and overseas, have annual average wind speed greater than 10 mph, and these could possibly be considered as locations for wind turbines. It is estimated that if WECS were installed Navywide, energy savings would be the equivalent of 700,000 barrels of oil a year.

Navy Public Works Centers (PWCs) and Engineering Field Divisions (EFDs) must have information dealing with design, operations, and maintenance (including costs) when they consider installations of wind turbines. To effectively apply wind power, engineers must first determine the feasibility of installation. If application is favorable, appropriate designs and siting procedures must be available.

The small WECS under 100 kW size, generally, would be owned and operated by the Navy. In the case of larger systems (above 100 kW), the Navy could enter into a joint agreement with a utility company, buying power from a commercial wind system to supply energy, or it could contract with private industry to develop such an energy conversion mode on Navy-owned land. The Navy also is exploring the possibility of cooperative development with various government agencies for wind turbine systems of mutual benefit.

Numerous efforts are underway in the United States by government and industry to develop small-capacity (up to 60 kW size) wind power plants with relatively low-rated wind speeds (below 20 mph); these designs are found to be more compatible with the wind intensities generally encountered at most sites of interest (Ref 1.7 through 1.11). While wind turbine generators are currently available in limited quantities, the power conditioning methods and hardware for converting their variable output for practical usage are not fully developed. Also, extensive data on the performance and reliability of current WECS designs are unavailable because of limited experience with this equipment.

Various field demonstrations, therefore, were planned by CEL to collect operating and maintenance data on WECS of various sizes and to evaluate various power conditioning options available for utilizing variable output of wind systems. For small WECS now in pre- or limited production, present costs are $0.15 to $0.20 per kWhr over a predicted 25-year lifetime, assuming initial installed costs of $2,000 and higher per kW. With mass production, the installed costs for WECS will drop to $750 or less per kW and the WECS will generate power at around $0.04/kWhr, which is competitive with today's energy rates at Naval installations. These cost goals may be realizable by as early as 1985.

1.3 TYPICAL WECS SYSTEMS

The principal components of a typical wind energy conversion system are: (1) a turbine or a rotor, (2) a gearbox, (3) a generator, (4) a tower, and (5) a power conditioning system. Based upon the configuration of the rotational axis, there are two general types of WECS, namely, the horizontal axis or the vertical axis types as shown in Figures 1.1 and 1.2, respectively. The wind flow causes the bladed rotor to develop a

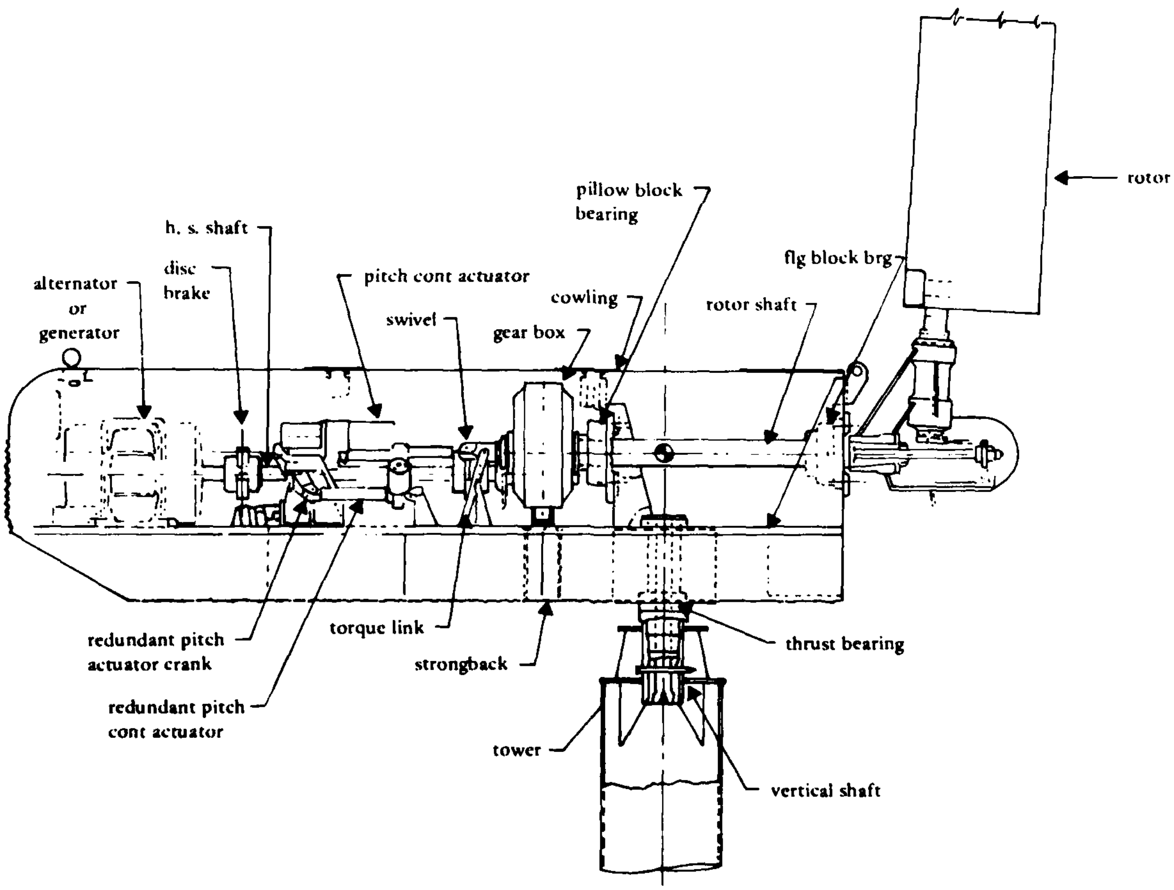

Figure 1.1. Details of a downwind WECS system currently under development by DOE.

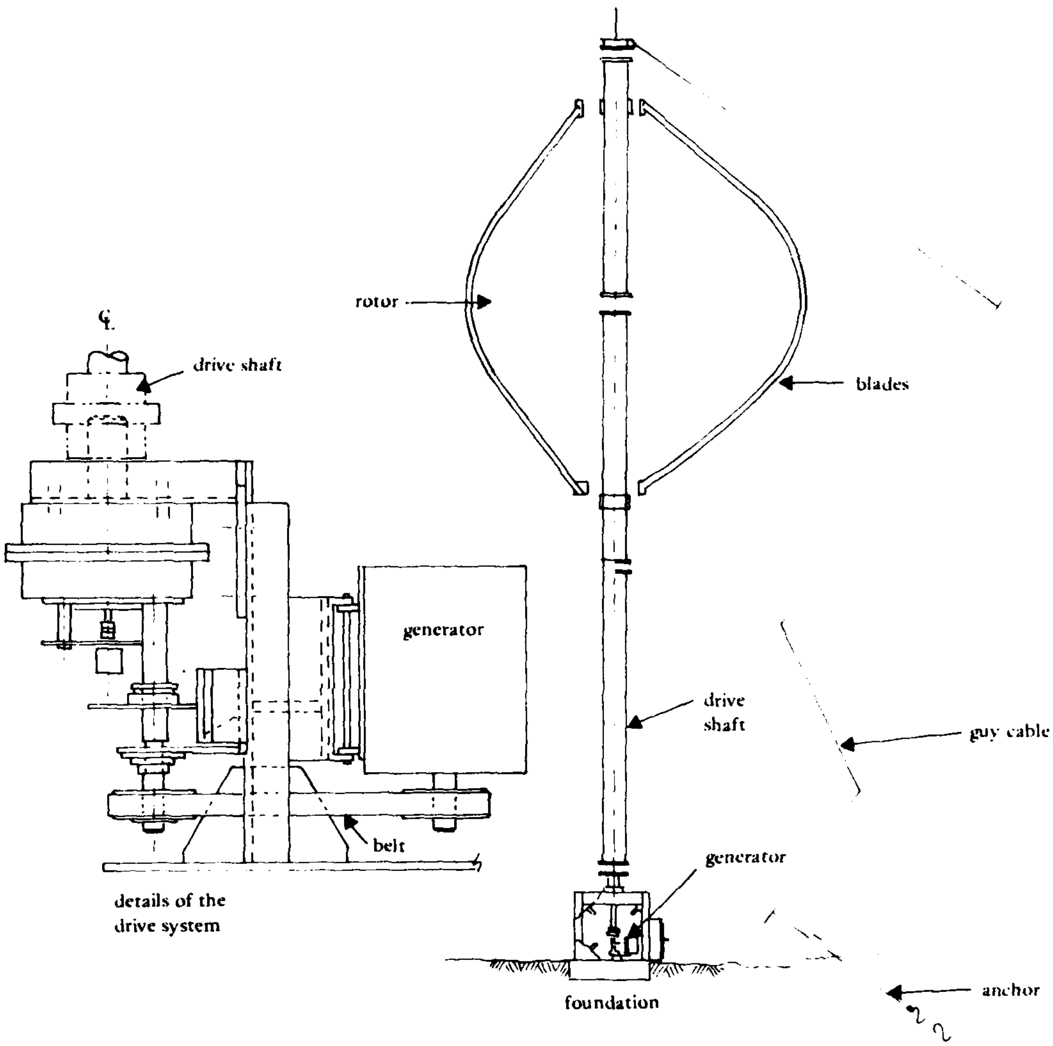

Figure 1.2. Details of a Darrieus vertical axis WECS currently under development by DOE.

torque that causes it to rotate at low speed (below 200 rpm about its axis, which is parallel to the wind direction in a horizontal axis machine, and is normal to the wind direction in a vertical axis system). The rotor shaft delivers the brake power to a system of transmission gears in the gearbox where the low speed is increased to a high speed of about 1,800 rpm to match the rated speed of a generator. In the horizontal axis machine, the gearbox and the generator are contained in a nacelle swivel mounted atop a tower 40 to 60 feet in height. The aerodynamic configuration of the nacelle allows yawing so that the rotor is always normal to wind flow for maximum extraction of energy. The horizontal axis WECS can be subdivided into two subcategories called upwind or downwind systems. An upwind system has its rotor situated upstream of

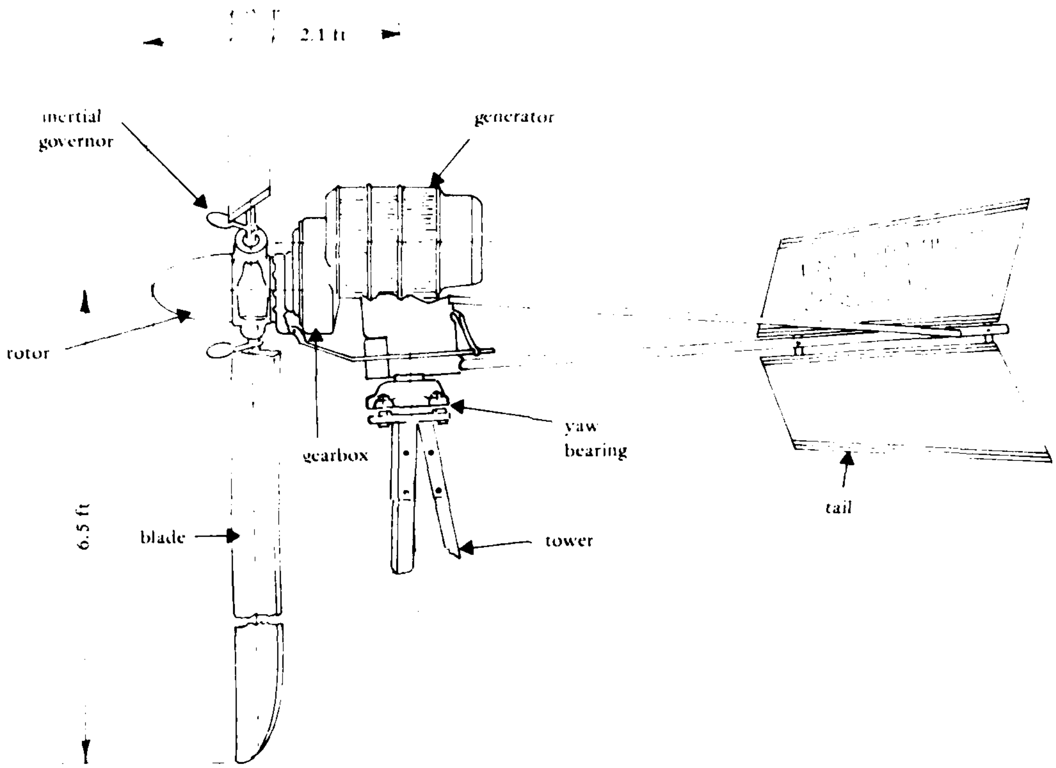

Figure 1.3. Configuration of a 2-kW Dunlite WECS at CEL.

the mounting tower and requires a tail to ensure yaw. Figure 1.3 depicts an upwind 2-kW WECS currently being evaluated at CEL. A downwind system, on the other hand, has its rotor located downstream of its mounting tower and is generally self-yawing. The small downwind-type WECS do not need any tails or other external yaw drives for their steering into the wind flow. The vertical axis WECS, such as the Darrieus design shown in Figure 1.2, has the ability to accept wind from any direction. Another advantage of such a system is that the generator can be located close to the ground, without costly bevel gearing, thus allowing simpler construction and less maintenance. Extensive details on various types of WECS are included in Chapter 4.

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Chapter 2

FUNDAMENTALS OF WIND ENERGY CONVERSION

This chapter presents the fundamental parameters required to establish or determine the available power in the wind based on existing wind data. The instantaneous power available in the wind is the kinetic energy per unit time of a column of air moving undisturbed through a finite rotor disc area. Explicitly, the power $P_a(z,t)$ is:

$$P_a(z,t) = \frac{\rho}{2} A\, u^3(z,t) \qquad (2.1a)$$

where

- z = elevation of the disc area centerline above local ground level
- t = time
- ρ = mass density of air
- A = area normal to the wind flow swept by the rotor
- $u(z,t)$ = instantaneous wind speed

The details of the flow configuration and the definition of various quantities involved here are shown in Figure 2.1. The expression of Equation 2.1a gives total power available in the wind flow, of which only a fraction can actually be extracted by a wind turbine. It is always convenient to express the available power $P_a(z,t)$ in kilowatts, while the units of other quantities involved vary depending on the system of units chosen. It is advisable to rewrite Equation 2.1a with a conversion factor, K, which allows for choice of units for P_a, A, and u. Thus,

$$P_a(z,t) = \frac{K\rho}{2} A\, u^3(z,t) \qquad (2.1b)$$

The values of the conversion factor (K) for various units of P_a, A, ρ, and u are listed in Table 2.1.

Table 2.1. Values of K for Various Units of P_a, A, ρ, and u

Units of Power, P_a	Unit of Disc Area, A	Unit of Air Density, ρ	Unit of Wind Speed, u	Value of K
Kilowatts	Square feet	Slugs[a] per cubic foot	Miles per hour	4.2793×10^{-3}
Kilowatts	Square feet	Slugs per cubic foot	Knots	6.5340×10^{-3}
Horsepower	Square feet	Slugs per cubic foot	Miles per hour	5.7363×10^{-3}
Watts	Square feet	Slugs per cubic foot	Feet per second	1.3564
Kilowatts	Square meters	Kilograms per cubic meter	Meters per second	1.0×10^{-3}
Kilowatts	Square meters	Kilograms per cubic meter	Kilometers per hour	2.1433×10^{-5}

[a]A slug is a unit of mass and is defined as:

$$\text{Mass in slugs} = \frac{\text{weight in pounds}}{\text{gravitational acceleration}} = \frac{W}{g}$$

Most of this chapter is devoted to examining the influence of air density and wind speed variations on the power production. A detailed discussion on the site wind characteristics with their application to power conversion is also included. In the following section of this chapter, it is found that the temporal variation in air density is

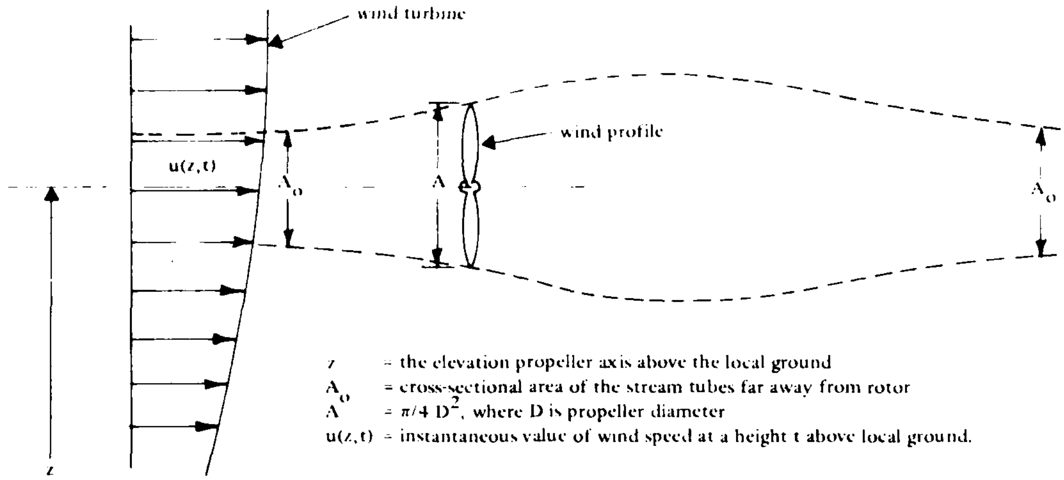


Figure 2.1. Schematic of wind profile and the wind turbine rotor.

accounted for by considering annual mean values only. On the other hand, the spatial variations of density, ρ, (e.g., variation of air density with altitude), are dealt with in the manner shown in Table 2.2 and Equation 2.2. The temporal variations in wind speed, u, in Equation 2.1b are handled by using the mean and standard deviation of the instantaneous wind speed. The spatial variation in wind speed (i.e., its variation with altitude) is accounted for by using either a power law or a log profile. The spatial variations in wind speed along longitudinal directions are extremely hard to compute. This section attempts to discuss some aspects of this type of variation in wind speed. Finally, the changes in air density due to humidity are fairly small for wind power computations.

2.1 INFLUENCE OF AIR DENSITY VARIATION

The density (ρ) of air varies greatly with altitude and also with the atmospheric conditions at a given location. For dry air, from properties of the NACA standard atmospheric, Table 2.2 was prepared to show variation in air density as a function of altitude (h) up to 10,000 feet. In Table 2.2, the temperatures are based upon mean experimental values, whereas the pressures are computed assuming sea-level air composition and the gravitational force. It can be seen from the NACA tabulation that the standard density at an atmospheric pressure of 14.696 lb/in.^{2} (29.92 inches of mercury) and a temperature of 59°F is 0.002378 slugs/ft^3. Next, for the dry air, the density can decrease from 0.002378 slugs/ft^3 at sea level to 0.001756 slugs/ft^3 at an altitude of 10,000 feet. Table 2.2 also shows the variation of atmospheric temperature with altitude. A plot of the variation of air density with altitude based on the tabulated values is given in Figure 2.2, which shows a gradual decrease in density with altitude.

Table 2.2. Properties of the NACA Standard Atmosphere

Altitude, h (ft)	Temperature		Density, ρ (slugs/ft^3)	Pressure, p	
	°F	°C		lb/ft^2	Inches of Mercury
0	59	15.00	0.002378	2,116.2	29.92
1,000	55.44	13.02	0.002310	2,040.9	28.86
2,000	51.87	11.04	0.002242	1,967.7	27.82
3,000	48.31	9.06	0.002177	1,896.7	26.82
4,000	44.74	7.08	0.002112	1,827.7	25.84
5,000	41.18	5.10	0.002049	1,760.8	24.90
6,000	37.62	3.12	0.001988	1,696.0	23.98
7,000	34.05	1.14	0.001928	1,633.0	23.09
8,000	30.49	-0.84	0.001869	1,571.9	22.23
9,000	26.92	-2.82	0.001812	1,512.8	21.39
10,000	23.36	-4.80	0.001756	1,455.4	20.58

The corresponding plot of air temperature with altitude is linear, thus implying a steady decrease of temperature with altitude. For comparison, the actual variation of air density based on field measurements for a region in the mountains of New England is also plotted in Figure 2.2. The plot shows a gradual decrease in air density from 0.00238 slugs/ft^3 at 2,500 feet above sea level to about 0.00182 slugs/ft^3 at 9,000 feet, whereas the value for the 2,000-foot elevation is about 0.002327 slugs/ft^3. It is clear that the actual variation based on the measurements is more nonlinear than the one based on NACA values. It is, therefore, obvious that the effect of altitude on air density and hence the available power in the wind at a location can be significant and, hence, must be properly accounted for while using Equations 2.1a or 2.1b.

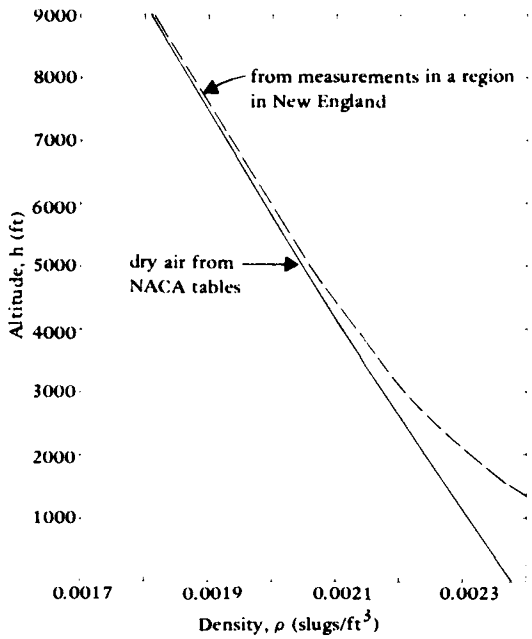


Figure 2.2. Variations of air density as a function of altitude, h, based on NACA dry atmosphere and comparison with actual observations for a region in New England.

The changes in the ambient air density due to daily and normal temperature and pressure variations can be estimated by using the perfect gas equation given by

$$\rho = p/(1714.66\ \theta) \quad (2.2)$$

with ρ being in slugs/ft³, p being the atmospheric pressure in lb/ft², and θ being the ambient temperature in degrees Rankine (°R). For a given location, the variations in pressure (p) are generally less than 3%, whereas the absolute temperature can vary by as much as 25% on a seasonal basis. Generally, for most places, the variation in ρ due to combined changes in p and θ cannot exceed 10% to 15%. The air density decreases slightly with increase in humidity, but corrections due to this change are fairly small.

Thus, while estimating wind power potential of a site, the density (ρ) in Equation 2.1a must be considered variable. Since the quantities ρ and wind speed (u) are statistically independent, the situation can be greatly simplified by taking the average of Equation 2.1a to yield

$$\langle P_a \rangle = \frac{\langle \rho \rangle}{2} A \langle u^3(z,t) \rangle \quad (2.3)$$

Hence, to compute the wind potential of a site, only annual mean values of the air density must be used. The mean values of density are not readily available, but the frequency of occurrence of air temperature for a location is generally given. The mean density for a location can be easily computed using Equation 2.2 from the mean temperature values.

2.2 VERTICAL DISTRIBUTION OF HORIZONTAL COMPONENT OF WIND SPEED

The commonly used properties of wind, such as velocity, pressure, and temperature, are defined in such a way that the instantaneous value is the sum of an average component and a fluctuating random term (Ref 2.1 and 2.2). Thus, the wind velocity, u(z,t), at any time, t, and vertical location, z, is given by:

$$u(z,t) = U(z) + u'(z,t) \tag{2.4}$$

where

$$U(z) = \langle u(z,t) \rangle = \frac{1}{T}\int_{o}^{T} U(z,t)\, dt \tag{2.5}$$

In Equation 2.5, the U(z) is the average of the quantity u(z,t) over a long period of time, T, and, by definition of Equation 2.5, the quantity

$$\langle u'(z,t) \rangle = 0 \tag{2.6}$$

Generally, the available wind data for a site are taken on an hourly basis, and the averaging period, T, is about a year. Thus, U(z) for wind power calculations can be the average annual wind speed at the site.

The atmospheric boundary layer extends to a height of about 3,300 feet. The composite effects of synoptic pressure patterns, coriolis forces, and surface drag cause the direction of the wind to change from flowing parallel to the isobars at higher elevations (geostrophic wind flow) to flowing normal to the isobars near the earth's surface. This turning effect is generally negligible below a height of 160 to 320 feet. Hence, for small WECS, the effect of wind direction turning as a function of height should be neglected.

2.2.1 Distribution Over Flat Homogeneous Terrain

The heating or cooling of air by convection from the ground and the ground roughness cause variations in wind velocity profiles even over flat homogeneous terrain. Heating or cooling of the air by the earth results in unstable or stable atmospheric conditions, respectively. With heating, buoyancy effects enhance turbulent mixing, which results in larger vertical velocities and lower horizontal velocities than those that prevail for stable conditions where buoyancy is damped out and stratified flows are preferred. For high geostrophic flows or in the absence of surface heating or cooling, a neutral atmospheric boundary layer occurs (Ref 2.3). For a neutral atmosphere, the average velocity, U(z), satisfies the relationship

$$\frac{\partial U}{\partial z} = \frac{v^*}{\kappa\, z} \tag{2.7}$$

where $v^* = \sqrt{\tau/\rho}$ = friction velocity

τ = surface shear stress

ρ = mass density of air

κ = Karman constant (= 0.41)

z = height above ground level

For a nonneutral atmosphere, Monin and Obukhov (Ref 2.1) have suggested that Equation 2.7 be modified by adding a universal function $\phi(z/\mathcal{L})$ to yield

$$\frac{\partial U}{\partial z} = \frac{v^*\,\phi}{\kappa\, z} \tag{2.7a}$$

where $\mathcal{L} = -\,v^{3*}\,\rho\, c_p\, \bar{\theta}/\kappa\, g\, H$ and is the unique length scale of Monin and Obukhov

c_p = specific heat at constant pressure

g = gravitational acceleration

$\bar{\theta}$ = mean air temperature

H = vertical turbulent heat flux

The vertical heat flux, H, is further defined by

$$H = \rho c_p \langle \theta' w' \rangle \tag{2.8}$$

with θ' and w' being the fluctuating components of air temperature and vertical velocity. Clearly, under neutral conditions, $\phi(z/\mathcal{L}) = 1$, and Equation 2.7a upon integration yields a standard logarithmic profile for U(z), namely,

$$U(z) = U_o + \frac{v^*}{\kappa} \log \frac{z}{z_o} \tag{2.9}$$

U_o is the velocity at the tip of the viscous sublayer and z_o is the roughness height. For small values of z (i.e., in layers very close to the ground), $\phi(z/\mathcal{L}) \rightarrow 1$, so that Equation 2.9 always applies in such layers no matter what stability conditions prevail. The above expression for the velocity profile is valid for small roughness elements, such as are encountered over short grass, ice, or mud flats. For larger variations in roughness parameter, such as over buildings, tall trees, or hilly terrains, Equation 2.9 must be modified by subtracting the zero level displacement from z as determined from field measurements. Hence, an expression for modelling wind flow over buildings and thick trees (Ref 2.3) would be

$$U(z) = U_o + \frac{v^*}{\kappa} \log \frac{z - h}{z_o} \tag{2.9a}$$

where h is the datum-level displacement height.

Under strong stability conditions, such as at night with weak geostrophic flow, $\phi(z/\mathcal{L})/z$ is no longer a function of the height, z. Hence, from Equation 2.7a, U(z) is given by

$$U(z) = U_o + \frac{v^*}{\kappa}(z - z_o) \tag{2.10}$$

Another extreme case is that of a very unstable atmosphere, such as during the day with a strong geostrophic flow; the function $\phi(z/\mathcal{L}) = C_1 |z/\mathcal{L}|^{-1/3}$ and U(z) is given by

$$U(z) = U_o + C_1 \frac{v^*}{\kappa} \left(|z/\mathcal{L}|^{-1/3} - |z_o/\mathcal{L}|^{-1/3} \right) \tag{2.11}$$

In general, for the case $|z/\mathcal{L}| << 1$, using a Taylor series approximation, $\phi(z/\mathcal{L})$ can be represented by

$$\phi(z/\mathcal{L}) = 1 + \alpha_1 z/\mathcal{L} \tag{2.12}$$

with α_1 (= 0.6) being an empirical constant. The corresponding velocity profile, U(z), becomes

$$U(z) = U_o + \frac{v^*}{\kappa} \log \frac{z}{z_o} + \alpha \frac{z - z_o}{\mathcal{L}} \tag{2.13}$$

The above expression is known as the famous log-plus-linear law for the horizontal velocity profile, U(z).

2.2.2 Power Law Velocity Distribution

Another formula for computing distribution of the horizontal component of wind speed over ground is given by the power law

$$\frac{U}{U_1} = \left(\frac{z}{z_1} \right)^{\beta} \tag{2.14}$$

where β is a function of the ground roughness and the atmospheric stability conditions. Generally, the exponent is small during the day and large at night. Equation 2.14 is empirical and is widely used by engineers. The classical figure (Figure 2.3) from Davenport shows how surface roughness influences the wind profile. A complete nomogram on β-values for various roughness lengths, z_o, and the inverse of the Monin-Obukhov

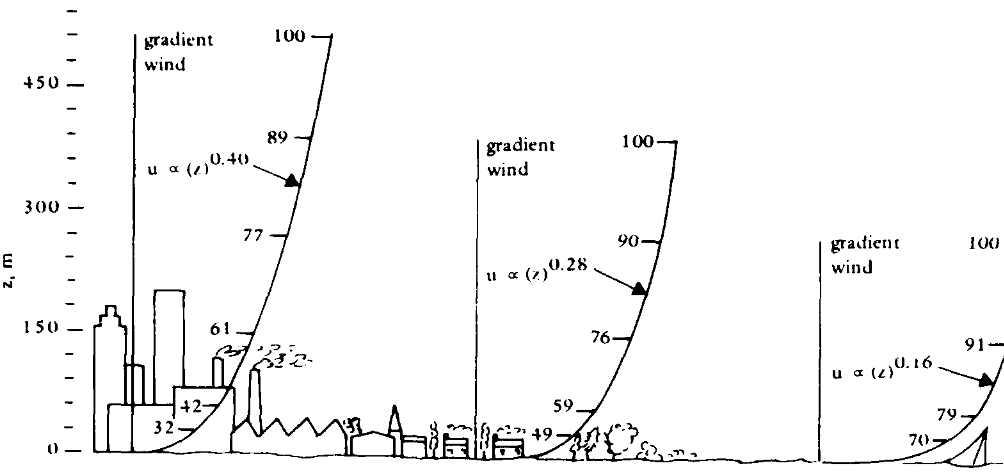


Figure 2.3. Empirical power laws over different terrain (after Davenport, 1963).

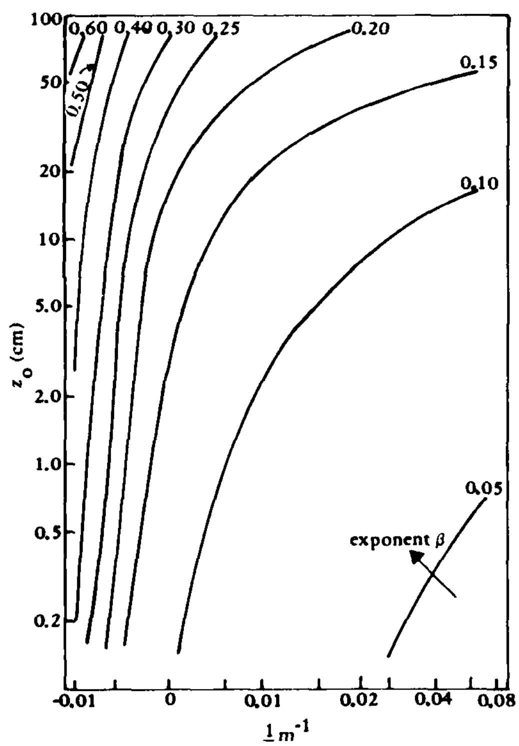


Figure 2.4. Variation of the exponent β with roughness z_o and the inverse of the Monin-Obukhov length $\mathcal{L}$ for the 11- to 46-meter layer a zero value of $1/\mathcal{L}$ corresponds to adiabatic conditions (Reg 2.1).

length, $\mathcal{L}$, valid for a height range of 35 to 150 feet, is given in Figure 2.4. While using the nomogram, a conversion factor from meters to feet must be used. Table 2.3 shows values of β for various stations in the United States. Generally, over smooth ground under neutral conditions, β can vary from 0.11 to 0.28. Figures 2.5a-c illustrate the wind field encountered by an approximately 30-foot-diam wind turbine mounted atop a 75-foot-high tower in a neutral, unstable, and stable atmospheric boundary layer, respectively. The influence of the variations in roughness height, z_o, and the stability condition on the wind profiles is shown in detail. It is obvious from the figures that under certain roughness and stability conditions, the wind shear over the wind turbine rotor is very large.

Table 2.3. Values of Exponent β in the Power Law for Equation 2.14

Station Name	Anemometer Height (ft)	Approximate Period at Each Height	Observed Annual Mean Speed (mph)	Value of β
Brunswick, ME (NAS)	65 14	1955-58 1959-64	9.44 6.98	0.197
Boston, MA (Logan)	70 31	1955-57 1958-63	14.85 13.10	0.155
Quonset Point, RI (NAS)	57.5 11.3	1955-58 1959-64	11.70 8.39	0.204
New York City, NY (J.F.K. Airport)	50.3 30.8	1955-57 1958-62	12.73 12.06	0.110
Atlantic City, NJ (A.C. Airport)	70.0 18.6	1959-61 1962-64	12.04 10.25	0.124
Hampton, VA (Langley)	89.3 12.2	1955-59 1960-64	10.45 6.89	0.209
Virginia Beach, VA (Oceana)	39.0 12.2	1955-59 1960-64	9.64 7.29	0.240
Charleston, SC (Municipal Airport)	71.6 18.6	1955-58 1959-64	10.42 6.64	0.145
Valparaiso, FL (Eglin)	37.2 18.85	1955-58 1959-64	8.43 6.64	0.280
Biloxi, MS (Keesler AFB)	56.7 12.2	1955-57 1958-64	9.10 7.72	0.194
New Orleans, LA (Moisant)	49.4 18.6	1955-59 1960-64	8.99 7.72	0.157
Port Arthur, TX (Jefferson County)	53.0 18.6	1955-60 1961-64	11.30 9.42	0.174
Corpus Christi, TX (NAS)	58.5 20.40	1955-60 1961-64	14.27 11.41	0.213

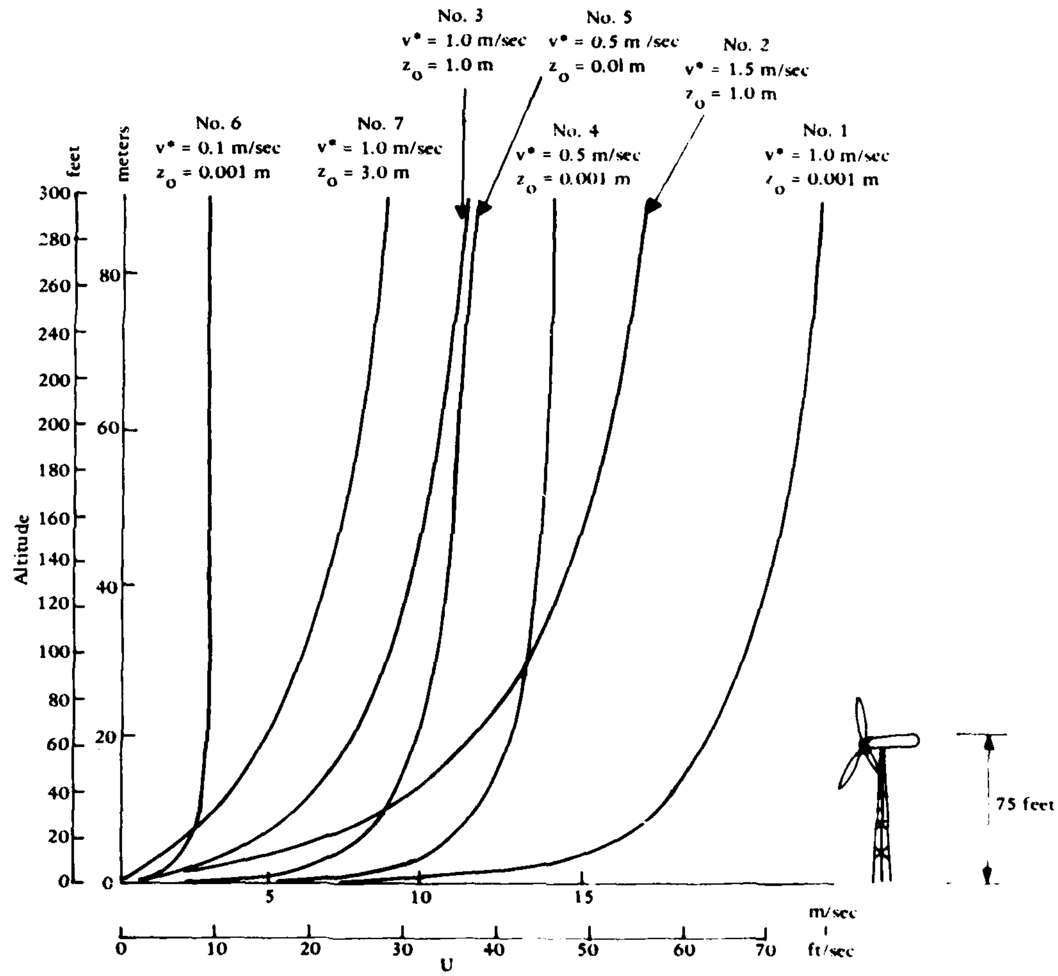


Figure 2.5a. Neutral wind profiles.

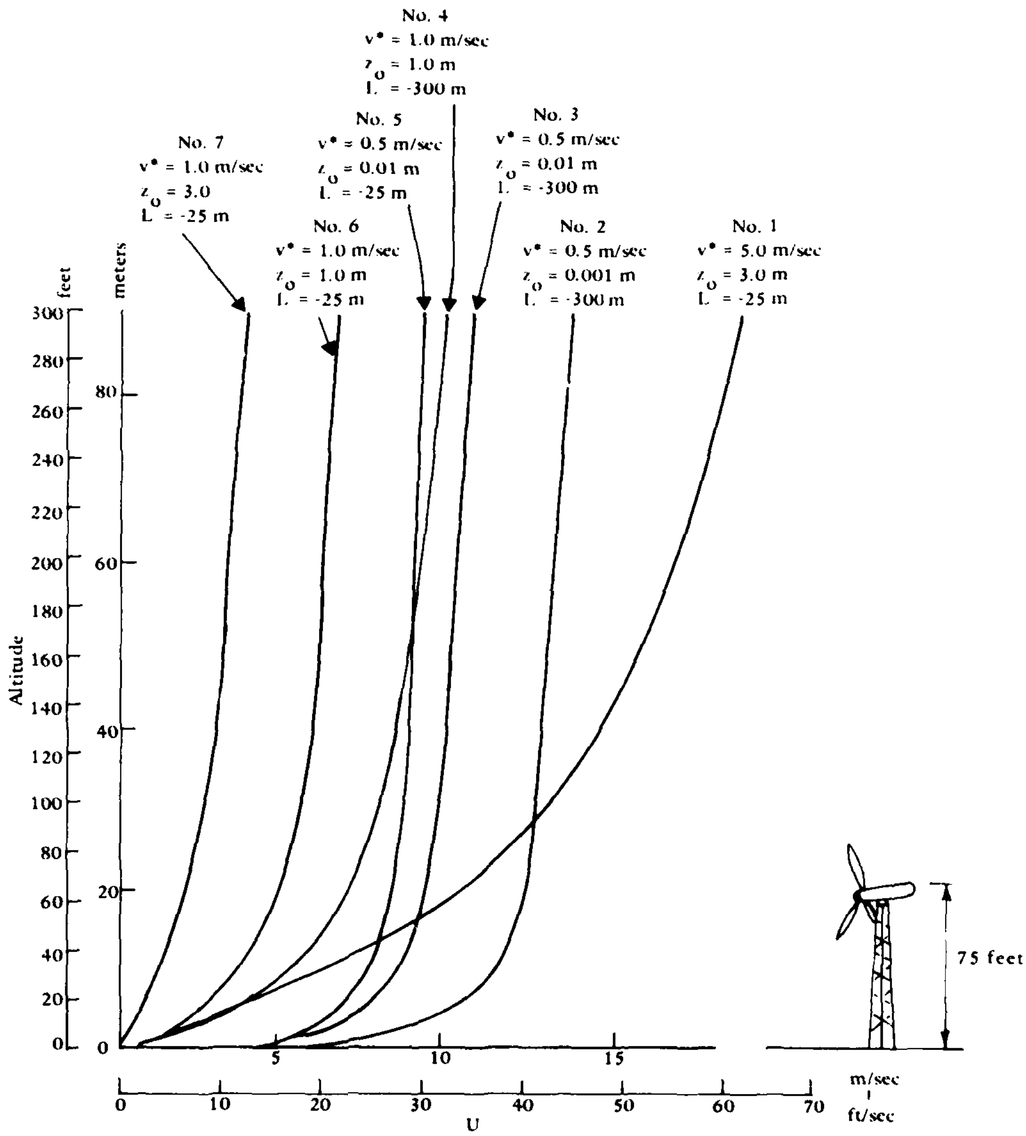


Figure 2.5b. Unstable wind profiles

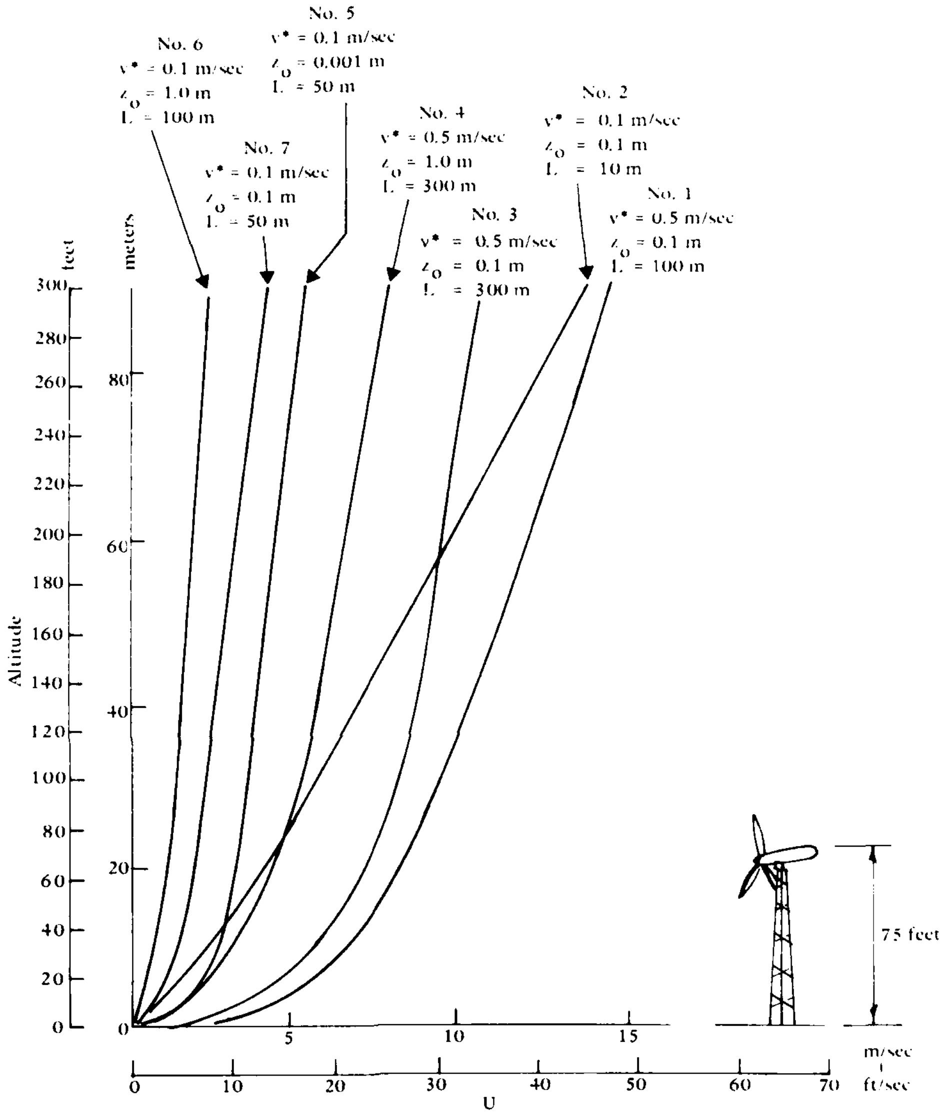


Figure 2.5c. Stable wind profiles.

2.2.3 Commonly Used Formula for Velocity Distribution

It is conjectured by Munn that the average values of U(z) over a period of 1 year or longer can follow the log law given by Equation 2.9. Hence, for the purpose of this study, the log law for velocity profile will be used. The existing wind data for a given site or region were generally taken at a nearby weather station. In most instances the instrument height above the ground varied from 10 to 33 feet to record the surface winds only. Small-capacity wind power equipment will be located at heights of 40 to 80 feet for cost-effective power generation. Hence, to obtain the realistic estimates, the power computations based upon the existing data must be multiplied by a factor

$$AF = \left[\frac{U_o + \frac{v^*}{\kappa} \log \frac{z_2 - h}{z_o}}{U_o + \frac{v^*}{\kappa} \log \frac{z_1 - h}{z_o}} \right] \qquad (2.15)$$

where z_1 is the instrument height, and z_2 is the center of the proposed power plant above the ground. In Equation 2.15, the wind velocity, U_o, at the tip of the sublayer can be about 5.5 times the friction velocity, v^*. Furthermore, for a given terrain, the values for v^* and z_o can be obtained from a reference book. Finally, h, the datum-level displacement for a site, is obtainable from field measurements. Because in most cases the proposed WECS tower height (z_2) is greater than the instrument height (z_1), the factor AF will generally be greater than unity.

2.3 EFFECTS OF TERRAIN IRREGULARITIES ON THE WIND FIELDS

Changes in terrain (such as forests, hills, valleys) or discontinuities in surface texture can disturb the ground winds, as can also man-made obstructions (such as buildings, cities, and other structures).

In the region of disturbance, there are zones of high wind speeds and of low wind speeds. The knowledge of these wind fields is extremely important in selecting WECS sites with a view toward utilizing the regions of high winds while avoiding the regions of low winds.

2.3.1 Surface Discontinuities

An abrupt change in surface roughness causes the formation of an "internal boundary layer" (as shown in Figure 2.6) when the surface texture changes from smooth to rough. Examples of such boundary layers include where the sea or a lake joins the shore, where a forest meets a plain, or where a city blends with a rural community. Extensive experimental and analytical literature on this topic exists (see list of references in References 2.3 to 2.5).

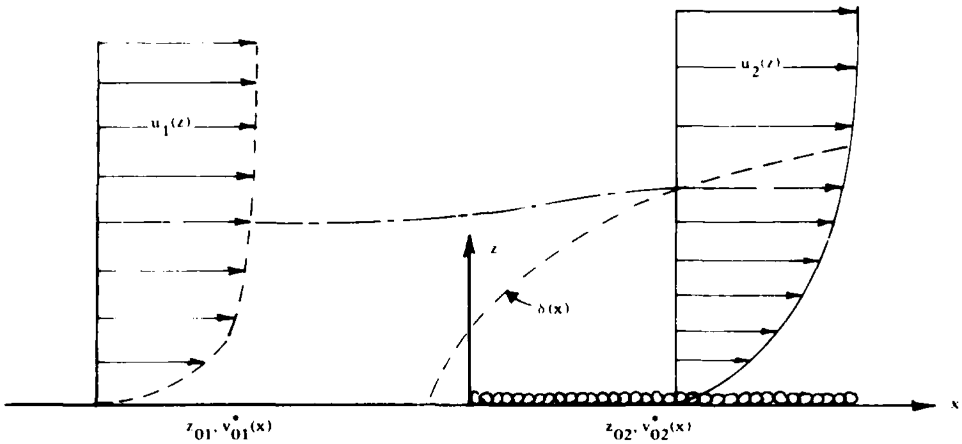


Figure 2.6. Schematic representation of the development of an internal boundary layer: flow from smooth to rough.

Temperature discontinuities on the earth's surface also create internal boundary conditions having the same features as roughness effects. As is well known, in the absence of strong geostrophic winds, the thermal gradient between land and an adjoining body of water creates circulations forming a sea breeze. Typical velocities of sea breeze type of circulations are about 10 to 15 mph; they occur with a consistent periodicity. In coastal areas, a part of WECS output will be derived from such flows.

2.3.2 Hills and Mountains

The flow over hills or mountains can be first discussed in terms of long, essentially two-dimensional hills with wind perpendicular to the hillside. For the neutral atmosphere, typical wind flow patterns that can occur are illustrated in Figure 2.7 for various shaped hills. The regions of high velocity that occur in the flow regime are clearly marked. There is not much literature covering field studies of flow over hills, but there is considerable material available involving wind tunnel and analytical work that has been reviewed in Reference 2.6.

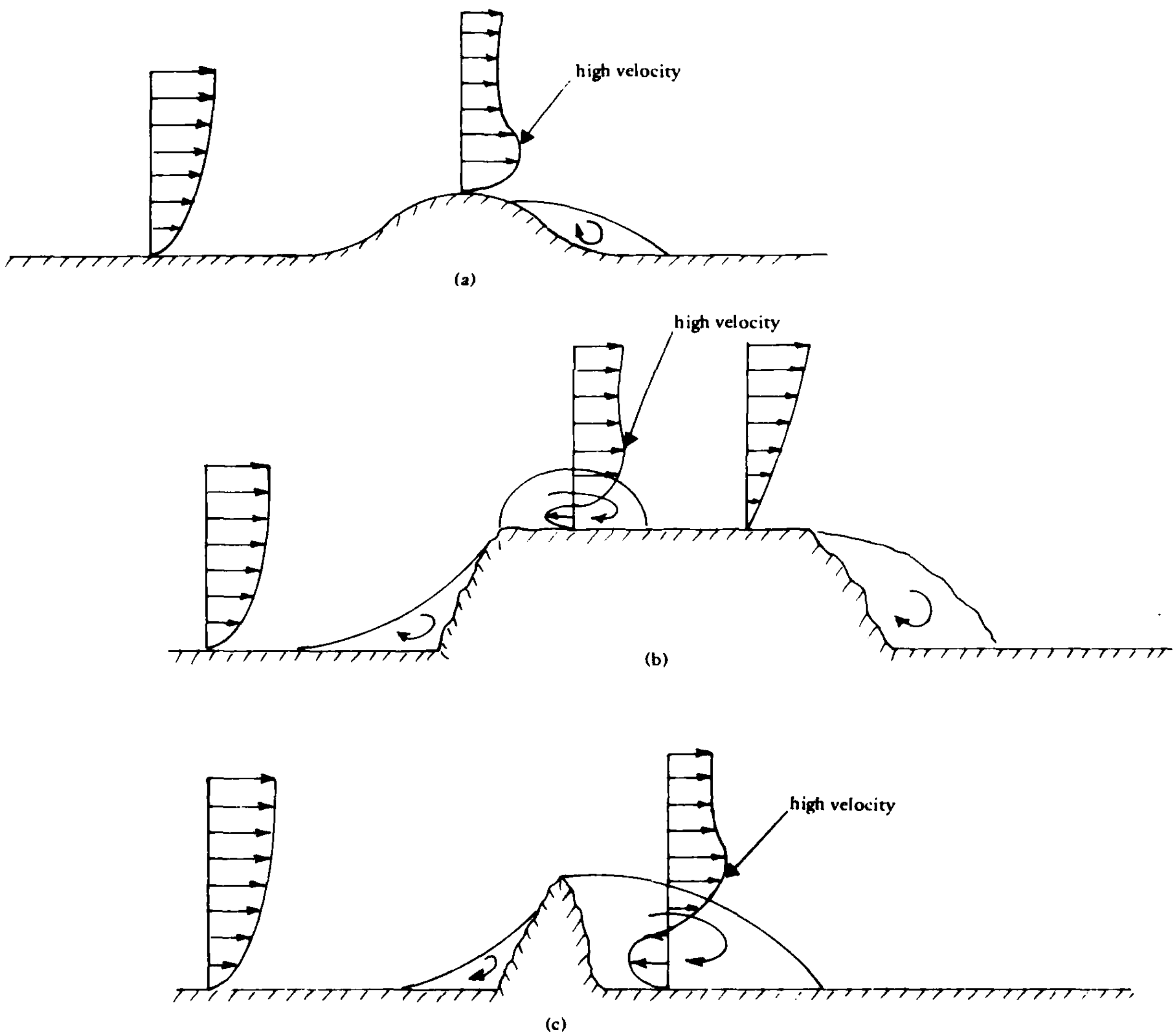
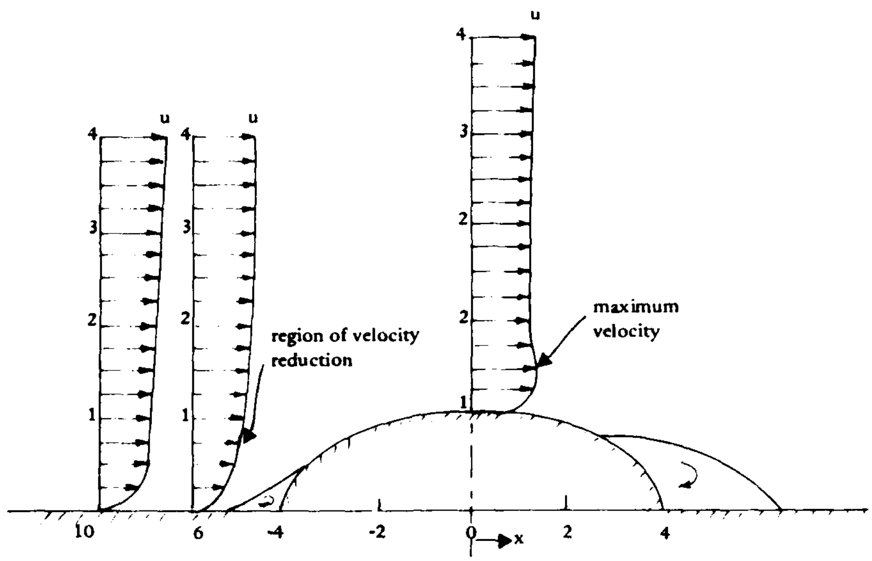


Figure 2.7. Typical flow patterns over two-dimensional hills.



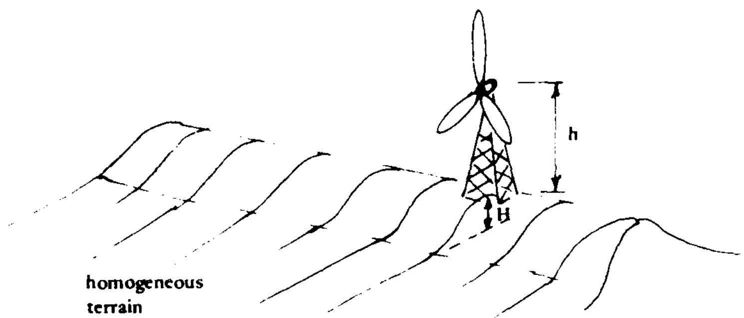


Figure 2.8. Wind flow over two-dimensional elliptical hill.

The wind flow over semi-elliptical, two-dimensional hills (Figure 2.8) has been analyzed extensively (Ref 2.7 and 2.8). Results of computation for neutral boundary layers are shown in Figure 2.9. Generally, the results can be summarized as follows: for neutral and unstable atmosphere, the peak wind flow occurs at approximately half a hill height above the hilltop and the magnitude of these winds is equivalent to wind velocities at three hill heights over level ground. For stable boundary layers, this conclusion cannot be drawn. Computations of flow fields for hills of elliptical geometry shown in Figure 2.8 are not so straightforward. Flow separation that occurs at the sharp leading edge greatly complicates mathematical analyses; however, these flow fields are discussed later in an empirical sense.

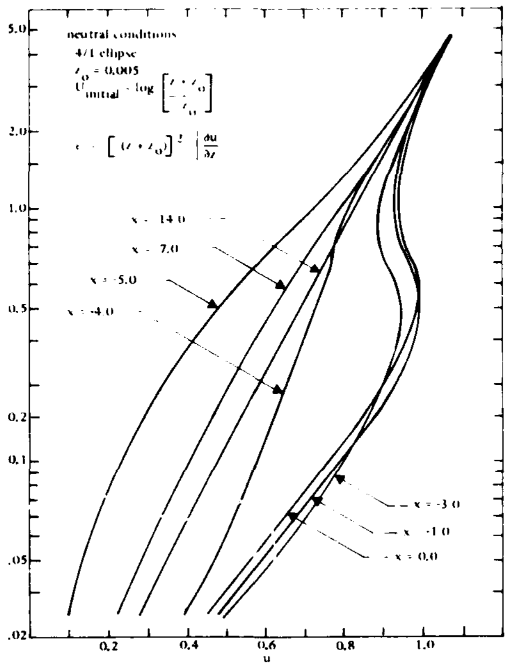


Figure 2.9. Boundary layer development over a 4/1 ellipse for neutral atmosphere.

Three-dimensional flow fields are even more complex and their mathematical treatment is scarce, but some limited results are discussed in Reference 2.6. Qualitatively, three-dimensional effects tend to relieve blockage of the flow and thus reduce the wind speed at the top of the hill and decrease the size of the separation region. Next, the stratified flow over mountains results in high flow down the lee side of the mountain (Figure 2.10). Considerable literature exists on computational procedures for mountain flow (Ref 2.9). These computational procedures in general neglect the frictional effects near the ground, and details of the boundary layer necessary for siting WECS in such areas are needed.

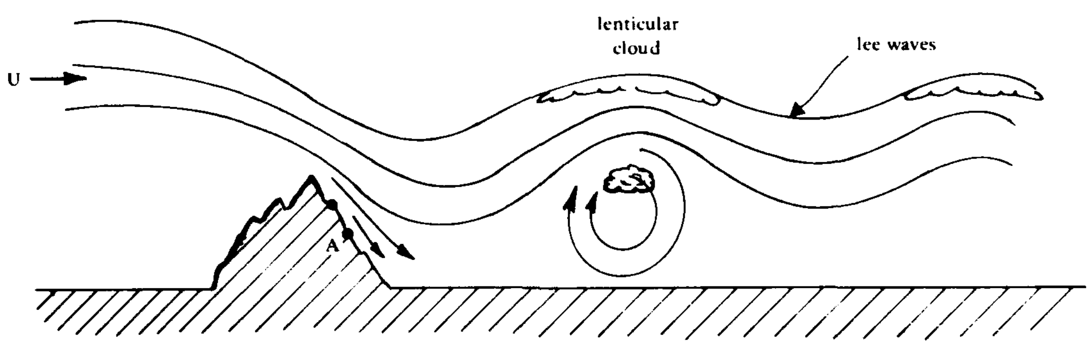


Figure 2.10. Lee waves forming behind a mountain.

2.3.3 Wind Flows in Valleys

An infinite plane is difficult to find in nature. Even in the flattest parts of the world, bases are built in a terrain containing slopes and cliffs, which can behave as valleys. The meteorologically important properties of valleys for siting WECS include:

1. Orientation to the geostrophic wind

2. The geometrical dimensions of the valley, including length, width, depth, slope of the sides, slope of the valley floor, and the presence of bends or constrictions

When a strong geostrophic wind is blowing in a direction roughly parallel to the valley, there is a funnel effect that results in a speed enhancement of the flow, particularly at points where the valley narrows or its sides become steeper (Ref 2.10). When geostrophic wind flow is at right angles to the valley, complex flow patterns occur; however, there is generally a region of relatively high winds. For instance, under stably stratified atmospheric conditions, a strong flow occurs down the lee side of the valley (Figure 2.10), which suggests an optimum WECS site at position A. Under neutral atmosphere, on the other hand, the flow generally separates at the top of the valley, resulting in a recirculation eddy on the lee side (as shown in Figure 2.11). Although the wind under neutral conditions is not as strong as in the stable case, site A still provides relatively constant wind; however, for this case the wind is up the slope. Scorer (Ref 2.11) cites upslope winds of 5 to 12 mph during winter days and winds on the order of 25 mph during summer days.

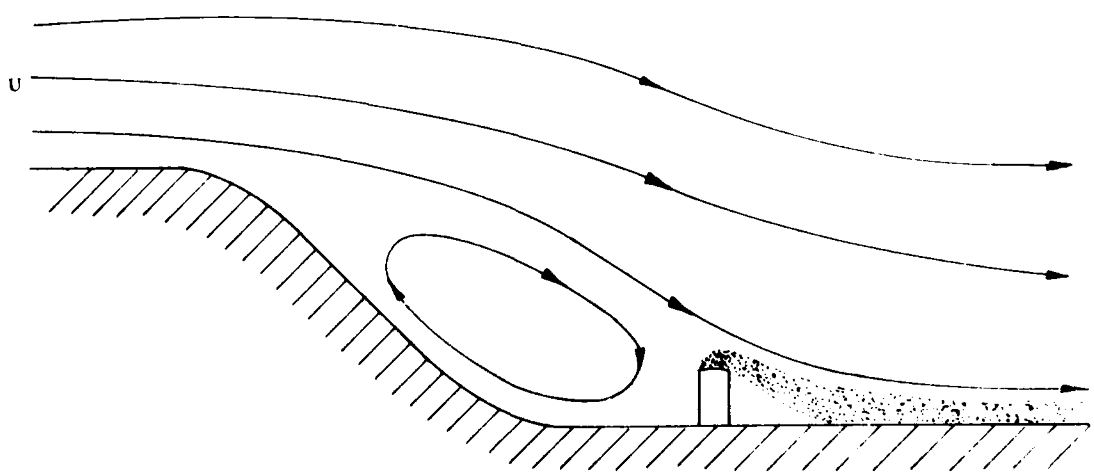


Figure 2.11. Schematic representation of downwash in a valley.

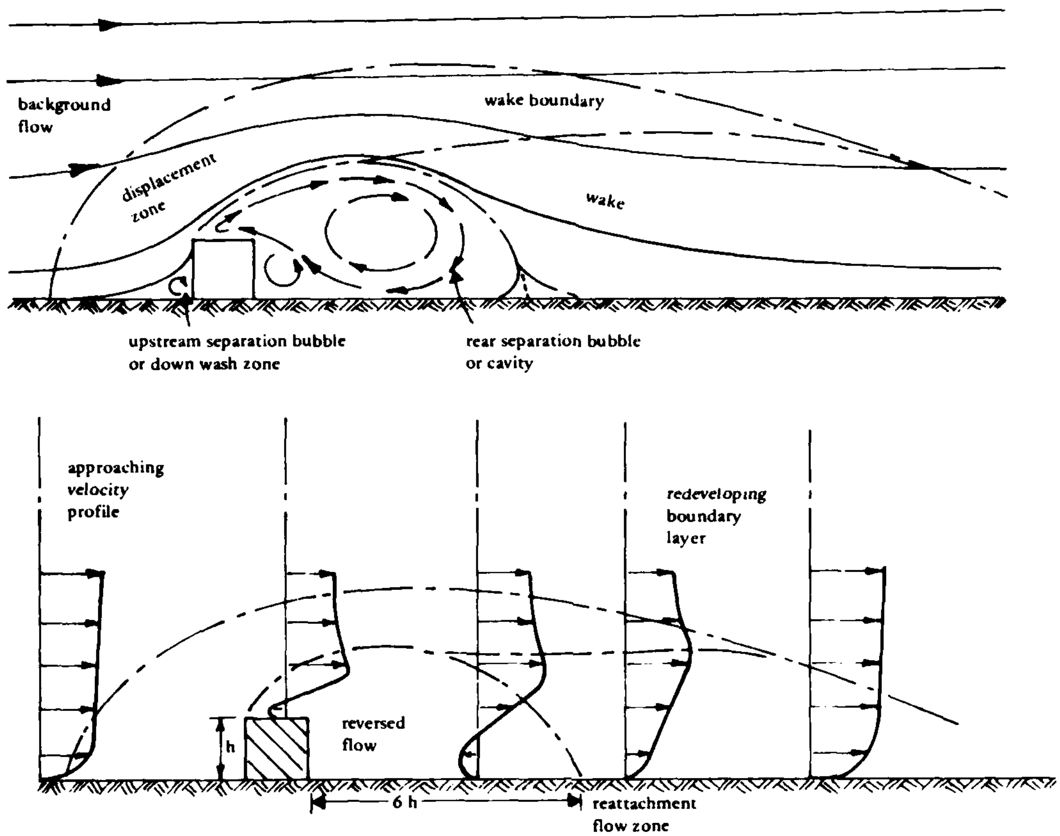


Figure 2.12. Definition of flow zones near a sharp-edged building.

Under light geostrophic wind flows, there is no satisfactory physical model for wind patterns in the valley. The understanding of the local winds can give rise to proper siting of WECS in the valleys. A good discussion on valley winds is given in Reference 2.11.

2.3.4 Wind Flow Over Man-Made Structures

The typical flow field over a two-dimensional building normal to the incident wind is shown in Figure 2.12. Clearly the flow separates in front of the bluff body and reattaches at a distance of approximately 6 h from the front face of the building. The flow in front of the body will separate only if the wind profile has shear. The flow separation also occurs on the sharp edge due to flow over a corner. The leading edge separation forms a large recirculating bubble behind the building, which reattaches about 16 building heights downstream. The wind velocities in this separation region are very low and thus will not provide a good site for a WECS. It is therefore concluded that WECS located behind long tall buildings should be sufficiently high to protrude outside the recirculating region, or sufficiently downstream so that the flow is reattached. For three-dimensional bodies, the flow over buildings follows the same pattern as discussed in preceding paragraphs except that the separation regions and the acceleration of the wind over the building are less. The flow fields over three-dimensional buildings are shown in Figure 2.13, which shows the region of disturbed flow behind the building, namely, the wake. The figure also gives plots of distance downstream to which the wake extends as a function of the building height and width ratio. This type of information is extremely useful when siting WECS near a tall and wide building.

2.4 WIND SPEED AND POWER DATA

Since the power in the wind flow varies as cube of the wind speed, this parameter is extremely important in WECS design considerations. The annual average value and frequency of distribution are clearly of great importance in assessing the energy potential of a given site or a region. The wind speed, $u(z,t)$, for a given site as a function of time (t), is not readily available from historical data. Generally, the wind data available from the National Weather Center and Navy meteorological stations are documented as a function of frequency of occurrence of wind speed for a given bandwidth, as shown in Table 2.4. The values in the table are derived from hourly observations; these tabulations are a percentage frequency of wind direction to 16 compass points and calm by wind speeds (knots) in increments of Beaufort classifications. The percentage frequencies are shown by both direction and speed, including the mean wind speed for each direction. The tabulation also shows the frequency for each wind speed bandwidth for all directions, including the calm, such that the frequencies for calm periods given by f_1 and f_2 represent the frequencies for the wind speeds between 1 and 3 knots and so on.

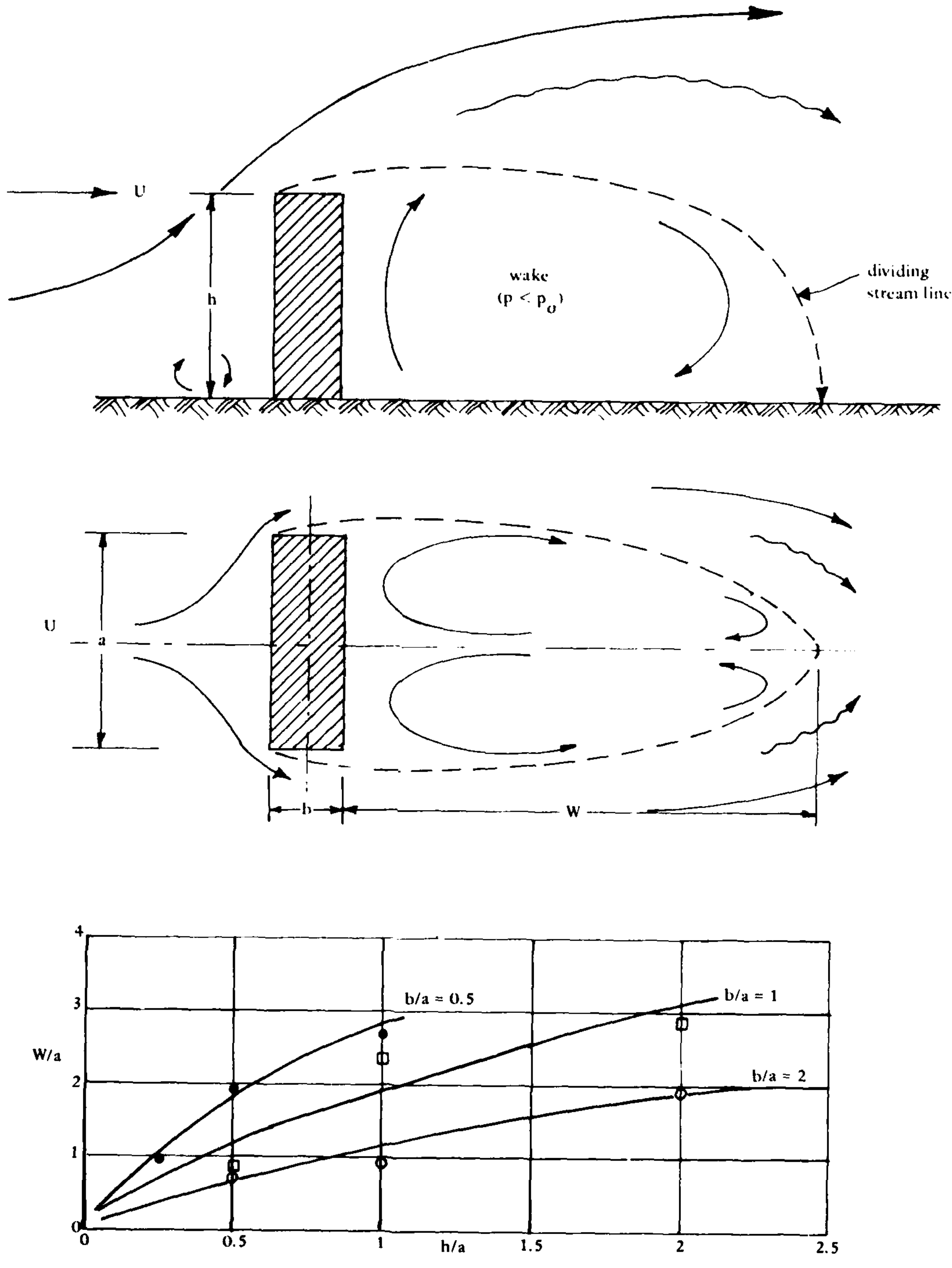


Figure 2.13. Flow over buildings showing influence of the building downstream.

Table 2.4. Percentage Frequency of Surface Wind Direction and Speed From Hourly Observations, Station 12850, Key West NAS, 1953-1968

[From ETAC/USAF Air Weather Service]

Wind Direction	Wind Speed Percentages for Wind Speeds in Knots of --											Percentage	Mean Wind Speed (knots)
	1-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	41-47	48-55	≥56		
N	0.6	1.8	2.5	1.7	0.4	0.1	0.0	0.0				7.2	9.2
NNE	0.4	1.5	2.6	1.9	0.3	0.1	0.0	0.0				6.8	9.4
NE	0.7	2.3	4.0	2.9	0.5	0.1	0.0	0.0				10.4	9.2
ENE	0.4	1.8	3.3	2.1	0.4	0.0	0.0					7.9	9.3
E	0.7	2.6	6.0	5.6	1.2	0.1	0.0	0.0		0.0		16.3	10.3
ESE	0.4	2.0	4.7	4.3	0.7	0.1	0.0	0.0	0.0			12.2	10.1
SE	0.5	2.4	4.5	3.3	0.5	0.1	0.0	0.0	0.0			11.3	9.5
SSE	0.3	1.2	1.9	1.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	4.6	8.8
S	0.4	1.5	2.1	1.1	0.2	0.0	0.0	0.0	0.0	0.0		5.4	8.5
SSW	0.2	0.6	0.9	0.5	0.1	0.0	0.0	0.0	0.0			2.3	9.1
SW	0.2	0.6	0.7	0.5	0.1	0.0	0.0	0.0		0.0		2.2	8.6
WSW	0.1	0.3	0.4	0.3	0.1	0.0	0.0			0.0		1.3	8.9
W	0.2	0.5	0.6	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.7	8.2
WNW	0.1	0.3	0.4	0.3	0.1	0.0				0.0		1.2	8.7
NW	0.3	0.7	0.9	0.6	0.2	0.1	0.0	0.0	0.0	0.0		2.9	9.1
NNW	0.2	0.8	1.1	0.9	0.3	0.1	0.0	0.0				3.4	9.9
Variable	--	--	--	--	--	--	--	--	--	--	--	--	--
Calm	--	--	--	--	--	--	--	--	--	--	--	f_1[a] = 2.9	--
	$f_2 = 6.0$	$f_3 = 20.9$	$f_4 = 36.7$	$f_5 = 27.3$	$f_6 = 5.3$	$f_7 = 0.8$	$f_8 = 0.1$	$f_9 = 0.0$	$f_{10} = 0.0$	$f_{11} = 0.0$	$f_{12} = 0.0$	100.0	9.2[b]

NOTE: Total number of observations = 135,118

[a] f equates to frequency of wind speed in percent.

[b] Overall average wind speed.

The wind data for a site are sometimes shown as a graphic representation called a wind rose (i.e., a polar diagram of annual wind durations from different directions). One form of a wind rose is shown in Figure 2.14a, in which segments show the percentage of the time that the winds of specified magnitude and direction can be expected to occur at San Nicolas Island. It is clear from the wind rose that the prevailing winds at the site are from the northwesterly direction. Another form of wind rose that is commonly used is shown in Figure 2.14b, where length of various size rectangular symbols represents the frequency of a certain strength wind from a given direction. The wind rose of Figure 2.14b shows the prevailing winds from either the southwest or the northeast directions. Wind rose diagrams of this type can also be used to generate frequency information similar to that given in Table 2.4. For easy usage, the available data must be analyzed and reduced to (a) a speed duration curve or (b) a speed frequency curve.

2.4.1 Speed and Power Duration Curves

The speed duration curve is a plot of range of wind speeds as ordinates against the number of hours in the year the speed equals or exceeds each particular value. As an example, Figure 2.15 illustrates construction of speed and power duration curves from long-term data given in Table 2.4. Clearly, the wind speed will be greater than zero for 8,760 hours in the year, and point 1 on the plot (Figure 2.15) corresponds to this. Point 1 on the plot of Figure 2.15 is obtained by observing that wind speed will always be above zero for 8,760 hours in the year. Next, from Table 2.4, it can be seen that wind speed is greater than 1 knot for $(1-f_1) \times 8{,}760$ hours in the year (point 2). Further, the coordinates of point 3 on the plot are derived to be $4,(1-f_1-f_2) \times 8{,}760$; thus, the speed duration can be completed easily. The corresponding power duration plot can be computed simply by using Equation 2.1b with u in knots, $A = 1\ ft^2$, and $K = 6.534 \times 10^{-3}$ to obtain the required ordinate values in kW/ft^2.

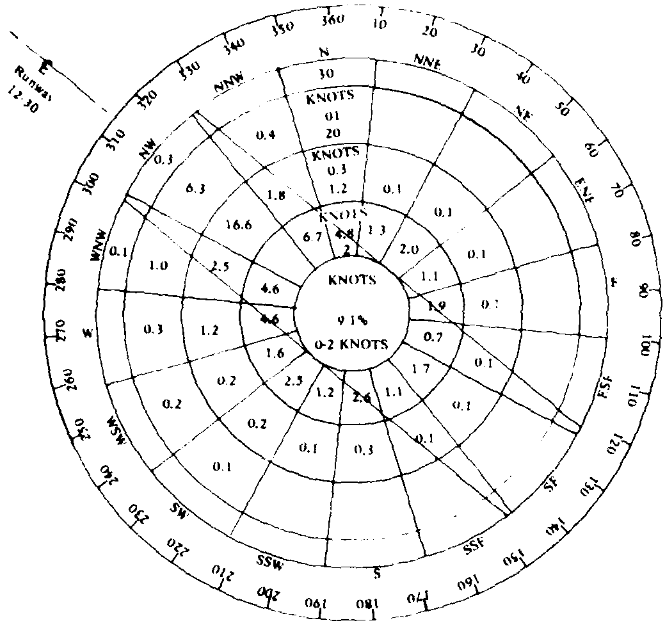


Figure 2.14a. Annual wind rose pattern for San Nicolas Island (PMTC).

Note: 1. Numbers located in the segments show the percentage of time that winds of the indicated speeds and direction can be expected to occur at the particular location.
2. Period of record: April 1945 - September 1960.

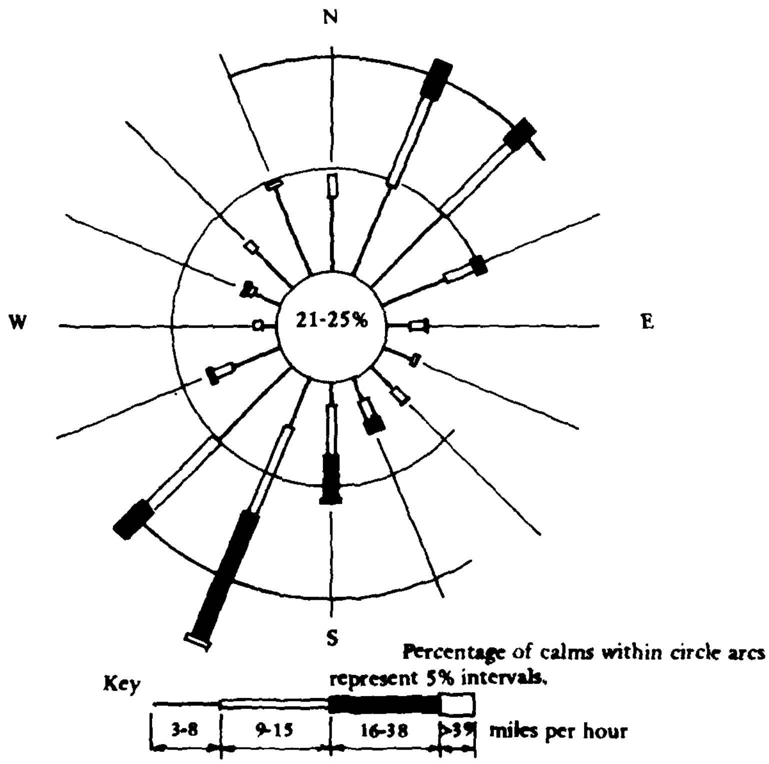


Figure 2.14b. Wind rose for a site.

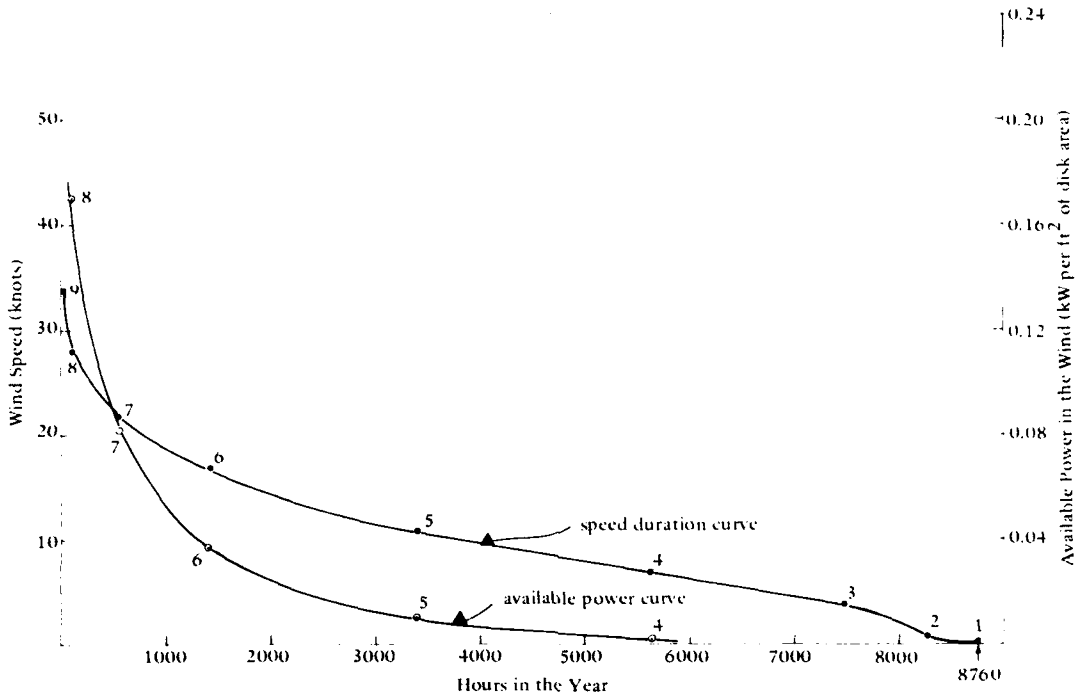


Figure 2.15. Speed and power duration curve construction.

As examples, Figure 2.16 shows three speed duration curves. Curve A is prepared from long-term data from a site at Adak, Alaska, with an annual average wind speed of 14.05 mph. Curve B is plotted from existing data for a location at San Nicolas Island, 60 miles off the coast of Port Hueneme, with an average speed of 11.40 mph. Finally, Curve C represents the speed duration plot for a location at Point Mugu with an average speed of 6.45 mph. These plots clearly show the great difference that can exist between wind regimes at two sites such as San Nicolas Island and Point Mugu, which are separated only by a short distance of about 60 miles. The examples also show the superiority of a good site such as the one corresponding to Curve A at Adak, Alaska.

In Figure 2.17, the speed duration curves for the three sites are converted to power duration plots by using Equation 2.1b. The difference in the wind regimes at the three sites when viewed in light of the available power becomes much more pronounced, and it shows that only sites A and B will have potential for economic power generation.

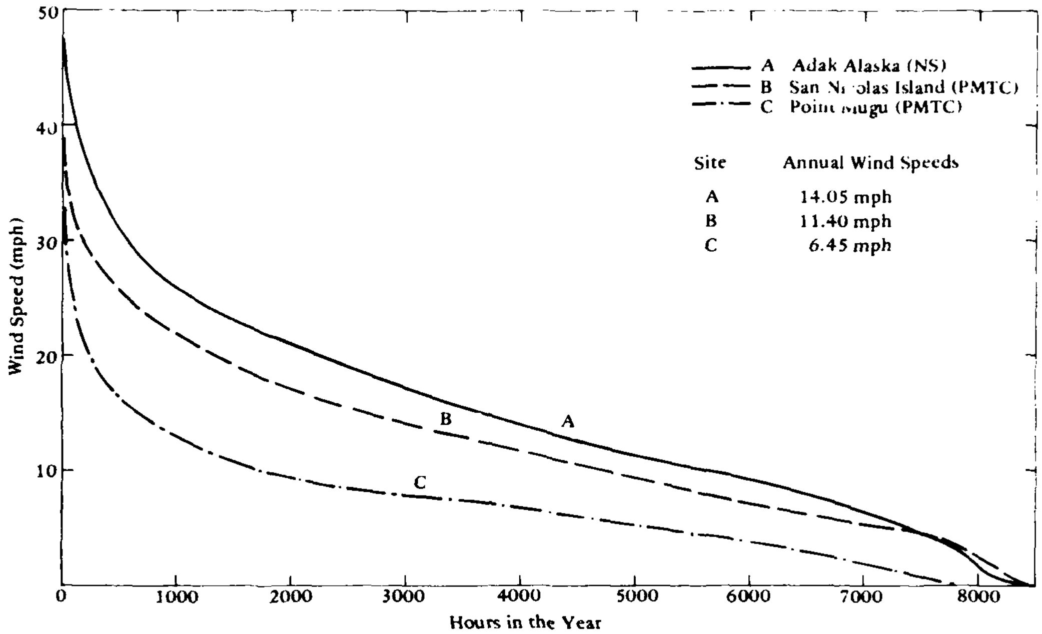


Figure 2.16. Speed duration curves for three Navy sites.

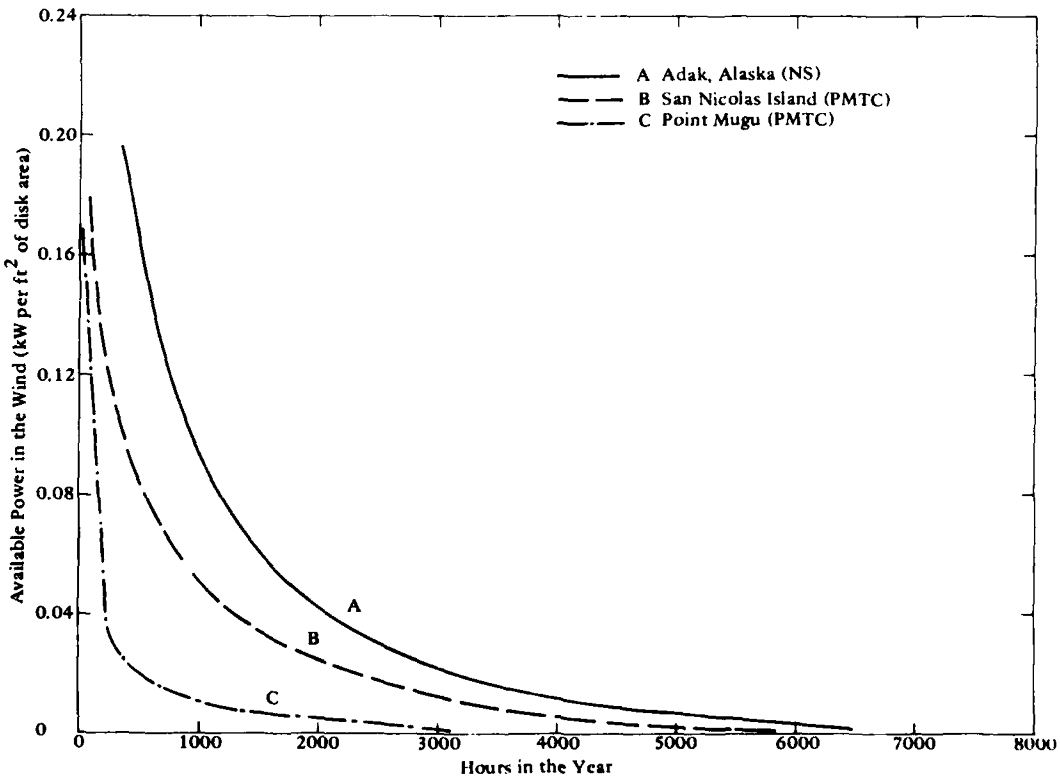


Figure 2.17. Power duration curves for three Navy sites.

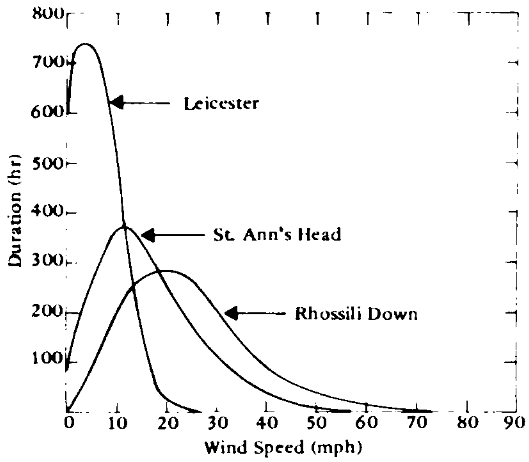


Figure 2.18. Wind speed frequency curves.

2.4.2 Speed Frequency Curves

These represent the annual hours of duration of various wind speeds at a given location plotted against the magnitude of wind speeds as an abscissa. Frequency of wind speed data must be available for a given wind speed value and not the ranges of wind speed, as given in Table 2.4. Examples of frequency duration curves for the three sites discussed in Reference 2.12 are given in Figure 2.18. The general shape of the curves is typical of the frequency curve for any site. It can further be stated that due to the existence of calm periods at any site, the intercept on the ordinate axis is never zero. Finally, it is concluded by Putnam (Ref 2.13) that the duration of the most prevalent wind decreases with the increase in mean speed at a site.

Frequency duration curves have not been used much in wind power work; instead, speed duration curves are preferred to present site characteristics data. However, it is more convenient to use frequency duration curves when calculating the output of a WECS at a site.

2.5 ENERGY PATTERN FACTOR

In following Golding (Ref 2.12), the "energy pattern factor," terms X(U) of a given site, can be defined as:

$$X(U) = \frac{\langle\rho\rangle \int_{0}^{T} u^3(z,t)\, dt}{\langle\rho\rangle\, U^3(z)\, T} \qquad (2.16)$$

where $U(z)$ is the average wind speed taken over a period of time, T, which is normally a month or a year. In other words, $X(U)$ is defined as the ratio of actual energy in the undisturbed wind stream passing through a unit disc area to the energy calculated from the cube of the mean wind speed taken over a period of time, T, for the same disc area. As is clear from Equation 2.16, $X(U)$ is a function of the average wind speed, U, which in turn is a function of the averaging interval, T, for durations less than a year. Hence, $X(U)$ is a function of the averaging interval, T, as well. As derived in Reference 2.14, an alternative expression for $X(U)$ is:

$$X(U) = 1 + 3 \frac{\langle u^2 \rangle}{U^2}$$

where the quantity $\langle u^2 \rangle / U^2$ is related to the turbulent intensity at a site. Based upon the results of Equation 2.17, some important conclusions about the energy pattern factor can be derived immediately as follows:

1. *Since the turbulent intensity for a site is a positive quantity,* $X(U)$ is always greater than unity.

2. *The turbulent intensity and, hence, the quantity* $\langle u^2 \rangle / U^2$ *for a* site over a short period of time (less than an hour) is very small. Hence, the quantity $X(U)$ for periods on the order of an hour or less is very close to unity.

3. Next, in the atmospheric layers close to the ground, the size of turbulent eddies is unaffected by the average wind speed. Thus, the quantity $\langle u^2 \rangle / U^2$ decreases with increasing average wind speed (U) of the site. It can, therefore, be stated that the quantity $X(U)$ decreases with an increase in the average wind speed (U). This is demonstrated by plotting actual values of $X(U)$ as a function of U in Figure 2.19, which shows variation of annual energy pattern factor with average wind speed for the Pacific Northwest.

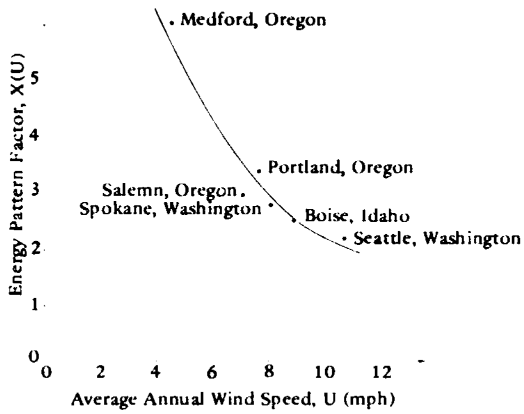


Figure 2.19. Variation of annual energy pattern factor with average wind speed for a region in the Pacific Northwest.

Generally, the X(U) for any site can be computed from its monthly or yearly speed duration curves by numerical integration of Equation 2.16. One important use of the energy pattern factor concept is to show how misleading it is to compute available energy based upon the cube of the long-term mean wind speeds taken over a period of a month or longer. On the other hand, the energy pattern factor values based on short periods of time (an hour or less) are generally small and, hence, inclusion of their effect into available energy estimates can be neglected. Thus, in testing WECS in the open atmosphere, the data taken by averaging continuously over a small time interval of about 5 to 20 minutes yield satisfactory estimates. This procedure of data collection minimizes scatter in the data due to its random nature. For a given region, the concept of X(U) is extremely useful in calculating the available energy in the wind simply from the knowledge of annual mean speed. The concept of energy pattern factor is extremely useful while siting WECS at a location with limited wind data because the long-term data from neighboring stations can be utilized to correlate with the on-site short-term measurements to predict WECS performance.

2.6 WIND CHARACTERISTICS AND POWER PRODUCTION

Generally, the winds in the planetary atmospheres are a large-scale phenomenon resulting from a gradual surface temperature gradient, which causes the air to move from one latitude to another. The resulting direction of such winds is greatly influenced by the speed of the earth's surface due to its rotation about the central axis, which varies from a value of about 1,000 mph at the equator to zero at the poles. This influence is further compounded by atmospheric pressure differences that cause air to flow from a region of high pressure into one of low pressure. Throughout the year under average conditions, two bands of high pressure circle the earth, each one situated between approximately 30° and 40° latitude in the two hemispheres. There also exists a belt of low pressure (called "doldrums") along the equator that causes trade winds to blow along the northeasterly direction between 30°N and the equator (Figure 2.20) and southeasterly between 30°S and the equator. The pressure difference belts also give rise to the persistent westerly winds between 40° and 60° latitude in both north and south hemispheres, respectively. Due to this mesoscale phenomenon, it is possible to predict the prevailing wind direction in many parts of the world with some success. The direction of trade winds is often affected by storms and cyclonic depressions.

A knowledge of the prevailing direction of the wind is important in determining the exposure of a prospective site. Frictional effects due to trees, broken and uneven ground, buildings or other obstructions, and local surface temperature gradients greatly influence wind flow at low altitudes. A good site always has a full exposure to the prevailing wind flow.

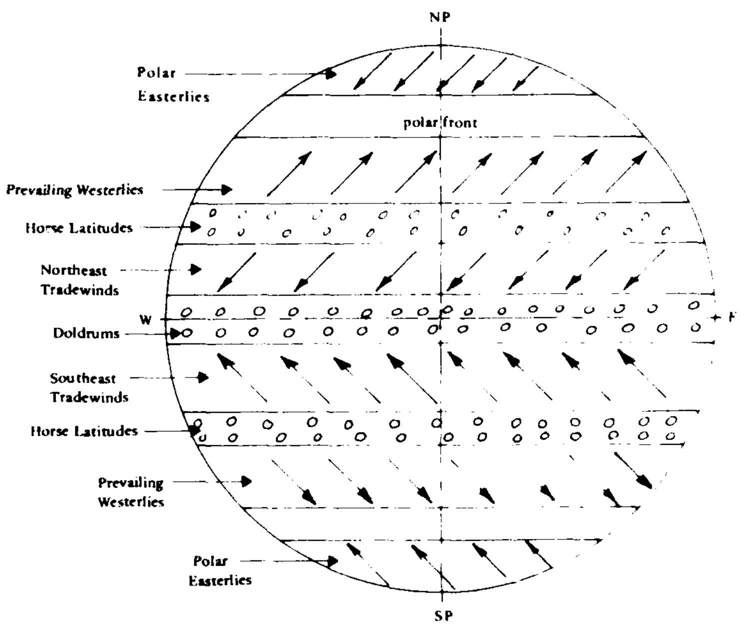


Figure 2.20. Idealized belts of prevailing winds in the atmosphere based on the three-cell model.

When considering the use of wind for power production, the following factors about the wind behavior must be considered:

1. *At what Naval locations in CONUS and overseas is there sufficient wind to be economically useful?*

2. What annual amounts of wind energy can be expected for Navy wind application?

3. What is the distribution of wind in time (during the day, month, or year, or even over longer periods)?

4. What are the probable directions of very high wind speeds, or of calm periods, during any given period?

2.6.1 Naval Potential of Wind Energy

Two important considerations enter the practical utilization of wind: (1) the annual average wind speed and (2) the cost of power generation by present methods, such as a diesel engine or a public utility. The practical and economical utilization of wind power is governed by the above two factors, including the annual capital charges and O&M costs for the WECS system. An annual average wind speed that makes wind power economical at a site where the cost of power generation is high might not be so at another site where the cost is lower. A relationship of the wind power generation economics as a function of annual average wind speed of a site will be developed in Chapter 6.

Extensive investigations show that, generally, a site must have annual average wind speeds of at least 10 mph for cost-effective wind power generation. There are at least 177 facilities out of a total of 377 Naval shore establishments that are characterized by an average wind speed of 8 mph. The wind speeds of 8 mph are based upon surface winds with no effort to locate instrumentation in regions of high winds, whereas a normal WECS will be located at least 33 feet above the ground where prevailing winds will be higher. It is possible that many of the sites with 8-mph average wind speeds have local sites with 10-mph wind speed potential. A majority of such installations are required to conduct critical missions and are located on remote islands and isolated hilltops. Most remote sites, in general, have an abundance of some form of local energy, such as wind. Because of the higher cost of supplying fuel to such locations, the WECS have potential to deliver power at a cost comparable to that from fossil fuel power plants. If energy storage is utilized, wind power generation could replace conventional plant capacity as well as save fuel. There are other applications of wind power, which include wind-driven heat pumps to operating desalination plants.

Table 2.5 lists wind characteristics for some of the Navy locations in the United States and overseas. Most of the data in the table have been extracted from the report, "Wind Power Climatology in the United States" (Ref 2.15), and the data have not been corrected for varying heights of the wind anemometer. Also, possible distortions in the wind flow pattern by natural terrain features, trees, and buildings are not accounted for on this basis; no particular set of these data can be blindly accepted as representative of a particular region. The States are listed first, alphabetically, then the other overseas locations. The information listed in the table is as follows:

1. Average wind speed in miles per hour

2. Average annual power available in the wind in watts per square foot of the disc area

3. Average monthly power (for all 12 months) available in the wind in watts per square foot of the motor area

2.6.2 Variations of Average Wind Speed With Time

These variations must be considered for (1) daily or diurnal, (2) monthly, (3) yearly, and (4) long-term periods. The wind speed and direction data based on long-term measurements covering the above factors are available from the National Weather Center.

Table 2.5. Monthly Average Available Power at Various Naval Sites in the United States and Overseas

State	Location	Annual Average Wind Speed (mph)	Available Power in the Wind, watts/ft^2												
			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AK	Adak, NS	14.05	1,501.3	132.0	144.6	163.5	140.3	113.3	69.1	67.5	79.90	102.5	155.5	149.0	162.6
AK	Barrow, NARL	12.44													
AK	Cape Prince of Wales	21.76													
AK	Dutch Harbor, NS	11.05	865.9	109.9	116.4	91.4	69.1	41.8	38.7	21.4	32.5	52.3	120.8	129.8	82.4
CA	El Centro, NAAS	8.87	472.0	30.3	39.0	53.0	64.4	69.7	58.5	24.8	22.6	24.5	26.6	30.3	23.5
CA	San Bruno	10.94	654.0	29.7	39.9	56.7	70.6	83.0	86.7	73.0	63.3	53.0	43.7	24.8	28.2
CA	San Nicolas Island, PMTC	11.40	776.7	47.1	61.6	91.4	94.8	107.8	75.6	49.9	51.4	50.8	43.4	55.7	49.2
CA	Treasure Island, NSA	10.65													
CA	San Francisco	10.6													
DC	Washington National	9.90	390.19	43.9	46.8	50.5	41.5	29.4	25.4	19.2	13.6	20.7	26.3	31.9	33.13
FL	Key West NAS	10.94	486.81	48.9	53.3	53.3	54.5	37.8	30.3	24.2	22.0	41.2	41.2	43.0	45.5
FL	Mayport NAAS	8.29	286.14	25.4	32.5	28.5	27.9	20.7	20.7	12.4	12.1	34.1	27.9	22.9	21.0
FL	Orlando	9.44	360.46	26.6	34.1	40.6	37.2	30.7	25.7	21.4	26.3	28.2	33.1	30.7	30.0
FL	Pensacola Ellyson Field	8.98	289.85	26.9	32.2	35.9	34.7	26.6	19.2	14.9	13.6	20.1	17.6	22.9	25.0
GA	Atlanta	9.4													
HI	Honolulu IAP	11.28	568.57	36.5	40.6	50.8	50.5	48.0	53.3	58.5	60.1	43.6	39.6	41.2	47.4
HI	Barbers Point NAS	9.56	353.03	32.8	30.7	32.2	31.6	28.8	30.03	31.0	31.6	23.9	23.5	32.2	29.4
HI	Kaneohe Bay MCAS	11.52	523.97	40.5	44.6	48.6	48.3	43.3	42.4	44.3	44.3	35.9	35.0	41.80	52.0
HI	Kaneohe Bay	11.28													
HI	Kahului NAS	12.78	1,029.67	62.8	63.2	74.3	85.5	103.7	113.3	116.1	116.7	87.6	67.8	76.5	61.9
IL	Glenview NAS	9.67	471.9	50.8	50.8	62.8	63.8	42.4	25.7	17.3	16.1	22.3	32.5	44.3	42.4
IN	Indianapolis	10.8													
KS	Olathe NAS	10.59	501.67	44.3	48.6	65.3	57.9	43.0	36.2	21.4	21.4	28.2	31.6	47.0	42.1
KY	Louisville WBAS	8.64													
LA	New Orleans	9.0													
MA	Boston, Logan IAP	13.59	843.62	97.25	99.41	97.25	83.00	60.39	46.46	39.64	33.45	40.57	40.57	71.23	85.79
MA	South Weymouth NAS	8.75	334.48	38.71	38.71	45.22	42.12	26.01	17.96	13.32	17.34	16.41	21.99	28.49	31.59
MA	Nantucket	13.36	828.76	94.15	107.16	92.29	85.79	58.84	43.36	32.21	35	52.34	66.28	80.83	92.29
MD	Patuxent River NAS	9.32	442.21	49.2	54.8	57.6	45.8	30.04	23.53	18.27	18.27	25.7	31.59	42.74	43.05
MD	Baltimore, Friendship APT	11.05	609.49	63.80	78.35	82.07	64.73	47.07	36.23	29.73	24.47	34.07	36.23	55.43	58.22
MD	Aberdeen, Phillips AAF	9.1	405.09	39.02	52.65	53.57	48.62	29.42	20.44	16.10	17.03	21.37	29.42	37.47	36.54
ME	Brunswick NWSED	8.18													
MN	Alexandria	12.32	851.06	68.44	66.59	81.14	89.81	77.12	62.56	39.14	49.86	56.37	81.45	81.45	60.7
NJ	Lakehurst NAS	8.52	345.96	41.2	49.0	51.5	40.6	29.1	19.2	15.2	12.7	14.9	18.6	30.7	33.8
NJ	Trenton	9.33	390.22	38.71	45.22	45.22	60.08	26.32	21.99	14.56	17.03	21.68	28.49	43.36	37.16

continued

Table 2.5. Continued

State	Location	Annual Average Wind Speed (mph)	Available Power in the Wind, watts/ft^2												
			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NY	New York, Kennedy IAP, NSA	11.86	624.36	74.95	80.21	80.52	63.18	46.76	43.05	37.78	32.83	37.16	43.36	53.58	55.75
NY	Rochester	11.2													
NC	Cape Hatteras	12.21	628.07	60.39	70.92	64.73	62.56	44.60	42.74	36.23	41.81	55.75	49.55	51.41	52.03
OH	Columbus	8.29	304.74	33.76	36.55	42.12	35.93	22.92	16.10	11.46	16.84	13.63	17.03	30.97	28.86
PA	Philadelphia	9.79	342.79	40.57	43.05	52.65	41.19	28.80	24.17	19.20	16.10	18.89	26.01	29.42	33.76
RI	Quonset Point NAS	9.67	457.12	50.79	50.79	50.48	48.31	37.47	26.01	18.89	21.68	25.71	35.62	41.81	43.67
RI	Providence	10.7													
SC	Charleston	8.64	301.03	28.8	38.4	40.26	36.23	21.37	19.82	16.72	16.10	19.51	18.27	21.98	25.09
TN	Memphis	9.4													
TX	Kingsville NAAS	9.79	471.38	34.38	40.26	50.17	56.68	52.96	48.62	43.98	35.62	33.14	23.85	32.21	30.35
TX	Corpus Christi NAS	13.01	780.44	64.73	71.85	84.23	88.57	81.45	69.68	58.53	47.38	46.46	44.60	63.80	53.27
TX	Beeville NAAS	8.41	312.18	25.09	31.28	38.40	39.95	34.38	26.32	21.99	18.89	18.58	16.10	23.54	22.30
TX	Dallas NAS	10.48	509.15	48.01	51.41	65.04	61.63	47.69	44.60	30.04	25.40	26.32	30.66	41.81	40.57
VA	Norfolk NAS	10.13	449.68	47.69	56.37	52.96	43.05	31.90	26.01	23.23	24.78	34.38	39.33	40.26	39.64
VA	Oceana NAS	8.75	364.21	41.81	42.12	46.46	39.02	26.01	19.20	16.10	16.10	25.76	28.80	30.04	33.14
WA	Seattle, Tacoma	10.94	524.01	60.06	65.04	65.35	53.58	40.26	37.16	29.11	26.01	32.21	41.81	47.53	60.39
	Barbado, West Indies, Seawell	12.5													
	St. George, Bermuda NWSED	12.09													
	Roosevelt Roads, Puerto Rico NWSED	9.56													
	Agana, Guam NWSED	9.10													
	Keflavik, Iceland FWF	14.74													
	FWF Argentia, Canada	18.19													
	Wake Island	13.24													
	NWSED Yokosuka, Honshu, Japan	10.25													
	San Salvador Islands, AAFB	11.28													
	Attu Aleutian Islands NAU	13.01													
	Midway Islands NS	11.87													
	Rota, Spain	8.18													
	Sigonella, Sicily NWSED	8.64													

1. Diurnal Variations. In summer, a lowering of temperature with increasing altitude produces thermal convection and a resultant intermixing of air at various altitudes. Thus, momentum of the higher speed upper air (geostrophic flow) is transmitted downward to the lower layers resulting in an increase in wind speed. Generally, therefore, there is a trend toward higher wind speeds during the day than at night. Up to 15 to 20 miles inland from the coast, land and sea breezes occur. Relatively rapid increase in temperature of the land during the day causes sea breezes and less rapid cooling of the sea at night which, in turn, causes a wind from land to sea. The curves of diurnal variation in wind speed for Oak Ridge, Tenn., for various heights above ground, are shown in Figure 2.21. Next, Figure 2.22 shows curves for diurnal variation in wind speed for three stations located in various regions of the United States, namely, Livermore, Muskegon, Coast Guard Station, and Oak Ridge. The wind speed curve for Livermore shows a more pronounced diurnal variation in speed, second in order clearly is the curve for Oak Ridge. For a cost-effective application, a good correlation between wind speed and the load demand is extremely important. An optimum match between the diurnal variation in wind speed and the load demand can reduce the plant capacity as well as displace fuel. For a stand-alone system with storage at a remote site, such a match results in minimum size storage required to serve a given load.

2. Monthly Variations. Day-to-day variations of wind speed and direction are often great and usually somewhat unpredictable in advance for a site where WECS utilization is being considered (see Figure 2.23). The monthly average wind speed for a given location varies widely throughout the year. As can be seen from Table 2.5, the magnitude of the average monthly wind speed for a location can vary markedly. Generally, for most sites located in CONUS, the winds are stronger in the winter, which is desirable because the increased demand for energy occurs at the same time as well. Figure 2.24 shows plots of monthly variations in wind speed for three CONUS sites, and Figure 2.25 gives plots of the available power in the wind for the same sites. Clearly, the stronger winds at the three sites are encountered during winter and spring. Once again, for a cost-effective application of wind power at a Navy site, a good correlation of wind with the demand must be maintained.

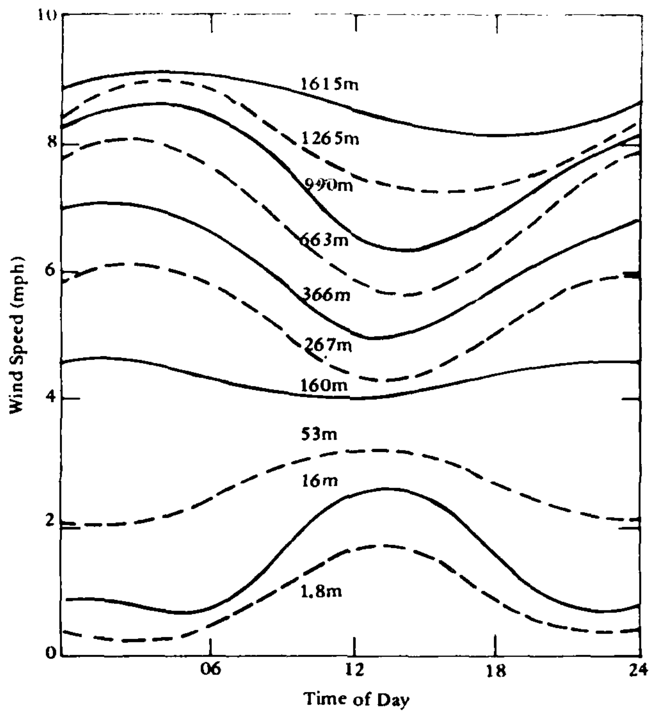


Figure 2.21. Daily curves of wind speed for several heights above the ground at Oak Ridge, Tennessee (5-year averages).

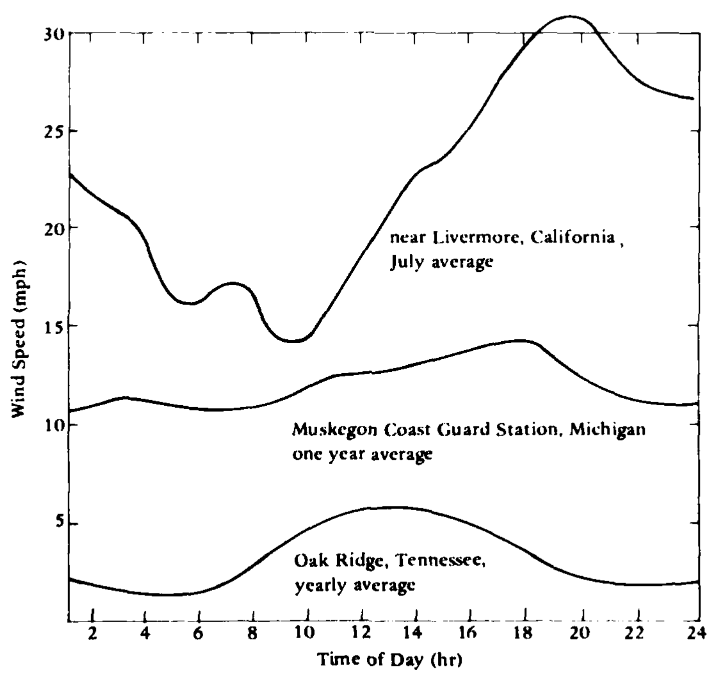


Figure 2.22. Sample daily wind variations.

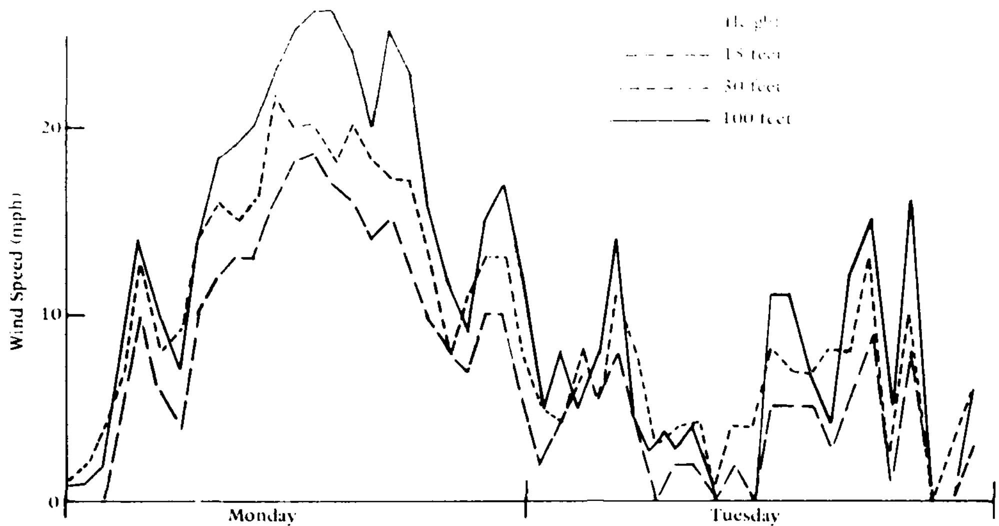


Figure 2.23. Hourly wind speeds at three heights.

3. <u>Annual Wind Patterns</u>. The measurement of annual wind speeds shows a wide variation from place to place on the earth's surface. These speeds do, however, range from under 1 mph to above 40 mph. The past wind data generally give mean hourly values throughout the year, or only the number of hours in a year for which the speed lay within certain limits, such as in the Beaufort representation. The most useful form of representation for wind power application, of course, is the speed duration curve defined earlier.

4. <u>Long-Term Mean Wind Speeds</u>. The annual mean value of wind speed over long terms does not vary much. An examination of the records for the 50 stations in the CONUS for a 30-year period reveals that none of the annual mean values fall more than 18% below the long-term average, and at 31 of the stations, the annual mean values did not fall below 12-1/2%. Hence, for wind power work, annual mean wind speeds can be considered constant over a long term.

2.6.3 Duration of High Wind Speeds and Calm Spells

A knowledge of the annual duration of high wind speeds indicates the period when a WECS system should be shut down to avoid damage resulting in loss of energy. Most WECS units will operate safely at wind speeds to about 46 mph. The annual duration of wind speeds exceeding 46 miles

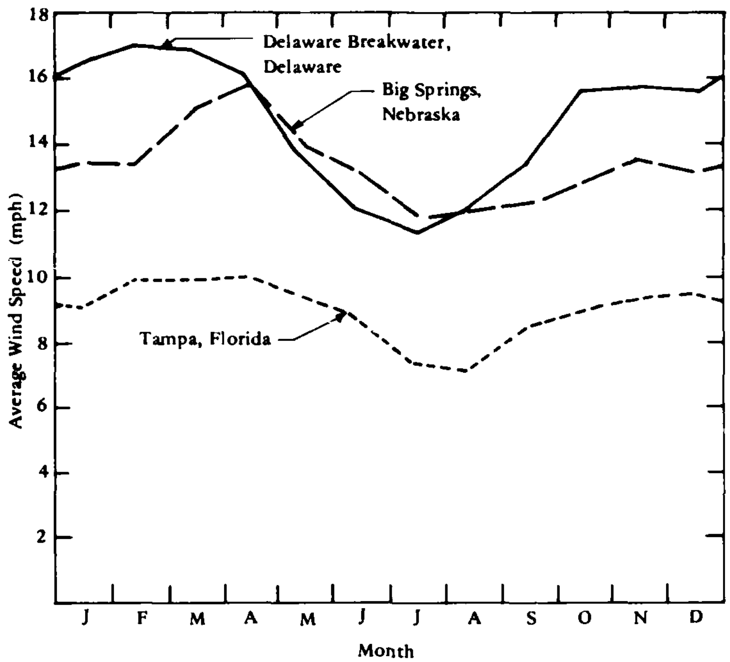


Figure 2.24. Average monthly wind speeds at three sites.

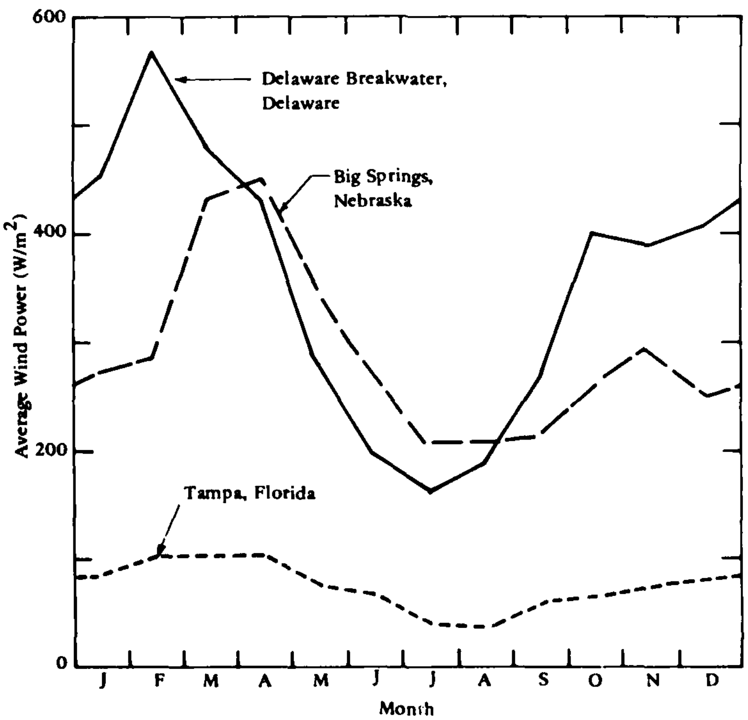


Figure 2.25. Average monthly wind power available at three sites.

against annual mean wind speed for a number of widely spaced sites is given in Figure 2.26. Clearly, the duration of wind speeds above 46 mph increases with the mean wind speed of the site.

The annual duration of calm winds is important since it indicates those times during which a storage system must be utilized. Figure 2.27 depicts an annual duration of wind speeds under 4 mph for a number of widely spaced sites. The duration of calm periods generally tends to be on the order of 30% for a site with an annual mean wind speed of 7 mph down to 3% or less for a site with an annual mean wind speed of 25 mph. When sizing storage systems for a stand-alone WECS installation, the number of consecutive hours of calm periods is extremely important. Even at moderately windy locations, a lengthy calm-wind period can occur.

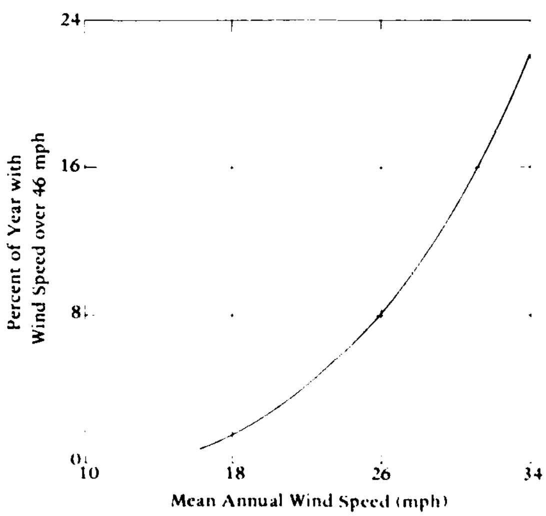


Figure 2.26. Annual duration of wind speed exceeding 46 mph as a function mean annual wind speed of a site.

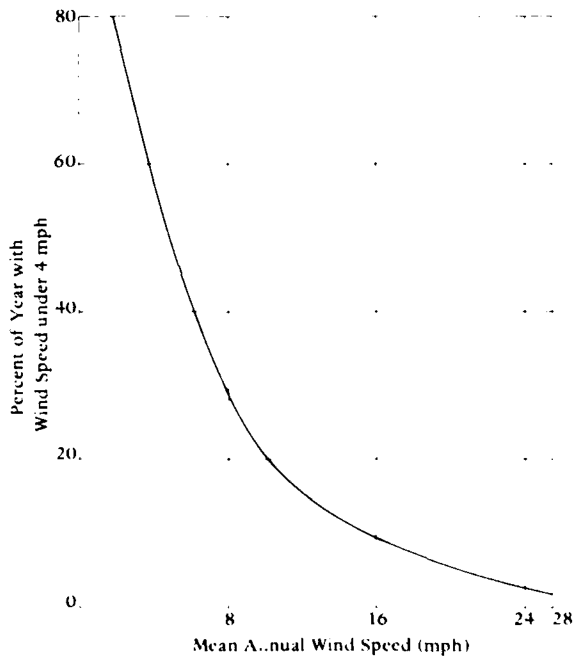


Figure 2.27. Annual duration of wind speeds under 4 mph as a function of mean annual wind speed of a site.

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Chapter 3

MEASUREMENT OF WIND BEHAVIOR

The nature of wind at a given site is very complex; the conventional measurements of "wind speed and direction" do not fully characterize it. Turbulence in the wind is responsible for the random fluctuation of the wind speed and direction. A typical example of a wind speed recording at a site is shown in Figure 3.1a. The sample recording is for a 13-minute interval in which the speed fluctuates between 6 and 13 mph. Hence, to characterize wind fully, measurements must be made to determine the turbulence or gustiness characteristics of wind flows. Proper knowledge of wind turbulence characteristics is extremely important in computing structural loading on WECS installations.

Measurement of wind behavior can, depending on the degree of sophistication required, be determined using methods that range from a wetted finger into the wind to fairly complex anemometers (Ref 3.1 and 3.2). The term anemometer will be used throughout this discussion as the generic term for describing any device used to measure wind velocity involving speed and direction.

To obtain a profile of wind behavior at any site, it is necessary to measure (Ref 3.2 through 3.5):

1. Wind speed and profile
2. Prevailing wind direction
3. Wind duration

3.1 WIND SPEED AND PROFILE

At the crude end of the spectrum of wind speed measurement methods, one that is used almost universally is the Beaufort scale, devised by Admiral Sir Francis Beaufort in 1805. The scale, which is an empirical approach to wind strength measurements, subjectively assigns (based on experienced observers) a number (B) to various strengths of wind. Table 3.1 depicts Beaufort numbers and equivalent speeds in knots, mph, and m/sec.

A wind speed and direction measuring instrument (e.g., an anemometer) is designed to yaw with the resultant wind direction, as shown in Figure 3.1b. Hence, the anemometer always measures the resultant wind speed, u, given by

$$u = \sqrt{(U_x + u'_x)^2 + u'^2_y} \qquad (3.1)$$

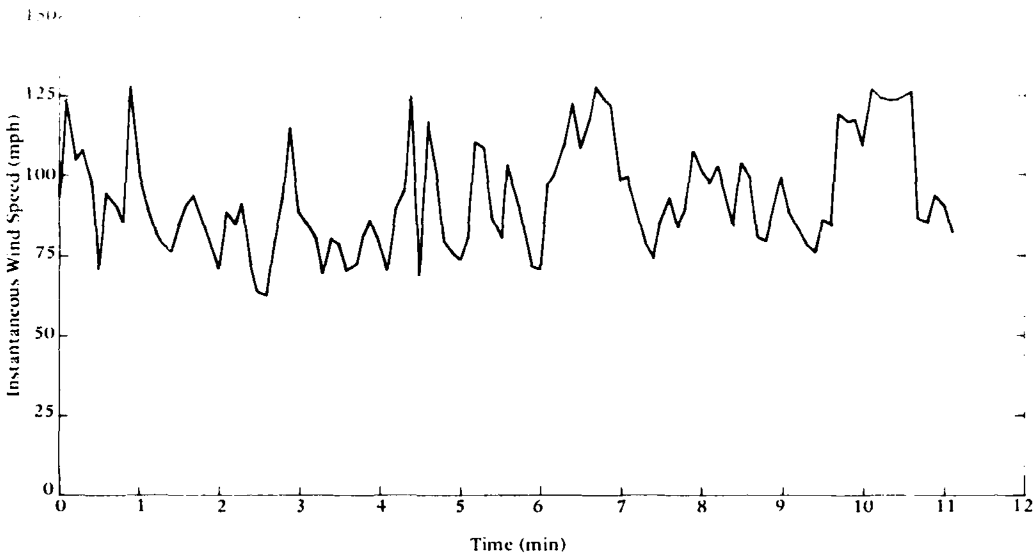
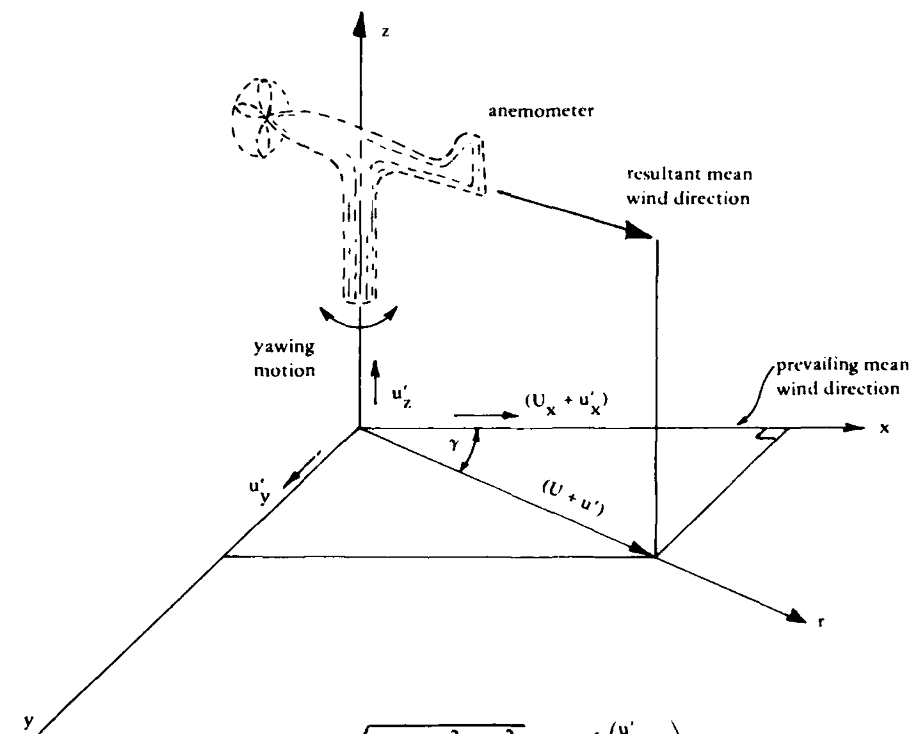


Figure 3.1a. A typical wind speed as a function of time recorded by an aneometer.



$$u = (U + u') = \sqrt{(U_x + u'_x)^2 + u'^2_y}, \quad \gamma = \sin^{-1}\left(\frac{u'_y}{U + u'}\right)$$

Figure 3.1b. A schematic of wind-anemometer interactions for measuring wind velocity.

Table 3.1. The Beaufort Scale of Wind Forces (Ref 3.3, available from Methuen Inc. in America)

Beaufort Number (B)	Description of Wind	Equivalent Mean Velocity in Knots	Limits of Mean Speed at 33 Feet Above Flat Ground in an Open Situation[a]			Mean Wind Force in lb/ft^3 at Standard Density ($P = 0.0105\ B^3$)
			Knots	Statute Miles Per Hour	Meters Per Second	
0	Calm	0	<1	<1	<0.3	0
1	Light air	2	1-3	1-3	0.3-1.5	0.01
2	Light breeze	5	4-6	4-7	1.6-3.3	0.08
3	Gentle breeze	9	7-10	8-12	3.4-5.4	0.28
4	Moderage breeze	13	11-16	13-18	5.5-7.9	0.67
5	Fresh breeze	19	17-21	19-24	8.0-10.7	1.31
6	Strong breeze	24	22-27	25-31	10.8-13.8	2.3
7	Moderate gale	30	28-33	32-38	13.9-17.1	3.6
8	Fresh gale	37	34-40	39-46	17.2-20.7	5.4
9	Strong gale	44	41-47	47-54	20.8-24.4	7.7
10	Whole gale	52	48-55	55-63	24.5-28.4	10.5
11	Storm	60	56-63	64-72	28.5-32.6	14.0
12	Hurricane	68	64-71	73-82	32.7-36.9	18
13	--	76	72-80	83-92	37.0-41.4	23
14	--	85	81-89	93-103	41.5-46.1	29
15	--	94	90-99	104-114	46.2-50.9	35
16	--	104	100-108	115-125	51.0-56.0	43
17	--	114	109-118	125-136	56.1-61.2	52

[a]Approximate corrections: for 50 feet add 10%, for 100 feet add 25%, for 20 feet subtract 10%, for 10 feet subtract 20%.

where u is the instantaneous wind speed composed of a mean value, U, and a fluctuating component, u', such that

$$u = U + u' \qquad (3.2)$$

Since the r-axis is chosen in the direction of the resultant mean wind, U(r,z), the turbulent instantaneous values of the wind are [U(r,z) + u'(r,z,t)], 0, and u'(r,z,t) in the r, y, and z directions, respectively. Now the mean value, Ū(r,z), is the time average defined by

$$\langle u(r,z,t)\rangle = \lim_{T\to\infty} \frac{1}{T}\int_0^T u(r,z,t)\,dt \qquad (3.3)$$

where U(r,z) = <u(r,z,t)>. Then by definition the mean value of the fluctuating component is zero. The averaging interval, T, can be anywhere from a few seconds to one year. For wind power work, hourly averaged readings provide satisfactory estimates of wind potential.

3.1.1 Rotating Cup Anemometers

These instruments are, perhaps, the most widely used for wind speed measurements, and consist of a group of three or four hemispherical (or conical) cups, each mounted on horizontal spokes extending outward from a central spindle. The circular rim of each cup is in a vertical plane that passes through the common axis of rotation, and the convex side of each cup faces in the direction of rotation. The basis of the instrument's function is that the wind pressure on the concave side of the cup exceeds that on the convex side; the anenometer rotates independently of wind direction. Figure 3.2 depicts a typical rotating anemometer. Wind tunnel tests for this type of instrument have shown that in steady winds up to 80 mph, the error is less than 0.6 mph.

Recording of the data taken is done by several means. For example, one type records by tilting a small cup of mercury to make contact with a battery circuit to operate any of a number of types of electromagnetic recorders. Another variation of this is the cup-generator anemometer in which cup rotation results in the revolution of a small generator. This revolution generates current in proportion to the number of revolutions per minute (rpm), which can be translated into a suitable speed measurement. Today a new breed of digital recorders employing microprocessor controls (data loggers) is becoming increasingly popular. Some have running averaging capability, including programmability.

A variant of the cup-generator type is the hand-held anemometer, which is useful in making first-cut site surveys. The instrument is a portable version of the cup-generator anemometer and will register, typically, speeds from 0 to 60 knots. Figure 3.3 is a typical hand-held anemometer.

Another form of a rotating anemometer is the lightweight windmill-weathervane type in which the wind turns a propeller mounted on a small weathervane type of tail (which heads the propeller into the wind). The rotation of the propeller generates a current via a small generator which, through the proper analog, is converted to a wind velocity reading. Figure 3.4 depicts a typical windmill-weathervane type of anemometer.

3.1.2 The Dines Anemometer

The Dines anemometer is not dependent upon mechanical rotation to provide the measurement, but rather depends upon the classical Bernoulli's equation.

$$\frac{1}{2}\rho u^2 + p = \text{Constant} \qquad (3.4)$$

where u = air velocity in ft/sec

p = static air pressure in lb/ft^2

ρ = air density in $slugs/ft^3$

i.e., the velocity head plus the static pressure equals a constant.

Typically, measurements involve recording the pressure difference between the total pressure head given by Equation 3.4 and the static pressure. The resulting pressure difference is proportional to u^2. The principle is the same as that used for the pitot-static tube airspeed measuring device used on aircraft.

Figure 3.5 depicts a section view of a typical Dines anemometer.

3.1.3 Gust Anemometers

Several types of gust anemometers are available, of which perhaps the most simple and direct is in the form of a small perforated sphere mounted at the end of a lever arm (mounted horizontally to measure vertical gusts, and vertically to measure horizontal gusts). A gust above a set threshold moves the sphere due to the increase in drag force on the sphere, and this gust force is recorded as a change in wind speed over the time it occurred. Figures 3.6 and 3.7 depict typical gust anemometers.

The gustiness in wind tunnels has been measured with hot-wire anemometers that rely on a principle analogous to the "wet-finger" technique. This method, however, is not very successful in the atmosphere because of calibration drift caused by the deposition of impurities on the sensor. Considerable interest is being shown in the sonic anemometer for making the measurements in the atmosphere. This instrument is ideally suited for measuring turbulence.

For performing wind speed profile recordings, an array of at least five sensors spaced at logarithmic height intervals is desirable. The disturbing effects of the anemometer and supports must also be recognized. An anemometer must be mounted outward from the tower at a distance greater than the diameter of the tower.

A new method of measuring wind profile in the atmosphere uses a tethered kite anemometer (Ref 3.6). The measuring equipment, consisting of a sled kite and a tail with a no-stretch tethering line, is portable and inexpensive. It is a very satisfactory tool for making wind profile measurements.

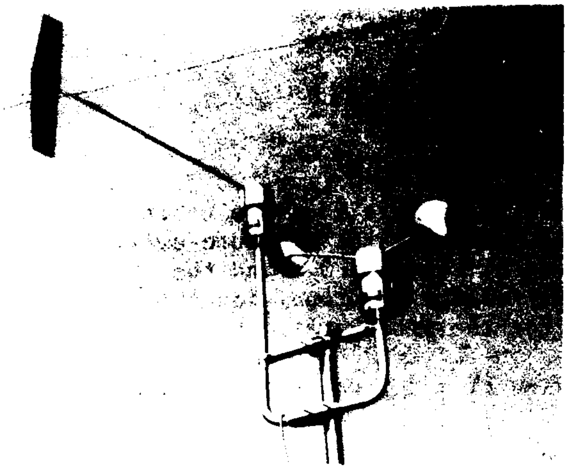


Figure 3.2. Typical rotating cup anenometer.

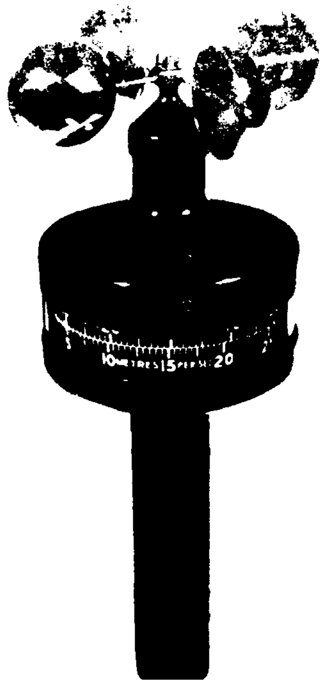


Figure 3.3. Typical hand-held anemometer.

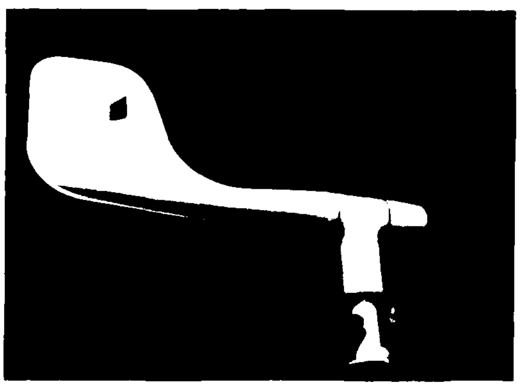


Figure 3.4. Typical windmill-weathervane type anemometer.

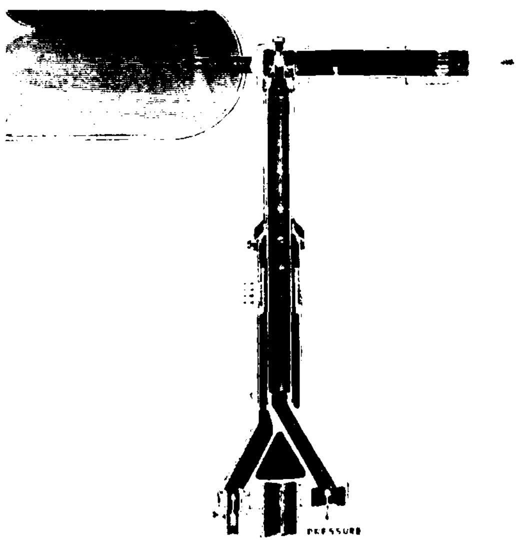
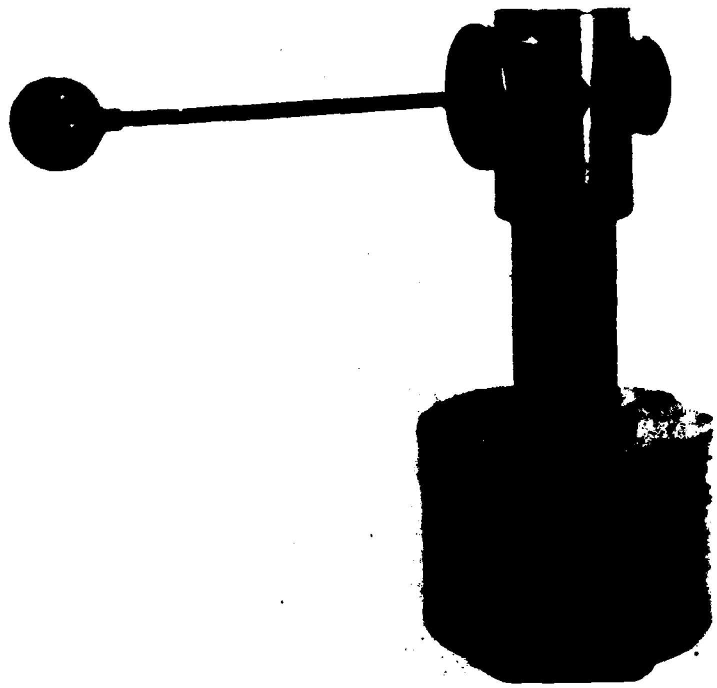
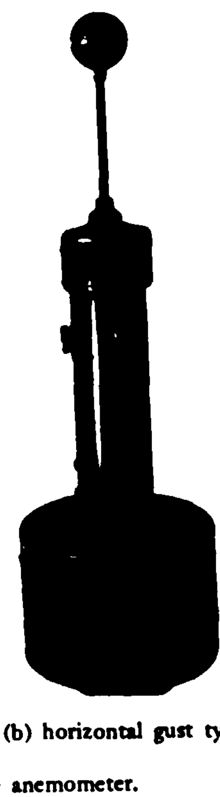


Figure 3.5. Section view typical dines type anemometer.



(a) vertical gust type



(b) horizontal gust type

Figure 4.6. Typical gust type anemometer.

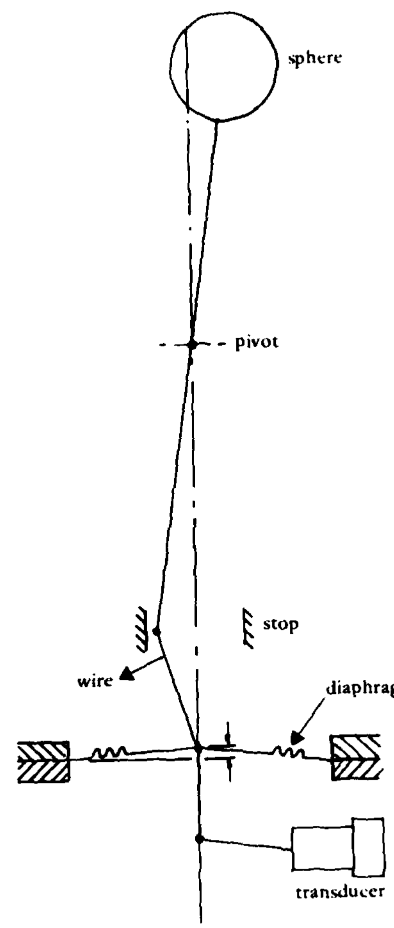


Figure 3.7. Principle of the gust anemometer.

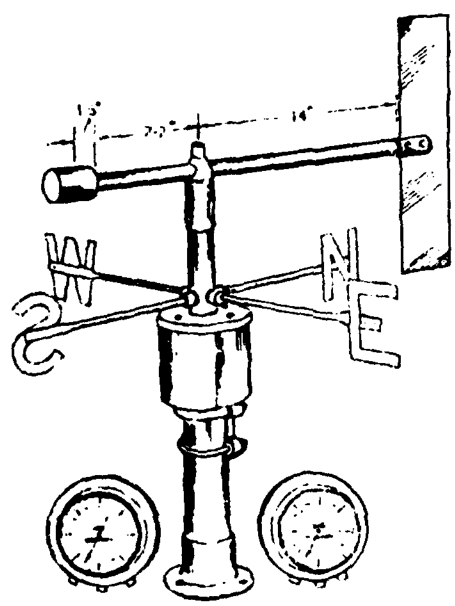


Figure 3.8. Combined wind direction indicator and anemometer.

3.2 WIND DIRECTION

For the most part, wind direction is measured by weathervane type devices which, when rotating into the wind, make contact with electrical contact points aligned with a compass rose, thus giving a direction of the wind. Figure 3.8 presents a wind direction indicator combined with an anemometer. As shown in Figure 3.1, the direction measured by a vane is γ with the x-axis and is random in nature. The higher the turbulence in the wind is, the higher the random variation in wind direction is.

3.3 WIND DURATION

Anemometers referred to in 3.1.1 above are generally equipped with small digital recorders or paper type recorders which, via counting a level of rpm, can record its duration (as a wind speed duration) either directly on a counter or on a paper tape.

3.4 REFERENCES

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3.6. R. W. Baker, R. L. Whitney, and E. W. Heneson. "Wind profile measurements using a tethered kite anemometer," in Proceedings of the National Conference, Spring 1979, San Francisco, Calif., Apr 16-19, 1979, pp 115-119.

Chapter 4

WIND ENERGY CONVERSION SYSTEMS

The power in the wind at any moment is the kinetic energy in a mass of air moving at a given speed in some particular direction. To convert this power or a fraction of it into usable power, it is necessary to place in the path of the wind some machine that retards it, thus resulting in a transfer of power from the wind to the machine. Since wind power is proportional to the cube of the wind speed, reduction of this flow speed diminishes the power in the wind, and the output of the machine is that lost by the wind except for the inherent aerodynamic losses that must occur in the conversion. The wind machine must either move along the wind against a back pressure as a sail of a ship or remain stationary but capable of rotating about an axis that exerts a braking effect. This report is concerned with the second kind of wind machines only.

4.1 THE EXTRACTION OF POWER FROM THE WIND

A. Betz in 1927 applied the simple momentum theory to wind turbine performance calculations (Ref 4.1). The following analysis outline covers the essential points of Betz's analysis.

As shown by the flow configuration of Figure 4.1, the retardation of the wind flow through the wind turbine occurs in two stages, one before and one after its passage through the turbine rotor. Then,

u_1 = wind speed at a considerable distance upwind (prevailing wind speed)

u_R = wind speed actually through the rotor

u_2 = wind speed a considerable distance downwind of the rotor

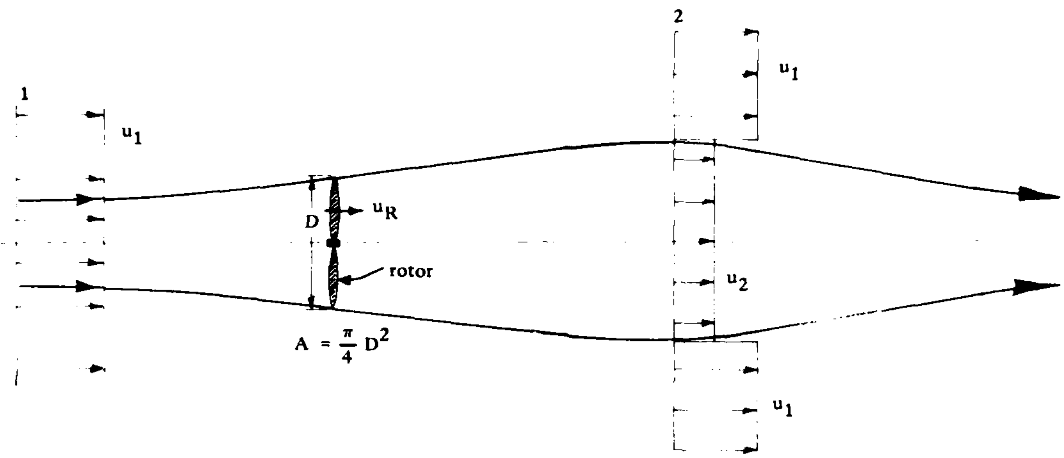


Figure 4.1. Flow configuration through a wind turbine rotor.

Further, if m is the mass of air flowing through the rotor in unit time, the rate of change of momentum M is

$$M = m(u_1 - u_2) \tag{4.1}$$

which is equal to the rotor thrust, T. Hence, the power absorbed by the rotor is given by

$$P_w = M\,u_1 = m(u_1 - u_2)\,u_R$$

Again, the rate of change of kinetic energy in the wind is (1/2)m $(u_1^2 - u_2^2)$. Since the power absorbed by the rotor must be equal to the rate of change of kinetic energy in the wind,

$$u_R = \frac{u_1 + u_2}{2} \tag{4.2}$$

After substituting for u_R into the expression for power (P_w) and also realizing that the mass flow rate (m) through the rotor is $m = \rho A u_r$,

$$P_w = \frac{\rho\,A\,u_1^3}{2}(1 - a)(1 + a)^2 \tag{4.3}$$

where $a = u_2/u_1$ is called the interference parameter and is related to the induced drag due to the pressure of the machine in the flow field. The maximum value of power (P_w) in Equation 4.3 occurs for a = 1/3 and is

$$P_{wmax} = \frac{16}{27}\left(\frac{\rho A u_1^3}{2}\right) \quad (4.4)$$

The maximum value of rotor thrust is

$$T_{rmax} = \frac{8}{9}\left(\frac{\rho A u_1^2}{2}\right) \quad (4.5)$$

Hence, from Equation 4.5 it can be seen that the maximum fraction of the power in the wind that could be extracted by an ideal wind turbine is 16/27 or 0.593. If this fraction is applied, the formula for the maximum possible power theoretically obtainable is $0.593(\rho A u_1^3/2)$. The associated value of maximum rotor thrust from Equation 4.5 is $0.444 \rho A u_1^2$. To give some idea of the possibilities, Table 4.1 has been prepared showing power and associated rotor thrust values for different wind speeds and different areas swept by the rotor of the WECS.

Table 4.1. Maximum Power and Thrust Values of Various Size Rotors at Different Wind Speeds

$[P_{max} = 0.593(\rho A u_1^3/2),\ T_{rmax} = 0.444(\rho A u_1^2)]$

Wind Speed (mph)	Power (kW) From Various Rotors			Thrust (lb) on the Rotor for Various Rotors		
	12.5 Feet	25 Feet	50 Feet	12.5 Feet	25 Feet	50 Feet
10	0.38	1.5	6.0	27.90	111.60	446.4
20	3.08	12.3	49.2	111.60	446.4	1,785.4
30	10.4	41.6	166.4	251.1	1,004.3	4,017.2
40	24.6	98.4	393.4	446.4	1,785.4	7,141.7
50	48.2	192.8	771.2	697.4	2,789.7	11,158.8
60	83.2	332.8	1,331.2	1,004.3	4,017.2	16,068.7

4.1.1 Power Coefficient and Rated Wind Speed

Because of aerodynamic imperfections in any practical machine and of mechanical and electrical losses, the power extracted is less than that calculated above (see Table 4.1). So that, in practice, the multiplying factor in Equation 4.4 cannot be greater than about 0.40 or less (Ref 4.2). Hence, for a WECS with its rotor axis located at an elevation, z, above the local ground, the instantaneous power output, $P_w(z,t)$, is

$$P_w(z,t) = C_p(u) \frac{\rho A u^3(z,t)}{2} \tag{4.6}$$

where the factor $C_p(u) = P_w(z,t)/(1/2)\rho A u_1^3$ is called the "power coefficient" of a wind turbine. Next, the maximum thrust on the rotor given by values in Table 4.1 can be less than the factor 0.444. Hence, for an actual wind turbine rotor, the thrust, T_r, is given by

$$T_r = C_T \rho A u_1^2 \tag{4.7}$$

where the factor $C_T(u) = T_r/\rho A u_1^2$ is called the rotor "thrust coefficient."

Another parameter of interest in the theory of wind turbines is the "rated wind speed" (i.e., the lowest wind speed at which the full output is produced). At wind speeds higher than rated, the output of the machine is limited to the rated output through the rotor blade pitch control mechanism. Usually, at wind speeds two to three times the rated speeds due to excessive rotor thrust, the machine must be furled or stopped. The wind speed at which this happens is called the "cut-out" or "furling speed." Likewise, the lowest wind speed at which the rotor starts to produce usable power is known as the "cut-in" speed. Figure 4.2 shows the output versus wind speed characteristics of a 20-kW WECS and also illustrates the various terminology used in the field. The broken line shows the output characteristics of a constant speed rotor whereas the solid line shows the output curve for a variable speed design. In the range of wind speeds between the rated speed and the furling speed, the broken line gives the output of an unfeathered rotor. Overall, the output from a constant speed machine is generally less than that from a variable type.

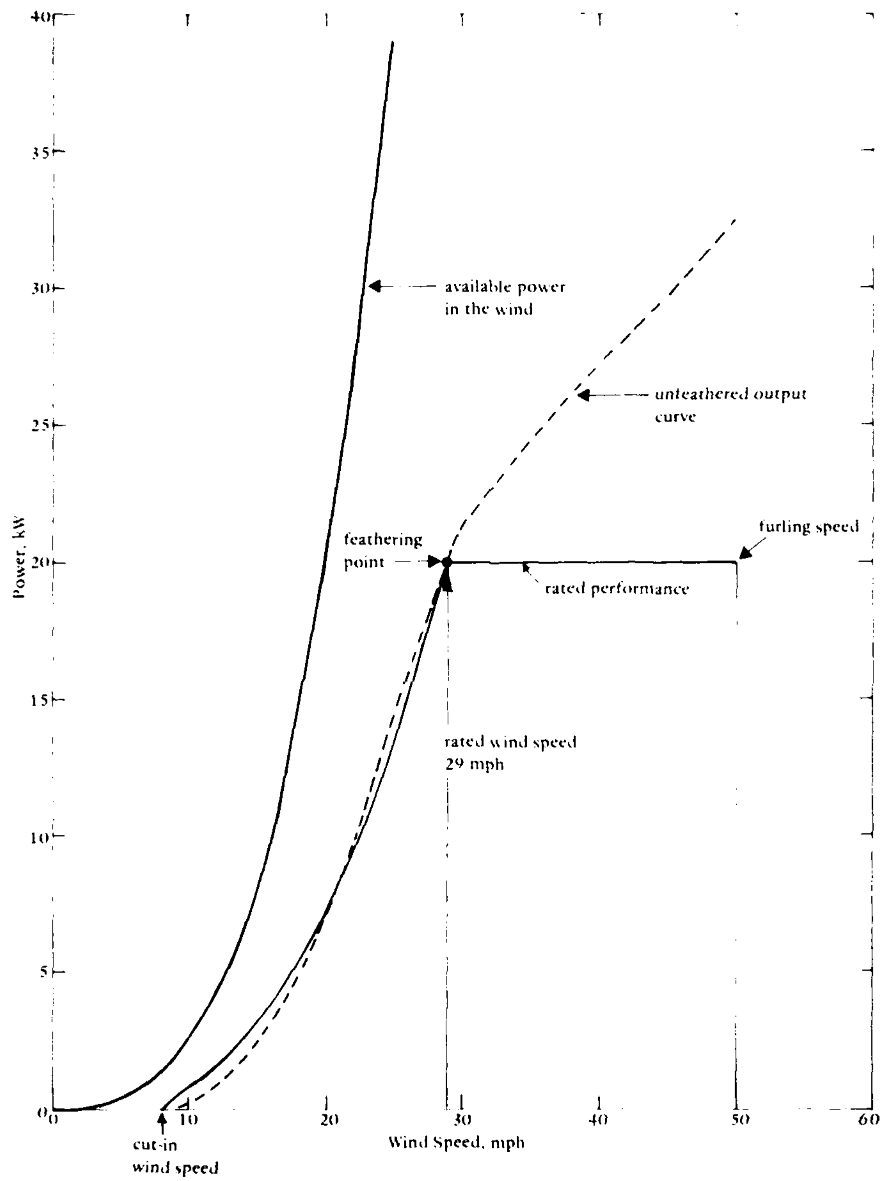


Figure 4.2. A plot of output versus wind speed for the 20-kW WECS.

The power coefficient, C_p, for a given plant is easily obtainable from its design and performance characteristics by solving Equation 4.6 for C_p. As an example, the values of $C_p(u)$ for the 20-kW WECS selected for demonstration at the Marine Corps Air Station, Kaneohe, Hawaii, were calculated and are listed in Table 4.2. The values of C_p for the variable speed system vary from 0.329 at a wind speed of 9 mph to about 0.328 at the rated wind speed of 29 mph. The plot of $C_p(u)$ as a function of u for the 20-kW variable speed WECS is shown in Figure 4.3. For an optimum energy conversion, a variable speed rotor machine must be operated at a fixed tip-speed-to-wind-speed ratio, thus resulting in a constant C_p for all wind speeds between cut-in and rated wind speed values. Due to deviations from a fixed tip-speed-to-wind-speed operation, and also due to variable losses in the transmission and the generator (which depend on wind speed), a constant C_p is not realized (Ref 4.3). Also for comparison, the $C_p(u)$ for a 20-kW constant speed rotor WECS with a design speed of 23 mph was calculated as a function of wind speed (Table 4.2) and the values are plotted in Figure 4.3. Clearly, for wind speeds less than 21 mph, the C_p for a constant speed rotor turbine is much less than the corresponding data for the variable speed rotor turbine. Since most WECS systems will be installed at locations where most of their operation will be below the rated speed, the output of a variable speed rotor is generally higher than that of a constant speed system.

4.1.2 Output Duration Curves and Specific Output

The total energy output of a wind turbine over a time period, T (generally a month or a year), is obtained by integrating Equation 4.6 as

$$E_w = \frac{\rho A}{2} \int_0^T C_p(u)\, u^3\, dt \qquad (4.8)$$

Table 4.2. C_p and Power Output as a Function of u for a 20-kW Wind Turbine Generator of the Variable Speed and Constant Speed Types

Wind Speed (mph)	Variable Speed Operation		Constant Speed Operation	
	$C_p(u)$	Output (kW)	$C_p(u)$	Output (kW)
8	0	0	0	0
9	0.329	0.595	0.085	0.154
10	0.375	0.934	0.145	0.361
11	0.382	1.270	0.195	0.648
12	0.385	1.662	0.234	1.01
13	0.388	2.130	0.264	1.45
14	0.387	2.655	0.285	1.95
16	0.384	4.032	0.320	3.27
18	0.379	5.522	0.345	5.03
20	0.373	7.450	0.363	7.25
22	0.365	9.710	0.370	9.84
24	0.356	12.29	0.366	12.64
25	0.351	13.71	0.364	14.21
26	0.346	15.20	0.360	15.81
27	0.340	16.72	0.350	17.21
28	0.334	18.32	0.342	18.76
29	0.328	19.99	0.328	19.99
30	0.296	20	0.296	20
34	0.204	20	0.204	20
38	0.146	20	0.146	20
40	0.126	20	0.126	20
46	0.083	20	0.083	20
50	0.065	20	0.065	20
52	0	0	0	0

The integral in Equation 4.8 for a given site can be evaluated numerically provided a power duration curve for the site is available. As an example, assume that the wind speed duration curve for the MCAS site was drawn and is shown in Figure 4.4 as a solid line. The generator output duration curve can be derived from the speed duration curve by cubing the ordinate and multiplying by $1/2\rho AC_p$. A plot of the generator output duration curve so constructed is shown in Figure 4.4 as a broken line. Finally,

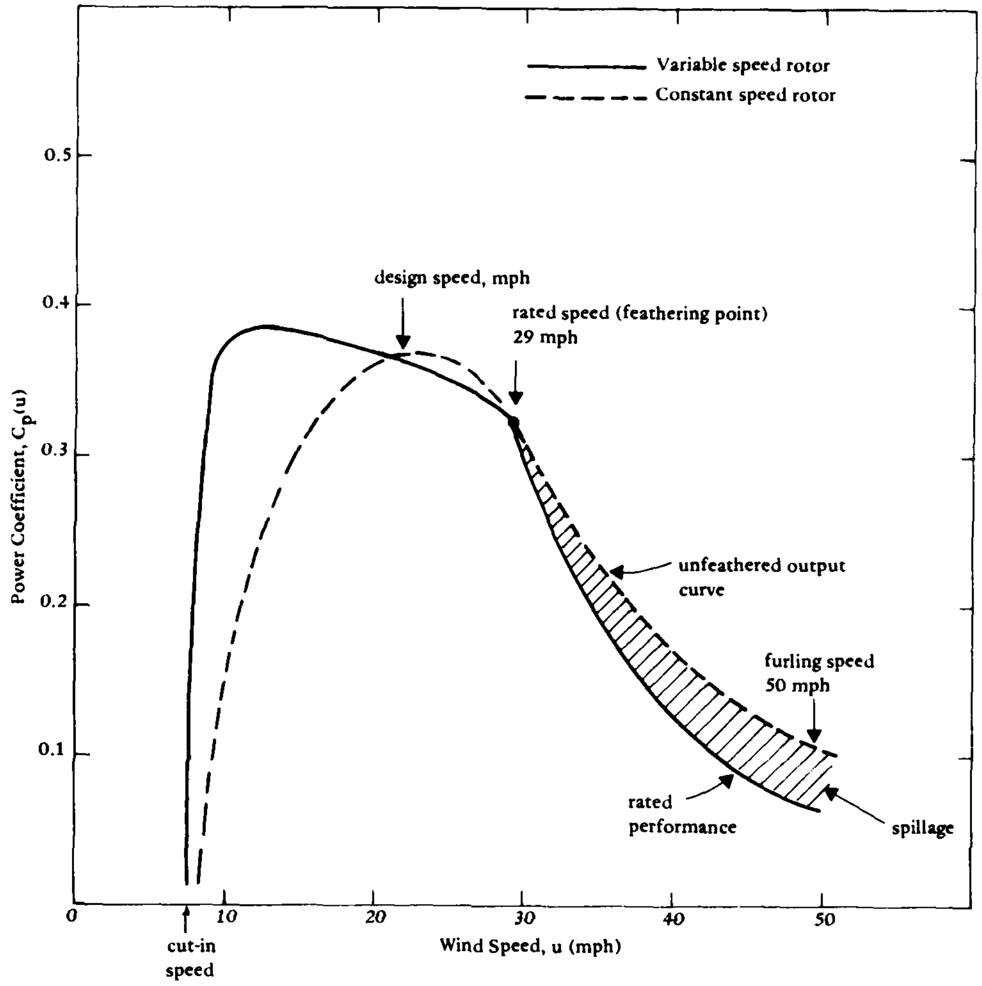


Figure 4.3. A plot of power coefficient, $C_p(u)$, versus wind speed, u, for a variable speed and a constant speed turbine.

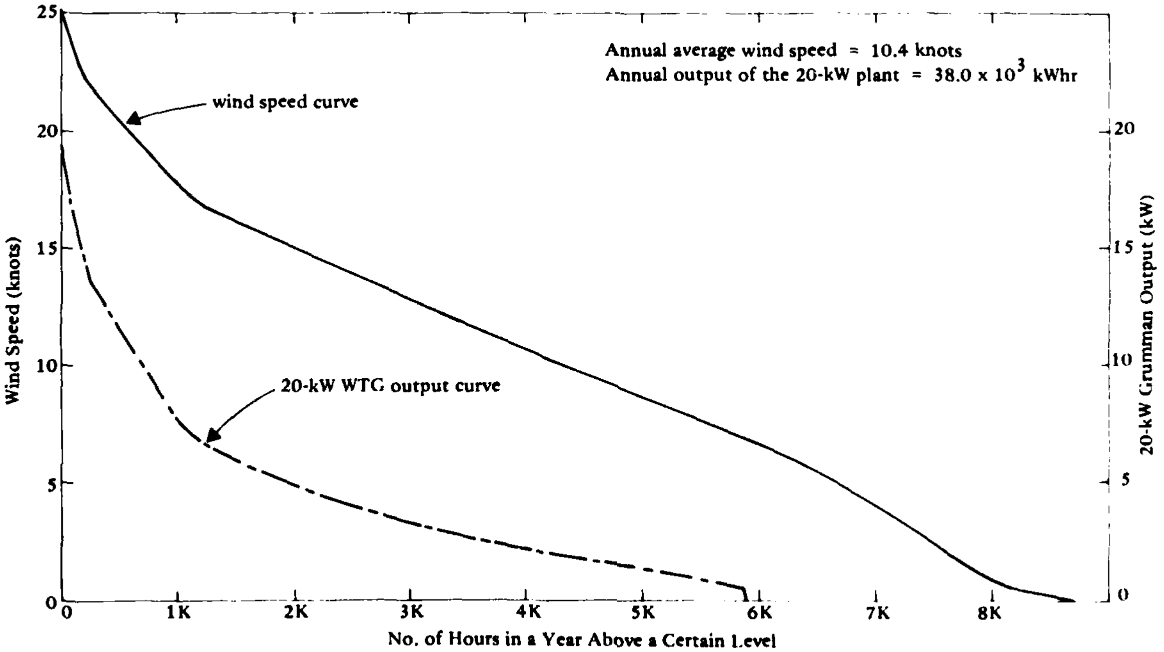


Figure 4.4. 20-kW WECS output duration curve at MCAS, Kaneohe, HI.

the total energy output in kWhr of the WECS over a time period, T (about a year), is given by the area under the output duration curve. It is also clear from the wind speed duration curve at this site that the speed is greater than 25 knots (the rated speed of WECS) for about 135 hours in a year; hence, the 20-kW system at Kaneohe will produce its full output of 20 kW for only 135 hours in a year.

"Specific output" is a commonly used parameter for evaluating the performance of WECS installations (Ref 4.4). For a given location, it is defined as the ratio of the total annual output of WECS to its rated output. Since the annual output is generally measured in kWhr and the rated output of the machine is specified in kW, the specific output has the units of kWhr per kW per year. Analytically, the specific output is

$$S_o = \frac{E_w}{P_{wrated}} \tag{4.9}$$

where E_w is given by Equation 4.8 and P_{wrated} is the rated output of the turbine. Physically, the S_o for a given WECS installation indicates the equivalent number of hours of full output operation in a year. In other words, if the S_o of a plant at a site is multiplied by the rated output of a plant, the annual output of the WECS is obtained. A higher value of S_o indicates a good installation, while a low value implies a poor installation. Thus, the S_o plays an important role in appraising a site for a wind power installation. A value of about 3,500 for S_o is considered to be good from an economic point of view. Table 4.3 gives values of S_o for some Navy sites. The practical use of specific output for WECS is demonstrated in Chapter 6.

4.2 TYPES OF WIND ENERGY CONVERSION SYSTEMS

In the evolution of wind turbine designs, many types of wind energy conversion schemes have been devised. In fact, more patents for wind systems have been applied for than nearly any other type of device. The wind turbines using rotors as energy collectors can be classified in terms of their axis of rotation relative to the windstream direction.

Primarily, there are two basic types of WECS, namely, the horizontal axis machine and the vertical axis machine (Ref 4.5,4.6). In the horizontal axis type machine, the axis of rotation is parallel to the windstream direction. In the vertical axis type of machine, the axis of rotation is normal to the windstream as well as to the earth's surface.

Table 4.3. Specific Output as a Function of Annual Average Wind Speed for Some Example Navy Sites

Site	Annual Average Wind Speed (mph)	Specific Output (kWhr/kW-yr)
Adak, AK	14.05	3,950
Brooklyn, NY	12.0	3,170
Corpus Christie, TX	11.9	3,340
Glen View, IL	11.2	2,740
Kaneohe Bay, HI	11.3	3,170
Key West, FL	10.6	2,470
China Lake, CA	8.2	1,890
San Bruno, CA	10.6	2,740
San Nicolas Island, CA	11.4	2,950
St. George, Bermuda	12.4	3,370

The various horizontal axis type WECS are shown in Figure 4.5, which illustrates designs ranging from a propeller-type rotor to a diffuser augmented rotor configuration (Ref 4.7,4.8). The possible variations of the vertical axis WECS design are given in Figure 4.6, which shows machines ranging from a Darrieus configuration to an airfoil type. There is a third class of WECS where the rotational axis is parallel to the earth's surface but normal to the windstream direction. Such designs resemble a waterwheel and are classified as crosswind horizontal axis machines (see Figure 4.5, which shows a crosswind Savonius system).

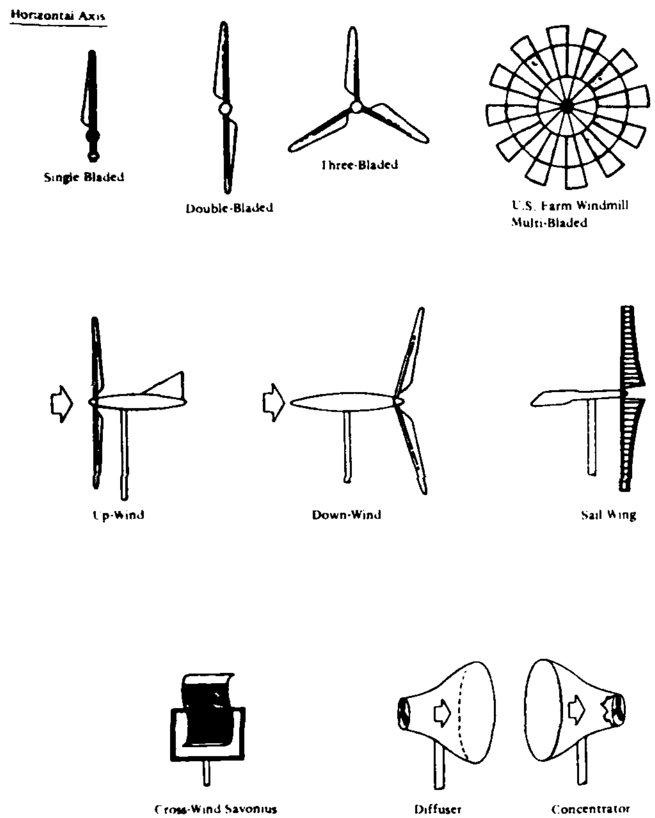


Figure 4.5. Various types of horizontal axis WECS.

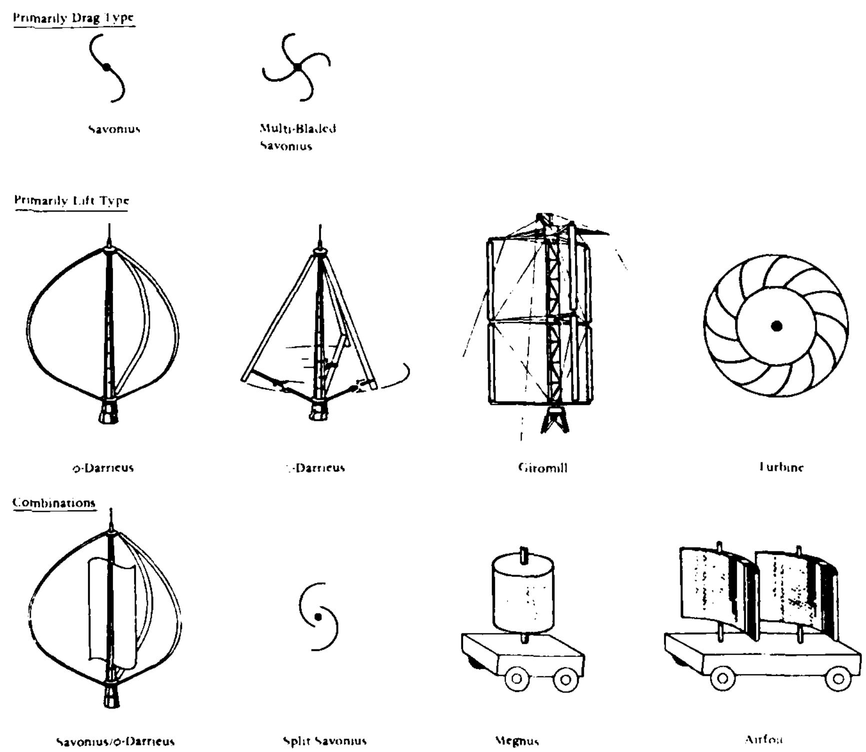
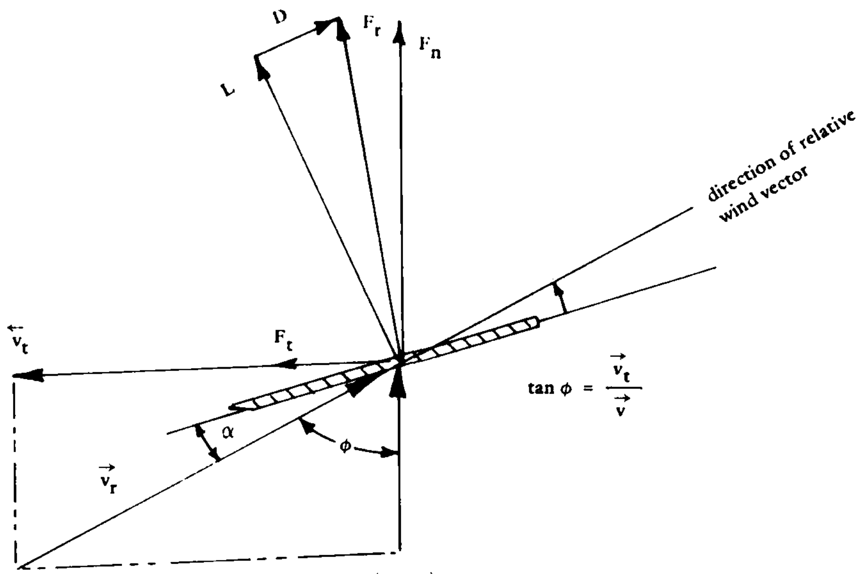


Figure 4.6. Various types of vertical axis WECS.



$\vec{v} = \left(\frac{1+a}{2}\right)\vec{u}$ (from Equation 4.2)

α = angle of attack
$\vec{v}$ = wind velocity at the blade element
a = interference factor
L = lift force on the blade element
D = drag force on the blade element
$\vec{v}_t$ = linear velocity of the blade element
$\vec{v}_r$ = relative velocity at the blade element

Figure 4.7. Wind velocity diagram at a blade element of a horizontal axis WECS.

4.2.1 Horizontal Axis Type WECS

Operational Principles. The horizontal axis WECS designs are the most common ones in practical use today. These types of machines, generally, have their power-extracting surfaces placed at a small angle to the relative wind vector instead of being normal to the incident windstream. The driving force, instead of being displaced in the direction of the relative wind vector, makes an angle with it. The flow configuration and the velocity diagram for the blade element of a machine are illustrated in Figure 4.7 (Ref 4.9). Referring to Figure 4.7, assume that the active surface with a flat or airfoil section is placed so as to make an angle ($\phi + \alpha$) with the direction of incident wind, $\vec{v}$, which is the speed at the rotor. The aerodynamics due to incident wind move the surface with a velocity, $\vec{v}_t$, in a direction normal to $\vec{v}$. The velocity of the relative wind is $\vec{v}_R$, which is the vector difference $(\vec{v} - \vec{v}_t)$ so that $\tan \phi = |\vec{v}_t|/|\vec{v}|$. The relative velocity makes an angle of attack, α, with the blade element, which generates lift and drag forces on the element as

$$L = C_L \frac{1}{2} \rho A \left|\vec{v}_R\right|^2 \tag{4.10}$$

and

$$D = C_D \frac{1}{2} \rho A \left|\vec{v}_R\right|^2 \tag{4.11}$$

where C_L and C_D are the lift and drag coefficients, respectively. The values of C_L and C_D for a given airfoil shape are determined experimentally and are a function of α and Reynolds number (Re) of wind flow. Hence, it can be shown that the efficiency of such a turbine is given by

$$\eta = \frac{1 - \kappa \dfrac{|\vec{v}_t|}{|\vec{v}_1|}}{1 - \kappa \dfrac{|\vec{v}_t|}{|\vec{v}|}} \tag{4.12}$$

where $\kappa = D/L$. This equation is formulated using simple vector algebra. The efficiency, η, is a function of parameter κ and the ratio $|\vec{v}_t|/|\vec{v}|$. For a blade element with no drag (s = 0), κ is zero and the efficiency is unity. The efficiency is low if $|\vec{v}_t|/|\vec{v}|$ is very large or very small. In practice, $|\vec{v}_t|/|\vec{v}|$ for a WECS with horizontal axis is about 4 to 6. The analysis given here is for a blade element without rotation. Figure 4.8 shows the plots of C_p versus tip speed with wind speed ratio λ $(=|\vec{v}_t|/|\vec{v}|)$ for four types of horizontal axis machines (Ref 4.10). Clearly, the two-bladed propeller shows the maximum power coefficient values. The figure also shows the ideal efficiency curve for propeller-type rotors.

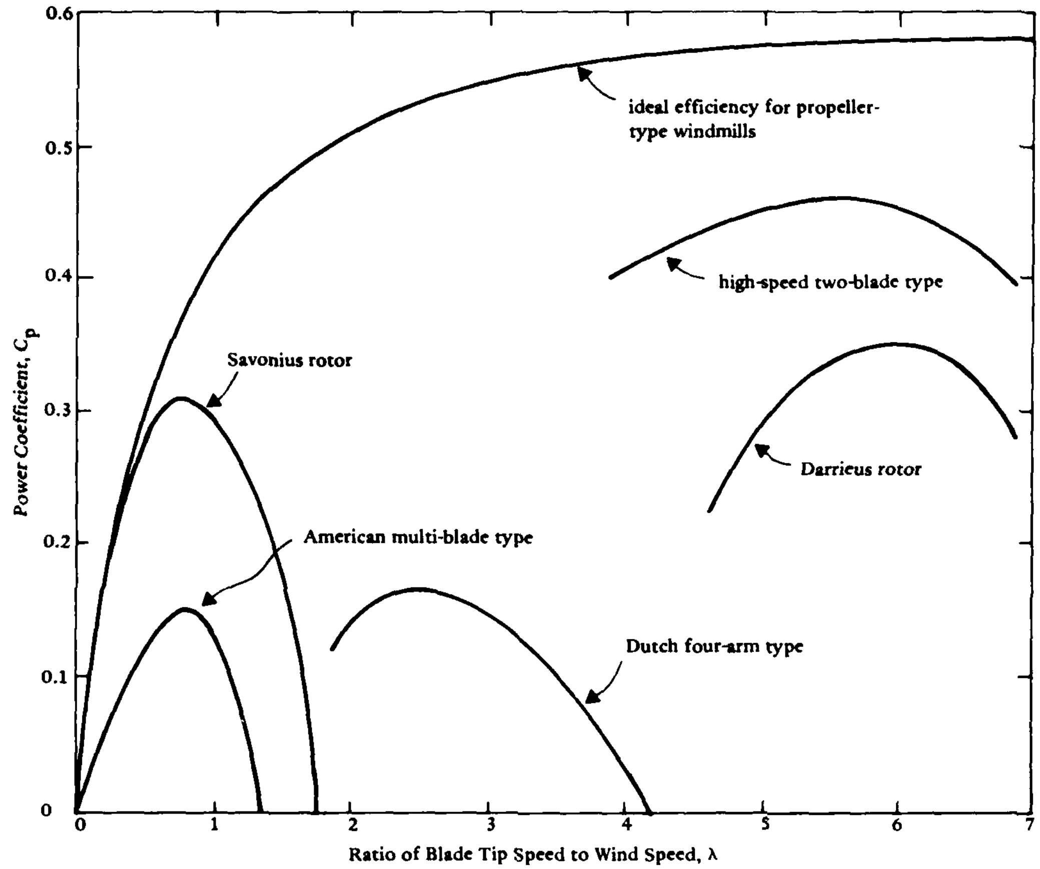


Figure 4.8. Typical performances of various types of wind machines.

The Dutch four-arm type machine (Figure 4.9) (the first propeller-type windmill) was the first horizontal axis type WECS. This was the predecessor of the modern machines designed to generate electrical power from wind. Examples of the modern wind machines that have been used widely are the American multi-blade type and the high-speed propellers.

The horizontal axis type WECS can be designed with different numbers of blades ranging from one to as high as 50. The one-bladed machines have a counterweight. The WECS system can be fixed-yaw with a rotating tower or a yaw-active to allow the system to follow wind direction. The fixed-yaw machines are fixed so that the rotor cannot rotate around a vertical axis, while the yaw-active systems are designed to rotate about the vertical axis.

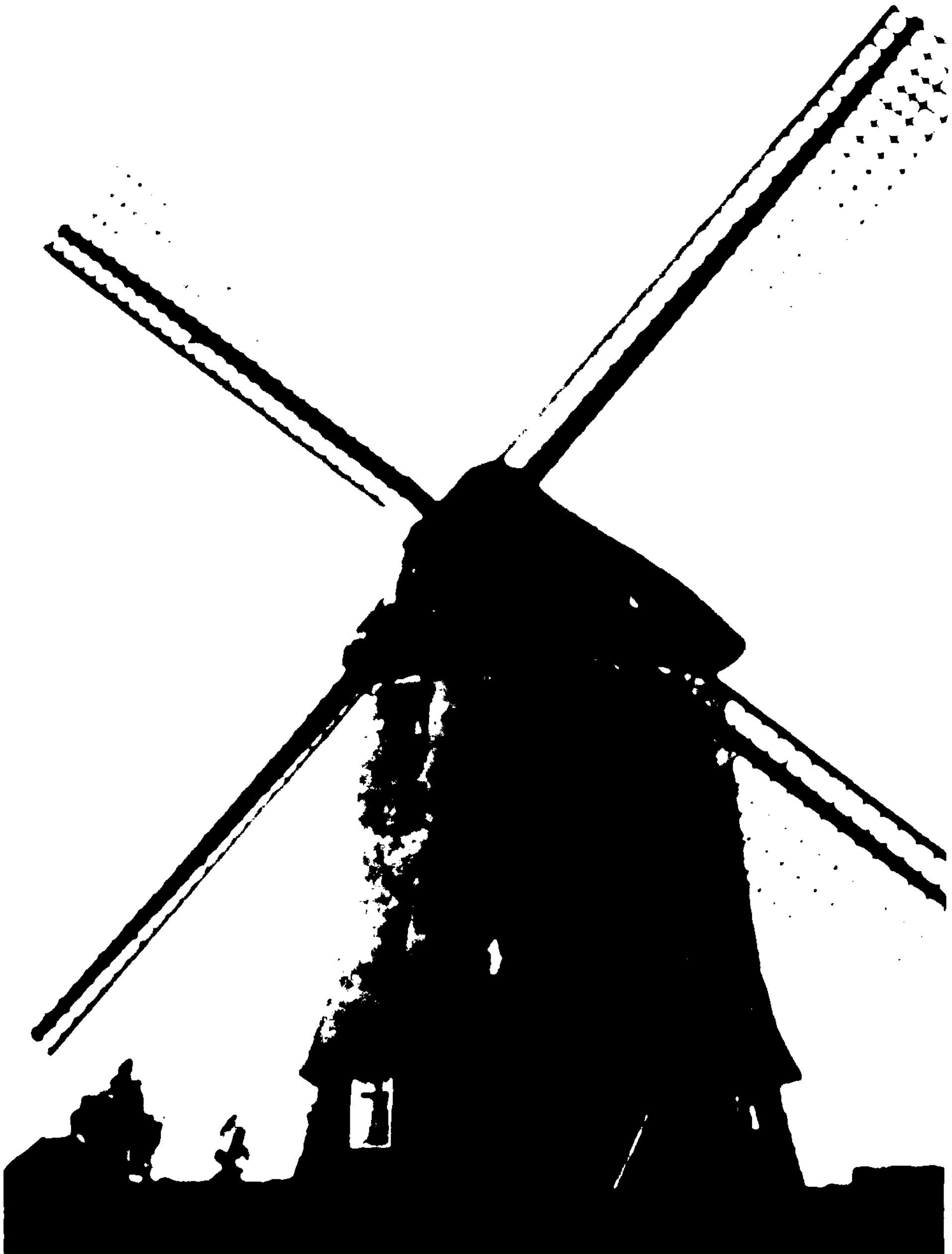


Figure 4.9. Four-bladed Dutch windmill.

The rotor blades on this type of machine are directly coupled to the hub assembly, which is mounted on the main shaft. A variety of schemes are employed to control the rotor rotational speed not to exceed its rated value. Some of these schemes involve feathering the rotor blades mechanically, aerodynamic blade stall, flaps or spoilers on the blade surface, flaps on the blade tips, and devices that will turn the rotor sideways to the windstream. The rotor on these designs can be placed upwind (i.e., in front of the tower) or downwind (in back of the tower).

Physical Description. The principal components of the typical horizontal axis type WECS are: (1) the rotor turbine, (2) the gearbox, (3) the generator, (4) the tower, and (5) power conditioning. The wind causes the bladed-rotor turbine to rotate at low speed about the horizontal drive shaft that is always parallel to the force of the wind. The drive shaft delivers the energy to an assembly of transmission gears in the gearbox where low speed (less than 200 rpm) is increased to high speed (about 1,800 rpm), which is necessary for the shaft driving the generator or an alternator. The gearbox and the generator are contained within a weathertight nacelle, which is swivel-mounted atop the tower. The aerodynamic configuration of the nacelle permits yawing so that the horizontal shaft of the rotor turbine is parallel to the wind flow. Figure 1.1 depicts a typical nacelle-type unit. For upwind-type WECS, quite often a tail is incorporated to ensure yaw. Figure 1.3 depicts the 2-kW WECS being tested at CEL. The power conditioning systems are necessary to regulate the generator's output for proper utilization by the load.

Propeller Blades. The propeller blades typically are straight and untwisted with a rectangular planform (or tapered). The airfoil is usually in the form of an NACA 0015 or similar cross section. Material and construction methods vary; these are illustrated in Figure 4.10. In operation, the blades are subjected to two types of loads; both are distributed. Centrifugal loads predominate in low wind conditions, while oscillatory aerodynamic loading predominates at higher wind speeds.

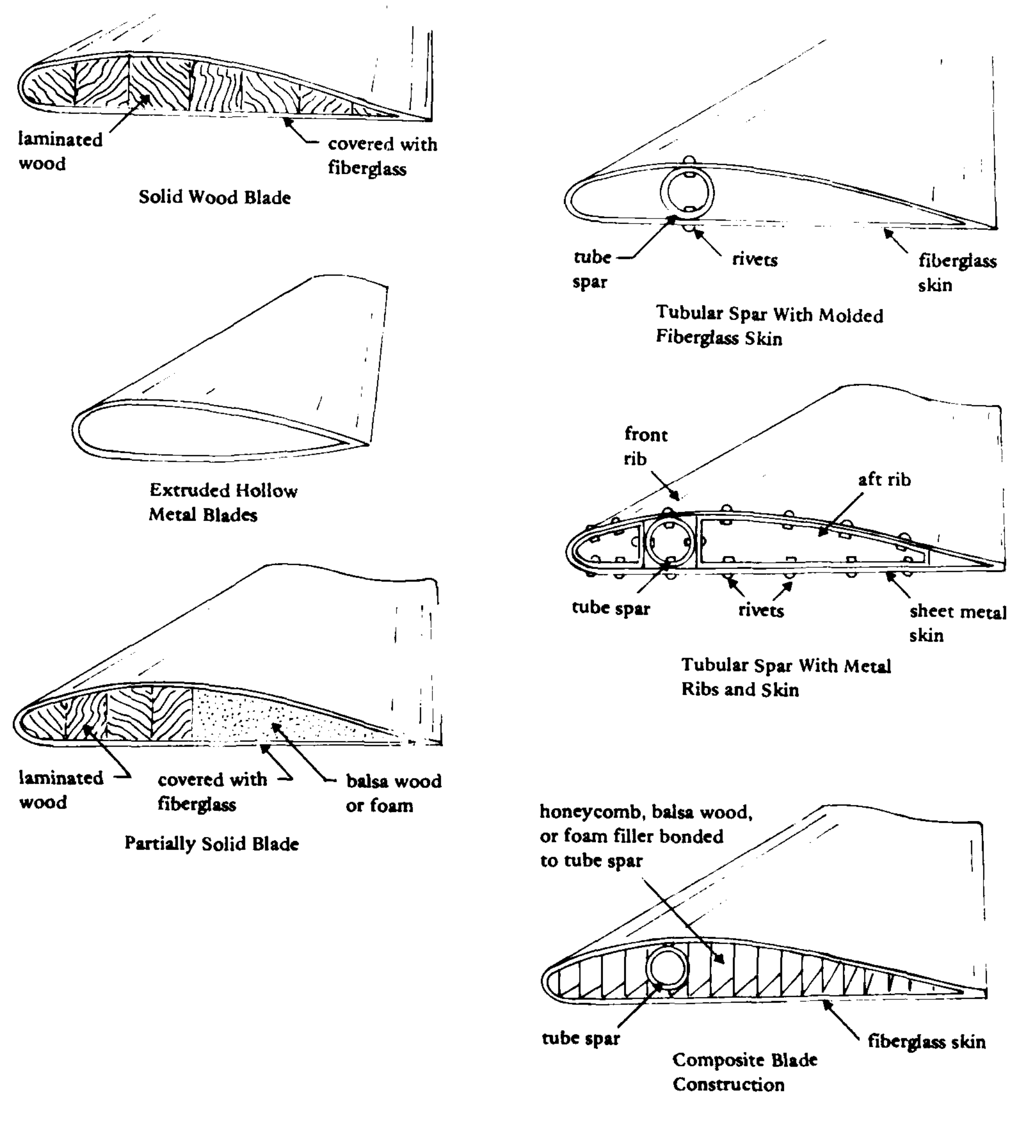


Figure 4.10. Different blade construction methods.

Figure 4.11 depicts loading forces on the blades (and the resulting thrust force as it induces a bending moment in the tower). Figure 4.12 illustrates the forces acting on the airfoil-shaped blade section of the WECS rotor.

Mechanical Components. The essential mechanical components of a typical WECS are shown in Figure 4.13 and are:

Hub - holds the blades at their root and transmits blade loads to the main shaft.

Main Shaft - horizontal shaft that transmits blade torque to the transmission

Main Shaft Bearings - supports the main shaft and attaches it to the bed plate

Bed Plate - structural member that serves as the base to support all components and, in turn, connects them to the tower via the turret (or pintle) shaft.

Turret Shaft - rotational attachment of the bed plate to the tower that permits the entire unit to yaw into the wind.

Transmission - gearbox to increase rpm required by the generator or alternator.

Secondary Drive Shaft - transmits power (at a higher rotational speed) from transmission to generator or alternator.

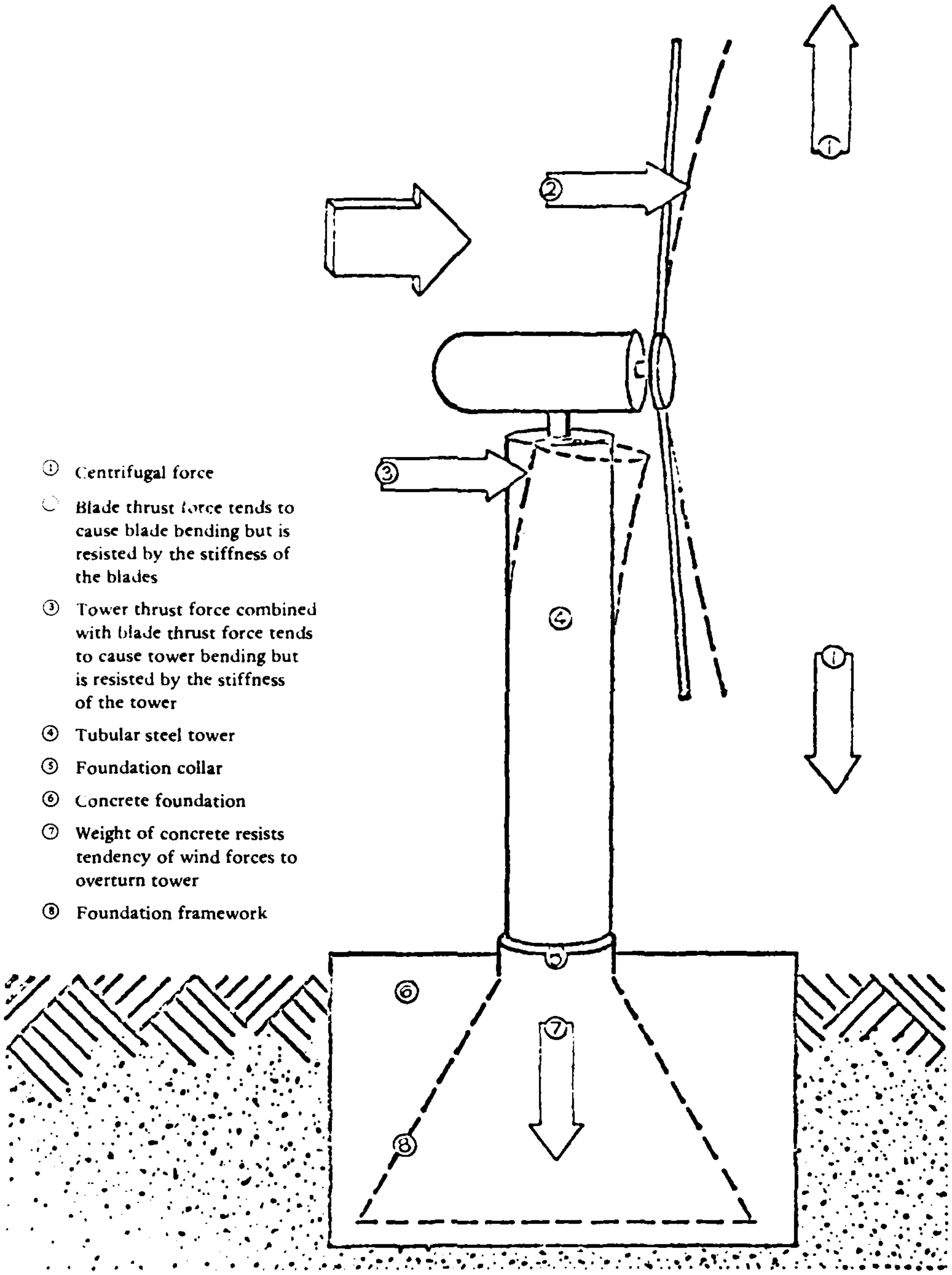
Alternator (or Generator) - converts mechanical shaft power to electrical power.

Brake - depending on WECS, holds the main shaft (and thus, propeller blades) stationary when needed for necessary repairs and maintenance.

Tower - depending on the installation, this can be a tubular steel support (as shown) of box beam construction or guy wire supported.

Foundation - usually a concrete base; however, the tower could be anchored to another structure or building (Figure 4.11).

Inverter and Power Conditioning Unit(s) - not shown; usually not integral with the mechanical components on the bed plate, but located remotely (off the tower). See Section 4.6 for a discussion of Power Conditioning.



[illegible] structural load imposed by wind forces on a WECS.

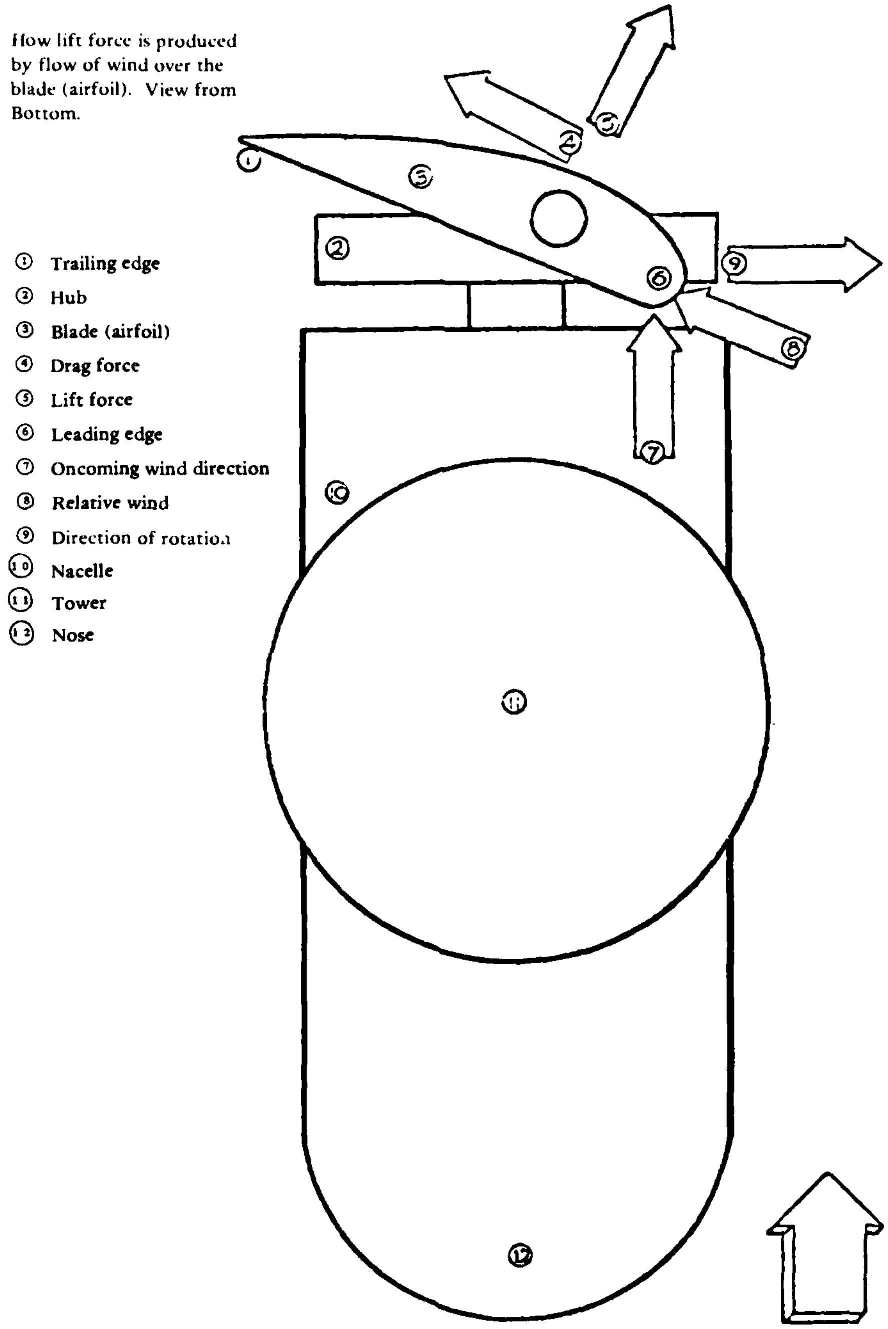


Figure 4.12. Aerodynamic and other forces acting on the airfoil.

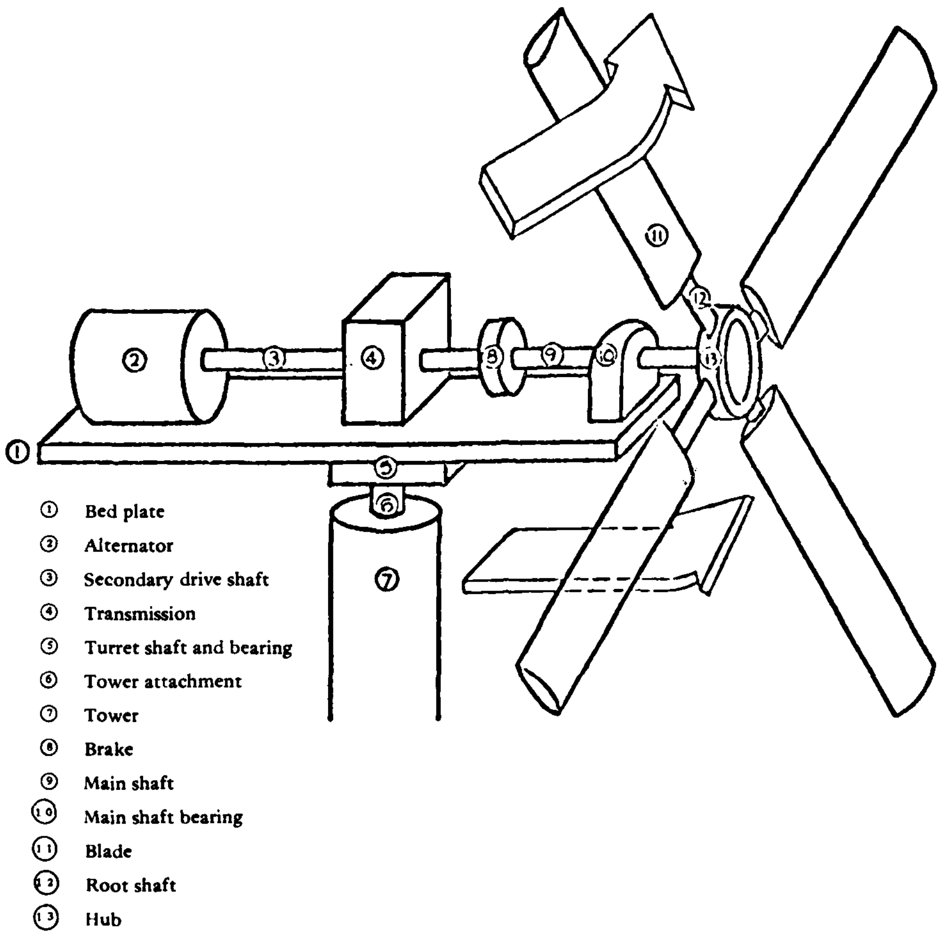
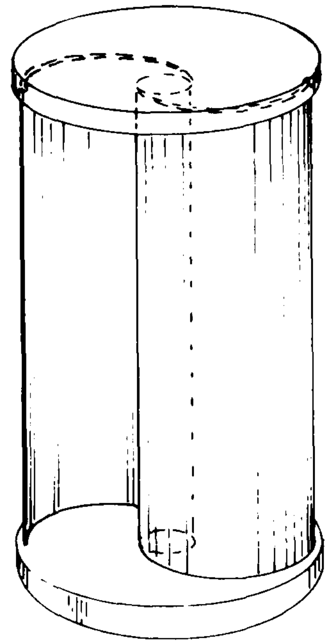


Figure 4.13. Mechanical components, view with nacelle removed (not to scale).

4.2.2 Vertical Axis Type WECS

The development of vertical axis type wind machines started around 1920, with the Darrieus rotor system invented in 1925 and the Savonius type of rotor in 1929 (Ref 4.7,4.11). Figures 1.2 and 4.14 show schematics of Darrieus- and Savonius-type systems, respectively. The Darrieus-type rotor has been under extensive development by the National Research Council of Canada since the early 1970s and also by the U.S. Department of Energy (DOE) for the last four years (Ref 4.12,4.13). It is now considered to be a potential major competitor to the propeller-type systems. Darrieus-type rotors are lift devices, consisting of curved blades with airfoil cross sections. They have low starting torques, but operate at high tip-to-wind speeds and, therefore, have relatively high power outputs per given rotor weight and cost. Various types of Darrieus rotor schemes have been suggested, including the ϕ-Darrieus, the Δ-Darrieus, the Y-Darrieus, and the ◊-Darrieus (Ref 4.7). The Darrieus rotors are designed to operate with one, two, three, or more blades. Darrieus rotors can also be combined with various types of auxiliary rotors to increase their starting torques. However, such additions increase the weight and system cost.



CHARACTERISTICS:

- Self-Starting
- Low Speed
- Low Efficiency

Figure 4.14. Savonius rotor.

The Savonius rotor basically operates as a two-stage turbine wherein the wind impinging on the concave side is circulated through the center of the rotor to the back of the convex side (Ref 4.14). The wind flow over the convex surface creates a negative pressure, thus generating additional torque on the rotor. This type of wind turbine has been used for water pumping, ship propulsion, and building ventilation. The Savonius rotor type of turbine has been used for extracting energy from ocean waves. Another application of the Savonius type of concept has been the development of an ocean current meter.

Another form of a vertical axis wind turbine is a vertically straight-bladed wind turbine with cyclically pitched blades (see Figure 4.15) (Ref 4.15). The machine is called a "cycloturbine," and it differs from the classic Darrieus (or eggbeater) in that its blades do not remain at a fixed "flat" angle, but follow a preset schedule of angle (see Figure 4.16), allowing more favorable use of aerodynamic force on the blades. The amount and timing of pitch control are determined by a cam device mounted atop the main shaft, actuating the blades via pull rods. A tail vane affixed to the cam allows correct orientation relative to the windstream direction.

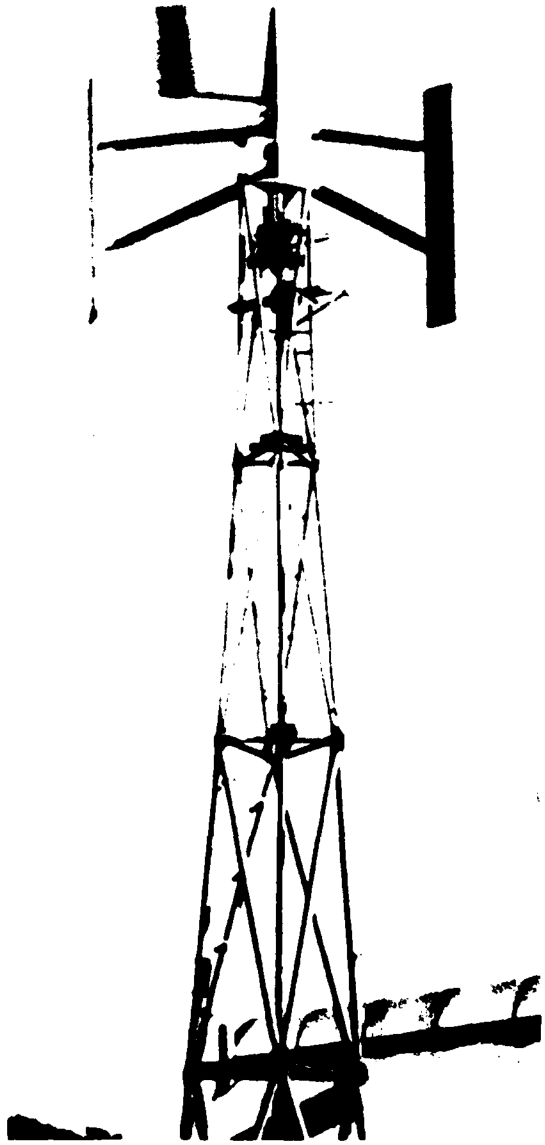


Figure 4.15. Pinson Energy Corp. cycloturbine model C2E.

Operational Principles. The operational principle of a vertical axis wind turbine is based on the aerodynamics of a rotating airfoil. As the rotor blade revolves around the main shaft, it experiences a lift and drag force as shown in Figure 4.17. As is true with any airfoil, the lift-to-drag ratio (L/D) increases with increasing angle of attack until stall. The angle of attack, α (Figure 4.17), for a rotating airfoil is dependent on the rotational speed, $\vec{\omega}$, the wind speed, $\vec{v}$, and the blade angular position, $\vec{\theta}$. The expressions for the rotor torque for a Darrieus machine can be found in Reference 4.16.

The Darrieus wind turbine offers the following advantages relative to the more conventional propeller-type WECS.

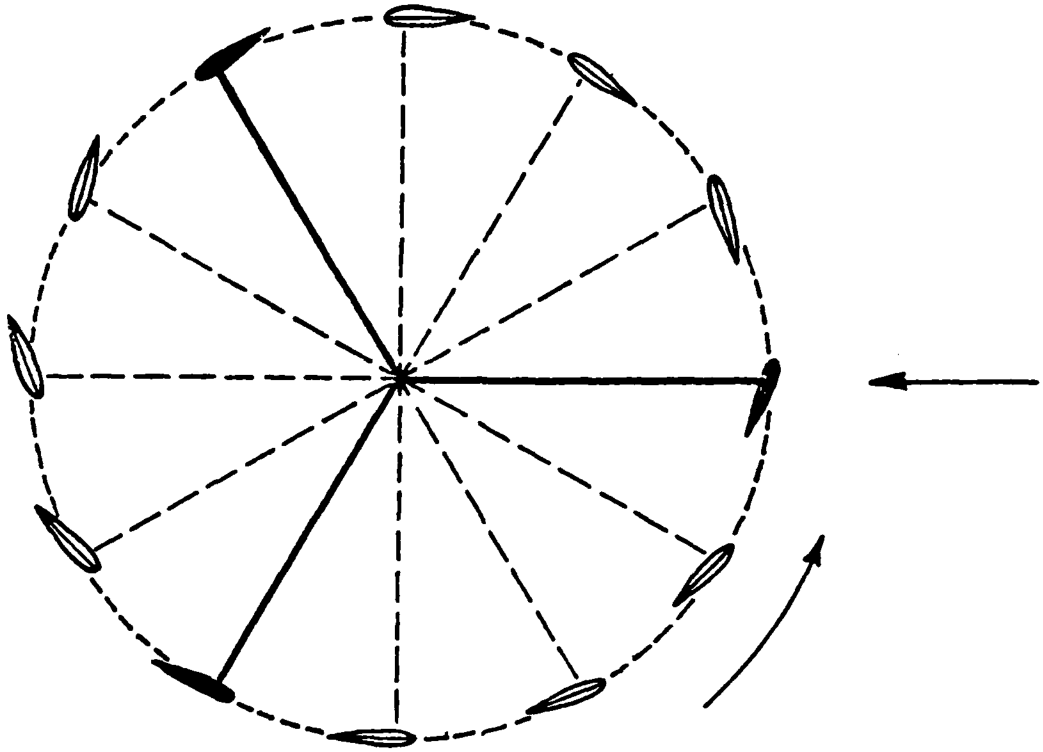


Figure 4.16. A representation of the operation of the Cycloturbine.

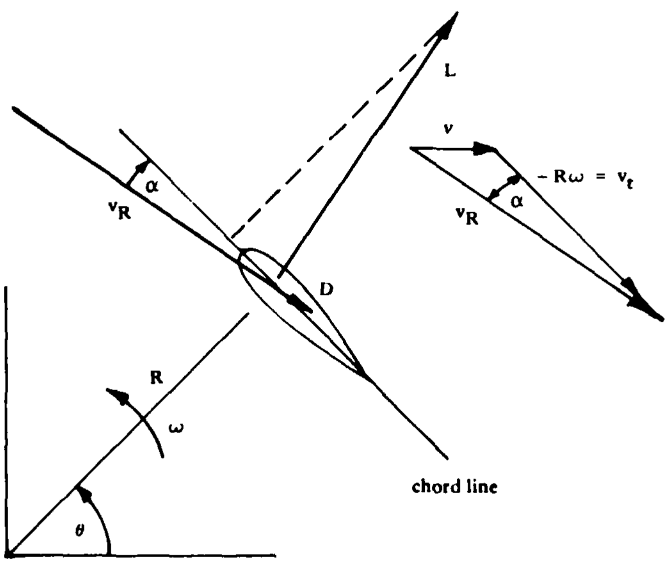


Figure 4.17. Aerodynamic forces acting on a rotating airfoil.

1. The vertical symmetry eliminates need for a yaw control and can accept wind from any direction.

2. The generator to be driven by the turbine can be located close to the ground level without using costly bevel gearing, simpler tower construction, and inexpensive maintenance.

3. Fabrication costs are lower.

4. The system is easier to scale up structurally for higher output power rating.

More investigation and development work is needed before it can be concluded whether a vertical axis WECS is better than a horizontal axis type or vice versa. At the present time, it is essential that relative cost-efficiency comparisons are made of both types for a given application. For comparison, Table 4.4 shows the construction features of both types of WECS.

Table 4.4. Wind Turbine Characteristics

Item	Horizontal Axis	Vertical Axis
Direction Dependence	Yaw mechanism fixed or active	Nondirectional
Self-Starting	Yes	No
Support	Tall rigid structure	Wires and foundation
Maximum Efficiency	45%	51%
Pitch Control	Optional	Optional
Lift or Drag Type	Both	Both

4.2.3 Crosswind-Type WECS

Various horizontal crosswind devices have been developed but have not been found to be very effective for practical utilization (Figure 4.5), since they must be turned into the wind as the wind direction changes, the same as the conventional head-on horizontal axis types. Fairly complex schemes must be used to collect the output power from such devices, thus resulting in loss of overall system efficiency. Furthermore, the efficiency of such a turbine is inherently low (Ref 4.17). In summary, there appears to be no significant advantage of the crosswind horizontal axis machines over either horizontal axis rotors or vertical axis rotors.

4.3 TRANSMISSION SYSTEMS FOR WECS

Most WECS rotors turn at low rotational speeds (below 200 rpm) and the electrical generators generally, except for DC types, are designed to operate at or near 1,800 rpm. This incompatibility in rotor and generator speeds necessitates the use of a transmission system for a WECS. There are two fundamentally different approaches for the transmission of WECS. One approach is to use a fixed-ratio, step-up transmission. The second approach uses a variable ratio drive that allows the rotor to operate at variable speeds while maintaining a fixed rpm for the generator. One example of a variable speed transmission is the Voight variable speed drive (Ref 4.18). The inventor of the system claims that such a drive has an unlimited power and torque transmission, a constant ratio with a high degree of accuracy, a speed variation over a wide range, and a nonslip drive. The principal difficulty of this approach is a lack of hardware with proven operating and reliability data.

Various types of drive systems with a fixed ratio are (Ref 4.19):

1. Fixed ratio gearbox
2. Belt drive
3. Chain drive
4. Hydrostatic drive

In the great majority of WECS designs, the step-up drive is of the gearing type, with one or several trains. The technique of step-up gearing is more completely developed and permits the use of transmissions with excellent efficiency and reliability of operation. These transmissions can be used up to high power levels, considerably in excess of 1,000 kW.

The belt or chain transmissions have some operating experience but have not been used sufficiently in wind power work for consideration as competitors of step-up gear transmissions. The industrial use of hydraulic transmissions has been limited to the automotive industry only, and there are no data on their use with WECS. One obvious drawback of a hydraulic drive system is poor efficiency. Table 4.5 gives the characteristics of various types of drive systems.

Table 4.5. Drive System Component and Technology Availability

Type	Availability	Remarks
Fix Ratio Gearbox	Fully catalogued	Well developed
Belt Drive	Fully catalogued	Not reliable or very efficient
Chain Drive	Fully catalogued	Not as efficient as gears
Hydrostatic	Special	Inefficient

4.4 ELECTRIC GENERATORS FOR WECS

Extensive debate has persisted about types of generators that are most suitable for wind energy conversion to electricity, with focus on two basic considerations: (1) technical and (2) economic. Generally, small WECS (below 2 kW size) have DC generators. WECS in the 2-kW to megawatt size range are generally designed to produce AC power and utilize three types of generators as follows (Ref 4.20,4.21):

1. A synchronous generator
2. An induction generator
3. A DC generator with an inverter to produce 60-Hertz synchronous AC power

There have been new generator developments recently involving special types of machines that can deliver constant frequency output when driven by variable shaft input speeds. These devices can offer some promise for WECS applications in the future (Ref 4.21). However, none of these has reached the stage of development where any utility experience has been accumulated.

This section addresses technical requirements and limitations of each type to assist in evaluating their full economic impact.

4.4.1 Synchronous Generators

The synchronous generator has the most natural attraction because of its long-term association with the power industry. Since DC power generation was displaced, the synchronous generator has been the primary source of AC power. With an AC utility system, an inherent need exists to provide reactive power to loads and the transmission network for voltage support and regulation. A synchronous generator provides the necessary reactive power for both. The standard synchronous generator is available both in brush type (self-excited) and brushless version with a permanent magnet rotor. Experience at CEL has shown that a permanent magnet type rotor alternator has a higher efficiency and reliability. The advantage of a self-excited alternator is that of maintaining the terminal voltage constant by controlling the field excitation irrespective of the rotor speed. The standard relationship for the rotational speed of a synchronous generator is given by

$$N_s = \frac{120\ f}{P} \tag{4.13a}$$

where N_s = synchronous speed in rpm

f = line frequency in Hertz

P = number of poles on the generator

For example, based on Equation 4.13a, a 4-pole synchronous generator delivering AC power at 60 Hertz must run at a rotational speed of 1,800 rpm.

The one drawback of synchronous operation is stability, particularly under fault conditions; however, wind-turbine-driven generators raise new stability questions of their own. Due to the random nature of the wind, rapid variations in mechanical input torque to a synchronous generator cause the electrical output to follow closely, causing a potential loss of synchronism with the system. These stability questions impose special stability requirements, such as a power system stabilizer, on the synchronous generators. The addition of such equipment increases the cost of synchronous operation. The efficiency versus load characteristics of a 20-kW synchronous generator are given in Figure 4.18 (Ref 4.22).

The total costs and the cost per kW capacity for synchronous generators are shown in Table 4.6 and Figure 4.19. Three different quality classes of synchronous generators are shown with some overlap of size, thus giving some measure of the increase in cost with quality. It should be emphasized that with increasing size of the machine, an increased quality of design and construction has been observed. In the highest quality class, specification sheets describing the units clearly indicate a device with substantial improvement in workmanship. The cost of controls required with the generator has been allocated according to Table 4.7 as percentage of basic generator cost.

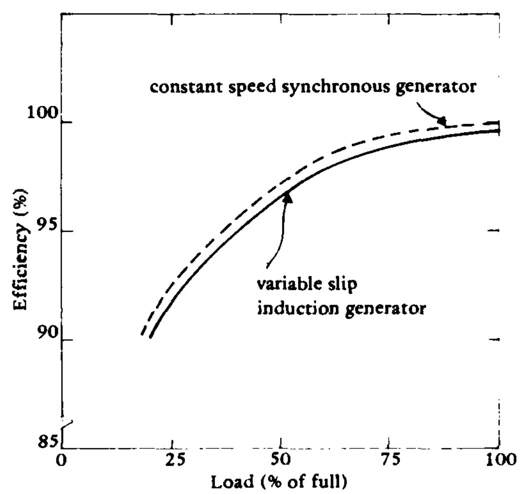


Figure 4.18. Efficiency versus load characteristics for synchronous and induction generators.

The cost per kW drops very quickly as the size of the machine increases. In fact, in each class the smallest machine has the largest cost per kW. The primary reason for this large initial cost is the frame costs and other threshold equipment costs. Typically, small generators are placed in the frame of a higher rating machine.

Table 4.6. Synchronous Generator Costs[a]

[1,800 rpm; 480 volts]

kW	Cost ($)	Cost With Control ($)	$/kW With Control
Basic Machine			
2.5 (1-ϕ)	560	756	302
4 (1-ϕ)	715	965	241
5 (1-ϕ)	760	1,026	205
7.5 (1-ϕ)	980	1,323	176
12 (1-ϕ)	1,045	1,411	118
12 (3-ϕ)	1,115	1,505	125
20 (1-ϕ)	1,220	1,647	82
20 (3-ϕ)	1,270	1,715	86
Higher Quality (All 3-ϕ)			
7.5	1,365	1,843	245
10.0	1,520	2,052	205
12.5	1,620	2,187	175
15.0	1,810	2,444	163
20.0	2,190	2,957	148
Highest Quality (All 3-ϕ)			
15	2,890	3,902	260
25	3,295	4,448	178
40	3,610	2,513	113
50	4,015	5,018	100
60	4,235	5,294	88
75	4,750	5,938	79
100	4,990	5,988	60

[a]1977 dollars based on Reference 4.22.

4.4.2 Induction Generator

The induction generator is becoming a possible solution to grid-integrated wind power generation. Since this form of generation is asynchronous operation, the apparent problems of synchronous operation are overcome. Induction motors are one of the most commonly used electric motors; thus, it is possible that the low cost of production will make this an attractive form of generation. As a general rule, induction generators have not been used in the power industry.

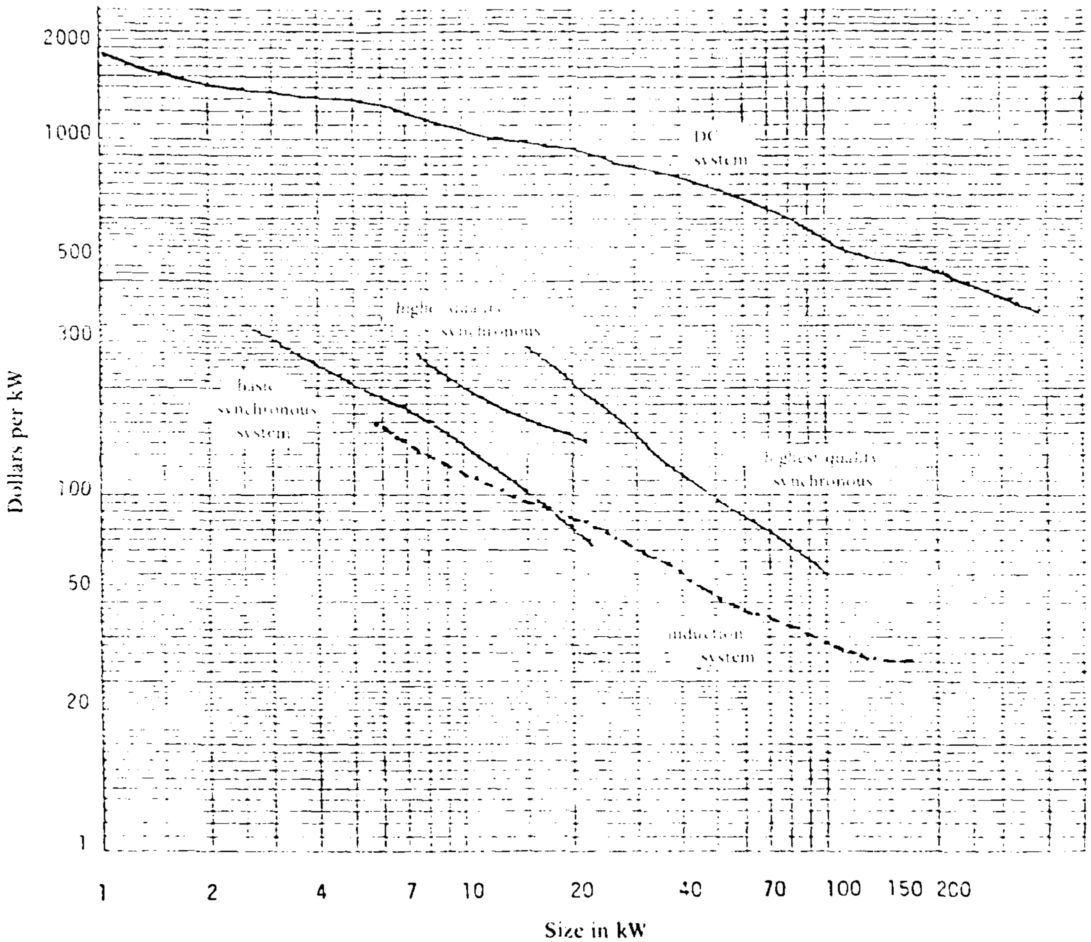


Figure 4.19. Cost of generation systems.

Table 4.7. Cost of Controls

Machine Size in kW	Percentage of Basic Machine Cost
Below 40	35.0
40 → 100	25.0

In the induction machine, alternating currents are present in both the stator and the rotor windings, those in the rotor usually being the result of electromagnetic induction from the stator. The rotor-and-stator-mmf waves and associated flux waves rotate around the air gap at synchronous speed, N_s, given by Equation 4.13a. The rotor structure itself, however, normally rotates at a different speed. At rotor speed $N_r < N_s$, the synchronous speed gives rise to a motor action, whereas at rotor speed $N_r > N_s$, generator action results. When dealing with induction machines, the term slip, s, is generally used:

$$s = \frac{N_s - N_r}{N_s} \qquad (4.13b)$$

The typical torque slip characteristics of an induction machine are given in Figure 4.20. Starting conditions are those for s = 1. In order to physically obtain operation in the region of s > 1, the motor must be driven backward against the direction of rotation of its magnetic field by a source of mechanical power capable of counteracting internal torque, T.

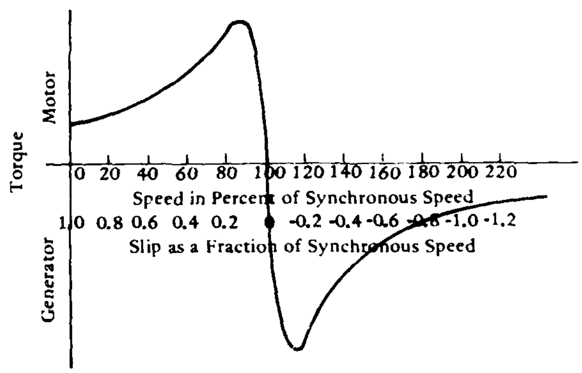


Figure 4.20. Induction-machine torque-slip curve in both motor and generator region.

In the region of s < 0, the machine works as a generator. It is the operation in this region that is of interest for wind power application. Normally, the slip range for normal operation of an induction machine is $0.05 \leqq s \leqq -0.5$. Slip speed variation can be obtained by using a wound rotor motor and inserting external resistance in the rotor circuit. In the normal operating range, the external resistance simply increases the rotor impedance, necessitating a higher slip for a desired rotor mmf and torque. The influence of increased rotor resistance on the torque-speed characteristics of an induction generator is shown in Figure 4.21 (Ref 4.23). Hence, significant slip variation in the induction generator can be accomplished simply by increasing the resistance in the rotor circuit.

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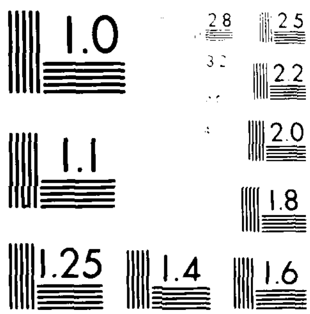

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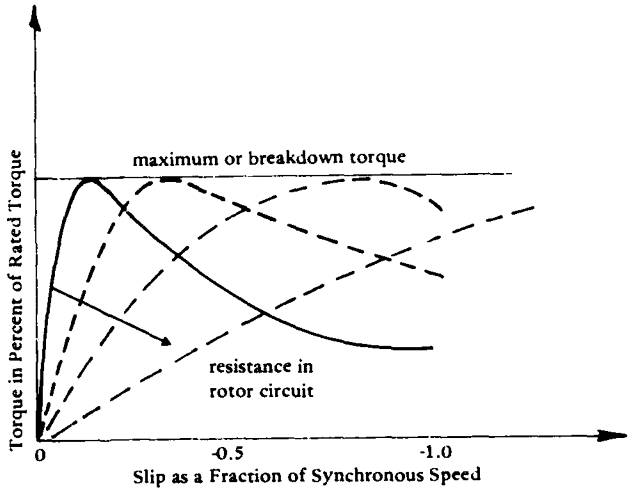

Figure 4.21. Induction generator torque-slip curves showing effect of changing resistance in rotor circuit.

There are two basic problems with the induction generators that require attention. First, a reactive source for both the generator and the remainder of the system is required since an induction generator operates on reactive power. Furthermore, voltage stability problems are known to exist for induction generator operation. Both of these problems must be addressed to answer satisfactorily the usefulness of induction generators for wind power generation.

Induction generator costs are not typically available. Therefore, wound rotor induction motor costs are provided. A wound rotor induction motor can easily be operated in generator mode by suitable control of the rotor circuits. Some modification to rotor circuits is required because of larger currents present during generator operation.

In general, the induction generator costs per kW are less than comparable synchronous generator costs (Ref 4.22). Table 4.8, Table 4.9, and Table 4.10 characterize the cost of induction generator equipment. Table 4.9 is included to show the price variance as speed is decreased. In most cases, as the speed is reduced from 1,800 rpm to 600 rpm, the cost doubles. This price increase is associated with increased iron for the magnetic poles, which is required for the machine to run at slower speeds and produce 60-Hertz power. Table 4.10 provides costs for the induction generator system. The cost in dollars per kW of induction systems is given in Figure 4.19 and is found to be less than the synchronous and the DC systems.

Table 4.8. Wound Rotor Induction Motor Costs at Constant 1,800 rpm (No Control)[a]

[Class B insulation, 480 volts, 3 phase, 1,800 rpm]

kW	Cost ($)	$/kW
1.2 - 3.7	462	385 - 125
5.6	526	94
7.5	621	83
11.2	790	71
15.0	952	64
18.7	1,076	58
22.3	1,196	54
29.8	1,419	48
37.3	1,542	41
44.7	1,782	40
60.0	2,036	34
75.0	2,428	32
93.2	2,760	30
112.0	3,029	27
150.0	3,900	26
187.0	4,975	27

[a]*1977 dollars.*

Table 4.9. Wound Rotor Induction Motor Cost at Various Speeds (No Control)

[*Class B insulation*; 480 volts; 3 phase]

kW	Cost ($)	$/kW	Speed (rpm)
1.5	462	308	1,800
1.5	416	277	1,200
1.5	494	329	900
1.5	682	454	720
1.5	759	506	600
15	952	64	1,800
15	1,165	78	1,200
15	1,327	88	900
15	1,776	118	720
15	2,068	138	600
60	2,036	34	1,800
60	2,454	41	1,200
60	2,891	48	900
60	3,758	63	720

Table 4.10. Induction Generator System[a]

[Generator, control, and capacitors]

kW	Cost ($)	$/kW
5.6	888	160
7.5	1,016	135
11.2	1,272	114
15.0	1,493	100
18.7	1,630	90
22.3	1,847	83
29.8	2,158	72
37.3	2,348	63
44.7	2,494	56
60.0	2,854	48
75.0	3,349	45
93.2	3,826	41
112.0	4,067	36
150.0	5,232	35
187.0	6,722	36

[a]Sufficient capacitance has been added to correct to a power factor of 80% at 50% load.

4.4.3 Induction Versus Synchronous Generators

The salient features of both types of machines are given in Table 4.11. Both types have rated and partial power efficiencies that are almost equal (Figure 4.18). The induction generator does have some advantages in that it is a very simple and highly reliable machine. It is somewhat lower in cost than the synchronous generator. It is more tolerant of wind gusts and shows better stability and damping characteristics when connected to a utility network because of its variable slip operation. It also has a greater tolerance for overspeeds than the synchronous generator. The principal disadvantage of the induction generator is that it must draw its excitation from the line and, therefore, needs power factor correction capacitors on the line to avoid excessive reactive current flow and does not provide any direct means of voltage control.

The synchronous generator, on the other hand, has the advantage of its own excitation source. It is also the standard utility machine, well understood and accepted. It does have the disadvantage of having more complex control requirements and inherently less stable operation.

Table 4.11. Induction Versus Synchronous Generators for Connection to Utility Network

Synchronous	Induction
More readily accepted and understood by utilities	Does not need precise synchronization before connecting to network
Directly compatible with off network applications (self-exciting)	Better transient operating characteristics
Greater flexibility in management of reactive power and system voltage	Lower cost (with power factor correction) for 1,000 kW and above
Slightly higher efficiency	Less weight on tower
Single bearing type readily available	Automatic loss of excitation if separated from network by fault (safety feature)
	Better overspeed capability
	Higher reliability

4.4.4 Direct Current (DC) Generators

In many small commercially available wind power generation systems, a DC generator is present. This DC system is attractive because the operation and control problems are less complicated. Simple DC motor controls prevail that can accommodate a wide mechanical torque variance with some variation in output voltage, but usually within a manageable range. In general, the one unattractive feature of this mode of generation is the fact that it is not AC. Hence, some means must be available to either use the DC power directly or provide an inverter, probably a solid state system, to convert DC to AC. This latter action adds costs to the DC system, which already is the most expensive electromechanical converter.

In Table 4.12, costs and weights for DC generators are shown (Ref 4.22). The cost per kW for these units is substantially more than either synchronous or induction machines (Figure 4.19). A comparison of the weights of various generator systems is given in Figure 4.22, which shows that DC generators are the heaviest and the induction systems are the lightest for the same kW capacity.

Table 4.12. DC Generator Costs and Weights

[Class B insulation; continuous duty; 125 volts]

kW	Cost ($)	Cost With Control ($)	$/kW With Control
1	542	732	732
1.5	645	880	587
2	714	964	482
3	1,006	1,358	453
4.5	1,411	1,905	423
6.5	1,789	2,415	372
9	2,028	2,738	304
13	2,490	3,362	259
17	2,884	3,893	229
21	3,212	4,336	207
25	3,529	4,764	191
33	4,322	5,835	177
40	5,227	6,534	163
50	5,557	6,946	139
65	6,898	8,623	133
85	8,646	10,807	127
100	9,895	11,874	119
125	11,823	14,188	114
170	15,144	18,173	107
200	16,804	20,164	101
240	18,196	21,835	91
320	24,205	29,046	91
400	29,736	35,683	89

4.5 TOWERS FOR WECS

The candidate towers for WECS are the steel truss, steel shell, reinforced concrete shell, prestressed concrete shell, and the guyed pole types. Irrespective of its type, the tower must support and orient the rotor in the selected wind regime and be capable of reacting to the forces imposed by the rotor and by the wind acting on the tower itself for the design conditions. Fatigue strength of the tower must be great enough to withstand the rotor-induced vibratory loads, including the effects of startup, shutdown cycles, gust variations, tower shadow, and gravity for 30 years. The tower stiffness must be such that the resulting tower natural frequencies avoid integral multiples of the rotor frequency. The tower must be strong to resist any buckling caused by the loads.

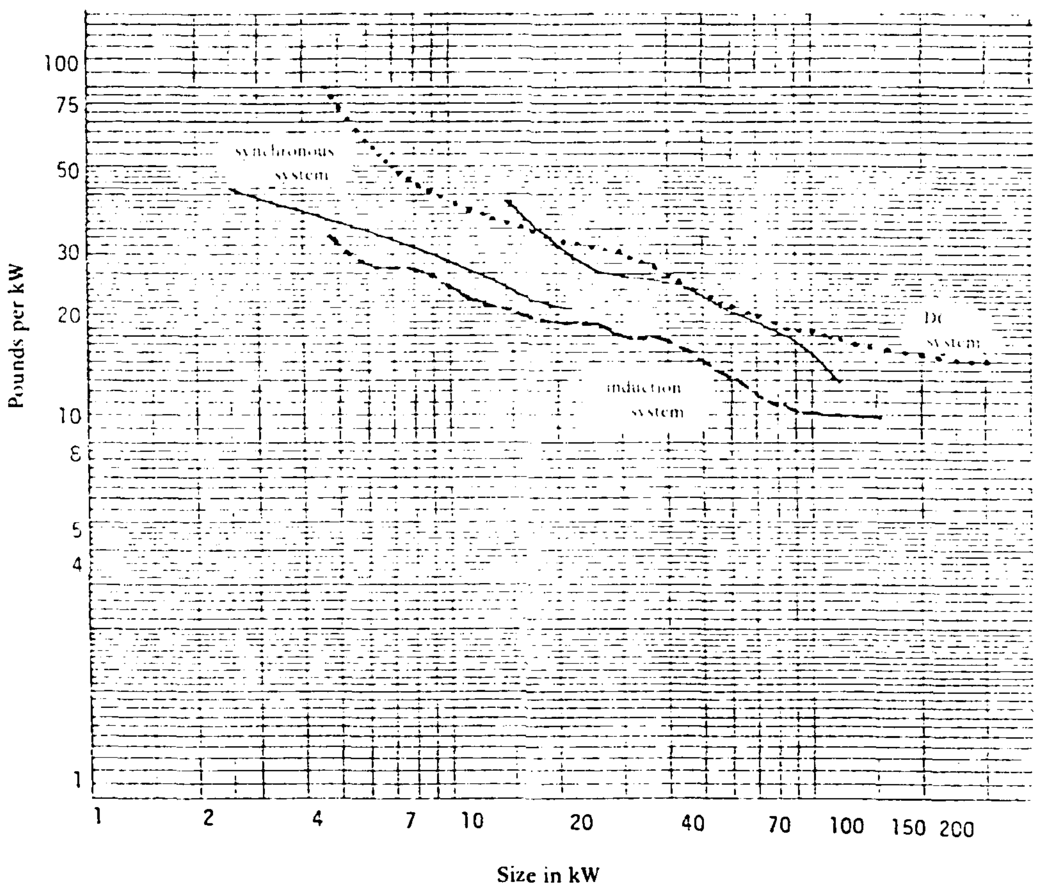

Figure 4.22. Weights of generation system.

4.5.1 Types of Towers

General illustrations of the basic types of towers are shown in Figure 4.23. The various types are discussed as follows (Ref 4.19):

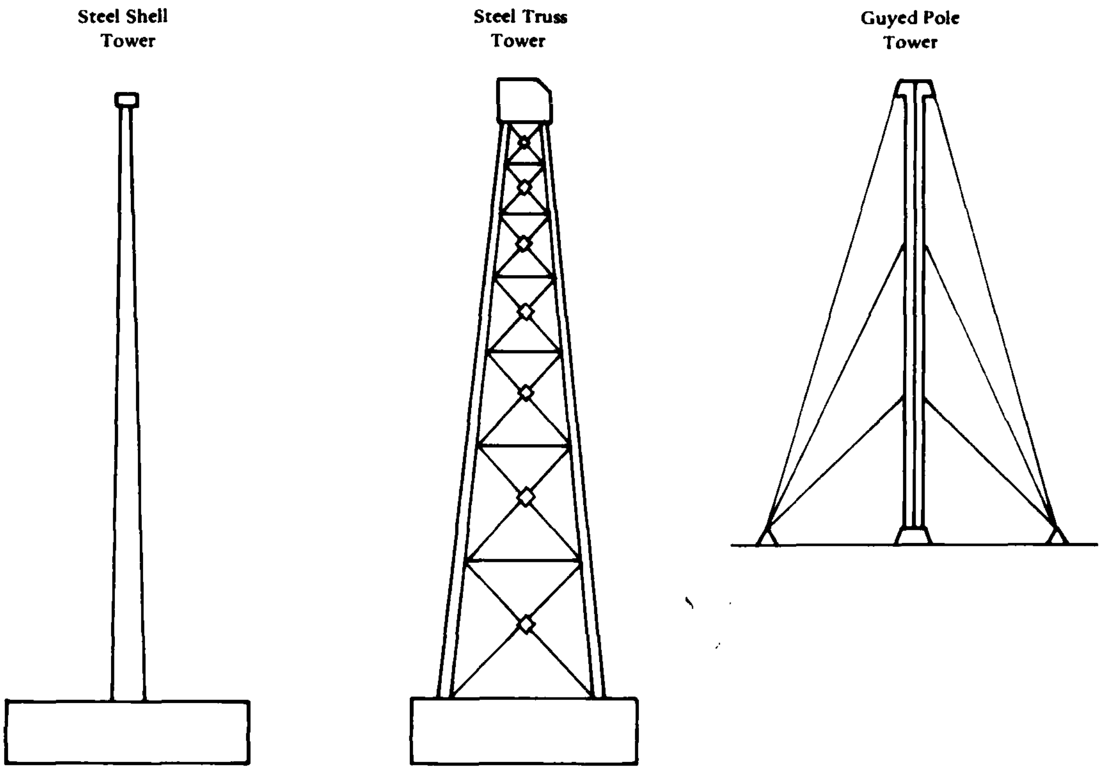

Figure 4.23. Various tower types for WECS.

Truss Tower. The steel truss tower is the most economical of any of the towers suitable for WECS. The use of standard steel sections, connections, and erecting techniques ensures ready availability throughout the United States. Modifications for instrumentation platforms, strengthening, or stiffening can easily be made after construction. There is also some small cost advantages for high-quantity production. Disadvantages are aesthetics and the exposed environment of the servicing steps and the tower components.

Reinforced Concrete Tower. The reinforced concrete tower is a truncated circular cone put in place using slip forms. Because of the poor tensile properties of concrete, heavy reinforcing steel, both longitudinal and spiral, is required to ensure adequate strength and stiffness. As a result, the walls are thick and the tower is heavy and expensive. In addition, cracks can develop from applied forces, which produce tensile stresses, and from shrinkage during curing. Tower material and labor are readily available for this type.

Steel Shell Tower. The steel shell tower is a fully monocoque, truncated circular cone fabricated from rolled conical segments that are field-welded in position at the site. It has aesthestics, but is more costly than either the truss or reinforced concrete towers. In addition, erecting specialists are required for construction.

Guyed Pole. The guyed pole tower consists of a circular steel or wooden cylinder supported near the top by steel cables that provide bending stiffness and also at intermediate levels to provide strength against buckling.

4.5.2 Selection of Optimum Tower Height for a WECS

Many agruments have been made from time to time regarding the importance of increasing tower height above that needed to provide adequate ground clearance to the rotor of a WECS. This minimum ground clearance is usually around 10 meters because of the increased amount of fine grain turbulence below this level, the undoubted decrease in mean wind speed, and the safety element. It is not simply a question of improvement in wind characteristics that is to be examined, but also an improvement in the operating conditions for the WECS rotor itself. Hence, it is an interesting but practical problem to determine the optimum tower height for a WECS given a specific turbine and tower type.

The first important relationship, from the point of view of this discussion, is that between annual mean wind speed at a given elevation above local ground and specific output, S_o. To approximate the annual energy output, the wind velocity distribution will be assumed to be (Ref 4.24)

$$\bar{T} = e^{\pi \bar{u}^2 / 4\bar{h}^{2\beta}} \qquad (4.14)$$

where

$$\bar{T} = H/8760; \qquad \bar{u} = u(z)/u_p(h_o); \qquad \bar{h} = h/h_o$$

and
$u(h)$ = wind speed at elevation z
T = time in hours that the speed exceeds u
$u_p(h_o)$ = mean wind speed at 32.8 feet (10 meters)
h = turbine height above ground
p = velocity profile power law exponent

As discussed in Reference 4.24, it is assumed further that the WECS output is according to the relationship

$$\bar{P}(\bar{u}) = \begin{cases} 0 & \bar{u} < \bar{u}_c \\ a + b\bar{u}^2 & \bar{u}_c \leqq \bar{u} \leqq \bar{u}_r \\ 1 & \bar{u}_r \leqq \bar{u} \leqq \bar{u}_o \\ 0 & \bar{u}_o \leqq \bar{u}_o \end{cases} \tag{4.15}$$

In Equation 4.15, $\bar{P} = P/P_r$ and the constants a and b are determined such that the rotor cuts in at $\bar{u}_c$ with a power ratio $\bar{P}_c$ and reaches the rated power level 1 at $\bar{v}_r$. Hence, the WECS performance in specific output, S_o, is given by

$$S_o = 8760 \int_0^1 \bar{P}(\bar{u})\, d\bar{T} \tag{4.16}$$

The integral in Equation 4.16 can be evaluated to yield a simple expression for S_o as

$$\frac{S_o}{8760} = \frac{u(1 - \bar{P}_c)}{\bar{h}(1 - \bar{u}^2/\bar{u}_r^{\,2})} \left[e^{\delta_c} - e^{\delta_r} \right] + \bar{P}_c\, e^{\delta_c} - e^{\delta_o} \tag{4.17}$$

where
$$\delta_c = -(u/\pi)(\bar{u}_c/\bar{h}^p)^2$$
$$\delta_r = -(u/\pi)(\bar{u}_r/\bar{h}^p)^2$$
$$\delta_o = -(u/\rho)(\bar{u}_o/\bar{h}^p)^2$$

The specific output equation given above is approximate. It agrees with other more accurate estimates to within about 10%. The cost of a self-supporting steel tower as a function of its height and the design horizontal load (Ref 4.25) is assumed to vary as

$$C_{TO} \propto \bar{h}^{0.5} L_h \qquad (4.18)$$

where C_{TO} is the cost and L_h is the load. This relationship is used for the total expected cost of the tower (i.e., including site preparation, foundations, and construction). It is important to determine how L_h varies with height. If two main assumptions are made about the wind characteristics at a site, a simple expression for L_h can be derived. The assumptions are:

1. Maximum short-duration wind speed does not vary with height above ground, so that the load under "shutdown" conditions does not increase significantly with tower height.

2. Maximum horizontal tower load occurs at full-rated output, when the contribution to the total made by the wind load on the tower itself is relatively small for short towers and greater with taller towers.

After accounting for these and other factors of lesser importance, the conclusion is that the load, L_h, relates to the ratio of tower heights

$$L_h \propto \bar{h}^{0.17(\bar{h}-1)} \qquad (4.19a)$$

and that the cost,

$$L_h \propto \bar{h}^{-0.17(2+\bar{h})} \qquad (4.19b)$$

Hence, the total system cost, C_w, is

$$C_w = 1 + \chi_o \bar{h}^{-0.17(2+\bar{h})} - 1 \qquad (4.20)$$

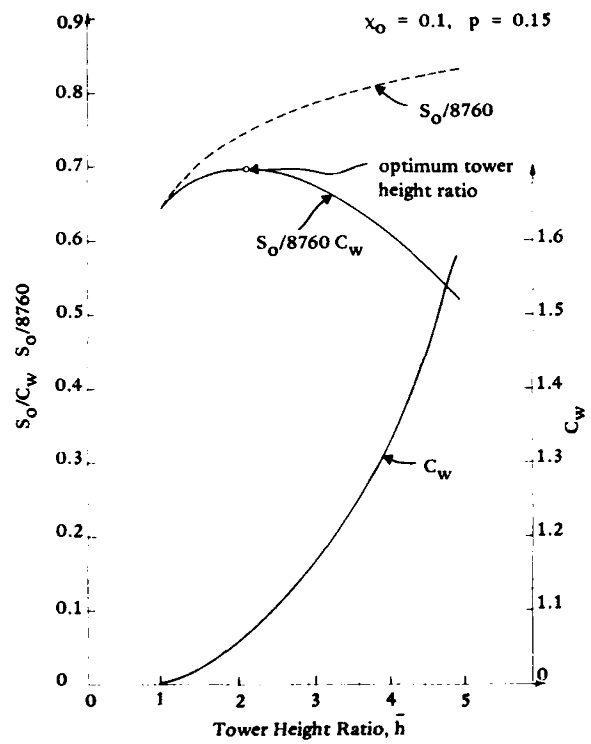

Figure 4.24. Variation of specific output, tower cost, and the ratio S_o/C_w as a function of tower height ratio.

where χ_o is the fraction at height h_o of the cost of the erected tower to the total cost. If C_w is plotted against $\bar{h}$, steeply rising values of cost result for values of $\bar{h} \geq 3$, particularly for higher values of χ_o. To obtain the greatest benefit from increased tower height, the quantity S_o/C_w must be minimized. If S_o/C_w is plotted against tower $\bar{h}$ (Figure 4.24), the curve has a peak for some value of $\bar{h}$, thus showing that there is an optimum height for a given WECS installation based upon the local terrain texture. Table 4.13 shows the optimum tower heights for various terrain types and the χ_o values.

On a good hilltop site, there seems to be justification for keeping the tower height to the minimum based upon clearance requirements and operational safety. There is an advantage in increasing tower height in open-level country in a region where there are low average wind speeds, particularly if the tower cost is a relatively small fraction of the total system cost.

Table 4.13. Optimum Tower Heights for a 20-kW WECS in Various Terrains

Velocity Law Exponent, p	Optimum Tower Height (ft) When Ratio of Cost of a 33-Foot Tower to Total System Cost is --		
	0.1	0.2	0.3
p = 0.20 (suburban area)	77	58	50
p = 0.10 (level terrain)	65	44	35
p = 0.12 to 0.15 (low level coastal sites)	67 to 75	48 to 53	38 to 43
p = 0.08 to 0.1 (good hill sites)	60 to 65	38 to 44	33 to 35

NOTES:

(1) Site annual average wind speed at 33-foot height = 10 mph.
(2) Rated wind speed for the WECS = 20 mph.
(3) Cut-in wind speed for the WECS = 8 mph.
(4) Shut-down wind speed for the WECS = 50 mph.
(5) Rated power = 20 kW
(6) Power at cut-in = 1.6 kW.

At intermediate sites (e.g., on level ground in coastal areas), there can be justification for modest increases in tower height and, at the extreme (i.e., on the fringe of urban areas), there will almost certainly be justification for building taller towers. The assumptions of vertical wind gradient used in the assessment are that the exponent (1) in suburban areas is more than 0.2, (2) in level country is 0.1, (3) at low-level coastal sites is 0.12 to 0.15, and (4) at good hill sites is 0.1 or less.

4.6 POWER CONDITIONING SUBSYSTEMS FOR WECS

Because of the variable nature of wind, a WECS rotor turns at variable speed and the generator driven by such a prime mover will deliver electricity with variable voltage and frequency. It is, however, possible to design a constant speed rotor by controlling the blade pitch. But as shown in Figure 4.3, the power, and hence the total energy output from such a propeller, will be less than that obtainable from the variable speed type. The reduction in output of a constant speed WECS machine becomes significant at a location where the prevailing wind speed is less than the rated wind speed of the machine most of the time. Clearly, a majority of the Navy sites fall in the above category.

4.6.1 Load Matching for WECS

To improve the cost effectiveness of wind energy systems, it is best to extract as much power as is possible from the wind, allowing the prime mover to rotate at varying speeds. This not only improves energy conversion, but also results in the simpler design of mechanical elements. Hence, to keep the cost per kWhr of energy produced as low as possible, it is essential to fully utilize the output from the generator (i.e., utilization of the generated power between cut-in and rated speeds must be done by matching the load to the generator's instantaneous output). Thus, to follow the generator's output versus wind speed characteristics over its entire operating range, the available load should be infinitely variable. In practice, however, the infinitely variable load is almost impossible to achieve. One convenient solution is to divide the load to be serviced into a series of small units and switch them in and out of the circuit to match the generator's output (Figure 4.25) (Ref 4.26). Next, Figure 4.26 shows the schematic of the switching sequence. An upward arrow shows the loading being switched into the generator circuit, and the downward arrow denotes the load being switched out of the generator circuit. To ensure stall-free operation of the wind turbine rotor, a slight delay must be introduced between switching in and out moments (about 2 to 5 Hertz).

4.6.2 Power Conditioning Methods

A variable speed WECS rotor would drive a conventional AC generator with DC excitation at a variable speed, resulting in variable frequency and voltage. To interconnect the WECS to existing power systems at a

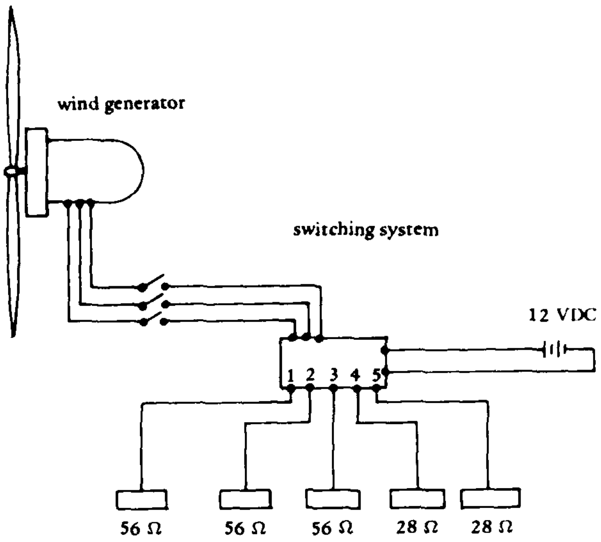

Figure 4.25. Switching system schematic.

Navy installation, the output of a wind system should be of constant frequency and voltage. Constant voltage can be obtained by common voltage regulator techniques, but obtaining constant frequency from a variable generator is not simple. Yet, it is extremely important for a WECS to generate electrical energy in parallel with other power sources. The basic factors to be considered in discussing power conditioning technology associated with converting wind energy into electrical energy are as follows:

A. Type of output desired

1. DC
2. Variable frequency AC
3. Constant frequency AC

B. Wind turbine rotational speed

1. Constant speed
2. Nearly constant speed or variable slip
3. Variable speed

C. Utilization of electrical energy output

1. Battery storage
2. Other forms of storage
3. Interconnection with AC grid

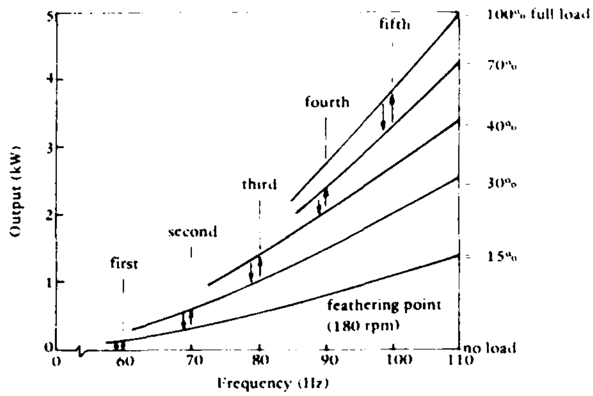

Figure 4.26. Wind turbine generator and switching system characteristics.

Direct DC generation is practical only on a small scale at present, limited to about a 2 kW size or less. Wind turbine speed need not be constant and the system usually employs small battery storage. Small-scale power requirements at very remote sites to operate repeaters and radio beacons can be satisfied adequately using such systems. There is no real need for any type of power conditioning other than voltage regulators for such installations.

The power conditioning systems capable of producing constant voltage synchronous power from WECS are:

1. DC motor-driven AC generator

2. Solid state inverter (or AC-DC-AC link)

3. Synchronous inverter

4. Field-modulated inverter

5. Automatic load matching system with a variable transformer

<u>1. DC Motor-Driven AC Generator</u>. This system consists of generating DC power from wind by using either a DC generator or by a variable speed AC generator with a transformer-rectifier unit. The DC power thus

generated is utilized to operate a DC motor-driven synchronous or induction generator at ground. The schematic of such a system is shown in Figure 4.27. The maintenance costs of such systems can be very high.

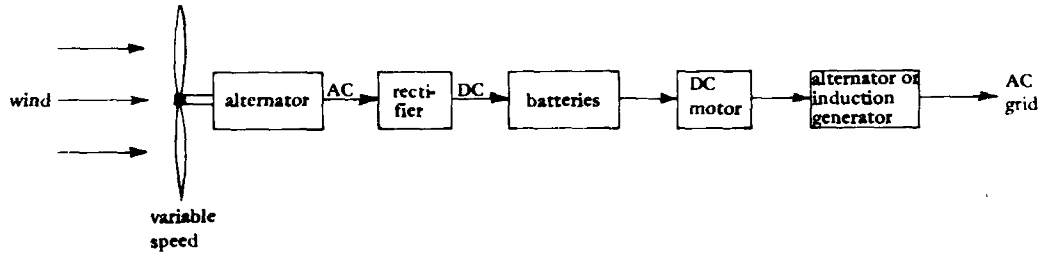

Figure 4.27. A wind power installation with a DC motor-AC generator set for power-to-grid applications.

2. Solid State Inverter. One method of obtaining constant voltage and frequency power from wind power plants utilizes a system of batteries and a solid state inverter shown in Figure 4.28. The batteries store the energy. Such a system has been used in windy, remote areas of the world to generate electricity from the wind. The system is self-contained and is capable of supplying uninterruptible power to the load as desired. The cost of the power conditioning hardware and the storage batteries and the inherent inefficiencies in the various components increase the cost of power generated.

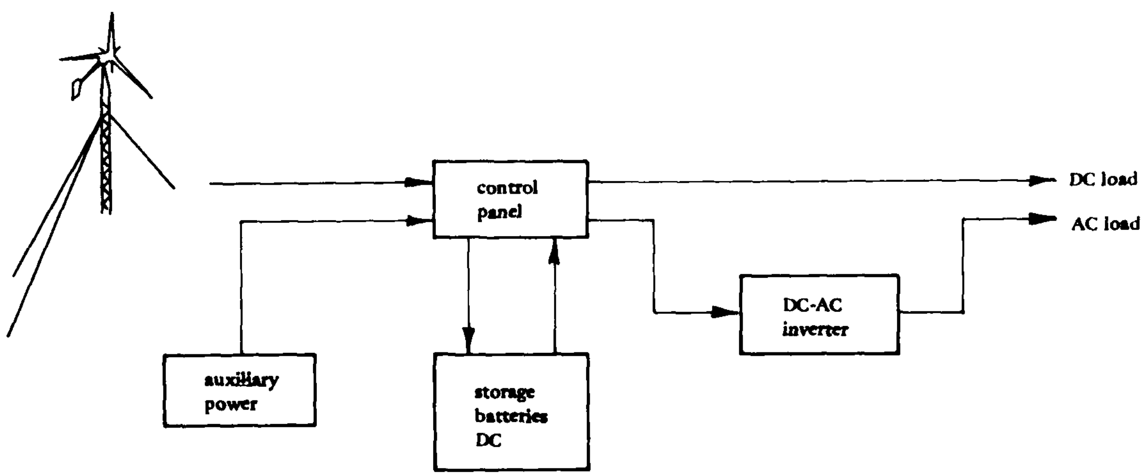

Figure 4.28. A wind power installation for a remote Navy site.

3. <u>Synchronous Inverter</u>. Recently, a synchronous inversion technique for wind power utilization has been developed by Wilkerson (Ref 4.27). The hardware design utilizes the AC grid as the storage reservoir in addition to using it for fixing both the voltage and frequency of the power available from the wind. A schematic of such an inversion scheme is shown in Figure 4.29. This system takes the rectified output of an AC wind generator through an inverter system and feeds it to the existing grid lines. The inverter system design is such that it accepts the DC power from the wind generator, converts it to AC, and feeds it into the grid lines (Figure 4.30). The load connected to the lines obtains power at the voltage and frequency fixed by the grid lines. If at any instant the wind generator produces more power than is required by the load, the excess flows into the grid network. If the wind generator output is less than the load required, the difference is provided by the grid lines. Hence, the grid acts as a limitless storage medium for a small-capacity wind generator, and the load to be served by this arrangement receives constant voltage and frequency power as desired.

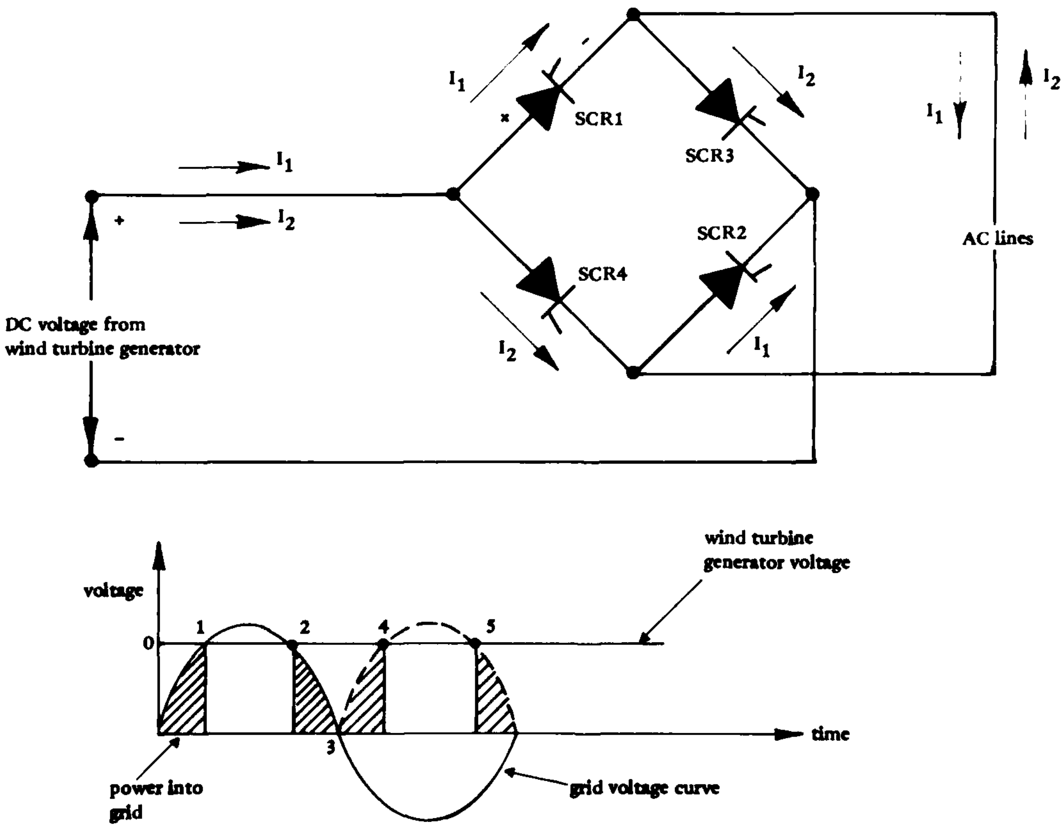

Figure 4.29. The principle of operation of a synchronous inverter.

Such a scheme can be used for integrating a small-capacity wind generator with a diesel power plant at remote Navy sites. However, the existing grid must have a strength of at least three to four times that of the wind generator being integrated. Such a system adds to the cost of a given wind plant installation. The modern inverter designs have efficiencies ranging from 75% to 95%. The inefficiency of the inverter will contribute to an increase in the cost of wind power generation on a kWhr basis. To make this method of power conditioning economical, improved designs are required.

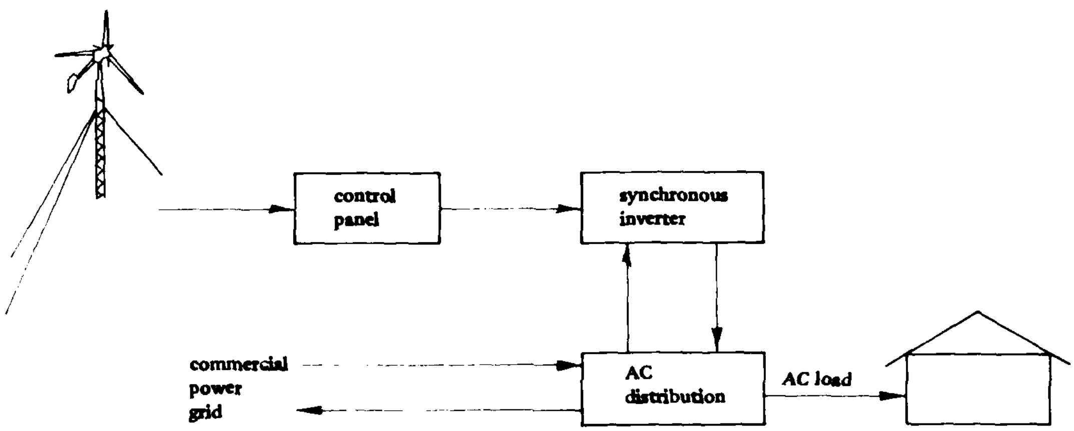

Figure 4.30. A wind power installation with a synchronous inverter for generation in parallel with another source.

4. Field-Modulated Alternator. The field-modulated generator systems are being actively developed for use in wind energy conversion systems (Ref 4.21). A schematic of such a system is shown in Figure 4.31. The system draws its field modulation by AC excitation drawn from the line. The concept has good promise for higher efficiency, but the idea still needs considerable development.

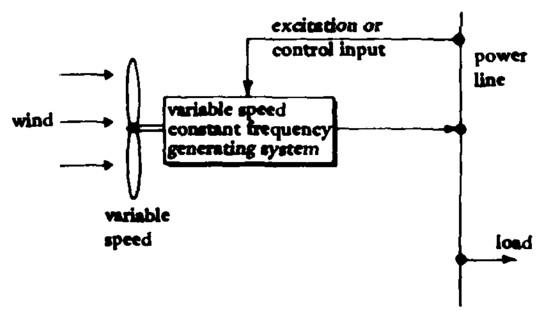

Figure 4.31. The schematic of a field-modulated alternator.

5. Automatic Load Matching System With a Variable Transformer. A concept of one such scheme (Figure 4.32) using the automatic load matching system appears very promising (Ref 4.27). The generator output can be passed through a constant voltage autotransformer to keep a relatively constant voltage at the load. The generator can then share the load with the existing power source. Storing wind energy in thermal form for subsequent use in space heating can be effectively done using a variable frequency AC (or DC) system in conjunction with a heating coil-thermal storage arrangement. The system can be used for charging batteries at a remote site.

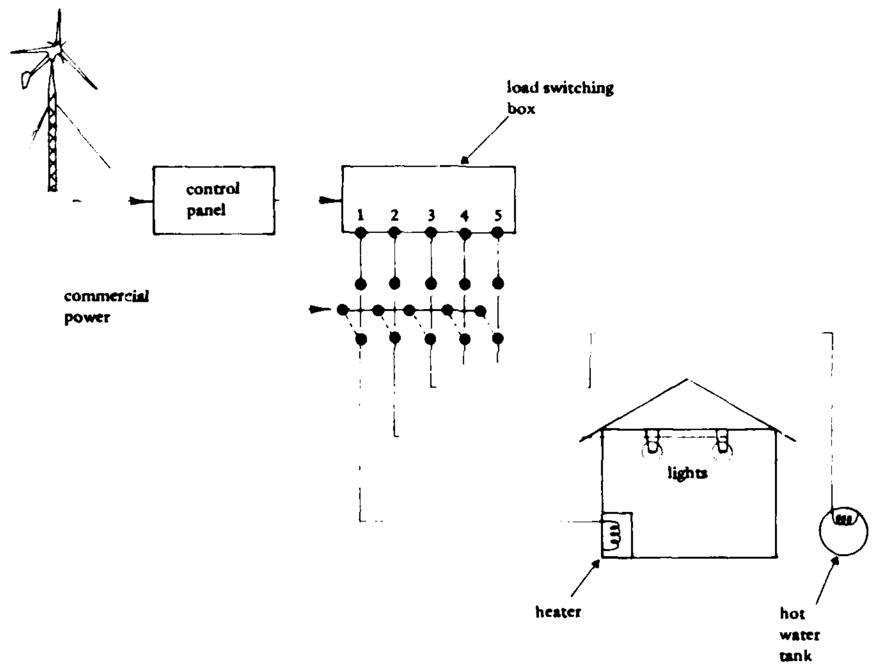

Figure 4.32. Load matching device for using variable frequency AC power from WECS.

Table 4.14 summarizes the cost of all five systems for 5- and 10-kW sites. Clearly, the load matching system is the least expensive of all the systems, but it cannot provide constant frequency power. Next, Figure 4.33 shows the efficiencies of all the systems at various fractions of full load values. Once again, the load matching scheme has the highest efficiency of all the systems. The power conditioning systems for various types of generators and power requirements are shown in

Table 4.14. Cost of Various Power Conditioning Systems for 5- and 10-kW Wind Generators

Type	Cost ($) for --		Comments
	5-kW Generator	10-kW Generator	
1. DC Motor-Driven AC Generator	3,500	5,000	High maintenance; commercially available
2. Solid-State Inverter	5,000	8,000	Low maintenance; high reliability; commercially available
3. Synchronous Inverter	2,000	4,000	Operates with an existing power grid only; commercially available
4. Field-Modulated Alternator	1,000	1,500	System still under development; not commercially available
5. CEL Switching System With a Variable Transformer	1,000	1,200	System under development; does not provide synchronous power; components commercially available

Table 4.15. Clearly, the induction generators do not require any power conditioning system and, hence, are gaining quite a widespread use in the wind power industry.

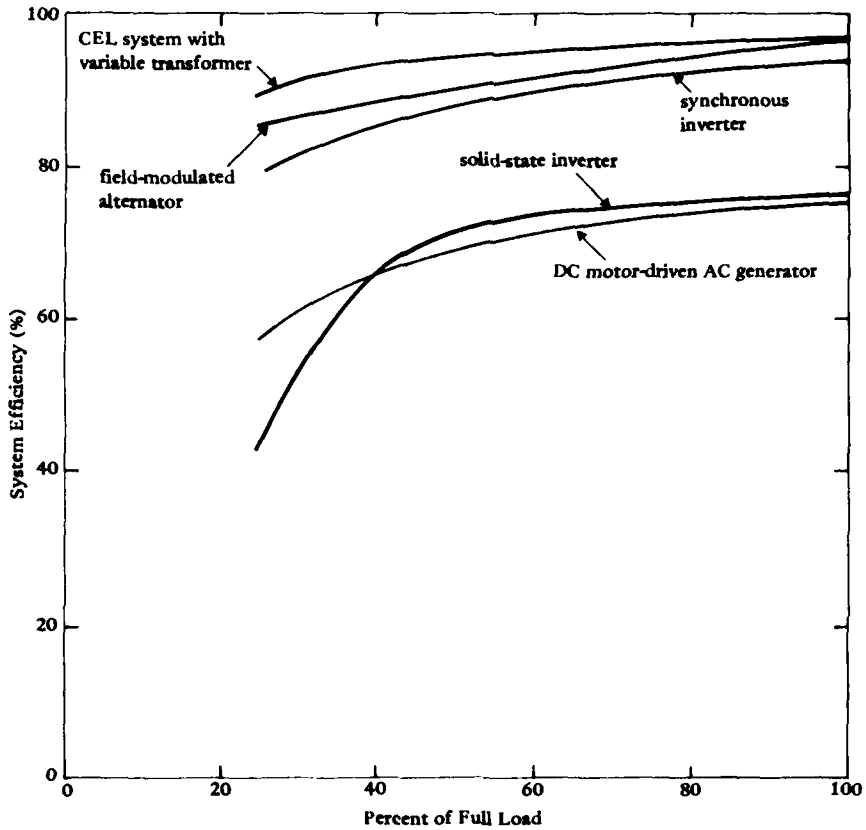

Figure 4.33. Efficiency of various power conditioning systems.

4.7 COMMERCIALLY AVAILABLE WECS

A checklist of WECS systems and component subsystems, together with manufacturers and distributors, is given in Appendix A.

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Table 4.15. Various Power Conditioning Types for Wind-Driven Generator Systems

Type of Generator	Power Conditioning Systems				
	CEL Load-Matching System	Field-Modulated Alternator	DC Motor AC Generator	Solid-State Stand-Alone Inverter	Synchronous Inverter
AC Power					
Permanent Magnet			X	X	X
Self-Excited	X	X	X	X	X
Induction		none required			
DC Power	X		X	X	X

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Chapter 5

SITING SMALL WIND ENERGY CONVERSION SYSTEMS

A recent survey (Ref 5.1) indicated that improper siting was a common cause of dissatisfaction among small WECS users. That is, the user either did not get the power output or the machine reliability and life as expected prior to installation. If poor siting instances were a cause of complaints in the past, they will certainly continue to be a source of user dissatisfaction in the future. In the past, wind machines have been primarily used in applications where they were the only option available for providing power in rural areas. Hence, the user was likely to be satisfied with whatever performance he could glean from the winds. Modern wind machines, however, must compete with other options for providing power as well as with the central grid.

Navy activities will need to be reasonably certain of the cost of wind power for their application before deciding on a wind energy conversion system (WECS). Such an assessment requires an accurate knowledge of wind characteristics at the machine site. This chapter presents a procedure for choosing the best available site for a given WECS and for estimating the necessary wind characteristics for the chosen site. In some cases, extensive on-site measurements can be required before an accurate analysis of a WECS installation performance can be made.

5.1 SITING PHILOSOPHY FOR SMALL WECS

A prospective Navy activity must consider many factors other than siting before deciding upon utilizing wind as a source of energy. Among these factors are logistics, environmental and legal constraints (such as wind right and land use), in addition to economic considerations. The potential user activity must also be aware of the available hardware and of the most viable storage and/or backup systems for a given application.

The selection of a wind system, except for a simple water pumper or a battery charger, will require more extensive analysis than is customary for most Navy procurements. Obviously, a detailed plan must be prepared in advance if the analysis is to be successful. The following outline based on Reference 5.2 is a suggested analysis strategy.

5.1.1 Feasibility of Wind Power at a Site

1. Initial wind resource assessment
   a. Survey available WECS.
   b. Estimate power output.*
   c. Estimate power needs.
2. Economic analysis
   a. Analyze cost of WECS.
   b. Consider legal and other institutional issues.
   c. Formulate total budget.

5.1.2 Site and System Selection

1. Final wind resource assessment
   a. Select candidate sites.*
   b. Determine available power at candidate sites.*
2. Selection of WECS
   a. Estimate power requirements quantitatively.
   b. Estimate power output quantitatively.*
   c. Choose WECS and storage and/or backup system.

5.2 DETERMINING WIND POWER FEASIBILITY AT THE SITE

The first step in deciding upon use of wind power is to determine if a WECS can satisfy the load demand or can meet a significant fraction of the demand to make wind energy economical at the site. One way of determining feasibility is to examine current and historical use of wind energy in the immediate vicinity of the Navy activity. If applications of wind power similar to the one being considered by a Navy activity have been successful in the past, or if WECS are currently in widespread use, wind power will probably be a feasible source of power.

If there is no local history on wind power use, an estimate of the probable annual power available in the wind must be made for the site under consideration. The first step in this process, of course, is to estimate the mean annual wind speed. Once the annual wind speed is known, then an estimate of the average annual power output can be made. Mean annual wind speeds can generally be obtained from on-base wind recording stations. If wind speeds are not recorded locally, other sources, such as National Weather Service Stations, nuclear power plants, colleges or universities, U.S. Agricultural Extension Service, or State and Federal forest services, can provide this information. In areas with flat terrain, such as the Great Plains, these wind speeds should be representative of the local values to a distance of 50 to 100 miles from the station (Ref 5.3); on the other hand, in coastal area locations along the coast, it will be windier than at sites a few miles inland.

*These items require a knowledge of the site wind characteristics and hence only these items will be discussed in this chapter.

In remote areas or in regions where large, local variations in wind speed can be expected, the shapes of well-exposed trees can indicate the local wind speed (Ref 5.4). Figures 5.1 and 5.2 illustrate two indicators of tree shape that have been found to be good indicators of local wind speed. Figure 5.1 illustrates the concept of the Griggs-Putnam index. In Figure 5.2, the deformation ratio is defined. Both of these parameters quantify the degree of flagging or wind sculpturing of pine or fir trees. Deciduous trees are also shaped by the wind, but they are more difficult to "read" and have not been studied as extensively. Tables 5.1 and 5.2 give a preliminary calibration of both the Griggs-Putnam index and the deformation ratio in terms of the annual mean wind speed (Ref 5.5).

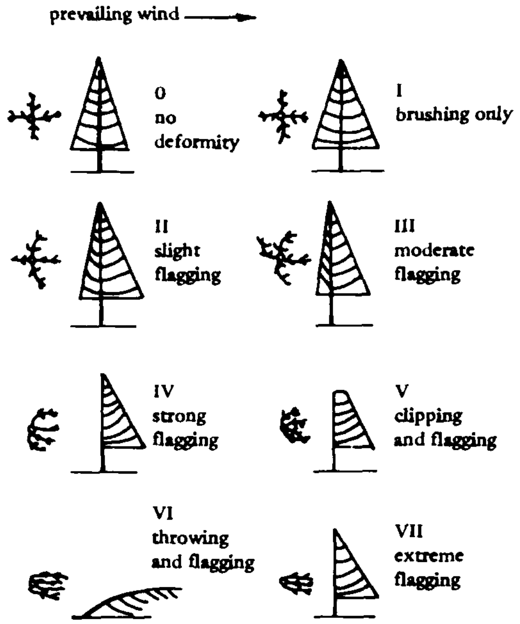

Figure 5.1. Wind speed rating scale based on the crown shape and the degree twigs, branches, and trunk are bent (Ref 5.3).

The Griggs-Putnam index is the easiest indicator to use. The tree in question is simply classified by comparing its shape with Figure 5.1. The deformation

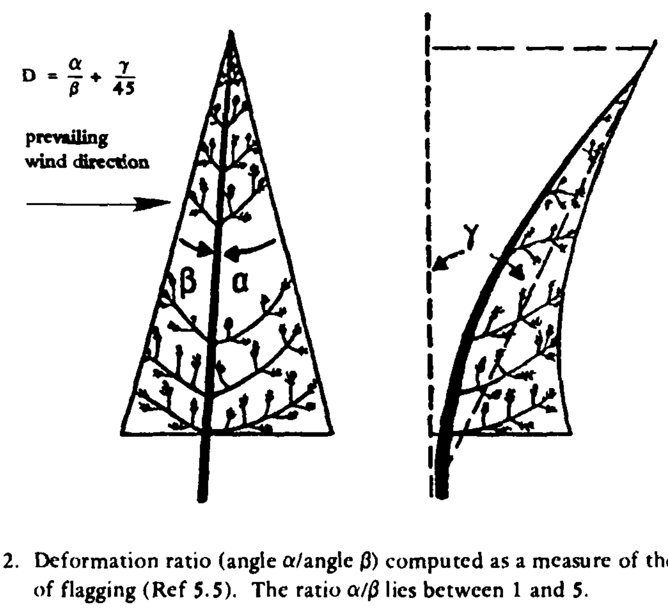

Figure 5.2. Deformation ratio (angle α/angle β) computed as a measure of the degree of flagging (Ref 5.5). The ratio α/β lies between 1 and 5.

ratio is best determined from a photograph of the tree that is taken perpendicular to the prevailing wind direction. Caution should be observed when using these indicators. The absence of flagged trees does not necessarily mean that the local wind speed is low, because the species of trees in the vicinity could not be susceptible to flagging, the trees could be sheltered, or the trees could be exposed to strong winds that come from several directions. Secondly, the tables given here are based on data for ponderosa pine and Douglas fir only; in addition, these data were gathered at locations where the seasonal variation in wind speed is small. Thus, annual mean wind speeds derived from the above parameters should be applied cautiously. Although the parameters could aid in determining feasibility, final computations of annual power output selection of a particular wind machine should not be based on these indicators alone.

Table 5.1. Mean Annual Wind Speed Versus the Griggs-Putnam Index[a]

Item	Griggs-Putnam Index (as in Figure 5.1)				
	I	II	III	IV	V
Probable Mean Annual Wind Speed Range, mph	6-10	8-12	11-15	12-19	13-22

[a]These data were prepared by E. W. Hewson, J. E. Wade, and R. W. Baker of Oregon State University.

Table 5.2. Mean Annual Wind Speed Versus the Deformation Ratio[a]

Item	Deformation Ratio (as in Figure 5.1)						
	I	II	III	IV	V	VI	VII
Probable Mean Annual Wind Speed Range, mph	4-8	7-10	10-12	12-15	14-18	15-21	16-24

[a]These data were prepared by E. W. Hewson, J. E. Wade, and R. W. Baker of Oregon State University.

Once the approximate mean wind speed for a site has been determined, the annual power output for a particular machine can be estimated. Figure 5.3 shows how the average annual power output is related to various machine characteristics. This particular figure is for a two- or three-bladed machine having a cut-in speed between 6 and 12 mph. It is assumed that such a turbine has a power output curve similar to that indicated in Figure 5.4. Figure 5.3 is also based on the assumption that the wind frequency distribution curve can be represented by the Rayleigh distribution (Ref 5.6). From Figure 5.3 one fact of machine performance is clear: power output is extremely sensitive to small changes in wind speed.

5.3 SELECTING A SITE FOR A WECS

For most small WECS, the general location of the wind turbine will be fixed. It must be near the point of power consumption. In other applications, the user could site his machine at any location over a fairly windy area and take advantage of terrain enhancement of the local wind speed. However, even if the location of the machine is fairly well fixed, siting remains important. Small changes in the height of the machine above the ground or in the placement of the machine with respect to nearby obstacles can result in significantly larger power output or in increased machine life.

Figure 5.5 is a decision tree showing a philosophy for attacking the problem of determining exactly where to place a wind machine. As the figure shows, the first step is to identify the prevailing wind directions. Otherwise, the prevailing wind direction can be determined from the wind summaries of nearby weather stations, from windflagged vegetation, or from measurements at the site.

For siting small wind machines, two classifications of terrain should be considered: flat and complex. A very conservative definition of flat terrain can be given with the aid of Figure 5.6 (Ref 5.7). According to this definition, terrain can be considered flat if the following holds:

1. The maximum terrain relief (h) is less than 200 feet within a 2.5-mile radius of the site.
2. The machine is at least 2 h to 3 h above ground.
3. The ratio h/ℓ is less than 0.03, where ℓ is the length over which the largest terrain difference occurs.

The distance between the ground and the bottom of the rotor disk (i.e., 3 h) will seldom exceed 60 feet for most small installations. According to this definition, the maximum terrain relief cannot exceed 20 feet within 2.5 miles of the site in order for the terrain to be considered flat (Criterion No. 3). For the case of wind turbine siting, this definition seems overly restrictive. A more practical criterion would be to consider the terrain flat if only items 1 and 2 of the above definition were satisfied upwind of the site.

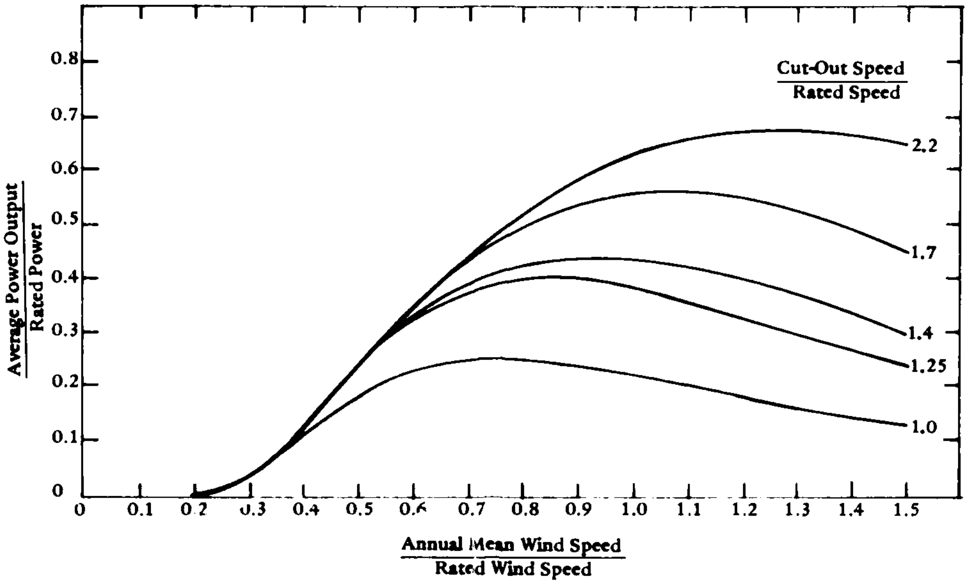

Figure 5.3. Expected average power output for WECS based on annual mean wind speed and machine characteristics (Ref 5.5).

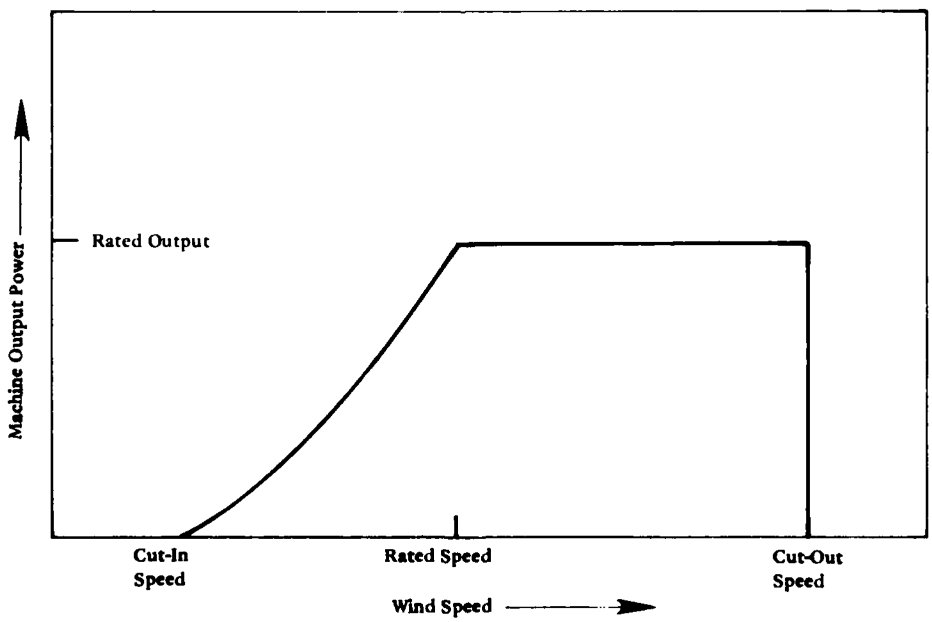

Figure 5.4. Typical power output curve for a typical wind turbine generator.

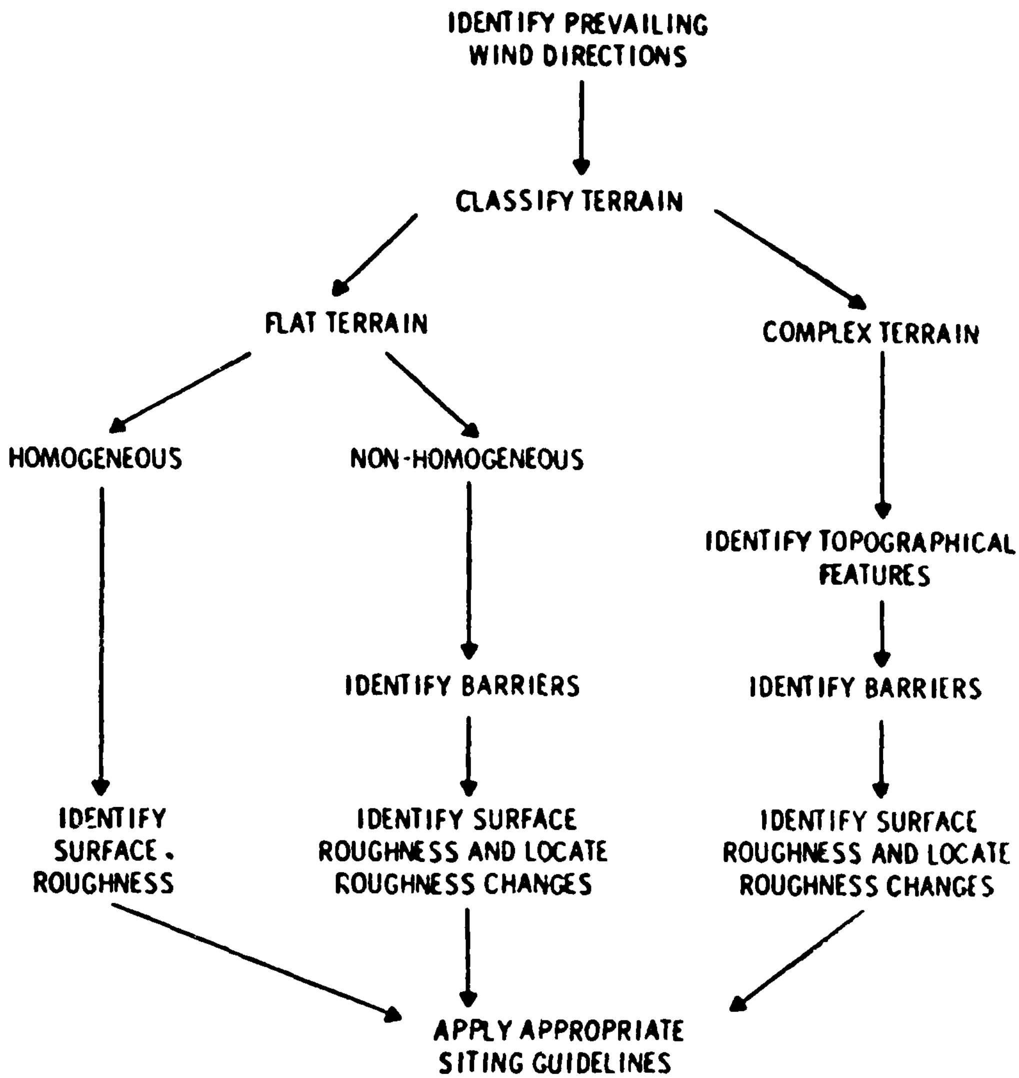

Figure 5.5. Development of a siting strategy based upon terrain classification.

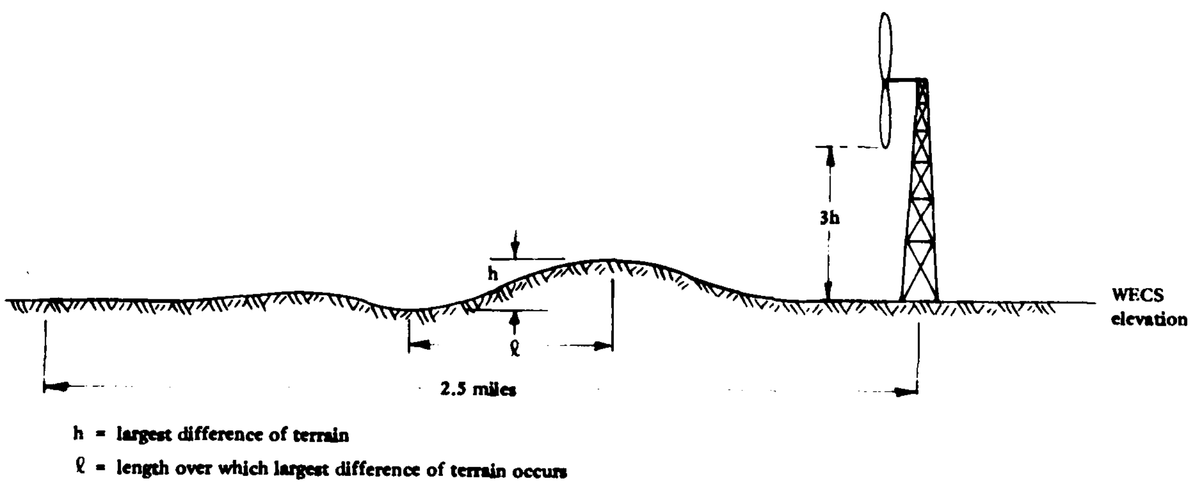

Figure 5.6. Determination of flat terrain (Ref 5.7).

If the local terrain is flat and the character of the surface (i.e., surface roughness) is uniform for about one-half mile upwind of the potential site, the terrain can be considered homogeneous. In other words, the mean datum line does not change along the horizontal direction. In this situation, the available wind power can only be increased by increasing the height of the tower upon which the machine is placed. A Siting Handbook for Small Wind Energy Conversion Systems (Ref 5.2) contains information on how much the available wind power can be increased by increasing tower height for various values of surface roughness. However, the potential WECS user must weigh the potential benefits of increasing tower height against the increased costs of a higher tower.

If the terrain is flat but not homogeneous (i.e., there are obstacles or changes in surface roughness upwind of the site), several siting options exist:

- Choose a site that is not downwind of barriers that are along the prevailing wind direction.
- Site enough upwind or downwind of the barriers so that the machine is outside the region of flow disturbance.
- Place the machine rotor above the region of disturbance if a barrier cannot be avoided (see Tables 5.3, 5.4, and Figure 5.7).
- Identify significant changes in roughness and take advantage of the changes in the resulting wind speed profile (see Figure 5.8).

Detailed information on the flow over barriers is given in Chapter 2 and also in A Siting Handbook for Small Wind Energy Conversion Systems (Ref 5.2). This document also contains procedures for calculating the transition heights for roughness changes. All of these guidelines, however, must be viewed as approximations. For example, in determining the optimum location for a WECS downwind of a change in roughness, it should be realized that actual transition heights vary from day to day with the meteorological conditions. The transition from a region of flow affected by one roughness to a region affected by another does not occur abruptly; instead, the transition occurs over several tens of feet. Nevertheless, one principle stands out: there is a greater advantage in increasing tower height in rough terrain than in smooth (see Figure 5.8).

Siting in hilly and mountainous (i.e., complex) terrain is more difficult than selecting a site in a flat area. Wind patterns over complex terrain are affected by interactions between the topographical features, barriers, surface roughness, and the atmospheric stability conditions. All of these effects result in winds that can display considerable variations in speed and direction over short distances.

If possible, the effects of terrain on the wind should be used to an advantage. It could be possible to find a location with considerable local wind speed enhancement. If the WECS location is fixed, the effects of terrain must be understood in order to estimate the probable effects of the terrain on the wind at the site.

In complex terrain, the mean annual wind speed, diurnal variations, and other features of the wind could differ considerably from those of nearby weather stations. These differences could be beneficial or detrimental to the wind power potential.

Table 5.3. Wake Behavior of Variously Shaped Buildings (Ref 5.9)

Building Shape (Width/Height)	Downwind Distances (in Terms of Building Heights, h)								
	5h			10h			20h		
	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase
4	36	74	25	14	36	7	5	14	1
3	24	56	15	11	29	5	4	12	0.5
1	11	29	4	5	14	1	2	6	--
0.33	2.5	7.3	2.5	1.3	4	0.75	--	--	--
0.25	2	6	2.5	1	3	0.50	--	--	--
Height of the wake flow region (in building heights)		1.5			2.0			3.0	

Table 5.4. Available Power Loss and Turbulence Increase Downwind From Shelterbelts of Various Porosities (Ref 5.9)

Porosity[a] (Open Area/Total Area)	Downwind Distances (in Terms of Shelterbelt Heights, h)								
	5h			10h			20h		
	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase
0% (no space between trees)	40	78	18	15	39	18	3	9	15
20% (with loose foliage, such as pine or broadleaf trees)	80	99	9	40	78	--	12	32	--
40% (with dense foliage, such as Colorado Spruce)	70	97	34	55	90	--	20	49	--
Top of Turbulent Zone (in terms of shelterbelt height)		2.5			3.0			3.5	

[a]Determine the porosity category of the shelterbelt by estimating the percentage of open area and by associating the foliage with the example tree type.

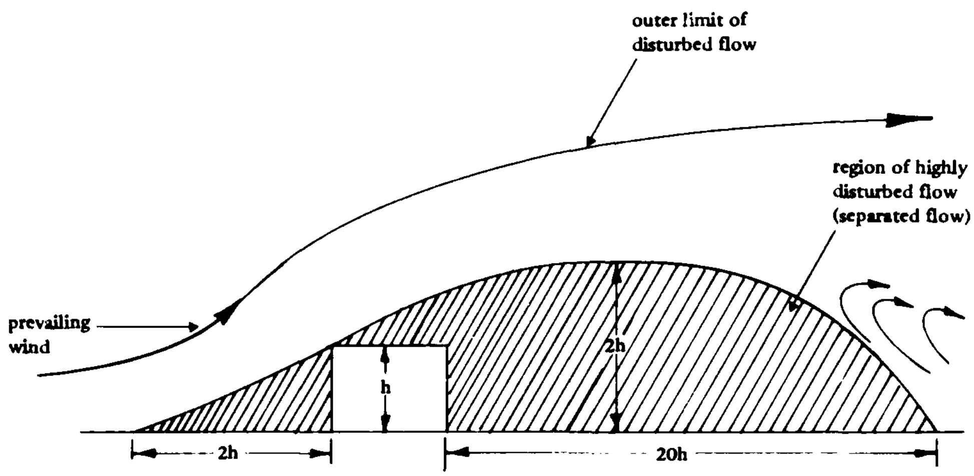

Figure 5.7. Zone of disturbed flow over a small building (Ref 5.7, 5.8, 5.9).

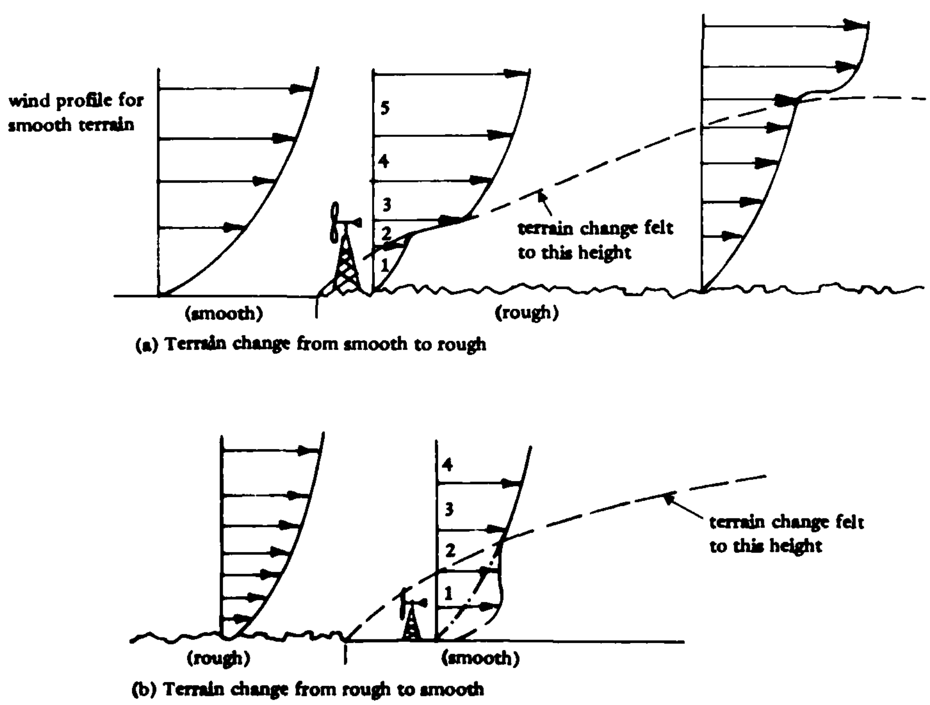

Figure 5.8. Wind speed profiles near a change in terrain (Ref 5.10).

For siting purposes, topographical features can be divided into two broad classifications: elevated features and depressions. The first classification includes ridges, isolated hills or mountains, and escarpments (cliffs or buttes). The second classification includes all depressions, such as valleys, canyons, passes, gorges, and basins.

The advantages of siting on elevated terrain features are:

1. The hills act like a huge tower, raising the WECS into regions of higher wind flow.
2. Hills can actually act to accelerate the flow over or around them, thereby increasing the available wind power.

On the other hand, if elevated terrain features exist upwind of the potential site, they can be detrimental because they could either (1) completely block the site from high winds or (2) create hazardous turbulence or winds with severe gustiness.

The possible advantages of siting within depressions are: (1) the funneling of the prevailing wind through the features, and (2) the possibility of finding thermally driven circulations that could provide useful wind power. Whenever the prevailing wind blows parallel to a pass or a mountain gap, the possibility exists that the winds will be funneled through the feature, and the local wind speed increased.* This effect can also be found in long valleys or canyons. A hypothetical example of this phenomenon is shown in Figure 5.8.

Just as thermally driven circulations cause coastlines to be breezier than the interior, thermally driven circulations can result in winds that flow in and out of basins or up and down sloping mountain valleys. In some situations, these circulations can result in usable winds, such as those in San Gorgonio Pass in Southern California.

Another situation in which a pass or gorge can be a good WECS site exists when a mountain range divides two distinct air masses, as is commonly observed in the summer along the West Coast of the United States. Coastal ranges divide cool, dense, marine air from warmer, less dense air in the interior, which results in strong pressure gradients across the mountains with good winds through many of the passes.

However, there could be drawbacks to siting in depressions. For example:

1. Small depressions could be sheltered from all winds.
2. Valleys perpendicular to the prevailing wind will experience little flow.
3. Depressions are more susceptible to air stagnation conditions.
4. The duration of winds in a valley could change frequently during the 24-hour period and hence could cause more dynamic loading on the WECS components.

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*This cannot always occur. If the gap is in a relatively short ridge, the wind can blow around the ridge. Likewise, if the gap is located in a ridge that is sheltered by another ridge, no local enhancement can be observed.

As illustrated in Figure 5.5, the best approach to siting in complex terrain is to consider the effects of the various topographical features in descending order of size. The overall effects of the topographical features are assessed first, then the effects of any barriers and surface roughness are considered in order to pinpoint the best site or to evaluate a predetermined site.

5.4 SITE ANALYSIS

For some WECS applications, the site evaluation process is completed once feasibility is established and the best site chosen. However, if more precise economic or performance information is needed before the decision to install a WECS can be made, additional analysis of wind characteristics at the site is necessary. Table 5.5 describes three approaches to this analysis and includes the advantages and disadvantages of each.

Table 5.5. Various Methods of Site Analysis for WECS

Method	Approach	Advantages	Disadvantages
A	Use wind data from a nearby station; determine power output characteristics.	Little time or expense required for collecting and analyzing data. If used properly, can be acceptably accurate.	Only works well in large area of flat terrain where average annual wind speeds are 10 mph or greater.
B	Make limited on-site wind measurements, establish rough correlations (Ref 5.3) with nearby stations, then compute power output characteristics.	If there is a high correlation between the site and the station, this method should be more accurate than the first method.	Of questionable accuracy, particularly where there is seasonable modulation of wind speeds and directions.
C	Collect wind data for the site and analyze it to obtain power output characteristics.	Most accurate method. Works in all types of terrain.	Requires at least a year of data collection. Added costs of wind recorders. Data period must represent typical wind conditions.

The first approach makes use of the same data source as the feasibility analysis - nearby weather stations. Method A, however, differs from the feasibility study in that the data are analyzed in more detail. For example, the seasonal and diurnal variations in wind speed can be of interest since in many applications, a close match is required between power output and load if wind power is to be economically feasible. If an energy storage system is under consideration, wind return time statistics should be examined because these statistics are the expected or maximum observed times the wind speed may remain below a certain value, such as the machine cut-in speed. These statistics are also needed for estimating the required storage capacity.

Even though Method A is the simplest of the three, a good deal of work is required if a detailed performance analysis is desired. Often, wind data obtained from the nearby weather station will not include wind characteristics that are of interest in site analysis. Obtaining these characteristics can require some reworking of the data.

Method A can only be used for sites very near (less than 10 to 20 miles) the weather station and for high wind areas having little terrain relief and no large contrasts in terrain type. If these conditions are not met, some sort of on-site measurement program is mandated for an accurate economic analysis. In carrying out a measurement program, the wind-sensing equipment must be sited as carefully as the machine. For example, if the wind machine were placed at some elevation above the surface to avoid the wake of an obstacle, the wind sensor must be placed at this same position.

Methods B and C differ from each other primarily in the length of time that on-site measurements are made. The purpose of Method B is to provide a better estimate of the annual mean wind speed at the site by placing an anemometer at the site and determining the mean wind for a short period of time, for example, one to three months. The mean wind speed is determined at a nearby weather station for this same period of time. The annual mean wind speed at the weather station is multiplied by the ratio of the short-term mean at the WECS site to the short-term mean of the weather station. This value is assumed to be the annual average at the site. Method B, although a traditional approach, is of questionable accuracy. The proper correction factor cannot be obtained from such short-term measurements. Method B is recommended only for regions where the wind speed and direction are very persistent and where there is little seasonal variation. Reference 5.11 gives an example of this method while siting 20-kW WECS at Kaneohe, Hawaii.

Method C is the most accurate and the most involved approach, requiring extended on-site measurements. Even so, some uncertainty can exist in regard to how representative of the long-term average one year's data can be. The character of the wind, like any other meteorological phenomenon, is variable. Some years can be windier than normal and some years can be less. Clearly, the period over which the measurements are made must be reasonably representative of "typical conditions." Judging how typical the wind conditions have been over the period of measurement requires a good deal of meteorological sophistication as well as long-term residence in the area.

The major drawback to both Method B and C is the cost involved. Even a modest measurement program can be a significant fraction of the cost of a small WECS.

5.5 IMPORTANCE OF PROPER SITING

The user must be convinced that the cost of the power generated by the WECS will be cheaper over the life of the machine than the power generated by other alternatives, or that any greater cost would be outweighed by other considerations, such as the desirability of achieving energy independence. In most CONUS locations, the cost of WECS power would have to be considerably cheaper than the alternatives because the activity could prefer to pay a premium for the convenience and historical reliability of central grid power. Obviously, the behavior of the wind at the machine site has an important bearing on the ultimate cost of the power generated. The accuracy to which these wind characteristics must be known and the resulting accuracy of the economic and performance analysis will depend upon the application of the machine and its costs.

Proper siting procedures must attack two basic problems: (1) finding the best, or at least an acceptable location for the machine within a given area, and (2) accurately estimating the wind characteristics at the site. Locating a site is the simplest problem because basic features of flow over obstacles and many terrain features are fairly well understood (Ref 5.12). Guidelines can be formulated that will enable a person siting a machine to avoid a disastrous choice of location. Such guidelines are given in A Siting Handbook for Small Wind Energy Conversion Systems (Ref 5.2).

Accurately estimating the wind characteristics at a site is more difficult. Even in the case where data from a nearby weather station can confidently be applied, there are hidden pitfalls. For example, the elevation, location, or exposure of the weather station anemometer can change over the period of data collection, thus affecting the mean wind speed and other wind characteristics. Although changes in anemometer location and exposure can be noted in the wind records (especially for National Weather Service data), the data user must know how to look for these comments. Such a level of commitment, however, cannot often be possessed by potential users. Most Navy activities will need assistance in machine siting, site evaluation, and economic or performance analysis at least until there is widespread experience with WECS utilization. Extensive work under DOE sponsorship is under progress (Ref 5.13) to advance siting techniques for WECS.

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Chapter 6

THE ECONOMICS OF WIND POWER GENERATION

An economic analysis for a WECS can be commonly defined as a comparison between alternatives, such as onsite fossil fuel power generation or the total utility, in which the differences between the costs of the alternatives are expressed in monetary terms. The primary purpose of an economic analysis is to provide information that the decision maker can use in the WECS for a particular application. The source being free, it is obvious that the cost of energy generation by the wind depends upon (1) the annual energy output of the WECS, (2) acquisition cost, (3) annual operating and maintenance costs, (4) useful life of the WECS, and (5) the terminal value of the equipment.

6.1 COST PARAMETERS

Money has value over time as expressed by the price it commands. This fact must be formally included in the economic analysis by expressing the life-cycle costs of each alternative in terms of their "present value" - a process which specifically accounts for the time value of money (Ref 6.1). The present value life-cycle cost method to be used for estimating future costs is determined by adding the cumulative operational and maintenance present value costs to the capital investment.

6.1.1 Net Present Value Based on Uniform Annual Costs

$$NPV = I + (\bar{A})\ CUS_{(i_D=0,\bar{N})} + (F)\ CUS_{(i_D,\bar{N})} - T_v \qquad (6.1)$$

where NPV = total present value life-cycle cost, in dollars

I = present value acquisition cost, in dollars

$\bar{A}$ = recurring uniform annual cost for operation and maintenance

$CUS_{(i_D,\bar{N})}$ = Cumulative-Uniform-Series factor, i_D, is the differential inflation rate (%); $\bar{N}$ is the economic life, and the discount rate is 10%

F = present cost of procuring the total quantity fuel or electricity required for operating the alternative device or facility for one year, in dollars

T_v = present value of the terminal value of equipment

The present value acquisition cost (I) includes all costs covering procurement of equipment, cost foundation, and erection. The cost per kilowatt of installed capacity will vary with:

1. The type of wind turbine
2. The actual magnitude of the installed capacity
3. The rated wind speed of the turbine

The type of WECS plant cannot be considered independently of the size because very small systems (below 2 kW) will be direct current and wili operate at variable speed; medium-sized plants up to 20 kW may be either DC or AC, and plants larger than 20 kW and up to 100 kW will be almost invariably alternating current without storage. In this report, the emphasis is primarily on the economic choice of the main design features, particularly the rated wind speed, in relation to the wind regimes applying to regions having varying costs of energy generation by alternative sources. The typical capital cost per kW of rated capacity for various sizes of WECS is given in Table 6.1, which shows that for smaller systems (below 5 kW), the capital cost per kW ranges from $4,500 to $5,000. The cost figure of $1,550 per kW for an 8-kW DOE system is based upon the mass production estimates in quantities of 1000 or more.

Table 6.1. Capital Cost of Various Sizes and Types of WECS Equipment

WECS Plant		Cost of Various WECS Subcomponents									
Rated Capacity (kW)	Rated Wind Speed (mph)	Wind Turbine Generator		Tower		Foundation and Erection		Power Conditioning System		Total	Output Power Characteristics
		$/kW	% of Total Cost	$/kW	% of Total Cost	$/kW	% of Total Cost	$/kW	% of Total Cost	$/kW	
2 Self-excited synchronous generator, 3-phase	23	2,000	44.4	800 60-foot free-standing truss	17.78	1,500 concrete foundation	33.3	200 load matching device	4.44	4,500	Variable frequency AC power for heating applications
5 Permanent magnet synchronous generator, 3-phase	26	1,500	49.7	320 60-foot free-standing truss	10.6	800	26.5	400 single phase live commutated inverter	13.2	3,020	Grid-integrated 60-Hertz power
8[a] *Self-excited* synchronous generator, 3-phase	20	800	51.6	300 60-foot guided pole	19.4	200	12.9	250 single phase live commutated inverter	16.1	1,550	Grid-integrated 60-Hertz power
10[a] Induction generator, 3-phase	26	550	37.4	320 50-foot free-standing truss	21.8	600	40.8	--	--	1,470	Grid-integrated 60-Hertz power
20 Synchronous, 3-phase	29	1,000	51.3	100 38-foot free-standing concrete	5.1	500	25.6	350 3-phase live commutated inverter	17.9	1,950	Grid-integrated 60-Hertz power
1[a] DC generator	20	2,250	45.0	1,000 60-foot guided	20.0	1,250	25.0	500 batteries with 10 kWhr of storage	10.0	5,000	Stand-alone system for a remote site

[a]Mass produced system.

The operating and maintenance cost ($\bar{A}$) of a WECS will naturally depend upon the plant size, type, and design, and on its location. Most machines will be designed to operate automatically and can be installed in groups so that only a small maintenance staff will be needed. Typically, such plants would normally be installed as auxiliaries supplementing the main supply at remote Naval installations and, here again, maintenance for properly designed equipment would be low. Due to limited experience in operating WECS, the operating and maintenance data are very scarce and sketchy. Some of the figures on maintaining large WECS (above 40 kW) systems come from experience with such equipment in Denmark (Ref 6.2). These data show that the average operating and maintenance figures per year are about 1% of the capital cost of the equipment. The maintenance of small equipment installed in a dispersed mode is usually undertaken by the owner who does not account for the maintenance performed. Even here, the normal maintenance consists of periodic attention to the batteries and, very occasionally, to the machine and supporting structure. The figures given below are probably typical guidelines for the operating and maintenance data:

Plants up to 10 kW	- 3% to 5% of capital cost
Plants from 10 kW to 20 kW	- 2% to 3% of capital cost
Plants from 20 kW to 100 kW	- 1% to 2% of capital cost

The specific values of Cumulative-Uniform-Series factor (CUS) as a function of i_D and $\bar{N}$ are given in Appendix B. Note for nonfuel related costs, $i_D = 0$. The recommended values of i_D to be used for labor and material and various fuels and purchased electricity are given in Table 6.2. The life ($\bar{N}$) of the WECS components cannot easily be expressed as a definite number of years because the number varies for different parts. For a WECS rotor, the blades, due to safety and reliability reasons, will need to be replaced after a period of 5 to 10 years, while the supporting tower and foundation can have a useful life of 30 to 40 years.

Small DC WECS installations for remote site applications will include batteries for storage; these will need to be replaced frequently (every 4 to 5 years). The guidelines for maximum economic life ($\bar{N}$) of various systems are listed in Table 6.3. For the purpose of this work, the useful economic life of a WECS is taken to be 25 years.

Table 6.2. Recommended Values for Differential Fuel Escalation Rates

Labor and Material	0%
Coal	5%
Fuel Oil	8%
Natural Gas and LPG	8%
Electricity	7%

Table 6.3. Maximum Economic Life ($\bar{N}$)

[Technological lives are established for the categories of investments listed below even though the equipment or facilities involved may have a physical life of a greater number of years. In the absence of better data, these figures may be used in computing the present worth life-cycle cost.]

Buildings (Insulation, Solar Screens, Heat Recovery System, Solar Installations, etc.)	25 Years
Utilities, Plants, and Utility Distribution Systems	25 Years
Energy Monitoring and Control Systems	15 Years
Controls (Thermostats, Limit Switches, Automatic Ignition Devices, Clocks, Photo Cells, Flow Controls, Temperature Sensors, etc., when these constitute the major end item of the project.)	15 Years
Refrigeration Compressors	15 Years
Wind Turbine Rotor Blades	5 to 10 Years
Wind Turbine Mechanical Components	20 to 25 Years
Wind Turbine Tower Storage Batteries	4 to 5 Years

The cost (F) of procuring the total quantity of input fuel (i.e., coal, fuel oil, natural gas, diesel fuel, and LPG) or purchased electricity for operating the alternative device or facility for 1 year must be considered carefully. This cost figure must account for all procurement and shipment costs to each site and, hence, can vary considerably from site to site. As an example, Table 6.4 gives unit costs of fuel for five Naval sites located in different regions of the world. Note that for a WECS facility, F is zero.

Table 6.4. Unit Cost of Diesel Fuel at Five Navy Sites (1980 dollars)

Site	Unit Cost of Fuel	
	mills/kWhr	$/MBtu
San Nicolas Island	54	4.66
Adak, Alaska	43	3.71
Grand Turk	42	3.62
Midway	47	4.05
Barrow, Alaska	50	4.31

The present value of the equipment's terminal value (T_v) at the end of its economic life for WECS generally will be assumed to be zero. Due to expenses involved in removal, dismantling, or disposal, in some cases the terminal value could actually be negative. This would be true if dismantling or demolition costs exceeded scrap or salvage value. For a more complete discussion of terminal value, the reader is referred to Section III, page 43 of NAVFAC P-442 (June 1975) (Ref 6.1). In general, for WECS installations located on remote islands and hilltops (due to accessibility and logistics problems), the terminal value will be considered to be zero.

6.1.2 Discount Rates Different Than 10%

Appendix B provides the values of $CUS_{(i_D,\bar{N})}$ based upon a discount factor of 10%. When a requirement exists to use a discount factor other than 10%, the $CUS*_{(i,\bar{N})}$ may be calculated as follows:

$$CUS_{(i,\bar{N})} = \left(\frac{1 + e_r}{i - e_r}\right)\left[1 - \left(\frac{1 + e_r}{1 + i}\right)^{\bar{N}}\right] \qquad (6.2)$$

where $\bar{N}$ = economic life of a WECS installation

i = discount rate plus differential inflation rate

e_r = escalation rate

The value of CUS defined by Equations 6.2 and 6.3 can be easily substituted into the Net Present Value expression defined by Equation 6.1 to perform the present value life-cycle cost.

6.1.3 Payback Period Computations

Supplementary data for military construction projects supported by economic analysis often include a discounted payback period. "Payback" is achieved when total accumulated present value savings are sufficient to offset the investment cost of a proposed alternative to the "status quo." The payback period is simply the total elapsed time between the point of initial investment and the point at which payback will occur. The following equation is used for determining the payback period.

$$CUS_{(i_D=0,N=\bar{N}_p)} = \frac{CUS_{(i_D=0,N=\bar{N}_c)}\ (I_2 - I_1)}{(NPV_1 - I_1) - (NPV_2 - I_2)} \qquad (6.3)$$

where NPV_1 = total present value life-cycle cost of the existing system (such as a diesel plant, purchased electricity, etc.)

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*Developed for annual payments at the end of the year, compared to midyear values given in the tables.

NPV_2 = total present value life-cycle cost of the proposed alternative, which is the WECS installation

I_1 = present acquisition cost of the existing system

I_2 = present acquisition cost of the proposed WECS installation

$\bar{N}_p$ = payback period

$\bar{N}_c$ = common time period for the two systems being compared

The expression for determining the payback period given by Equation 6.3 must include interpolation for determining the results. The final results within 0.3- to 0.5-year accuracy will be sufficient for most economic life-cycle computations.

6.2 ENERGY OUTPUT PARAMETERS OF WECS

As previously stated, the output obtainable from a WECS installation depends upon the power duration curve for its site and upon the rated wind speed chosen in its design. For a given diameter rotor wind turbine, the higher the rated wind speed, the lower the cost per kilowatt of plant capacity. This is plausible since the capacity increases with the cube of the rated wind speed.

6.2.1 Specific Output Versus Average Wind Speed Plots

The quantity specific output (S_o) defined in earlier chapters plays an important role in computing energy output of a WECS installation. The universal plots of specific output (S_o) versus annual average speed (U) for worldwide locations for WECS with three different rated winds of 20, 25, and 30 mph were prepared by Stodhart (Ref 6.2), and are included as Figure 6.1 for easy usage. Clearly, the specific output decreases rapidly with increase in rated wind speed. The results shown in Figure 6.1 are based on actual test data on small WECS as shown by the tabulation of Table 6.5. For a more refined analysis, however, a systematic approach for computing the output of a WECS (Ref 6.3) can be utilized.

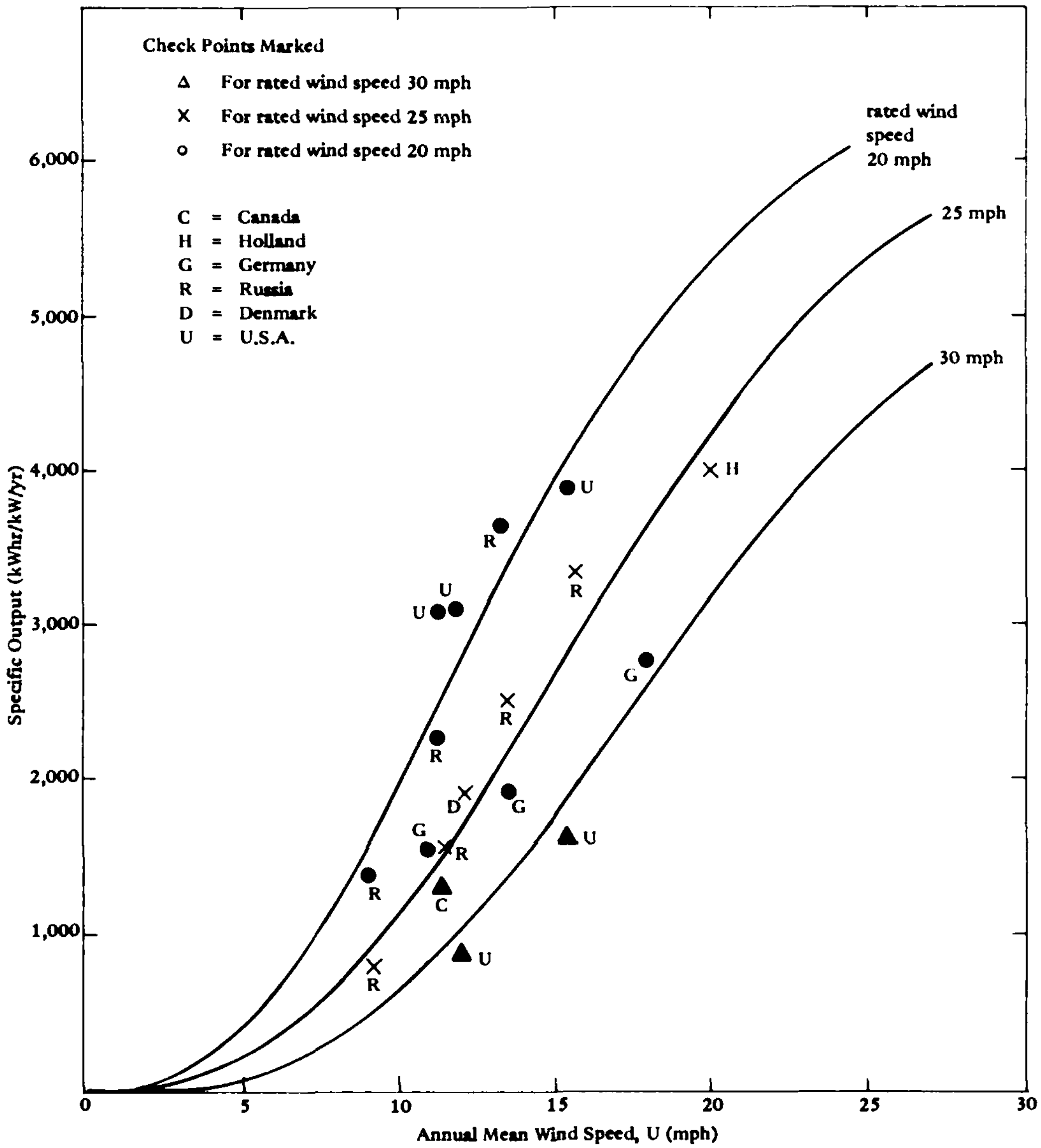

Figure 6.1. Specific output/wind speed curves for different parts of the world (from Golding, Ref 6.2).

6.2.2 Total Energy Output of a WECS

Once the rated wind speed and the annual average wind speed for the WECS installation are known, the annual energy output, E_w, is

$$E_w = S_o P_{rated} \tag{6.4}$$

Clearly, E_w is also the amount of purchased electricity or fossil fuel saved or displaced by the application of WECS. Generally, units for E_w are MBtu/yr.

Table 6.5. Specific Output (S_o) as a Function of Annual Average Wind Speed (U) for Various WECS Installations

WECS Installation	Plant Size (kW)	Plant Rated Wind Speed (mph)	Annual Average Wind Speed (mph)	Annual Output (kWhr)	Specific Output, S_o (kWhr/kW/yr)
Wincharger machines, 32 volts, operated in Canada	1.0	30.0	11.4	1,320	1,320
Wind turbine generator operated for 2.5 months in Holland	50.0	24.6	20.0	20,000	4,000
Nordwind machine based upon manufacturer data	18.0	18.0	11.2 18.0	28,000 50,000	1,550 2,790
Russian design with a rotor diameter of 3.5 meters	1.0	24.6	9 13.5 15.7	855 2,500 3,315	855 2,500 3,315
Grumman WECS at MCAS Kaneohe	20	29.0	14.0	35,000	1,750
Dunlite WECS at CEL	2.0	22.0	6.5	1,300	650
Elektro WECS at San Nicolas Island	5.0	26.0	11.4	11,500	2,280

6.2.3 Normalized Uniform Annual Cost for a WECS

When a total life-cycle cost analysis is being defined, it is often convenient to express the results in a format that is normalized with the energy displaced. That is, the cost per kWhr of energy generated by a WECS can readily be compared with that of purchased or onsite-generated electricity being displaced. Hence, the normalized uniform annual cost, C', is given

$$C' = \frac{NPV}{CUS(i_D,\bar{N})\ E_w} \qquad (6.5)$$

where C' = normalized uniform annual cost

NPV = net present value life-cycle cost of WECS

$CUS(i_D,\bar{N})$ = Nth year factor from Appendix B

E_w = energy displaced annually

Thus, the equation can be used for computing the cost of energy generated by WECS.

6.2.4 Minimum Wind Speed for an Economical WECS Installation

It is always extremely important for wind engineers and designers to know the minimum mean wind speed for a site where a WECS installation is economical. The minimum economical annual mean speed, U_{min}, of a site depends upon WECS design features, such as rotor diameter and rated wind speed, the capital cost in dollars per kW capacity of the plant, the difference in O&M costs of operating a WECS and the present mode of power, and the cost of energy or fuel being displaced by the WECS facility. By applying the net present value annual cost computations, it is possible to derive an equation for the minimum mean annual wind speed (U_{min}) for an economical WECS at a given site. If suffixes 1 and 2 are used to denote net present value costs of the present mode of power and the WECS, respectively, then

$$NPV_1 = \bar{A}_1 \, CUS(i_D{=}0,\bar{N}) + F \, CUS(i_D,\bar{N}) \quad (6.6a)$$

and

$$NPV_2 = I_2 + \bar{A}_2 \, CUS(i_D,\bar{N}) \quad (6.6b)$$

Next, by substituting for NPV_1 and NPV_2 into the payback equation (Equation 6.3) and rearranging, the following expression for the minimum value of the specific output, $S_{o,min}$, for the WECS installation is obtained

$$S_{o,min} = \frac{C_w}{C_e \; CUS(i_D,\bar{N})} [1 + x \; CUS(i_D=0,\bar{N})] \qquad (6.7)$$

where $S_{o,min}$ = minimum value of specific output for the WECS installation to be economical at the site in question

C_w = I_2/P_{rated} = capital cost of a WECS installation in dollars per kW rated capacity

C_e = total cost of present source of energy in dollars per kWhr

$\bar{N}$ = useful life of WECS equipment in years

x = $(\bar{A}_2 - \bar{A}_1)/I_2$ = annual O&M cost differential between the costs of present source of power and that of the WECS facility

The specific output, S_o, of a WECS installation is a function of plant rated speed and the site annual mean speed. Hence, for a given wind plant design, Equation 6.7 gives the minimum value of the annual mean wind speed for an economical installation. As discussed earlier, the universal curves (Figure 6.1) showing specific output of WECS with different rated wind speeds as a function of site annual mean wind speed can be utilized to obtain U_{min} values. Consequently, plots of U_{min} versus $S_{o,min}$ for WECS with rated wind speeds of 20, 25, and 30 mph were derived and are given in Figure 6.2 for easy usage.

The minimum annual mean wind speed plots given here are extremely useful in computing the minimum mean wind speed for a WECS installation readily. The information can be used as follows. Assume 5 kW (= P_{rated}) is being considered for a site with an annual mean wind speed (U=) of 10 mph to displace purchased electricity costing $0.07/kWhr (= C_e). The annual O&M cost of operating the WECS is taken to be 3% of I_2, thus giving x = -0.03. Now the various quantities involved are computed to be

C_w = $2,400/kW

$CUS(i_D=7\%,\bar{N}=25)$ = 18.049

$CUS(i_D=0,\bar{N}=25)$ = 9.524

$S_{o,min}$ (from Equation 6.7) = 2,442.3

Next,

U_{min} (from Figure 6.2) = 11.2, 14.5, and 17.3 for WECS rated speeds of 20, 25, and 30 mph

Since the annual mean wind speed for the site is 10 mph, the WECS application is not economical. On the other hand, if the cost of energy, C_e = \$0.09/kW, $S_{o,min}$ = 1,900, which yields a value for U_{min} of 9.5 mph for a WECS with a rated wind speed of 20 mph. Hence, a WECS installation of this design becomes economical for the new value of C_e at the site. The example discussed here is typical of many Navy applications and is based upon realistic figures for capital cost; thus, it is safe to conclude that for a WECS facility to be economical at a Navy base, the annual mean wind speed must be at least 10 mph.

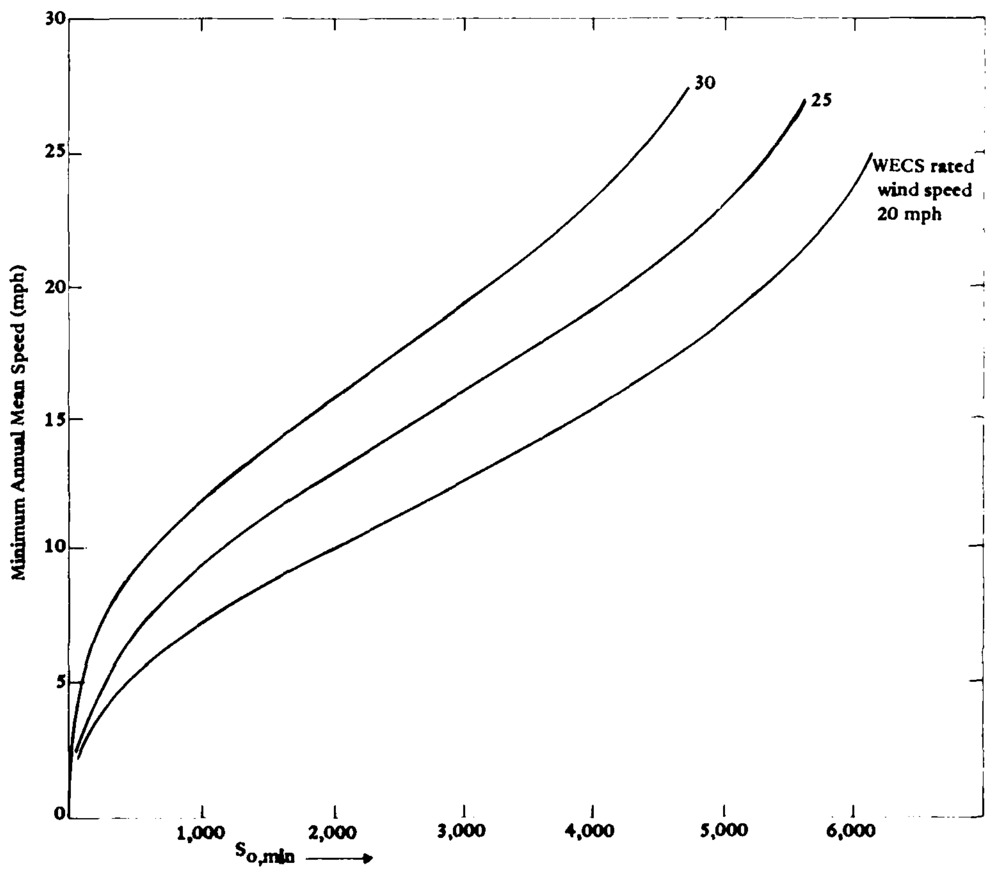

Figure 6.2. The plots of U_{min} versus $S_{o,min}$.

6.3 EXAMPLES OF ECONOMIC ANALYSIS FOR WECS

Two WECS systems, namely, one 8 kW size with a rated wind speed of 20 mph, and one 6 kW size rated at 26 mph, were selected to perform the economic analysis based upon the foregoing discussion in this chapter. Table 6.6 gives the WECS capital costs, annual energy output, fuel costs for the diesel or purchased electricity at the site, and estimated O&M costs for both the diesel plants and the wind turbine. The five sites selected for examples have varied wind characteristics ranging from annual mean wind speeds from 11.4 to 16.8 mph and are located in remote areas. The economic analysis was performed using the following definitions for determining the various parameters.

$$\text{Differential Capital Expenses (amortized)} = \Delta I' = \frac{(I_1 - T_{v1}) - (I_2 - T_{v2})}{E_{s(yr)}\ CUS_{(i_D=0,\bar{N})}} \left(\frac{\$}{\text{MBtu}}\right) \tag{6.8}$$

$$\text{Differential O\&M Contribution} = \Delta A' + \Delta F' = \frac{(NPV_1 - I_1 + T_{v1}) - (NPV_2 - I_2 + T_{v2})}{E_{s(yr)}\ CUS_{(i_D=0,\bar{N})}} \tag{6.9}$$

$$\left(\text{For Uniform Annual Costs, } \Delta A'^{*} = \frac{\bar{A}_1 - \bar{A}_2}{E_{s(yr)}\ CUS_{(i_D=0,\bar{N})}} \left(\frac{\$}{\text{MBtu}}\right)\right) \tag{6.10}$$

$$\text{Differential Cost of Fuel} = \Delta F' = [F_1 - F_2] \frac{CUS_{(i_D,\bar{N})}}{E_{s(yr)}\ CUS_{(i_D=0,\bar{N})}} \left(\frac{\$}{\text{MBtu}}\right) \tag{6.11}$$

$$\text{Differential Life-Cycle Cost} = \frac{NPV_1 - NPV_2}{E_{s(yr)}\ CUS_{(i_D=0,\bar{N})}} \left(\frac{\$}{\text{MBtu}}\right) \tag{6.12}$$

Payback Period = [use Equation 6.3]

$$\frac{\text{Annual Energy Savings}}{\text{Capital Cost}} \left(\frac{\text{MBtu}}{\text{yr \$K}}\right) = \left(\frac{1000\ E_{s(yr)}}{(I_2 - I_1)}\right) \tag{6.13}$$

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*$\Delta A'$, $\bar{A}_1$, and $\bar{A}_2$ exclude fuel costs.

Table 6.6. Capital Cost, O&M Cost, and Annual Energy Output Data on Two Types of WECS Installations at Five Different Navy Sites

Item	San Nicolas Island	Adak	Grand Turk	Kaneohe Bay	Opana
6-kW Plant With Rated Wind Speed of 26 mph					
Capital Cost					
Wind Generator System ($K)	13.0	13.5	13.0	13.0	13.5
Annual Average Wind Speed (mph)	11.4	13.9	15.9	12.0	16.8
Wind Generator Annual Output (kWhr)	16.5×10^3	23.3×10^3	26.2×10^3	16.4×10^3	30.6×10^3
Operating Cost					
Wind Generator O&M (Annually) ($K)	0.30	0.35	0.30	0.3	0.3
Diesel Generator:					
Fuel (mills/kWhr)	54	43	42	--	--
O&M (Annually) ($K)	0.40	0.45	0.40	--	--
Purchased Electricity:					
Cost Per kWhr (mills)	--	--	--	43	43
8-kW Plant With Rated Wind Speed of 20 mph					
Capital Cost					
Wind Generator System ($K)	9.5	10.0	9.5	9.5	10.0
Wind Generator Annual Output (kWhr)	31.5×10^3	42.5×10^3	50×10^3	33.0×10^3	51×10^3
Operating Cost					
Wind Generator O&M (Annually) ($K)	0.40	0.45	0.40	0.40	0.45
Diesel Generator:					
Fuel (mills/kWhr)	54	43	42	--	--
O&M (Annually) ($K)	0.65	0.70	0.65	--	--
Purchased Electricity:					
Cost Per kWhr (mills)	--	--	--	43	43

Table 6.7. Economic Analysis for Two Types of WECS Installations (Power-to-Grid)

Parameter of Interest	Opana[a] (NCS)	Kaneohe Bay[a] (MCAS)	Grand Turk (NAVFAC)	Adak (NS)	San Nicolas Island (PMTC)	Navywide Application[b]
6-kW Plant With Rated Wind Speed of 26 mph						
Differential Life Cycle Cost[c], $/MBtu	-2.24	1.67	-2.90	-2.57	-2.91	
Discounted Payback Period, years	11.0	no payback	8.5	9.5	11.0	
Annual Energy Savings/ Capital Cost, MBtu/yr/$K	26.29	14.63	23.39	20.02	14.72	
Annual Energy Savings, BOE/yr	6.2	32.8	52.4	46.6	33	35,000 BOE/yr
Capital to Implement, $K	13.5	13.0	13.0	13.5	13.0	8,500 $K
Annual O&M Savings[d], $K/yr	2.21	1.05	2.25	2.11	1.92	1,795 $K/yr
8-kW Plant With Rated Wind Speed of 20 mph						
Differential Life Cycle Cost[c], $/MBtu	-3.84	-2.74	-5.61	-5.64	-7.23	
Discounted Payback Period, years	3.5	6.5	2.5	3.9	3.0	
Annual Energy Savings/ Capital Cost, MBtu/yr/$K	59.2	40.3	61.1	49.3	38.5	
Annual Energy Savings, BOE/yr	10.2	66.0	100.0	85.0	63.0	44,000 BOE/yr
Capital to Implement, $K	10	9.5	9.5	10.0	9.5	6,300 $K
Annual O&M Savings[d], $K/yr	3.27	2.05	4.25	3.78	3.69	2,142 $K/yr

[a]Purchased electricity from a central plant.

[b]6-kW plant: 940 units at 177 Naval locations worldwide.
8-kW plant: 630 units at 177 Naval locations worldwide.

[c]Normalized on energy savings or displacement; based on FY79 fuel costs, levelized over economic life.

[d]Includes savings for energy. Fuel escalation rate = 8%/yr; economic life = 25 years; electricity escalation rate = 7%/yr.

$$\text{Annual Energy Savings (BOE)} = \frac{E_{s(yr)}}{5.8} \quad (6.14)$$

$$\text{Capital to Implement (\$K)} = \frac{I_2}{1,000} \quad (6.15)$$

$$\begin{array}{l}\text{Annual O\&M}\\ \text{Savings (\$K/yr)}\end{array} = \frac{(NPV_1 - I_1 + T_{v1}) - (NPV_2 - I_2 - T_{v2})}{1,000\ CUS_{(i_D=0,\bar{N})}} \quad (6.16)$$

$$\begin{array}{l}\text{Normalized Uniform}\\ \text{Annual Cost, } C'\end{array} = \frac{NPV_2}{E_w\ CUS(i_D, N=\bar{N})} \quad (6.17)$$

The results of the analysis are given in Table 6.7, which shows that the payback periods are typically 8 to 11 years for the 6-kW WECS and as low as 3 years for the 8-kW system. The economic analysis presented here conforms with the prescribed procedures used to satisfy the first step towards completing the Integrated Logistics Support requirement. This requirement must be satisfied for each product prior to deployment.

6.4 REFERENCES

6.1. Naval Facilities Engineering Command. P-442: Economic analysis handbook. Alexandria, Va., Jun 1975.

6.2. E. W. Golding. The generation of electricity by wind power. London, E. and F. N. Spon Ltd., 1955. (1976)

6.3. J. K. Shultis, L. A. Poch, and N. D. Eckhoff. "Optimum selection of a wind turbine generator system," Journal of Energy, vol 3, no. 3, May-Jun 1979, pp 145-150.

Chapter 7

THE WECS SYSTEM - APPLICATION EXAMPLES

This chapter is a compilation of examples describing how WECS should be selected using the information in this handbook. Each example focuses on some aspect of the decision making process while illustrating the types of calculations required. The block diagram of Figure 7.1 helps organize the thinking behind the WECS selection process for a given application.

7.1 EXAMPLE 1: SPACE HEATING USING A WECS INSTALLATION

The plan is to displace the diesel-generated power, if economical, with wind-generated electric power for space heating of a building at a Navy installation near Buffalo, N.Y. The preliminary data collected by onsite analysis and research are:

1. The heating season is from mid-October to mid-April, lasting approximately 6 months.
2. The heating requirement is 570 MBtu per heating season (see Table 7.1 for details).
3. The nature of the terrain is flat and homogeneous, with trees up to 30 feet in height.
4. The monthly wind characteristics for the site are given in Table 7.2. The annual average wind speed for the site is 12.43 mph, with the average value for the heating season extending from October to April being 13.29 mph.
5. The present cost of energy at the site is $0.08/kWhr.

It can be seen that two of the planning chart evaluation steps (Figure 7.1), namely, that of determining the nature of site wind characteristics and estimating the load requirements, are already completed (Tables 7.1 and 7.2). The next step is to calculate the WECS rotor size, including the rest of the equipment. The wind characteristics data given in Table 7.2 are in watts per square foot of the rotor disk area. It could have been given in raw wind speed with percentage frequency of occurrence, which would require performing the calculations of Chapter 2. Since the WECS installation is required to displace the diesel-generated power, its size can be based upon the average available power in the wind and on the average load demand. The disk area of the

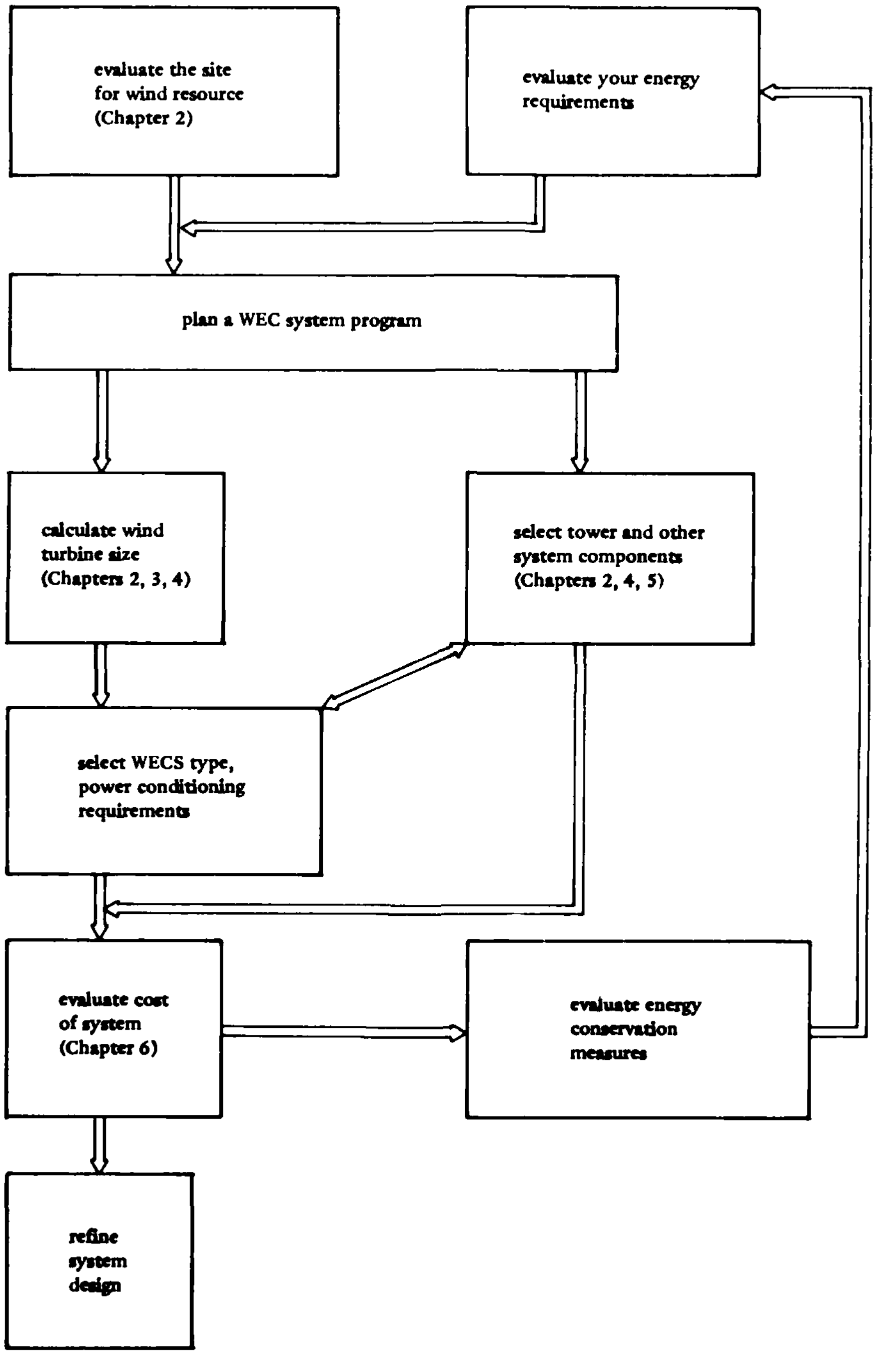

Figure 7.1. Planning a wind energy conversion system (WECS) for a given application.

turbine rotor required, calculated in Table 7.3, amounts to 1,393.2 ft^2, which requires a rotor diameter of about 42 feet. The actual energy generated and displaced by such a WECS installation is also shown in Table 7.3. The energy displaced by a WECS, plotted in Figure 7.2, amounts to about 87.74% of the total consumption.

Table 7.1. Heating Requirement for the Season for Example 1

[Total number of months heating required = 6]

Month	Heating Requirements	
	MBtu	kWhr
October	36	3,103.4
November	85	7,327.6
December	98	8,448.3
January	108	9,310.3
February	108	9,310.3
March	115	9,913.8
April	25	2,155.2
Total	575	49,568.9
Average = $\frac{\text{Total}}{\text{No. of months}}$	95.83	8,261.48

Table 7.2. Wind Characteristics for Example 1

Month	Average Wind Speed (mph)	Power Available in the Wind (watts/ft^2)	Power Extractable From the Wind by a WECS[a] (watts/ft^2)
October	11.5	15.4	4.93
November	13.3	21.0	6.72
December	13.5	23.2	7.42
January	13.5	23.5	7.52
February	13.9	23.9	7.65
March	14.1	27.3	8.74
April	13.2	22.1	7.07
May	11.9	14.9	4.77
June	11.6	14.10	4.51
July	11.1	12.30	3.94
August	10.5	11.0	3.52
September	11.1	13.5	4.32
Average	12.43	18.52	5.93

[a]The overall power coefficient for WECS = 0.32.

Table 7.3. Actual Energy Generated and Displaced by WECS With a Rotor Diameter of 42 Feet (Example 1)

Month	WECS Output (kWhr)	Heating Requirement (kWhr)	Amount of Diesel Power Required After Displacement (kWhr)
October	5,081.7	3,103.4	0
November	6,703.3	7,327.6	624.3
December	7,648.3	8,448.3	800.0
January	7,751.4	9,310.3	1,558.9
February	7,122.3	9,310.3	2,188.0
March	9,008.9	9,913.8	904.9
April	7,052.5	2,155.2	0
May	4,916.8	0	0
June	4,498.8	0	0
July	4,061.2	0	0
August	3,628.3	0	0
September	4,309.3	0	0
Total	63,018.6	49,568.9	6,076.1

NOTES:

$$\text{Rotor disk area required} = \frac{\text{Average load demand}}{\text{Average monthly power in the wind}}$$

$$= \frac{8,261.48}{5.93} = 1,393.2 \text{ ft}^2$$

Rotor diameter required = 42.1 $\cong$ 42 feet

Usable energy generated by the WECS = 49,568.9 - 6,076.1

= 43,492.8 kWhr

$$\text{Percent of usable energy generated by WECS} = \frac{43,492.8}{63,018.6} = 69.02$$

The size of the WECS installation can be determined as demonstrated by the calculations of Table 7.4. It is found to be 18 kW, with a rated wind speed of 20 mph. If an 18-kW size WECS is not a standard size available commercially, the next available size must be chosen for the application. The energy displaced by the WECS is then computed based upon the new size WECS. For this application, however, it will be assumed that an 18-kW WECS is readily available. Next, the capital cost of a horizontal axis type WECS with different rated wind speeds and rotor diameters is given in Table 7.5. It can be derived (from the table) that the capital cost of the system amounts to about $1,500/kW.

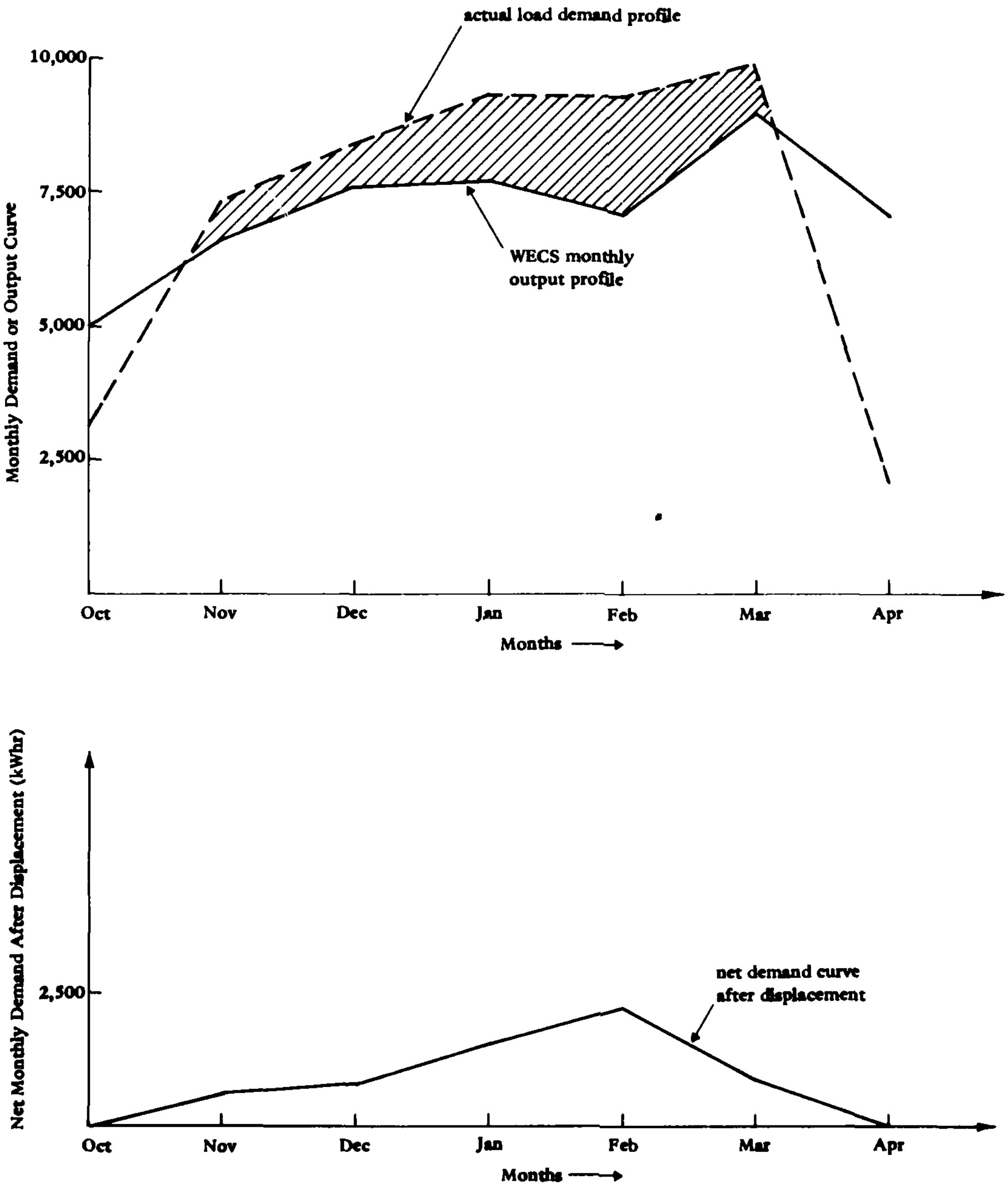

Figure 7.2. Monthly, demand, WECS output, and net demand after displacement for example no. 1.

Table 7.4. Characteristics of Selected WECS Installation (Example 1)

Wind Turbine Generator

Rated wind speed = 20 mph
Rotor diameter = 42 feet
Rated output, P_{rated} = $1/2\ \rho\ C_p(u)\ A\ u^3_{rated}$ = 18 kW
$[C_p(u) = 0.32]$

From Table 7.4, the capital cost of a 42-foot-diameter rotor with a rated wind speed of 20 mph and rated capacity of 18 kW = $1,500/kW.

Cost of WECS system = (18)(1,500) = $27,000

Power conditioning, load matching device = $270

Total capital cost = 27,000 + 270 = $27,270

Annual O&M costs (2% of capital cost) = $545.5

Quality of power generated = variable voltage
variable frequency

Tower height = 60 feet (flat terrain, see Chapters 4 and 5)

Table 7.5. Capital Cost (Including Installation) of Horizontal Axis WECS With Different Rated Wind Speeds and Sizes (Example 1)[a]

WECS Size (kW)	WECS With Rated Wind Speeds of -- 20 mph		25 mph		30 mph	
	Rotor Size (ft)	Cost/kW ($)	Rotor Size (ft)	Cost/kW ($)	Rotor Size (ft)	Cost/kW ($)
2	13.98	2,775	10.00	2,700	7.61	2,600
5	22.11	2,200	15.82	2,100	12.03	2,000
8	27.96	1,900	20.01	1,800	15.22	1,700
10	31.26	1,750	22.37	1,650	17.02	1,575
15	38.29	1,575	27.40	1,510	20.84	1,450
20	44.22	1,475	31.64	1,400	24.06	1,325
30	54.15	1,300	38.75	1,240	29.48	1,200

[a]Oak Ridge National Laboratory. Report No. ANL/CES/TE 78-9: Wind turbines, by John C. Yeoman. Dec 1978.

Table 7.4 also shows the power conditioning system and the tower height chosen for the installation. Next, the cost of power displaced by a WECS can be computed by the method given in Chapter 6. The details of the economic calculations are given in Table 7.6. The cost of power is found to be \$0.037/kWhr, which is well below the present cost of power. Hence, a WECS installation is economically feasible for this application. The standard differential life-cycle cost product analysis for the application is given in Table 7.7.

Table 7.6. Cost of Power Generation for the 18-kW Size WECS (Example 1)

Annual usable output for WECS (Table 7.3) = 43,492.8 kWhr

NPV for WECS = $I + \bar{A}\ CUS(i_D=0,\bar{N}=25)$

$I = \$27,270$

$\bar{A}(2\%\ \text{of}\ I) = (0.02)(27,270) = 545.4$

$CUS(i_D=0,\bar{N}=25) = 9.524$

Therefore

NPV = \$32,464.4

Cost of power generation (\$/kWhr)

$$C' = \frac{NPV}{CUS(i_D=8\%,\bar{N}=25)\ E_w}$$

$CUS(i_D=8\%,\bar{N}=25) = 20.05$

Therefore

$$C' = \frac{32,464.4}{(20.05)(43,492.8)} = \$0.0372/\text{kWhr}$$

NOTE: Explanation of terms used here can be found in Chapter 6.

7.2 EXAMPLE 2: GRID-INTEGRATED WECS

If, in Example 1, the 18 kW size were designed to generate power in parallel with the grid line, all of its output would be available for use to displace the energy consumption. This arrangement would require an additional investment in a line-commutated inverter. Table 7.8 shows the calculations on the economics of power for the system. The cost of power generation is found to be \$0.0305/kWhr, thus establishing that the use of a WECS in this mode is more economical than the one for Example 1. The differential life-cycle cost analysis for the example is given in Table 7.9.

Table 7.7. Differential Life-Cycle Cost Product Analysis (Example 1)

1.	Acquisition cost of (typical) application (Incremental if baseline has to be procured)	27.27	$K
2.	Adjusted acquisition cost of application [(0.9)(1)]	24.54	$K
3.	Present worth, terminal value of application	0	$K
4.	Net adjusted capital investment of application [(2) - (3)]	24.54	$K
5.	Economic life of application	25	yr
6.	CUS factor for economic life of application	9.524	
7.	Capital investment, annualized [(4) ÷ (6)]	2.577	$K/yr
8.	Annual nonenergy differential O&M savings (+) or penalty (-) [Actual costs x CUS(i_D=0,$\bar{N}$=25)]	-5.191	$K/yr
9.	Annual energy savings/displacement		
	a. Energy type: purchased electricity		
	(1) Annual energy savings (+) or penalty (-)	504.5	MBtu/yr
	(2) Unit cost [Present cost x CUS(i_D=8%,$\bar{N}$=25)]	138.28	$/MBtu
	(3) Annual cost savings (+) or penalty (-)	69.765	$K/yr
	b. Energy type		
	(1) Annual energy savings (+) or penalty (-)		MBtu/yr
	(2) Unit cost		$/MBtu
	(3) Annual cost savings (+) or penalty (-)		$K/yr
	c. Energy type		
	(1) Annual energy savings (+) or penalty (-)		MBtu/yr
	(2) Unit cost		$/MBtu
	(3) Annual cost savings (+) or penalty (-)		$K/yr
	d. Total annual energy savings [9a (3) + 9b (1) + 9c (1)]	504.5	MBtu/yr
	e. Total annual cost savings for energy [9a (3) + 9b (3) + 9c (3)]	69.765	$K/yr
10.	Total annual cost savings [(9e) + (8)]	64.57	$K/yr
11.	Savings-to-Investment Ratio [(10) ÷ (4)], SIR	2.63	
12.	Annual energy savings-to-acquisition cost ratio [9(d) ÷ (1)]	18.5	MBtu/yr / $K

Table 7.8. Cost of Power Generation for the 18-kW Size Grid-Integrated WECS (Example 2)

Annual usable output for WECS (Table 7.3) = 63,018.6 kWhr

Additional investment for the invertor = \$5,400

Total capital cost of the system, I = 27,000 + 5,400 = \$32,400

$\bar{A}$(2% of I) = (0.02)(32,400) = \$648

NPV for the WECS = 32,400 + 648(9.524) = \$38,571.6

Cost of power generation

$$C' = \frac{38,571.6}{(20.05)(63,018.6)} = \$0.0305/\text{kWhr}$$

7.3 EXAMPLE 3: WECS APPLICATION WITH STORAGE

Problem: Design a wind energy conversion system with storage for a remote site located on a hilltop at Naval Weapons Center, China Lake. The site in question houses a critical communication type of load that has an average constant demand of 500 watts throughout the year. Presently, the power to the load is supplied by a 5-kW diesel generator. The cost of fuel used at the site is \$0.05/kWhr and, due to remoteness, the transportation cost for delivering fuel to the location is \$0.07/kWhr. The site wind characteristics are generally uniform throughout the year, and their daily variation is listed in Table 7.10. The annual average wind speed for the site is about 12.92 mph.

By following the procedure of Example 1, the obvious step is to derive the energy extractable by a WECS as shown in Table 7.10. The calculations of Table 7.10 were performed using a conversion factor of 0.30. The next step is to calculate the WECS rotor diameter, including the size of the storage system and the rest of the equipment. As shown by Table 7.10, the size of the WECS installation can be based upon the average available extractable power from the wind and on the average load demand. The rotor disk area required for this case amounts to 111.6 ft^2, and it takes a rotor diameter of 11.92 feet. The actual energy generated by a WECS rotor of this size is shown in Table 7.11. It can be seen from the table that the total daily power generation from such a rotor is about 12 kWhr. The actual energy generated by a WECS rotor of this size is shown in Figure 7.3.

The next step in the computations is to calculate the size of storage needed to satisfy the load demand. The storage requirement can be based upon the total energy delivered to storage during the wind periods. The size of storage required thus is calculated in Tables 7.11 and 7.12. Actual storage capacity provided is 5 kWhr. With this amount of storage, the WECS installation provides 3,544 kWhr to load, which is about 80.9% of the total demand. Tables 7.12 through 7.14 show the

Table 7.9. Differential Life-Cycle Cost Product Analysis (Example 2)

1.	Acquisition cost of (typical) application (Incremental if baseline has to be procured)	32.4	$K
2.	Adjusted acquisition cost of application [(0.9)(1)]	29.16	$K
3.	Present worth, terminal value of application	0	$K
4.	Net adjusted capital investment of application [(2) - (3)]	29.16	$K
5.	Economic life of application	25	yr
6.	CUS factor for economic life of application	9.524	
7.	Capital investment, annualized [(4) ÷ (6)]	3.06	$K/yr
8.	Annual nonenergy differential O&M savings (+) or penalty (-) [Actual costs x CUS(i_D=0,$\bar{N}$=25)]	-6.172	$K/yr
9.	Annual energy savings/displacement		
	a. Energy type: purchased electricity		
	(1) Annual energy savings (+) or penalty (-)	731.02	MBtu/yr
	(2) Unit cost [Present cost x CUS(i_D=8%,$\bar{N}$=25)]	138.28	$/MBtu
	(3) Annual cost savings (+) or penalty (-)	101.09	$K/yr
	b. Energy type		
	(1) Annual energy savings (+) or penalty (-)		MBtu/yr
	(2) Unit cost		$/MBtu
	(3) Annual cost savings (+) or penalty (-)		$K/yr
	c. Energy type		
	(1) Annual energy savings (+) or penalty (-)		MBtu/yr
	(2) Unit cost		$/MBtu
	(3) Annual cost savings (+) or penalty (-)		$K/yr
	d. Total annual energy savings [9a (3) + 9b (1) + 9c (1)]	731.02	MBtu/yr
	e. Total annual cost savings for energy [9a (3) + 9b (3) + 9c (3)]	101.09	$K/yr
10.	Total annual cost savings [(9e) + (8)]	94.918	$K/yr
11.	Savings-to-Investment Ratio [(10) ÷ (4)], SIR	3.26	
12.	Annual energy savings-to-acquisition cost ratio [9(d) ÷ (1)], E/C	22.56	MBtu/yr / $K

economics of the WECS system chosen. It is shown that the cost of energy delivered by the installation, \$0.098/kWhr, is comparable to the present cost of fuel delivered to the site, \$0.12/kWhr. Hence, the system is economical as a fuel displacer for the remote site.

Table 7.10. Site Wind Characteristics (Example 3)

Time of the Day	Hourly Average Wind Speed (mph)	Available Power ($watts/ft^2$)	Power Extracted by the WECS System[a] ($watts/ft^2$)
0000	12.5	10.0	3.00
0001	11.6	8.0	2.40
0002	6.6	1.5	0.45
0003	6.1	1.2	0.36
0004	6.6	1.5	0.45
0005	7.3	2.0	0.60
0006	8.3	3.0	0.90
0007	9.2	4.0	1.20
0008	9.2	4.0	1.20
0009	9.9	5.0	1.50
0010	10.50	6.0	1.80
0011	11.60	8.0	2.40
0012	13.20	12.0	3.60
0013	13.20	12.0	3.60
0014	14.60	16.0	4.80
0015	15.70	20.0	6.00
0016	16.90	25.0	7.50
0017	18.40	32.0	9.60
0018	18.90	35.0	10.50
0019	18.90	35.0	10.50
0020	19.10	36.0	10.80
0021	19.10	36.0	10.80
0022	16.90	25.0	7.50
0023	15.70	20.0	6.00
Average	12.92	14.93	4.48

[a]Overall power coefficient = 0.30.

NOTES:

Average demand = 500 watts

$$\text{WECS rotor disk area} = \frac{\text{Average demand}}{\text{Average power density delivered by WECS}}$$

$$= \frac{500}{11.48} = 111.6 \text{ ft}^2$$

Rotor disk area = 11.92 ft²

Table 7.11. Actual Energy Generated and Displaced by WECS With a Rotor Diameter of 11.92 Feet (Example 3)

Time of the Day	WECS Hourly Output (kWhr)	Energy Extracted From Storage, Hourly (kWhr)	Energy Delivered to Storage by WECS (kWhr)
0000	0.335	-0.165	0
0001	0.268	-0.232	0
0002	0.050	-0.450	0
0003	0.040	-0.460	0
0004	0.050	-0.450	0
0005	0.067	-0.433	0
0006	0.100	-0.400	0
0007	0.134	-0.366	0
0008	0.134	-0.366	0
0009	0.167	-0.333	0
0010	0.201	-0.299	0
0011	0.268	-0.232	0
0012	0.408	-0.092	0
0013	0.408	-0.092	0
0014	0.535	0	0.035
0015	0.670	0	0.170
0016	0.837	0	0.537
0017	1.071	0	0.571
0018	1.172	0	0.672
0019	1.172	0	0.672
0020	1.205	0	0.705
0021	1.205	0	0.705
0022	0.837	0	0.337
0023	0.670	0	0.170
Total	12.0	4.37	4.574

NOTES:

Amount of energy needed to be stored daily = 4.57 kWhr

Using battery storage, amount of wind energy recoverable from storage daily (50% efficiency) = (4.57)(0.50) = 2.29 kWhr

Usable energy generated by WECS in 1 year = (12 - 2.29)(365)

= 3,544 kWhr

Total load demand in 1 year = (12)(365) = 4,380 kWhr

Percent of usable energy produced by WECS = 3,544/4,380 = 80.9

Table 7.12. Characteristics of Selected WECS Installation (Example 3)

Wind Turbine Generator

Rated wind speed = 20 mph
Rotor diameter = 11.92 feet
Rated output, P_{rated} = $1/2\ \rho\ C_p(u)\ A\ u^3_{rated}$ = 1.7 kW

$[C_p(u) = 0.30]$

From Table 7.5, the capital cost of a 11.92-foot-diameter rotor with a rated wind speed of 20 mph and rated capacity of 1.7 kW = $2,800/kW

Cost of WECS system = (2,500)(1.7) = $4,760
Annual O&M of WECS (3% of capital cost) = $142.8

Storage system

Size of storage = 4.57 kWhr
Type of storage = batteries, 12 volts
Capacity of each battery = 105 amp-hr
Storage capacity of each battery = (12)(105) = 1.260 kWhr
Number of batteries required = 4.57/1.26 ≅ 4
Cost of each battery = $70
Cost of storage system = (4)(70) = $280
Actual storage capacity = 5 kWhr
Annual O&M costs (20% of capital cost) = (0.2)(280) = $56

Tower

Type - guyed pole
Height - 50 feet (hilly terrain, see Chapters 4 and 5)

Total system capital cost = 4,760 + 280 = $5,040
Total system O&M costs = 142.8 + 56 = $148.8

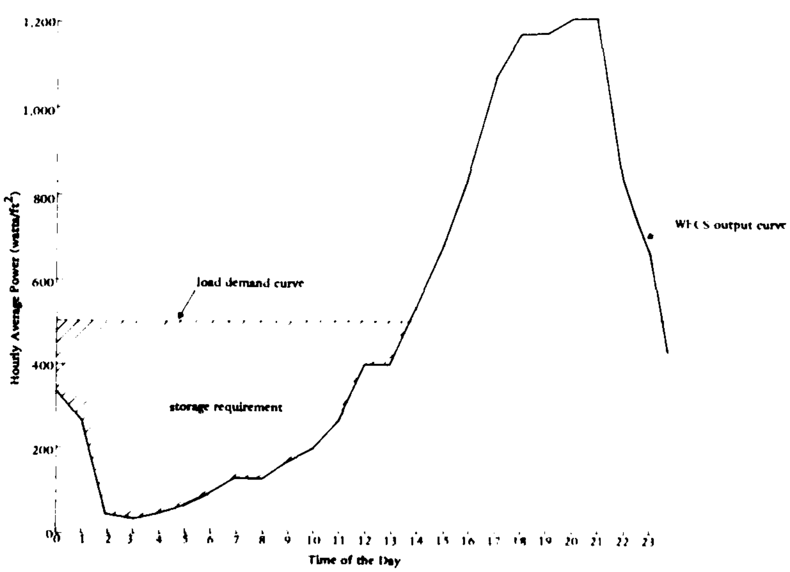

Figure 7.3. Extractable energy density and time for the WECS showing the demand line and storage requirements for example 3.

Table 7.13. Cost of Power Generation for the 1.7 kW Size (Example 3)

Annual usable output for the system (Table 7.11) = 3,544 kWhr

NPV for WECS = $I + \bar{A}\ CUS(i_D=0, \bar{N}=25)$

$I = \$5,040$

$\bar{A} = \$198.8$

$CUS(i_D=0, \bar{N}=25) = 9.524$

Therefore

NPV = \$6,933.4

Cost of power generation (\$/kWhr)

$$C' = \frac{NPV}{CUS(i_D=8\%, \bar{N}=25)\ E_w}$$

$CUS(i_D=8\%, \bar{N}=25) = 20.05$

Therefore

$$C' = \frac{6,933.4}{(20.05)(3,544)} = \$0.098/\text{kWhr}$$

Present cost of fuel delivered to site = 0.05 + 0.07 = \$0.12/kWhr

Table 7.14. Differential Life-Cycle Cost Product Analysis (Example 3)

1.	Acquisition cost of (typical) application (Incremental if baseline has to be procured)	5.040	$K
2.	Adjusted acquisition cost of application [(0.9)(1)]	4.536	$K
3.	Present worth, terminal value of application	0	$K
4.	Net adjusted capital investment of application [(2) - (3)]	4.536	$K
5.	Economic life of application	25	yr
6.	CUS factor for economic life of application	9.524	
7.	Capital investment, annualized [(4) ÷ (6)]	0.476	$K/yr
8.*	Annual nonenergy differential O&M savings (+) or penalty (-) [Actual costs x $\overline{\text{CUS}}(i_D=0,N=25)$]	0.469	$K/yr
9.	Annual energy savings/displacement		
	a. Energy type: diesel fuel		
	(1) Annual energy savings (+) or penalty (-)	41.11	MBtu/yr
	(2) Unit cost [Present cost x $\overline{\text{CUS}}(i_D=8\%,N=25)$]	138.21	$/MBtu
	(3) Annual cost savings (+) or penalty (-)	5.682	$K/yr
	b. Energy type		
	(1) Annual energy savings (+) or penalty (-)		MBtu/yr
	(2) Unit cost		$/MBtu
	(3) Annual cost savings (+) or penalty (-)		$K/yr
	c. Energy type		
	(1) Annual energy savings (+) or penalty (-)		MBtu/yr
	(2) Unit cost		$/MBtu
	(3) Annual cost savings (+) or penalty (-)		$K/yr
	d. Total annual energy savings [9a (3) + 9b (1) + 9c (1)]	41.11	MBtu/yr
	e. Total annual cost savings for energy [9a (3) + 9b (3) + 9c (3)]	5.682	$K/yr
10.	Total annual cost savings [(9e) + (8)]	6.151	$K/yr
11.	Savings-to-Investment Ratio [(10) ÷ (4)], SIR	1.356	
12.	Annual energy savings-to-acquisition cost ratio [9(d) ÷ (1)], E/C	8.16	MBtu/yr / $K

*Annual cost of transporting fuel to the site = (3,544)(0.07) = $248.08.
Annual O&M costs for WECS installations = 198.8.
Hence, net annual O&M savings = 248.08 - 198.8 = $49.28.

Chapter 8

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Appendix A

COMMERCIALLY AVAILABLE SMALL WIND MACHINES: A CHECKLIST OF SYSTEMS, MANUFACTURERS, AND DISTRIBUTORS

The wind machines and components in this checklist were commercially available in the United States as of June 30, 1980. The list is not exhaustive, but represents a compilation of the responses from a mailing to all known manufacturers of wind energy equipment in the United States. The wind systems included are all rated at <1 to 100 kW (or nonelectrical equivalent). Information on pricing, delivery, warranties, and maintenance can be obtained by contacting the manufacturer or distributor of a wind machine or component.

SUMMARY - ELECTRICAL WIND MACHINES

The following table is a summary of the major characteristics of each electrical wind machine. The data are arranged according to power output.

Name and Model Number	Size (rated kW)	Rotor Diameter (ft/m)	No. of Blades	Rated Speed [mph/ (m/sec)]	Cut-In Speed [mph/ (m/sec)]
Energy Development Co. (USA) - 445	45	45.0/13.95	4	30/13.4	7/3.1
Dominion Aluminum Fabricators (Canada) VAWT 35 X 55[a]	37	36.7/11.2	2 (Darrieus)	33/14.8	13/5.8
Grumman Energy Systems (USA) Windstream 25-B	20	25.0/7.62	3	29/12.9	8/3.6
Energy Development Co. (USA) - 440	20	38.0/11.6	4	25/11.2	5/2.2
Zephyr Wind Dynamo - 15 kVA	15	20.0/6.10	3	30/13.4	8/3.6
Dominion Aluminum Fabricators (Canada) VAWT 20 x 30[a]	14	20.0/6.10	2 (Darrieus)	30/13.5	12/5.4
Millville Windmills (USA) 10-3-IND	10	25.0/7.60	3	25/11.0	9/4.0
Wind Power Systems, Inc. (USA) Storm Master 10 (Prototype)	6	32.8/10.0	3	18/8.0	8/3.6
Aerowatt S.A. (France) 4100FP7G	4.1	32.7/9.30	2	16/7.2	7/3.1
Dakota Wind & Sun, Ltd. 4 kW	4	14.0/4.3	3	27/12.0	8/3.6
Dynergy - 5 Meter[a]	3.3	15.0/4.6	2 (Darrieus)	24/10.7	10/4.4
Product Development Institute (USA) Wind Heat System (Prototype)	3	13.6/4.15	3	27/12.0	12/5.4
Product Development Institute (USA) Wind Jennie (Prototype)	3	12.5/3.8	3	25/11.1	12/5.4

continued

SUMMARY - ELECTRICAL WIND MACHINES (continued)

Name and Model Number	Size (rated kW)	Rotor Diameter (ft/m)	No. of Blades	Rated Speed [mph/(m/sec)]	Cut-In Speed [mph/(m/sec)]
Kedco, Inc. (USA) 1620	3	16.0/4.88	3	25/11.1	11/4.9
North Wind Power Company (USA) Eagle 3 kW-32V	3	13.6/4.14	3	27/12.2	8/3.6
North Wind Power Company (USA) Eagle 3 kW-110V	3	13.6/4.14	3	27/12.2	8/3.6
Altos, The Alternate Current (USA) BWP-12A	2.2	8.0/2.4	24	38/17.1	8/3.6
Pinson Energy Corporation (USA) C-2E (Prototype)[a]	2	12.0/3.66	3	24/10.7	7/3.1
Altos, The Alternate Current BWP-12B	2	11.5/3.5	NA	28/12.5	8/3.6
American Wind Turbine, Inc. (USA) 16-ft	2	15.3/4.7	48	20/9.0	10/4.5
Dunlite Electrical Products (Australia) 81/002550 (Standard Model)	2	13.5/4.10	3	25/11.0	8/3.6
Kedco, Inc. (USA) 1210	2	12.0/3.65	3	26/11.6	11/4.9
Kedco, Inc. (USA) 1610	2	16.0/4.88	3	22/10.0	10/4.4
North Wind Power Company (USA) Eagle 2 kW-32V	2	13.6/4.15	3	22/10.0	8/3.6
North Wind Power Company (USA) Eagle 2 kW-110V	2	13.6/4.2	3	22/10.0	8/3.6
Whirlwind Power Company (USA) Model A	2	10/3.0	2	25/11.2	8/3.6
Kedco, Inc. (USA) 1605	1.9	16.0/4.88	3	20/8.9	7/3.1
Enertech Corp. (USA) 1500	1.5	13.2/4	3	22/9.8	8/3.6

continued

SUMMARY - ELECTRICAL WIND MACHINES (continued)

Name and Model Number	Size (rated kW)	Rotor Diameter (ft/m)	No. of Blades	Rated Speed [mph/(m/sec)]	Cut-In Speed [mph/(m/sec)]
Altos, The Alternate Current (USA) BWP-8A	1.5	8.0/2.4	24	28/12.5	8/3.6
Aero Power Systems, Inc. (USA) SL1500	1.43	10.0/3.05	3	25/11.2	6/2.7
Kedco, Inc. (USA) 1200	1.2	12.0/3.65	3	22/10.0	7/3.1
Kedco, Inc. (USA) 1205	1.2	12.0/3.65	3	22/10.0	8/3.6
Kedco, Inc. (USA) 1600	1.2	16.0/4.88	3	17/7.6	7/3.1
Aerowatt S.A. (France) 1100PF7G	1.125	16.7/5.09	2	16/7.2	7/3.1
American Wind Turbine, Inc. (USA) 12-ft	1	11.5/3.5	36	20/9.0	10/4.5
Dunlite Electrical Products (Australia) 82/002550 (High Wind Speed Model)	1	10.0/3.1	3	37/16.5	14/6.3
Sencenbaugh Wind Electric (USA) 1000	1	12.0/3.65	3	23/10.3	6/2.7
Aerolectric Company (USA) C-9/C-90 Wind Wizard	0.6	9.0/2.75	3	26/11.6	9/4.0
American Wind Turbine, Inc. (USA) 8-ft	0.5	7.6/2.3	24	20/9.0	10/4.5
Sencenbaugh Wind Electric (USA) 500	0.5	6.0/1.8	3	24/10.8	10/4.5
Sencenbaugh Wind Electric (USA) 400-14HDS	0.4	7.0/2.13	3	20/9.0	9/4.0
Aerowatt S.A. (France) 300FP7G	0.35	10.7/3.26	2	16/7.2	7/3.1
Winco - Division of Dynatechnology (USA) 1222H	0.2	6.0/1.83	2	23/10.3	7/3.1
Aerowatt S.A. (France) 150FP7G	0.13	6.7/2.04	2	16/7.2	7/3.1

continued

SUMMARY - ELECTRICAL WIND MACHINES (continued)

Name and Model Number	Size (rated kW)	Rotor Diameter (ft/m)	No. of Blades	Rated Speed [mph/(m/sec)]	Cut-In Speed [mph/(m/sec)]
Aerowatt S.A. (France) 24FP7G	0.028	3.3/1.00	2	16/7.2	7/3.1
Zephyr Wind Dynamo Tetrahelix S	0.007	2.0/0.61	2	25/11.2	12/5.4
Jay Carter Enterprises (USA) - 25	25	32.0/9.76	2	25/11.0	7/3.1
Aero Power Systems (USA) - SL1000	1	10.0/3.1	3	22/10.0	7/3.1
Aero Power Systems (USA) - SL1500	1.5	12.0/3.65	3	22/10.0	7/3.1
Independent Energy Systems (USA) - Sky Hawk	4	15.0/4.65	3	23/10.3	8/3.6
Power Group International (USA)	4	14.0/4.26	3	22/10.0	7/3.1
Astral Wilcon (USA) - AW.10.B	10	26.0/7.88	3	23/10.3	8/3.6
Tumac Industries, Inc. (USA) VAWT 7 x 6.5-meter Darrieus	7.5	19.5/6.5	3	28/	12/5.4
Environmental Energies, Inc. (USA) (Helical Wind Turbines)	15	24.0/7.3	multi-bladed helical	25/11.0	7/3.1
Hinton Research and Development Corp. Model 2	3	11.0/3.35	2	28/12.5	10/4.5

[a] Vertical axis.

ELECTRICAL WIND MACHINE MANUFACTURERS

Aerolectric 13517 Winter Lane Cresaptown, MD 21502	Contact: Telephone:	Kevin Moran 609-547-3488
Aero Power 2398 Fourth Street Berkeley, CA 94710	Contact: Telephone:	John Harold or Tom Cummins 415-848-2710
Aerowatt, S.A. c/o Automatic Power, Inc. P. O. Box 18738 Houston, TX 77023	Contact: Telephone:	Robert Dodge or Ernest Tindle 713-228-5208
Alcoa Alcoa Laboratory Alcoa Center, PA 15069	Telephone:	412-339-6651
Altos: The Alternate Current P. O. Box 905 Boulder, CO 80302	Contact: Telephone:	Edward Gitlin 303-442-0885
Astral/Wilcon P. O. Box 291 Milbury, MA 01527	Telephone:	617-865-9412
Bergey Wind Power Co. 2001 Priestly Ave. Norman, OK 73069	Telephone:	405-364-4212
Bertoia Studio 644 Main St. Bally, PA 19503	Telephone:	215-845-7096
Jay Carter Enterprises P. O. Box 684 Burkburnett, TX 76354	Telephone:	817-569-0181
Chalk Wind Systems P. O. Box 446 St. Cloud, FL 32769	Telephone:	305-892-7338
American Wind Turbine, Inc. 1016 East Airport Road Stillwater, OK 74074	Contact: Telephone:	Nancy Thedford Office Manager 405-377-5333
Dakota Wind & Sun, Ltd. P. O. Box 1781 811 First Avenue, NW Aberdeen, SD 57401	Contact: Telephone:	Paul Biorn or Orv Lynner 605-229-0815

Dominion Aluminum Fabricators 3570 Hawkestone Road Mississauga, Ontario Canda L5C 2V8	Contact: Telephone:	Chuck Wood, Program Manager 416-270-5300
Dragonfly Wind Electric P. O. Box 57-A Albion, CA 95410	Telephone:	707-937-4710
Dunlite Electrical Products Co. Enertech Corporation P. O. Box 420 Norwich, VT 05055	Contact: Telephone:	Ed Coffin or c/o Robert Sherwin 802-649-1145
Environmental Energies, Inc. Front Street Copemish, MI 49625	Telephone:	616-378-2000
Dynergy Corporation P. O. Box 428 1269 Union Avenue Laconia, NH 03246	Contact: Telephone:	Robert Allen 603-524-8313
Grumman Energy Systems 4175 Veterans Memorial Highway Ronkonkoma, NY 11779	Contact: Telephone:	Ed Diamond or Ken Speiser 516-575-6205
Hinton Research 417 Kensington Salt Lake City, UT 84115	Telephone:	801-487-3896
Jacobs Wind Electric Co., Inc. Route 13, Box 722 Fort Myers, FL 33908	Telephone:	813-481-3113
Kaman Aerospace Old Windsor Rd. Bloomfield, CT 06002	Telephone:	203-242-4461
Kedco, Inc. 9016 Aviation Boulevard Inglewood, CA 90301	Contact: Telephone:	Wind Program Manager 213-776-6636
McDonnell Aircraft Co. P. O. Box 516 St. Louis, MI 63166	Telephone:	314-232-3575
Megatech Corp. 29 Cook St. Billerica, MA 01866	Telephone:	617-273-1900
Mehrkam Energy Development Co. 179 East Road 2 Hamburg, PA 19526	Telephone:	215-562-8856

Millville Windmills & Solar Equipment Company P. O. Box 32 10335 Old Drive Millville, CA 96062	Contact: Telephone:	Devon Tassen 916-547-4302
North Wind Power Company P. O. Box 315 Warren, VT 05674	Contact: Telephone:	Don Mayer 802-496-2955
Pinson Energy Corporation P. O. Box 7 Marstons Mills, MA 02648	Contact: Telephone:	Herman Drees 617-477-2913
Power Group International Corp. Suite 106 13315 Stuebner-Airline Rd. Houston, TX 77014	Telephone:	713-444-5000
Product Development Institute 508 South Byrne Road Toledo, OH 43609	Contact: Telephone:	Tom Nichols 419-382-0282
Sencenbaugh Wind Electric P. O. Box 11174 Palo Alto, CA 94306	Contact: Telephone:	Jim Sencenbaugh 415-964-1593
Tumac Industries 650 Ford St. Colorado Springs, CO 80915	Telephone:	303-596-4400
TWR Enterprises Sun-Wind-Home Concepts 72 West Meadow Lane Landy, UT 84070		
Winco Div. of Dyna Technology 7850 Metro Parkway Minneapolis, MN 55420	Contact: Telephone:	Len Attema 612-853-8400
Windworks, Inc. Box 329, Route 3 Mukwonego, WI 53149	Telephone:	414-363-4408
Whirlwind Power Co. 2458 W. 29th Ave. Denver, CO 80211	Telephone:	303-477-6436
Wind Power Systems, Inc. P. O. Box 17323 San Diego, CA 92117	Contact: Telephone:	Ed Salter 714-452-7040

Winflo Power Ltd.
90 Esna Dr.
Unit 15
Markham, Ontario
Canada L3R 2R7

W.T.G. Energy Systems, Inc. P. O. Box 87 1 LaSalle Street Angola, NY 14006	Contact: Telephone:	Al Wellikoff 716-549-5544
Zephyr Wind Dynamo Company P. O. Box 241 21 Stamwood Street Brunswick, ME 04011	Contact: Telephone:	Bill Gillette 207-725-6534

SUMMARY-MECHANICAL WIND MACHINES

The following TABLE is a summary of the major characteristics of each mechanical wind machine. The data are arranged according to pumping capacity (gal/hr) with an approximately 100' head elevation.

Name and Model		Capacity (Gal/Hr.)	Elevations (Feet)	Cyl. Dia. (Inches)	Rotor Dia. (Feet)	Rated Wind Speed MPH/(m/s)	Cut-In Wind Speed MPH/(m/s)
Aermotor	702-16	1,700	100	5 3/4	16	20/(9)	9/(4)
Aermotor	702-14	1,050	98	4 1/2	14	20/(9)	9/(4)
Dempster	14 ft.	NO DATA AVAILABLE @ 100' ELEV.			14	15/(6.7)	5/(2.2)
Aermotor	702-12	730	98	3 3/4	12	20/(9)	9/(4)
Dempster	12 ft.	630	108	3 1/2	12	15/(6.7)	5/(2.2)
Heller-Aller	Baker 12	600	100	3	12	15/(6.7)	7/(3.15)
Aermotor	702-10	470	100	3	10	20/(9)	9/(4)
Heller-Aller	Baker 10	460	100	2 1/2	10	15/(6.7)	7/(3.15)
Dempster	10 ft.	357	102	3	10	15/(6.7)	5/(2.2)
Aermotor	702-8	325	94	2 1/2	8	20/(9)	9/(4)
Heller-Aller	Baker-8	250	100	2	8	15/(6.7)	7/(3.5)
Dempster	8 ft.	248	107	2 1/4	8	15/(6.7)	5/(2.2)
Heller-Aller	Baker-6	150	100	2	6	15/(6.7)	7/(3.15)
Dempster	6 ft.	130	95	2	6	15/(6.7)	5/(2.2)
Aermotor	702-6	130	95	2	6	20/(9)	9/(4)
Sparco	D	58	13.1	N.A.	4.17	18/(8)	5/(2.2)
Sparco	P	58	32.8	N.A.	4.17	18/(8)	5/(2.2)
Wadler	271	NOT APPLICABLE			(Savonious)	N.A.	2/(0.9)
Wadler	273	NOT APPLICABLE			(Savonious)	N.A.	2/(0.9)
Wadler	370	NOT APPLICABLE			(Savonious)	N.A.	2/(0.9)
Wadler	672	NOT APPLICABLE			(Savonious)	N.A.	2/(0.9)

<u>MECHANICAL WIND MACHINE MANUFACTURERS</u>

Aermoter Division Valley Industries P. O. Box 1364 Conway, AR 72032	Contact: Telephone:	Stan Anderson 501-329-9811
American Wind Turbine, Inc. 1016 East Airport Road Stillwater, OK 74074	Contact: Telephone:	Nancy Thedford, Office Manager 405-223-4026
Bowjon 2829 Burton Ave. Burbank, CA 91504	Telephone:	213-846-2620
Dempster Industries, Inc. P. O. Box 848 Beatrice, NB 68310	Contact: Telephone:	Roy Smith 402-223-4026
Dynergy Corporation P. O. Box 428 1268 Union Ave. Laconia, NH 03246	Contact: Telephone:	Bob Allen 603-524-8313
Heller-Aller Company Perry & Oakwood Street Napoleon, OH 43545 Mfg. of Baker Windmills	Contact: Telephone:	James Bradner or Charles Buehrer 419-592-1856
Molinos De Viento, S.A. Calle 53, No. 1 Chihuahua, State of Chihuahua Mexico		
Sparco (Denmark) c/o Enertech, Inc. P. O. Box 420 Norwich, VT 05055	Contact: Telephone:	Edmund Coffin at Enertech 802-649-1145
Wadler Manufacturing Co., Inc. Route 2, Box 76 Galena, KS 66739	Contact: Telephone:	Jerry Wade 316-783-1355

WIND MACHINE DEALERS/DISTRIBUTORS

COMPANY	PRODUCT NAME
Aermotor 1243 Majesty Drive Dallas, TX 75247	Aermotor Contact: Mr. William E. Barney Telephone: 214-634-1950
Aermotor 2385 South Cherry Fresno, CA 93706	Aermotor Contact: Telephone: 209-486-7200
Aermotor 900 Nabco Avenue P. O. Box 1321 Conway, Arkansas 72032	Aermotor Contact: Miles Patten Telephone: 501-329-2969
Aermotor 6448 Warren Drive Norcross, GA 30093	Aermotor Contact: Telephone: 404-449-1840
Aermotor 518-M North Douglas Avenue Altamonte Springs, FL 32701	Aermotor Contact: Telephone: 305-862-0171
Aermotor 2421 West Main Ft. Wayne, IN 46808	Aermotor Contact: Telephone: 219-432-2595
Aermotor 4655 Colt Road Rockford, IL 61109	Aermotor Contact: Telephone: 815-874-9502
Aermotor 801 Howard Street Omaha, NB 68102	Aermotor Contact: Marvin Vesenik Telephone: 402-341-1716
Aermotor 8105 Lewis Road Minneapolis, MN 55427	Aermotor Contact: Telephone: 612-544-4106
Aermotor 2803 South Longview Drive Middletown, PA 17057	Aermotor Contact: Telephone: 717-939-9311
Aermotor 1575 Avon Street Extended Charlottesville, VA 22901	Aermotor Contact: Telephone: 804-977-0445
Alternate Energy Systems 150 Sandwich Street Plymouth, MA 02360	Elektro, Dunlite, Winco Contact: Telephone: 617-747-0771

Wind Machine Dealers/Distributors (Continued)

COMPANY	PRODUCT NAME
Automatic Power, Inc. P. O. Box 18738 Houston, TX 77023	Aerowatt Contact: Robert Dodge Telephone: 713-228-5208
Dean Bennet Supply Company 4725 Lipan Street Denver, CO 80211	Aermotor, Dunlite, Winco Contact: Deana Bennet Telephone: 303-433-8291
Clean Energy Products 3534 Bagley, N. Seattle, WA 98103	Jacobs, Kedco, Sencenbaugh, Wincharger Contact: Ed Kennell Telephone: 206-633-5505
Coulson Wind Electric RFD 1, Box 225 Polk City, IA 50226	Re-conditioned Jacobs, Winco, Winpower Contact: R. Coulson Telephone: 515-547-3488
Crowdis Conservers RR 3, MacMillan Mt. Cape Breton, Nova Scotia Canada BOE 1BO	North Wind Contact: Daniel Atkins
Edmond Scientific Company 380 EDS Corp. Bldg. 101 East Gloucester Pike Barrington, NJ 08007	Aerolectric (Wind Wizard) Contact: Robert F. McKelvery Telephone: 609-547-3488
Empire Energy Devlopment Corp. 3371 West Hampden Avenue Englewood, CA 80110	Altos, Winco Contact: David L. Flook Telephone: 303-789-1363
Environmental Energies, Inc. P. O. Box 73 Front Street Copemish, MI 49625	Elektro, Dunlite, Re-conditioned Jacobs Contact: Timothy J. Horning Telephone: 616-378-2000
Energy Alternatives 52 French King Highway Greenfield, MA 01301	Elektro, Dunlite, Winco, Sencenbaugh Contact: Frank Kaminsky or Klaus Kroner Telephone: 413-773-5175

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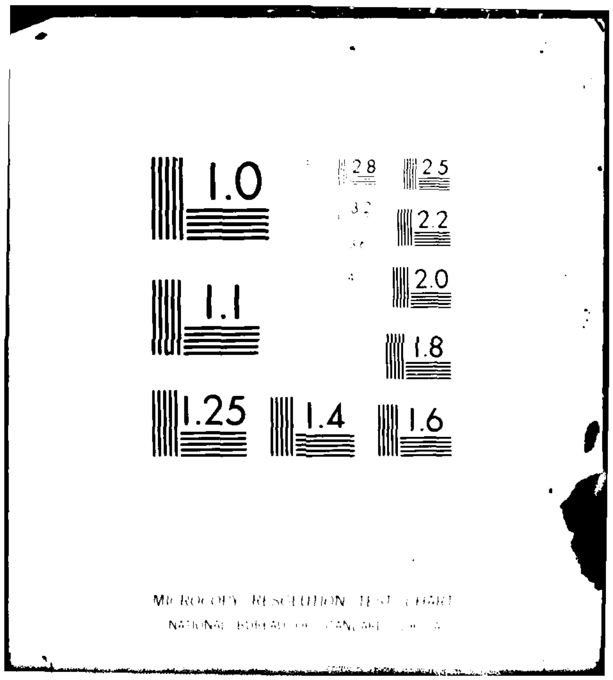
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COMPANY	PRODUCT NAME
Energy Development Company 179E Road #2 Hamburg, PA 19526	Winco, Homebuilt Contact: Terrance or Helena Mehrkam or Karen Votyas Telephone: 215-562-8856
Energy - 2000 Route 800, RFD #3 Winstead, CT 06098	Re-conditioned Jacobs (North Wind) Contact: Robert Hebert Telephone: 203-379-5185 or 413-528-3440
Enertech Corporation P. O. Box 420 Norwich, VT 05055	Dunlite, Winco, Sencenbaugh, Sparco Contact: E. Coffin Telephone: 802-649-1145
Environmental Resource Group Box 3A, RD 2 Williston, VT 05495	North Wind, Sparco Contact: Perry Kleine Telephone: 802-879-0511 or 802-878-4000
Fenton's Feeders Route 1, Box 124 Arcadia, FL 33821	Aermotor (Water pumping) Contact: Catherine Fenton, Bill Autry, or Nell Gammage Telephone: 817-494-2727
Independent Energy Company 314 Howard Avenue Ewarthmore, PA 19081	Elektro, Dunlite, Winco Contact: Kendall B. Hampton Telephone: 617-368-6992
Independent Energy Company 6043 Sterrettania Road Fairview, PA 16415	Re-conditioned Jacobs, Dakota Wind Electric Contact: John D'Angelo Telephone: 814-833-0829
Kramco P. O. Box 1536 Allentown, PA 18105	Re-conditioned Jacobs, Winco Contact: Telephone: 215-437-6758
Laholms Motor & Bilelektriska A/B Export Office & Information Wind Kraft A.E.S.C. Box #104 S-312 01 Laholm, Sweden	Wind Kraft A.E.S.C. Contact: Eric Alkstad Int. Phone: 00946-43020371 Cable: WERKOMP
Makia Ocean Engineering Box 1194 Kailua, Oahu, Hawaii 96734	Dunlite Contact: Henry Horn Telephone: 808-259-5904 or 808-259-5722

Wind Machine Dealers/Distributors (Continued)

COMPANY	PRODUCT NAME
Natural Power Systems, Inc. 3316 Augusta Avenue Omaha, NB 68144	Dakota Wind Electric, Dunlite, Sencenbaugh, Sparco Contact: John Traudt Telephone: 402-334-5881
O'Brock Windmill Sales Route 1, 12th Street North Benton, OH 44449	Baker Contact: Ken O'Brock Telephone: 216-584-4681
Pacific Energy Systems 615 Romero Canyon Road Santa Barbara, CA 93018	North Wind Contact: Fred Carr Telephone: 805-969-5603
Prairie Sun & Wind Company 4408 - 62nd Street Lubbock, TX 79409	Re-conditioned Jacobs, Winco, Aeropower, Dakota Wind Electric Aermotor Contact: Ken Ketner Telephone: 806-795-1412
Real Gas & Electric P. O. Box 193 Shingletown, CA 96088	Elektro, Dunlite Contact: Solomon Kagin Telephone: 916-474-3852
Rede Corporation P. O. Box 212 Providence, RI 02901	Dominion Aluminum Fabricating (DAF) Contact: Ronald Beckman Telephone: 401-751-7333
Schupbach, Ralph 321 - 13th Street Alva, OK 73717	Winco Contact: Ralph Schupbach Telephone: 405-327-1685
Shingletown Electric P. O. Box 237 Shingletown, CA 96008	Elektro, Dunlite Contact: Robert E. Eckert Telephone: 916-474-3852
Sunflower Power Company Route 1, Box 93-A Oskaloosa, KS 66066	Re-conditioned Jacobs, North Wind Contact: Steve Blake Telephone: 913-597-5603
Wind Engineering Corporation Box 5936 Lubbock, TX 79417	Re-conditioned Jacobs, DAF, Dynergy, Dakota Wind Electric Contact: Telephone: 806-763-3182
Windependence Electric P. O. Box M1188 Ann Arbor, MI 48106	Re-conditioned Jacobs Contact: Craig Toepfer Telephone: 313-769-8469

ANEMOMETERS AND RECORDERS

Anemometers are devices which measure the wind. The manner in which they accomplish this task ranges from an odometer which records the number of miles of wind that pass the recorder, to three-axis anemometers that record wind velocity on three separate planes.

As with all wind system sub-components, anemometers vary widely in terms of accuracy, the type of information obtained, and cost. The value of a certain anemometer or anemometry system will depend largely upon the specific application for which it is used. Again, wind system distributors can help select the proper anemometer or anemometry system.

Aeolian Kinetic P. O. Box 100 Providence, RI 02901	Telephone:	401-421-5033
Aircraft Components 700 North Shore Drive Benton Harbor, MI 49022	Telephone:	616-925-8861
Bendix Environmental and Process Instruments Division 1400 Taylor Avenue Baltimore, MD 21204	Telephone:	301-321-5200
Climet, Inc. 1320 West Colton Avenue Redlands, CA 92373	Telephone:	714-793-2788
Danforth Div. of Eastern Company 500 Riverside Industrial Pkwy. Portland, ME 04103	Telephone:	207-797-2791
Davis Instrument Mfg. Co., Inc. 513 E. 36th Street Baltimore, MD 21218	Telephone:	301-243-4301
Dwyer Instruments, Inc. P. O. Box 373 Michigan City, IN 46360	Telephone:	219-872-9141
Hightstown, NJ.	Telephone:	609-448-9200
Marietta, GA	Telephone:	404-427-9406
Anaheim, CA	Telephone:	714-630-6424
Cleveland, OH	Telephone	216-234-5888
Houston, TX	Telephone:	713-446-1146
Kahl Scientific Instruments Corp. P. O. Box 1166 El Cajon San Diego, CA 92022	Telephone:	714-444-2158

Kenyon Marine P. O. Box 308 Guilford, CT 06437	Telephone:	203-453-4374
Kenyon Marine 2734 S. Susan Street Santa Ana, CA 92704	Telephone:	714-546-1101
Maximum, Inc. 42 South Avenue Nitick, MA 01760	Telephone:	617-785-0113
Meterology Research, Inc. P. O. Box 637 Altadena, CA 91001	Telephone:	213-791-1901
Natural Power, Inc. Francestown Turnpike New Boston, NH 03070	Telephone:	603-487-5512
Sencenbaugh Wind Electric P. O. Box 11174 Palo Alto, CA 94306	Telephone:	415-964-1593
Sign X Laboratories, Inc. Stetson Road Brooklyn, CT 06234	Telephone:	203-774-5233
R. A. Simeri Instrument Div. 238 West Street Annapolis, MD 21401	Telephone:	301-849-8667
M.C. Stewart Ashburnham, MA 01430	Telephone:	617-827-5840
Taylor Instruments P. O. Box 1 Arden, NC 28704	Telephone:	704-684-8111
Texas Electronics, Inc. Box 7225, Inwood Station Dallas, TX 75209	Telephone:	214-631-2490
TSI 500 Cardigan Road P. O. Box 43394 St. Paul, MN 55164	Telephone:	612-483-0900
Westberg Manufacturing Inc. 3400 Westach Way Sonoma, CA 95476	Telephone:	707-938-2121

Robert E. White Instruments, Inc. 51 Commercial Wharf Boston, MA 02110	Telephone:	617-742-3045
Windflower Wind-Computer Lund Enterprises, Inc. 1180 Industrial Avenue Escondido, CA 92025	Telephone:	714-746-1211
Wind Power Systems, Inc. P. O. Box 17323 San Diego, CA 92117	Telephone:	714-566-1800
Weather Measure Corporation P. O. Box 41257 Sacramento, CA 95841	Telephone:	916-481-7565

WECS TOWERS

All wind machines must be placed on a support structure, generally a tower. A variety of factors influence the final choice of a tower for a particular wind machine and application. Two tower types, guyed and free-standing, are applicable for most wind energy installations.

Wind system distributors can help select the best tower for a particular site, but several factors should be considered. Wind machines should be at least 30 feet above the nearest obstruction. The tower must also support the weight of the wind machine and withstand loads imposed by the wind. These loads are a function of both the wind velocity and wind machine rotor diameter. Aesthetics, building codes, and zoning are also considerations in some areas.

There are eleven American Manufacturers of towers designed specifically for WECS. A number of foreign manufacturers offer their towers through WTG distributors. In addition, there are a number of tower manufacturers who have not been active in the WECS field but may have suitable equipment.

American Tower Company Shelby, OH 44875	Telephone:	419-347-1185
Astro Research Corporation 6390 Cindy Lande Carpinteria, CA 93013	Telephone:	805-684-6641
Bayshore Concrete Bayonne, NJ		
Natural Power Inc. Francestown Turnpike New Boston, NH 03070		
North Wind Power Company Box 315 Warren, VT 05674		
Solargy Corporation 17914 E. Warren Ave. Detroit, MI 48224	Telephone:	313-881-5510
Tele-Tower Mfg. Inc. P. O. Box 3412 Enid, OK 73701	Telephone:	405-233-4412
Texas Towers 1309 Summit Drive Plano, TX 75074	Telephone:	214-423-2376
Tri-Ex Tower Corporation 7182 Rasmussen Avenue Visalia, CA 93277	Telephone:	209-625-9400

Unarco-Rohn
6718 West Plank Road
P. O. Box 2000
Peoria, IL 61601

Valmont Industries, Inc. Telephone: 402-359-2201
Valley, NB 68064

BATTERIES

Because the wind is an intermittent energy source, it is often necessary to find a means of storing its energy. Although many energy storage systems such as heat, compressed air and flywheels are now being investigated, the state-of-the-art for electricity storage is the lead acid battery.

There are several types of storage batteries new commercially available. Each type has characteristics that make it best suited for a particular application. The ultimate choice of batteries depends on the total wind system characteristics including wind at the site, the wind turbine generator, and the load.

Batteries Manufacturing Company
14694 Dequindu
Detroit, MI 48212

Bright Star
602 Getty Avenue
Clifton, NJ 07015

Burgress Div. of Clevite Corp., Gould
Box 3140
St. Paul, MN 55101

C & D Batteries Eltuce Corp.
Washington & Chewy Street
Conshohocken, PA 19428

Delatron Systems Corporation
553 Lively Boulevard
Elk Grove Village, IL 60007

Delco-Remy Division of GM
Box 2439
Anderson, IN 46011

Eggle-Pichen Industries
Box 47
Joplin, MO 64801

ESB Incorporated - Willard
Box 6949
Cleveland, OH 44101

Exide
5 Pen Center Plaza
Philadelphia, PA 19103

Ever Ready - Union Carbide Corp.
270 Park Avenue
New York, NY 10017

Globe-Union
5757 No. Greenbay Avenue
Milwaukee, WI 53201

Gould Incorporated
485 Calhoun Street
Trenton, NJ 08618

Gulton
212 T Dorham Avenue
Metuchen, NJ 08840

Hydrate Battery Corp.
P. O. Box 4204
Lynchburg, VA 24502 Telephone: 804-846-8749

Keystone Battery Company
8301 Imperial Drive
Waco, TX 76710

Mule Battery Company
325-T Valley Street
Providence, RI 02908

RCA
415 South 5th Street
Harrison, NJ 07029

Saft America, Inc. Telephone: 912-247-2231
711 Industrial Blvd.
P. O. Box 1886
Valdosta, GA 31601

Surrette Storage Battery Co., Inc.
Box 711
Salem, MS 01970

Trojan, Inc. Telephone: 415-864-1565
1125 Mariposa Street
San Francisco, CA 94107

INVERTERS

Inverters are devices that convert direct current power (DC) to the alternative current (AC) more commonly used in this country.

There are a number of considerations in selecting an inverter for a WECS including the amount and quality of the power required, overload capabilities, and cost.

The majority of these systems are designed to operate with a battery bank storage system and are known as "stand alone" inverters. There is also available an inverter known as a synchronous inverter or "line commutated" inverter. These inverters are designed to feed the power produced to an A.C. line and requires the A.C. line for a voltage signal.

It should be noted that there are quite a few inverter manufacturers and most wind turbine generator distributors also sell inverters.

Allied Electronics 2400 W. Washington Blvd. Chicago, IL 60612	350 to 1000 watt; 12 volt input Telephone:	 312-421-4200
ATR Electronics, Inc. 300 E. 4th Street St. Paul, NM 55101	Telephone:	612-222-3791
Best Energy Systems for Tomorrow P. O. Box 280 Necedah, WI 54646	Telephone:	800-356-6794
Carter Motor Company 2711 W. George St. Chicago, IL 60618	Telephone:	312-588-7700
Dynamote Corporation 1200 W. Nickerson Seattle, WA 98119	Telephone:	206-282-1000
Eico Electronic Instrument Co. 283 Malta Street Broklyn, NY 11207	110 to 220 watt; 12 volt input	
Electro Sales Co., Inc. 100 Fellsway West Somerville, MA 02145	20 to 2000 watt; 12 to 200 volt input Telephone:	 617-666-0500
Elgar Corporation 8225 Mercury Court San Diego, CA 92111	Telephone:	714-565-1155
Heath Company Benton Harbor, MI 49002	175 watt; 12 volt input Telephone:	 616-983-3961

LaMarche Mfg. Company 106 Bradrock Drive Des Plaines, IL 60018	100 to 10,000 watt; 24 to 120 volt input Telephone:	312-279-0831
Newark Electronics 500 N. Pulaski Road Chicago, IL	100 to 250 watt; 12 volt input Telephone:	312-638-4411
Nova Electric 263 Hillside Avenue Nutley, NJ 07110	30 to 120 watt; 12 to 110 volt input Telephone:	201-661-3432
Ratelco, Inc. 610 Pontius Avenue, N. Seattle, WA 98109	0.5 KVA to 15 KVA; 24 to 120 volt DC input Telephone:	206-624-7770
Real Gas & Electric, Inc. P. O. Box F Santa Rosa, CA 95402	5 KVA maximum; 75 to 200 volt DC Telephone:	707-526-3400
Soleq Corporation 5969 Elston Avenue Chicago, IL 60646	1500 to 6000 watt; 12 to 112 volt input Telephone:	312-792-3811
Topaz Electronics 3855 Ruffil Road San Diego, CA 92123	200 to 3000 watt; 12 to 125 volt input Telephone:	714-279-0831
Willmore Electronics Box 2973 Durham, NC 27705	45 to 1500 watt; 12 to 120 volt input Telephone:	919-489-3318

LINE COMMUTATED INVERTERS

Gemini Synchronous Inverters Windworks Box 329, Route 3 Mukwonago, WI 53149	4 to 1000 kW; variable voltage input Telephone:	414-363-4408

Appendix B

INFLATION-DISCOUNT FACTORS

<u>NOTE</u>: In these tables, the single-amount factors are to be applied to one-time costs occurring in isolated years. Cumulative-uniform-series factors are to be applied to identical annually recurrent cash flows.

Table 0

PROJECT YEAR INFLATION-DISCOUNT FACTORS

Differential Inflation Rate = 0%[a]
Discount Rate = 10%

Project Year	Single Amount	Cumulative Uniform Series
1	0.954	0.954
2	0.867	1.821
3	0.788	2.609
4	0.717	3.326
5	0.652	3.977
6	0.592	4.570
7	0.538	5.108
8	0.489	5.597
9	0.445	6.042
10	0.405	6.447
11	0.368	6.815
12	0.334	7.149
13	0.304	7.453
14	0.276	7.729
15	0.251	7.980
16	0.228	8.209
17	0.208	8.416
18	0.189	8.605
19	0.172	8.777
20	0.156	8.933
21	0.142	9.074
22	0.129	9.203
23	0.117	9.320
24	0.107	9.427
25	0.097	9.524
26	0.088	9.612
27	0.080	9.692
28	0.073	9.765
29	0.066	9.831
30	0.060	9.891

[a]These factors are to be applied to cost elements which are anticipated to escalate at the same rate as the general price level.

Table 7

PROJECT YEAR INFLATION-DISCOUNT FACTORS

Differential Inflation Rate = 7%[a]
Discount Rate = 10%

Project Year	Single Amount	Cumulative Uniform Series
1	0.986	0.986
2	0.959	1.946
3	0.933	2.879
4	0.908	3.787
5	0.883	4.670
6	0.859	5.529
7	0.836	6.364
8	0.813	7.177
9	0.791	7.968
10	0.769	8.737
11	0.748	9.485
12	0.728	10.212
13	0.708	10.920
14	0.688	11.608
15	0.670	12.278
16	0.651	12.930
17	0.634	13.563
18	0.616	14.180
19	0.600	14.779
20	0.583	15.363
21	0.567	15.930
22	0.552	16.482
23	0.537	17.019
24	0.522	17.541
25	0.508	18.049
26	0.494	18.543
27	0.481	19.023
28	0.467	19.491
29	0.455	19.946
30	0.442	20.388

[a]These factors are to be applied to cost elements which are anticipated to escalate at a rate 7% faster than general price levels.

Table 8

PROJECT YEAR INFLATION-DISCOUNT FACTORS

Differential Inflation Rate = 8%[a]
Discount Rate = 10%

Project Year	Single Amount	Cumulative Uniform Series
1	0.991	0.991
2	0.973	1.964
3	0.955	2.919
4	0.938	3.857
5	0.921	4.777
6	0.904	5.681
7	0.888	6.569
8	0.871	7.440
9	0.856	8.296
10	0.840	9.136
11	0.825	9.961
12	0.810	10.770
13	0.795	11.565
14	0.781	12.346
15	0.766	13.112
16	0.752	13.865
17	0.739	14.603
18	0.725	15.329
19	0.712	16.041
20	0.699	16.740
21	0.687	17.427
22	0.674	18.101
23	0.662	18.762
24	0.650	19.412
25	0.638	20.050
26	0.626	20.676
27	0.615	21.291
28	0.604	21.895
29	0.593	22.488
30	0.582	23.070

[a]These factors are to be applied to cost elements which are anticipated to escalate at a rate 8% faster than general price levels.

LIST OF SYMBOLS

A	Area normal to the wind flow swept by the rotor
$\bar{A}$	Recurring uniform annual cost for operation and maintenance
a	Interference parameter, which is related to the induced drag due to the pressure of the machine in the flow field
AF	A multiplier
C'	Normalized uniform annual cost
C_1	A constant
C_e	Total cost of present source of energy in $/kWhr
C_L	Lift coefficient
C_D	Drag coefficient
c_p	Specific heat at constant pressure
$C_p(u)$	Power coefficient of a wind turbine
C_T	Rotor thrust coefficient
C_{TO}	Cost of a self-supporting steel tower
CUS	Cumulative-Uniform-Series factor
$CUS_{(i_D,\bar{N})}$	Cumulative-Uniform-Series factor
C_w	Total system cost
D	Drag
e	Exponential
e_r	Escalation rate
E_w	Rated output of a wind turbine
F	Present cost of procuring the total quantity fuel or electricity required for operating the alternative device or facility for one year, in dollars
f	Frequency
g	Gravitational acceleration

H	Vertical turbulent heat flux
$\bar{T}$	Time in hours that the speed exceeds u
h	Altitude
I	Present value acquisition cost, in dollars
i	Discount rate plus differential inflation rate
I_1	Present acquisition cost of the existing system
I_2	Present acquisition cost of the proposed WECS installation
i_D	*Differential inflation rate (%)*
K	Conversion factor
L	Lift
L_h	Design load
M	Rate of change of momentum
m	Mass of air flowing through the rotor in unit time
$\bar{N}$	Economic life of a system
$\bar{N}_c$	Common time period for the two systems being compared
$\bar{N}_p$	Payback period
NPV	Total present value life-cycle cost, in dollars
NPV_1	Total present value life-cycle cost of the existing system (such as a diesel plant, purchased electricity, etc.)
NPV_2	Total present value life-cycle cost of the proposed alternative, which is the WECS installation
N_r	Generator rotor speed
N_s	Synchronous speed
P	Number of poles on the generator
p	Atmospheric pressure

P_a	Instantaneous power available in the wind
P_c	Power output at cut-in speed
P_r	Rotor rated output
$P(u)$	WECS output as a function of wind speed u
P_w	Power absorbed by the rotor
P_{wrated}	Rated output of a wind turbine
P_{wmax}	Maximum value of power
s	Slip
S_o	Equivalent number of hours of full output operation in a year
$S_{o,min}$	Minimum value of the specific output
T	Averaging period of time
t	Time
T_r	Rotor thrust
T_{rmax}	Maximum value of rotor thrust
T_v	Present value of the terminal value of equipment
U	Mean wind speed value
u	Wind speed
u'	Fluctuating wind speed component
U_1	Average value of wind speed at height z_1 above ground
u_1	Wind speed at a considerable distance upwind (prevailing wind speed)
u_2	Wind speed a considerable distance downwind of the rotor
u_c	Rotor cut-in wind speed
u(h)	Wind speed at elevation h
U_{min}	Minimum economical annual mean wind speed of a site
U_o	Velocity at the tip of the viscous sublayer

u_o	Rotor cut-out wind speed
$u_p(h_o)$	Mean wind speed at 32.8 feet (10 meters)
u_R	Wind speed actually through the rotor
u_r	Rotor rated wind speed
$U(z)$	Average of the quantity $u(z,t)$ over a long period of time
$u(z,t)$	Instantaneous wind speed
v^*	Friction velocity
$\vec{v}$	Direction of incident wind
$\vec{v}_R$	Velocity of the relative wind
$\vec{v}_t$	Velocity
w'	Fluctuating component of vertical velocity
x	$(\bar{A}_2 - \bar{A}_1)/I_2$ = annual O&M cost differential between the costs of present source of power and that of the WECS facility
$X(U)$	Energy pattern factor
z	Height above ground level
$z1$	Instrument height
z_2	Center of the proposed power plant above the ground
z_o	Roughness height
α	Angle of attack
α_1	Empirical constant (= 0.6)
β	Function of the ground roughness and the atmospheric stability conditions; velocity profile power law exponent
γ	Direction measured by a vane
η	Efficiency
θ	Ambient temperature in degrees Rankine (°R)
$\bar{\theta}$	Mean air temperature

$\vec{\theta}$	Blade angular position
κ	Karman constant (= 0.41)
λ	Tip-speed-to-wind-speed ratio
ρ	Mass density of air
τ	Surface shear stress
$\phi(z/\mathcal{L})$	Universal function
$\mathcal{L}$	Unique length scale of Monin and Obukhov
χ_o	Fraction at height h_o of the cost of the erected tower to the total cost
$\vec{\omega}$	Rotational speed

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