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4E

WIND TURBINES

by

John C. Yeoman, Jr.

ICES
INTEGRATED COMMUNITY ENERGY SYSTEMS

TECHNOLOGY EVALUATIONS

Prepared by:

Oak Ridge National Laboratory
Operated by Union Carbide Corporation
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December 1978

Prepared for

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The four E's of the cover logo embody the goals of the Community Systems Program of the Department of Energy, DOE, namely:

- to conserve *Energy;*
- to preserve the *Environment;* and
- to achieve *Economy*
- in the design and operation of human settlements (*Ekistics).*

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FOREWORD

The Community Systems Program of the Division of Buildings and Community Systems, Office of Energy Conservation, of the United States Department of Energy (DOE), is concerned with conserving energy and scarce fuels through new methods of satisfying the energy needs of American Communities. These programs are designed to develop innovative ways of combining current, emerging, and advanced technologies into Integrated Community Energy Systems (ICES) that could furnish any, or all, of the energy-using services of a community. The key goals of the Community System Program then, are to identify, evaluate, develop, demonstrate, and deploy energy systems and community designs that will optimally meet the needs of various communities.

The overall Community Systems effort is divided into three main areas: (a) Integrated Systems, (b) Community Planning & Design, and (c) Implementation Mechanisms. The *Integrated Systems* work is intended to develop the technology component and subsystem data base, system analysis methodology, and evaluations of various system conceptual designs which will help those interested in applying integrated systems to communities. Also included in this program is an active participation in demonstrations of ICES. The *Community Planning & Design* effort is designed to develop concepts, tools, and methodologies that relate urban form and energy utilization. This may then be used to optimize the design and operation of community energy systems. *Implementation Mechanisms* activities will provide data and develop strategies to accelerate the acceptance and implementation of community energy systems and energy-conserving community designs.

This report, prepared by Oak Ridge National Laboratory, is part of a series of Technology Evaluations of the performance and costs of components and subsystems which may be included in community energy systems and is part of the Integrated Systems effort. The reports are intended to provide sufficient data on current, emerging and advanced technologies so that they may be used by consulting engineers, architect/engineers, planners, developers, and others in the development of conceptual designs for community energy systems. Furthermore, sufficient detail is provided so that calculational models of each component may be devised for use in computer codes for the design of Integrated Systems. Another task of the Technology Evaluation activity is to devise calculational models which will provide part-load performance and costs of components suitable for use as subroutines in the computer codes being developed to analyze community energy systems. These will be published as supplements to the main Technology Evaluation reports.

It should be noted that an extensive data base already exists in technology evaluation studies completed by Oak Ridge National Laboratory (ORNL) for the Modular Integrated Utility System (MIUS) Program sponsored by the Department of Housing and Urban Development (HUD). These studies, however, were limited in that they were: (a) designed to characterize mainly off-the-shelf technologies up to 1973, (b) size limited to meet community limitations, (c) not designed to augment the development of computer subroutines, (d) intended for use as general information for city officials and keyed to residential communities, and (e) designed specifically for HUD-MIUS needs. The present documents are founded on the ORNL data base but are more technically oriented and are designed to be upgraded periodically to reflect changes in current, emerging, and advanced technologies. Furthermore, they will address the complete range of component sizes and their application to residential, commercial, light industrial, and institutional communities. The overall intent of these documents, however, is not to be a complete documentation of a given technology but will provide sufficient data for conceptual design application by a technically knowledgeable individual.

Data presentation is essentially in two forms. The main report includes a detailed description of the part-load performance, capital, operating and maintenance costs, availability, sizes, environmental effects, material and energy balances, and reliability of each component along with appropriate reference material for further study. Also included are concise data sheets which may be removed for filing in a notebook which will be supplied to interested individuals and organizations. The data sheets are colored and are perforated for ease of removal. Thus, the data sheets can be upgraded periodically while the report itself will be updated much less frequently.

Each document was reviewed by several individuals from industry, research and development, utility, and consulting engineering organizations and the resulting reports will, hopefully, be of use to those individuals involved in community energy systems.

ABSTRACT

This evaluation of wind turbines is part of a series of Technology Evaluations of possible components and subsystems of community energy systems. Wind turbines, ranging in size from 200 W to 10 MW, are discussed as candidates for prime movers in community systems. Estimates of performance characteristics and cost as a function of rated capacity and rated wind speed are presented. Data concerning material requirements, environmental effects, and operating procedures also are given and are represented empirically to aid computer simulation.

ICES TECHNOLOGY EVALUATION

TECHNOLOGY EVALUATION SUMMARY SHEET OF

WIND TURBINES

By: John C. Yeoman, Jr., ORNL December, 1978

1 INTRODUCTION

Wind, a form of solar energy, is caused primarily by unequal heating of the earth's surface by the sun. Wind turbines convert the kinetic energy of the air into shaft power which, in turn, is converted into electric power by generators.

Wind turbines are divided into two categories: (1) horizontal-axis wind turbines for which the axis of rotation is parallel to the direction of the wind stream, and (2) vertical-axis wind turbines for which the axis of rotation is perpendicular to both the surface of the earth and the direction of the windstream. Horizontal-axis wind turbines are lift devices that usually have two blades and must have a yaw mechanism to rotate the blades to face the wind. Vertical-axis wind turbines also are lift devices but do not need any mechanism to direct the blades to face the wind. The Darrieus system is the most common type of vertical-axis wind turbine; however, it is not self-starting.

2 MATERIALS BALANCE

Wind turbines require fabrication materials as primary material inputs. The availability of basic raw stock, such as steel, aluminum, concrete, and copper wire is critical for the development of wind turbines. Equations DS-1 through DS-4 give, respectively, the amounts of steel, aluminum, concrete, and copper wire needed to fabricate horizontal-axis wind turbines of various rated capacities and rated windspeeds.

$$W_S = B_1 + B_2X + B_3X^2 + B_4Y + B_5Y^2 \quad \text{(Eq. DS-1)}$$

where:

W_S = Amount of Steel (metric tons)

X = Rated Capacity (kW)

Y = Rated Wind Speed (m/s)

B_1 = $.747240 \times 10^3$ $\quad$ B_4 = $.0705491$

B_2 = $-.154333 \times 10^3$ $\quad$ B_5 = $.156045 \times 10^{-5}$

B_3 = 7.95833

Standard error: $.392176 \times 10^2$

$1000 \leq X \leq 10{,}000$

$5 \leq Y \leq 9$

$$W_A = B_1 + B_2X[\mathrm{Tan}(B_3 + B_4Y + B_5Y^2)] \quad \text{(Eq. DS-2)}$$

where:

W_A = Amount of Aluminum (metric tons)

X = Rated Capacity (kW)

Y = Rated Wind Speed (m/s)

B_1 = $-.708108$ $\quad$ B_4 = $-.477637$

B_2 = $.927263 \times 10^{-2}$ $\quad$ B_5 = $.0260486$

B_3 = 2.43678

Standard Error: $.617298$

$1000 \leq X \leq 10{,}000$

$5 \leq Y \leq 9$

$$W_C = B_1 + B_2X + B_3X^2 + B_4X^3 + B_5X^4 + B_6Y + B_7Y^2 + B_8Y^3 + B_9Y^4 \quad \text{(Eq. DS-3)}$$

where:

W_C = Amount of Concrete (metric tons)

X = Rated Capacity (kW)

Y = Rated Wind Speed (m/s)

$B_1 = .405701 \times 10^3$ $B_6 = -.0568232$

$B_2 = -.117217 \times 10^3$ $B_7 = .454368 \times 10^{-4}$

$B_3 = .508074 \times 10^2$ $B_8 = -.697293 \times 10^{-8}$

$B_4 = -8.28520$ $B_9 = .345011 \times 10^{-12}$

$B_5 = .428183$

Standard Error: $.271913 \times 10^2$

$1000 \leq X \leq 10,000$

$5 \leq Y \leq 9$

$$W_{Cu} = B_1 + B_2X + B_3X^2 + B_4Y + B_5Y^2 \qquad \text{(Eq. DS-4)}$$

where:

W_{Cu} = Amount of Copper Wire (metric tons)

X = Rated Capacity (kW)

Y = Rated Wind Speed (m/s)

$B_1 = 6.19951$ $B_4 = .794344 \times 10^{-3}$

$B_2 = -1.16667$ $B_5 = .640270 \times 10^{-7}$

$B_3 = .0597222$

Standard Error: .418536

$1000 \leq X \leq 10,000$

$5 \leq Y \leq 9$

A vertical-axis wind turbine requires about 30% less copper wire than its horizontal-axis counterpart of the same size. It also will require less steel and concrete. The amount of aluminum required will be the same for both horizontal-axis and vertical-axis wind turbines.

The distance between wind turbines affects their efficiency; the minimum distance between wind turbines should be 15 blade diameters. Moreover, no more than three wind turbines should be aligned in any one direction.

3 PERFORMANCE

The total power available from the wind passing through a unit area normal to the wind is:

$$P = 1/2\rho V^3 \qquad \text{(Eq. DS-5)}$$

where:

P is the power in W/m^2,
ρ is th atmospheric density in kg/m^3, and
V is the wind speed in m/s.

The amount of power delivered by a wind turbine divided by the total power available in the windstream is defined as the efficiency or power coefficient, Cp, of the wind turbine. From fluid theory it can be shown that the Cp is limited to a value of 0.593 or less. Equation DS-6 gives the power coefficient for a horizontal-axis wind turbine as a function of the blade tip-to-wind speed ratio, and Eq. DS-7 gives the power coefficient of a vertical-axis wind turbine as a function of the blade-tip-to-wind speed ratio.

$$Cp = B_1 + B_2X + B_3X^2 \qquad \text{(Eq. DS-6)}$$

where:

Cp = Two Blade Power Coefficient
X = Tip-to-Wind Speed Ratio
B_1 = -.377463 B_3 = -.0298519
B_2 = .319277

Standard Error: $.519951 \times 10^{-2}$
$3.7 \leq X \leq 6.8$

$$Cp = B_1 + B_2X + B_3X^2 \qquad \text{(Eq. DS-7)}$$

where:

Cp = Darrieus Rotor Power Coefficient
X = Tip-to-Wind Speed Ratio

$B_1 = -2.48503 \qquad B_3 = -0.0825923$

$B_2 = \ .970120$

Standard Error: $.677752 \times 10^{-2}$

$4.6 \leq X \leq 6.8$

The location of wind turbines is important. Wind turbines should be located where the wind speed is high for maximum power generation. Figure DS-1 shows the mean annual wind speed across the United States. Maximum wind power is available in New England, the Plains, and Pacific Northwest. Wind power is at a maximum in the winter and spring. On a daily basis, wind power is greatest between noon and 2:00 p.m., local standard time.

Mean Annual Wind Power (W/m^2) Estimated at 50 m Above Exposed Areas. Over mountainous regions (shaded areas), the estimates are lower limits expected for exposed mountain tops and ridges.

Fig. DS-1 Mean Annual Wind Power

4 ENVIRONMENTAL EFFECTS

The major problem with wind turbines concerns aesthetics. Wind turbines are relatively large and highly visible; however, special choice of paint colors can soften the visual impact.

Wind turbines also can interfere with television reception for several miles. Interference is worse on the upper UHF channels.

5 OPERATION AND MAINTENANCE

Wind turbines usually "cut-in" when the wind speed reaches 50% of the rated speed, and the power output increase until it reaches the rated output at the rated wind speed. The power output then remains constant as the wind speed increases.

Wind turbines will have control circuitry to provide fully automatic operation and to protect the system. Human intervention will be needed only for periodic inspections, maintenance, and repairs.

It is estimated that maintenance will require that the wind turbine be non-operational for 3% of the time. Wind conditions usually are such that most wind turbines operate only 60% of the time; therefore, scheduled maintenance will not require shutting down.

The expected operational life of a wind turbine is 30 yr.

6 COST CONSIDERATIONS

To estimate costs, horizontal-axis wind turbines are categorized into two groups: one ranges in size from 1 kW to 30 kW; the other from 100 kW to 10 MW. Because the wind turbines in each group are entirely different in design concepts, each group has different costs. Wind turbines between 30 and 100 kW have characteristics of both groups and thus cannot be specifically categorized.

The capital costs, in terms of $/kW, include the cost for the manufacturing of the wind turbine components, transportation to the site, preparation of the site, and the assembly and erection of the wind turbine system. Land costs are not included.

It is estimated that a crew of 50 men would be required to erect a horizontal-axis wind turbine. One crew could erect 10.5 wind turbines per year.

Equation DS-8 gives the capital costs of a *small* horizontal-axis wind turbine as a function of rated capacity and rated wind speed; Eq. DS-9 gives the capital costs of a *large* horizontal-axis wind turbine as a function of rated capacity and rated wind speed. Costs are given in 1975 dollars.

Cost of a small horizontal-axis wind turbine as a function of rated capacity can be calculated as follows:

$$W = B_1 + B_2X + B_3X^2 + B_4X^3 + B_5X^4 + B_6Y + B_7Y^2 + B_8Y^3 + B_9Y^4 \quad \text{(Eq. DS-8)}$$

where:

W = Capital Cost of a small horizontal-axis wind turbine ($/kW)

X = Rated Capacity (kW)

Y = Rated Wind Speed (m/s)

$B_1 = .605775 \times 10^3$	$B_6 = .199046 \times 10^4$
$B_2 = -.77470 \times 10^3$	$B_7 = -.380795 \times 10^3$
$B_3 = .108528 \times 10^3$	$B_8 = .302233 \times 10^2$
$B_4 = -7.01642$	$B_9 = -.864540$
$B_5 = .165035$	

Standard Error: $.107341 \times 10^3$

$2 \leq X \leq 20$

$4 \leq Y \leq 12$

Cost of a large horizontal-axis wind turbine as a function of rated capacity can be calculated as follows:

$$W = B_1 + B_2/X + B_3/X^2 + B_4/Y + B_5/Y^2 \quad \text{(Eq. DS-9)}$$

where:

W = Capital Cost of a large horizontal-axis wind turbine ($/kW)

X = Rated Capacity (kW)

Y = Rated Wind Speed (m/s)

B_1 = $.317403 \times 10^3$ B_4 = $.231098 \times 10^6$

B_2 = $-.283282 \times 10^4$ B_5 = $-.714143 \times 10^7$

B_3 = $.299949 \times 10^5$

Standard Error: $.643768 \times 10^2$

$50 \leq X \leq 10{,}000$

$6 \leq Y \leq 12$

Capital costs *in 1977 dollars,* of a two blade vertical-axis wind turbine are given in Equation DS-10. This design has a rated wind speed of 10 m/s and a height-to-diameter ratio of 1.0. The capital costs of vertical-axis wind turbines are less than those of horizontal-axis wind turbines because tower construction is simpler, the generator is located on the ground, and no yaw mechanism is needed.

$$W = B_1 + B_2X + B_3X^2 + B_4X^3 + B_5X^4 \qquad \text{(Eq. DS-10)}$$

where:

W = Capital Cost of Vertical-Axis Wind Turbines, (\$/kW)

X = Rated Capacity (kW)

B_1 = -1.62333×10^3 B_4 = 0.231821

B_2 = 2.34459×10^2 B_5 = -1.60027×10^{-3}

B_3 = -11.4057

Standard Error: 0.0

$70 \leq X \leq 600$

Capital costs of wind turbines evaluated here are estimates based on assumed values of several parameters; they are sensitive to the values of these parameters; and they are liable to change. The parameters for which values had to be assumed included optimum wind turbine design, production level, the learning curve for production runs, and the costs of certain wind turbine components, particularly the blades.

The operating costs of wind turbines consist of insurance, maintenance, overhead, and other miscellaneous costs. Table DS-1 gives these costs, on an annual basis, as a percentage of the capital cost of the wind turbine.

Table DS-1 Operating Costs of Wind Turbines

Operating Item	%of Capital Cost
Insurance	0.2
Maintenance	2.0
Overhead	1.0
Other	0.4

The cost of energy will depend on the operating costs, the capital costs, the cost of money, depreciation, and taxes.

7 STATUS

Wind turbines can offer a reliable source of energy. Present technology can produce units that are capable of competing economically with conventional power sources.

The economics of wind turbines improve as the site mean wind speed increases, but the rate of improvement diminishes for wind speeds greater than 8 m/s. Thus, unique sites with exceptionally high wind speeds are not a requirement for wind turbine installations.

The energy cost of wind turbines is relatively insensitive to operation at off-design wind speeds, within a reasonable range. Therefore, it is likely that only a limited number of standard designs will be required for utility applications leading to the capability for routine factory production and the ensuing reduction in cost.

The largest uncertainty in wind turbine energy costs is the uncertainty in the capital costs of the first production units and the learning curve that should be applied to future units.

The economic characteristics of wind turbines may be improved by technical advances on the blade and hub assembly, but the likelihood of achieving such improvements and their effects is difficult to estimate.

Currently, both horizontal-axis and vertical-axis wind turbines are in the developmental stages. Several demonstration units have been, or are being built to obtain performance data and to confirm the reliability and stability of large units.

Studies are needed to determine the optimum locations for wind turbine installations. Currently available wind data are insufficient for successful implementation of a large-scale wind energy program.

TECHNOLOGY EVALUATION OF

WIND TURBINES

Prepared by John C. Yeoman, Jr., ORNL

Date December, 1978

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The purpose of this technology evaluation is to provide information on the performance characteristics, costs, and other factors relevant to the commercialization of wind turbines. The evaluation divides wind turbines into two groups: horizontal-axis and vertical-axis. The rated capacity of the horizontal-axis wind turbine evaluated here ranges from 200 to 20,000 W for currently available models and from 10 kW to 10 MW for models that will be available soon. The rated capacity of the vertical-axis wind turbines evaluated here ranges from 70 to 700 kW. These will be available in the near future. The performance and cost data are in terms of kilowatts of electricity, rather than shaft horsepower because this is the accepted practice in the literature.

1.2 ORIGIN OF WIND

Wind, a form of solar energy, is caused primarily by unequal heating of the earth's surface by the sun. Air above bodies of water remains relatively cool during the day, while air over land is heated. The heated air over the land becomes less dense and rises. The heavier, cooler air over the water flows in to replace it, creating local breezes.[1]

At night the process reverses. Air over land cools more rapidly than air over water. The cool land air moves to replace the rising, warmer air over water.

Circulating planetary winds are caused by the greater heating of the earth's surface near the equator than near the poles. This causes cold surface winds to blow from the poles to the equator to replace the hot air that rises in the tropics and moves in the upper atmosphere towards the poles.

The rotation of the earth also affects the planetary winds. Inertia in the cold air moving near the surface toward the equator tends to twist it to the west, while the warm air moving in the upper atmosphere towards the poles tends to be turned towards the east. This causes large counter-clockwise circulation of the air around low pressure areas in the northern hemisphere and clockwise circulation in the southern hemisphere.

Because the earth's axis of rotation is inclined at an angle of 23.5° to the plane in which it moves around the sun, seasonal variations in the heat received from the sun result in seasonal changes in the strength and direction of the wind.

The manner in which the wind speed varies with height is important. A well established formula relating wind speeds at two levels, 1 and 2, is shown in Eq. 1.1:

$$V_1/V_2 = (h_1/h_2)^{\alpha} \qquad \text{(Eq. 1.1)}$$

where:

V_1 and V_2 are the wind speeds at levels h_1 and h_2, and

α = the wind profile exponent dependent on atmospheric stability and nature of the terrain upwind of the wind turbine.

Some typical values of α are:

0.16 for flat, open country,
0.28 for rough, wooded country, and
0.40 for urban areas.

The wind profile exponent is an important cost parameter because the blade hub is at least 50 meters above the ground. Wind energy must be integrated vertically over the blade disc to obtain an accurate projection of the wind turbine energy extraction.[2]

1.3 TYPES OF WIND TURBINES

Wind turbines are divided into two categories: (1) horizontal-axis for which the axis of rotation is parallel to the direction of the windstream, and (2) vertical-axis for which the axis of rotation is perpendicular to both the surface of the earth and the direction of the windstream. Each category is discussed below.

1.3.1 Horizontal-Axis Wind Turbines

Horizontal-axis wind turbines can be either lift or drag devices. Lift devices are preferred, because they can generate more force than can drag devices. Moreover, a drag device cannot move faster than the wind speed. Consequently, lift devices can obtain higher tip-to-wind speed ratios and thus, a higher power output-to-weight ratio and subsequently a lower cost-to-power-output ratio. Systems can be designed with different numbers of blades, ranging from one-bladed devices with a counterweight, to devices with 50 or more blades. Some horizontal-axis wind turbines are designed to be yaw-fixed, that is, they cannot be rotated around the vertical axis perpendicular to the windstream. Generally, this type would be used where the prevailing winds blow from one direction. Most types are yaw-active and will rotate so as to always face the wind.

Horizontal-axis wind turbines may be designed with either upwind or downwind rotors, depending on whether the blades rotate on the upwind or downwind side of the supporting tower.[1] Figure 1.1 shows a two-blade, downwind, horizontal-axis, wind turbine with a rated capaciy of 100 kW.

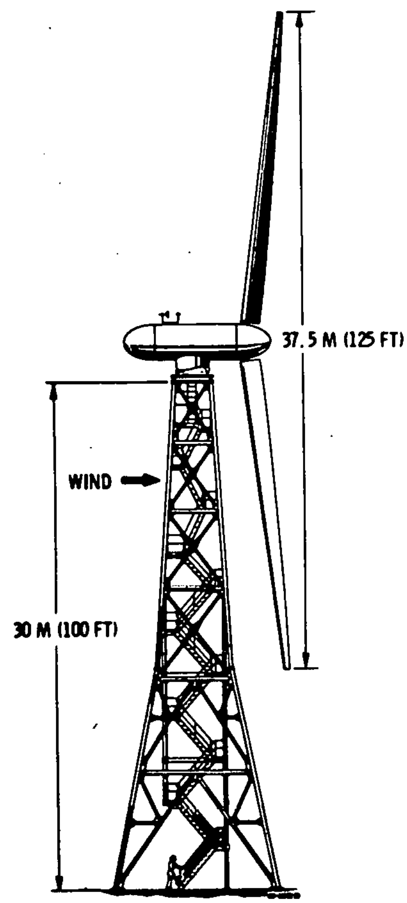


Fig. 1.1 Horizontal-Axis Wind Turbine with Rated Capacity of 100 kW

Figure 1.2 shows the internal mechanisms of a horizontal-axis wind turbine.[3]

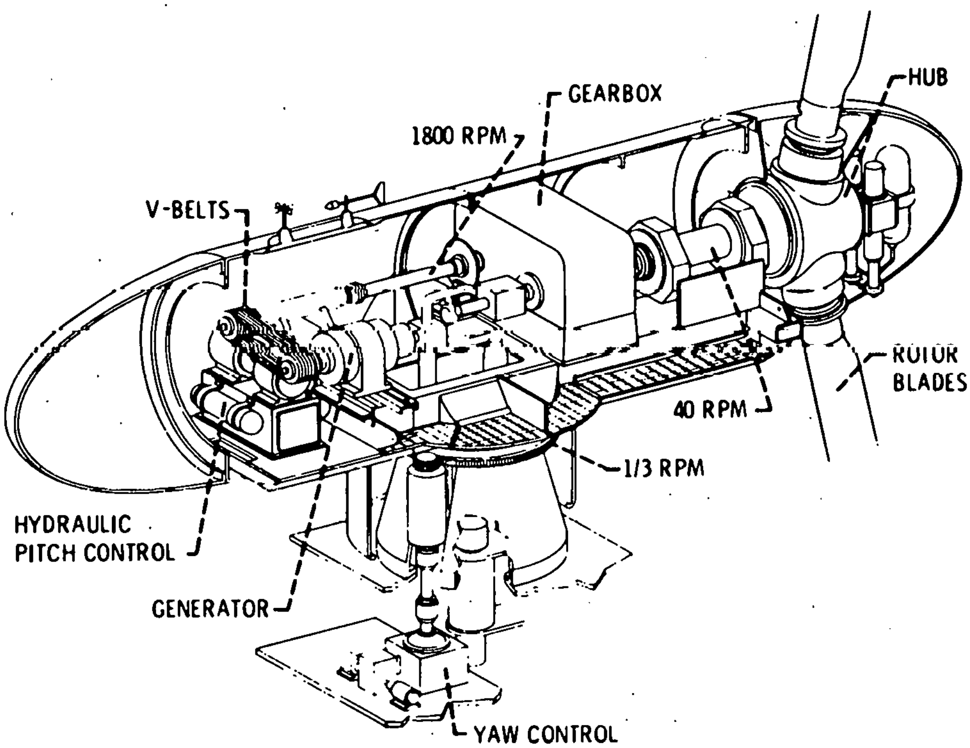


Fig. 1.2 Internal Mechanisms of Horizontal-Axis Wind Turbine[3]

1.3.2 Vertical-Axis Wind Turbines

Vertical-axis wind turbines also can be either lift or drag devices. Vertical-axis wind turbines have a major advantage over horizontal-axis wind turbines in that they do not have to be turned into the wind as the direction of the windstream changes. This reduces the design complexity of the system and eliminates gyro forces (due to blades yawing) that stress the blades, bearings, and other components in horizontal-axis systems.

The major vertical-axis wind turbine is the Darrieus system. Darrieus systems are lift devices, characterized by curved blades with airfoil cross-sections. Darrieus wind turbines can be designed with one, two, three, or more blades. One drawback of Darrieus systems is that they are not self-starting. Figure 1.3 shows three-bladed Darrieus system.[4]

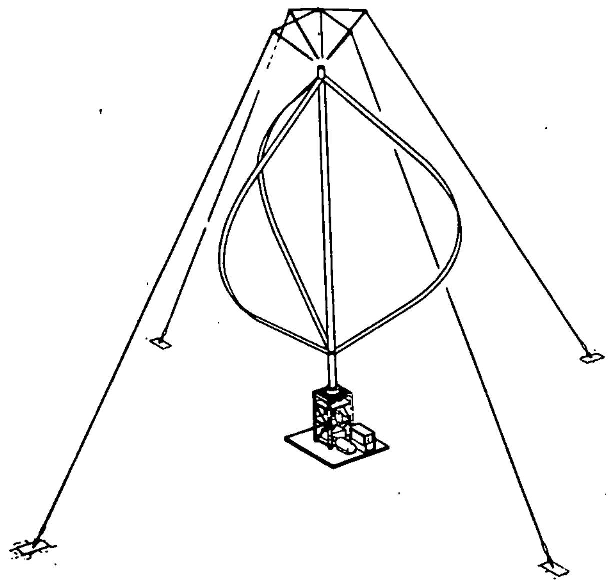


Fig.1.3 Vertical-Axis Wind Turbine

1.4 SELECTION CRITERIA

Selection criteria for wind turbines in the ICES program include:

(1) power generation potential,
(2) cost,
(3) reliability and maintenance,
(4) environmental effects, and
(5) material requirements.

The performance, materials, and cost data are presented graphically and, as an aid to computer simulation, each graph is modelled empirically by an equation. Modelling was done with a computerized, unconstrained, unweighted, non-linear least-squares method. The particular form of equation for each graph was determined by trying several equations and selecting the one that gave the best results. The equations should not be used with values of the independent variables outside the indicated ranges. Therefore, the proper equations for each graph are given with the graph.

Standard error is presented to give an estimate of the accuracy of the model in terms of its ability to characterize designs not included in the original data set. The definition of standard error used in this evaluation is:[5]

$$\text{Standard Error} = \frac{[\Sigma(W - \overline{W})^2]^{1/2}}{N} \qquad \text{(Eq. 1.2)}$$

where:

W = actual value of the dependent variable
$\overline{W}$ = calculated value of the dependent variable
N = degrees of freedom

2 STANDARD PRACTICE

2.1 STANDARD RATINGS

Individual wind turbines are charactrized by their rated capacity and rated wind speed. Rated capacity is defined as the full-load continuous power output. Rated wind speed is defined as that wind speed at which the wind turbine is designed to produce its rated capacity. Constant-speed operation is obtained by varying the pitch of the blades.

Because the power output of a wind turbine varies with air temperature and air density, the standard air temperature for the performance data is 25°C, and the standard air density corresponds to sea level air at 25°C.

2.2 MANUFACTURERS' DATA

Only horizontal-axis wind turbines are available at this time. Sizes range from 200 to 20,000 W. Table 2.1 gives various manufacturers and the specifications of their equipment.[6,7,8,9] All the wind turbines listed come in kit form, and the prices do not include the cost of transportation or installation. The prices are in 1977 dollars and include the cost of the tower.

Table 2.1 Manufacturers of Horizontal-Axis Wind Turbines and Specifications for Equipment

Manufacturers	Rated Capacity (W)	Rated Wind Speed (m/s)	Weight (kg)	Rotor Size (m)	Cost ($/kW)
Grumman	20,000	12.5	-	8.0	1,093
Kedco	1,200	9.4	91.6	3.6	1,912
	1,200	7.1	98.4	4.9	2,412
	2,000	11.2	114.3	3.6	1,297
	2,000	9.4	121.1	4.9	1,597
Sencenbaugh	500	11.1	110.2	1.8	4,400
	1,000	10.0	136.1	3.6	2,650
Winco	200	10.3	60.8	1.8	2,625

3.1 HORIZONTAL-AXIS MATERIALS INPUTS

Horizontal-axis wind turbines require fabrication materials as primary material inputs. The availability of basic raw stock such as steel, aluminum, concrete, and copper wire is critical for the development of wind turbines. Figures 3.2 through 3.5, respectively, show the amount of steel, aluminum, concrete, and copper wire estimated to be needed for construction of horizontal-axis wind turbines of various rated capacities and rated wind speeds.[10] Figure 3.1 shows the total weight of horizontal-axis wind turbines of various rated capacities and rated wind speeds. The data in Fig. 3.1 were obtained by summing the data in Figs. 3.2 through 3.5.

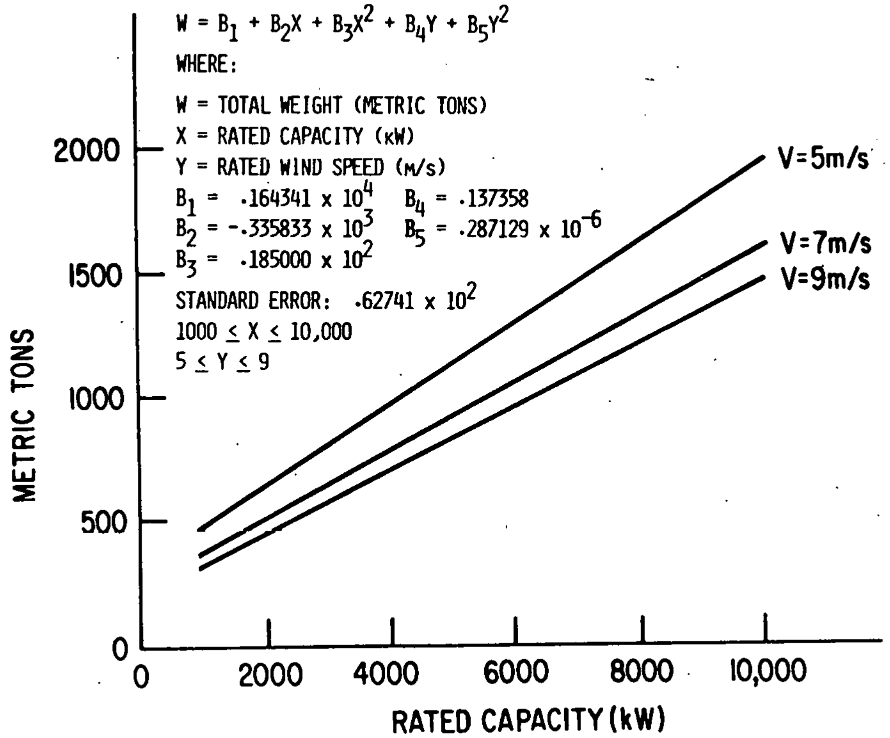


Fig. 3.1 Total Weight of Horizontal-Axis Turbines

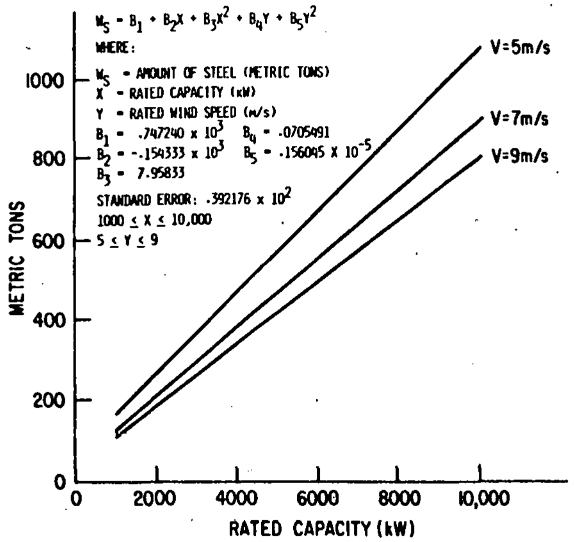


Fig. 3.2 Steel Requirements of Horizontal-Axis Turbines

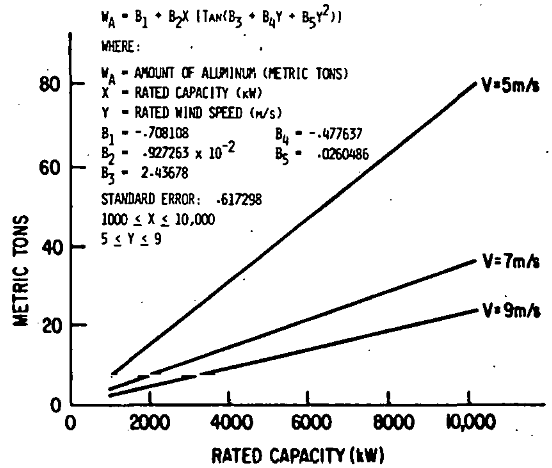


Fig. 3.3 Aluminum Requirements of Horizontal-Axis Turbines

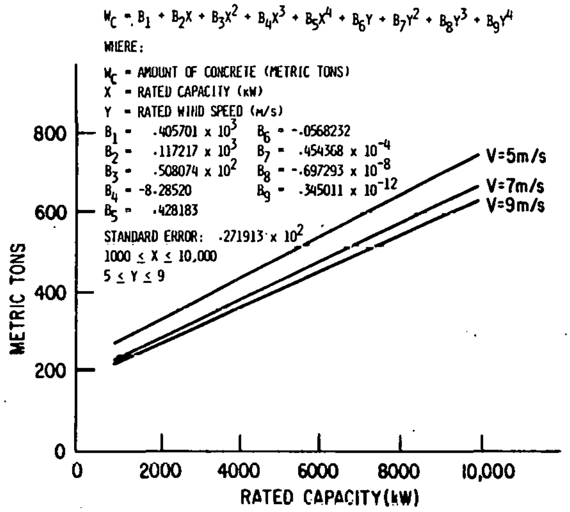


Fig. 3.4 Concrete Requirements of Horizontal-Axis Turbines

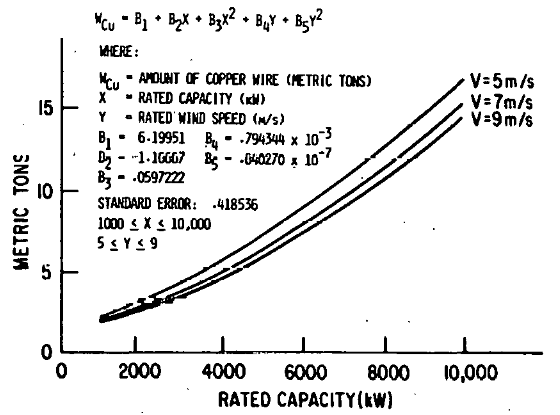


Fig. 3.5 Copper Wire Requirements of Horizontal-Axis Turbines

3.2 VERTICAL-AXIS MATERIALS INPUTS

Vertical-axis wind turbines also require fabrication materials as primary material inputs. Although the material requirements of vertical-axis wind turbines have not been analyzed as extensively as those of horizontal-axis wind turbines, several conclusions can be reached from characteristics of each type:

(1) Vertical-axis wind turbines will require about 30% less copper wire than horizontal-axis wind turbines of the same size.[10] This is because vertical-axis wind turbines do not need any yaw control.

(2) Vertical-axis wind turbines will require less steel because of simpler tower construction.

(3) Less concrete will be required because vertical-axis wind turbines will weigh less and thus require smaller foundations.

(4) The amount of aluminum required will be about the same, because aluminum is used only in the blades in both systems.

3.3 WIND TURBINE LAND REQUIREMENTS

The distance between wind turbines affects their efficiency. Figure 3.6 shows the unit efficiency as a function of separation distance and the number of units in tandem.[11]

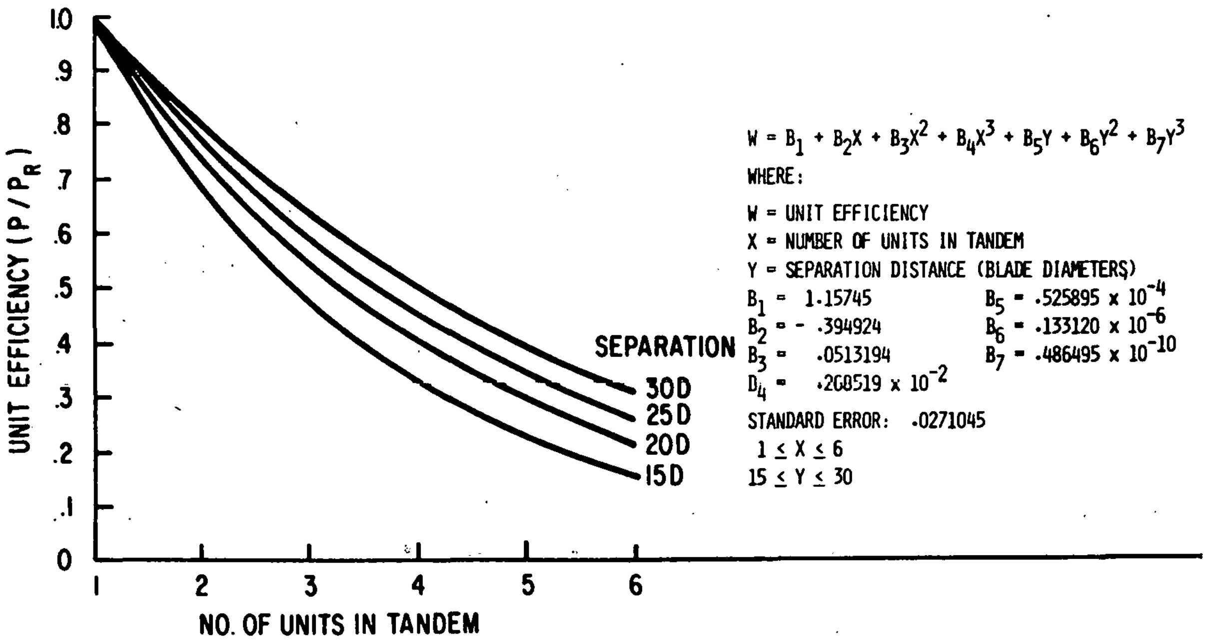


Fig. 3.6 Effect of Separation Distance and Number of Units on Individual Turbine Efficiency

Unit efficiency, P/P_R, is defined to be the power generated by a wind turbine (in a line of wind turbines) divided by the power that would have been generated had the wind turbine stood alone. The number of units in tandem is the number of wind turbines aligned along the direction of wind. For example, if five wind turbines, spaced 20 blade diameters apart, are in tandem, along the direction of the wind, the unit efficiency of the third unit is 0.59. In other words, the effect of the first and second units on the performance of the third unit is such that the third unit will produce 59% of the power it would have produced had it stood alone. Figure 3.7 shows group efficiency as a function of separation distance and the number of units in tandem.[11] Group efficiency is defined as the sum of the unit efficiencies of the units in a group divided by the number of units in the group.

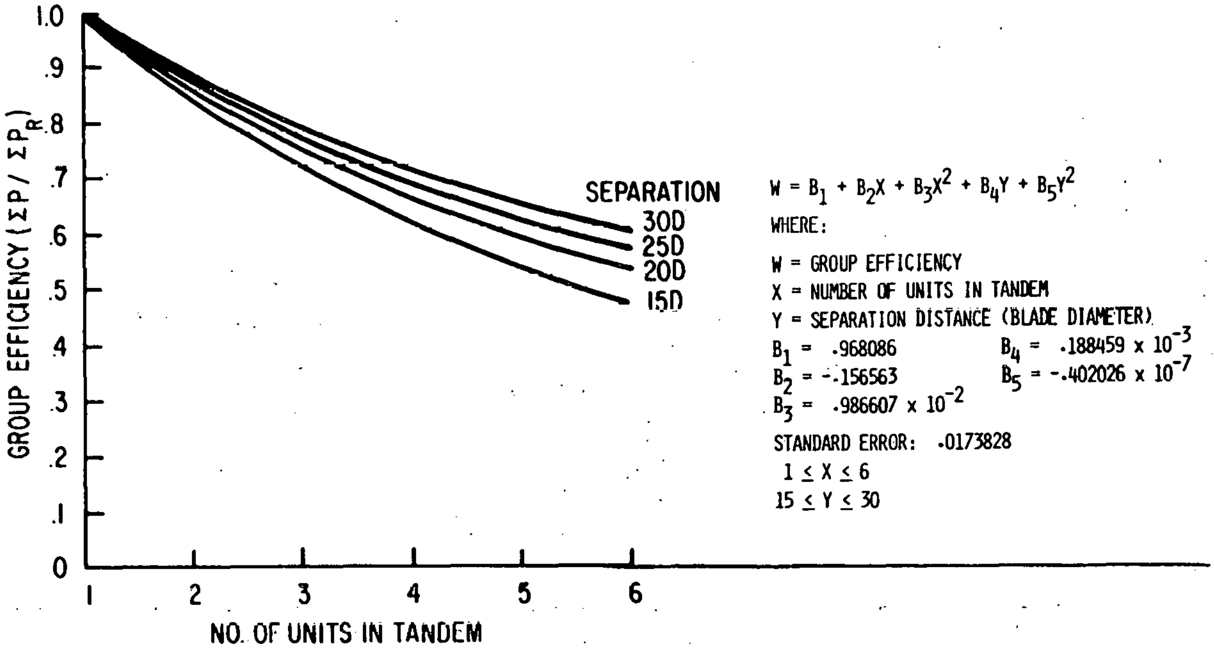


Fig. 3.7 Effect of Separation Distance and Number of Units on Group Efficiency

Figures 3.6 and 3.7 show that minimizing the number of units aligned in any one direction is much more important than the separation distance.[11]

When wind turbines are grouped together, certain configurations minimize the amount of land required for the installation. The land-use factors of a configuration is a measure of the effectiveness of land use of an installation. The land-use density is defined as the total rated capacity of an installation divided by the land area it occupies. Figure 3.8 gives the land-use factors for multi-turbine installations.[11] The higher the land-use factor, the higher the land-use density. In each case, the configuration shown is optimum for that number of wind turbines. The land-use factors apply only to identical horizontal-axis or vertical axis wind turbines. In each case the minimum separation between turbines is 15 blade diameters. For example, with three units, each with an output of 1500 kW, blade diameters of 60 m, and a separation between turbines of 15 blade diameters, one would multiply the land-use factor, 6, by the ouput of one unit, 1500 kW and divide by the separation distance squared 810,000 m^2 ($60^2 \times 15^2$) to get a land-use density of 11,000 kW/km^2.

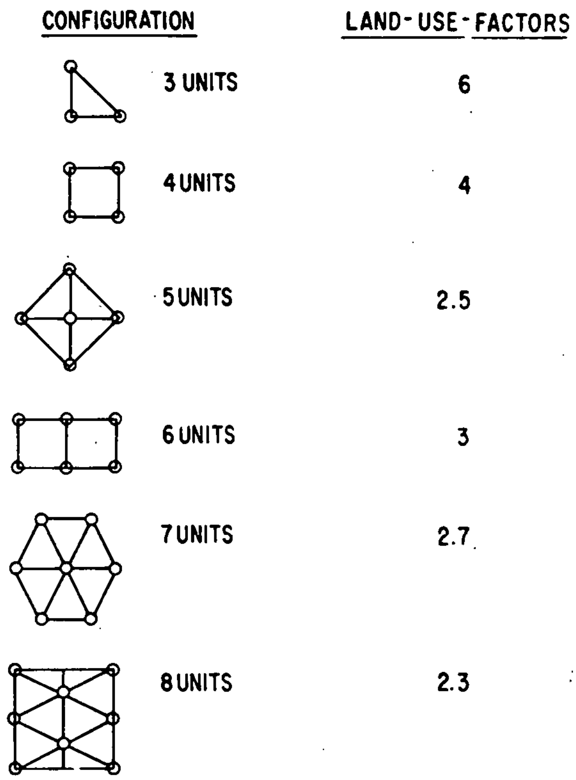


Fig. 3.8 Land-Use Factors for Multi-Turbine Installations with at Least 15 Blade Diameters between Turbines

4.1 PRIMARY ENERGY INPUTS

The total power available from the wind passing through a unit area normal to the wind is given in Eq. 4.1.[12]

$$P = 1/2\rho V^3 A \qquad \text{(Eq. 4.1)}$$

where:

- P is the power in W
- ρ is the atmospheric density in kg/m^3; and
- V is the wind speed in m/sec.
- A is the windstream area in m^2.

Because wind power is proportional to the cube of the wind speed, small increases in wind speed result in significant increases in wind power. Changes in the density of the atmosphere also affect the amount of wind power. Figure 4.1 shows the power available in one square meter of windstream vs wind-speed.[11] Figure 4.2 shows the effects of elevation on wind power,[12] and Fig. 4.3 shows the effects of temperature on wind power.[12]

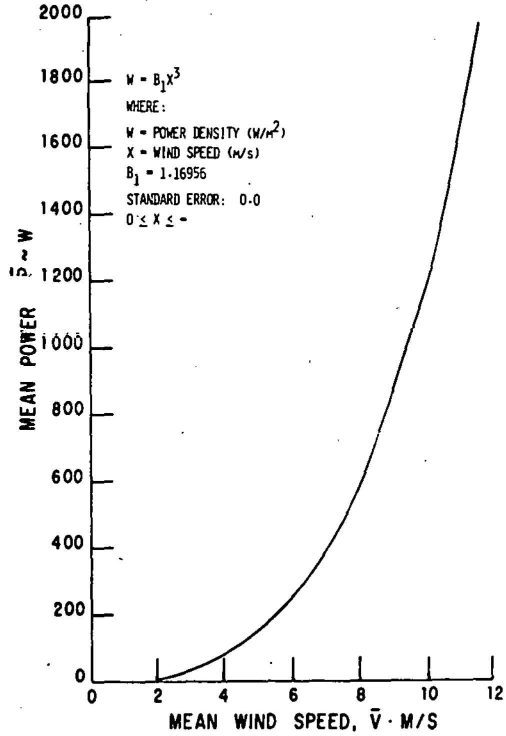


Fig. 4.1 Windstream Power Vs Wind Speed

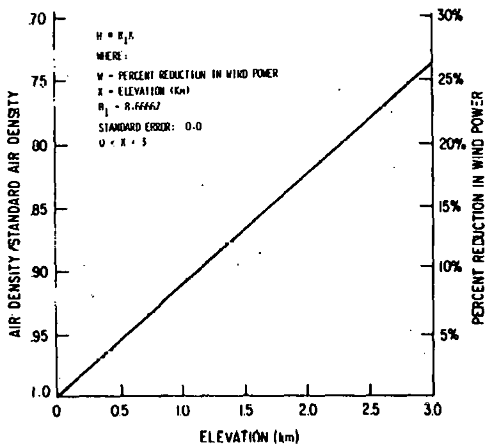


Fig. 4.2 Effect of Elevation in Windstream Power at Constant Wind Speed

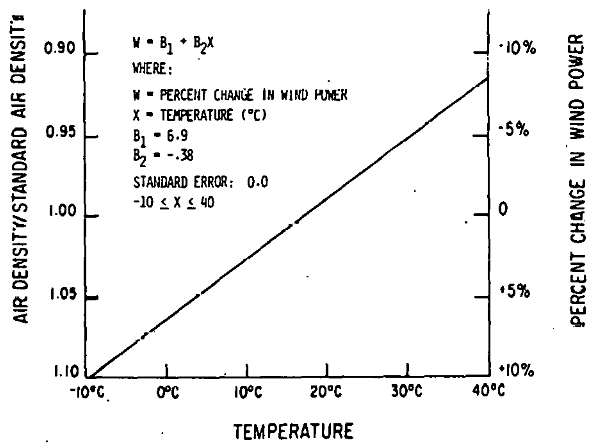


Fig. 4.3 Effect of Temperature on Windstream Power at Constant Wind Speed

The amount of power delivered by a wind turbine, divided by the total power available in the windstream, is defined as the efficiency or power coefficient, Cp, of the wind turbine. From fluids theory, it can be shown that Cp is limited to a value of 0.593.[1] Figure 4.4 shows the power coefficient of various wind turbines versus the ratio of the blade tip speed to wind speed.[1] The values were determined experimentally.

A. $C_P = B_1 + B_2X + B_3X^2$

WHERE:

- C_P = IDEAL POWER COEFFICIENT
- X = TIP-TO-WIND SPEED RATIO
- B_1 = .278242
- B_2 = .143804
- B_3 = -.0162704

STANDARD ERROR: .0163397

$0 \leq X \leq 7$

B. $C_P = B_1 + B_2X + B_3X^2$

WHERE:

- C_P = TWO BLADE POWER COEFFICIENT
- X = TIP-TO-WIND SPEED RATIO
- B_1 = -.377463
- B_2 = .319277
- B_3 = -.319277

STANDARD ERROR: $.519951 \times 10^{-2}$

$3.7 \leq X \leq 6.8$

C. $C_P = B_1 + B_2X + B_3X^2$

WHERE:

- C_P = DARRIEUS ROTOR POWER COEFFICIENT
- X = TIP-TO-WIND SPEED RATIO
- B_1 = -2.48503
- B_2 = .970120
- B_3 = - .0825923

STANDARD ERROR: $.677752 \times 10^{-2}$

$4.6 \leq X \leq 6.8$

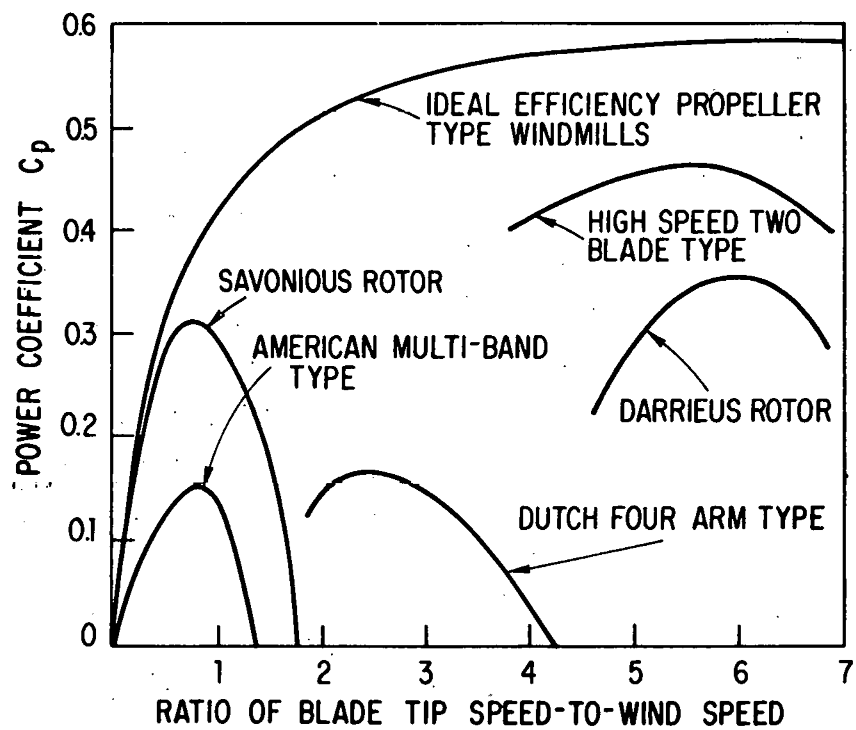
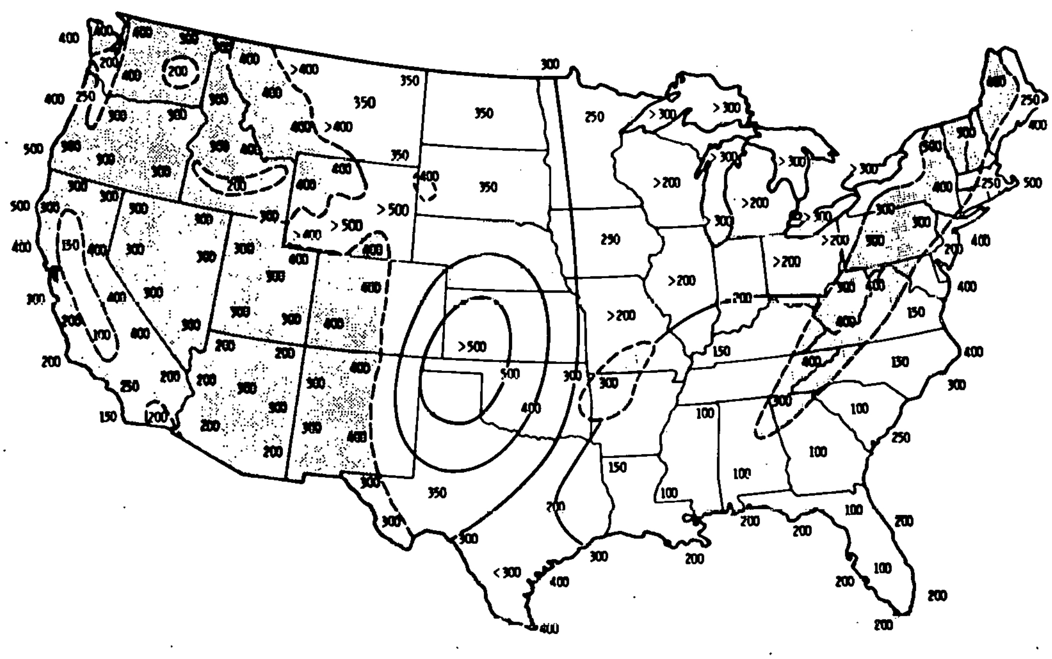


Fig. 4.4 Power Coefficients of Various Wind Turbines

Because individual wind turbines must turn at a constant speed, the blade tip speed must be constant. Thus, as the wind speed changes, the blade-tip-speed-to-wind speed ratio also will change. Wind turbines are designed so that the blade-tip-speed-to-wind speed ratio maximizes the power coefficient. This is done by gearing the drive mechanism so that the optimum blade tip speed produces the proper generator speed. The power coefficient of a wind turbine is a function only of the blade-tip-speed-to-wind-speed ratio and the blade design.

4.2 WIND TURBINE SITING

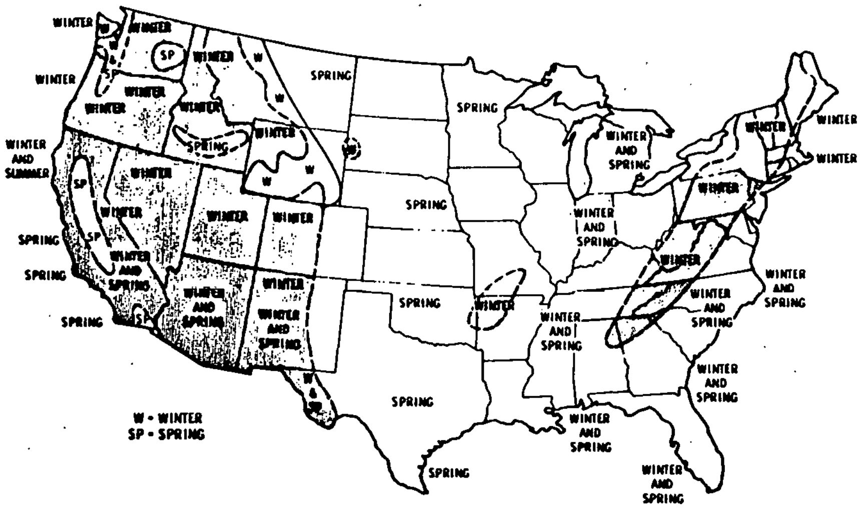
The peak and annual power generation of wind turbines is highly dependent on site-specific characteristics of wind. Figure 4.5 shows the mean annual wind power across the United States.[12]



Mean Annual Wind Power (W/m^2) Estimated at 50 m Above Exposed Areas. Over mountainous regions (shaded areas), the estimates are lower limits expected for exposed mountain tops and ridges.

Fig. 4.5 Mean Annual Wind Power

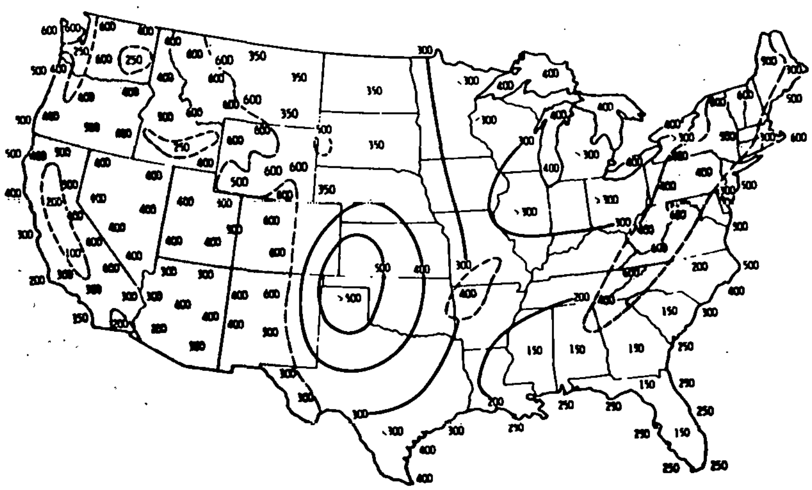
Figure 4.6 shows the seasons of maximum wind power across the United States.[12]



Season(s) of Maximum Wind Power. Over mountainous regions (shaded areas), the season(s) indicated is for exposed mountain sites. Seasons are abbreviated, where necessary, as follows: W = winter, SP = spring.

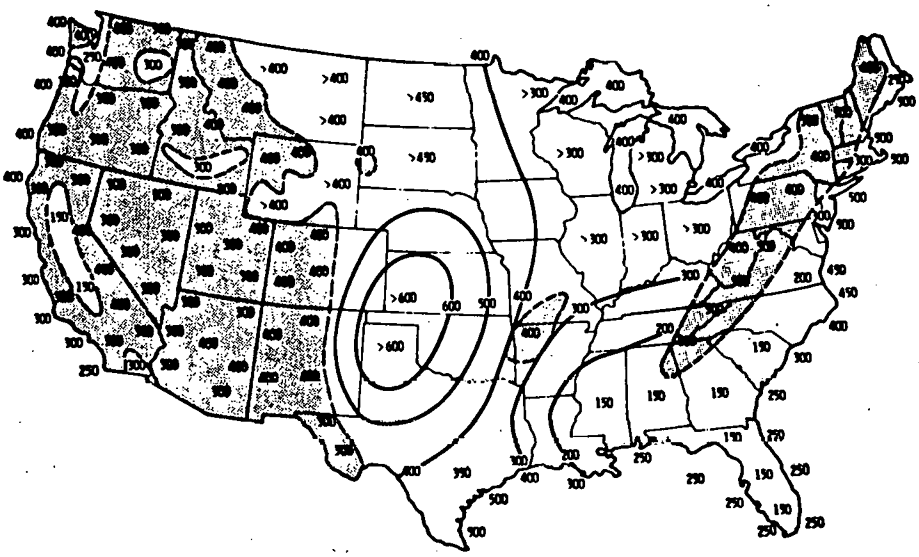
Fig. 4.6 Season of Maximum Wind Power

Figures 4.7 through 4.10 show the wind power available across the United States on a seasonal basis.[12]



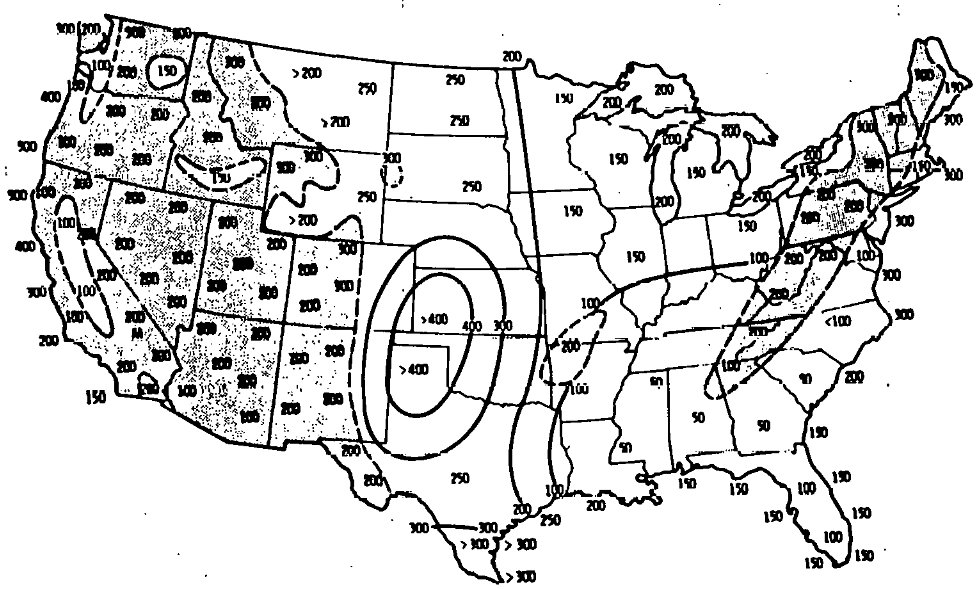
Winter - Average Wind Power (W/m^2) Estimated at 50 m Above Exposed Areas. Over mountainous regions (shaded areas), the estimates are lower limits expected for exposed mountain tops and ridges.

Fig. 4.7 Winter-Average Wind Power



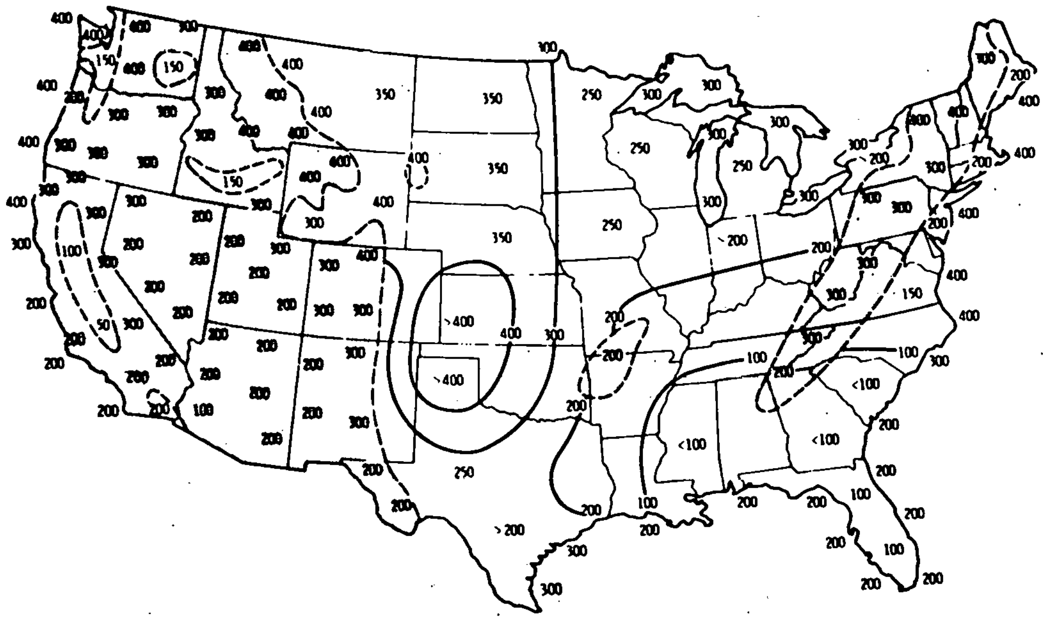
Spring - Average Wind Power (W/m^2) Estimated at 50 m Above Exposed Areas. Over mountainous regions (shaded areas), the estimates are lower limits expected for exposed mountain tops and ridges.

Fig. 4.8 Spring Average Wind Power



Summer - Average Wind Power (W/m^2) Estimated at 50 m Above Exposed Areas. Over mountainous regions (shaded areas), the estimates are lower limits expected for exposed mountain tops and ridges.

Fig. 4.9 Summer Average Wind Power



Fall - Average Wind Power (W/m^2) Estimated at 50 m Above the Exposed Areas. Over mountainous regions (shaded areas), the estimates are lower limits expected for exposed tops and ridges.

Fig. 4.10 Fall Average Wind Power

These figures show that the maximum wind power is available in New England, the Plains, and the Pacific Northwest. They also show that wind power is at its maximum in the winter and spring.

For maximum power generation, wind turbines should be located on flat ground with little or no surface vegetation. Wind turbine efficiency decreases as the terrain becomes hilly and vegetation increases. Care should be taken to locate wind turbines sufficiently far from buildings so that they do not encounter backflow caused by the separation of the boundary layer passing over the building.

Available wind power is a function also of the time of day. Wind power in the United States generally reaches a maximum somewhere between noon and 2:00 p.m. local standard time (LST). Wind power is at its minimum between midnight and 6:00 a.m. LST.[11] However, These are only general results. Wind power is very site-specific; so before any large wind turbines are built, much more detailed study will be necessary.

5 ENVIRONMENTAL EFFECTS

5.1 THERMAL DISCHARGE

Wind turbines do not discharge significant amounts of heat to the environment.

5.2 NOISE ATTENUATION

Noise is not a problem with wind turbines. Gear and generator noise is masked by proper enclosures, and means are available to make improvements, if necessary.[10]

5.3 AESTHETICS

Wind turbines are relatively large and highly visible. The largest horizontal-axis wind turbines will have towers over 65 meters high and blades of more than 120 meters in diameter. Ideally, wind turbines will be located in open flat areas which increase their visibility. If upwind rotors are installed, a wide choice of tower designs will be available to minimize aesthetic impact.[2]

5.4 CLIMATIC INFLUENCE

Wind turbines will represent such a small perturbation of the atmospheric energy balance as not to be a consideration in climatic changes.[10] However, the downstream wake of a wind turbine may have an adverse effect on stack gases and other pollution sources.

5.5 COMMUNICATIONS INTERFERENCE

The rotating blades of a wind turbine can interfere with television reception by producing video distortions; however, there is no audio distortion.[2] Television interference is caused by the Doppler Effect when transmissions are bounced off the moving blades. Interference increases with increasing frequency and is therefore worse on the upper UHF channels. Interference decreases as distance from the turbine to the receiver increases, but may be significant up to a few miles.[19] The interference is site-specific, being dependent on the location of the transmitter, receiving antenna, and the wind turbine.

6.1 OPERATING RANGES

A typical wind turbine performance curve is shown in Fig. 6.1(a). At a cut-in wind speed, A, the wind turbine begins to produce power and monotonically produces more power as the wind speed increases until it reaches the rated wind speed, B. Above this wind speed, the wind turbine's power output is constant until the wind turbine's cut-out wind speed, C, is reached. At wind speeds greater than the cut-out speed, the wind turbine does not produce power.

A typical wind speed frequency distribution is shown in Figure 6.1(b). Only a small percentage of time is spent at either the extremely low or high ends of the distribution. The convolution of the curves in Fig. 6.1(a) and 6.1(b) Tp(v) x p(v), yields the power frequency distribution of the wind turbine's output as a function of the wind speed, Fig. 6.1(c). The integral of the curve in Fig. 6.1(c) yields the average expected power output of the wind turbine.

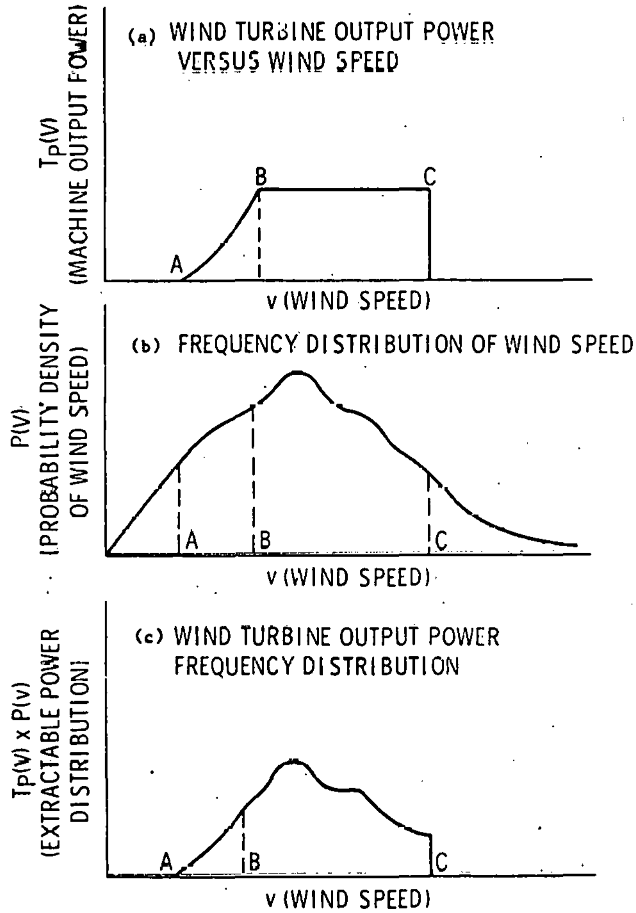


Fig. 6.1 Interaction of Wind Turbine Characteristics and Wind Statistics to Produce the Wind Turbine Power Frequency Distribution

The frequency distribution of the wind speed, Fig. 6.1(b) is seldom known. Usually only the annual mean wind speed is known for a particular location. The wind speed frequency distribution can be approximated by the Rayleigh distribution. Only the annual mean wind speed need be known to make the Rayleigh distribution approximation. Equation 6.1 gives the Rayleigh distribution of the wind speed frequency.

$$P(v) = \frac{v\pi}{2\bar{v}^2}\, e^{-\left(\frac{v^2\pi}{4\bar{v}^2}\right)} \qquad \text{(Eq. 6.1)}$$

where:

- $P(v)$ is the frequency distribution of the wind speed;
- v is the wind speed; and
- $\bar{v}$ is the annual mean wind speed.

The Rayleigh distribution is accurate when the annual mean wind speed exceeds 4.5 m/s.

Table 6.1 lists the values of $\bar{v}\,P(v)$ vs $v/\bar{v}$. This is the normalized Rayleigh distribution. As an example of how to use the normalized Rayleigh

Table 6.1 Values of Normalized Rayleigh Distribution

Rayleigh Distribution

$$P(v) = \frac{\pi}{2}\,\frac{v}{\bar{v}^2}\quad 2 \times P \left(\frac{-v^2\pi}{4\bar{v}^2}\right)$$

$\frac{v}{\bar{v}}$	$\bar{v}P(v)$	$\frac{v}{\bar{v}}$	$\bar{v}P(v)$	$\frac{v}{\bar{v}}$	$\bar{v}P(v)$	$\frac{v}{\bar{v}}$	$\bar{v}P(v)$
0.0	0.000	1.1	0.6680	2.1	0.1033	3.1	0.0026
0.1	0.1559	1.2	0.6083	2.2	0.0772	3.2	0.0016
0.2	0.3044	1.3	0.5415	2.3	0.0567	3.3	0.0010
0.3	0.4391	1.4	0.4717	2.4	0.0409	3.4	0.00061
0.4	0.5541	1.5	0.4025	2.5	0.0290	3.5	0.00036
0.5	0.6454	1.6	0.3365	2.6	0.0202	3.6	0.00021
0.6	0.7104	1.7	0.2759	2.7	0.0138	3.7	0.00012
0.7	0.7483	1.8	0.2219	2.8	0.0093	3.8	0.00007
0.8	0.7602	1.9	0.1752	2.9	0.0062	3.9	0.00004
0.9	0.7483	2.0	0.1358	3.0	0.0040	4.0	0.00002
1.0	0.7162						

distribution, assume that a given location has an annual mean wind speed, $\bar{v}$, of 10 m/s, and it is desired to know what percent of the time the wind speed, v, at this location will be 20 m/s. In this case, $v/\bar{v}$ equals 20/10 equals 2, so from Table 6.1 the normalized Rayleigh distribution, $\bar{v}P(v)$, is 0.1358 or, because $\bar{v}$ = 10, P(v) = 0.01358. The wind speed will be 20 m/s (19.5 to 20.5) 1.358% of the time.

The percentage of time that the wind speed is below the wind turbine's cut-in speed plus the percentage of time the wind speed is above the cut-out speed is called the percent down time. The percent down time can be estimated using Eq. 6.2, derived from the Rayleigh distribution.

$$\text{Percent down time} = 1 - e^{-a^2/2\sigma^2} + e^{-c^2/2\sigma^2} \qquad \text{(Eq. 6.2)}$$

where:

a = cut-in wind speed

c = cut-out wind speed

$\sigma^2 = 2\bar{v}^2/\pi$

Figure 6.2 presents a graphical representation of Eq. 6.2, giving the percent down time as a function of the ratios of cut-in wind speed to

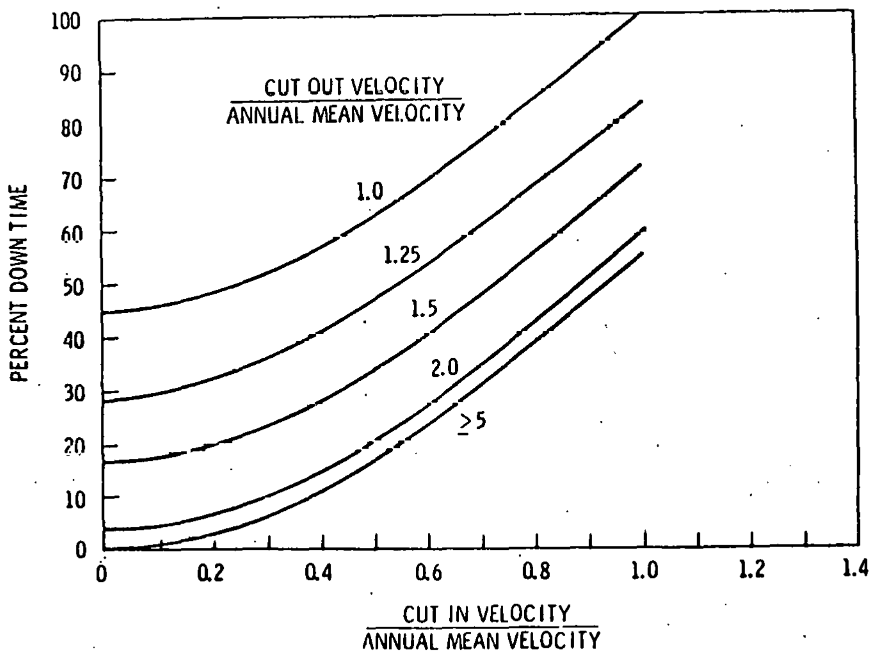


Fig. 6.2 Percent Down Time

mean wind speed and cut-out wind speed to mean wind speed. For a wind turbine with a given cut-in wind speed, a, and cut-out wind speed, c, the annual mean wind speed, $\bar{v}$, that will result in the minimum down time is given by Eq. 6.3.

$$\bar{v}_{\text{min down time}} = \left[\frac{\pi}{4}\,\frac{(c^2 - a^2)}{(\ln c^2 - \ln a^2)}\right]^{1/2} \qquad \text{(Eq. 6.3)}$$

Substitution of Eq. 6.3 into Eq. 6.2 yields Eq. 6.4, a formula for estimating the minimum percent down time for a wind turbine with a given cut-in wind speed, a, and cut-out wind speed, c.

$$\text{Minimum percent down time} = 1 - e^{-\frac{a^2(\ln c^2 - \ln a^2)}{c^2 - a^2}} + e^{-\frac{c^2(\ln c^2 - \ln a^2)}{c^2 - a^2}} \qquad \text{(Eq. 6.4)}$$

The percentage of time a wind turbine operates at its rated output is the percentage of time the wind speed is between the rated wind speed and the cut-out wind speed. Equation 6.5 estimates the percentage of time a wind turbine will operate at its rated output.

$$\%\ \text{time running at rated output} = e^{-b^2/2\sigma^2} - e^{-c^2/2\sigma^2} \qquad \text{(Eq. 6.5)}$$

where:

b = rated wind speed,
c = cut-out wind speed, and
$\sigma^2 = 2\,\bar{v}^2/\pi$.

Figure 6.3 graphically represents Eq. 6.5.

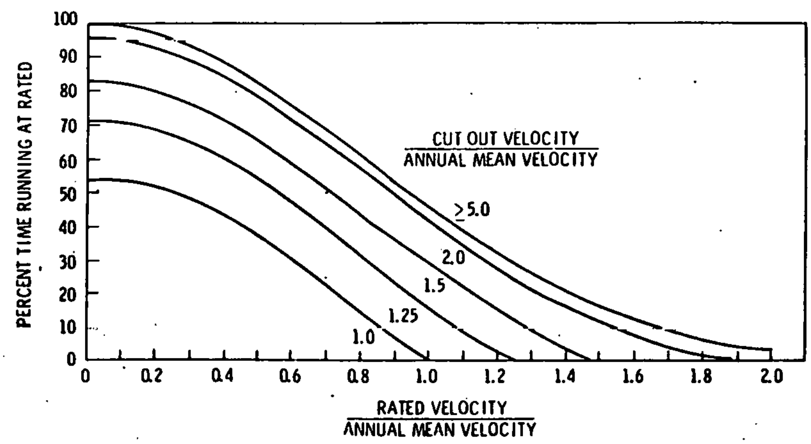


Fig. 6.3 Percent Time Running at Rated Velocity

6.2 OPERATING PROCEDURES

Wind turbines have control circuitry to provide fully automatic operation and to protect the system. Human intervention is needed only for periodic inspection, maintenance, and repairs.[14]

The starting sequence initiates after three verifications have been made. The first, adequtae wind, is satisfied by the average wind speed being above a fixed value for about 2 min. The other two verifications are checks of the network and turbine conditions. Vertical-axis wind turbines are brought up to speed by induction motors.[14] Horizontal-axis wind turbines are self-starting; the pitch control allows the blades to start if the wind speed is sufficient.

Two stopping modes are designated. An emergency stop is initiated by mechanical or electrical sensors indicating trouble, such as a loss of line voltage or excessive vibration.[13] Vertical-axis wind turbines use spoilers for emergency stops. The setting on the spoilers is such that they will automatically deploy at a few rpm above the normal operating speed.[4] Horizontal-axis wind turbines use a brake, placed close to the blades to minimize gearbox torque for emergency stops.[15] A normal stop occurs when the wind speed drops below the "cut-in" speed or exceeds the maximum design speed.

Horizontal-axis wind turbines require pitch and yaw controls. The blade rpm and power output, under varying wind conditions, can be regulated by varying the pitch angle of the blades around their longitudinal axis.[15] Yaw control is necessary to maintain the orientation of the blade plane perpendicular to the wind direction. Yaw control is accomplished by a hydraulic motor driving through a gear train. The gearbox is designed so that the turntable will be held rigidly against the wind load. The speed of the motor is limited to 1/3 rpm. This is required to limit gyroscopic forces. Yaw control is intended only to trim the system to the average wind direction, not to follow sudden wind direction changes.[15]

7 MAINTENANCE AND RELIABILITY

7.1 MAINTENANCE

Wind turbines require no special maintenance procedures. Typical maintenance requirements are lubrication and replacement of parts subject to wear. Maintenance will require that the wind turbine be unoperational for 3% of the time. Wind conditions are such that most wind turbines will operate only 60% of the time, so scheduled maintenance will not require shutting down.[10]

7.2 RELIABILITY

It is estimated that wind turbines will be operational 98% of the time that wind conditions are sufficient.[10]

7.3 EXPECTED LIFE

The expected operational life of either a horizontal-axis or vertical-axis wind turbine is 30 years.[2,16]

8.1 CAPITAL COSTS -- HORIZONTAL-AXIS WIND TURBINES

The capital costs, in terms of \$/kW, include the cost of manufacturing the wind turbine components, transportation to the site, preparation of the site, and the assembly and erection of the wind turbine system. Land costs and costs for connecting with the user are not included as part of the capital costs.[10] All costs are in 1975 dollars.

Horizontal-axis wind turbines are categorized by size into two groups for estimating capital costs. One group ranges in size from 1 kW to 30 kW; the other from 100 kW to 10 MW. Sizes in between will have characteristics of both groups. Because wind turbines in each group are entirely different in design concepts, capital costs of each are based on different considerations. The capital costs shown are for production quantities of 10,000 units per year for each group.[10]

Figure 8.1 shows the capital cost and blade diameters of small horizontal-axis wind turbine systems as a function of rated capacity and rated wind speed.[10]

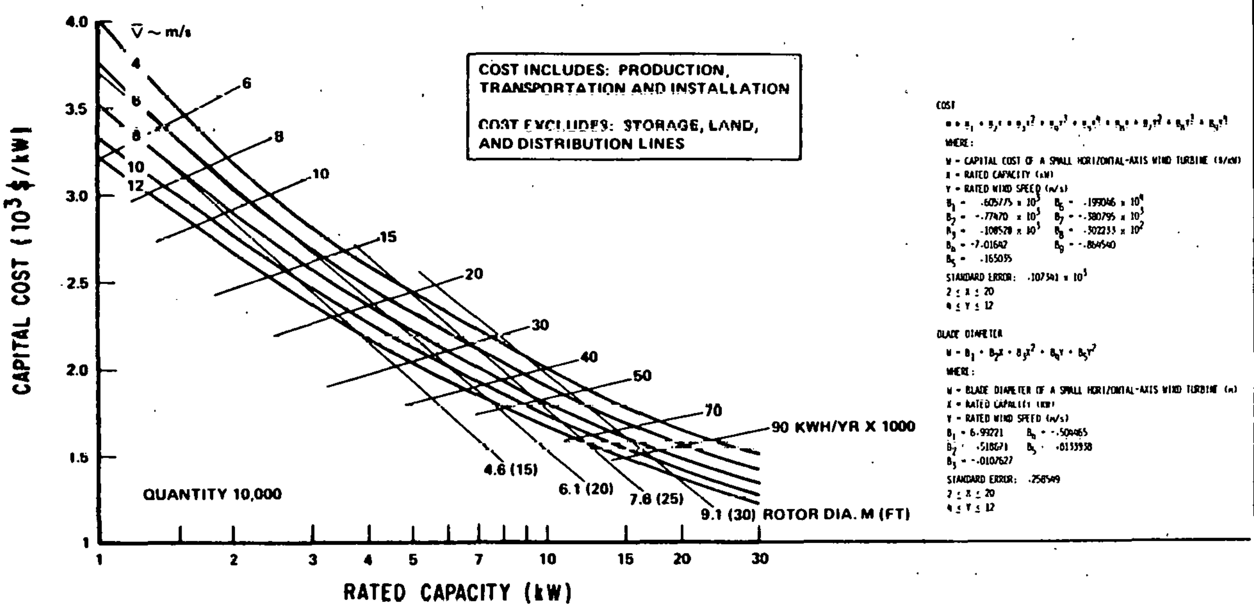


Fig. 8.1 Installed Capital Costs of Small Horizontal-Axis Wind Turbine Generating Systems

The capital costs and blade diameter of large horizontal-axis wind turbines are shown in Fig. 8.2 as a function of rated capacity and rated wind speed.[10]

COST

$W = B_1 + B_2/X + B_3/X^2 + B_4/Y + B_5/Y^2$

WHERE:

W = CAPITAL COST OF A LARGE HORIZONTAL-AXIS WIND TURBINE ($/kW)

X = RATED CAPACITY (kW)

Y = RATED WIND SPEED (m/s)

$B_1 = .317403 \times 10^3$ $\quad B_4 = .231098 \times 10^6$

$B_2 = -.283282 \times 10^4$ $\quad B_5 = -.714143 \times 10^7$

$B_3 = .299949 \times 10^5$

STANDARD ERROR: $.643768 \times 10^2$

$50 \le X \le 10{,}000$

$6^* \le Y \le 12$

BLADE DIAMETER

$W = B_1 + B_2X + B_3X^2 + B_4X^3 + B_5X^4 + B_6Y + B_7Y^2 + B_8Y^3 + B_9Y^4$

WHERE:

W = BLADE DIAMETER OF A LARGE HORIZONTAL-AXIS WIND TURBINE (m)

X = RATED CAPACITY (kW)

Y = RATED WIND SPEED (m/s)

$B_1 = .132499 \times 10^3$ $\quad B_6 = -.366196 \times 10^2$

$B_2 = .0674065$ $\quad B_7 = 4.90114$

$B_3 = -.192907 \times 10^{-4}$ $\quad B_8 = -.390765$

$B_4 = .257061 \times 10^{-8}$ $\quad B_9 = .0121294$

$B_5 = -.120890 \times 10^{-12}$

STANDARD ERROR: 4.68568

$38 \le W \le 122$

$50 \le X \le 10{,}000$

$4 \le Y \le 12$

*NOTE: WIND SPEEDS UNDER 6 M/X ARE NOT INCLUDED BECAUSE AN ADEQUATE MODEL COULD NOT BE FOUND

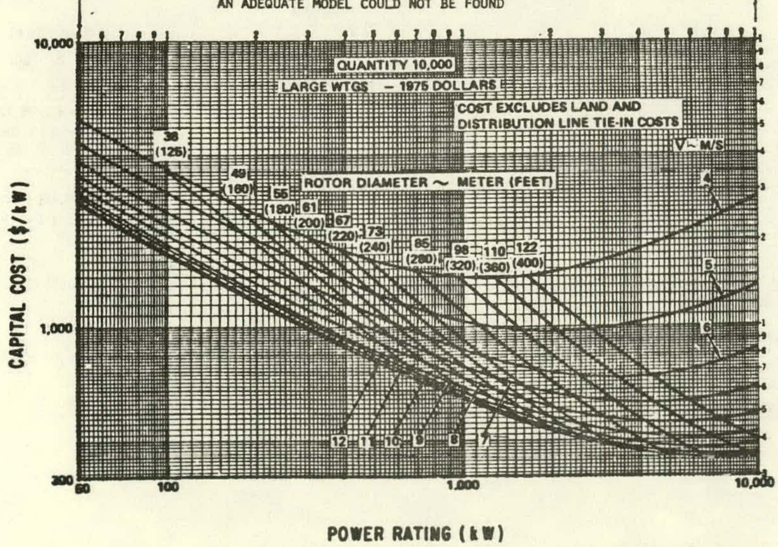
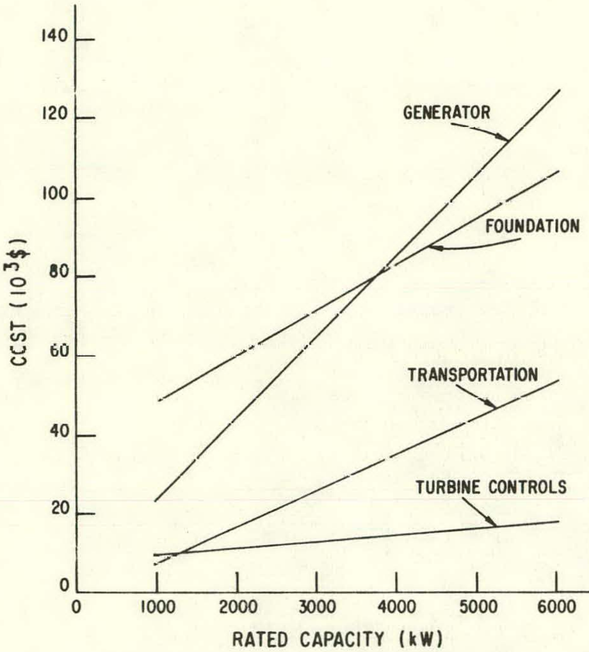


Fig. 8.2 Installed Capital Costs of Large Horizontal-Axis Wind Turbine Generating Systems

ICES TECHNOLOGY EVALUATION

Figures 8.3 through 8.5 break down the capital costs of large horizontal-axis wind. turbines. Figure 8.3 gives the costs of the generator, the foundation, transportation to the site, and the turbine controls. Figure 8.4 gives the cost of the hub, the blades, the drive system, the platform, and the gearbox. Figure 8.5 gives the costs of the tower, the yaw control, assembly and erection, the power conditioning, and site preparation.

It is estimated that a crew of 50 men would be required to erect a horizontal-axis wind turbine. One crew could erect 10.5 wind turbines per year.[10]



GENERATOR

$W = B_1 + B_2X$

WHERE:

W = GENERATOR COST (\$)
X = RATED CAPACITY (kW)
B_1 = .18000 x 10^4
B_2 = .200000 x 10^2
STANDARD ERROR: 0.0
$1000 \leq X \leq 6000$

FOUNDATION

$W = B_1 + B_2X$

WHERE:

W = FOUNDATION COST (\$)
X = RATED CAPACITY (kW)
B_1 = .361568 x 10^5
B_2 = .109635 x 10^4
STANDARD ERROR: .116509 x 10^4
$1000 \leq X \leq 6000$

TRANSPORTATION

$W = B_1 + B_2X + B_3X^2$

WHERE:

W - TRANSPORTATION COST (\$)
X = RATED CAPACITY (kW)
B_1 = .326392 x 10^4
B_2 = .490987 X 10^5
B_3 = .577614 x 10^3
STANDARD ERROR: .853822 x 10^2
$1000 \leq X \leq 6000$

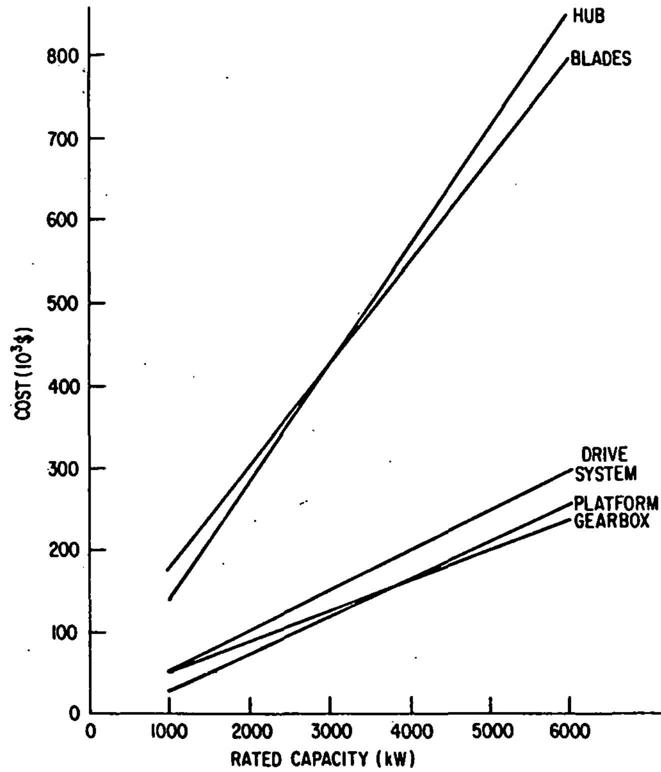
TURBINE CONTROLS

$W = B_1 + B_2X$

WHERE:

W = TURBINE CONTROL COST (\$)
X = RATED CAPACITY (kW)
B_1 = 877568 x 10^4
B_2 = 1.35135
STANDARD ERROR: .487501 x 10^3
$1000 \leq X \leq 6000$

Fig. 8.3 Horizontal-Axis Wind Turbine Component Costs



HUB

$W = B_1 + B_2X + B_3X^2$

WHERE:

W = HUB COST (\$)
X = RATED CAPACITY (kW)
$B_1 = .135546 \times 10^5$
$B_2 = .120570 \times 10^3$
$B_3 = .345920 \times 10^{-2}$
STANDARD ERROR: $.974787 \times 10^4$
$1000 \leq X \leq 6000$

PLATFORM

$W = B_1 + B_2X + B_3X^2$

WHERE:

W = PLATFORM COST (\$)
X = RATED CAPACITY (kW)
$B_1 = .202783 \times 10^4$
$B_2 = .223626 \times 10^2$
$B_3 = .382666 \times 10^{-2}$
STANDARD ERROR: $.702458 \times 10^3$
$1000 \leq X \leq 6000$

BLADES

$W = B_1 + B_2X$

WHERE:

W = BLADE COSTS (\$)
X = RATED CAPACITY (kW)
$B_1 = .528135 \times 10^5$
$B_2 = .123577 \times 10^3$
STANDARD ERROR: $.405562 \times 10^4$
$1000 \leq X \leq 6000$

GEARBOX

$W = B_1 + B_2X$

WHERE:

W = GEARBOX COST (\$)
X = RATED CAPACITY (kW)
$B_1 = .179642 \times 10^5$
$B_2 = .361797 \times 10^2$
STANDARD ERROR: $.317563 \times 10^4$
$1000 \leq X \leq 6000$

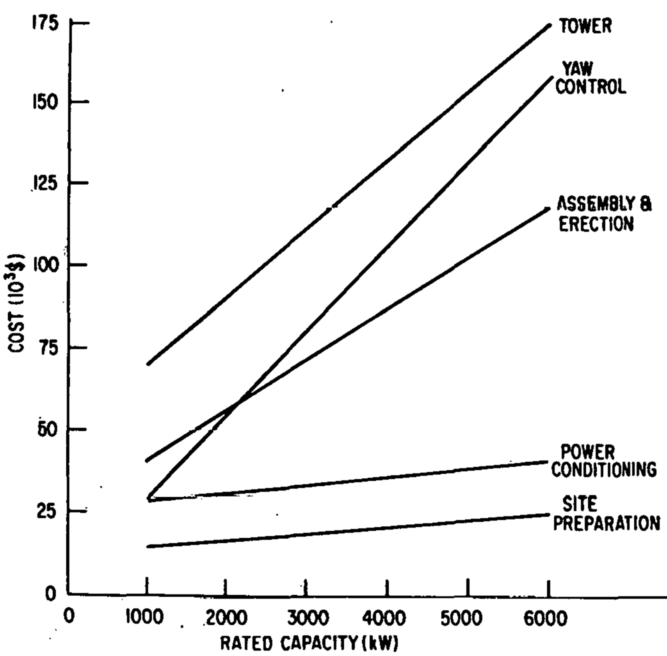
DRIVE SYSTEM

$W = B_1 + B_2X$

WHERE:

W = DRIVE SYSTEM COST (\$)
X = RATED CAPACITY (kW)
$B_1 = .855946 \times 10^4$
$B_2 = .480189 \times 10^2$
STANDARD ERROR: $.300152 \times 10^2$
$1000 \leq X \leq 6000$

Fig. 8.4 Horizontal-Axis Wind Turbine Component Costs



TOWER

$W = B_1 + B_2X$

WHERE:

W = TOWER COST (\$)
X = RATED CAPACITY (kW)
$B_1 = .497946 \times 10^5$
$B_2 = .211392 \times 10^2$
STANDARD ERROR: $.473868 \times 10^4$
$1000 \leq X \leq 6000$

POWER CONDITIONING

$W = B_1 + B_2X$

WHERE:

W = POWER CONDITIONING COST (\$)
X = RATED CAPACITY (kW)
$B_1 = .262081 \times 10^5$
$B_2 = 3.06622$
STANDARD ERROR: $.144258 \times 10^4$
$1000 \leq X \leq 6000$

YAW CONTROL

$W = B_1 + B_2X$

WHERE:

W = YAW CONTROL COST (\$)
X = RATED CAPACITY (kW)
$B_1 = .414865 \times 10^4$
$B_2 = 2.59473$
STANDARD ERROR: $.193278 \times 10^4$
$1000 \leq X \leq 6000$

SITE PREPARATION

$W = B_1 + B_2X$

WHERE:

W = SITE PREPARATION COST (\$)
X = RATED CAPACITY (kW)
$B_1 = .136297 \times 10^5$
$B_2 = 2.00946$
STANDARD ERROR: $.768261 \times 10^3$
$1000 \leq X \leq 6000$

ASSEMBLY AND ERECTION

$W = B_1 + B_2X$

WHERE:

W = ASSEMBLY AND ERECTION COST (\$)
X = RATED CAPACITY (kW)
$B_1 = .262054 \times 10^5$
$B_2 = 1.55608$
STANDARD ERROR: $.310512 \times 10^4$
$1000 \leq X \leq 6000$

Fig. 8.5 Horizontal-Axis Wind Turbine Component Costs

8.2 CAPITAL COSTS -- VERTICAL-AXIS WIND TURBINES

The capital costs, in 1977 dollars, of a two blade vertical-axis wind turbine are given in Fig. 8.6 as a function of rated capacity.[17] These data assume a rated wind speed of 10 m/s and height to diameter ratio of 1.0. The capital costs of vertical-axis wind turbines are less than those of horizontal-axis wind turbines because of the simpler tower construction, location of the generator at ground level, and preclusion of a yaw mechanism. However, the capital costs of this vertical-axis wind turbine design begin to increase above a rated capacity of 300 kW because of the need for struts and stronger blades.

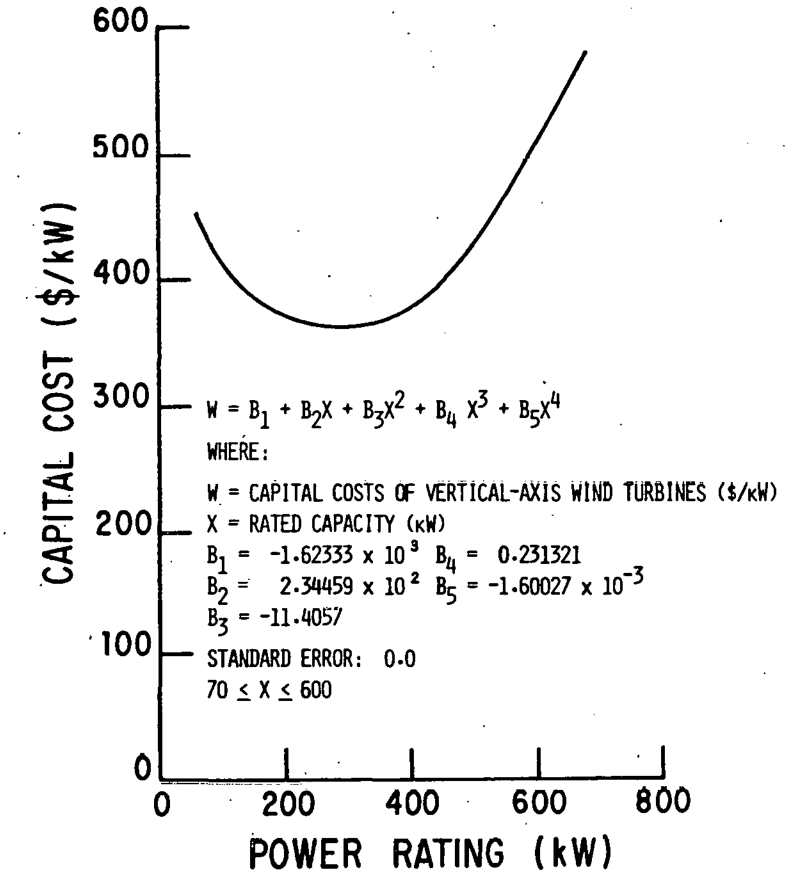


Fig. 8.6 Capital Costs of Vertical-Axis Wind Turbines

8.3 CAPITAL COST SENSITIVITY

The capital costs of wind turbines evaluated here are estimates, based on assumed values of several parameters. The capital costs are sensitive to these assumed values and are subject to considerable uncertainty. Parameters for which values had to be assumed included optimum wind turbine designs, production level, the learning curve for production runs, and the costs of certain wind turbine components, particularly the blades.[2] The data presented on the capital costs of horizontal-axis wind turbines assumed production level of 10,000 units per year and a learning curve of

90%. An illustration of the uncertainty in the capital costs is given in the JBF study on wind energy system costs.[2] By combining and normalizing the results of six studies for 1.0 to 1.5 MW machines, the capital costs ranged from $405 to $889/kW. A 95% learning curve and a 100-unit/yr production rate were assumed.

8.4 WIND TURBINE OPERATING COSTS

The operating costs of wind turbines consist of insurance, maintenance, overhead, and other miscellaneous costs. Table 8.1 gives these costs, on a yearly basis, as a percentage of the capital cost of the wind turbine.

Table 8.1 Operating Costs of Wind Turbines

Operating Item	% of Capital Cost
Insurance	0.2
Maintenance	2.0
Overhead	1.0
Other	0.4

The cost of energy will depend on the operating costs, the capital costs, the cost of money, depreciation and taxes.

9 STATUS

Wind turbines can offer a reliable source of energy. Present technology can produce units that are capable of competing economically with conventional power sources.

As the site mean wind speed increases, the economics of wind turbines improve, but the rate of improvement diminishes for wind speeds greater than 8 m/s. Thus, unique sites with exceptionally high wind speeds are not needed for wind turbine installations.[2]

The energy cost of wind turbines is relatively insensitive to operation at off-design wind speeds, within a reasonable range. Therefore, it is likely that only a limited number of standard designs will be required for utility applications leading to the capability for routine factory production and the ensuing reduction in cost.[2]

The largest uncertainty in wind turbine energy costs is the uncertainty in the capital costs of the first production units and the learning curve that should be applied to future units.[2]

The economic characteristics of wind turbines may be improved by technical advances on the blade and hub assembly, but the likelihood of achieving such improvements and their effects is difficult to estimate.

Currently, both horizontal-axis and vertical-axis wind turbines are in the developmental stages. Several demonstration units have been, or are being, built to obtain performance data and to confirm the reliability and stability of large units.

Studies are needed to determine the optimum locations for wind turbine installations. Currently available wind data are insufficient for successful implementation of a large-scale wind energy program.

REFERENCES

1. Eldridge, F.R., *Wind Machines*, NSF-RA-N-75-051 (October, 1975).
2. JBF Scientific Corporation, *Summary of Current Cost Estimates of Large Wind Energy Systems*, DSE/2421-1 (February, 1977).
3. Puthoff, R.L., *100 kW Experimental Wind Turbine Generator Project*, Proc. of the Second Workshop on Wind Energy Conversion Systems, Washington, D.C., NSF-RA-N-75-050, pp. 21-36 (June 9-11, 1975).
4. Braasch, R.H., *Vertical-Axis Wind Turbine Program*, Vertical-Axis Wind Turbine Workshop, SAND76-5586, Albuquerque, New Mexico, p. 39 (May 17-20, 1976).
5. Steel, R.G., and J.H. Torrie, *Principles and Procedures of Statistics*, McGraw-Hill, New York, p. 169 (1960).
6. Grumman Energy Systems, Data sheet, W25-4-77 (October 25, 1977).
7. Kedco Incorporated, Wind Generator Data sheet (October 20, 1977).
8. Sencenbaugh Wind Electric, Data sheet (October 25, 1977).
9. Winco, Division of Dyna Technology, Inc., Data sheet, D181-R (October 28, 1977).
10. Coty, U.A., *Wind Energy Mission Analysis*, San-10-75-1 (September, 1976).
11. Garate, J.A., *Wind Energy Mission Analysis*, COO-2578-1 (February 18, 1977).
12. Elliott, D.L., *Synthesis of National Wind Energy Assessments*, BNWL/Wind-5 (July, 1977).
13. Seniec, T.B., et al, *TV and FM Interference by Windmills*, University of Michigan, COO/2846-76 (February, 1977).
14. Cliff, W.C., *The Effects of Generalized Wind Characteristics on Annual Power Estimates from Wind Turbine Generators*, Battelle Pacific Northwest Laboratories, PNL-2436, (October, 1977).
15. Jorgensen, G.E., et al, *Design, Economics, and System Considerations of Large Wind-Driven Generators*, IEEE Transactions on Power Apparatus and Systems, 95(3), p. 870 (May/June, 1976).
16. Weingarten, L.I., and L.V. Feltz, *Material and Manufacturing Considerations for Vertical-Axis Wind Turbines*, Sandia National Laboratory, Albuquerque, New Mexico (March, 1975).
17. Sullivan, W.N., Sandia Laboratories, personal communication (May 18, 1978).

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