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ALTERNATIVE ELECTRICAL ENERGY SOURCES FOR MAINE
Appendix K
WIND ENERGY CONVERSION

T. Labuszewski

MIT Energy Laboratory Report No. MIT-EL 77-010
December 1977

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W.J. Jones   M. Ruane

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This appendix is one of thirteen volumes; the remaining volumes are as follows: A. Conversion of Biomass; B. Conservation; C. Geothermal Energy Conversion; D. Ocean Thermal Energy Conversion; E. Fuel Cells; F. Solar Energy Conversion; G. Conversion of Solid Wastes; H. Storage of Energy; I. Wave Energy Conversion; J. Ocean and Riverine Current Energy Conversion, and L. Environmental Impacts.

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Appendix A	Conversion of Biomass - C. Glaser, M. Ruane
Appendix B	Conservation - P. Carpenter, W.J. Jones, S. Raskin, R. Tabors
Appendix C	Geothermal Energy Conversion - A. Waterflow
Appendix D	Ocean Thermal Energy Conversion - M. Ruane
Appendix E	Fuel Cells - W.J. Jones
Appendix F	Solar Energy Conversion - S. Finger, J. Geary, W.J. Jones
Appendix G	Conversion of Solid Wastes - M. Ruane
Appendix H	Storage of Energy - M. Ruane
Appendix I	Wave Energy Conversion - J. Mays
Appendix J	Ocean and Riverine Current Energy Conversion - J. Mays
Appendix K	Wind Energy Conversion - T. Labuszewski
Appendix L	Environmental Impacts - J. Gruhl

Numerous people shared reports and data with us and provided comments on the draft material. We hope that everyone has been acknowledged through the references in the technical sections, but if we missed anyone, thank you!

Ms. Alice Sanderson patiently weathered out many drafts and prepared the final document.

Preface

The Energy Laboratory of the Mass. Inst. of Tech. was retained by the Central Maine Power Company to evaluate several technologies as possible alternatives to the construction of Sears Island #1 (a 600 MWe coal fired generating plant scheduled for startup in 1986). This is an appendix to Report MIT-EL 77-010 which presents the results of the study for one of the technologies.

The assessments were made for the Central Maine Power Company on the basis that a technology should be:

1) an alternative to a base-load electric power generation facility. Base-load is defined as ability to furnish up to a rated capacity output for 6570 hrs. per year.

2) not restricted to a single plant. It may be several plants within the state of Maine. The combined output, when viewed in isolation, must be a separate, "stand-alone", source of power.

3) available to deliver energy by 1985.

APPENDIX K

WIND ENERGY CONVERSION

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

Windmills have been used for thousands of years. The earliest record of the use of windmills dates back to 1700 B.C. when the Babylonian Emperor, Hammurabi, used windmills for irrigation. The Chinese, at about the same time, record utilization of windmills as brine pumps. Table 1.1 (Golding, 1955) outlines the historical development of wind energy conversion systems (WECS).

Table 1.1

Windmill chronology

Date	
B.C.	
2000	(?) Chinese and Japanese windmills in use.
1700	(?) Hammurabi reported the use of windmills for irrigation in Babylon.
circa 200	Hero of Alexandria describes a small windmill.
134	Arabian explorer Istachri mentions windmills in Persian province of Segistan.
100	(?) Windmill in use in Egypt.
A.D.	
7th century	Persian windmills in use (vertical axis type).
1105	French document permitting construction of windmills
1191	First reported windmill in England.
circa 1270	Windmill Psalter containing earliest illustration of a windmill (horizontal axis, sail type)
13th century	Manuscript Aristotle's Physica; illustration of windmill with tailpole.
1327	Deed referring to a windmill at Lytham St. Anne's (Lancashire).
circa 1340	Illustration of a windmill in the Luttrell Psalter.
1349	Flemish brass illustrating a windmill in St. Margaret's Church, Kings Lynn.
1390	Picture of a windmill on a rug in the Germanic Museum of Nuremberg.
1393	Records in the chronicles of the city of Speyer tell of an engineer from the Netherlands being called in to build a windmill.
14th century	English illustration of a windmill with four sails in a Decretal of Gregory IX.
1439	First corn-grinding windmill built in Holland.
circa 1500	Sketch by Leonardo da Vinci (1452–1519) of windmill construction.
1506	Woodcut showing a windmill in 'Expositio Sequentiarum'.
1665	Construction of postmill at Outwood, Surrey. This is still working.
1737	Illustration in Belidor's 'Architecture Hydraulique' Tome II, Livre 3^e, Ch. II, of French windmill with primitive form of propeller having two blades.
1745	Edmund Lee patented a method of turning mills into wind automatically.
1750	Andrew Meikle invented the fantail.
1759	John Smeaton awarded a gold medal by the Royal Society for his paper on windmills and water mills.
1772	Andrew Meikle introduced the 'spring sail'.
1789	Stephen Hooper invented the 'roller reefing sail'.
1807	Sir William Cubitt invented the self-reefing or 'patent' sail.
1891	Establishment of windmill experimental station at Askov, Denmark, under Professor P. La Cour.
First half of 20th Century	Development of windmills for the generation of electricity and for water supply to individual premises. This period is that of the changeover from sail to propeller-type windmills.
Post World War II	Researches, in a number of countries, on the possibilities of large-scale utilization of wind power.

For the past 30 years, wind power has been largely ignored in the United States. Prior to World War II, about 20,000 - 30,000 windmills were used in the Midwest to pump water and provide electricity to isolated farms. Under President Roosevelt's Rural Electrification Act, farmers were able to obtain inexpensive central station electricity, and windmills soon vanished from the Plains. Due to rising fuel prices, however, there has been renewed interest in these devices. The next three sections summarize recent worldwide developments. (For further reading on this, see [S.T.U., 1976] [Jagaden, 1976].)

1.1 European Designs

World War II brought severe fuel shortages to Europe. Many WECS of 50 KW or less rated power were constructed. These usually drive DC generators which charge batteries. After the war, they became uneconomical and closed down until the mid-fifties when the Suez Crisis caused high fuel costs in Europe. In 1957, a 200 KW unit was built in Gedser, Denmark, and ran successfully until lack of funding in 1967 forced its shutdown. From the fifties to the early sixties, the English also experimented in this size WECS. The French and Germans experimented with these types until the mid-sixties. The French, in particular, built some units, rated at approximately 1 MW capacity, which experienced mechanical difficulties. These countries have currently begun developmental efforts once more.

1.2 American Efforts

Just prior to World War II, the use of wind power for bulk electric power generation was advanced under the guidance of one man, Palmer C. Putnam. He outlines in his book (Putnam, 1948) his involvement during the late thirties with a private turbine fabricator, the S. Morgan Smith Co. of Vermont, the Massachusetts Institute of Technology, and famed scientist Vannevar Bush. Through his efforts, the Smith-Putnam machine was built on a mountain (Grandpa's Knob) in Vermont; the device was 125 ft. tall and was rated at 1250 KW. It supplied 3-phase 60-cycle AC power intermittently while accumulating valuable test data for the Central Vermont Public Service Corporation for almost four years. The threat of never completing this machine (because of policy priorities relating to World War II) forced the developers to rush orders for forgings before designs were verified. They had realized that their design for the rotor could be weak, but it was too late to have it changed. In April, 1945, one of the blades failed near the hub (at rotor root). The project was abandoned in November, 1945, after $1.5 million in company funds had been spent. After design corrections, the lowest installation cost applicable for a block of six machines was 190 dollars/KW. It was estimated that this power was worth only 125 dollars/KW to the Central Vermont Public Service Corporation. Palmer maintained that with more comprehensive design work and testing, the cost could have been lowered to 125 dollars/KW.

In the late forties, Putnam's assertion was reviewed for the FPC (Thomas, 1945), (Thomas, 1946). It was concluded that large 500 ft. towers with giant dual 3-blade rotors could be built in the U.S. for $68 to $75/KW and generate 6-8 MW. The report, not endorsed by the FPC, was not implemented.

1.3 The Current Wind Energy Program

In 1973, the National Science Foundation's Research Applied to National Needs (NSF-RANN) program funded wind energy research and application under a budget of $1.8 million. After transferral of the program to the Energy Research and Development Administration in 1975, the budget grew to an estimated 1977 level of over $24 million. President Carter in his new energy reform program has stated support for solar energy, of which wind energy is a derivative. "To accelerate the development, commercialization, and utilization of reliable and economically viable wind energy systems" is the stated objective of the Federal Wind Energy Program managed by the Wind Systems Branch (WSB) of ERDA's Division of Solar Energy (see Figure 1.1)

Table 1.2 outlines program funding. In Figure 1.2, organization of program goals is shown. For further details, readers may refer to (ERDA, 1977); also a selected listing of NASA/ERDA reports is contained in Table 4.1. For the current thrust of the federal program, see Section 2.7.

Table 1.2

PROGRAM ELEMENTS & WIND ENERGY FUNDING (x 1000)[a]

Program Elements/Sub-elements	FY 73-74[b]	FY 75[b]	FY 76	TQ[c]	FY 77 (est.)
1. Program Development and Technology	429	5,605	7,698	2,987	
1.1 Mission Analysis	12	1,043	831	371	
1.2 Applications of Wind Energy	--	579	556	230	
1.3 Legal/Social/Environmental Issues	--	422	200	300	
1.4 Wind Characteristics	14	399	992	669	
1.5 Technology Development	279	2,281	3,069	364	
1.6 Advanced Systems	124	881	2,050	1,053	
2. Farm and Rural Use (Small) Systems	--	736	1,507	231	
3. 100 KW Scale Systems	865	970	1,439	628	
4. MW Scale Systems	500	600	3,140	832	
5. Large Multi-Unit Systems	--	--	582	292	
TOTALS	1,794	7,911	14,366	4,970	24,000

a - In obligations; other federal documents may list outlays or costs incurred
b - includes NSF funding
c - Transition Quarter (July-September 1976)

Figure 1.1

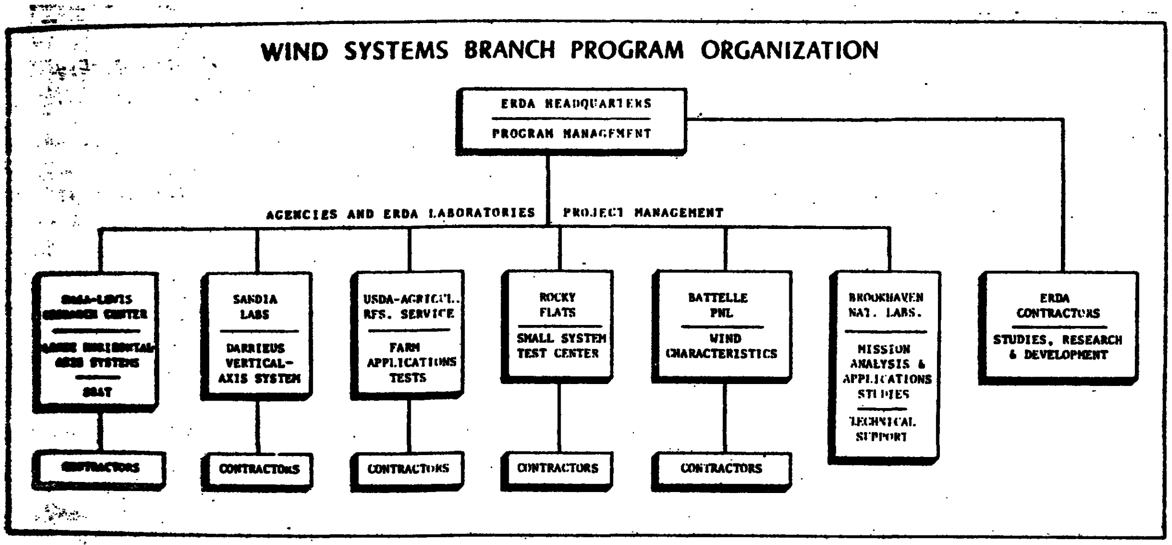
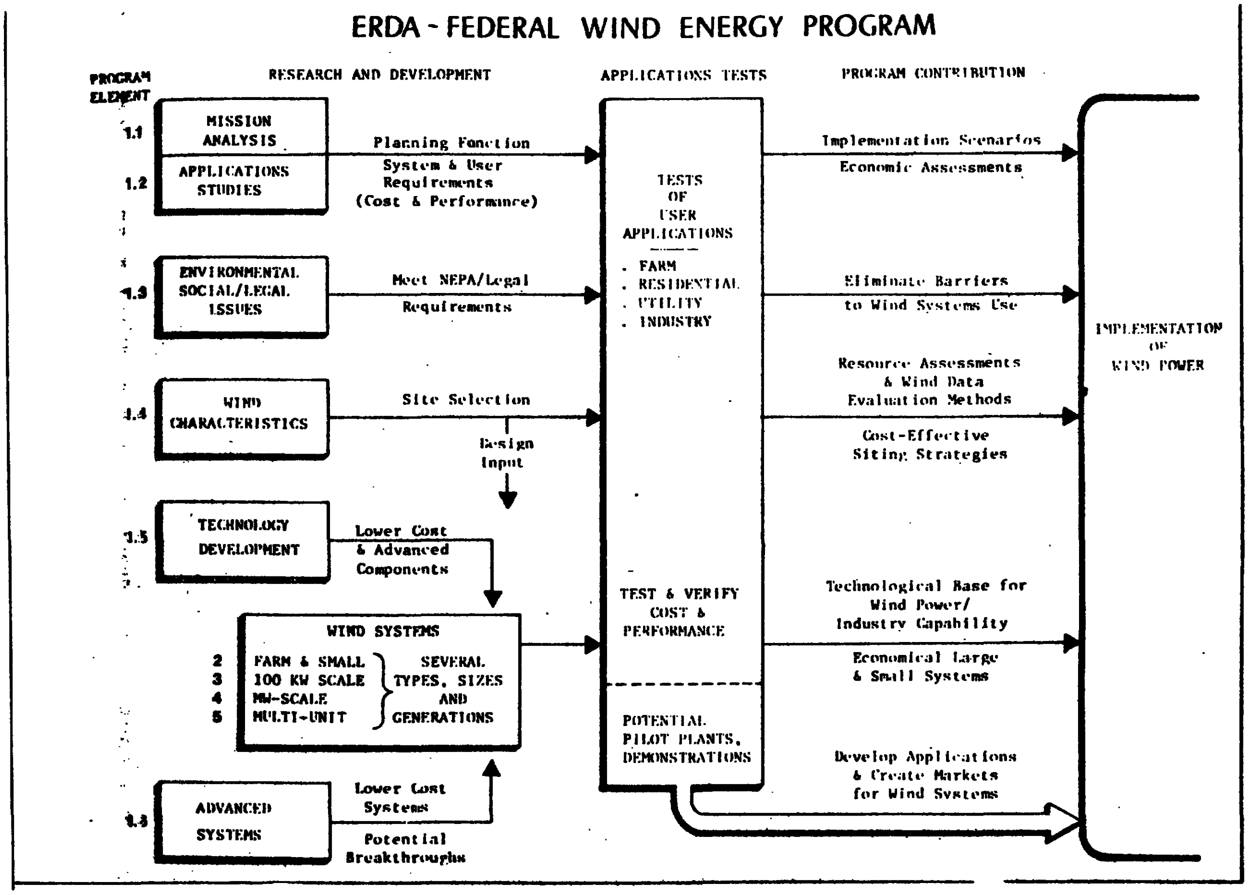


Figure 1.2



2.0 WIND POWER AND SITING CRITERIA

Wind is air in motion, and air has mass; when this mass has velocity, the resulting wind possesses kinetic energy which is proportional to 1/2[mass x $(\text{velocity})^2$]. The mass of air passing through an area A per unit of time is ρAV, causing power to vary as the cube of the velocity:

$$P = \frac{1}{2}\rho AV^3 \tag{2.1}$$

ρ = density of air
A = cross-sectional area
V = wind velocity
P = power in wind

The ratio of actual power extracted by a wind machine to this theoretically available power across some area is called the power coefficient. A. Betz of Gottingen in 1927 showed that the maximum fraction of the power that could be extracted by an ideal horizontal axis wind turbine was 16/27 or 0.593 of the actual power in the wind. A way in which this can be understood is for the reader to imagine a "piece" of moving air as it approaches a windmill. The moving section of air has kinetic energy; as it strikes the windmill blades it delivers kinetic energy to the blades, which, in turn, transmit the energy via the shaft to the electric turbine. If all of the kinetic energy is extracted from that "piece" of air, the "piece" will stop (it now has zero velocity) at the rear of the windmill blades. The next "piece" or "section" of air cannot approach the blades; the first, or preceding, "piece" of air is blocking its path.

If, on the other hand, one were to extract only a part of the energy in the first "piece," there would be enough energy left in it to enable it to pass on downstream, and get out of the way of the next "piece" so that a portion of its kinetic energy could be extracted, leaving just enough energy in the second "piece" so that it, too, can "get out of the way" to accommodate the same process with all subsequent "pieces" of wind.

In this manner, it can be visualized that in order to extract energy from wind on a continuous basis, the wind that impinges on the windmill blades must be left with enough energy to "get out of the way." The optimization performed by Betz gives the maximum extraction efficiency. This can be used to examine the performance of an ideal wind-driven machine (Table 2.1).

Table 2.1

Power Output from an Ideal Wind-Driven Machine

$(P = 0.593KAV^3)$

Wind speed (mph)	m/s	Power in kilowatts from circular areas				
		dia = 12.5 ft.	dia = 25 ft.	dia = 50 ft.	dia - 100 ft.	dia = 200 ft.
10	4.5	0.38	1.5	6.0	24	96
20	9.1	3.08	12.3	49.2	196	784
30	13.6	10.4	41.6	166.4	666	2,644
40	18.2	24.6	98.4	393.6	1,574	6,296
50	22.7	48.2	192.8	771.2	3.085	12,340
60	27.2	83.2	332.8	1,331.2	5,325	21,300

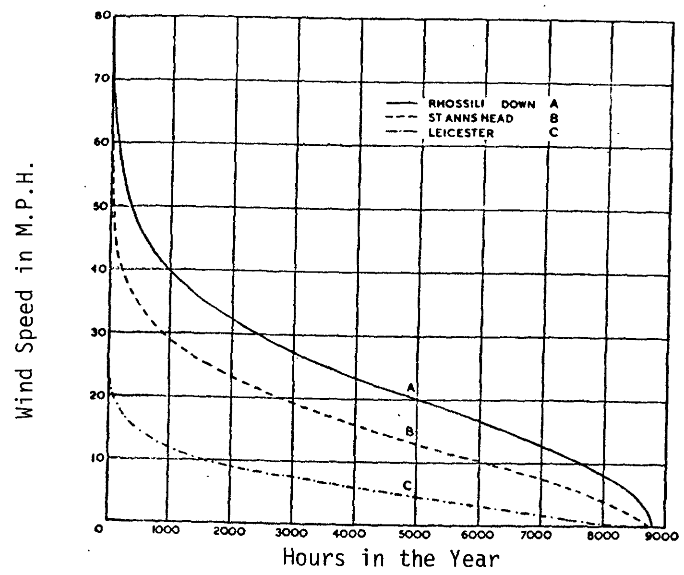
Due to frictional boundary layer effects, the velocity of the wind increases with height above the ground. Therefore, it is profitable to raise a windmill into the higher wind regions. The relation normally used to project wind speed data from one height to another is:

$$V = V_m \left(h/h_m\right)^{\alpha} \tag{2.2}$$

where V and h are the wind speed and height of the extrapolated wind speed; V_m and h_m are the measured wind speed at the measured height above ground. The coefficient α is dependent upon altitude, the general frictional characteristics of the area, such as flat, hilly, etc., and upon such specific local factors as houses, trees. etc. A typical value of α is 0.17. A wind speed extrapolated from 9 meters (30 feet) to 42.7 meters (140 feet), for example, is 1.3 times its value at 9 meters.

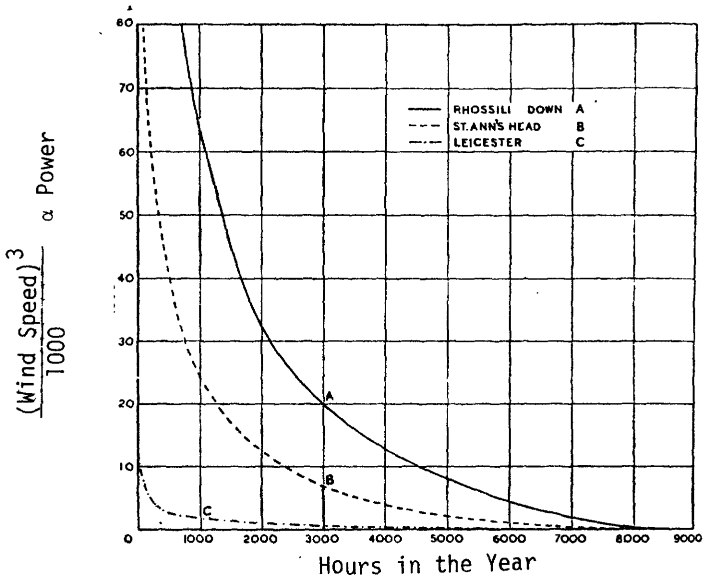
Since power in the wind is proportional to the cube of the velocity, a prime concern when designing a wind machine is the characteristics of the wind at the site of the machine. The annual average and distribution, or frequency of occurrence, of the wind, must be known. Wind speeds normally are averaged for some small time, such as a minute, once every hour, and displayed as a velocity-duration curve (see Figure 2.1), or a power-duration curve (Figure 2.2). These data (Golding, 1955) represent three sites in England: A, at the top of a 633 ft. hill with an average wind speed of 24 mph; B, (forty miles from A) at an elevation of 142 ft., wind speed 16.2 mph; and C, elevation 267 ft., and wind speed 6.2 mph. The curves in Figure 2.1 show the great difference which exists between wind regions at an inland site (C), a coastal site (B), and also the advantage which can be gained by choosing a good site (A), only a short distance from one which is considered as reasonably windy.

Figure 2.1



Velocity Duration Curves

Figure 2.2



Power Duration Curves

The curves of Figure 2.2 can be converted to power-duration curves by cubing the ordinates so as to make them proportional to the power in the wind for a given swept area. The differences between the sites as potential sources of energy now become much more apparent, especially when it is realized that the areas under the curves are proportional to the annual amounts of energy in the wind. There are other statistics possible for the wind, but these are the important ones in determining wind energy sites.

It is possible to correlate average wind speed data over a region and plot lines of constant velocity, called isovent lines. These lines inform us of potential areas for sites. However, they do not find the sites for us. As was illustrated in Figures 2.1 and 2.2, non-specially selected sites can vary greatly (A & B) from optimum ones. This is precisely the problem with the main body of data (mostly from the U.S. meteorological services) available at this moment. The data are from non-optimum sites, usually airports, which are generally selected to be in non-windy regions. The measuring devices are sometimes "shadowed" by tall structures, creating erroneous wind data. They are not distributed evenly over the countryside but tend to be clumped around cities.

Therefore, the need exists for wind data that can be used in estimating optimum wind power extraction; such surveys are planned under the federal program. The need also exists to refine exact site-selection techniques; at the present moment, one looks for site characteristics such as ridges and hills which accelerate the wind, and then tediously measures wind with an annerometer at each site. Alternatively, ecological data have been used to derive sites (Putnam, 1948), using signs such as crests swept clean of trees or having short wind-damaged foliage (a sign of high winds).

2.1 Horizontal Axis vs Vertical Axis

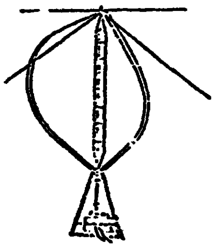
A main distinguishing characteristic between various machines is whether the blades revolve on a vertical or horizontal axis with respect to the earth. The Darrieus and Savonius windmills are vertical-axis machines as shown in Figure 2.3; various horizontal machines are depicted in Figures 2.4, 2.5, and 2.6.

Figure 2.3

Wind Machine Design

VERTICAL AXIS WIND ROTORS

DARRIEUS ROTOR



BACKGROUND

PATENTED IN 1931 (US AND FRANCE)

CURRENTLY UNDER STUDY AT NATIONAL AERONAUTICAL ESTABLISHMENT, OTTAWA, CANADA

CHARACTERISTICS

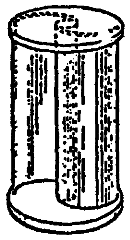
EFFICIENCY ~ 35%

TIP SPEED TO WIND SPEED ~ 6 TO 8

POTENTIALLY LOW CAPITAL COST

CURRENTLY NOT SELF STARTING

S-ROTOR



BACKGROUND

PATENTED IN 1929 (US AND FINLAND) BY S. J. SAVONIUS

CURRENTLY USED AS AN OCEAN CURRENT METER

OTHER APPLICATIONS SHOWN FEASIBLE

CHARACTERISTICS

TIP SPEED TO WIND SPEED ~ .8 TO 1.8

EFFICIENCY ~ 31%

SELF STARTING

VERTICAL AXIS ROTORS OPERATE INDEPENDENTLY OF WIND DIRECTION AND THUS HAVE A POTENTIAL FOR HIGH EFFICIENCY IN CHANGING WINDS

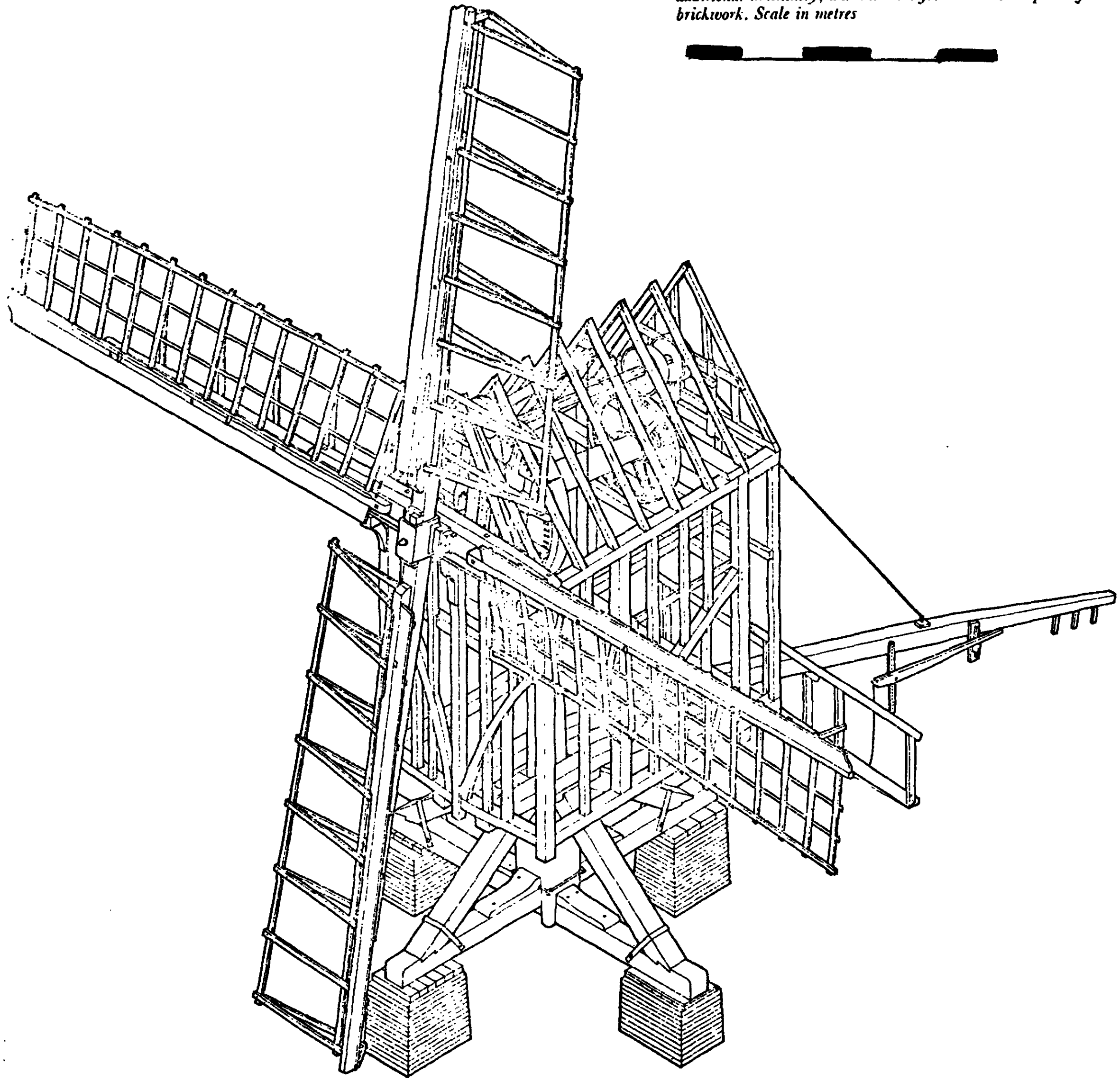
Source: W. Vance, PB-231 341, December 1973

Figure 2.4

England

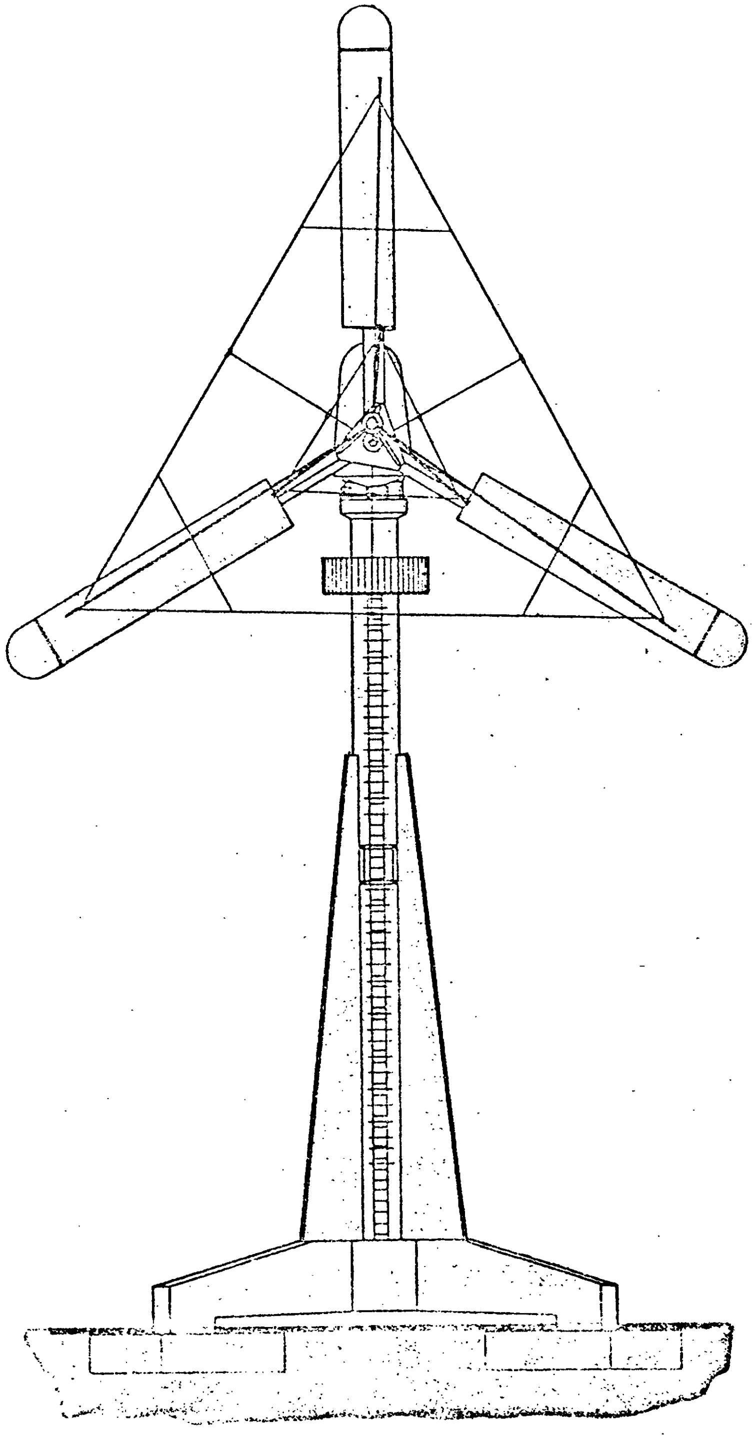
Bourn Mill, Cambridgeshire, 1636

An early open trestle post mill, much altered and repaired, but retaining the simple pitched roof of the medieval mill. The body has been extended at the rear to provide space for additional machinery, and the underframe raised on piers of brickwork. Scale in metres



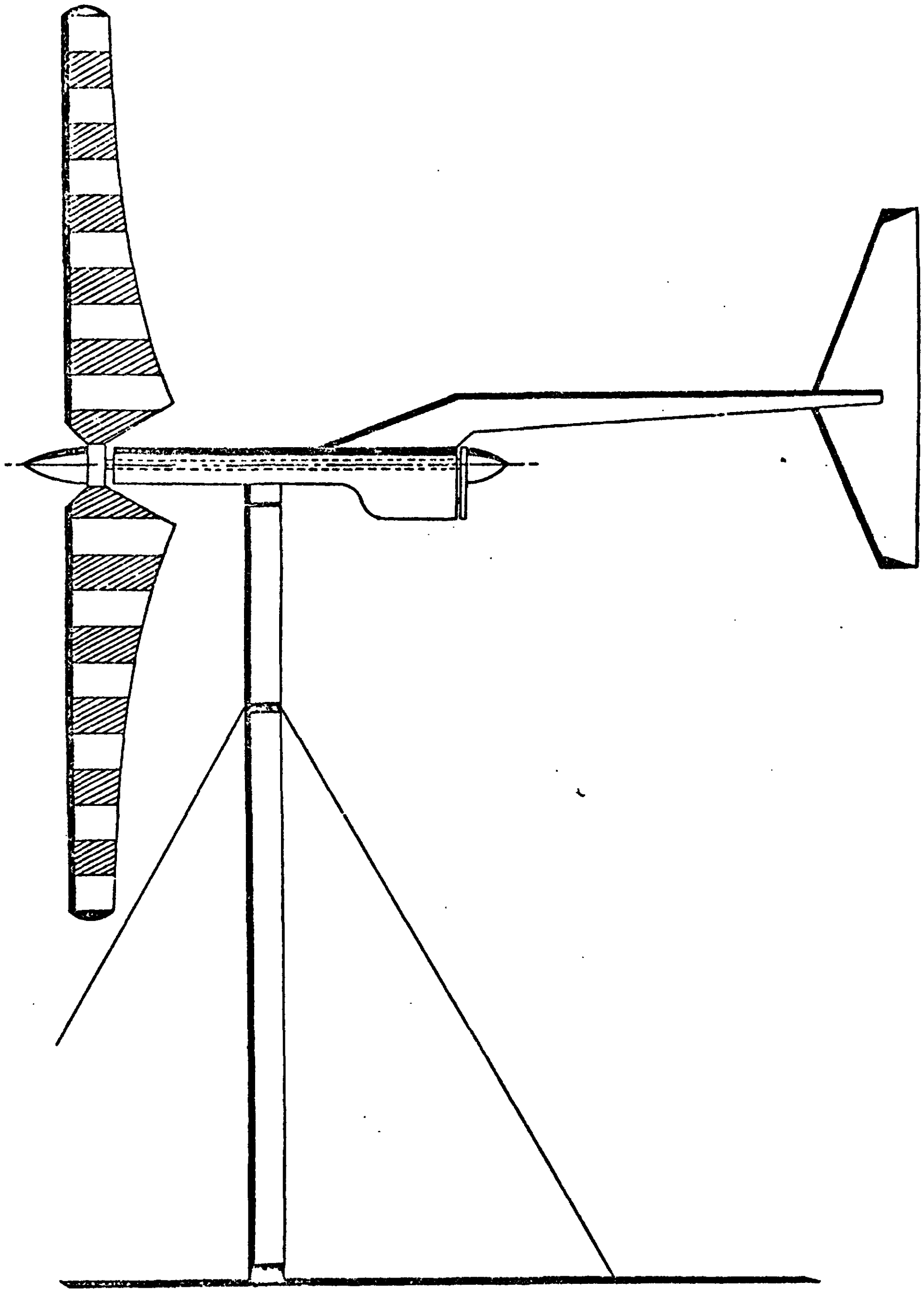
Source: "Windmills and Watermills," Reynolds, John, Praeger Publishers, N.Y.

Figure 2.5



100 kW Windmill, USSR, 1931

Figure 2.6



Princeton University sailwing wind generator

The horizontal type can be called a turbine (horizontal axis wind turbine, or HAWT) because it employs "lift" forces to turn its "propeller" or rotor.

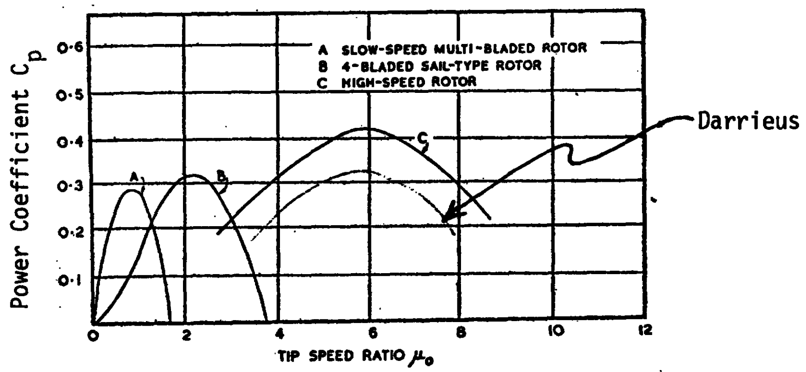
Most vertical devices, such as the Savonius, employ "drag" forces, that is, the resistance of the surface of the rotor to the wind. This is less efficient, and not a very economical use of materials, since the cross-section of material is larger than the cross-section of wind intercepted. However, as they are simple and have the ability to respond to gusting winds in any direction, they have uses for small-scale applications.

Another class of vertical-axis machines can truly be called vertical axis wind turbines, (VAWT), since they use lift forces as well as drag. The Darrieus in Figure 2.3 is the best example. It is still not as economical in materials as a HAWT, nor is it self-starting. This can be overcome when it is hooked to a generator which can be driven as a motor to get it up to speed. It has also experienced some fabrication and flutter problems in its complex "eggbeater" blades. However, it does have a major advantage over the HAWT in that its gearbox and generator can be on the ground, while in a HAWT these are in a pod on a tower. Also, there is no need to rotate the device into the wind, as with a HAWT, when the wind changes directions.

Returning to power coefficients, C_p, note that for a HAWT, the maximum C_p is 0.593; however, due to air "spilling" from the tips of the blades as the rotor turns, and deviations of the practical rotor design from the "ideal", the best attainable C_p is about 0.50.

For a VAWT, the best C_p is about 0.45. This is shown in Figure 2.7 along with an American Prairie mill (A) and a Dutch mill (B). C_p is plotted vs. velocity ratio, and μ, the ratio of the "tip" of a blade to the wind speed. For each design there is some value of μ for which the efficiency is best.

Figure 2.7



Power Coefficients for Different Types of Rotor

Weighing all these pros and cons, the HAWT becomes the design basis for the large megawatt scale designs needed for bulk power, since higher efficiency and more economical use of materials (lowest weight) are prime concerns for large scale use. For small uses, simplicity makes vertical axis machines a good alternative today. These are precisely the lines NASA/ERDA are following -- they are developing megawatt-scale HAWT's for utility use and vertical axis machines for small, private use.

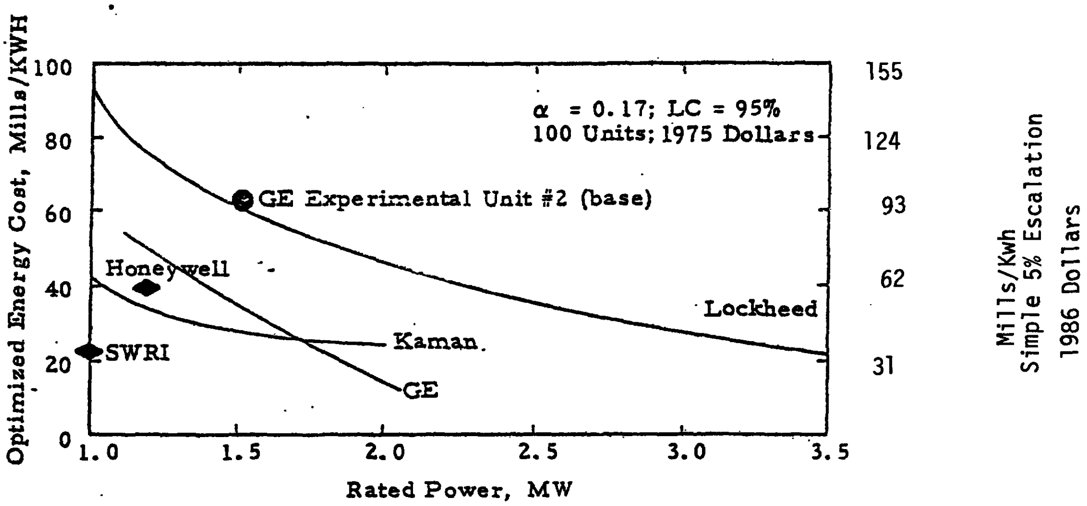
2.2 Large vs. Small Machine Wind-Power Use

One may wonder what the optimum number of rotors per machine is. Single-rotor-per-tower designs are better because the power equation is proportional to the swept-out area besides the cube of the wind velocity. This area equals $\pi D^2/4$; if one compares the power in the same wind (taken at the height of the rotor shaft, with variations of wind versus height across the rotor ignored as a first cut) of two rotors with swept-out diameters each one-half that of a single-rotor design, their aggregate power is $(1/2)^2 + (1/2)^2 = 1/2$ that of the single-rotor case. This worsens as the number of divisions increases.

If each home had a WECS, or if a power company were operating an array of machines, it can be shown (see Section 2.8) that some basic power level can always be counted on. The advantage of optimum siting would be lost with home siting since every home is not at an ideal wind site. Some facts and figures follow.

The typical U.S. home consumes 8,000 to 10,000 KWH/yr of energy, exclusive of heating or air conditioning. In (Simmons, 1975), the Automatic Power Co. of Houston, Texas, is quoted as selling a wind generator capable of meeting this demand for $21,960, 1974 prices, exclusive of the tower and auxiliary equipment. It would have a two-blade rotor diameter of 30 ft. From the JBF Report (JBF, 1977) used for Section 4 on Economics, we have Figure 2.8 showing that, as the rated power (and size) of a machine increases, the energy cost decreases. Along these same lines, Figure 2.9 shows how the energy cost falls dramatically for larger-rotored machines. Both figures have had a second cost axis added for 1986 dollars. To convert the given costs to 1986 dollars, an annual escalation rate of 5% is assumed. This will allow comparison with other technologies in terms of the same 1986 dollars.

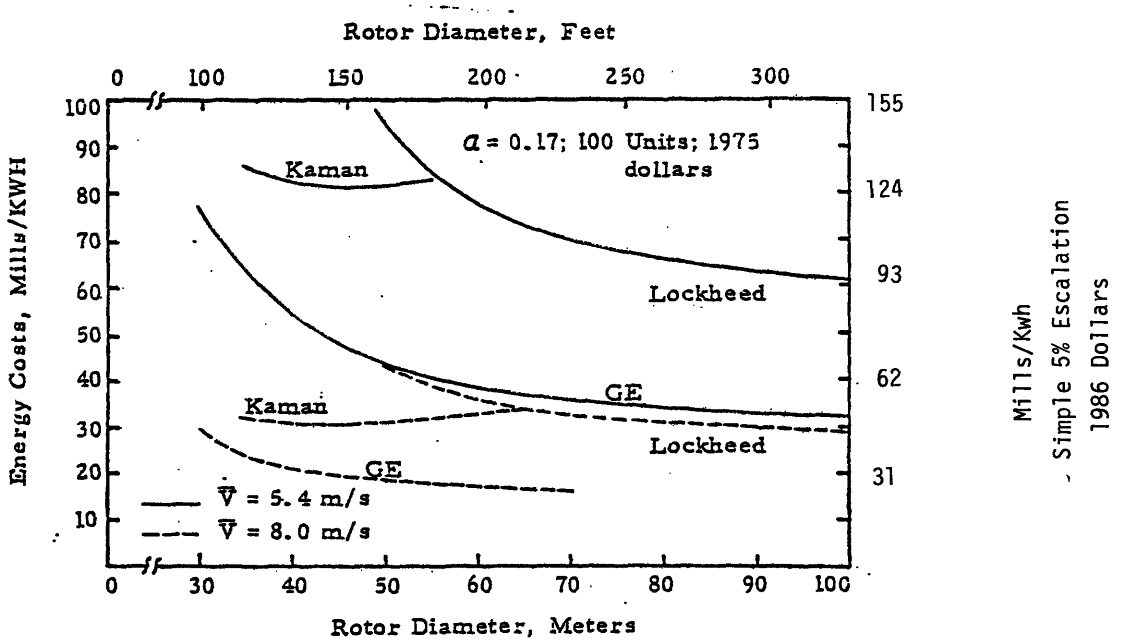
Figure 2.8



Energy Cost as a Function of Rated Power for an Optimized WECS Design (Varying Wind Speeds)

from (JBF, 1977)

Figure 2.9



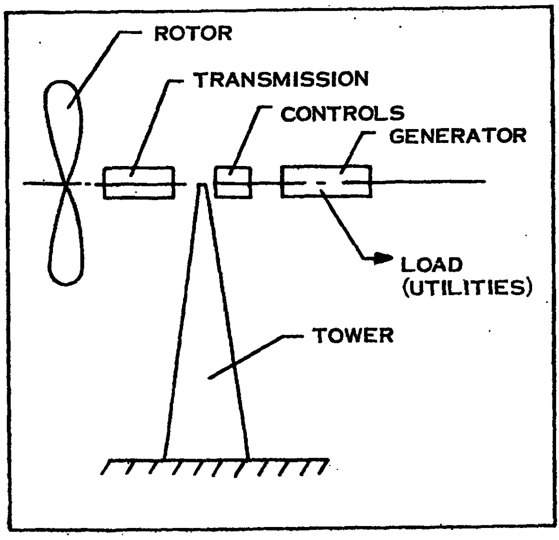
Energy Costs as a Function of Rotor Diameter

from (JBF, 1977)

2.3 Optimum Design Component Breakdown

A system component breakdown schematic* is shown in Figure 2.10. The conversion of wind energy into electrical power requires the following types of components: a turbine (rotor), transmission, generator, and tower. The wind turbine rotor converts the kinetic energy in the wind into shaft rotational power. An optimized rotor will have blades that are a compromise between the ideal design (having varying taper or width, airfoil, and twist with length of the blade) and a less-than-ideal design that is easier and cheaper to manufacture.

Figure 2.10



MAJOR OPTIONS CONSIDERED INCLUDE

- OPERATING MODE
- ROTOR TYPE
- POWER REGULATION TECHNIQUE
- SYSTEM CONFIGURATION
- COMPONENTS
  - ROTOR
  - TRANSMISSION
  - GENERATOR
  - CONTROLS
  - TOWER

System Concept Considerations

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*The discussion is in general terms of system components; for a good technical description, see (General Electric, 1976) (Kaman, 1976) -- the two NASA/ERDA-commissioned wind turbine design studies.

The blades are likely to be the most expensive item. For the Plumbrook 100 KW machine (see Figure 2.10), the two blades cost $320,000 out of a total of $985,000 (Kocivar, 1976). If we minimize the number of blades (two), or if two operate almost as well as three, we realize large savings, due to reduced interference between blades. For higher tip-speed ratios, the efficiency of the rotor goes up as the number of blades goes down (Figure 2.7). In fact, (not shown on that figure), the best efficiency, about 50%, is reached for a blade designed for a tip-speed ratio of about 11 or 12. Beyond this, the efficiency decreases as tip speed no longer is negligible compared with the speed of sound.

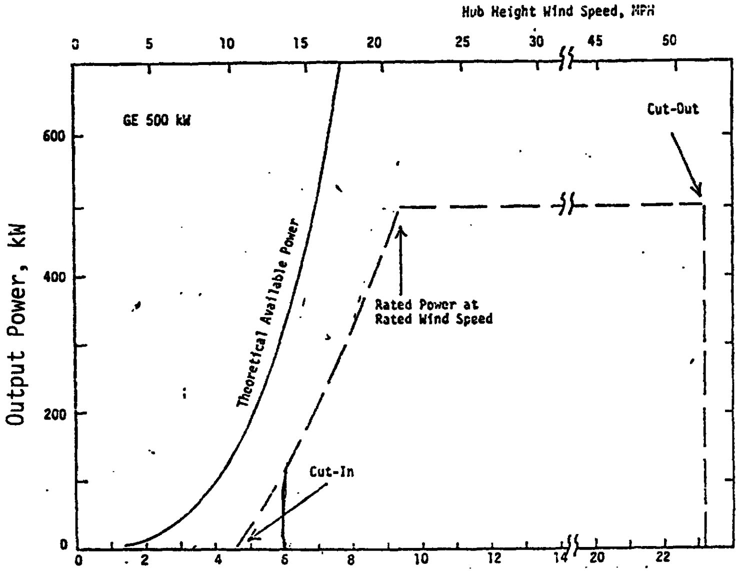
Once a portion of the energy in the wind is converted to rotating shaft power, the shaft speed (between 20 and 40 rpm) is generally made compatible with the dynamic characteristics of the electrical generating equipment by means of a transmission (gearbox). The electrical generator then converts the output of the transmission into electricity. For an electrical utility network, this would be AC, 3-phase, 60-Hertz. A control system is also required to regulate and protect the components. All these components are mounted in horizontally rotatable pod or nacelle (the rotor must point into the wind to extract power) atop a supporting tower which allows for ground clearance of rotor tips and places the rotor into the higher wind region.

2.4 Operating Mode

Predicated on 60 Hz AC output in varying winds, a WECS can operate in two basic modes. It can run at whatever velocity extracts maximum power (see Figure 2.7) or it can keep constant shaft rpm. The first is not yet proven cost-effective. Although more power is being extracted over the range of wind velocities, complex controls must be provided to keep the ratio of tip speed to wind velocity constant. Since the rpm will not be constant, the current is not a constant 60 Hz frequency of the generated electricity. It can be converted, but the conversion equipment is also complex and incurs losses.

The second method, maintaining a constant rpm, also results in a simpler gearbox transmission. This is accomplished by varying the pitch angle of the rotor blades, thus keeping the power output more or less constant, and by the constraint of the AC power grid upon the generator. This can be seen in Figure 2.11, the power output curve for different mean wind speeds for the General Electric 500 KW wind turbine (a design study which was never built).

Figure 2.11



Assumed Power Output Curve for the GE(500 kW Rated Power) Wind Turbine

from (General Electric, 1976)

In Figure 2.11, the solid curve on the left is the theoretical power curve, while the dotted curve is the power output of the turbine. When the power input to the generator is less than that at rated wind speed, the rotor tends to turn at a slower rpm and hence will turn the synchronous generator too slowly to generate 60-cycle current. The power grid constraint makes the generator run as a motor at 60-cycle and constant rpm, drawing power from the grid in doing so. At wind speeds less than rated, power is less than rated power. This type of curve is the type the NASA/ERDA machines all follow. The flat portion of the "power out" curve is at 500 KW, the rated power, the maximum allowed level for the generator. When power is generated for velocities greater than V_r, the control system alters the pitch angle of the rotor blades to a less efficient level to "dump" the excess power so as not to overload the generator. Cut-in velocity is the wind speed at which the blades begin to turn. Cut-out is the wind speed at which too much force loading is being put on the system. At cut-out, the blades are feathered and a brake is applied to the rotor, stopping electricity production until the wind goes below cut-out level.

The mean wind speed for which this system was designed is about 6 meters per second. This corresponds to the lower part of the nearly vertically rising curve; the idea is always to avoid dumping energy since that reduces efficiency. If a system is not operated near its peak value, efficiency is lost here also. The design wind speed, a system trade-off parameter, affects the capacity factor (ratio of actual energy generated in a year to that generated in a year at the rated level). Obviously, a high-capacity factor means that the system utilization level is high but efficiency is suffering, and vice versa, with a low-capacity factor. This parameter must be optimized, taking economic usage considerations into account, during WECS design.

2.5 Operational Factors

The system described in Section 2.4 is built, basically, with "off-the-shelf" items giving high lifetime mechanical reliability. The gearbox, generator, and tower are all commercially used in other applications. The tower is normally a high-tension power line design.

The blades are the only items that are special and are, for the present, hand crafted. They are designed using helicopter blade technology. A few problems have occurred since they are not exactly helicopter blades. However, the problems are being examined and manufacturers state that they can and are being solved.

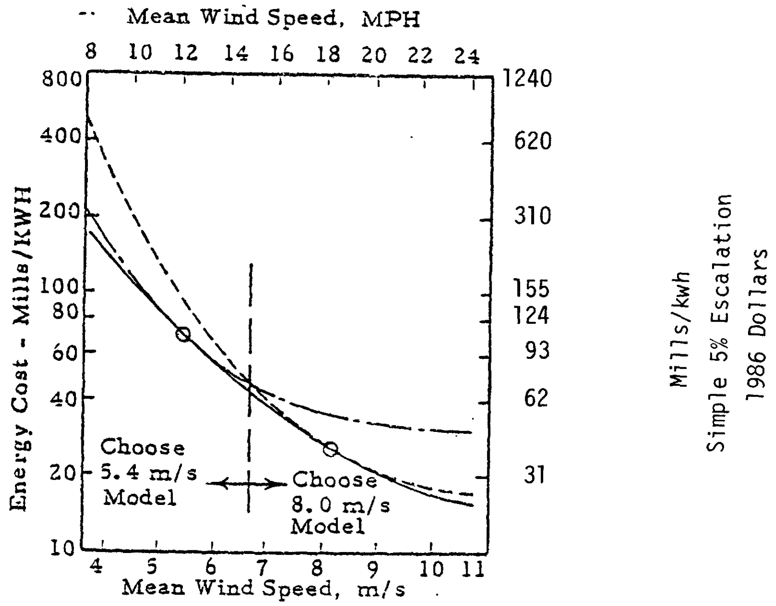
The initial two NASA/ERDA designs have aluminum blades (see Figure 2.10). Later NASA/ERDA designs will have fiberglass blades.

Operations and maintenance costs are not expected to be high (see Table 4.2 for estimates). The systems are designed for unattended operation once operational status is achieved. Exact figures cannot be given here for lack of data. No machine has ever run in commercial usage. All have been custom machines of varying designs up until now.

An important aspect of regional and site usage of WECS is that a few different models can be modularized for different average wind-speed ranges without significant loss of efficiency. The penalty paid for reasonable variations from non-optimum wind speed operation is small, offering potential cost reductions due to economics of mass production and prefabrication (JBF, 1977), (Figure 2.12).

WECS are also relatively insensitive to system lifetimes (from G.E. and Lockheed data). These data are plotted in Figure 2.13 for a 1.0 MW machine in a 5.4 m/s mean wind speed; economic factors are listed to the right. The JBF study states that the slight increase in energy cost (mills/KWH) on system life increases due to amortization over a longer time period.

Figure 2.12



Energy Cost Variation with Mean Wind Speed, Based Upon a Production Quantity of 1000.

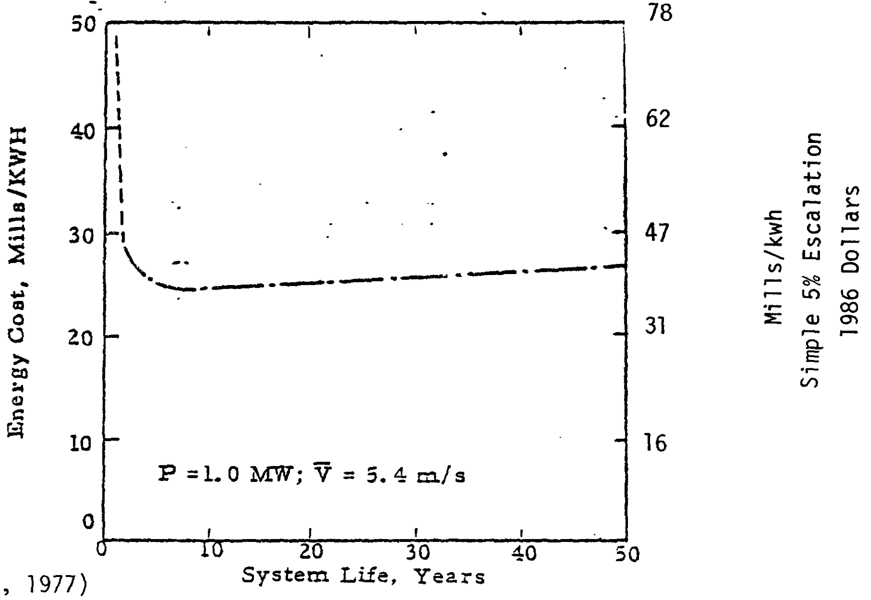
——— Locus of Optimum Designs - Minimum Energy Cost Curve

—— – System Optimized for 5.4 m/s (12 MPH) Mean Wind Speed

·– – – System Optimized for 8.0 m/s (18 MPH) Mean Wind Speed

from (JBF, 1977)

Figure 2.13



from (JBF, 1977)

Effect of Lifetime Variation on Power Cost

2.6 The Federal Wind Power Program Development Status as of 1977

The Federal Wind Power Program has had private contractors build a 100-KW rated HAWT in Sandusky, Ohio, at the NASA Plumbrook Station. This is called the "Model 0," or MOD-0 and is presently being reconfigured and used for testing and gathering data on operating procedures.

Two larger units, the 200 KW MOD-OA and 1.5 MW MOD-1 evolving from the MOD-0 presently exist; their specifications appear in Table 2.2. In the first phase of a test implementation program, 17 candidate sites for two MOD-OA's and one MOD-1 have been selected, and wind data and environmental data collected at them. The first MOD-OA is now being installed at Clayton, New Mexico. A MOD-OA unit has also been promised for Culebra, Puerto Rico. These units will be operated as part of the local power grid to identify interfacing problems. Construction has begun of a larger 3-MW MOD-2 unit by Lockheed. For a size comparison of the MOD-OA, MOD-1, and MOD-2, see Figure 2.14.

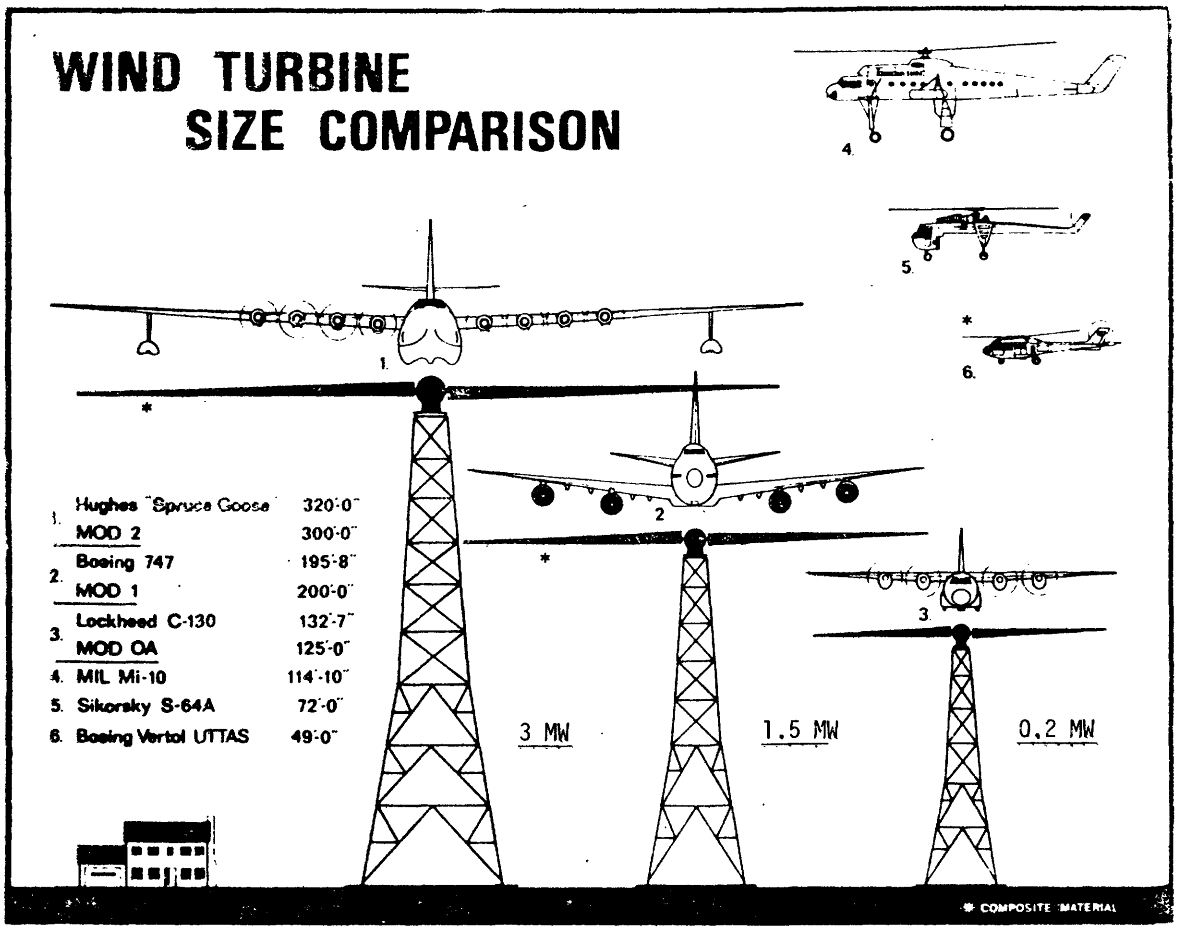
The technical know-how is here. Feasibility and economical use must be proven and that is what is being attempted by the Federal program. "Soft" data studies on reliability (capacity credit), siting, and wind data studies are continuing.

Table 2.2

Specifications of the MOD-OA and MOD-1 Wind Turbines

	MOD-OA	MOD-1
Total Height	165 ft.	250 ft.
Total Weight	91,000 lbs.	N.A.
Tower:		
Type	steel truss	steel truss
Height	100 feet	150 ft.
Base	30 x 30 ft.	N.A.
Peak	7 x 7 ft.	N.A.
Weight	47,000 lbs.	N.A.
Foundation	200 cu. yd. concrete slab	concrete slab
Rotor:		
Number of Blades	2	2
Type	aluminum	fiberglass
Rotor Diameter	125 ft.	200 ft.
Swept Area	12,265 sq. ft.	31,400 sq. ft.
Rotor Weight	4,000 lbs.	N.A.

Figure 2.14

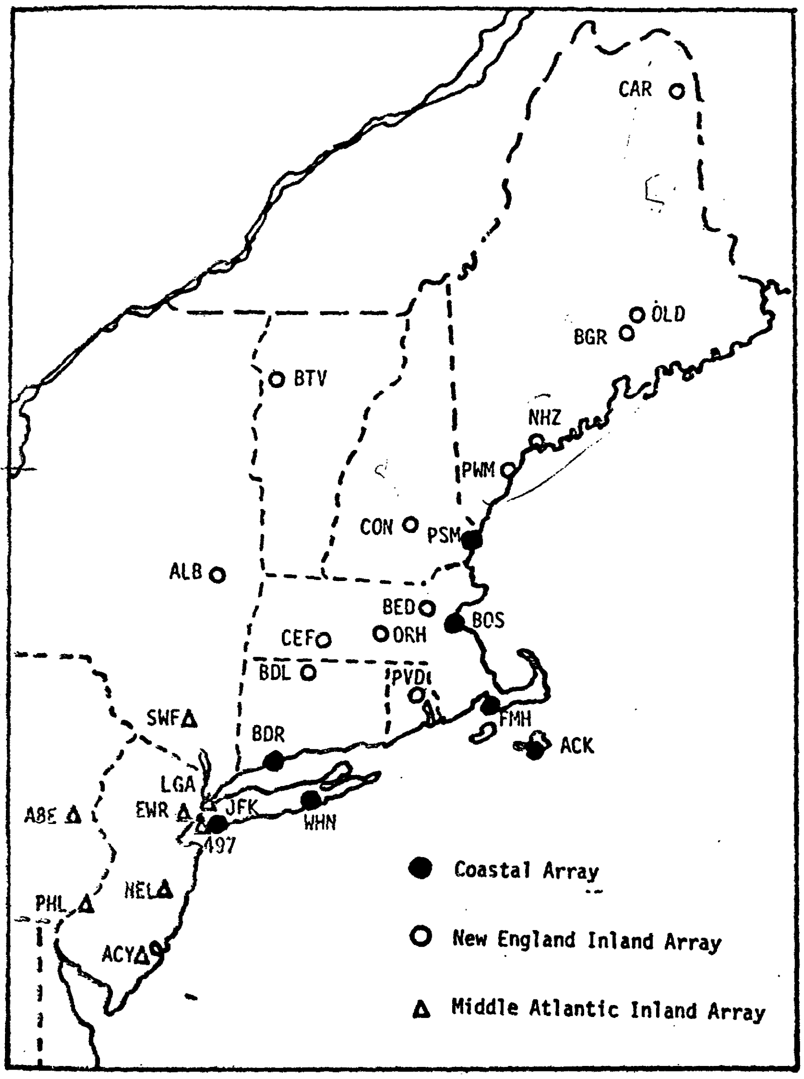


2.7 Reliability

A single wind turbine may be described by a capacity factor but at any time its power output is random. However, if many wind turbines are sufficiently dispersed over the countryside in an "array," such that wind speed variations are uncorrelated with each other, there will always be some power level in the system that can be "relied" upon. This "reliable" power can be expressed as a fraction of the rated power per generator. This has been done in a recent study (Justus, 1976). This study used five years of airport wind data (see Section 2.1) for the arrays and sites shown in Figure 2.15. The five Maine sites were included in the large "28-site array" and the New England Inland Array. Best results were achieved with the coastal array. Section 3 explains how these data might be interpreted for Maine.

These wind data were analyzed for reliable power levels using various WECS. The G.E. 500 KW rated unit usually had the best results. This design therefore represents the best current design model for achieving good capacity factors and reliability. Justus found monthly capacity factors and their standard deviations for 28 various site arrays of wind machines. The General Electric 500 MW unit had an annual capacity factor of 0.38 with a worst month case of 0.22 and a best month case of 0.54. These low capacity factors did not include storage.

Figure 2.15



Map of New England - Middle Atlantic Area Array Sites, Showing Three Sub-Group Arrays Studied Separately.

ALL OTHER SITES

ABE - Allentown, PA
ACK - Nantucket, MA
ACY - Atlantic City, NJ
ALB - Albany, NY
BOL - Windsor Locks, CT
BDR - Bridgeport, CT
BED - Bedford, MA
BOS - Boston, MA
BTV - Burlington, VT
CEF - Chicopee, MA
CON - Concord, NH
EWR - Neward, NJ
FMH - Falmouth, MA
JFK - New York City
(J.F. Kennedy, NY)
LGA - New York Vity
(La Guardia), NY
NEL - Lakehurst, NJ
ORH - Worcester, MA
PHL - Philadelphia, PA
PSM - Portsmouth, NH
PVD - Providence, RI
SWF - Newburgh, NY
WHN - Westhampton, NY
497 - New York
(Floyd Bennett) NY

MAINE SITES

BGR - Bangor
CAR - Caribou
NHZ - Brunswick
OLD - Oldtown
PWN - Portland

To test reliability with storage, frequency distributions of array power levels were prepared (see 2.1 for frequency distribution curves) and subjected to "return time analysis." An array power <u>return time</u> for a given power level is defined as the time required until array power returns above that level, once array power drops below the level. Power reliability without storage, from the power frequency distribution information, can be combined with power reliability data with storage, from the return time analyses (which tell the frequency or probability that an array will have a return time of a certain value or less).

If we provide storage for this gap in time when the power is below some level, then the probability becomes a power level reliability which can be used to compare wind power reliability with and without storage. Results for the seven site coastal array for January, April, July, and October, are shown in Table 2.3.

Table 2.3

Reliability of Power Levels of 10, 100, and 200 KW per Generator, with and without Storage. 7 Site Coastal Array or Individual Site. T is Storage Time in Hours. R is Reliability in Percent. T = 0 Indicates No Storage

		JAN								APR								JUL								OCT							
		GE				KAMAN				GE				KAMAN				GE				KAMAN				GE				Kaman			
		500		1500		500		1500		500		1500		500		1500		500		1500		500		1500		500		1500		500		1500	
		T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %	T hrs.	R %
10 KW/GEN.	IND.	0	78	0	60	0	73	0	57	0	80	0	60	0	73	0	55	0	72	0	44	0	63	0	38	0	74	0	51	0	67	0	46
	ARRAY	0	98	0	91	0	94	0	57	0	99	0	93	0	96	0	89	0	99	0	87	0	92	0	80	0	97	0	87	0	91	0	81
100 KW/GEN.	IND	0	64	0	54	0	57	0	51	0	66	0	53	0	54	0	48	0	54	0	36	0	38	0	31	0	59	0	44	0	46	0	40
	ARRAY	0	83	0	75	0	66	0	65	0	83	0	74	0	66	0	66	0	70	0	56	0	35	0	42	0	75	0	63	0	55	0	54
		20	90	22	90	31	90	32	90	13	90	17	90	27	90	21	90	15	90	22	90	26	90	28	90	19	90	28	90	34	90	39	90
		27	95	28	95	36	95	36	95	15	95	19	95	35	95	27	95	17	95	26	95	32	95	35	95	27	95	42	95	48	95	66	95
		47'	99	44	99	46	99	46	99	20	99	23	99	45	99	40	99	22	99	36	99	57	99	50	99	49	99	82	99	79	99	87	99
200 KW/GEN.	IND.	0	56	0	49	0	43	0	45	0	59	0	48	0	38	0	41	0	44	0	31	0	21	0	22	0	51	0	40	0	30	0	32
	ARRAY	0	65	0	62	0	42	0	50	0	65	0	62	0	43	0	51	0	44	0	37	0	17	0	23	0	53	0	49	0	30	0	38
		29	90	28	90	53	90	45	90	20	90	25	90	40	90	38	90	29	90	33	90	79	90	54	90	39	90	38	90	68	90	56	90
		19	95	38	95	68	95	59	95	25	95	33	95	53	95	52	95	37	95	49	95	104	95	71	95	53	95	48	95	103	95	77	95
		66	99	64	99	88	99	83	99	37	99	43	99	79	99	79	99	60	99	110	99	124	99	124	99	80	99	74	99	162	99	128	99

from (Justus, 1976)

The reliability levels of 10 KW power per generator are compared only for single sites versus arrays without storage. These data show that the improved statistics of arrays mean that some small amount of power (e.g., 10 KW per generator) is virtually always available with the array configuration. For 100 KW per generator and 200 KW per generator, the table compares reliabilities for individual sites and arrays without storage (T = 0) and the storage time in hours required to produce the given array levels with 90%, 95%, and 99% reliability.

The best case G.E. 500 KW machine has its return times circled at 200 KW for 95% reliability; it shows that 53 hours of storage in October is the worst case. Figure 2.16 also shows a sample of the distribution frequency data in graphical form. From the figure, it can be seen that by interpolation, the G.E. 500 KW wind turbine would have 90% reliable 200 KW per generator power output if there were a storage system with about 29 hours of power storage (i.e., 5800 KWH storage capacity per generator, 200 KW x 29 hours).

Time auto-correlations of wind data were also performed. It was found that, especially in the summer, a very high 24-hour correlation exists for arrays (the wind is basically at the same level at a given time from one day to the next). Further analysis of continuous wind data from the East Coast array showed wind speeds were the highest from noon to eight o'clock, especially in the summer. Conversion of these data to power vs. time of day per individual generator leads to Figure 2.17 for Boston. It shows that this diurnal variation of power follows summertime afternoon air conditioner load patterns well. However, these are preliminary data. Still, given this positive diurnal variation which follows utility load patterns, it probably can be said that reliabilities are even higher than return time analysis indicates. Return time analysis only distinguishes monthly time of year, not hours of the day.

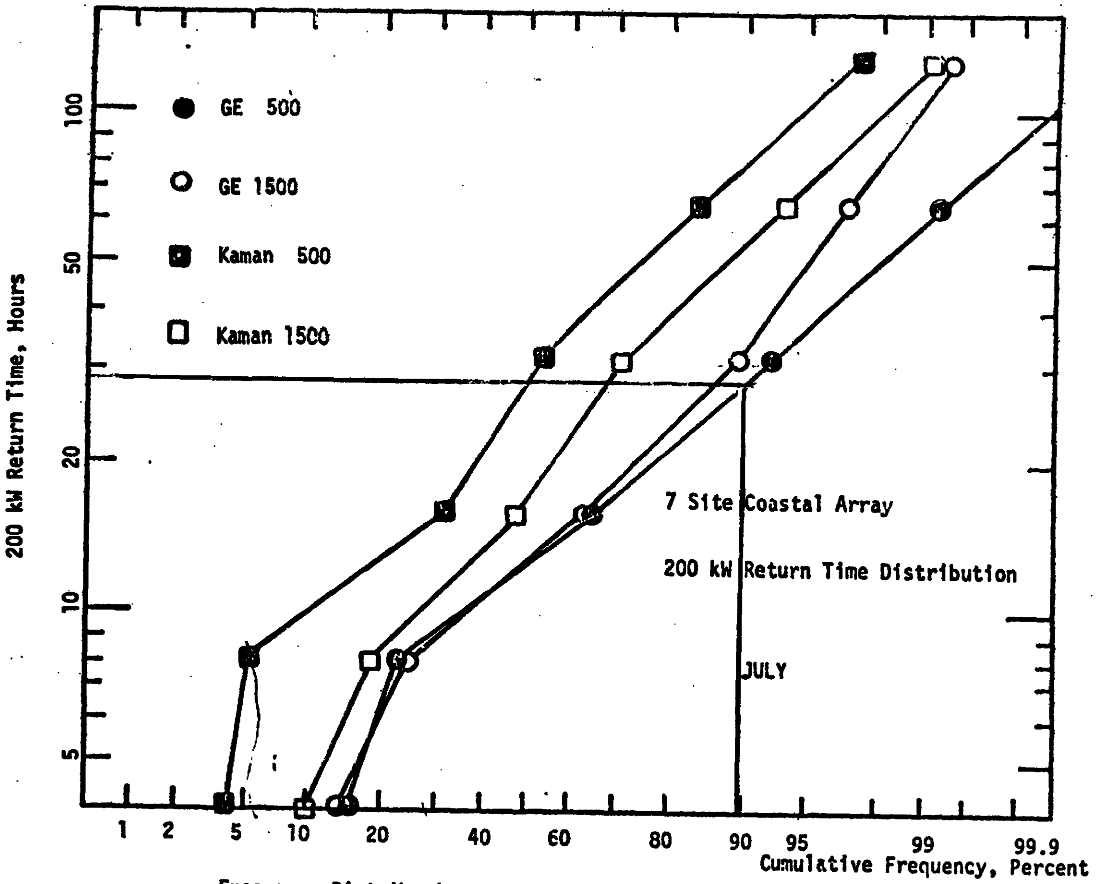
A recent study in Connecticut reinforces these general conclusions for WECS combined with storage (Coste and Lotker, 1977, p. 51). It was found that such combinations could provide reliable energy supplies, but that high average wind speeds (15 mph) and high costs (80 to 160 mills/KWH - 1975 dollars) might be needed.

Table 2.4

Five year monthly mean windspeed $\overline{V}$ at the 43 m (140 ft.) level for full array and 5 site Maine array. σ is standard deviation of monthly averages about five year monthly mean.

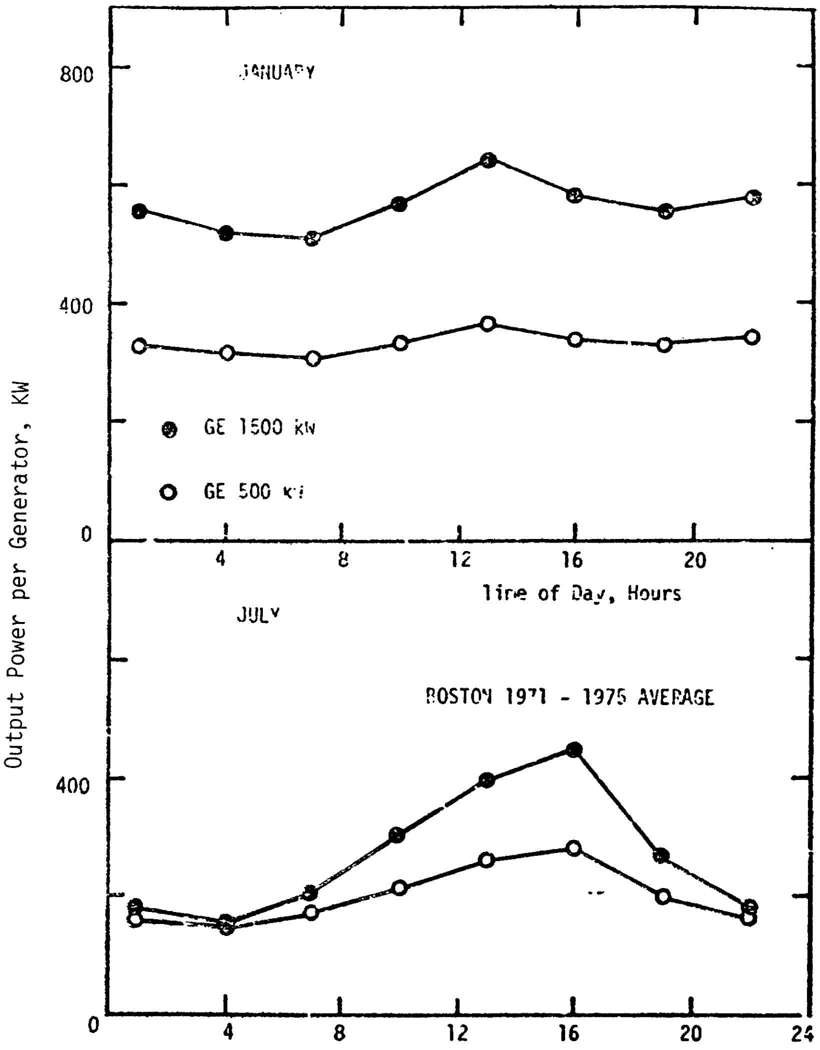
Month	28 Site Full Array		5 Site Maine Array	
	$\overline{V}$, m/s	σ, m/s	$\overline{V}$, m/s	σ, m/s
Jan	6.8	0.8	5.5	0.8
Apr	6.8	0.6	6.0	0.5
Jul	5.5	0.3	4.9	0.4
Oct	5.9	0.4	6.4	0.4
Annual	6.2	0.6	5.7	0.5

Figure 2.16



Frequency Distribution of 200 kW Return Times for 7 Site Coastal Array in July.

Figure 2.17



Time of Day, Hours

Mean Power Output for GE 500 KW and GE 1500 KW Wind Turbines Versus Time of Day in January and July (Boston)

3.0 APPLICABILITY TO MAINE

The purpose of this section is to point out particular aspects of the state of Maine which make WECS feasible or infeasible for use there.

3.1 Special Resource Needs

Traditionally, the coast of Maine, like the entire New England coast, is a region of high average wind velocity. If we return to the discussion on reliability in section 2.8, we recall that the seven site coastal array (Figure 2.15) consistently provided the best reliability with and without storage (for storage of 24 to 48 hours, the reliability was 95% at a value of 200 KW for the 500 KW G.E. machine) and the best test capacity factors. Unfortunately, none of the Maine sites from the 28-site array were included in this coastal array. In the report, monthly mean wind speeds (at hub height) and standard deviations were given for the five Maine sites for four months only. When these data are reduced to montly mean wind speeds and deivations for a "five-site Maine array," we see that it compares with the 28-site array, which is not quite as good as the coastal array (see Table 2.4).

These data, however, are suspect (as mentioned in Sections 2.1 and 2.8) because they are airport wind data. They do not reflect optimized wind sites since airports are not generally located in windy sites. An example that these sites were at best random is that Caribou (see Figure 2.15 for map), a northern inland site having a lower wind potential, had by far the greatest wind velocity averages.

Perhaps some of the data from the missing eight months would have made the "Maine array" more favorable also. It's probably safe to assume then that a WECS array in Maine at optimum sites could equal or better the coastal array.

Still, the 28-site array has an annual capacity factor of 0.38. As a fuel saver (see Section 4.1), a similar Maine array would need 1/.38 = 2.63 installed rated KW for every KW of conventional power for which fuel is saved.

For capacity credit (see Section 4.1), it should be possible to obtain 95% reliability at 200 KW for an array of G.E. 500 KW generators though storage would be needed (such as 24 to 48 hours for an array of optimum sites). We see that to generate the energy equivalent of 100 MW of conventional generation (70% reliable) we might need as many as 370 wind turbines. For 600 MW energy equivalent, as many as 2200 units would be required. If we assume that the new NASA/ERDA MOD-2 unit, rated at 3 MW, has the same reliability as the MOD-0 at six times the power level (not necessarily true), we would need 1/6 of the machines, or 370. This is assuming our design is the G.E. 500 KW design or one like it. This is not unreasonable, however, since there are many ways of optimizing a design (as witnessed by the different performance characteristics) and simple calculations such as these help define which of these "optimums" are most useful. At times such an array would produce near rated power (1100 MW).

We note, as for most states, only very basic wind data are available so far for Maine. This means that the only data found (by this report) were airport data and some basic isovent maps (as previously explained, not useful in more than a general way). The need therefore exists for a comprehensive wind survey to be performed on the state with potential WECS sites being singled out in the manner of finding hidden veins of ore; the end result being a large data base from which final siting can be performed on a local basis, and a determination made of potential WECS capacity.

3.2 Support Facilities

The fact remains that while a wind turbine is a non-polluting energy source, it will take up a considerable amount of room (typical dimensions: tower - 130', rotor - dia - 200', total ht. - 230'). According to an environmental assessment study on installed a MOD-0A or MOD-1 unit (ERDA, 1976) the ground area required for a site would be, at a minimum, a radial zone around the tower of 175' and 250' respectively. Estimating this zone to be about 200' for the G.E. 500 KW unit, the total land area required for 2200 WECS sites is 9.9 square miles. This doesn't include area used for power lines from each site to the main grid, access roads, etc., and the area for the sites is a minimum. Up to 550' radial distance might be required to protect from blade failure damage, raising the area to 75 square miles. The total area required for everything might be more than 75 square miles. A Swedish study (Ljungstrom, 1976) found that for 5,000 - 10,000 MW generated in Sweden by 1990, 350 to 870 square miles would be used. The same rate in Maine would yield 40-50 square miles for 600 MW. Such a large area of wind turbines with the accessory equipment such as power lines might clutter up what is generally considered an unspoiled state. For these environmental impacts, see Part 5, especially Section 5.1, visual intrusion.

4.0 WECS ECONOMICS

Unless otherwise noted, the data and charts presented in this section on the economics of wind turbines are primarily from a special technical report prepared for ERDA's Division of Solar Energy, the Federal Wind Energy Program, by JBF Scientific Corporation of Washington, D.C.

It is entitled "Summary of Current Cost Estimates of Large Wind Energy Systems," (JBF, 1977) and has the latest data in it as its issuance is February 1977. It summarizes data accumulated in eight different studies performed for the Federal Wind Energy Program listed in Table 4.1. Readers of this section wishing more detail on all the factors involved are directed to the report and the sources in Table 4.1.

Table 4.1

Data Sources

	Title	Contractor	Draft Report Date	Subject
1.	Design Study of Wind Turbines 50KW to 3000KW for Electric Utility Applications - Analysis and Design	Kaman Aerospace Corporation (Subcontracted from NASA Lewis Research Center)	Feb. 1976	Machine Design Study
2.	Design Study of Wind Turbines 50KW to 3000KW for Electric Utility Applications - Analysis and Design	General Electric (Subcontracted from NASA Lewis Research Center)	Feb. 1976	Machine Design Study
3.	Wind Energy Mission Analysis	General Electric	26 Oct. 1976	Mission Analysis
4.	Wind Energy Mission Analysis	Lockheed-California	Sept. 1976	Mission Analysis
5.	Wind Power for the California Aqueduct	The Aerospace Corp.	March 1976	Regional Analysis
6.	The Application of Wind Power Systems to the Service Area of the Minnesota Power and Light Company	Honeywell, Inc.	Oct. 1976 - Executive Summary 31 March 1976 Quarterly Report No. 3	Regional Analysis
7.	Applications Study of Wind Power Technology to the City of Hart, Michigan	Michigan State	Dec. 31, 1975	Regional Analysis
8.	Operational, Cost, and Technical Study of Large Windpower Systems Integrated with our Existing Electric Utility	Southwest Research	April 1976	Regional Analysis

4.1 WECS: Fuel Saver vs Capacity Credit

There are two basic ways to analyze cost and savings inherent with wind systems. The method used until recently is to calculate cost of fuel saved over some period of time by using the available energy from wind generation. This is the "fuel saver mode." Basically, this is to say that the energy from WECS is random just as the wind -- when we do have this energy, we turn off our most expensive conventional generating equipment, saving some amount of fuel costs.

Although we don't know when we will get the energy, we still know basically how much we will get over some reasonable period of time -- that is, the wind turbine can be given a capacity factor, (the ratio of the energy [kilowatts (power) x hours (time)] produced say, in a year, divided by the maximum energy possible [rated power x time]). The cost accounting is usually done over some time span, a year, for example. All the costs incurred over the time, such as the return on equity, operation and maintenance costs, money costs, etc. are added up and then divided by the total energy generated. This is usually called the energy cost and is in units of mills/KWH. To be economically feasible, this cost must be less than or equal to the cost in mills/KWH of some fuel or mix of fuels that, over the same timespan, represents the same block of generated energy. When the two are equal, this is called the "break-even" (no savings or loss) energy cost. Obviously lower values of energy cost are desirable to create savings.

In the above description, there were several variables affecting the break-even energy cost. Machine parameter variables (capacity factor, rated power, rotor size, etc.) determine WECS direct costs. There is the fuel that WECS energy replaced. Oil may be very expensive, while coal is less so. Then there are fuel price increases beyond inflation rates - an energy cost now that might be a losing proposition could turn out over a long time span to save money due to fuel price escalations. And there are money costs (i.e., financing charges and different schemes for paying for WECS). All must be determined for each site and design considered.

The other method for cost accounting WECS economics is to give them some "capacity credit." This means that at some high level of reliability (95%), with or without storage (see Section 2.8 on reliability studies), an array or group of wind turbines have a minimum fraction of their rated power that will always be available. Therefore, power companies can "credit" this minimum installed fraction of the total rated power as part of their base load of installed power. Here the WECS costs become more tractable as we can now compare them to the installation, capital, fuel, operating and maintenance costs of some conventional power-producing system of equal installed "credited" power. In this way, WECS capacity, when put in arrays of wind turbines, can be compared with other energy sources besides those using costly fuel such as gas turbines.

The next two sections will summarize WECS costs in tables and graphs for both the fuel saver mode and using capacity credit. However, most of the work done in this vein has been accounting for WECS economics as a fuel saver only, especially since hard operating data are less available than capital data on machine costs.

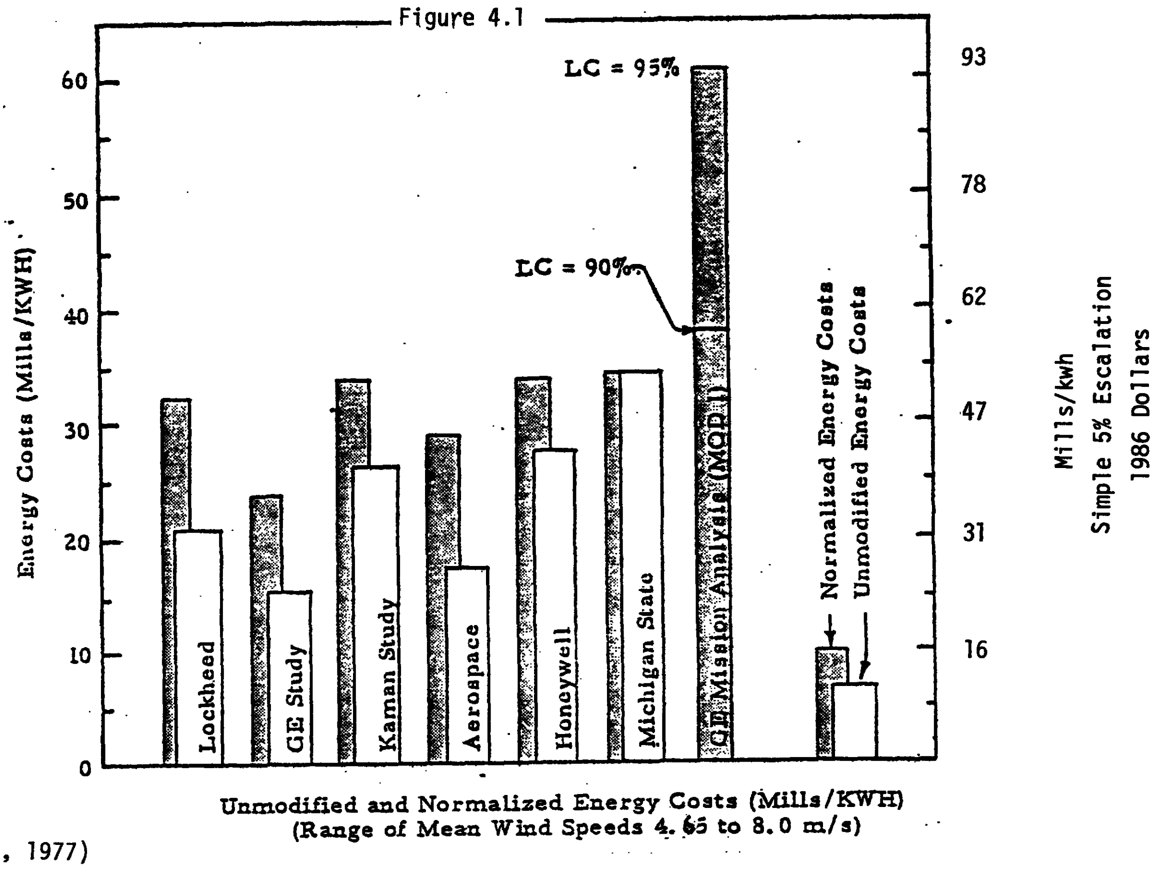
Capital cost goals (dollars per rated installed kilowatt) can also be defined if most variables such as operating costs, return on equity, installation cost, etc., are expressed as functions of machine capital cost (such as % yearly value of the purchase price of a wind turbine system). However, the total cost goal of the system is of most importance, and is usually more often detailed and of greater interest.

The values in tables and figures shown here are for 1975 dollars, and are normalized to the same costs of money (as far as this can be done for precomputed data), the same machine and wind parameters (α = .17, see Section 2.2), a production run of 100 units, and a learning curve of 95%.* The resulting costs are referred to as normalized WECS costs. The only data used for the study from a unit that was actually fabricated (instead of merely planned on paper) is from the second G.E. MOD-1 1.5 MW unit. The second unit was used to lessen the effect of R&D and first stage planning costs on the costs. However, it was basically a hand-crafted unit and thus does not truly reflect modern production savings. It will be seen from the following figures that the MOD-1 usually has a higher cost. A simple 5% escalation rate was assumed to estimate costs in 1986 dollars for comparison with other energy technologies.

4.2 WECS as a Fuel Saver

Analysis of energy costs as a fuel saver have been obtained from the data sources in Table 4.1 and are summarized in Figure 4.1. The study costs are normalized and there is a relatively small spread in the normalized costs from 42 to 60 mills/KWH (1986 dollars). This indicates that when basic design assumptions are made as close as possible, most experts agree in cost. However, these values are lower than the energy costs based upon the second G.E. MOD-1 unit.

Figure 4.1



Unmodified and Normalized Energy Costs (Mills/KWH)
(Range of Mean Wind Speeds 4.65 to 8.0 m/s)

from (JBF, 1977)

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*A learning curve quantifies cost reductions due to experience. LC = 90% means that a second production run unit will cost 90% of a first production run unit.

It should be recognized that energy costs and capital costs are interrelated, and that any uncertainty in the capital costs results in an uncertainty in the energy costs. Figure 4.2 shows the unmodified system capital costs as presented in the reports, and the normalized ones.

Table 4.2

Estimates of Possible Fuel Savings for Assumed WECS Implementation Rates

Source	GE MISSION ANALYSIS		LOCKHEED MISSION ANALYSIS	
Assumptions	Rapid Implementation	Medium Implementation	High Demand* Low Fuel Cost	High Demand High Fuel Cost
Year	2000	2000	1995	1996
WECS Rated Power Installed, Gigawatts	240.6	68.7	100.4	264.2
WECS Annual Energy Output, KWH x 10^9	581.3	165.9	440	1,246
WECS Capacity Factor	0.276	0.276	0.500	0.538
WECS, average % of Demand	7.3	2.1	8.1	19.3
WECS, Equiv. bbl. oil, x 10^6	852	245	779	2,204
Total U.S. Elec. Demand, KWH x 10^9	7,900	7,900	5,400	6,450

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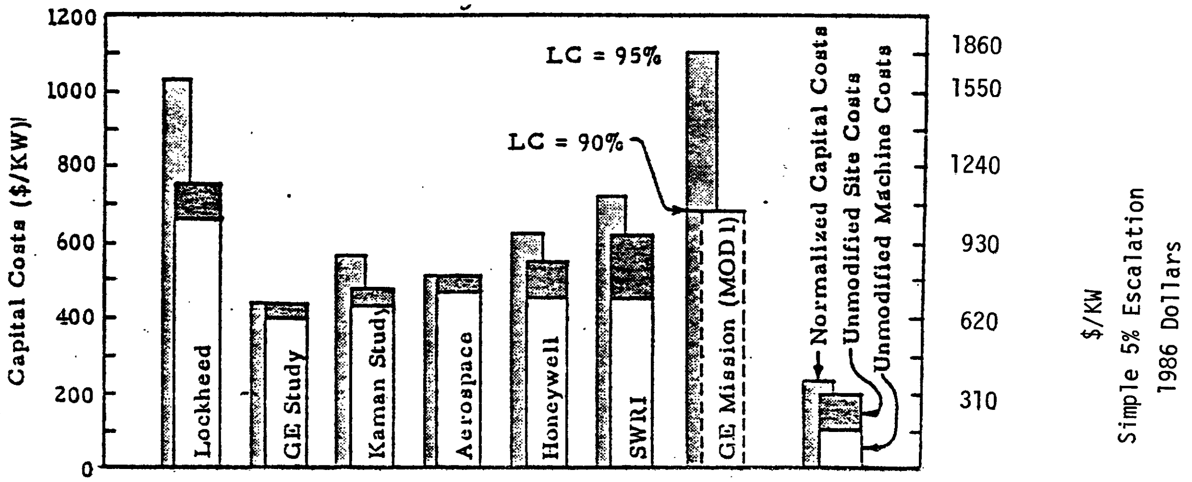
*Lockheed's preferred scenario.

from (JBF, 1977)

Figure 4.2



Unmodified and Normalized WECS Capital Costs ($/KW)

from (JBF, 1977)

The use of WECS by electric utilities could, in general, save quantities of coal, nuclear, oil, and gas fuels. For simplicity, all of these fuels have been measured in units of barrels of oil of equivalent energy. The G.E. Mission Analysis (Table 4.2) estimated that a 150-MW WECS farm would save approximately 744,000 equivalent barrels of oil per year. Their estimate was based upon the use of a high wind regime.

Lockheed estimated fuel savings of 1,252,000 equivalent barrels of oil per year for the same size farm; the greater estimated savings are due to the larger rotor and high capacity factor (Table 4.2). If capacity factor is reduced to the G.E. value, the resulting fuel savings are within 20% of the G.E. estimate. Lockheed also estimated that if rapid implementation of WECS occurs by 2000, to a level of 7% of total U.S. energy consumption, annual fuel savings would be on the order of 800 million equivalent barrels of oil. This is in Table 4.3 along with the capital investment requirements associated with the WECS -- no storage case, indicating that a total investment of approximately 80 to 100 billion would be required. If capacity credit is allowed, the figures are less proportional.

Table 4.3

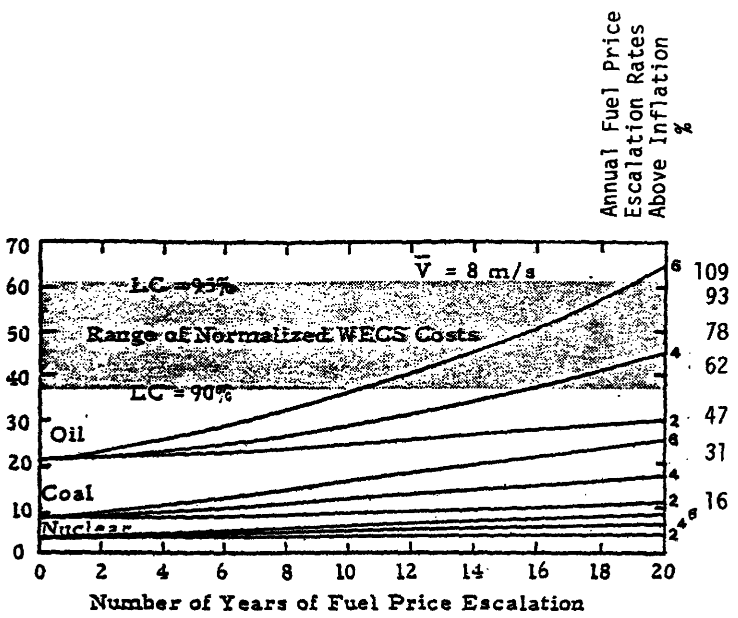
Investment Requirements, Rapid WECS Implementation

Source	Assumed WECS Rated Power $\times 10^6$ KW	WECS Energy $\times 10^9$ KWH/yr	% Nat. Elec. Energy Demand	WECS Inv. \$ $\times 10^9$	Fuel Savings \$ $\times 10^9$/yr
Lockheed	100.4	440.0	6.8	60.5	9.35
GE	240.6	581.3	7.5	99.3	10.22

from (JBF, 1977)

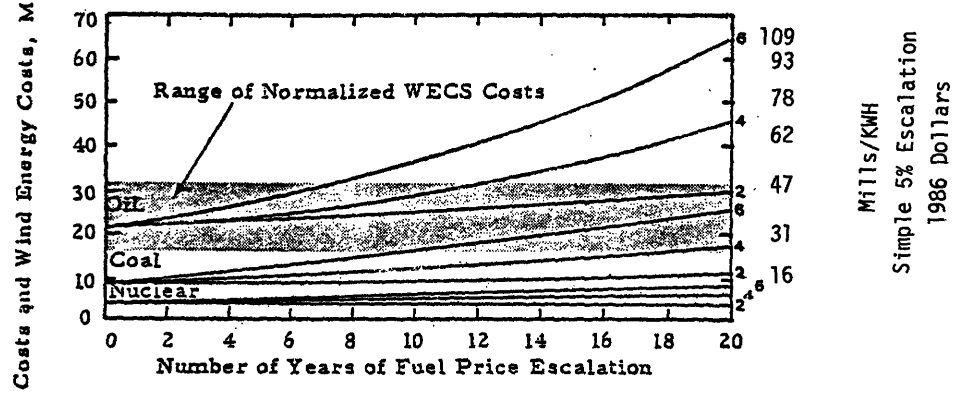
Earlier it was implied that fuel saver costs were enhanced by fuel escalation prices. Figures 4.3 through 4.5 show fuel escalation curves superimposed over the ranges of normalized WECS costs for the second G.E. MOD-1 unit (at an 8 m/s wind site) and for 8 m/s and 6 m/s wind regimes respectively. The fuel price escalation curves show the effects of annual price increases of 2%, 4% and 6% above the inflation rate for oil, coal, and nuclear fuel over a 20-year period. In comparing the WECS energy costs with fuel costs in these figures, it should be remembered that no credit is given for lower capital requirements of conventional equipment due to installation of WECS.

Figure 4.3



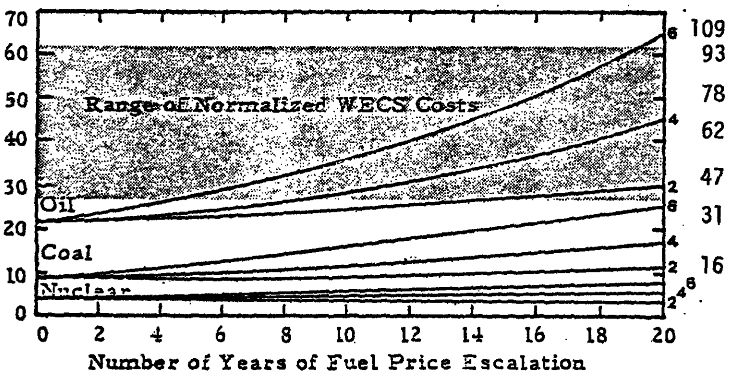
Normalized Wind Energy Costs for the Second GE MOD 1 Unit vs. Escalating Fuel Costs

Figure 4.5



Study Estimates of Normalized Wind Energy Costs for 8 m/s Wind Regime vs. Escalating Fuel Cost

Figure 4.5.



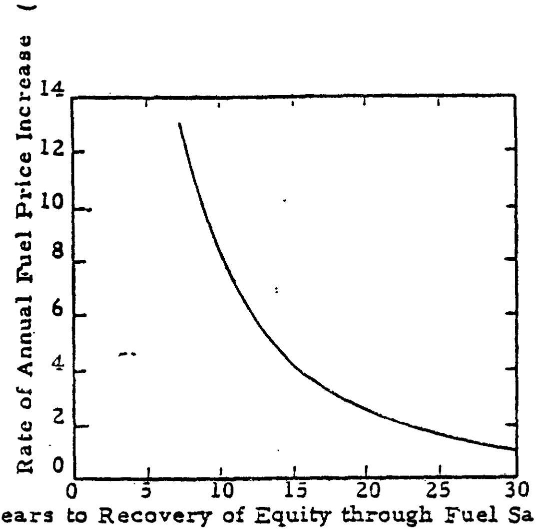
Study Estimates of Normalized Wind Energy Costs for 6 m/s Wind Regime vs. Escalating Fuel Costs

from (JBF, 1977)

The data presented in Figures 4.3 through 4.5 provide estimates bounding the time interval that must elapse before WECS energy costs become competitive with conventional fuel costs. The time interval for WECS to reach competitive energy costs in Figure 4.3 is pessimistic because the energy costs associated with megawatt scale WECS are likely to decrease over time as a result of R&D programs aimed at advancing the state of technology.

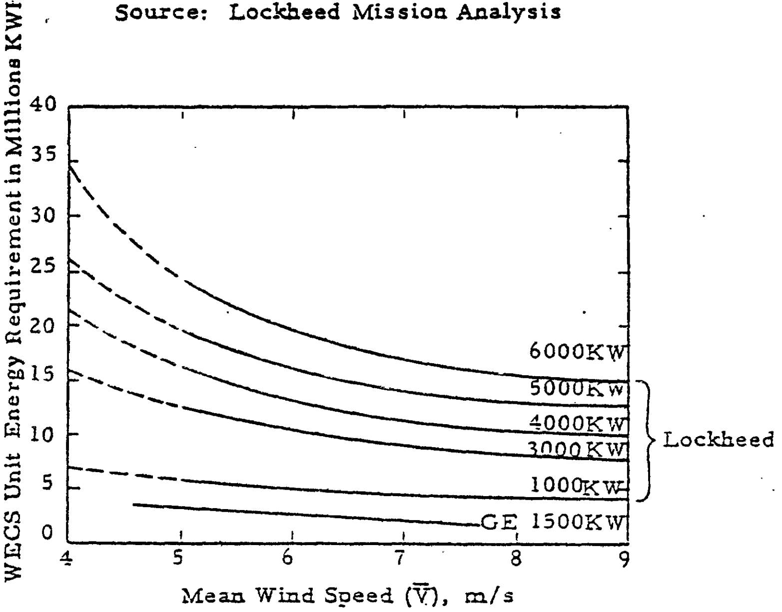
The time intervals for WECS to reach competitive energy costs, reported in Figures 4.2 and 4.3, are undoubtedly more optimistic because they represent study estimates based on the existence of an "optimized" system, designed with no consideration given to the possibility of cost escalations during hardware development. The data presented in these three also imply a range of improvement in WECS energy costs which could be achieved through R&D. Along capital cost lines, Figure 4.6 shows the years to recover the equity through fuel savings based on different rates of annual fuel price increases. This points out that if the energy crisis is going to get worse, as President Carter has recently stated, WECS energy will prove more attractive. President Carter's statement of energy implementation through solar energy (the basis for winds), tax breaks, and federal aid may make financing easier, especially for municipal or other government authorities.

Figure 4.6



Effect of Fuel Price Rise on Time to Recover Investment
Source: Lockheed Mission Analysis

from (JBF, 1977)



Installed WECS Unit Energy Requirement vs. Mean Wind Speed Source: Lockheed, GE Mission Analysis

from (JBF, 1977)

4.3 WECS With Capacity Credit

The magnitude of capacity credit attributed to WECS is a function of machine reliability, the wind distribution, the energy demand profile and the assigned overall power availability requirements. Determination of the economics of capacity credit to be allocated to WECS is quite complex and depends on the mix of conventional generation displaced by wind energy. The methodology to do this is still emerging and will be refined and extended under the two regional studies now being conducted this year for the Federal Wind Energy Program.

However, as we saw in Section 2.8 on on reliability, capacity credit is very closely related to reliability of WECS arrays which are geographically dispersed to give the highest reliability. Also it was shown in Section 2.8 that for the Northeast, wind speeds are not only very highly correlated on a 24-hour basis, but (although these are preliminary data, not to be taken as completely proven) on a diurnal basis. Wind speeds statistically are highest in summer during a noon to eight o'clock peak (meaning highest wind energy is available then) corresponding to summertime air conditioner and work-day high load factors (see Figure 2.14). These data were only done for one Eastern city (Boston) and utilized wind speed data from non-optimum sites and measuring equipment, hence one is led to believe sites could be selected with even better behavior. It is with this in mind that the following data from the reliability study of Section 2.8 (Justus, 1976) are presented showing the cost effectiveness of various wind turbine designs as a fuel saver.

Using a system (explained in his text) the author evaluates the break-even wind turbine cost in dollars per rated kilowatt under alternate assumptions. Condition 1 (pessimistic) assumes that the amount of each type of fuel saved by the use of wind power is saved in proportion to the amount of fuel of that type presently used (i.e., if present fuel usage is 60% coal and 40% oil, then 60% of the fuel saved will be coal and 40%, oil). This assumption implies that wind availability is so random that no better than this proportional replacement can be reached. Condition 2 (optimistic) assumes that only the most expensive fuel (e.g., oil) will always be replaced by wind power. This assumption implies that wind power is always available during times when expensive fuel is in use, an optimistic assumption. In other words, reliability and therefore some capacity credit exist. Actual conditions would be expected to fall somewhere between conditions 1 and 2, with 2 being more nearly correct as the reliability increases. Figures are shown in Table 4.4 for a coastal array for five turbine designs. The ratios in the last two lines must be greater than one for WECS to be cost-effective as a fuel-saver.

Table 4.4

Estimated Cost-Effectiveness of Various Wind Turbines Based on Five Year Average Capacity Factors at the 7 Site Coastal Array. Condition 1 Refers to Only Proportional Fuel Replacement (pessimistic). Condition 2 Refers to Only Most Expensive Fuel Replacement (optimistic). Ratios of Necessary to Actual $/kW Greater than 1 are Cost-Effective.

$/KW Added - 1986 Dollars - Constant 5% Escalation

Wind Turbine	GE 500	GE 1500	Kaman 500	Kaman 1500	Boeing 1000
Annual Capacity Factor	0.48	0.22	0.31	0.16	0.37
Break-Even $/kW (Condition 1)	1000	458	646	333	771
1986 $/KW	1550	710	1001	516	1195
Break-Even $/kW (Condition 2)	1500	807	1047	647	1207
1986 $/KW	2325	1251	1623	1003	1871
Estimated Actual $/kW	974	449	841	498	600
1986 $/KW	1510	696	1304	772	930
Ratio Necessary to Actual (Condition 1)	1.03	1.02	0.77	0.67	1.29
Ratio Necessary to Actual (Condition 2)	1.54	1.80	1.24	1.30	2.01

from (JBF, 1977)

It was found by the G.E. analysis that the WECS capacity credit could be a major component of break-even cost. In regions where fuel costs are high and the utility is heavily dependent on oil-fired generating equipment, the contribution of capacity credit to break-even cost is less than 40%. When the value of WECS to the utility results mainly from displacement of new base load capacity, which uses less expensive fuels, the contribution of capacity credit to the break-even cost may be as high as 80%.

Table 4.5 and Figure 4.7 present these data on break-even costs, estimated by G.E. without rigorous analysis. Table 4.5 shows the impact of wind regime on break-even capital costs. Figure 4.6 represents the break-even capital cost for WECS as a function of mean wind speed for the Northeast where fuel and plant costs are higher than average, and for the West, where they are lower than average. Thus, it can be seen that capacity credit improves cost feasibility, and that WECS systems in the Northeast stand a better chance of being implemented. Nevertheless, the exact load demand curve of power vs time for different times of the year and the exact prices of fuel, installation, operation and maintenance, etc., costs must be known for Maine for an exact analysis, as well as having wind data that are thorough and appropriate.

Table 4.5

WECS Breakeven Capital and Energy Cost Goals Based on 1975 Fuel and Plant Prices

1975 Dollars Only

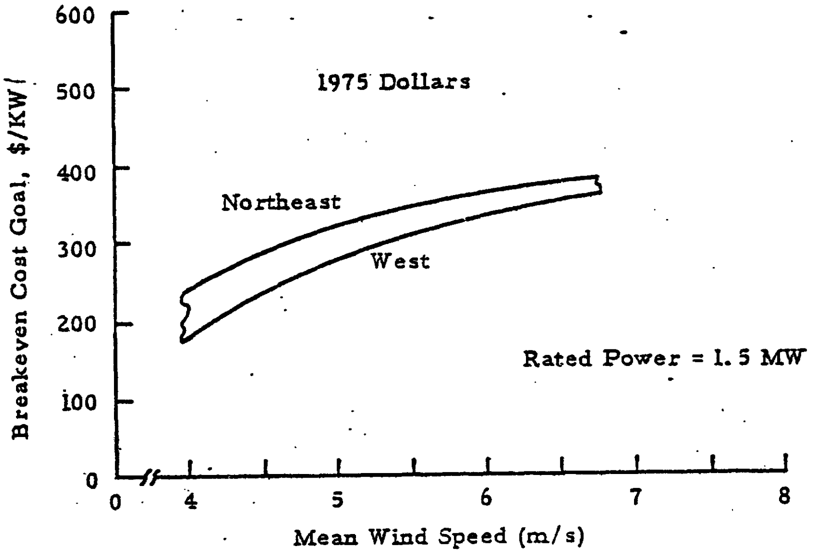
Wind Regime	Wind Speed	WECS Breakeven Capital Cost Goal*	Capacity Factor Used	WECS Breakeven Energy Cost Goal
	m/s	$/KW		mills/KWH
High	≥ 6.7	360	0.38	20
Moderate	5.4 - 6.7	310	0.33	20
Low	4.0 - 5.4	200	0.22	19

*Assuming no fuel price escalation

Source: GE Mission Analysis

from (JBF, 1977)

Figure 4.7



Maximum and Minimum Values of WECS Breakeven Costs
(Assuming no fuel price escalation)

Source: GE Mission Analysis

from (JBF, 1977)

4.4 Other parameters

Minimum energy cost decreases with increasing mean wind speed in a decreasing fashion, that is, good wind environments are needed but they don't have to be the best, Some variations of energy cost with WECS parameters are shown in other sections. Figure 2.12 in Section 2.6 shows how only a few optimized wind regime units need be made for any wind regime. And Figure 2.5 in Section 2.3 shows how energy cost decreases with rated power, pointing to how large modular units are the most cost-effective and available to utilities. It doesn't show, however, that rated powers greater than 3.0 MW and blade diameters over 300 feet cause non-standard commercial parts and scaling-strenth problems so that costs probably go up beyond these limits. Figure 2.9 in Section 2.3 shows energy cost vs rotor diameter. Note how much cheaper it is for large machines, and how the cost due to scaling strength effects and lack of experience in large sites causes costs to increase or level out eventually.

5.0 ENVIRONMENTAL IMPACTS

This section defines the major effects of WECS (the NASA/ERDA MOD-OA, and MOD-1 in particular) upon the environment and points out ones that affect Maine especially. The material in this section is from "Installation and Field-Testing of a Large Experimental Wind Turbine Generator System at Clayton, New Mexico" (ERDA, 1976).

5.1 Visual and Noise Intrusion

In urban areas, people accept similar tower structures such as radio and transmission line towers. The nacelle at the top of the tower is streamlined. Annular trace of the blades is avoided by proper painting and strobing blade tip aircraft lights into a vertical position if required. Sites must be open to avoid adverse wind flows so that foliage camouflage cannot be used. Maine is considered especially scenic outside of urban areas and wind turbines with power lines might be opposed in an otherwise virgin setting, especially if forest clearing for better wind effects is necessary. A variation of this problem is that individual or small groups of wind turbines might be more acceptable than large "wind farms."

The recent resurgence of public interest in wind energy technology would indicate that any public reaction would be mixed. ERDA/NASA experience with the MOD-0-WECS at Plumbrook, Ohio, suggests that it is possible that there may be no adverse visual impact associated with solitary wind turbines.

Noise associated with the operation of large horizontal axis wind turbines is insignificant. Noise measurements have been made at the MOD-0 wind turbine in Plumbrook, Ohio; gear noise and the sound of wind passing over the blades during operation cannot be heard above wind noise at distances greater than 50 feet from the turbine.

5.2 Erection and Site Access

Erection of a MOD-OA or MOD-1 is expected to take nine months or less and use ten men or less. Some permanent access roads may have to be built. Of large equipment, only a large crane is needed to assemble the unit. Some site clearing of remote regions is expected; however, most sites will be picked for openness as this means better wind quality. Destruction of areas of trees is thus unlikely. Total area taken up by WECS is not expected to be large (see Section 3.2).

5.3 Public Danger

Three dangers are inherent in tower windmills: first, possibility of injury due to unauthorized climbing or access; two, tower failure; three, blade failure. The first problem is shared with public facilities such as water and transmission towers. When necessary, fencing can be erected. Also, an elevator-like platform to the top could be remote-controlled. The second problem occurs with any tower and the wind turbine failure is most likely due to very high winds or earthquakes. Here a limited use cordon, slightly larger than the height of the tower (should it fall) could be provided around the tower. The maximum wind design speed is usually 120 mph. Anyone out in wind that high would be in serious trouble anywhere.

The problem computations performed by the NASA-Lewis Research Center indicate that an unrestrained MOD-OA or MOD-1 wind turbine blade could be propelled up to 550 feet from the tower base if it broke away from the hub at its constant operating rpm and at optimum blade throw angle (less than optimum means a shorter distance). To eliminate this possibility, sensors on the blades, rotor, tower, etc. would automatically shut down and brake the system at any warning of structural failure or excessive loading (such as icing). Blades could also be feathered and braked at cut out speed (40 mph for MOD-OA and 60 for the MOD-1). Due to uncertainties regarding blade loading experienced by early machines (see Section 1), the MOD-OA wind turbine will be equipped with a heavy steel "fail-safe" cable which connects the two rotor blades through the hub (if rotor failure occurs, this cable will serve to prevent shedding, minimize blade throw and maintain ground clearance).

5.4 Airspace Restrictions

In general, structures below 500 feet are not required to have aircraft warning lights; the largest unit to date, the MOD-2, is 330-feet tall at the tip of a vertical upper blade. Near airports, the FAA may require the painting of the blades with orange and white bands to increase the turbine's daytime visibility, and the installation of 300 mm red warning lights on the tower and/or blades.

5.5 Radio Signal Interference

Large horizontal axis wind turbine rotors can cause interference with high frequency waves. The signals which may be affected are in the FM radio, television and microwave frequencies at reception points where geometries favorable for interference occur among the wind turbine, transmitter and receiver. (FM radio and television rotor reflected interference signals carry amplitude modulation at various frequencies.) Therefore investigation of interference on an individual site-by-site basis must be performed. Some general rules follow.

The primary criterion for microwave interference is the ratio of the voltage of the interference signal reflected from the turbine rotor (V_{int}) to the voltage of the primary signal received at the microwave antenna (V_{in}). Where

$$\begin{aligned} \frac{V_{int}}{V_{in}} &\leq 1\% = \text{no serious interference;} \qquad (5.1) \\ &= 1\% - 5\%, \text{ some nuisance problems;} \\ &\geq 5\% \text{ noticeable interference.} \end{aligned}$$

It is believed that microwave interference can be avoided by careful, detailed siting.

For the MOD-0A aluminum metal rotor and MOD-1 fiberglass rotor, reflection is about the same. The MOD-0A rotor is approximately one-half the size of the MOD-1 but fiberglass is 50% less reflective than aluminum. Amplitude modulation at one Hz or less will be caused by rotor rpm, and up to 100 Hz by scattering of radio waves as they illuminate the curved surfaces of the revolving blades. The severity of interference is regulated by the distance of the wind turbine from the transmitter, the frequency of the signal, the geometry of the receiver with respect to the wind turbine and transmitter and the quality of the receiving antenna and set. Signals in fringe reception areas with shorter wave lengths and higher frequencies will be most affected. When a modulated interference signal reaches or exceeds a threshold percent ($s = 0.15$) of the signal received, noticeable distortion of the television image (video signals are AM, audio, FM) occurs. This interference in cities or urban areas is usually no worse than that due to steel skeleton buildings. In rural districts, houses will usually be too far away from WECS to be affected.

Aircraft FAA/VOR navigation beacon interference could result if aircraft fly within three or four kilometers of a WTG which is in the line-of-sight of a nearby VOR facility. Such a condition would be due to reflection and frquency modulation of the time-bearing signal, particularly if the modulation occurs at 30 Hz. Careful WTG siting could eliminate this problem.

5.6 Wildlife Danger

Danger to wildlife is restricted exclusively to flying birds, and almost exclusively to migrating types. Most of these birds fly at altitudes well above WTG height. Regional wildlife assessments for Maine would tell for a particular site which migratory types could be flying low. The probability of a flying bird being struck by a revolving blade is slight, and the chances of a bird hitting the tower are the same for any other type of girder tower; this is less than the chance for a solid building. Night-time is usually the likely time for bird collisions to to loss of visual reference and disorientation due to flashing tower lights,

6.0 CONCLUSIONS

- Existing wind data for Maine are inadequate for designing and evaluating large-scale applications of wind energy conversion systesm (WECS), although Maine, and especially the coast, is generally a high wind speed region.

- Horizontal axis wind turbines (HAWT) are preferable to vertical axis wind turbines (VAWT) for the production of bulk central electric power. VAWT are more desirable for very small applications.

- HAWT are composed of off-the-shelf commercial technologies, except for the turbine blades which are of unprecedented size and must be hand-crafted. Current development plans include units ranging from 0.5 to 3.0 MW capacity. Pilot unit testing of these units has just begun. No commercial experience exists with large-scale WECS.

- WECS can best be operated in a fuel saver mode. Capacity credits for reliable power are small because of wind variability. Selecting sites with high mean wind speeds and installing storage increase the reliable power level and capacity factor.

- As a fuel saver, WECS are theoretically expected to supply energy at a 1986 cost of between 40 and 60 mills/KWH for sites with mean wind speeds between 10 and 18 mph. Pilot plant experience indicates 1986 costs of 65 to 100 mills/KWH are likely.

- Study estimates show fuel saver WECS energy costs becoming competitive with coal costs between 1986 and 1997, if coal costs escalate at 6% above inflation. Lower coal cost escalation delays the break-even point. Pilot plant experience places break-even beyond 1995. These comparisons assume WECS escalation will be completely offset by savings from technological developments and production efficiencies.

- Capital cost studies for WECS units show 1986 costs between $750/KW and $1750/KW. Pilot plant experience would indicate $1900/KW 1986 costs. Capacity credit mode break-even costs range from $570/KW to $2670/KW in 1986 dollars. The pilot plant is expected to be cost-effective in a capacity credit sense when installed in arrays which increase reliable power ratings.

- Environmental impacts include possible aesthetic objections to numerous (300 to 2200 for the energy equivalent of a 600 MW coal plant) large (320') structures; land use restrictions; danger from blade failure; airspace restrictions; TV, radio, and microwave interference and wildlife (birds) danger.

7.0 REFERENCES

Coste, W., and M. Lotker, "Evaluating a Combined Wind Power/Energy Storage System," Power Engineering, pp. 48-51, May 1977.

ERDA, "Installation and Field Testing of a Large Experimental Wind Turbine Generator System at Clayton, NM," Wind Systems Branch, Division of Solar Energy, Energy Research and Development Administration, Nov. 1976.

ERDA, "Summary Report - Federal Energy Program," Wind Systems Branch, Division of Solar Energy, Energy Research and Development Administration, Jan. 1977.

General Electric, "Design Study of Wind Turbines, 50 KW to 3000 KW for Electric Utility Applications, Analysis, and Design," prepared for NASA Lewis Research Center, Contract NAS-3-49403, Feb. 1976.

Golding, E.W., The Generation of Electricity by Wind, E. & F.N. Spon Ltd., Great Britain, 1955.

Jagaden, T.S., "Windmills Stage a Comeback," IEEE Spectrum, Nov. 1976.

J.B.F., "Summary of Current Cost Estimates of Large Wind Energy Systems," Special Technical Report, JBF Scientific Corp., Report HQS/2521-77/1, ERDA Contract No. E(49-18)-252, Feb. 1977.

Justus, C.G., "Wind Energy Statistics for Large Arrays of Wind Turbines (New England and Central U.S. Regions)," Final Report, Georgia Institute of Technology, School of Aerospace Engineering, Aug. 1976.

Kaman, "Design Study of Wind Turbines, 50 KW to 3000 KW for Electric Utility Applications, Analysis and Design, Kaman Aerospace Corp., Prepared for NASA Lewis Research Center, Feb. 1976.

Kocivar, B., "World's Biggest Windmill Turns on for Large Scale Power," Popular Science, Vol. 208, No. 3, p. 73, March 1976.

Ljungström, O., "Large Scale Wind Energy Conversion Systems (WECS): Design and Installation as Affected by Site Wind Energy Characteristics, Grouping Arrangements and Social Acceptance," Wind Engineering, Vol. 1, 1977.

Percy, T., "Electric Power from the Wind," Office of the Chief Engineer, Federal Power Commission, 1945.

Percy, T., "The Wind Power Aerogenerator - Twin Wheel Type," Office of the Chief Engineer, Federal Power Commission, March 1946.

Putnam, P.C., Power from the Wind, Van Norstrand, Reinholt Co., Pub., Copyright by S. Morgan Smith Co., 1948.

Simmons, D.M., Wind Power, Noyes Data Company, 1975.

S.T.U., Proceedings of the Advanced Energy Systems Workshop, Aug. 1974, Vols. I and II, S.T.U./Vattenfall, S.T.U. Information Section, S.T.U. Investigation No. 52; Stockholm, Sweden, 1976.