Dr # 1227

COO/2578-1/1

WIND ENERGY MISSION ANALYSIS

Executive Summary

February 18, 1977

Work Performed Under Contract No. EY-76-C-02-2578

Space Division
General Electric Company
Philadelphia, Pennsylvania

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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FEBRUARY 1977

**JOHN A. GARATE
PROGRAM MANAGER**

**PREPARED FOR THE UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
DIVISION OF SOLAR ENERGY**

**ERDA CONTRACT NO. EY-76-C-02-2578
(FORMERLY: E(11-1)-2578)**

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GENERAL ELECTRIC

SPACE DIVISION

Valley Forge Space Center

P. O. Box 8555 • Philadelphia, Penna. 19101

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WIND ENERGY MISSION ANALYSIS

Table of Contents

	Page
PRINCIPAL RESULTS AND CONCLUSIONS	1
WECS DESIGN, COST AND PERFORMANCE CHARACTERISTICS	4
WIND ENERGY DISTRIBUTION	6
WIND AVAILABILITY	8
ELECTRIC UTILITY APPLICATION	10
RESIDENTIAL APPLICATION	18
PAPER INDUSTRY APPLICATION	22
AGRICULTURAL APPLICATION	22
REMOTE COMMUNITIES APPLICATION	23
ASSUMPTIONS AND LIMITATIONS OF THE ANALYSIS	24
DEFINITIONS	26

FOREWORD

The Federal Wind Energy Program was initiated in fiscal year 1974 as a modestly funded activity under the auspices of the National Science Foundation after nearly 30 years of relative inactivity in this country toward utilization of wind energy. The program has grown rapidly, and in January of 1975 was transferred from the National Science Foundation to the then newly-formed Energy Research and Development Administration (ERDA).

To pursue the development of wind energy a number of parallel activities were initiated to address the many questions existing at the initiation of the program. These activities were developed to address certain areas by more

than one project in order to provide comparative results and to furnish a measure of the level of uncertainty. Other projects were devised to be complementary and to investigate specific questions in more depth. This report represents the results of one of these projects.

Many uncertainties exist in the present level of understanding of the operation, performance, and economics of wind energy systems. Before a firm answer is obtained regarding the long term potential economics and utilization of windpower, present estimates must be verified by the development, testing, and evaluation of modern, advanced wind turbines.

The General Electric Space Division conducted this study and was supported by TEMPO (GE Center for Advanced Studies) and GE's Electric Utility and Systems Engineering Department (EUSED). TEMPO investigated alternative implementation scenarios including the analysis of institutional barriers and impacts to implementation; EUSED performed the breakeven cost analysis of WECS in the electric utility sector.

PRINCIPAL RESULTS AND CONCLUSIONS

OBJECTIVES AND SCOPE

The principal objectives of this study were 1) to assess the potential for wind energy conversion systems on a national scale, 2) identify high potential applications for WECS, 3) define functional, performance, operational, and cost goals for WECS, 4) evaluate the impact of the wide scale deployment of WECS on energy users, and 5) identify the institutional and non-technical problems associated with the acceptance of wind energy systems.

The study concentrated on broad applications of WECS over large geographic areas encompassing the entire United States. Emphasis was placed on identifying and exploring high aggregate energy users who have significant potential to utilize wind energy in place of other alternatives.

ASSESSMENT OF WIND POTENTIAL

There is sufficient wind energy available in the United States to provide over a trillion kilowatt hours of electricity annually, which is equivalent to 13.6% of the projected energy demand in the year 2000 A.D. This estimate is conservative. If more optimistic assumptions were used concerning unit spacing, unit power ratings, and available land area, the estimate would more than double. Further, including the energy in the winds over off-shore areas would dramatically increase this estimate even further.

The available wind energy is the maximum level attainable and requires the construction and installation of over 300,000 large WECS units. If these units were installed by the year 2000 A.D., wind could produce close to 14% of the electric utility demand in that year. It is unlikely this can be achieved by the year 2000 A.D. A more realistic estimate of the energy contribution in that year is between 0.5 to 7 percent of the energy demand. The actual contribution will depend upon the rate and vigor at which WECS systems are implemented in the electric utility sector.

Adequate levels of wind energy can be found over half of the land area of the United States without resorting to the use of lands with competing or conflicting uses, e.g., like cities, national parks, national historical sites, and irrigated cropland. Over 214,000 square miles appear suitable for WECS within the Continental United States.

The HIGH energy regime (mountains and high terrain regions) is the most attractive region for initial installation of WECS. These regions are capable of producing annually 15 kwh/mi² of land area compared to an effective national average of only 5 kwh/mi². However, the availability of suitable topography will limit the energy potential of this regime to approximately 4% of the total available wind energy. Extensive utilization of the less cost effective MODERATE and LOW wind regimes will be required to provide a significant energy contribution to national requirements.

The number of sites that can be utilized for WECS, and the available wind energy, is very much dependent on the spacing required to avoid aerodynamic interference. The

minimum practical spacing that can be achieved with large systems is a critical issue which needs early exploration and resolution.

ELECTRIC UTILITY SECTOR

The single most important potential application of WECS which will yield maximum national impact is in electric utilities. This is because the utility sector annually consumes a very large portion of the nation's energy resources and serves all sectors of the economy.

WECS can be classified as an intermittent base load device since it can provide power only when the wind blows. It will be used to displace primarily base load power generating equipment and it will be necessary to provide supplemental backup capacity to provide adequate overall system reliability. This backup capacity would most likely be in the form of gas turbines because of their low capital costs.

Projections by the electric utility industry predict a shift in national generation capacity toward nuclear power. In this eventuality, WECS will compete primarily with low cost nuclear and coal base load equipment. Fuel savings will arise primarily from displacements of the conventional base load fuels (nuclear and coal) and to a small degree, from displacements of the high cost fossil fuels, oil and natural gas. Between the years 1980 and 2000, WECS has the potential for a cumulative saving, depending on the implementation rate,

- between 270 million and 4 billion barrels of oil (equivalent) in nuclear, coal, oil and natural gas fuels.
- between 18 and 260 million barrels of oil.

The present cost of WECS is significantly greater than the breakeven cost which will make it attractive to the utilities. Incremental revenue requirements are funds required to offset the difference between WECS production costs and breakeven costs. These could be obtained in various ways—including guaranteed low cost loans, direct subsidy, or increases in the price of electricity. Table 1 shows the revenue requirements for implementation in the various wind regimes with the smallest amounts needed for the areas of highest wind energy.

Table 1. Incremental Revenue Requirements for WECS (85% Learning)

Regime	Potential Energy Contribution (%)	Number of Units Required To Achieve Break Even	Incremental Revenue Requirements (Dollars)
HIGH	4	180	\$29.5M
MODERATE	41	753	\$100M
LOW	55	20,232	\$1.86B
Total	100	121,165	\$1.99B

Although fuel price increases over the next few years could reduce this requirement substantially, this mechanism cannot be relied upon for planning purposes. An effective mechanism for reducing the requirement is investing in R&D

PRINCIPAL RESULTS AND CONCLUSIONS-CONT'D

to improve and reduce the cost of current designs. Table 2 shows the incremental requirement can be reduced by \$1.41 billion with only a 25 percent reduction in the initial cost of WECS—a reasonable goal.

Table 2. Impact of R&D on Incremental Revenue Requirements (85% Learning)

Regime	Energy Contribution (%)	Number of Units Required To Achieve Break Even	Incremental Revenue Requirements With Present WECS Costs Reduced 25% By R&D (Dollars)
HIGH	4	53	\$8.7M
MODERATE	41	221	\$31.4M
LOW	55	5,933	\$540M
Total	100	6207	\$580M

Fuel price increases, plant cost increases, and less reliance on nuclear power significantly increase the value of WECS to the utilities and reduce the incremental revenues required for implementation. For example, a nuclear moratorium in the northeast would increase WECS breakeven costs by 30%. If the price of all fuels in the utility sector were to double in the next 10 years due to fuel escalation (independent of inflation) and then continue to escalate at an annual rate of 6%, WECS breakeven cost would increase about 55%.

WECS does not need to be coupled with a storage device for utility power system applications provided reliable back-up generation is provided. However, if the cost of storage is small, then WECS coupled with storage is economically attractive. For the northeast, a storage plant cost value near 250 \$/KW is the breakeven cost of storage which is well below current projections in most cases.

OTHER APPLICATIONS

In addition to the electric utilities, WECS should be considered for application in single family residences, agriculture, paper mills, and remote communities. Table 3

summarizes key characteristics of the various applications, and Table 4 shows the number of units required to achieve breakeven and the corresponding incremental revenue requirements. The data is shown for 0.85 learning, a level which should be easily achievable in mass production.

RESIDENTIAL APPLICATION

The residential sector is a sizeable market, conservatively estimated at 9.3 million small WECS units. With a potential for producing 207 billion kwh/year, it is the second largest application investigated. WECS will be competing with electricity at 3¢/kwh (in 1975 dollars) resulting in a high breakeven cost, and escalation in residential electricity prices over the next few years will increase the value of WECS to the homeowner even further.

The breakeven cost or value of the residential WECS depends on the investment approach of the homeowner. A conservative (low) estimate has been made by assuming WECS is financed through a conventional home mortgage and the incremental mortgage cost for the first year is offset by the savings in utility bills.

Based on current prototype prices, WECS will reach breakeven at 1636 units with an incremental revenue requirement of \$2.67M. This can be reduced by \$1.89M if R&D can reduce the present cost of WECS by 25%.

In general, adding storage capability to WECS produces a combined breakeven value above the breakeven cost of WECS alone. Storage will be most effective with large mismatches occurring between houseloads and wind availability. Over the full range of mismatches (0 to 100%) the combined cost goals of a WECS unit with storage varies from about \$4000 to \$6000 for 10 kw units when competing with 3¢/kwh electricity prices (in 1975 dollars), and from about \$6,800 to \$10,000 when competing with 5¢/kwh electricity (in 1975 dollars).

Without adequate energy storage, the utility will be required to supply full electrical power to residences during wind outages. Therefore, the capital investment by the

Table 3. Summary of Key Application Characteristics

Application	WECS Unit Size (kw)	Market Size (Saturation)				Prototype Cost of WECS (\$/kw)	Breakeven Cost (\$/kw)	Competing With
		Total Number of WECS Units	Capacity (gw)	Annual Energy Output				
				Billion (kwh)	Quads			
Electric Utilities	1500	313,500	470	1070	10.7	2398**	239**	~1.9¢/kwh Elec.
Residences	10	9,300,000	93	207	2.1	3947	533	3¢/kwh Elec.
Agriculture	35	780,000	27	43	.43	2187	367	2.7¢/kwh Elec.
Paper Mills	1500	1,000	1.9	2.9	.029	2292**	186**	1.7¢/kwh Elec.
Remote Communities	1500	1,000	1.0	2.5	.025	2671	626	3.9¢/kwh Diesel-oil

** — Effective values for application for comparison purposes only. Numbers represent mixture of WECS in different wind regimes.

Table 4. Number of Units Required to Reach Breakeven and Corresponding Incremental Revenue Requirements

Application	With Current Prototype Costs		With Present WECS Costs Reduced 25% By R&D		
	Number of WECS Units Required To Achieve Breakeven	Incremental Revenue Requirements (Dollars)	Number of WECS Units Required To Achieve Breakeven	Incremental Revenue Requirements (Dollars)	Savings in Incremental Revenue Requirements (Dollars)
Electric Utilities	21,165	\$1.99B	6,300	\$580M	\$1.41B
Residences	1,635	\$2.67M	500	\$780K	\$1.89M
Agriculture	649	\$2.5M	15	\$750K	\$1.70M
Paper Mills	1,000*	\$522M*	1,000*	\$321M	\$201M*
Remote Communities	156	\$44.8M	46	\$13.0M	\$31.8M

*Number of units required to breakeven exceeds saturation. Revenues based on installing 1000 units by year 2000 A.D.

utilities in power generation equipment may not be diminished by residential use of WECS. Indeed, cost of electricity to the home-owner may even increase. Resolution on this issue will have an important bearing on the success of implementation in the residential sector.

PAPER INDUSTRY

The paper industry is made up of almost 600 individual plants which produced, in 1973, 62 million tons of paper and paper board. It is the fourth ranking manufacturing consumer of fuel and energy in this country, and relies heavily on on-site power generation. It has been estimated that approximately 150 plants could use WECS, and the maximum number of 1500 kw WECS units approaches one thousand.

The WECS breakeven cost in the paper industry will be very low (\$186/kw) because it will be competing with low cost electricity purchased by the industry. With this low breakeven cost, and small market size (1000 units), WECS will not become cost effective in this application. Further, considering the low energy output (2.9 billion kwh) the incremental revenue requirement (\$201M-\$522M is quite large.

To be successful in this application, electricity prices would have to increase considerably, or, a commitment would have to be made for implementation in the utility sector. This would increase mass production and would reduce WECS unit costs before introduction into the paper mill industry.

AGRICULTURE

The estimated size of the agricultural market for WECS is 780,000 units. Its principal use would be for irrigation pumping, crop drying, space and hot water heating, and refrigeration. This is the third largest application investi-

gated, and has the potential for producing 43 billion kwh/year. WECS will be competing with electricity at 2.77¢/kwh (in 1975 dollars) and will reach breakeven after mass production of only 649 units (0.08% of the total market) with an incremental revenue requirement of \$2.5M. This can be reduced by \$1.7M, if R&D can reduce the present cost of WECS by 25%.

Serious barriers to be contended with include the possibility of penalties imposed by the utilities on farmers who use WECS, the high purchase cost (around \$14,000), and the current status of WECS as an unproven product.

REMOTE COMMUNITIES

The total market potential for wind energy in communities remote from utility service is limited; an estimated 1000 WECS units would serve most suitable candidates into the next century. Candidates include native American villages, small farm and ranch communities, island communities, rural towns and condominium or vacation home complexes. It is an excellent application for an early use of WECS, since it has the highest breakeven cost of all the applications evaluated, and can serve as a vehicle for the development of utility class WECS. Its contribution to national energy needs is small however.

WECS will be competing with on-site diesel generated electrical power costing 3.9¢/kwh, and the breakeven cost has been estimated as \$626/kw.

With this high breakeven cost, breakeven occurs at 156 units with a total revenue requirement of \$44.8M. If the initial cost of WECS can be reduced 25% through R&D, the incremental revenue requirement is reduced to \$13M, and breakeven occurs with the 46th WECS unit.

Significant barriers to implementation include possible utility penalties (in those communities where, in the future, utilities may supply power), and the current status of WECS as an unproven product.

WECS DESIGN, PERFORMANCE, AND COST CHARACTERISTICS

The conventional propeller type WECS is currently under intensive development by NASA and has an extensive data base. The baseline design used in this study, developed by General Electric under contract to NASA-LeRC, is shown in Figure 1. The rotor subsystem uses two filament-wound, fiber glass blades. The rotor diameter and blade length are a function of the wind regime for which the system is designed. A mechanical power transmission and electric generator are housed within a nacelle to convert rotor rotation into electric power. The nacelle is mounted on a pintle which contains drive mechanisms for turning WECS about the vertical axis. The rotor is located downwind to provide stability during changes in wind direction. Operation is at constant RPM for all operable wind conditions. A flexible coupling separates the main shaft from the gearbox and compensates for small misalignments which occur at assembly or develop later over the life of the unit. Each bearing has a split housing to permit ease of disassembly for maintenance.

Figure 1. 1500 KW WECS Baseline Design

The transmission system is oriented with the high speed shaft in the top position to simplify accessibility—an important feature to minimize maintenance costs. Attached to the high speed shaft, at the left of the transmission, is a hydraulic disc brake which is capable of bringing the system to an emergency stop in 20 seconds. The generator is an 1800 RPM, 4160 V, synchronous unit, equipped with an exciter and voltage regulator.

The control system employs a microcomputer, along with necessary sensors and actuators. The system provides automatic capability for start-up and shut-down, nacelle turning, power regulation, mutual electric protection of the network and WECS, data computation and control of system parameters during maintenance and emergency modes, and communications with a remote headquarter site.

System design is strongly influenced by expected wind environment. Operating and design characteristics of three different 1500 kw WECS power systems are shown in Table 5. The design of each machine has been optimized to minimize energy cost for the expected operating median wind speed. Rated velocity is the velocity at which WECS produces 1500 kw of electrical power and capacity factor is the ratio of WECS annual energy output to the energy output assuming operation at rated power (1500 kw) for one year.

Table 5. Design Characteristics of Three 1500 KW WECS UNITS

Design Wind Speed (MPH)	18	15	12
Rotor Diameter (FT)	190	219	278
Rotor Speed (RPM)	40	31.5	20.6
Rated Velocity (MPH)	22.2	20.3	16.8
Design Annual Energy Output (Millions of KWH)	6.62	5.85	5.29
Capacity Factor	0.50	0.45	0.40

OPERATIONAL CHARACTERISTICS

The 18 mph, 15 mph, and 12 mph WECS units were picked to study the HIGH, MODERATE, and LOW wind regimes, respectively. The energy output of the three 1500 kw power systems operating in the study wind regimes is shown in Table 6. The energy output and capacity factors are considerably smaller than the design case because each of the regimes encompass a range of wind speeds, only one of which results in optimum WECS performance. Effective regime capacity factors are thus below the optimum value for each machine.

Table 6. Operational Characteristics of 1500 KW Power Systems In The Favorable Wind Regimes

Wind Regime	HIGH	MODERATE	LOW
Annual Energy Output (Millions of KWH)	5.01	4.33	2.92
Capacity Factor	0.38	0.33	0.22

COST VOLUME RELATIONSHIP

It is important to know the future costs of the power systems as a function of number of units built, since in the national analysis, very large quantities are involved, and mass production will reduce costs considerably below the cost of the first unit. The best method of predicting these costs is by means of learning curve techniques. Figure 2 shows a typical variation of WECS costs as a function of

number of units produced. The three curves give a comparison of WECS costs in \$/kw for the HIGH, MODERATE, and LOW wind regimes. Table 7 tabulates the costs of the Nth unit and shows the effect of learning curve.

Figure 2. Cost of 1500 KW WEC – 1975 Dollars
(0.85 Learning Curve)

Table 7. Cost of 1500 KW WECS as a Function of
Number Produced (\$/KW)

Learning Curve	Number of Units Produced	HIGH	MODERATE	LOW
0.90	1	1586	1913	2671
	10	990	1180	1600
	100	680	820	1130
	1,000	480	570	800
0.85	1	1586	1913	2671
	10	710	850	1200
	100	420	500	700
	1,000	250	300	410

The unit costs of the first power units were based on the General Electric quotations to NASA-LeRC for the construction and installation of two 1500 KW power systems. The costs are in 1975 dollars, and include the costs of installation and transmission lines. The differences in costs are primarily due to the differences in rotor size.

MEDIUM AND SMALL SIZED POWER SYSTEMS

WECS power systems with capacities of 500 KW, 35 KW, and 10 KW were used in analyses of the remote community, agriculture and residential applications, respectively. The design characteristics of these systems for the applicable wind regimes are shown in Table 8.

The costs of the medium and small sized WECS units are shown in Table 9. Costs for the 500 KW power systems were determined for the NASA-LeRC design study program, and costs for the 35 KW and 10 KW power systems were determined from actual vendor quotations for production of 100 units. From these quotations, the costs for single units were estimated based on a 0.90 learning curve.

Table 8. Characteristics of Small WECS Power Systems

Wind Regime	500 KW		35 KW	10 KW
	MODERATE	LOW	LOW	LOW
Rotor Diameter (FT)	157	193	46.4	30.4
Rotor Speed (RPM)	38	27	106	151
Rated Design Velocity (MPH)	19.5	16.5	19.1	16.8
Annual Energy Output (Kwh)	1.55×10^6	1.03×10^6	55,709	23,301

Table 9. Cost of 500 KW, 35 KW, and 10 KW WECS Power Systems as a
Function of Number Produced (\$/KW)

Number of Units Produced	500 KW		35 KW		10 KW	
	LC = 0.90	LC = 0.85	LC = 0.90	LC = 0.85	LC = 0.90	LC = 0.85
1	3566		2187		3947	
10	2100	1700	1300	995	2300	1750
100	1500	950	930	580	1650	1000
1,000	1100	550	660	330	1180	600

WIND ENERGY DISTRIBUTION

COMPOSITE DISTRIBUTION AT SURFACE LEVEL

A composite map depicting the variation of surface level wind energies over the USA was prepared from surface wind energy data, off-shore wind energy data, and wind energy data from climatological charts of the upper atmosphere.

The surface distributions were developed from tabulations of annual surface wind energy data. Emphasis was given to the use of data from first order National Weather Stations which experienced a minimum number of changes in the location and height of their anemometers in the period of record.

Surface data were extrapolated upward to generate a composite wind energy map at 50 meters height, representative of hub centerline height for large (1500 kw) WECS. To facilitate the calculation of WECS performance at various locations throughout the USA, the map was divided into three favorable energy bands, or regimes, as shown in Figure 3.

TIME VARIATION OF WIND ENERGY

The seasonal and diurnal variations of wind energy are shown in Figures 4 and 5. In both cases, the variations for the LOW and MODERATE wind energy regimes were based on data for Rapid City, SD where both seasonal and diurnal surface wind energy variations were found to typify those derived for extensive areas of the US.

On the other hand, the HIGH wind energy regime occurs exclusively over high mountain peaks and ridges, and it is reasonable to assume that the patterns of diurnal and seasonal wind energy variations will be the same as those found in the free air flow above the surface boundary layer. These patterns are typified by the curves developed for Whiteface Mountain, NY and substantiated by measurements made atop the WKY-TV tower in Oklahoma City, OK. The data shows that diurnal variation of wind energy in the high terrain area will be opposite to that observed near the surface, while the seasonal variation of energy is quite similar to the surface variations. The Whiteface Mountain data were used to develop the seasonal and diurnal variations for the HIGH wind regions.

Figure 3. Favorable Wind Regimes

Figure 4. Seasonal Variations, Model of Wind Energy In The Favorable Wind Regimes

Figure 5. Diurnal Variation Model of Wind Energy In The Three Favorable Wind Regimes

WIND AVAILABILITY

The amount of electrical energy available from the wind is dependent upon the distribution of wind energy throughout the USA, the amount of land area in the favorable wind regimes suitable for installation of individual power systems, and the size, efficiency and packing density of the power systems in each wind regime. These factors, and their use in the calculation of available wind energy are discussed below. Off shore areas were not included in the estimate of available wind energy.

WIND REGIME AREAS

The total area within the favorable wind regimes is about 1,574,000 square miles. Seventy-four percent of this area is in the LOW regime characterized by wind velocities of 9 to 12 mph. The HIGH regime, characterized by velocities of 15 mph and greater, comprises only 3.5% of the total area. The relationship between energy and wind speed is shown in Figure 6.

AVAILABLE LAND

The amount of land available for installation of WECS depends upon land usage, as well as the suitability of the terrain to support construction and installation of the power systems. In estimating the land areas available for WECS, institutional areas such as military bases, national parks, national monuments and Indian reservations were excluded from consideration. Land use categories were developed and land use factors, i.e., the fraction of land that can be considered for WECS, were estimated for each category. Similarly, topographical factors were developed and applied to the land areas to estimate the suitability of the terrain for construction of power systems.

Energy levels below 2 Mwh/m²/yr are inadequate for economical power production. HIGH wind regimes characterized by high wind velocities, are found over mountainous areas, as well as off shore.

Figure 6. Relationship Between Wind Energy and Mean Wind Velocity

Table 10 summarizes the excluded areas and the total land areas available for WECS installation. Only 13.5% of the total land area within the favorable wind regimes is considered available and suitable for WECS. By far, the largest amount of available land is in the LOW regime (74%), while only about 25% and 1% of the available lands are in the MODERATE and HIGH regimes, respectively.

Table 10. Land Area Available for WECS
(Thousands of Square Miles)

Regime	Regime Area	Not Available			Available for WECS		
		Institutional Lands	Other Land Uses	Poor Topography	Area	Fraction of Regime Area (%)	Distribution of Area (%)
LOW	1104	201.5	325.5	420.4	156.8	14.2	74
MODERATE	415	85.6	79.3	196.2	53.9	13.0	25
HIGH	55	2.2	10.8	39.0	3.0	5.5	1
Total	1574	289.3	416	655.8	214	13.5	100

PACKING DENSITY

The number of power systems that can be installed within a given area is defined as the packing density and is limited by the minimum non-interference aerodynamic separation distance between machines. This minimum distance has been estimated to be 15 rotor diameters. The packing density, in number of machines per square mile, was estimated based on locating WECS units at the center of hexagons, separated by 15 rotor diameters, center-to-center. Hexagons provide the highest packing density over large areas. Optimum, 1500 KW power systems were assumed to be dispersed in each regime. Table 11 shows the computed packing densities. More units per square mile can be placed in the HIGH regime because of the smaller diameter.

Table 11. WECS Packing Densities

Wind Regime	Rotor Diameter	Packing Density (Units/Mi ²)
LOW	331 ft.	1.301
MODERATE	278 ft.	1.851
HIGH	218 ft.	3.01

AVAILABLE ENERGY

The maximum number of power units (saturation limit) that can be installed in the available area is a function of unit size. Table 12 shows the saturation limits assuming 1500 KW units. The corresponding values of installed WECS capacity and total electrical energy output are also shown.

The available wind energy is predominantly in the LOW and MODERATE wind regimes, whereas the HIGH wind regime can contribute only 4%. This is primarily due to the absence of high wind areas in the USA. Most of the available energy (55%) is in the LOW regime, and 41% is in the MODERATE regime.

The efficiency factor, defined as the ratio of electrical energy output to available land area, is an important measure of the effectiveness of WECS utilization. It accounts for the system efficiencies and required spacing requirements, as well as land use and topographical limitations. Although the total energy contribution is small, WECS is most efficient in the HIGH wind regime where the energy output is 15 million kwh per square mile of land, per year. On a national basis, the effective efficiency factor is only 5 million Kwh/Mi².

Table 12. Available Wind Energy at Saturation

Regime	Available Area (Thousands of Mi. ²)	Number of Installed Units	Installed Electrical Capacity (GW)	Electrical Energy Output (Billions of Kwh/yr)	Efficiency Factor (Millions of Kwh/Mi. ²)
HIGH	3.0	8,960	13.4	45	15
MODERATE	53.9	99,800	150	433	8
LOW	156.8	204,800	307	592	4
Total	214	313,500	470	1070	5

ELECTRIC UTILITY APPLICATION

WECS can be classified as an intermittent baseload device since it provides power only when the wind blows. It will be used primarily to displace baseload power generating equipment and supplemental backup capacity will be required to provide adequate overall system reliability. This backup capacity would most likely be in the form of gas turbines because of their low capital costs. However, the gas turbines would run only in peak load demand periods whenever full capacity is not available from WECS.

Large scale implementations of WECS will have two principal effects: 1) reduction in the consumption of fossil and nuclear fuels, and 2) reduction in the installed capacity of conventional power generating equipment. The value, or breakeven cost, of WECS to the utilities will vary with the specific types and quantities of fuel and generating equipment displaced.

MAXIMUM POTENTIAL

The available wind energy totals 1070 billion Kwh per year in the Continental USA and to deliver this energy, all available land area must be used — a condition called saturation. A total of 313,500 WECS units would be required (each rated at 1500 kw) with a combined generating capacity of 470 gigawatts. In terms of USA projected energy requirements in the year 2000 AD, WECS energy output would satisfy 14% of the demand for electricity projected in this study as shown in Table 13. The projected demand is 7,900 billion Kwh.

It is not likely however, that 313,500 units will be installed by 2000 AD. The number actually installed will depend upon the rate and extent to which WECS will be implemented.

IMPLEMENTATION RATES

Three implementation rates were selected to scope the impact of WECS on the utilities. Figure 7 shows the implementation curves in terms of WECS installed generating capacity, and Figure 8 shows implementation in terms of installed units. In both cases, the saturation level was used as the upper limit to the curves. The electrical utility projected growth curve is shown for perspective. The potential for WECS by the year 2000 AD, based on the implementation curves, is shown in Table 14. As can be seen, a better estimate of the true potential for wind, in the year 2000 A.D., is between 0.5% and 7.3%, depending upon the rate at which WECS is implemented.

FUEL SAVINGS

Fuel savings arise primarily from displacements of the conventional base load fuels (nuclear and coal) and to a smaller degree, from displacements of the higher cost fossil fuels, oil and natural gas. Even without WECS, only 6% of the fuel consumed in the year 2000 A.D. will be oil and natural gas. Total projected consumption levels are

Figure 7. WECS Implementation Curves In Utility Sector (WECS Installed Capacity)

Table 13. Potential for WECS At Saturation

No. of 1500 KW Units	313,503
Installed WECS Capacity (Gigawatts)	470.3
Annual Energy Output (Billions of KWH)	1,069.5
% Of Year 2000 A.D. Utility Installed Capacity	27.4
% Year 2000 A.D. Utility Energy Demand	14.0

shown in Table 15. With RAPID implementation of WECS, Table 16 shows that 852 million equivalent barrels of oil could be saved annually by the year 2000 A.D. through reductions in the consumption of nuclear, coal, oil, and gas fuels.

Over the twenty year period of RAPID implementation, (1980-2000) the cumulative savings would be 4.1 billion equivalent barrels of oil. The actual savings of oil during this time period would be 260 million barrels.

The potential fuel savings, in the year 2000 A.D., is shown in Figure 9 as a function of WECS energy contribution. The savings corresponding to SLOW, MEDIUM, and RAPID implementation are shown to illustrate the impact of implementation rate.

Table 14. Potential for WECS In Year 2000 A.D.

IMPLEMENTATION RATE	RAPID	MEDIUM	SLOW
No. Of 1500 KW Units Installed WECS Capacity (Giga Watts)	160,400 240.6	45,700 68.7	11,430 17.2
Annual Energy Output (Billions of KWH)	581.3	165.9	41.5
% Of Year 2000 A.D. Utility Energy Demand	7.3	2.1	0.5

Table 15. Year 2000 Annual Fuel Consumption Without WEC Systems

Fuel	Annual Consumption	BTU/Year	Percent of Total
Nuclear	47701×10^{12} BTU	47.7×10^{15}	65.4
Coal	950.2×10^6 Tons	20.9×10^{15}	28.7
Oil	535.6×10^6 Bbls	3.4×10^{15}	4.7
Gas	880.2×10^9 CF	$.9 \times 10^{15}$	1.2
Total	—	72.9×10^{15}	100.0

Figure 8. WECS Implementation Curves in Utility Sector (Number of 1500 KW Machines)

Table 16. Annual Fuel Savings in the Year 2000 A.D. Due to WECS (Rapid Implementation)

Fuel	BTU/Year	Equivalent Barrels of Oil	Percent of Total	Percent Reduction in Consumption
Nuclear	2.3×10^{15}	365 Million	42.9	4.8
Coal	2.3×10^{15}	369 Million	43.3	11.0
Oil	$.6 \times 10^{15}$	100 Million	11.7	17.6
Gas	$.1 \times 10^{15}$	13 Million	2.1	11.7
Total	5.3×10^{15}	852 Million	100.0	7.3

Figure 9. Annual Fuel Savings From WECS, In the Year 2000 A.D.

ELECTRIC UTILITY APPLICATION -CONT'D

BREAKEVEN COSTS

Breakeven costs (the maximum price the utility will be willing to pay for WECS) are a function of the region of the country where WECS will be used, since this determines the price of fuels and power generation equipment with which it will be competing, as well as the wind energy regime. Figure 10 shows the envelope of maximum and minimum values computed for WECS in various regions of the country. The curve shows that breakeven costs depend significantly upon wind regime. Table 17 compares the breakeven costs of the three wind regimes with the initial cost of WECS units which would be used in those regions. In the LOW wind regime WECS costs are high due to the large rotor sizes, and breakeven costs are low, due primarily to the low capacity factor.

The breakeven costs were calculated assuming the price of utility fuels increase at the same rate as general inflation, which was taken as 6%. Subsequent analyses have shown that this very closely approximates (within about 3%) the case of no inflation and no escalation of fuel prices. In addition, no credit was taken for possible increases in the cost of competing power systems due to environmental and safety considerations and continued need for technology development. This has resulted in a conservative bias to the computed breakeven costs.

Breakeven costs were computed using conventional utility techniques for evaluating generation costs. System grids were synthesized to typify the generation mixes of the various regions. Implicit in the analysis is a rapid nuclear generation growth to meet greatly increasing system loads. A significant finding of the study is that WECS derives benefits from displacement of conventional generation equipment (capacity credit) as well as from savings of fuels.

INCREMENTAL REVENUE REQUIREMENTS

The present cost of WECS is significantly greater than the breakeven costs which will make it attractive for the various applications. Incremental revenue is an important measure of the cost barrier to WECS implementation. It is defined as the difference between production costs and breakeven costs and could, for example, be in the form of loan guarantees, subsidies, tax incentives or increased price of electricity to consumers.

The total incremental revenue requirements for implementation of WECS depends upon (1) Wind regime, (2) The cost of WECS at the end of the R&D Phase, (3) the cost reduction (learning curve) due to improved design processes and mass production, and (4) the break-even cost — which is a function of wind regime and future increases in fuel prices.

The relationship of incremental revenue to production cost, break-even cost and installed units is shown in Figure 11. The term $N_{B/E}$ is the number of production units required to reach break-even.

Figure 10. Maximum and Minimum Values of WECS Breakeven Costs

Table 17. Comparison of WECS Breakeven Costs with Initial Units

Wind Regime	WECS Breakeven (\$/KW)	WECS Initial Costs (\$/KW)
HIGH	360	1586
MODERATE	310	1913
LOW	200	2671

Figure 11. Incremental Revenue

Table 18 shows the required number of WECS units and incremental revenue requirements, assuming no benefits from R&D – that is the learning curves are based on the current estimated costs of the first 1500 KW prototype – and assuming no real increases in the cost of utility fuels over the next twenty-five years. The data from Table 17 were used for the analysis.

The power of the learning curve is immediately obvious. In the HIGH wind regime, for example, 5,832 machines must be built before breakeven occurs with a learning curve of 0.90, whereas only 180 machines would be required with a learning curve of 0.85.

With 0.9 learning, breakeven occurs in the LOW regime at 8.6 million units. However, all the available land area is filled (saturated) before this level is reached; in other words, WECS does not breakeven in the LOW regime. This is because of the high capital cost of the larger machines required for operation in the regime, and because of the lower breakeven value.

The incremental revenues required (0.9 learning) for full implementation in the LOW regime is \$66.4 billion, and \$4.5 billion, and \$564 million in the MODERATE and HIGH regimes. The differences reflect the different power systems costs and breakeven costs of the three regimes.

IMPACT OF R&D

The potential benefits of R&D can be explored by examining the impact of reducing the cost of WECS at the beginning of the implementation phase – that is, the cost of the first unit installed.

Figure 12 shows the impact of reductions in initial cost of WECS on the number of units required to breakeven. As can be seen, in the LOW regime, with 0.90 learning, a 42% reduction in initial cost would be necessary in order to breakeven by the time saturation occurs.

Table 18. Number of WECS Units and Incremental Revenue Requirements to Achieve Breakeven

Wind Regime	Number of Units Required to Breakeven		Incremental Revenue Requirement (Dollars)	
	LC = 0.9	LC = 0.85	LC = 0.9	LC = 0.85
HIGH	5,832	180	564M	29.5M
MODERATE	53,519	753	4.5B	100M
LOW	8,596,479	20,232	66.4B*	1.86B

*Based on Saturation Limit.

The incremental revenue requirements are shown in Figure 13. If the initial cost of WECS in the LOW regime can be reduced 42%, then, on the 0.9 learning curve, breakeven will occur at 204,775 units (the saturation level of the LOW regime). The corresponding incremental revenue requirement would be reduced from \$66.4 billion to \$10 billion.

In general, the return on investment for R&D is exceedingly high since dollar investments in R&D during early development of WECS will be repaid by very substantial reductions in incremental revenue requirements.

ELECTRIC UTILITY APPLICATION -CONT'D

Figure 12. Effect of Reductions In Cost of First WECS On Number Of Units Required To Breakeven (No Fuel Price Increases)

Figure 13. Effect of Reductions in Cost of First WECS Units on Incremental Revenue

IMPACT OF FUEL PRICE INCREASES

Increases in the price of fuels in the utility sector will enhance the value of WECS to the utilities and will be evidenced primarily by an increase in WECS breakeven costs. Table 19 and 20 shows the impact of 50% and 100% step change increases in the price of all utility fuels, followed by increases in fuel prices equal to the inflation rate of 6%. Here, no benefits from R&D are considered. Comparing with the basecase (no real fuel price increase) the reduction in units is substantial in all regimes. However, breakeven will not be achieved in the LOW regime with 0.90 learning, even with a 100% fuel price increase.

The incremental revenue requirement is shown in Table 21. The reduction in revenue requirements is large with large fuel price increases, but the total amount for implementation in the LOW regime is still substantial.

Table 19. Breakeven Costs As A Function of Fuel Price Increases (\$/kw)

Wind Regime	Fuel Price Increase Over Basecase		
	0%	50%	100%
HIGH	360	441	560
MODERATE	310	380	482
LOW	200	245	311

Table 20. Impact of Fuel Price Increases On Required Number Of Units Required to Reach Breakeven

LC	Wind Regime	Fuel Price Increase (%)		
		0	50	100
0.9	HIGH	5,832	1,536	320
	MODERATE	53,519	14,022	2,934
	LOW	8,596,479*	2,261,986*	470,938*
0.85	HIGH	180	76	28
	MODERATE	753	316	115
	LOW	20,232	8,515	3,080

*Exceeds Saturation Limit

Table 21. Effect of Fuel Price Increases On Incremental Revenue Requirements To Reach Breakevens (Dollars)

LC	Wind Regime	Fuel Price Increase (%)		
		0	50	100
0.90	HIGH	564M	182M	47.9M
	MODERATE	4.5B	1.4B	380M
	LOW	66.4B*	52.6B*	32.3B*
0.85	HIGH	29.5M	15.0M	6.9M
	MODERATE	100M	55M	25.3M
	LOW	1.86B	960M	440M

*Incremental Revenue Required to Reach Saturation Limit
No reduction in initial WECS Cost

COMBINED EFFECTS

Figure 14 and 15 show, in parametric form, the combined effect of reducing initial costs and increasing fuel

prices on the number of WECS units required to breakeven, and on the incremental requirements.

Figure 14: Combined Effect of Fuel Price Increase And Reduced WECS Initial Cost on Number of Units to Breakeven

Figure 15: Combined Effect of Fuel Price Increase and Reduced WECS Initial Cost on Incremental Revenue

ELECTRIC UTILITY APPLICATION -CONT'D

STORAGE

Use of storage systems with WECS permits the energy generated by WECS during the nighttime to be stored and used during the daytime for serving high cost daytime peaking loads. The use of storage with WECS also reduces the need for supplemental gas turbines to preserve the reliability of electricity service. While these two elements weigh to the benefit of storage with WECS, the capital cost of the storage device is a serious obstacle. Detailed studies of the northeast reveal that storage with WECS is attractive only if the capital cost of storage is less than approximately \$250/KW for 9 MWh of storage rated at 1000 KW.

Currently, the lowest cost form of bulk storage is the pumped storage hydro plant. Costs are geographically dependent, and there may be some favorable sites which still can be developed under \$250/KW. Other forms of storage, e.g. batteries, are still considerably more expensive. It should be noted, however, that for the penetrations considered in this study, storage was not a requisite to the application of WECS power systems provided reliable backup generation, such as gas turbines, were available.

IMPACT ON MATERIAL RESOURCES

The major materials of construction of WECS as presently conceived are concrete, steel, copper, fiberglass and resins. Table 22 shows the material requirements for WECS will not appreciably affect the US production of copper, steel, or cement since the requirements for each is less than 5%. However, with RAPID implementation plastics production will be affected since the requirements for glass fiber and resin will increase by 265%, and, with MEDIUM implementation by 43%. Since plastics production capacity would have to nearly quadruple by year 2000 for RAPID implementation, plastics availability will present a substantial barrier if no alternative is developed. Increases in material production capacity or material substitutions for WECS rotors would relieve this impact. Use of aluminum in the blades, for example, indicates very little strain on production facilities, as shown in Table 22. With less than MEDIUM implementation, the requirements for the glass fiber and resins are substantially reduced.

ENERGY PAYBACK OF MATERIALS

The energy payback time for WECS raw materials ranges from about 4 to 11 months, depending upon the wind regime. This is the amount of time for the energy generated by WECS to equal the energy required for producing the materials required for the production of WECS. Figure 16 compares the payback period of WECS with a 700 MW coal plant, and a 1150 MW nuclear plant. The LOW regime WECS unit has a payback period three times as long as the HIGH regime unit.

Table 22. WECS Material Requirements In Peak Year (% of U.S. Production)

Commodity	WECS Implementation	
	RAPID	MEDIUM
Steel	4.9	0.84
Concrete	2.9	0.5
Copper	3.5	0.7
Fiberglass and Resin	265.	43.
Aluminum*	6.3	1.0

*alternate blade

Figure 16. Material Energy Payback Time

LAND AREA REQUIREMENTS

The total land area required for a large installation of WECS is considerable. A 1000 MWs facility in the MODERATE and LOW regimes will require 360 and 521 square miles, respectively. Figure 17 shows the importance of WECS spacing on the required area. With a spacing of 10 rotor diameters, the area requirements drop by over a factor of 2.

For comparison, the land area requirement for a 2000 MW nuclear facility is less than one square mile. It should be noted that only a small portion of WECS land area requirements are for physical equipment. The major portion is to insure aerodynamic separation of units and is available for a multitude of other uses. An analogy can be drawn to rights-of-way for power lines.

BARRIERS TO IMPLEMENTATION

Major barriers have been defined which can impede the implementations of WECS on a large scale. These barriers deserve high priority attention because, unless they are resolved, the implementation of WECS will proceed slowly and it will be difficult for WECS to supply more than token amounts of power by the year 2000 A.D.

The INCREMENTAL REVENUE REQUIREMENTS for large scale implementation of WECS appear large, although comparisons with other choices of power generation have not been made in this study. The utilities would require these revenues to off-set the difference between production costs and breakeven costs. These could be, for example, in the form of low cost guaranteed loans, subsidies, tax incen-

tives, increased price of electricity to consumers, or other mechanisms which would increase the value of WECS to the utilities. If the incremental revenue requirements are excessive, utilities will be reluctant to invest in WECS. Certain favorable events will minimize the revenue requirements, and are considered achievable:

1. significant reductions in WECS production costs through R&D advances
2. attaining a 0.85 or better learning curve through mass production of WECS.

Further, increases in fuel prices (nuclear, coal, oil, gas) and escalating costs in competing power plant equipment will also reduce the revenue requirements.

The LAND AREA REQUIREMENTS for large scale use of WECS, compared to conventional power generating equipment, appears very large. This, of course, results from the low power density of the wind. Unless the land can be used for multi-purposes, it is unlikely the utilities will be able to obtain all the land that is needed. The area requirements can be minimized by reducing the separation between units to the smallest possible distance. A high priority should be placed on achieving this goal.

At this stage in development, WECS is classified as an UNPROVEN PRODUCT. This is a significant barrier at the present time because user skepticism exists concerning several key technical issues. These include performance, safety, life expectancy and reliability. Until these issues are thoroughly investigated and resolved the skepticism will remain and utilities will be reluctant to integrate WECS into power generations networks. Most of these issues can be successfully settled by normal R&D progress and achievements.

Figure 17. Impact of Unit Spacing on Land Area Requirements as a Function of WECS Installed Capacity

RESIDENTIAL APPLICATION

The potential for application of WECS in the residential market is substantial. The number of homes which could use WECS has been conservatively estimated as 9.3 million, excluding Standard Metropolitan Statistical Areas and high density rural areas. The estimate would increase substantially if these areas were included.

IMPLEMENTATION RATES

The impact of WECS will be a function of the rate and extent to which it is implemented. Two implementation rate curves were selected to study the range of effects and are shown in Figure 18. Saturation is not reached until well after the year 2000 A.D., even with RAPID implementation. With full implementation (saturation) WECS will produce 207 billion kwh/year, as shown in Table 23.

Table 24 shows the potential for WECS by the year 2000 A.D. for the RAPID and MEDIUM implementation rates. By the year 2000 A.D., WECS annual electric output could be between 34 billion and 103 billion kwh/year, with cumulative fuel savings between 165 million and 488 million barrels of oil (equivalent). In the calculations, 10 KW WECS units were assumed as baseline.

BREAKEVEN COSTS

The breakeven cost or value of the residential WECS depends on the investment approach of the homeowner. A conservative (low) estimate is obtained by assuming WECS is financed through a conventional home mortgage vehicle and the incremental mortgage cost for the first year is offset by the savings in utility bills. Escalating electricity prices would then provide an additional incentive to install WECS.

A comparison of WECS production costs with residential breakeven costs is shown in Figure 19. The horizontal lines are the breakeven costs for the indicated prices of electricity in 1975. No inflation or escalation in electricity prices is assumed to occur. The starting cost (\$3947/kw) is the estimated cost of the first WECS unit assuming no reductions in price due to R&D between 1975 and start of implementation (1985). Clearly, at this initial cost, WECS could only be competitive at electricity prices of 22.2¢/kwh. At electricity costing 5¢/kwh, the breakeven cost of WECS would be \$888/KW and would occur after approximately 200 units were mass produced. Breakeven costs as a function of electricity prices are shown in Table 25 and Figure 20. For analysis purposes, a conservative value of 3¢/kwh was used for the competitive price of electricity. The equivalent breakeven cost of WECS is \$533/kw.

Table 23. Potential For WECS At Saturation

No. of 10 KW Units (Millions)	9.3
Installed WECS Capacity (Gigawatts)	93
Annual Energy Output (Billions of Kwh/yr)	207

Figure 18. WECS Implementation Curves In The Residential Sector

Table 24. Potential For WECS In Year 2000 A.D.

Implementation Rate	RAPID	MEDIUM
No. of 10 KW Units (Millions)	4.6	1.53
Installed WECS Capacity (Gigawatts)	46	15.3
Annual Energy Output (Billions of Kwh/yr)	103	34
Cumulative Fuel Savings* (Millions of Equiv. Bbl OIL)	488	165

*Between 1985 and 2000 A.D.

Table 25. Summary of WECS Breakeven Costs And Number of Units Required to Reach Breakeven (LC = 0.85)

Cost Of Electricity (\$/kwh)	WECS Breakeven Cost (\$/kw)	N _{B/E} Number Of Units To Reach Breakeven
2	355	8000
3	533	1636
5	888	200
10	1777	8
15	2665	3
20	3553	2
22.2	3947	1

No inflation or escalation in electricity prices.

76SDS4267
18 FEBRUARY 1977

WIND ENERGY MISSION ANALYSIS EXECUTIVE SUMMARY

PREPARED FOR THE UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT
ADMINISTRATION
DIVISION OF SOLAR ENERGY

ERDA CONTRACT NO. EY-76-C-02-2578
(FORMERLY: E(11-1)-2578)

space division

GENERAL ELECTRIC

ACRONYMS, UNITS, DEFINITIONS AND CONVERSION FACTORS

1. ACRONYMS

WECS Wind Energy Conversion System

2. DEFINITIONS

Breakeven Costs: The cost of electricity from competitive sources determines the maximum (or breakeven) cost which a user will be willing to pay for WECS. High breakeven costs are desirable; low breakeven shows it will be difficult for WECS to complete. Breakeven cost is related to competing electric prices by:

$$(\$/KW)_{\text{Breakeven}} = \frac{E_{\text{WECS}} \times P_b}{FCR}$$

where:

E_{WECS} = annual energy (kwh) from WECS

P_b = price of competing electricity, \$/Kwh

FCR = Fixed Charge Rate, annual costs as percent of initial investment

Favorable Wind Energy Regimes: Areas within the USA with sufficient wind velocities to be useful for the production of electrical power. Expressed in energy instead of velocities for convenience of analysis.

LOW – Areas with wind energies between 2 and 4 Mwh/m²/yr (9-12 mph mean wind speed)

MODERATE – Areas with wind energies between 4 and 7 Mwh/m²/yr (12-15 mph mean wind speeds)

HIGH – Areas with wind energies greater than 7 Mwh/m² (mean wind speeds greater than 15 mph)

Implementation Rates: A descriptor term which designates specific WECS installation curves used in the study.

RAPID – 50% of saturation achieved by year 2000 A.D.

MEDIUM – 15% (approx.) of saturation achieved by year 2000 A.D.

SLOW – 4% (approx.) of saturation achieved by year 2000 A.D.

3. UNITS

POWER

KW – Kilowatt (1000 Watts)

MW – Megawatt (1 Million Watts)

GW – Gigawatts (1 Billion Watts) one gigawatt is a representative rating for a nuclear power plant

ENERGY

Kwh – Kilowatt Hour

Mwh – Megawatt Hour (10³ Kwh)

Mwh/m²/yr – Annual wind energy content per unit rotor area.

4. CONVERSION UNITS FOR FUEL SAVINGS CALCULATIONS

Power Plant Heat Rate = 10,000 Btu/Kwh

1 Quad = 10¹⁵ Btu

1 Bbl Oil = 5.8 x 10⁶ Btu

5. MISCELLANEOUS

1 Meter per second = 2.237 mph

ELECTRIC UTILITIES

A nuclear expansion scenario is inherent in the analysis of the electric utility sector. Nuclear plant construction costs assume acceptable nuclear safety requirements, and a plentiful supply of nuclear fuel.

The strategy assumed for installation of WECS is a function of the wind regimes. Power systems are first installed in the HIGH wind regimes (where they are closest to being cost effective) and then in areas of successively lower wind energy—the point of introduction being phased so that a continuously increasing rate of production is maintained. Installation continues in each regime until saturation occurs. It is further assumed that each wind regime contains WECS which have been specifically optimized for the regime.

A modest growth rate of 5.5% per year was assumed for the electric utility sector. This rate will require large investments in new power generation equipment by the utilities and will provide a sizeable opportunity for WECS. Lower growth rates however, will decrease the potential size of the WECS market.

IMPLEMENTATION RATES

The impact of WECS installations on users and manufacturers will be a function of the rate and extent this new technology is introduced into the market. Three implementation rates were selected for this study to scope the possible impact of WECS in high potential applications. The MEDIUM

implementation curve for the utility application was selected to achieve a level consistent with published (ERDA — 49 and FEA Project Independence) estimates for reasonable expectations of wind energy potential by the year 2000 A.D. The other two implementation curves were selected to evaluate the impact of higher and lower implementation rates.

WECS PRODUCTION COSTS

Future mass production costs for WECS have been estimated by the learning curve technique, which is a procedure based upon the observation that each time a job is repeated, fewer hours are required for completion. Experience within the General Electric Company indicate a learning curve factor between 0.8 and 0.9 should be achievable for WECS (for example, a learning curve factor of 0.8 means that each time production *doubles*, the cost of production drops 1-0.8 or 20%). The learning curve technique is best applied after the general design has stabilized since, during the R&D period, many unforeseen perturbations may cause erratic fluctuations in the price of each unit. For purposes of the baseline calculations in this study, it has been assumed that despite efforts to reduce the cost of WECS in the next few years, through R&D, the cost of a prototype unit built today is representative of the cost of the first unit installed at the start of the WECS implementation phase, in 1985. However, impact of reducing this cost through R&D was also explored.

ASSUMPTIONS AND LIMITATIONS OF THE ANALYSIS

The study was based on certain major assumptions which may have an important effect on the results and the interpretation of these results. The most critical assumptions and limitations of the analyses are presented below —

GENERAL

All costs presented in this report are in terms of 1975 dollars.

The entire study was performed for the horizontal axis WECS. Each application is assumed to be mutually exclusive of all others. This is not strictly true since, for example, implementation in the residential sector may impact the scale of implementation in the utility sector. However, since the potential impact of WECS in the utility sector is so large, the error made in the national assessment is relatively small.

WECS PERFORMANCE AND COST

The mission analysis required definitive performance information on WECS power systems in order to select machines for given applications and to accurately assess the energy and capacity contributions which could be expected from WECS. The baseline 1500 KW power system used in this study was adopted from the conceptual design study recently completed by General Electric for NASA-Lewis Research Center.

Unit costs of WECS power systems were based on General Electric's quotation to NASA-Lewis for construction and installation of two 1500 KW power systems. The cost quotation for the second unit, excluding non-recurring costs, provides the best possible estimate of the cost of large WECS units available today.

METEOROLOGY

Procedures developed and used for the first time in this study for predicting wind energy distribution show promise. However, certain assumptions remain to be tested and verified. Of particular importance are the assumptions made in the calculations which use the upper air wind energy data over high terrain areas, and in the techniques for vertical extrapolation of wind energy.

Diurnal wind variations of Whiteface Mountain in New York were assumed to characterize the HIGH wind energy regimes throughout the USA, as these were the only data available to describe high terrain areas at the time of performing this study. These data show wind energy to peak at nighttime which is out of phase with the electric utility demand peaks. The impact on overall study results is small, however, since the HIGH regime contributes only about 4%

of the total energy. The MODERATE and LOW regimes contribute the remainder and their wind energy peaks closely correspond with daily electric utility load demand.

AVAILABLE WIND ENERGY

The maps of wind energy presented in this report were developed to provide a mechanism for determining the upper limit to the energy in the winds over the entire USA, and were not intended to be used to locate specific sites for WECS installations. Energy bands (or wind regimes) were specified for the study and the total national land areas swept by winds with these energies were determined from the maps. These gross energies and swept areas were used to estimate the available energy. In general, the favorable wind regimes indicated on the maps define those regions in the country where large scale implementation of WECS is desirable.

Many instances will, and do, occur where wind data at specific locations outside the favorable wind regimes indicate high wind energies, inferring the desirability of installing WECS. These sites, and the surrounding region, should of course be explored. However, the question to be resolved is whether or not the observed velocities extend over large enough areas to allow more than token amounts of power to be produced. If so, the maps can be improved by incorporation of this data, and the current estimate of available wind energy (1 trillion kwh) can be revised upward. If not, the site may have very limited potential.

The available energy described in this report is over the continental USA only. The energies in off-shore areas, Alaska, Hawaii, Puerto Rico, and Guam are not included in the calculation, but energy distributions were prepared for these areas and are included in the Report Appendix.

The density of large arrays of WECS installed within a given area is limited primarily by the minimum non-interference aerodynamic separation distance required between machines. In this study, fifteen rotor diameters has been estimated as the minimum separation distance. This value was used for calculation of available energy production and to predict saturation limits (maximum number of machines) for implementation in the electric utility sector. However, this parameter is critical to the calculation of available energy on a national scale. For example, if technology development and design concepts could reduce this spacing to 10 rotor diameters, the estimate of available energy would double.

To add conservatism, government lands (parks, military bases, etc.) were excluded from the calculations of available wind energy. It is recognized that under certain conditions, some of these lands would be available for use, and the estimate of available wind energy would increase accordingly.

REMOTE COMMUNITIES APPLICATION

The total market potential for wind energy in communities remote from utility service is limited; an estimated 1000 WECS units would serve most suitable candidates into the next century. Candidates include native American villages, small farm and ranch communities, island communities, rural towns and condominium or vacation home complexes. This application places a very high value on electricity, due to the cost of either installing connector lines to a distant utility or generating power on site. Therefore, it is an excellent candidate for an early use of WECS, has the highest breakeven cost of all the applications evaluated and can serve as a vehicle for the development of utility class WECS.

The breakeven cost of 1500 KW WECS has been estimated based on competition with on-site diesel generated electrical power costing 3.9¢ /KWH, and financial criteria employed by small REA type utilities. The breakeven cost, with no inflation and no escalation in the price of fuel oil, was estimated to be \$626/KW.

With this high value of breakeven cost, breakeven occurs at 156 units (much before saturation) with a total revenue requirement of \$44.8M. If the initial cost of WECS can be reduced 25% through R&D, the incremental revenue requirement is reduced to \$13M, and breakeven occurs with the 46th WECS unit.

Storage requirements are long term in nature, and, in general, exceed cost goals. In some applications the cost of pumped hydro storage is below the cost of conventional diesel generated power, but widespread use is expected to be limited because of availability of suitable sites.

The problem of aesthetics and land area requirements do not appear to be important. The most significant barrier to implementation appears to be the possible utility penalties (in those communities where, in the future, utilities may supply power).

PAPER INDUSTRY APPLICATION

The paper industry application offers a mechanism for early introduction of large size WECS units. The industry is made up of almost 600 individual plants which, in 1973 produced 62 million tons of paper and paper board. It is the fourth ranking manufacturing consumer of fuel and energy in the country and, together with its allied products, the industry consumes about 10 percent of all the purchased fuel and energy used by manufacturers.

It is estimated that approximately 150 plants could use WECS based on their location within the favorable wind regimes. The average plant size is 100 tons of paper per day and could use six 1500 KW WECS units to augment on-site electrical generating equipment.

The maximum number of WECS units for this application approaches one thousand. Table 27 shows the potential for WECS when fully implemented.

Table 27. Potential for WECS In the Paper Industry
By Year 2000 A.D.

No. of 1500 KW Units	1000.0
Installed WECS Capacity (Gigawatts)	1.9
Annual Energy Output (billions of KWH/YR)	2.9

If implementation begins in the utility sector first, then it would be possible to expand production and achieve saturation in the paper industry by year 2000 A.D.

BREAKEVEN COSTS

The WECS breakeven cost in the paper industry is very low, and has been conservatively estimated as \$186/KW,* assuming no inflation and no escalation in electricity prices. Because large quantities of power are purchased from the utilities, paper mills, on the average, are paying approximately 14 percent less than the average of all users, or only 1.7¢/kwh. To breakeven, WECS must produce power at this cost.

The incremental requirements are relatively large for this application because of the low WECS breakeven cost. With 0.85 learning, the incremental revenue requirement is \$522M and with a 25% reduction in WECS initial cost through R/D, this reduces to \$321M, a savings of \$201M.

The large incremental revenue requirements pose a potentially serious barrier, considering the relatively small national energy contribution from WECS in this application. These large requirements primarily result from the low cost of purchased electricity, a trend which may change over the next few years.

*Note: This is an average for the industry. Breakeven costs were found to be \$150/KW and \$222/KW for the LOW and MODERATE wind regimes respectively.

AGRICULTURAL APPLICATION

The estimated size of the agricultural market for WECS is 780,000 units. Its principal use would be for irrigation pumping, crop drying, space and hot water heating, and refrigeration. A 35 KW WECS should be sufficient for most applications. The potential of WECS at full implementation is shown in Table 28.

By the year 2000 A.D., 360,000 units could be installed with RAPID implementation, and 120,000 with MEDIUM implementation. The potential for WECS in the year 2000 A.D. is shown in Table 29.

Breakeven costs for WECS, without inflation or escalation of electricity prices is estimated to be \$367/KW. Electricity price escalations would increase the value of WECS.

About 649 units are required to breakeven with 0.85 learning, and the incremental revenue requirements are \$2.5 million. With 25% reduction in initial WECS cost through R&D, the incremental revenue requirement becomes \$750 thousand, a \$1.70 million decrease.

The material requirements are not excessive for implementation of the 35 KW units. With RAPID implementation less than 1.5% of copper production in the USA would be required and this should be easily accommodated.

Other material demands are less than 0.5%. The energy payback time however, is in the order of two years.

Existing ponds and hot water tanks could be used to advantage as storage devices. However, batteries, which are best suited for dairy farm applications, do not appear to be cost effective. Goals for storage range from \$500/KW for dairy farms to \$250/KW for poultry farms.

Serious barriers to implementation will be the possibility of penalties imposed by the utilities on the farmers who use WECS and the high purchase cost (around \$14,000).

Table 28. Potential of WECS At Saturation

Number of 35 KW Units	780,000
Installed WECS Capacity (Gigawatts)	27
Annual Energy Output (Billions of KWH/YR)	43

Table 29. Potential of WECS By the Year 2000 A.D.

Implementation Rate	RAPID	MEDIUM
Number of 35 KW Units	360,000	130,000
Installed WECS Capacity (Gigawatts)	13	4.6
Annual Energy Output (Billions of KWH/YR)	21	7.2

The energy required for producing the materials for one 10 KW WECS unit is 72,663 kwh. With an annual energy output from WECS of 22,300 kwh (LOW regime) the energy payback period is 3-1/4 years - considerably longer than the utility case.

BARRIERS TO IMPLEMENTATION

Probably the most significant potential problem identified as a barrier to the implementation of WECS is the likelihood of penalties which utilities will impose on homeowners who use WECS equipment. The utilities must be prepared to supply power to the homeowner in the event of calm periods or WECS mechanical failures, and would probably impose penalties to offset the expense of the mostly idle power generating equipment. This would have the unfavorable impact of reducing the breakeven cost of WECS to very low values.

Even in the small sizes, WECS is classified as an unproven product. Problems of performance, safety, reliability and lifetime must be resolved. In addition, interfaces with the utility and load sharing problems must be defined and worked out.

Although WECS can become cost effective very quickly, the high cost will be a major concern to the homeowner. Homeowners (on a large scale) will be reluctant to purchase and install WECS with out-of-pocket monies, except in new homes where the cost can be included in the sale price of the home.

Even at 10 KW, WECS is very large, and aesthetics will be a barrier in the residential sector. The degree, however cannot be assessed at the present time. Based on historical precedence, it is unlikely homeowners - on a large enough scale to have significant impact - will want a large power unit installed on their property. Of course, certain innovative and highly motivated individuals will install the equipment, but these individuals are expected to be exceedingly few in number.

Table 26. Comparison of 10 KW and 1500 KW WECS Material Requirements (Lbs/KW)

	10 KW	1500 KW
Steel	1026	233
Copper	22.1	1.8
Concrete	2800	739
Fiberglass	-	26

Figure 23. Cost Goals of Storage Unit for WECS and Cost of WECS and Storage Combined (10 KW WECS)

RESIDENTIAL APPLICATION-Cont'd

Escalation in the price of electricity clearly enhances the value of WECS to the homeowner. Figure 21 shows the increase in breakeven costs arising from simultaneous 5% inflation and 6% escalation in electricity prices over a long period of time. The escalation as used here is the annual rate of change in current (outlay year) dollars, and therefore implicitly includes an inflation component. Thus, the electricity price is increasing about 1% faster than general price level (inflation).

INCREMENTAL REVENUE REQUIREMENTS

Assuming the homeowner will pay only the breakeven cost of WECS, an incremental revenue will be required to offset the difference between production costs and breakeven costs. Figure 22 shows the variation of incremental revenue and number of units required to breakeven as a function of the percent reduction in the initial cost of WECS. WECS should be capable of achieving a 0.85 learning curve in mass production. With this level of learning, WECS will breakeven at 1636 units, with an incremental revenue requirement of \$2.67 million. The number of units is less than 2% of saturation. A 25% reduction in the initial cost of WECS due to R&D (a reasonable amount) allows breakeven to occur with the 500th mass produced unit, with a revenue requirement of only \$780 thousand.

IMPACT OF STORAGE

Energy storage will enhance the value of WECS, if the price is right, by making available a large fraction of the excess energy which is otherwise lost because of load/wind mismatches. Figure 23 shows the cost goals for storage, and the cost goals for WECS and storage combined, competing with 3¢/kwh and 5¢/kwh electricity prices, as a function of energy from WECS delivered to the house. To breakeven, the cost of the two combined cannot exceed the uppline, and the maximum permissible cost of storage is shown by the vertical dimension within the shaded and cross hatched areas.

MATERIAL RESOURCE REQUIREMENTS AND ENERGY PAYBACK

With RAPID implementation, WECS will require at most, in the peak production year, 8.4% of the USA production of copper, 4.2% of the steel, and 2% of the cement production. These values appear sufficiently low to preclude any shortages in needed materials. Slower implementation rates, of course, would have even a lesser impact.

Comparing with the utility case, the residential application requires twice the quantities of steel and concrete, and four times the quantities of copper. Since WECS in the utility case will supply 2.9 times the generating capacity of the residential case, it is evident the residential application is a very inefficient use of materials. This is further illustrated in Table 26 which compares the material requirements for the 10 kw and 1500 kw WECS units.

Figure 21. WECS Breakeven Costs in Residential Sector Without Storage

Figure 22. Number of 35 KW WECS Units and Investment Required to Breakeven

Figure 19. WECS Breakeven Costs and Number of Units Required to Breakeven for Various Prices of Electricity in 1975 (10 Kw Units, LOW Regime, No Inflation or Escalation in Price of Electricity)

Figure 20. Breakeven Costs of WECS As A Function of Price of Electricity in 1975

This master is for Figure 1-2 of the
Executive Summary and Figure 1-2 of the
Final Report.

WIND ENERGY MISSION ANALYSIS

EXECUTIVE SUMMARY

NOTICE

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18 FEBRUARY 1977

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