#345.
4/7/80

PR. 1051

ATR-78(7598)-1

ELECTRIC UTILITY APPLICATION OF WIND ENERGY CONVERSION SYSTEMS ON THE ISLAND OF OAHU

Executive Summary

By
Charles A. Lindley
Walter C. Melton

February 23, 1979

Work Performed Under Contract No. EX-76-C-01-2439

Energy and Resources Division
The Aerospace Corporation
El Segundo, California

MASTER

U.S. Department of Energy

Solar Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$7.00
Microfiche \$3.50

ELECTRIC UTILITY APPLICATION OF WIND
ENERGY CONVERSION SYSTEMS ON THE
ISLAND OF OAHU
EXECUTIVE SUMMARY

23 FEBRUARY 1979

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Charles A. Lindley

Walter C. Melton

Energy and Resources Division
The Aerospace Corporation
El Segundo, California 90245

Prepared for the
U.S. DEPARTMENT OF ENERGY
Under Contract E(49-18)-2439

zb
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

FOREWORD AND ACKNOWLEDGEMENTS

The study summarized here was begun in late 1976 and was essentially completed by late 1977. The technical data, economic data, judgments and opinions obtained in the course of the study to quantify and characterize the Oahu scenario may in some instances be particular to that time frame.

This Executive Summary as well as the main report are based on the work of many people.

Charles A. Lindley was the Principal Investigator and performed the work reported in Sections 5, 6, and 9. Joseph E. Neiss performed the financial analyses reported in Section 8 by C.A. Lindley. Walter C. Melton performed the utility impact analysis reported in Section 7 and compiled and edited this Executive Summary.

The computer codes (of which there were no less than 16) were programmed by Patricia Merryman, Alf E. Bogen, and Stanley T. Wray, Jr. Ms. Merryman programmed all of the wind processing procedures, the WECS simulation, and the routine for computing LOLP. A.E. Bogen programmed the Cost of Production program under Aerospace Corporation research funding with computer systems help from Stan Wray. Stan Wray also programmed the load duration computer graphics.

E. Chipman Higgins and Richard Belt of the Hawaiian Electric Company readily supplied information and data, and patiently answered innumerable questions as did Professor Colin Rammage and his colleagues at the University of Hawaii.

Continuing encouragement and guidance were provided by Mr. Tom Reddoch of the University of Tennessee and DOE. Professor Robert E. Sullivan of the University of Florida provided a critical review of the analysis summarized in Section 7.

CONTENTS

	<u>Page</u>
FOREWORD	iii
1. BACKGROUND AND OBJECTIVES	1
2. STUDY PARTICIPANTS	1
3. HAWAII	1
4. HAWAIIAN ELECTRIC COMPANY	2
5. RESOURCE ASSESSMENT AND SITING	7
6. WECS SYNTHESIS FOR OAHU	9
7. UTILITY IMPACT ANALYSIS	21
8. KAHUKU POINT WECS ECONOMICS	32
9. GENERIC EXTENSION OF RESULTS	36
10. SUMMARY OF RESULTS AND CONCLUSIONS	41

FIGURES

	<u>Page</u>
1. HECO Transmission System	4
2. Locations of Wind Survey Sites	11
3. Kahuku WECS Field Layout - Phase 1; 45 MW (30 WTGs)	17
4. Kahuku WECS Field Layout - Phase 1+2; 150 MW (100 WTGs)	18
5. Kahuku WECS Field Layout - Phases 1, 2 and 3; 300 MW (200 WTGs)	19
6. Comparison of Power-Duration Curves for Kahuku WECS and Instrument Sites	20
7. Monthly HECO LOLP Distribution for Baseline Study Plan	23
8. Variation of HECO Annual LOLP with Capacity of an Additional Unit with .05 Forced Outage Rate	25
9. Equivalent Conventional Unit Capacity of Kahuku WECS Phase 1 (Conventional Unit Forced Outage Rate = .05)	25
10. Annual LOLP for HECO Baseline Study Plan Conventional Unit Availability Schedule	27
11. Annual LOLP for HECO Baseline Study Plan with Kahuku WECS Phases 1, 2 and 3 and Without G3	28
12. Annual Cost Savings Due to Kahuku WECS	30
13. Wind Energy System Saving.	33
14. Cumulative Wind System Saving.	33
15. Rate of Return Versus WTG Cost for Four Phases	34
16. WTG Break-Even Costs by Phase	37
17. Effect of Array Angle and Spacing on Conversion	39
18. WECS Design Tradeoff; Array Spacing and Angle of Wind Energy	39
19. Mean Annual Power Variation with Rated Power	40

TABLES

		<u>Page</u>
1.	Normalized Gross Demand Monthly Peaks (HECO, Island of Oahu)	3
2.	Installed HECO Generation	5
3.	Baseline Generation Expansion Plan	5
4.	HECO Fuel Oil Price Forecast: 1980-2000 (Current Dollars)	6
5.	Emphasis and Applications of Criteria for Each Search and Assessment Phase (Mountainous Terrain)	10
6.	List of Potential WECS Sites	12
7.	Summary of Comparative WECS Site Evaluation.	15
8.	Illustrative Expenditure and Status Scenario (1977 Dollars)	20
9.	Summary of WECS Output Results.	21
10.	LOLP for Baseline HECO System with WECS	24
11.	Baseline System Operating Performance 1980-94 (Current Dollars). . . .	29
12.	Percentage Improvement in Operational Cost Savings Due to Partial Spinning Reserve Policy	31
13.	Wind Energy Systems Applications in Hawaii - Financial Assumptions . .	35
14.	Summary of Economic Results	37
15.	Effect of Varying WTG Cut-Out Speed	40

EXECUTIVE SUMMARY

1. BACKGROUND AND OBJECTIVES

This study is one of a series of Application Studies contracted by the Wind Systems Branch of the Department of Energy. The purpose of these Application Studies is to explore the economic, technical, and operational issues in the practical application of large Wind Turbine Generators (WTGs) to electric utilities.

The objective of this study was to assess the potential for the application of Wind Energy Conversion Systems (a field of interconnected WTGs denoted in this report by the acronym WECS) in a specific utility context to gain advance information concerning their economic feasibility; their operational problems; the criteria and procedures for site selection; environmental impacts; legal, social, and other problems; and the balance of cost and benefits from the point of view of the consumer and the utility. This study addresses the circumstances of the Hawaiian Electric Company operations on the Island of Oahu.

2. STUDY PARTICIPANTS

The Aerospace Corporation had the primary responsibility for this study and performed all quantitative and qualitative analyses. However, substantial information was obtained from the Hawaiian members of the team without whose assistance the study could not have adequately reflected local Hawaiian attitudes and interests. Participants under subcontract to The Aerospace Corporation were the University of Hawaii (UoH) and the Hawaiian Electric Company (HECO). The Department of Planning and Economic Development of the State of Hawaii was also a contributor, but without contractual obligations in this study.

3. HAWAII

As indicated earlier, the location chosen for the study is the Island of Oahu in the State of Hawaii. Oahu is the fifth island from the East in the Hawaiian chain and is the location of Honolulu, Pearl Harbor, and the only international airport in the State. The island is by far the most developed and populous of the islands. Oahu has 82 percent of the population of the State with a corresponding 86 percent of the utility power demand, but only nine percent of the state's land area. The island's electrical power needs are served entirely by one investor-owned utility, HECO. The HECO utility transmission system is totally isolated from the other islands and probably will remain so for a long time to come because of the great technological difficulty and expense of electrical power transmission across the deep water channels to the neighboring islands. Until technology allows practical inter-island connections, the HECO utility net must operate in total isolation and its reliability and loss-of-load risks are entirely determined by internal actions.

Hawaii has encouraged development planning for wind energy and the other renewable alternatives. Because of the warm climate and outdoors life style, the per capita consumption of electricity in Hawaii is 25 percent less than on the

mainland. Thus, there is less potential for conservation. However, Hawaii is trying to conserve and the State is also actively pursuing a slow-growth policy where planning is the essence. These attitudes are in no small part due to the realization of Hawaii's vulnerability to interruption of its seaborne oil and the possible consequences of another OPEC embargo. Consequently, wind energy is a consciously recognized and pursued alternative in Hawaii.

4. HAWAIIAN ELECTRIC COMPANY

The Hawaiian Electric Company, Inc. (HECO) is an investor-owned Hawaii corporation incorporated under the laws of that state. HECO produces electricity for the islands of Hawaii, Maui and Lanai, as well as Oahu. Significant financial parameters for 1976 are listed below:

Operating Ratio	76.6%
Earnings per Share of Common	\$ 2.93
Net Tangible Assets per Share of Common	\$25.86
Percent of Total Capitalization	
Long-Term Debt	54.5%
Preferred Stock	13.0%
Common Stock	32.5%
Percentage of Long-Term Debt to Net Plant	45.2%
Ratio of Gross Plant to Gross Revenue	2.9
Gross Income as a Percent of Long-Term Debt	22.0%
Fuel Cost as a Percent of Revenue	42.6%

The 1976 sales (including Hawaii, Maui, and Lanai, as well as Oahu) breakdown is as follows:

	<u>1000s Customers</u>	<u>Avg. Rate mills/kWh</u>	<u>Sales MWH</u>	<u>% of Total Sales</u>	<u>Revenue (millions \$)</u>	<u>% of Total Revenue</u>
Residential	219.1	47	1.684E6	31.0	\$ 79.1	35.5
Commercial	33.3	54	1.087E6	20.0	58.8	26.4
Industrial	.5	32	2.598E6	47.7	81.8	36.7
Other	<u>1.5</u>		<u>.071E6</u>	1.3	<u>3.1</u>	1.4
Total	254.5*		5.440E6		222.8	

Load Growth

Prior to the 1973 energy crisis which was reflected in 1974 electricity usage, the energy consumption for the production of electricity had grown at an annual rate of 8.31 percent in the State of Hawaii. Almost all of Hawaii's consumption is on Oahu where, except for a very small amount of biomass based electricity purchased from a sugar mill, the generation comes from oil-fired plants.

* Figures do not add due to rounding

The electric energy consumption only increased by one percent from 1973 to 1974. However, the annual consumption picked up again in 1975 and in that year, HECO predicted an increase in electricity consumption at an average annual rate of 6.17 percent through the year 2000. The development of a very strong anti-growth movement which has manifested in a limited-growth statement of policy by the Hawaiian State Government has led to subsequent downward revisions.

The FPC load forecast developed by HECO on 3-17-76 is used in this study. This forecast gives an average growth rate of 4.62 percent for the 15-year period, 1980-94, ending with a peak 1994 load of 1825 MW and generation of 10.9×10^6 MWh. These numbers correspond to gross electric production (i.e., they include the power required to run generating plant auxiliary equipment).

Load Shape

HECO has an unusually flat seasonal variation of demand peaks. The monthly peaks occur in the Fall with October the highest and November only slightly lower as shown in Table 1 where the monthly peaks are normalized with respect to the October peak. The diurnal load shape varies somewhat from month to month. Generally, the daily peak occurs at 7PM in the winter and 8PM in the summer.

TABLE 1
NORMALIZED GROSS DEMAND MONTHLY PEAKS
(HECO, Island of Oahu)

Jan.	.953	July	.915
Feb.	.940	Aug.	.931
Mar.	.937	Sep.	.966
Apr.	.915	Oct.	1.000
May	.912	Nov.	.994
June	.895	Dec.	.987

Transmission System

A map of Oahu with the HECO transmission system superimposed is shown in Figure 1. Most of the HECO load is in the area including Honolulu and along the coast in the southeastern part of the island. The grid is supplied by power plants located along the southern edge of Oahu at Kahe, Waiau, and Honolulu.

Plans for New Generation

The present HECO generating system listed in Table 2 will be expanded with the installation of nine additional units in the next 15 to 20 years. The first eight will nominally be installed at the Kahe site although some of the gas turbines may be located at Waiau. The ninth and largest unit will probably be installed at Kahe also. These units are listed below in Table 3 along with a date for initial operation according to a plan which was under consideration by HECO in March of 1977. These initial operational capability dates are used in all of the analyses discussed in this report, and are identified as the "baseline plan."

Figure 1. HECO Transmission System

TABLE 2
INSTALLED HECO GENERATION

<u>KAHE P.P.</u>		<u>WAI'AU P.P.</u>		<u>HONOLULU P.P.</u>	
<u>Unit</u>	<u>Capacity</u>	<u>Unit</u>	<u>Capacity</u>	<u>Unit</u>	<u>Capacity</u>
K1	88 MW (Gross)	W1	8 MW (Gross)	H5	23 MW (Gross)
K2	88	W2	18	H7	42
K3	90	W3	52	H8	55
K4	90	W4	52	H9	60
K5	<u>141</u>	W5	60		180 MW
	497 MW	W6	57		
		W7	90		
		W8	90		
		G1	44		
		G2	<u>44</u>		
			515 MW		
TOTAL: 1192 MW (Gross)					

TABLE 3
BASELINE GENERATION EXPANSION PLAN

<u>Unit</u>	<u>Nom. Capacity</u>	<u>Initial Operation</u>
K6	141 MW (Gross)	October 1982
G3	60	October 1984
G4	59	July 1986
G5	60	December 1987
K7	170	June 1989
G6	59	January 1991
G7	60	September 1991
K8	170	August 1993
X1	223	December 1994

Energy Supply and Costs

All of HECO's units on Oahu are presently oil fired with either two percent sulfur residual fuel oil or 0.5 percent sulfur fuel oil or diesel fuel (a moderate amount used in the gas turbines). All of the oil is seaborne to Hawaii, there being no fossil fuel natural resources in Hawaii. The capital investment and transportation costs of oil relative to eastern coal have always mediated in favor of an oil-fired system.

There are no natural circumstances on Oahu that would facilitate the construction of a hydro facility. The topology of the Island is inadequate and the volcanic rock tends to be too porous for use in reservoirs.

Nuclear systems are generally not commercially available in sizes compatible with HECO demand projections for the next 30 years at least, and have not been considered for that reason alone. The Islands are very ecologically oriented, and nuclear units are not favorably viewed for that reason as well.

HECO's current contract for residual fuel oil expires at the end of 1980. Under this contract which has a built in escalation factor that depends on the price escalation of both natural gas and Los Angeles bunker oil, the 1977 price (delivered) for two percent sulfur residual fuel oil is \$11.33/bbl. Several percent of HECO's consumption is diesel fuel for the gas turbine peakers. That oil is priced slightly higher. There is a public service company tax of 7.5 percent on revenues, a PUC fee of .25 percent on revenues and a franchise royalty tax of 2.5 percent on revenues for a total Hawaii State tax of 10.25 percent. The corresponding revenue requirements factor (1.1142) raises the effective cost to HECO from \$11.33/bbl to \$12.62/bbl.

HECO has forecasted the price of .5 percent residual fuel oil and diesel fuel for the 1980-2000 time frame based on analyses performed for them by Sherman Clark Associates of Menlo Park, California. The HECO forecast which was used in the baseline calculations for this study is shown in Table 4. These prices are for oil delivered at Oahu but not including the 11.42 percent revenue requirements factor. The "real inflation" of oil from 1980 through 85 in Table 4 is three percent per year implying a general inflation rate of six percent per year. The general inflation rate corresponding to Table 4 for the 1986-2000 time frame was assumed by HECO to be five percent per year.

TABLE 4
HECO FUEL OIL PRICE FORECAST: 1980-2000
(Current Dollars)

Calendar Year	.5% Low Sulfur Residual (\$/bbl)	Diesel ** Fuel (\$/bbl)	Calendar Year	.5% Low Sulfur Residual (\$/bbl)	Diesel ** Fuel (\$/bbl)
1980	19.65	20.82	1990	43.60	46.20
81	21.46	22.74	91	46.80	49.59
82	23.43	24.83	92	50.24	53.23
83	25.58	27.10	93	53.92	57.13
84	27.93	29.59	94	57.88	61.33
1985	30.50	32.32	1995	62.13	65.83
86	32.76	34.71	96	66.69	70.66
87	35.19	37.29	97	71.58	75.84
88	37.79	40.04	98	76.84	81.42
89	40.59	43.01	99	82.48	87.39
			2000	88.53	93.80

* .5% Low Sulfur Residual: 6.2×10^6 Btu/bbl

** Diesel Fuel: 5.82×10^6 Btu/bbl

5. RESOURCE ASSESSMENT AND SITING

A sequential process of resource search and assessment must be completed before a utility can bring an operational WECS on line. This process has never been completed although a few utilities are now initiating the first steps. Although past experience cannot be called upon, it is expected that the process will be drawn out and moderately expensive for WECS sites located in mountainous terrain, such as on the Island of Oahu. A generic procedure applicable to mountainous terrain is outlined and discussed in this Section. The actual application of the procedure to Hawaiian Electric Company operations on the Island of Oahu in the State of Hawaii is discussed in Section 6.

Three-Phase Siting Sequence

The resource search and assessment process will normally develop in a series of phases which have an increasing level of detail. Three somewhat indistinct and overlapping phases can be identified:

- Phase 1: Preliminary WECS Feasibility Evaluation - to determine if there is a valuable wind resource somewhere in or near the utility service area. This Phase is primarily a top level wind resource search based on existing data where possible, but will normally require new instrument installations. Criteria other than wind energy are reviewed only to the extent required to eliminate areas where there is no hope of building a WECS. This Phase is planned to keep the utilities at-risk cost low until WECS feasibility is proved.
- Phase 2: WECS Area Selection - to determine which of several possible wind energy fields should be developed. The top level search is over and the careful assessment of the discovered resources is undertaken in this Phase. The tasks are to determine the geographical extent of high quality wind in the several candidate WECS areas, and to consider other legal, procedural and cost criteria to the extent required to make a decision on which one (or several) of the candidate WECS areas should be retained. A significant wind data instrumentation and analysis effort will usually be required.
- Phase 3: WECS Site Survey and WTG Layout Design - to establish the specific location of WTGs within the WECS area defined and selected earlier in Phase 2. This Phase could conceivably include the installation of WTGs in some of the locations while other locations are still being evaluated. Various legal and procedural requirements will be complied with in this Phase.

Siting Criteria Categories

Five basic categories of siting criteria have been identified. They are listed below in the order of importance that will usually obtain for wind machines to be located in mountainous areas:

- (1) Wind Energy Resource
- (2) Land Use and Availability
- (3) Environmental Impact
- (4) Site-Variable Costs
- (5) Weather and Terrain Limitations, Hazards

The order of importance will vary with the specific situation and may well be different for a nonmountainous area.

The following list of specific factors and criterion in each of the five basic categories is thought to be exhaustive and it is not expected that all of the criteria will be applicable in any one situation.

Wind Energy Resource

- a. Mean Wind Speed
- b. Extent of Energetic Area
- c. Directional Distribution of Wind Energy
- d. Diurnal Distribution vs. Demand
- e. Seasonal Distribution vs. Demand
- f. Speed-Duration Profile
- g. Frequency of Long Outages
- h. Vertical Wind Profile Over Mountain Tops
- i. Diversity

Land Use and Availability

- a. Cost and Market Availability
- b. Land Use Restrictions and Zoning
- c. Interaction With Nearby Land Users

Environmental Impact

- a. Esthetic Impact
- b. Fuel Displacement
- c. Aircraft Hazards
- d. Microwave and Television Interference
- e. Public Safety
- f. Watershed Impact
- g. Wind Break
- h. Flora and Fauna
- i. Historical and Archeological Sites

Site-Variable Costs

- a. Access Road Availability and Cost
- b. Collection and Transmission Line Costs
- c. Site-Related Construction Costs
- d. Hardware Delivery Transportation Costs
- e. Energy Royalties
- f. Labor Availability

Weather and Terrain Limitations, Hazards

- a. Destructive Winds
- b. Severe Icing
- c. Deep Snow, Avalanches
- d. Wind-Borne Salt, Pumice, Dust, etc.
- e. Flood, Earthquake, and Landslide
- f. Security and Vandalism

Phase-Dependent Application of Criteria

The importance and manner of consideration of each of the above nontechnical factors and criteria depends on the Phase of the effort. Many of the factors are simply matters of judgment in Phase 1. By the time of Phase 3, they are tasks that must specifically be addressed and disposed of--often by a procedural method prescribed by law. In many cases, the Phase 3 tasks are things that must be done but will not affect any siting decisions. That is, a given factor is often a judgmental criteria early on and a task to be done later on. The judgment early on has to do with how difficult or costly it will be to accomplish that task later.

In a screening process of so many variables and of many potential locations, efficiency demands that the strongest screening criteria be applied first to reduce the effort to manageable size. In mountainous terrain, it is clear that the first consideration should be the energy intensity of the wind resource. If flatland is found to have a very constant resource, other criteria such as land use should lead.

The relative importance and nature of consideration for the five categories of criteria are summarized in Table 5. The comments for the five categories in the column for each Phase tend to define that Phase in terms of what work is to be done. This manner of definition is consistent with the earlier definition of the Phases in terms of the Phase objectives. In either manner of definition, note that the distinction between Phases is loose and approximate and will surely depend on the specifics of a given situation for each category of criteria.

6. WECS SYNTHESIS FOR OAHU

Scenario WECS Site Selection for System Synthesis

A scenario WECS site selection for the Island of Oahu was done as a study task. It should be emphasized that the real selection for actual development has not yet been made by the Hawaiian members of the study team. The site selection criteria

Table 5

**EMPHASIS AND APPLICATIONS OF CRITERIA FOR EACH SEARCH AND ASSESSMENT PHASE
(MOUNTAINOUS TERRAIN)**

SEARCH & ASSESSMENT CRITERIA CATEGORY	Phase 1 Preliminary WECS Feasibility Evaluation	Phase 2 WECS Area Selection	Phase 3 WECS Site Survey and WTG Layout Design
Wind Energy Resource	<ul style="list-style-type: none"> Based on existing data plus augmentation with new instruments as required. Dominant factor in screening process. 	<ul style="list-style-type: none"> Instrument the several candidates areas for a WECS to determine extent and quality of wind resource. 	<ul style="list-style-type: none"> Instrument the selected WECS area for detailed data to be used in WTG siting.
Land Use and Availability	<ul style="list-style-type: none"> Screen out park lands and other areas <u>definitely</u> not available. 	<ul style="list-style-type: none"> Investigate land availability costs. Pickup options or establish royalties arrangement. Prepare for commitment. 	<ul style="list-style-type: none"> Commitment required to assure that the land is available at reasonable cost.
Environmental Impact	<ul style="list-style-type: none"> No Action 	<ul style="list-style-type: none"> Review any key environmental problems as possible discriminators in choice. 	<ul style="list-style-type: none"> Begin studies and analysis for environmental impact statements.
Site-Variable Costs	<ul style="list-style-type: none"> No Action 	<ul style="list-style-type: none"> Estimate costs for each candidate area. 	<ul style="list-style-type: none"> Site costs considered in detail for WTG layout design.
Weather and Terrain Limitations, Hazards	<ul style="list-style-type: none"> No Action 	<ul style="list-style-type: none"> Evaluation 	<ul style="list-style-type: none"> Weather and terrain problems considered in layout of WTGs in rugged or high altitude mountains.

of Section 5 were applied in cursory fashion to select a WECS area on Oahu for system synthesis. In the context of Section 5 the Oahu case involves mountainous terrain wind resources, and therefore, the value of the resource must dominate the selection procedure.

Available Sources of Wind Data

The main source of meteorological data for this study was the result of a major effort by Professor Colin Rammage and his colleagues of the University of Hawaii (UoH), beginning in 1975, to search out and quantitatively evaluate the wind resources of all the major Hawaiian Islands. The map in Figure 2 shows the approximate location of the sites operated by UoH, as well as a number of older sites, mostly at airports and military bases which carry long-term records for correlation. The UoH team provided running summaries of the monthly averages of wind speeds at their sites. These summaries were updated from time to time with new data, corrections and instrument calibration revisions. In addition, computer tapes of winds at six-minute intervals were provided for selected sites.

Figure 2. Locations of Wind Survey Sites

Selections Based on Wind Resource Criteria

Review of the wind data as they became available led to the identification of five possible WECS areas for Oahu. These are listed in Table 6. Essentially they are the two ends of each of the two mountain ranges that stand across the prevailing wind direction plus a pass in the leeward range. These five potential sites were considered more carefully using the other criteria for site selection to determine which would be most appropriate for the scenario WECS design.

TABLE 6
LIST OF POTENTIAL WECS SITES

<u>Name</u>	<u>Location</u>
Koko Head	SE Corner of Oahu
Kolekole Pass	Near Center of Waianae Range
Kahuku Point	N Corner of Oahu
Kaena Point	W Corner of Oahu
Honouliuli Region	E End of Waianae Range

Resource Magnitude Estimates

An attempt is made in Table 7 to develop and summarize estimates of the effects of the combination of the wind resource intensity, extent, and geometry on the output variables of a WECS exploiting that resource. Some liberties are taken in projecting from a single point wind resource reading to the total number of sites available and a mean wind speed representative of several sites.

Influence of Non-Resource Criteria on Oahu Site Selection

Of the remaining site selection criteria of Section 5, only the land use issues and esthetic impact are clearly critical to WECS site selection on Oahu.

Summary of Pertinent Hawaii Land Use Laws

There are two steps in the acquisition of a site which can be used for a WECS: (1) to gain access to the land and (2) to gain approval for its use as a site. Should the ground selected be in a conservation district (a most likely outcome, given the fact that most of the windy sites are in rugged uplands), then the two steps may be merged into a single negotiation. This results from the fact that the same government agency, the State Department of Land and Natural Resources (DL&NR), administers both aspects of publicly-owned conservation land; it can at once grant a lease, easement, license, or permit to use a given area of a conservation district and also grant a variance, or create a subzone, for this particular use. If it is private land in a conservation district which is sought for a WECS site, the private owner must grant the access but the DL&NR controls the use as before.

For acreage outside the conservation areas the consent of a County Planning Commission for land classified as agricultural or rural must be obtained, in addition to the right of access and occupancy by the owner of the land. If the land is held by the state, negotiations with both levels of Hawaii government are required. In the unlikely event that the site is on county land, the two steps would be collapsed into a single negotiation with the county government. All nonfederal lands are subject to the zoning laws of the State, administered by the State Land Use Commission (LUC). Proposed land uses which are at variance with the current zoning must be cleared with the LUC.

Although the normal means of allocating rights to use state land is by public auction or drawing, Hawaii law authorizes the DL&NR to issue short-term permits or longer-term licenses by negotiation when that is deemed to be in the public interest. If the proposal to construct a WECS can be demonstrated to the satisfaction of the department to be in the public interest, fully compatible with the environment, conservation and other concerns of the state's land use policies, it may be possible to obtain a site with a minimum of administrative procedure.

Application of Land Use Laws to Potential WECS Resources

Of the potential wind resource areas discussed earlier, only the Kahuku Point area involves private land. The Kahuku Point land belongs to the large Campbell Estate and is under agricultural zoning. It would therefore be necessary to buy the land or lease its use from the private owner. Since the United States Army is presently leasing most of the land for maneuvers, it would also be necessary to obtain some sort of concession to allow releasing of the portions needed for a WECS installation. Small plots of land are also under lease to the Navy on Opana and a nearby headland for communications antennas. The Comsat Corporation has its satellite communication antenna on the ridge to the west of Opana. For the purpose of this study, it has been assumed that interference with these antenna arrays would be minimal.

Since the zoning is agricultural, it would be necessary to obtain a special permit for wind power generation use from the County Planning Commission which they may grant at their discretion. This permit would also require the approval of the State LUC.

The other four sites are all on state lands and in conservation districts. Thus, access to the site, as well as permission to use it, must be sought from the DL&NR.

Esthetic Impact

The populace of the Hawaiian Islands is probably more sensitive to issues of esthetic impact than people of most other areas of the United States.

The esthetic impact problem is significantly different for the various WECS areas listed. The instrumented ridge at Koko Head would be a highly sensitive WECS site on esthetic grounds. It is visible from the tourist center of Waikiki, but not so prominent as the more famous Diamond Head. Also, at a distance of about 12 miles, it is unlikely that the WTGs on the crest would be visible to the naked eye from Waikiki. However, they would be clearly visible from various residential and hotel areas nearby, particularly from Hawaii Kai, a residential area adjoining the Head. They would also stand directly above Hanauma Bay, an underwater National Wildlife Preserve of coral reefs. It is assumed that esthetic objections to a WECS field on Koko Head would be very severe unless wind machines came to be considered a desirable decoration of the landscape.

A WECS installation in Kolekole Pass would be visible from only a limited number of areas to the northeast and southwest. Generally, the areas of visibility are restricted to the Scofield Military Reservation to the north and the Lualualei Naval Reservation to the south. The esthetic impact of the installation would be minimal.

The esthetic impact of a WECS on Kahuku Point could be relatively mild depending on the extent of the installation. A certain percentage of the installations at the higher elevations would be invisible to all population areas. Other locations would be clearly visible from inhabited areas around Kawela Bay and the resort hotel development on Kuilima Point. Certain locations might also be marginally visible from the town of Kahuku and from locations near the Polynesian Cultural Center at Laie. In general, the esthetic impact of WECS installations on Kahuku Point would range from small to moderate depending on the extent of the installation.

A WECS installation on Kaena Point would be relatively innocuous. Depending upon the exact location, they could either be totally invisible to the population or only marginally visible from a few beach locations near Waialua Bay.

A WECS installation at Honouliuli is in direct line of sight of several small communities surrounding Pearl Harbor and the harbor itself. However, the distances are such that WTGs would be clearly visible from the west side of the harbor, but too far away to be visible to the naked eye from the north or east shore, or from the tourist areas such as the U.S.S. Arizona.

Summary of Scenario Site Selection

The WECS site selection criteria judged significant for Oahu are summarized in Table 7. Koko Head and Kolekole Pass, because of their high mean wind speeds, offer the lowest wind energy costs among the sites considered. Since the mean wind speeds are so high, they might be even more economical if a WTG of slightly higher rated speed than 22.7 mph (10.15 m/s) became available. Unfortunately, because of the small size and concentrated nature of the resource at the two locations, neither would supply a substantial part of the HECO total generation needs. Also, the strong esthetic impact of an installation at Koko Head probably rules it out for WECS development in the near future.

Kahuku Point is the best of the three remaining WECS resource possibilities. Using the Mod 1 WTG design, it offers the possibility of up to 40 percent penetration of the present HECO generating capacity. The resource survey has not gone far enough to establish the distribution between higher and lower wind energies over the site, but at least a reasonable part of this large area is available at above 18 mph mean annual wind speed. Access to the land can probably be negotiated and the esthetic impact is moderate because of the primarily agricultural and undeveloped nature of the region. It should be relatively easy to avoid adverse interaction with the major communication antennas in the area. Interference with the present Army use of the area for maneuvers is a potential problem that needs further exploration.

The WECS resource on Kaena Point looks slightly less attractive because of the lower mean wind speed and the estimate of a moderate total WECS capacity. Both the capacity and the maximum available mean wind speeds are quite uncertain, since only one point at the lower end of the ridge has been surveyed to date.

The Honouliuli region is less attractive as a potential WECS site. Its total capacity is small, and because of its more moderate wind speeds, the energy cost will be

TABLE 7
SUMMARY OF COMPARATIVE WECS SITE EVALUATION

Potential WECS Site	Array Length Mi	Representative Mean Annual Wind Speed $V_{30'}$ mph	Number of Instrument Sites	Mean-to-Rated Speed Ratio	Approximate Rated Power Capacity P_R , MW	Approximate Capacity Factor	Approximate Mean Annual Power P , MW	Approximate Annual Energy E , kWh $\times 10^{-3}$	Array Altitude ft.	Diurnal Peaking	Exposure	Land Title/ Zoning	Possible User Interference	Esthetic Impact	Access and Construction Δ Cost	Comments
Koko Head	1	22	1	.97	40	0.65	26	.228	600	Mixed	NE-S All Trades	State Conservation	-----	Severe	-----	Esthetic issue controls. Too small for major impact. Search further inland.
Kolekole Pass	1	22	1	.97	40	0.65	26	.228	1800-2200	Mixed	NE-NW Partly Trade Shielded	State Conservation	-----	Slight	-----	No esthetic problem. Too small for major impact. Profitable. Survey for size.
Kahuku Point	12	18	4	.79	480	0.50	240	2.102	50-1000	Day	NW-E All Trades	Private Agriculture	U.S. Army (Maneuvers) U.S. Navy (2 Antenna Farms) Comsat Corp (Antenna)	Slight to Moderate	-----	Moderate esthetic and user interference problems. Large enough for major impact. Very profitable. Major opportunity.
Kaena Point	8	16	1	.70	320	0.40	128	1.12	1000-2000	Mixed	S-NE Partly Trade Shielded	State Conservation	Hawaiian Satellite Tracking Station	Slight	-----	Moderate esthetic and user interference problems. Resource size and maximum uncertain. Need further survey. Economics fair to poor now.
Honouliuli Region	3	14	1	.62	120	0.30	36	0.315	2000-3100	Night	W-S Partly Trade Shielded	State Conservation	-----	Moderate	Significant	Esthetic problem moderate. Resource small. Economics look poor.

significantly higher. It does not seem likely that switching to a lower rated speed machine will help the cost problem. With moderate concern over the esthetic impact, and probably the toughest road and construction job of the sites considered, this site is discarded from consideration.

The Kahuku Point wind resource was selected for the scenario site design effort of this study. It is reasonably economical, large enough to show an effect on HECO operations, and is probably available for WECS development.

Scenario WECS Design

The Kahuku WECS field layout was done in a series of four Phases, starting with 45 MW rated power in the first Phase and building to a total (four phases) of 450 MW at completion of Phase 4. The four Phases of WECS growth proceed from the area of highest wind energy to the lowest. The first three Phases are laid out in Figures 3, 4 and 5.

Site Resource Survey and WECS Design Costs

The total cost and time schedule for the entire three-stage resource search procedure and four-phase WECS construction for a Kahuku WECS in the HECO utility system is summarized in Table 8.

The Table highlights one serious impact of a careful survey and design effort. The survey lead times are several years, compared to less than one year required to accept delivery of a WTG from a going production line and install it. Unless a way is found to safely shorten this survey time, it will set the schedule for WECS exploitation.

WECS Output Synthesis

In this study, a classical Loss-of-Load Probability (LOLP) analysis was undertaken for the HECO system, including the WECS contribution. In addition, the impact of the WECS on HECO spinning reserve requirements and the consequent economics of operating with a WECS in the generation mix was investigated. An essential input to these computations is a representation of WECS output over a long period of time (≥ 1 yr) at one-hour time intervals corresponding to the available demand data. A detailed cross-correlation procedure based on data available from the four Kahuku instruments was developed for generating realistic time histories for the WECS output. The corresponding power duration curves for each of the four WECS Phases are shown in Figure 6. Power duration curves using the instrument outputs are also shown. The results are averaged against the number of WTGs associated with each development Phase.

Table 9 compares the overall capacity factors and annual energy outputs of the various WECS Phases with the results for single WTGs at the four surveyed sites.

Figure 5. Kahuku WECS Field Layout
Phases 1, 2 and 3; 300 MW (200 WTGs)

TABLE 8

**ILLUSTRATIVE EXPENDITURE AND STATUS SCENARIO
(1977 Dollars)**

Utility Application Studies Sites Instrumented (Approx)	\$0.2M 20	\$0.2M 30	\$0.5M 50	150	200	200	
Instrumentation and Data Reduction	\$0.2M	\$0.3M	\$0.5M	\$1.5M	\$ 2.0M	\$ 2.0M	
Correlation or Modeling Analysis	\$0.3M	\$0.4M	\$0.5M	\$1.5M	\$ 2.0M	\$ 2.0M	
Subtotal	\$0.7M	\$0.9M	\$1.5M	\$3.0M	\$ 4.0M	\$ 4.0M	
Cumulative Expense	\$0.7M	\$1.6M	\$3.1M	\$6.1M	\$10.1M	\$14.1M	
Utility Design			\$ 2M	\$ 1M	\$ 1M	\$ 1M	
Cumulative Expense			\$ 2M	\$ 3M	\$ 4M	\$ 5M	
Total WECS Cost (including land and interface costs) assumed to be \$1000/kW				\$ 45M	\$ 105M	\$ 150M	\$150M
Cumulative Expense				\$ 45M	\$ 150M	\$ 300M	\$450M
Total Cumulative Expense	\$0.7M	\$1.6M	\$3.1M	\$ 54M	\$ 164M	\$ 319M	\$469M
Cumulative Rated Capacity				45MW	105MW	300MW	450MW
Status	Utility- Specific Feasibility	WECS Area(s) Selection	WECS Detail Design	Phase 1	Phase 2	Phase 3	Phase 4
Nominal Year	1977	1979	1981	1983	1984	1985	1986

**Figure 6. Comparison of Power-Duration Curves
for Kahuku WECS and Instrument Sites**

TABLE 9

SUMMARY OF WECS OUTPUT RESULTS

<u>Site or Phase</u>	<u>Capacity Factor C_F</u>	<u>Annual Energy Output $\text{kWh} \times 10^{-9}$</u>
Kahuku Hill	.646	.00849
Kahuku Upper	.485	.00637
Kahuku Field	.378	.00497
Kahuku Lower	.247	.00325
Phase 1	.595	0.235
Phase 2	.455	0.418
Phases 1 & 2	.497	0.653
Phase 3	.386	0.507
Phases 1, 2 & 3	.441	1.160
Phase 4	.291	0.383
Phases 1, 2, 3 & 4	.391	1.543

7. UTILITY IMPACT ANALYSIS

A main motivation for installing WTGs in a utility grid will be to save conventional fuels (oil, coal, uranium, etc.). A main detraction will be capital expense. The extent to which the WECS can displace or postpone the installation of conventional equipment is very important because that capital will then be free to support the WECS installation. The factor which dominates decisions to install new generating units is the reserve margin between available capacity and expected customer demand. The results of reserve margin calculations for the HECO system integrated with the four development Phases for the Point Kahuku WECS are summarized below. Although it might be expected that a WECS will save some amount of capital expense associated with conventional units, by far the greatest savings will be in fuel cost. A summary of the analysis of fuel savings is also presented below.

Reserve Margin Analysis

In the consideration of the integration of a large-scale WECS into an electric utility, it is immediately observed that a WECS is not committed and dispatched in the manner of a conventional generating unit. Because the WECS fuel is free and O&M is only weakly dependent on operating time, it is obviously most economical to let the WECS produce as much electricity as it can—not start it up and shut it down like a conventional cycling unit which is meeting the variable component of daily demand. However, if the WECS is operated to produce as much electricity as possible, its output will generally vary up and down and there will be randomly distributed several day periods where the power produced is nil due to a lack of wind. This characteristic is not typical of a conventional baseload unit. Because of

the lack of control over the resource, the WECS cannot be committed to meet a rising demand or a crisis due to the failure of another unit, nor can it be counted on to meet the baseload demand component at a steady output level.

As a consequence of the above, the net conclusion in discussions of WECS implementations has often been that the installation of a WECS will not displace the installation of any amount of conventional capacity. However, using the same generating system reliability indices that utility planners rely on, it can be shown that typical WECS installations will indeed increase the overall system reliability and, therefore, that there is some conventional capacity displacement due to WECS. To do this credibly requires that the index be an hourly index and that the WECS forced outage rate depend on both time of day and time of year. The loss-of-load probability (LOLP) is the reliability index used in this analysis.

Sample LOLP Results for HECO Without WECS

The monthly distribution of LOLP for HECO conventional generation without a WECS is shown in Figure 7. These results were computed on an hourly basis whereas HECO ordinarily computes LOLP using daily peaks only. Because these monthly distributions of LOLP were computed without a WECS in the system, they indicate the monthly potential for increasing system reliability by adding a WECS. The demand time history used to compute the LOLP distributions of Figure 7 was constructed by scaling the 1976 HECO demand record to match HECO's forecast of the monthly peaks over the 15-year period. HECO's annual peak always occurs in October. Even though the normalized annual time history is the same for each year, always peaking in October, the months with the greatest LOLP vary from year to year. That is, the months with the greatest potential for system reliability improvement do not necessarily correspond to the annual demand peak. This is due to year-to-year variations of new installed capacity and month-to-month variations in maintenance schedules associated with units of various discrete capacities. This example leads to a general result that is often not recognized: for a WECS to have the potential for increasing system reliability, it is not necessary that the WECS seasonal performance match the seasonal variation of customer demand.

System LOLP Calculations Including WECS

The availability probability for various levels of WECS capacity (power output) can be computed for each hour of the day for any given month using historical wind data and a model of the WECS. The resulting probabilities (or their complement, the partial outage probabilities) can be convolved with availability data for the conventional units to obtain the overall system LOLP.

LOLP Improvement Due to WECS

If the baseline HECO generation plan is unaltered (in terms of both maintenance schedule and installation plans) and the four Phases of the Kahuku WECS are installed and made operational, there is a substantial improvement in the overall HECO system LOLP. The results are shown in Table 10 for LOLP computed as

Figure 7. Monthly HECO LOLP Distribution for Baseline Study Plan

TABLE 10
LOLP FOR BASELINE HECO SYSTEM WITH WECS

Year	Baseline LOLP (Events/year)	Baseline + Phase 1 LOLP (Events/year)	Baseline + Phases 1&2 LOLP (Events/year)	Baseline + Phases 1,2&3 LOLP (Events/year)	Baseline + Phases 1,2,3&4 LOLP (Events/year)
1980	.033	---	---	---	---
81	.157	---	---	---	---
82	.370	---	---	---	---
83	.098	.044	---	---	---
84	.437	.213	.122	---	---
1985	.257	.130	.078	.062	---
86	.542	.253	.131	.101	.080
87	.815	.458	.285	.233	.186
88	.593	.308	.176	.139	.110
89	1.198	.621	.342	.258	.203
1990	.949	.532	.294	.225	.180
91	.640	.342	.189	.146	.115
92	.942	.555	.327	.256	.204
93	1.250	.758	.458	.357	.287
94	1.589	.952	.557	.431	.347

outlined above. The substantial decrease in LOLP due to the installation of the WECS suggests that a modification of the installation schedule for the new conventional generation might be possible without compromising the system reliability as measured by LOLP. The modification should lead to a savings or postponement of capital expenditures for conventional units, of course.

Equivalent WECS Capacity Credit

A direct method of evaluating an "equivalent" WECS capacity credit was developed here to gain a more general understanding of the problem.

A hypothetical conventional unit with a forced outage rate of .05 which required no maintenance was added to the baseline generation plan described earlier. The capacity of this single unit was varied incrementally up to 120 MW and the HECO system LOLP recalculated for each of the 15 years in the span 1980-94. The resulting annual LOLP variation with the capacity of the added unit is shown in Figure 8. The curves show, in terms of annual LOLP, how much the addition of a single highly reliable conventional unit will improve the system reliability.

The hypothetical conventional unit was then removed from the system and the Phase 1 WECS was added to the HECO system. The annual LOLP was then recalculated. A distinct single value of LOLP is obtained for each year of the 15-year span studied. Figure 8 can be entered for the year of interest at the ordinate

Figure 8. Variation of HECO Annual LOLP with Capacity of an Additional Unit with .05 Forced Outage Rate

Figure 9. Equivalent Conventional Unit Capacity of Kahuku WECS Phase 1 (Conventional Unit Forced Outage Rate = .05)

value of LOLP calculated including the WECS, and the corresponding capacity of a single conventional unit can be read from the horizontal scale. The results for each of the 12 years beginning in 1983 are spotted on Figure 9 for Phase 1 of the Kahuku WECS.

The Phase 1 WECS installation is comprised of 30 WTGs with a total nameplate rating of 45 MW. Note that the equivalent capacity of the Phase 1 WECS varies year to year from 20 MW to 28 MW. This variation is due entirely to the variation in monthly distribution of the baseline LOLP as discussed earlier.

The 20 to 28 MW range in equivalent conventional capacity corresponds to a WECS capacity credit of from 44.4 to 62.2 percent. This is a lower-bound estimate because the maintenance schedule for the conventional units was not replanned for the addition of the WECS. The results therefore correspond to a suboptimal schedule and can only improve with rescheduling. The percentage capacity displacement decreases successively for the additional three Phases because the quality of the wind was successively poorer as discussed earlier. A lower quality wind is reflected in the WECS availability vector, of course. In fact, the availability vector and its affect on system LOLP is a measure of wind quality.

It should be reemphasized that the capacity credit results presented above are hypothetical in that the LOLP improvement due to the WECS is compared to the improvement due to the hypothetical introduction of a conventional plant with a rubber capacity. The real situation calls for analyzing the possible displacement of one of the presently planned HECO conventional units. This problem is discussed below.

Effect of WECS on LOLP for Planned HECO Generation

The HECO plan for the installation of new equipment used in this Study (called here the "baseline plan") was one of several under consideration in March of 1977. It was provided to Aerospace specifically for use in this Study but it has not been adopted by HECO as a firm plan. Such plans are always in a continual state of reappraisal and revision. The following analysis is therefore realistic but not definitive for HECO.

From the baseline installation schedule provided earlier, Units G3, G4, G5 and K7 are clear candidates for displacement or postponement by a WECS installed in the middle 1980s.

HECO bases their generation risk analysis on an LOLP index computed with daily peaks only and have therefore not defined a risk criterion consistent with hourly LOLP calculations. The approach taken here was to calculate the hourly LOLP for the baseline HECO installation and maintenance plan and use the results as a guide (the term criterion is too strong) for adequate reliability in the evaluation of the WECS. The annual LOLP for the baseline plan is charted in Figure 10. It was considered acceptable if the displacement of one or several of the planned installations by one or several of the Kahuku WECS Phases did not produce an annual LOLP significantly exceeding the highest baseline value (which occurred in 1994).

Figure 10. Annual LOLP for HECO Baseline Study Plan
Conventional Unit Availability Schedule

Figure 11 charts the annual LOLP corresponding to the displacement of G3 (a 70 MW gas turbine scheduled for initial operation in 1984) with the Kahuku WECS Phases 1, 2 & 3. Phase 1 alone and Phases 1 & 2 do not produce acceptable LOLPs. However, Phases 1, 2 & 3 taken together with the removal of G3 produce annual LOLPs as good as the worst year (1994) for the baseline case. It is concluded therefore that the installation of WECS Phases 1, 2 & 3 will displace G3. That is, the installation of 200 WTGs with a nameplate rating of 300 MW displaces 70 MW of conventional generation for a capacity credit of 23.3 percent.

As an alternative to displacing G3, the possibility of adding a WECS plus two new 70 MW gas turbines to displace K7 was investigated. K7 is a 178 MW oil-fired thermal unit. Consistent with HECO gas turbine experience, the gas turbines were assumed to have forced outage rates of .05. They were to become operational at the same time K7 would have in 1989. Adding the Phase 1 WECS to the two gas turbines brings the LOLP within reason. It is concluded that from a generation reliability standpoint Phase 1 plus two gas turbines can displace K7.

The displacement of G3, a unit costing approximately \$10M (1977 dollars) by Phases 1, 2 & 3 would add about \$33/kW to the value of the first 200 WTGs installed on Kahuku. The replacement of K7 with two gas turbines would save approximately \$35M (1977 dollars) in capital expenses but (in the presence of Phase 1 WECS generation) would impact the cost of production on the order of \$10M/year (1977

Figure 11. Annual LOLP for HECO Baseline Study Plan with Kahuku WECS Phases 1, 2 and 3 and Without G3

dollars) in the time frame immediately after installation in 1989. In both cases, the savings associated with these capital displacements were dwarfed by the savings associated with fuel displacement. Therefore it was decided to completely discount the capital value of the WECS and figure the WECS value solely on the basis of operational fuel savings.

Baseline System Cost of Production

The baseline system cost of production was computed to establish the basis for evaluating the economic worth of the four different Phases of WECS implementation. These computations were based on the baseline maintenance and installation schedules, unit performance data, hourly demand data, and fuel costs. The units were committed and dispatched according to the rules and policies established and used by HECO in their daily operations.

The computed system performance for each of the 15 years in the 1980-94 time frame is shown in Table 11. Some considerable year-to-year variation in capacity factor, hot and cold starts, and heat rate might be noted in Table 11. This variation is due to the variation of available installed units and can be correlated with the variations in installation and maintenance schedules.

TABLE 11

BASELINE SYSTEM OPERATING PERFORMANCE 1980-94
(Current Dollars)

Year	Gross Energy (1000 MWh)	Capacity Factor	Number of Starts		Gross Heat Rate (Btu/kWh)	Fuel Cost (mills/kWh)	Total Cost (mills/kWh)	Total Cost (millions \$)
			Hot	Cold				
1980	5811	.579	1608	891	9518	33.49	35.20	204.63
81	6047	.592	1833	919	9395	36.94	38.57	234.14
82	6310	.544	1903	951	9406	39.55	41.40	261.28
83	6597	.586	1471	960	9394	43.03	44.96	296.71
84	6907	.568	1926	1018	9519	47.73	49.73	343.54
1985	7206	.594	2005	1006	9525	52.19	54.27	391.01
86	7536	.596	2255	1021	9567	56.45	58.60	441.63
87	7882	.595	2508	1035	9709	61.75	63.98	504.28
88	8261	.625	2601	1024	9761	66.89	69.06	571.46
89	8628	.588	2699	1093	9549	70.26	72.68	627.10
1990	9041	.596	2602	1106	9626	75.97	78.49	709.64
91	9472	.600	2859	1131	9778	83.48	86.10	815.52
92	9955	.629	3060	1190	9856	90.80	93.52	930.98
93	10404	.605	3105	1231	9766	96.34	99.16	1031.69
94	10905	.569	3132	1285	9711	102.69	105.64	1151.95

Cost-of-Production Savings with WECS and Full Spinning Reserve

The Kahuku WECS was treated as a must-run unit which supplied a time history of electric energy. The WECS supply was subtracted from the HECO demand on an hourly basis and the conventional HECO generation was then optimally dispatched against the resulting residual demand. All of the unit commitment rules used by HECO were followed exactly. The WECS was treated as the top priority must-run unit. In the determination of the spinning reserve required to protect the system, the WECS was treated as a single unit that could suddenly be forced out in its entirety. Zero quick load pickup capability was attributed to the WECS. Such an operating policy would be consistent with a total inability to predict wind levels thus requiring spinning protection for the sudden disappearance of wind energy. This is an extremely conservative assumption because of geographic diversity within a mountainous WECS of the size of that hypothesized for Kahuku.

The annual savings in current dollars for each of the four Phases are plotted on a semi-log scale in Figure 12. Straight-line (semi-log) least squares curve fits are also shown. These curve fits were used to extrapolate the results for 30 years for use in calculating the WTG break-even costs presented later.

The variation about the straight line of the computed points in Figure 12 is due to the year-to-year variation of installation and maintenance schedules. The variation of installation and maintenance schedules leads to a year-to-year variation in generating efficiency which is reflected in the annual system heat rate. On years which have high system heat rates for the baseline system without a WECS, there is a greater potential for operational savings with the WECS.

Figure 12. Annual Cost Savings
Due to Kahuku WECS

Cost-of-Production Savings with WECS and Partial Spinning Reserves

For the preceeding results, a spinning reserve policy was adopted which would protect against the sudden and complete failure of the entire Kahuku WECS. Such a policy would be appropriate if there is a total inability to predict wind levels or count on the persistence of existing wind levels. In this Section, cost-of-production results are presented for a spinning reserve policy which would not explicitly protect against the sudden and complete failure of the entire Kahuku WECS. Such a policy would be appropriate if winds were completely predictable permitting conventional units to be brought on line and subsequently shutdown in accordance with a perfectly predicted schedule of wind energy availability. The partial spinning reserve policy evaluated in this Section exactly follows the Spinning Reserve Criteria described earlier, but only for those conventional units meeting the residual demand. That is, the policy is exactly that which HECO would currently use with their conventional units meeting their gross customer demand if the demand were decreased by the amount of the WECS output.

The results corresponding to this partial spinning reserve policy are presented in Table 12 in terms of the percent improvement in annual operating savings as a consequence of adopting this less conservative partial spinning reserve policy. As can be seen from the Table, the increase in cost savings is very nominal considering the concomittant increase in operating risk. It was therefore concluded that the WECS economic analysis should be based on the cost savings associated with the full spinning reserve policy as presented in the preceeding Section.

TABLE 12
PERCENTAGE IMPROVEMENT IN OPERATIONAL COST SAVINGS DUE
TO PARTIAL SPINNING RESERVE POLICY

<u>Year</u>	<u>Phase 1</u>	<u>Phases 1&2</u>	<u>Phases 1,2&3</u>	<u>Phases 1,2,3&4</u>
1983	nil			
1984	"	.05		
1985	"	.09	1.91	
1986	"	.09	2.24	3.16
1987	"	.11	2.36	3.44
1988	"	.18	2.82	4.23
1989	"	.10	2.24	3.56
1990	"	nil	1.78	2.72
1991	"	.01	2.76	4.12
1992	"	nil	2.90	4.52
1993	"	"	2.69	4.15
1994	"	"	2.65	3.99

It is an important finding of this Study that a complete lack of wind predictability, at least in terms of hourly averages, has negligible impact on HECO fuel costs. Because the WECS treated as a conventional unit with HECO's conservative spinning

reserve policy produces a negligible decrease in cost savings compared to a spinning reserve policy based on perfectly predictable winds, it is generalized that the cost of spinning protection against a WECS failure for an interconnected utility (which will have a less conservative policy) will also be negligible when compared to the savings due to the WECS. This conclusion may only pertain to situations where the WECS capacity is approximately the same fraction of conventional installed capacity as that studied here for HECO. Also, of course, it may not pertain to the extremely conservative policy of providing spinning reserve to protect against the simultaneous failure of the WECS and the largest conventional unit. That case was not studied here.

8. KAHUKU POINT WECS ECONOMICS

Economic evaluation of alternate energy systems is often based on "levelized cost" methods of analysis. Levelized methods of analysis, however, do not show the annual cost of service or the initial impact of the early years of operation. They also ignore the utilities' cash flow problems in the first few years of the WECS investment, which may be considerably more severe than indicated by the total investment in the WECS accounted on a levelized basis. Therefore, costs were computed on a cash flow basis to evaluate the economics of WECS application in HECO. Since tax effects can be significant to investment decisions, the analysis was done on an after-tax basis. Costs were computed on a discounted cash flow basis, with proper account taken of inflation effects on maintenance and other costs, and the normal utility policies of loan repayment and rate of return on investment.

The significant features of cash flow economics are shown in Figures 13 and 14. In Figure 13 is shown the "Wind Energy System Saving" for Phase I of the WECS. This amounts to the net annual cash inflow to the utility as a result of the WECS. This net saving is found by totaling the system savings of fuel, conventional system O&M, local taxes, and subtracting the WECS annual costs, which consist of initial investment, operating costs, and return on investment. The example of Figure 13 was computed with a WTG cost of \$1220/kW, which is the Phase I break-even cost as discussed later.

If revenue flows are matched so as to break even after 30 years where fuel cost is escalating, the net cash flow is negative for about the first six years. During this time the interest on the debt and the uniform debt payback rate exceed the fuel savings. Later in the system life the money cost on the remaining debt decreases and the fuel saving increases, leading to a positive and rapidly increasing cash flow. The integrated effect of these varying cash flows is shown in Figure 13 as the "Cumulative Wind System Saving." Because of the initial negative cash flows, the cumulative value drops until the total cash position in this case is 36 percent beyond the initial investment and the cumulative cash flow does not return to zero for approximately 15 years. Thereafter, it recovers to high values very rapidly.

These general results apply to all four Phases; a substantial net cash outflow ending in about six years, followed by recovery to zero cumulative cash flow about the end of 15 years. It is this cash flow problem, as much as the initial investment, that will

Figure 13. Wind Energy System Saving

Figure 14. Cumulative Wind System Saving

deter utilities from a decision to install WECS. The negative cash flow period and amount would be reduced or eliminated by shortening the WECS payback period, but a substantially lower WTG cost would be required to make this possible. The payback would then also be much less dependent on the long-term projection of fuel cost escalation.

Break-Even Costs

Since the cost of the WTGs is not known, all computational results are presented in terms of the break-even WTG price. The cash flow analysis starts with an assumed WTG cost and finds the resulting rate of return. The required rate of return of 11.7 percent equals the weighted cost of new capital consistent with the HECO financial parameters described earlier and determines the WTG break-even cost as shown in Figure 15. The cross-plot then also indicates the tradeoffs of break-even cost with rate of return.

Figure 15. Rate of Return Versus WTG Cost for Four Phases

Financial Assumptions

The assumptions for financing, interest rates, depreciation, inflation, etc., generally followed the practice and projections of HECO. These inputs are summarized in Table 13. All the inputs are reasonably typical of privately-owned utilities.

TABLE 13

**WIND ENERGY SYSTEMS APPLICATIONS IN HAWAII
FINANCIAL ASSUMPTIONS**

Debit Equity Ratios, %	
Long-Term Debt	53.0
Preferred Stock	13.0
Common Stock	34.0
Equity Ratio, %	47.0
Interest Rates, %	
Long-Term Debt	9.0
Invested Earnings	7.0
Dividend Rates, %	
Preferred	9.0
Common	15.0
Financing Cost, %	
Debt Funds	1.0
Equity Funds	2.0
Income Tax Rates, %	
Federal	48.0
State	6.4
Other Taxes, %	
Gross Revenue & Miscellaneous	10.2
Investment Tax Credit, %	10.0
Investment Tax Credit Liability Rate, %	50.0
Bond Retirement, Yrs	30.0
Amortization of Financing Cost, Yrs	20.0
Book Depreciation, Yrs	30.0
Book Depreciation Method: Straight Line	
Tax Depreciation, Yrs	24.0
Tax Depreciation Method: Declining Balance/Sum of Years Digits	
Material & Supplies, %	
Operating & Maintenance (Plant Cost)	1.6
Working Capital Allowance, %	
During Construction	1.0
Plant Operation	
Operating & Maintenance	12.5
Inflation Rate, %	
Plant Construction	
1978-1982	9.0
1983-1987	8.0
1988-1992	7.5
1993-1997	7.0
Operating & Maintenance	7.0
Materials & Supplies	6.0
General Inflation	5.5
Insurance (% Plant Cost)	0.06

Break-Even WTG Costs

Economic break-even results for the four Phases for the HECO baseline conditions are summarized in Table 14 and plotted in Figure 16. The break-even WTG costs vary from about \$1220/kW for Phase 1 to \$360/kW for Phase 4. This tremendous variation results primarily from the large variation of energy output per WTG at the different Phases.

The break-even WTG cost is shown in Figure 16 plotted against the level of WECS penetration in rated megawatts and in percentage of the 1982 utility total generating capacity.

9. GENERIC EXTENSION OF RESULTS

This Section extends the results of the study to situations generically similar to Oahu in other locations. Parametric and other means of extension are used as appropriate.

The most important characteristics of the Oahu case that are subject to generic extension are:

- (1) Tradewind resource
- (2) Mountainous terrain wind resource

Tradewind Resource; Generic Conclusions

The basic advantage of tradewinds for wind power generation is that they are very steady in force and direction for much of the year and their outages tend to be brief. Because of their steadiness, a WTG well matched to the resource will give full-rated power 40 percent to 50 percent of the time and some power 80 percent to 90 percent of the time. Capacity factors can exceed 65 percent. Even higher availabilities can be obtained by deliberately undermatching the WTG rated speed to the resource.

The relationship between capacity factor and dimensionless rated velocity is somewhat different from that for a more variable wind resource. The optimum matching of site to machine moves in the direction of a WTG rated velocity only slightly greater than the site mean wind speed. The WTG capacity factor is more sensitive to accurate matching of machine-rated speed to site mean wind speed than for the typical resources which have greater wind variability.

The steadiness of direction of the tradewinds makes the location of sites of mountain amplification of the winds more sharply defined. It also increases the feasibility of heavily exploiting these sites of mountain amplification by locating wind machines in very close array spacing normal to the prevailing wind direction without taking severe wake interference losses.

TABLE 14
SUMMARY OF ECONOMIC RESULTS

	Phase 1	Phase 2	Phase 3	Phase 4
<u>Wind Energy System Assumptions</u>				
Number of Wind Turbine Generators	30	70	100	100
MWe Each	1.5	1.5	1.5	1.5
Installed Capacity (MWe)	45	105	150	150
Year Installed	1982	1983	1984	1985
Year Operational - 1 January	1983	1984	1985	1986
Capacity Factor, %	59.6	45.6	38.7	29.2
Annual Mean Power, MW	26.8	47.9	58.1	43.8
<u>Analysis Results</u>				
Break-even WTG Cost (\$/kW 1977)	1,220	870	630	360
Years to Annual Positive Cash Flow	6	6	7	6
Years to Cumulative Positive Cash Flow	15	15	15	15
Weighted Average Cost of Capital, %	11.7	11.7	11.7	11.7
Internal Rate of Return, %	12.3	12.3	12.3	12.3

Figure 16. WTG Break-Even Costs by Phase

Mountainous Terrain Resource Enhancement

The most significant generic characteristic of the Oahu utility system is that the wind resources are in mountainous terrain. This leads to certain generic characteristics that will be typical of all mountain-enhanced wind resources.

Mountainous or terrain-enhanced wind resources are concentrated in relatively small spaces, typically with dimensions ranging from a few miles to less than a mile. Within these dimensions the wind energy that can be generated annually at each WTG site varies greatly over dimensions as small as the individual WTG.

Because strong variation of energy over just a few hundred feet will have severe economic impact, fiscal prudence demands a detailed and careful wind resource survey of mountain sites to locate the economic WTG sites and screen out the uneconomic ones. The effects of diversity, design for interference loss, and anomalous vertical gradients also call for careful individual WTG site surveys.

The cost of such surveys is small relative to the total economic impact on the WECS. The value of the survey, to be weighed against the cost, can be established from the basic system economics performance parametrics presented earlier.

If the WTG rated velocity (V_R) is held constant, the relation between break-even unit WTG cost and site mean wind speed ($\bar{V}$) for the Kahuku Point case studied is:

$$\Delta C \cong (4400 \text{ \$/kW}) (\Delta \bar{V} / \bar{V}) (\bar{V} / V_R)$$

Inserting typical values from this study, a site improvement of 2 mph in mean wind speed is worth

$$\Delta C \cong (4400 \text{ \$/kW}) (2/18) (.8) = \$390/\text{kW}$$

For a 1500 kW WTG this is: $\approx \$585,000/\text{WTG}$. This is a substantial value for a successful survey.

It appears that a rather intensive survey will be justified economically in most mountainous terrain situations.

In addition to detailed wind surveys, design techniques will be required for trading off various array configuration and utility integration alternatives. With minor adaptation, techniques used in this report can be used as design tradeoff tools. The losses incurred in close line arrays of WTGs at various array angles and WTG spacings for a particular wind history are illustrated in Figure 17. The tradeoffs between reduced output by closer spacing at a very energetic site and developing a less energetic site are then evaluated by a superposition as in Figure 18. Variations of energy output with WTG rated speed for various wind resources are illustrated in Figure 19, which must be worked against WTG cost variations to be defined elsewhere. Modest reductions of WTG cutout wind speed are shown to have negligible adverse effect on energy collected in a tradewind location as in Table 15.

Figure 17. Effect of Array Angle And Spacing on Conversion.

Figure 18. WECS Design Tradeoff; Array Spacing and Angle of Wind Energy

Figure 19. Mean Annual Power Variation with Rated Power

TABLE 15
EFFECT OF VARYING WTG CUT-OUT SPEED

Wind Record	Mean Wind Speed $\bar{V}$, m/s	Mean Site Wind Energy w/m^2	Mean Power $\bar{P}$, kW	Annual Energy $\sum E$ kW x 10^6	Capacity Factor C_F	Cut-Out Loss ΔC_F	Cut-Out Loss ΔC_F	Capacity Factor Change ΔC_F	Percent Energy Change %
			$V_{co} = 22.35 \text{ m/s (50 mph)}$			$V_{co} = 17.83 \text{ m/s (40 mph)}$			
K_H	9.12	683.5	876.9	7.69	0.585	-.002	-.013	-.011	-1.88
K_U	8.06	416.3	602.7	5.28	0.402	0	0	0	0
K_F	7.35	320.5	458.2	4.01	0.305	0	0	0	0
K_L	6.03	258.7	287.5	2.52	0.192	0	0	0	0
S-49	7.51	479.8	659.15	5.77	0.439	-.0015	-.0090	-.0075	-1.71
S-48	7.16	403.1	605.21	5.30	0.404	-.0005	-.0065	-.0060	-1.49

The preceeding discussion addressed the characteristics of mountain wind resources in the context of an isolated utility, such as HECO on Oahu. The limited dimensions of the island, which isolate the utility from load sharing and power exchange, also isolate the resource search to the dimensions of the island; less than 40 miles in any direction. Generic extension to the mountain resource situation in a nonisolated situation raises some very difficult problems.

10. SUMMARY OF RESULTS AND CONCLUSIONS

The results and conclusions of the study are summarized below in three categories: (1) findings specific to the Oahu utility application; (2) broader generic findings; and (3) methodologies, procedures and analytical tools useful to future WECS development and commercialization.

Specific Application Findings

The break-even WTG cost and feasible WECS penetration of the HECO system on Oahu are set by the characteristics of the limited mountain wind resource available on the island. The major wind resource, Kahuku Point, can provide about 45 to 150 MW of rated WECS capacity (4 to 13 percent penetration of present HECO generation) at WTG break-even unit costs ranging from about \$1220/kW down to about \$870/kW. Further penetration to 300 kW and 450 kW (26 and 39 percent, respectively) would use progressively poorer resources with break-even WTG costs ranging down from \$630 to \$360/kW. At least one other small (≈ 30 MW) but energetic site is available and others may yet be found.

The three dominating economic factors are the energy intensity of the wind resource, the unit cost of the WTGs, and the projected cost of the displaced petroleum fuels. Other factors such as the WECS displacement capacity, collection and transmission cost, land cost, prior survey and planning costs, and backup fuel for load pickup are of minor consequence.

When financed according to typical utility accounting practices, the WECS presents a cash flow problem in addition to the initial investment barrier. With 30-year amortization, the cash flow on the investment is likely to be negative for about the first six years and the cumulative negative cash flow position at that time may be 25 to 30 percent greater than the initial capital investment. This situation will be greatly eased if the WTG unit cost is low enough to allow cost recovery in much less than 30 years.

No substantive problems were found in the integration of the WECS into the HECO utility network. The WECS need not change the dispatching mode or the spinning reserve criteria under which HECO operates. The maintenance of spinning reserve adequate to protect against a sudden Kahuku WECS outage has negligible impact on HECO fuel costs. This conclusion is based on the HECO policy that protects against the sudden failure of the largest unit, the largest unit sometimes being a conventional unit and sometimes the WECS, depending on the current output of the WECS. The more conservative policy of protecting against the sudden simultaneous failure of the WECS and the largest conventional unit was not studied.

The WECS functions as a fuel saver. Although its capacity displacement is a large fraction (40 to 65 percent) in the best sites, the total number of good sites is not enough to displace a significant unit of planned HECO generation capacity.

Generic Extension of Findings

Very energetic mountain wind energy resources, such as those on Oahu (20 to 24 mph (9 to 11 m/s)), can result in WTG break-even costs up to \$1200-\$1400/kW for the reference WTG design in private utility applications, and roughly \$1600-\$1900/kW in publicly-owned utilities. Wind resources of this intensity appear to exist in many mountain locations, but supporting data is very limited, and confirming detailed resource data are almost nonexistent.

Such mountain wind resources tend to be found in small areas, from a few miles to less than a mile in extent and scattered through mountainous terrain. Each resource shows a large spread of energy intensity between WTG sites, and only a few sites in each will sustain the highest WTG break-even costs. Larger numbers of surrounding sites will sustain lower WTG break-even costs and should logically be developed in succeeding Phases as WTG unit costs are reduced.

Economically prudent development of such wind resources demands a careful and detailed survey and economic design tradeoffs before each Phase commitment. Such a detailed survey can be done using conventional wind instrumentation at costs that are very acceptable in terms of cost-benefit ratios. However, the time delays involved in the surveys are likely to become pacing items in the expansion of national WECS capacity. The problem could be aggravated by the lack of established search strategies and experienced practitioners of wind resource search.

The economic leverage of high energy mountainous resources justify constructing transmission lines to exploit a distant mountain area. This could lead to crossing the service area of other utilities as well as state lines in some instances. If WECS become a favored generation system at some future time, this could lead to many jurisdictional problems, calling for the formation of consortiums, negotiations between agencies of different states, and a need for strong Federal leadership.

Mountain wind resources appear to have a degree of intrinsic geographic diversity that may be very significant in their application. This characteristic needs more detailed experimental evaluation.

Tradewind resources also appear to have somewhat unique characteristics regarding power time duration relationships and requirements for matching WTGs to the resource. These also need more detailed experimental evaluation.

Economics dictate that wind energy be used to displace oil-fired generation first. Displacement of coal-fired generation will require lower WTG break-even costs. Direct displacement of existing nuclear-based generation is not foreseen, although the WECS will cause a remix of conventional generation which will often lead to a smaller nuclear capacity for optimum economics.

Methodologies, Procedures, and Analytical Tools

Several methodologies, procedures, and analytical tools developed during this study should prove useful in further application studies and in future WECS development and commercialization.

A comprehensive set of siting factors and criteria useful in future site selection was developed and evaluated. The step-by-step organization and properly sequenced application of these procedures for mountainous terrain site selection was developed and demonstrated by scenario application to the Oahu case. Several key projected problem areas were highlighted. The site-selection emphasis and procedure for flatland and mountain resources were shown to be fundamentally different. If the flatland wind resource is uniform over a wide land area, site selection will be dominated by land use, cost and esthetic considerations. The strong intrinsic variability of the energy and economic worth of mountain wind resources dictates that energy level must be the leading site-selection criteria, with all other considerations following after. A few land uses and values, of course, will hold veto power over WECS development.

A scenario WECS design used to estimate Oahu WECS performance forms the skeleton of a methodology for wind resource survey, WECS application evaluation, and WECS field design layout for mountainous terrain wind resources. The following WECS design tradeoff issues are explored to the depth necessary for the present application study and thereby advanced significantly in readiness for later design application:

- (1) WTG array performance tradeoffs between array angles and prevailing wind. WTG spacing at one to two diameters can greatly increase the WECS energy output of mountain wind resources of limited size. The resulting WTG wake interference losses are very dependent on the relationship of the array angle to the prevailing wind direction and the degree of wind directionality.
- (2) WTG array performance tradeoffs between array spacing and exploitation of lower energy sites. For any required total generation capacity, closer spacing may obviate the need to use poorer resources.
- (3) Geographic diversity within mountain wind resources. Properly used, these may increase the economic benefit to specific utilities.
- (4) Capacity factor and power effects of differing WTG site resource energy levels. These greatly effect economic optimizations.
- (5) Capacity factor and power effects of varying WTG rated speed and cutout wind speed. Moderate gains in total energy conversion can be made by selective matching of more than one available WTG design to various parts of a mountain resource. Economic benefit of such matching depends on cost variables to be determined elsewhere in the National Wind Program.

- (6) Significance of ridgetop overspeed conditions to survey validity. This affects selected search strategy, survey cost and risk of misestimated energy recovery and consequent economic loss.
- (7) Cost tradeoff parameters on value of resource search. In most of these design issues the analytical tools used in this study can be readily extended to guide the detailed mountain WECS design layout and optimization. This should assist in planning prudent expenditures for resource search and survey prior to mountain WECS resource selection.

Projected WECS Exploitation Scenario

At this point it is possible to project with some confidence the most likely path of practical commercial exploitation of WECS. It is necessary to make certain broad, implicit assumptions that do not appear to be excessively risky. Key among these assumptions are the following:

- (1) Scarcity of clean fossil fuel will continue, and petroleum costs will rise slightly faster than patterns controlled by normal inflation.
- (2) Public policy of reducing national dependence on imported oil will preempt "lesser" issues, such as public versus private power arguments.
- (3) A key criterion for WECS operational expansion will be break-even or more favorable economics based primarily on the offset fuel cost savings.
- (4) Practical operationally proven WTGs in utility scale may be available in production quantities at top break-even costs in five to seven years. The (real) costs will gradually scale down as production expands.

Based on these tenets, the likely predominant mode of WECS operational development over the next 20 to 30 years is projected as follows:

- (1) The next five to seven years will be occupied with small scale production and field operational confidence testing of numerous government and privately-funded WTG designs. The length of this consolidation period can be affected by the wisdom of the designers, the foresight of the utilities, the progress of the energy crisis, and government policy/actions regarding both public- and privately-funded WTG designs.
- (2) The first major operational WECS deployments should be made in the highest resource energy sites known and available at the time. These sites will be predominantly (almost exclusively) locations of mountainous terrain wind amplification.

- (3) The high energy level will help to assure WECS investment payout in a reasonable time at high initial production costs to minimize risk of long-term fuel cost uncertainty. In the most favorable circumstances of very high energy siting (9-10 m/sec avg), favorable WTG prices \$600-800/kW, 1977) and favorable financing (public utility), capital payouts in as little as 10 years are credible.
- (4) Energy from these predominately mountain sites could be economically transmitted and shared by large consortiums of users, both public and private.
- (5) The Federal Government will inevitably be a major participant in the resource development because of:
 - (a) Major Federal land holdings in the majority of high energy resource areas (Western mountains).
 - (b) Major hydroelectric installations and related transmission and distribution systems in many of the areas of interest.
 - (c) Favorable economics of public utility ownership, under present ground rules, for capital intensive generation. Private utility participation will increase as WTG costs come down.
- (6) If capital investment rate limitations do not limit the development rate, the magnitude of the wind resource search and validation task will limit it, because of the extreme spacial complexity and variability of mountain resources. The up-front cost and schedule delay of adequate resource search and validation will inevitably lead in some cases to shortcutting the search, resulting in costly errors in WTG siting.
- (7) Storage systems may not be built specifically to store wind energy in a utility in the foreseeable future because:
 - (a) Backup by conventional generation is more economical.
 - (b) Transmission from multiple resources and the character of mountain resources give a substantial but undefined geographical diversity to the WECS output.

It is likely therefore that wind energy storage will never be economical or required.
- (8) The eventual penetration of wind generation will depend primarily on the balance of far future fuel costs, WTG production prices, cost of capital, and electrical power demand.

The first economical WECS developments will probably supply energy to utilities located in the vicinity of high intensity wind resources. However, later stages of development may involve transmitting the resulting energy to using utilities many hundreds of miles away.