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This report describes the results of long-term field evaluation of four horizontal-axis, upwind, small wind energy conversion systems (SWECS) configured in an application mode. The long-term field evaluation of these SWECS covers performance, reliability, maintenance, maintainability, and availability data. The results of these evaluations have proven SWECS to be a viable source of alternative energy, but they must be properly designed and maintained to operate in a highly corrosive marine environment. In addition, the SWECS require frequent

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20. Continued

preventive maintenance, depending on design and location, including corrosion control at least every 3 months. The following recommendations resulted from the field evaluations: (1) do not use sliprings and bearings, if at all possible; (2) use sealed and self-lubricating bearings; (3) ensure that the tower is guyed and hinged for easy maintenance; (4) enclose as much as possible all components exposed directly to the marine environment, or select materials capable of withstanding the marine environment; (5) ensure that all controls are passive and fail safe, if possible; and (6) improve the programming of the synchronous inverter so that it matches generator impedance at all wind speeds.

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TN-N-1748

March 1986

By Dharam Pal

NCEL Technical Note

Sponsored By Naval Facilities Engineering Command

WIND ENERGY CONVERSION SYSTEMS:

EVALUATION OF RELIABILITY, AVAILABILITY, AND MAINTAINABILITY AT VARIOUS LOCATIONS.

ABSTRACT This report describes the results of long-term field evaluation of four horizontal-axis, upwind, small wind energy conversion systems (SWECS) configured in an application mode. The long-term field evaluation of these SWECS covers performance, reliability, maintenance, maintainability, and availability data. The results of these evaluations have proven SWECS to be a viable source of alternative energy, but they must be properly designed and maintained to operate in a highly corrosive marine environment. In addition, the SWECS require frequent preventive maintenance, depending on design and location, including corrosion control at least every 3 months. The following recommendations resulted from the field evaluations: (1) do not use sliprings and bearings, if at all possible; (2) use sealed and self-lubricating bearings; (3) ensure that the tower is guyed and hinged for easy maintenance; (4) enclose as much as possible all components exposed directly to the marine environment; (5) ensure that all controls are passive and fail safe; and (6) improve the programming of the synchronous inverter so that it matches generator impedance at all wind speeds.

NAVAL CIVIL ENGINEERING LABORATORY, PORT HUENEME, CALIFORNIA 93043

METRIC CONVERSION FACTORS

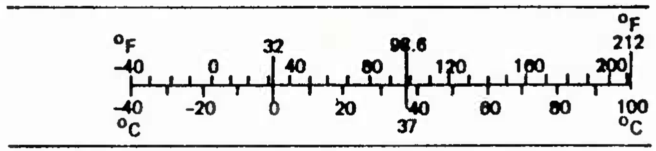
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
^oF	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	^oC

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
^oC	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	^oF



CONTENTS

INTRODUCTION

Under Naval Facilities Engineering Command sponsorship, the Naval Civil Engineering Laboratory (NCEL), as the lead laboratory for the Navy's Wind Energy Program involving shore facilities, is investigating the use of small wind energy conversion systems (SWECS) in the 1- to 50-kW range to generate electricity at Navy shore installations. The primary program objectives include:

1. Selection of a suitable site for long-term testing of a wind energy conversion system by determining annual average wind speed, minimum electromagnetic interference (EMI) to Navy installations, and special environmental conditions at the site.

2. Selection of an optimum size WECS required to meet the load power requirements based on site wind characteristics.

3. Collection and analysis of reliability, availability, and maintainability (RAM) data on various generic types and sizes of WECS.

4. Collection and analysis of performance and operational data to evaluate various WECS design characteristics.

5. Collection of operating and maintenance cost data and determination of the logistic support requirements for practical use of WECS at Navy bases.

Since 1980 SWECS technology has developed significantly; by 1983 over 8,000 SWECS had been installed. SWECS size has increased each year; the average size is now between 25 and 50 kW. This expansion has been caused primarily by the results of numerous wind farms installed in California. As soon as a SWECS is considered reliable by the manufacturer, larger generators are installed to increase capacity. The trend is to sell larger machines. In addition, sufficient reliability data are not made available during these commercial ventures for smaller machines in the 8- to 20-kW range, which currently is the most attractive size for Navy applications. For these reasons, the Navy needs to plan and collect data for long-term evaluation of the SWECS.

This report consolidates the results of long-term evaluations of four Navy-installed SWECS:

1. NCEL, Port Hueneme, Calif. - 2-kW WECS

2. Kaneohe Bay, Hawaii - 2-kW WECS

3. San Nicholas Island - 5-kW WECS

4. Treasure Island - 6-kW WECS

Data were obtained by evaluating the data collection procedures and forms that are currently being used. Both the NCEL and Kaneohe Bay WECS are currently operating and data will continue to be collected. The San Nicolas Island and Treasure Island WECS are no longer in operation.

The RAM and operational data collected and analyzed from each of these sites during long-term evaluation will provide the necessary information to develop guides, manuals, and procedures for Navy use of small (up to 60 kW) wind energy conversion systems. This information will then be used by Navy Public Works Centers and Engineering Field Divisions to design, install, operate, and maintain WECS.

NAVAL CIVIL ENGINEERING LABORATORY, PORT HUENEME, CALIF.

The upwind, 2-kW, horizontal-axis WECS at NCEL is a three-bladed, variable-pitch machine with a 12.5-foot-diam. rotor that drives a 2-kW brushless generator through a gearbox. The rotor, alternator, and gearbox are mounted as one unit on a free-standing, 60-foot-high steel tower.

The alternator is an 8-pole, 220-volt, 3-phase unit with a rotating field. The direct current (DC) power for the rotating field is provided via a voltage regulator by a small alternating current (AC) exciter armature mounted on the same shaft.

Overspeeding of the rotor in high winds and under no load is controlled by a centrifugal governor, which changes the blade pitch angle, thus reducing the rotor rotational speed. A magnetic latching device provided in the rotor hub prevents the centrifugal governor from changing the blade pitch when the prevailing wind speeds are equal to or below 30 mph. When wind speeds exceed 30 mph, the magnetic latching device unlatches the blade pitch change mechanism, thus allowing the blade to pitch as controlled by the governor.

The power conditioning consists of an automatic load-matching device that demonstrates the use of variable-frequency, wind-generated electricity to operate (1) resistive heaters for space heating, (2) a fan for ventilation, and (3) lights.

Detailed specifications for this wind system are as follows:

<u>Rotor</u>

Diameter	12.5 ft
Capture area	122.7 ft^2
Blade materials	Stainless steel
Number of blades	3
Rotor solidity*	10.0%
Rotational speed	130 to 180 rpm
Cut-in wind speed	8 mph
Cut-out wind speed	None
Rated wind speed	25 mph
Survival wind speed	100 mph
Overspeed control	Centrifugal governor with magnetic latching

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*Rotor solidity is defined as the ratio of total blade area to the rotor disk or capture area.

Transmission

Type . . . . Planetary gears, step-up
Gear ratio 5.1:1

Generator

Type . . . . Self-excited brushless rotor
Number of poles 8
Rated voltage . . . . 220 V, 3 phase
Power form . . . . 3 phase, variable frequency, 43 to 60 Hz
Rated power . . . . 2 kW at 25 mph, 3 kW at 30 mph
Power curve . . . . See graph in Figure 1
Field sliprings . . . . None
Yaw sliprings . . . . Five similar aeromotive type

Tower

Type . . . . Open truss, free standing
Height . . . . 60 ft
Protective coatings . . . . Heavy galvanized

Power Conditioning

Generic type . . . . Automatic load matching with relays for switching loads
Features . . . . Load relays operated with commercial control modules

Site Information

Annual average wind speed . . 6.5 mph
Corrosion potential . . . . . High
Environmental extremes . . . Heavy saltwater spray

Operating Performance

The site wind and the 2-kW WECS output data at Port Hueneme have been recorded continuously, and the results for a 9-month period from December 1983 to August 1984 are given in Table 1. The tabulated data show the average wind speed, the peak wind speed, the duration of the longest lull*, the wind speed duration distribution, and the WECS output in kW-hr both calculated and measured for each month. Since the 2-kW WECS has a cut-in wind speed of 8 mph and a rated wind speed of 25 mph, the measured wind speeds at the site were divided into seven categories, namely, between 0 to 8, 8 to 12, 12 to 16, 16 to 20, 20 to 24, 24 to 26, and 26 mph or greater. The duration (hours) of wind speed occurrence in each category is listed in the table. The average wind speed at the site for the 9-month period was 7.39 mph, and the monthly duration of wind speed values below the WECS cut-in speed ranged between 344 hours (December) and 525 hours (April), thus implying that Port Hueneme is a poor site for economic use of wind power.

The total WECS output measured during the 9-month period was 733.6 kW-hr. No output measurements were made during July and August because the wattmeter was being repaired. The computed monthly output

*Continuous occurrence of wind speeds below 6 mph.

of the WECS based upon its performance curve (Figure 1) shows the total output for the 9-month period to be 1,119.3 kW-hr. The wind speed and the WECS output histograms are given in Figure 2. The difference in the measured and the computed value of WECS output is due to some of the unaccounted energy used by a battery charging device being tested at the site.

Reliability

Since 1977, the 2-kW WECS has operated continuously except for three failures of the sliprings, two failures of the yaw bearings, and one failure of the blade-root bearing. During the 9-month evaluation period, the 2-kW WECS did not experience any reliability problems. During this period the WECS has operated for a total of 2,569 hours without failure.

Maintainability and Maintenance

The maintainability features of the 2-kW WECS are such that the entire unit must be lowered prior to performing any corrective maintenance. Preventive maintenance requirements include replacing oil in the gearbox every 6 months and providing periodic inspection for: (1) tower vibration, (2) rust condition, and (3) instrumentation operation.

Availability

Availability is expressed as a probability and combines the reliability and maintainability performance features of the WECS. Availability is computed by totaling the uptime (i.e., operating time) plus the available time to operate (ATTO) (i.e., machine could operate, but there was not sufficient or excessive winds or other external causes) and dividing by the total of uptime, downtime (i.e., machine is not capable of operating), and ATTO. The availability of the 2-kW WECS for the 9 months is found to be 1.0 (see Figure 3). It should be noted, however, that during this period there were only 2,569 hours of sufficient wind speeds at the site when the WECS generated usable power.

MARINE CORPS AIR STATION (MCAS), KANEOHE, HAWAII

The upwind, 12.5-kW, horizontal-axis WECS at Kaneohe has a three-bladed propeller system with mechanical blade control for pitch and a 23.0-foot-diam rotor that drives a 15-kW brushless alternator through an offset-hypoid gear. The rotor, gearbox, and alternator are mounted on a free-standing, 40-foot-high steel tower. The brushless alternator is a 6-pole, 180-volt, 3-phase unit.

A mechanically operated, blade-actuated governor provides positive speed control. A hydraulic-actuated snubber control device works in conjunction with the tailvane to control overspeeds in excess of 28 to 30 mph. This device, in turn, rotates the rotor (i.e., blades) to be tangent to the wind and will continue this process up to 100 mph. As the wind decreases to below 28 to 30 mph, the snubber control will allow a smooth transition of the rotor back to the normal operating orientation.

The power conditioning consists of a solid state, line-commutated frequency changer that converts power from the input source (i.e., brushless alternator) to AC power compatible with the utility line. The changer uses the AC utility line to operate; when the AC line is not present, the unit cannot operate.

Detailed specifications for this wind system are as follows:

<u>Rotor</u>

Diameter	23 ft
Capture area	415 ft^2
Blade material	Laminated wood
Number of blades	3
Rotor solidity	5.2%
Rotational speed	205 rpm peak
Cut-in wind speed	8 mph
Cut-out wind speed	None
Rated wind speed	27 mph
Survival wind speed	100 mph
Overspeed control	Centrifugal

<u>Transmission</u>

Type	Offset-hypoid gear
Gear ratio	6.1:1

<u>Generator</u>

Type	15-kW brushless alternator
Number of poles	6
Rated voltage	180 V
Power form	3 phase, AC
Rated power	12.5 kW at 27 mph wind speed
Power curve	See Figure 4
Field sliprings	2
Yaw sliprings	None

<u>Tower</u>

Type	Free standing, cylindrical concrete
Height	40 ft
Protective coatings	None required

<u>Power Conditioning</u>

Generic type	Single-phase (228- to 252-VAC), 60-Hz line-commutated inverter with silicon-controlled rectifiers
Features	15 kW (rated power output)

<u>Site Information</u>

Average available power in the wind	14.3 W/ft^2
Annual average wind speed .	12 to 13 mph
Corrosion potential	Very high
Environmental extremes . . .	None

Operating Performance

The site wind characteristics and the 12.5-kW WECS output data at Kaneohe have been recorded continuously, and the test results for a 13-month period from July 1983 through July 1984 are shown in Table 2. The wind characteristics shown in Table 2 follow the same format as that of Table 1 except that the rated wind speed of this WECS is 28 mph. The average wind speed for the 13-month period at Kaneohe was found to be 12.6 mph. The monthly duration of wind speeds below 8 mph, the cut-in speed value of the WECS, ranged between 7 hours (July 1983, June 1984) to 491 hours (February 1984). The high value of wind speed duration below 8 mph in February 1984 at the site was a rare occurrence and was due to a strange weather phenomenon that prevailed in the region. Based upon the site characteristics measured, the site is a good location for wind power application.

The total WECS output measured during the 13-month period was 14,599.5 kW-hr. The WECS was down for repairs in November and December 1983. The computed output of the WECS based upon the site winds and its performance curve (Figure 4) was established at 20,689 kW-hrs. The measured output of the WECS despite a 2-month downtime was about 71% of the computed value. The wind speed and the WECS monthly output histograms are given in Figure 5. It can be seen from the histograms that the WECS output for 5 months of the 13-month period was fairly close to the predicted values.

Reliability

The WECS at Kaneohe Bay was installed in January/February 1983. After initial startup and testing, a new rotor was installed in July 1983. An inspection of one of the rotors showed that a foreign object had hit one of the blades, causing it to split, which necessitated replacement of the entire rotor. In addition, the brake assembly had to be replaced in July 1983.

The WECS operated from July through October 1983 without incident. During a potential hurricane in October, the brake was applied. During later attempts to release the brake, the generator would not turn. The next 2 months were spent attempting to repair the WECS, but the attempts were not successful. The only time when access to the tower is permitted is Monday morning. All other times the radars on the base are transmitting. During this 10-week period the bucket truck that is used to gain access was either not available or was nonoperational. Finally on 4 January 1984, the generator was restored to operation. The mechanism to actuate the brake pads had been corroded to the extent that the pads could not be released. In June 1984, utility high voltage spikes blew the main line fuses in the SWECS power inverter. The fuses were replaced and there appeared to be no other problems.

Low power production in July led to a detailed inspection in mid-August. This inspection indicated no mechanical or electrical reason for low production. A later inspection on 27 August 1984 uncovered an electrical control board problem. The field excitation control for the wind plant is located on this board. The voltage spike in June had caused damage to the field excitation control, which resulted in intermittent power development. After the control board was replaced, a secondary problem was uncovered: the windings on the generator were shorted. The generator will thus require replacement.

The Mean Time Between Failures (MTBF) during 1984 is 1,375 hours. The WECS had operated 2,750 hours with two failures.

Maintainability and Maintenance

The maintainability features of the 12.5-kW WECS are such that the rotor, gearbox, or generator must be lowered prior to performing any corrective maintenance. Most preventive maintenance and some corrective maintenance can be performed with the equipment installed on the tower. There are currently plans to install a platform, which will allow maintenance to be performed more readily.

Because of the harsh salt air environment, the WECS requires extra attention. The governor springs and the brake assembly are most susceptible to the salt conditions and must be tended to on a scheduled basis.

On a quarterly or semiannual basis, the WECS should be thoroughly inspected from top to bottom and whatever adjustments (i.e., aluminum wedge blocks located in the alternator frame) necessary to assure safe and proper operation should be made. The results of the inspections currently being conducted will establish the desirable frequency of inspection. The inspection will include:

(1) checking the inverter

(2) testing the brake and brake assembly for proper operation

(3) greasing the cable winch and brake cable

(4) greasing governor springs and brake cable assembly

(5) checking tower vibration

(6) checking rust condition

(7) changing oil in the gearbox (recommended annually and requires about 1 gallon of oil)

(8) checking brake pad condition

Availability

The availability of the 12.5-kW WECS for the first 7 months of 1984 is shown in Figure 6. The availability is currently 0.897. This is based on 4,594 hours of operation or potential operation and 518 hours of nonoperational time.

SAN NICOLAS ISLAND, CALIF.

The upwind, 5-kW, horizontal-axis WECS at San Nicolas Island was a three-bladed, variable-pitch machine with a 16.4-foot-diam rotor, which drove a 5-kW, self-excited generator with field brushes through planetary gears. The rotor, generator, and gearbox were mounted as one unit on a free-standing, 50-foot-high, open-truss steel tower. The generator was a 16-pole, 190-Volt, 3-phase unit with a rotating field.

Overspeeding of the rotor was controlled by a centrifugal governor that increased blade pitch with increasing wind speed to control rpm. In winds greater than 45 mph, the tail automatically turned 90 degrees to turn the rotor out of the wind.

The power conditioning consisted of automatic load-matching devices that demonstrated the use of variable-frequency, wind-generated electricity for space heater application.

The environment has high corrosion potential caused primarily by heavy saltwater spray and moisture. The average wind speed over the operating life was about 15 mph.

Detailed specifications for this wind system are as follows:

<u>Rotor</u>

Diameter	16.42 ft
Capture area	211.7 ft^2
Blade materials	Laminated wood
Number of blades	3
Rotor solidity	5%
Rotational speed	100 to 200 rpm
Cut-in wind speed	8 mph
Cut-out wind speed	45 mph
Rated wind speed	24 mph
Survival wind speed	100 mph
Overspeed control	Centrifugal governor

<u>Transmission</u>

Type	Planetary gears, step-up
Gear ratio	4.12:1

<u>Generator</u>

Type	Self-excited with field brushes
Number of poles	16
Rated voltage	190 V, 3 phase
Power form	3 phase, variable frequency, 55 to 100 Hz
Rated power	5 kW
Power curve	See graph in Figure 7
Field sliprings	2
Yaw sliprings	3

<u>Tower</u>

Type	Open-truss guyed
Height	50 ft
Protective coatings	Heavy galvanized

Power Conditioning

Generic type	Automatic load matching with switching loads
Features	Load relays operated with commercial control modules

Site Information

Annual average wind speed .	15 mph
Corrosion potential	Very high
Environmental extremes . . .	High corrosion potential, high humidity

Operating Performance

The WECS at San Nicolas Island was installed in November 1979 and, following intermittent operation, the system was removed in February 1983 for complete reconditioning prior to eventual reinstallation. The WECS is currently stored at NCEL. The system had instrumentation but no data logger for long-term evaluation of wind conditions and operating performance. The field test results provided excellent design information for improving WECS reliability performance in a highly corrosive marine environment and also yielded the following information:

1. Sliprings need to be enclosed for protection from the environment, or a WECS that eliminates the need for sliprings should be selected.

2. WECS in this environment will require frequent (every 2 weeks) preventive maintenance.

Reliability

The WECS did not operate well initially. The corrosion of bearings, sliprings, electrical terminals, the feathering control, and the voltage regulator were the main problems. The rotor hub bearing showed corrosion of the race, including false brinelling (rectangular dents). This type of failure in the bearings indicates excessive system vibration. Proper lubrication would eliminate this type of condition. One method that was used to improve bearing life was to fill the rotor hub with a lubricating oil, which kept the bearing race coated with oil when the rotor was not turning, thus ensuring proper lubrication of the wearing surfaces. This arrangement also prevented corrosion of the bearing components because of the salt and the moisture from the environment. This design modification increased the MTBF from 90 to 280 days for the rotor.

The yaw sliprings were of normal design with no special considerations given to the operating environment. These three sliprings were mounted on the yaw shaft and separated by plastic spacers. The rings were connected to metal studs. The studs were insulated from the metal plate by plastic inserts placed around them. Moisture in the air resulted in grounding the studs to the metal, causing arcing at various points of the slipring assembly. This was the common cause of slipring failure.

Maintainability and Maintenance

The maintainability features of the WECS were such that the entire unit required lowering prior to performing any major corrective maintenance. Preventive maintenance requirements included replacing oil in the gearbox every 6 months and providing periodic inspections for: (1) tower vibration, (2) rust condition, and (3) instrumentation operation.

Availability

Because accurate data on operating hours and downtime were not available, and a data logger was not installed to provide long-term information, availability was not computed.

TREASURE ISLAND, CALIF.

The upwind, 6-kW, horizontal-axis WECS at Treasure Island was a three-bladed, variable-pitch machine with a 17.4-foot-diam rotor, which drove a 6-kW, 3-phase, permanent-magnet generator (i.e., alternator) through step-up planetary gears. The generator incorporated a rectifier, which converted the variable voltage and frequency electricity produced by the variable speed rotor to DC electricity.

The rotor, generator, and gearbox were mounted as one unit on a free-standing, 60-foot-high, open-truss steel tower. The generator was a 16-pole, 140-volt, 3-phase unit. Overspeeding of the rotor was controlled by a centrifugal governor that increased blade pitch with increasing wind speed to control rpm. In winds greater than 45 mph, the tail automatically turned 90 degrees to turn the rotor out of the wind.

Power conditioning was provided by a single-phase, line-commutated inverter. The corrosion potential was not very severe and environmental extremes were not significant. The average wind speed over the operating life of the WECS was between 8 and 10 mph.

Detailed specifications for this wind system are as follows:

Rotor

Diameter	17.42 ft
Capture area	238.3 ft^2
Blade material	Laminated wooden blades without twist
Number of blades	3
Rotor solidity	5.2%
Rotational speed	100 to 200 rpm
Cut-in wind speed	8 mph
Cut-out wind speed	45 mph
Rated wind speed	28 mph
Survival wind speed	100 mph
Overspeed control	Centrifugal governor

Transmission

Type	Planetary gears, step-up
Gear ratio	4.12:1

Generator

Type	3-phase, permanent-magnet rotor
Number of poles	16
Rated voltage	140 V
Power form	DC
Rated power	6.00 kW
Power curve	See Figure 8
Field sliprings	None
Yaw sliprings	3
Rotational speed	412 to 824 rpm

Tower

Type	Open truss, free standing
Height	60 ft
Protective coatings	Heavy galvanized

Power Conditioning

Generic type	Single-phase, line-commutated inverter
Features	120 VAC (rated voltage) 7.5 kW (rated power output)

Site Information

Average available power in the wind	4 to 5 W/ft
Annual average wind speed .	8 to 10 mph
Corrosion potential	Not very severe
Environmental extremes . . .	Not significant

Operating Performance

The WECS was installed at Treasure Island in September 1979 and operated until February 1983, when it was removed. The WECS performed satisfactorily. Between May 1980 and March 1981 (i.e., 295 days) 1,115 kW-hr of AC power were generated. This value corresponds to an annual output of 1,380 kW-hr. The inverter efficiency during this period was between 75 and 81%.

During the entire testing demonstration phase, one major technical problem was encountered: maintaining the synchronous inverter in a properly programmed state. Proper programming of the synchronous inverter involved setting the firing sequence of the silicon-controlled rectifiers (SCRs) to match the ambient wind conditions experienced at the site. When wind speeds are highly variable, maintaining the impedance of the WECS so that it is properly matched with that of the AC line is a chronic problem that must be frequently addressed. From December 1979 to May 1980, system performance was extremely poor. Over one 162-day interval, only 5 kW-hr of AC and 112 kW-hr of DC power were produced, which corresponds to an efficiency of about 2 to 6% for the inverter. This poor performance was due to the inverter being improperly programmed. After reprogramming, inverter performance improved significantly. The performance of the WECS from December 1979 to June 1981 is shown in Table 3. Overall inverter efficiency was 0.57.

In addition to the testing at Treasure Island, preliminary testing was done at NCEL, Port Hueneme. This preliminary testing was to evaluate the application of a synchronous inverter in integrating a variable-output, wind-driven generator with another power source. Synchronous inversion techniques for this application were in early stages of development, and data on performance, reliability, and power quality were lacking.

The initial testing at Port Hueneme indicated that the synchronous inversion techniques used suffered from impedance matching. For optimum performance of the WECS, it is extremely important to match the inverter impedance to that of the AC generator at all wind speeds.

One problem that persisted was keeping the inverter properly programmed to match its impedance with that of the AC generator at all wind speeds. A more efficient means of maintaining a properly programmed inverter is desired and could be accomplished by variable trigger voltage for the SCRs.

The WECS was removed from Treasure Island in March 1983 and returned to NCEL for refurbishment. The 6-kW WECS was installed in August 1983 at San Nicolas Island. On 13 October 1983 the WECS became inoperable and was eventually removed in January 1984.

Reliability

The WECS operated satisfactorily with only two critical failures. The first failure occurred in December 1979 and the second in April 1981. Both failures were caused by arcing at the electrical terminals located on the yaw shaft, which caused grounding of the generator to the tower. The operating times before failure had been about 120 and 460 days, which corresponds to a system MTBF of 290 days.

A more detailed engineering evaluation of the terminals on the tower indicated the insulation became weak because of marine salt, which resulted in a flashover. In grounding the generator to the tower, only two instead of three phases were producing power, thus greatly reducing the power output of the generator.

In February 1982, the propeller hub separated from the gearbox and the blades fell to the ground. The WECS was removed in March 1983 and returned to NCEL for refurbishment. The refurbishment included three new blades, new bearings, feathering controls, new seals, new sliprings, and brushes. The alternator and hub were inspected and found to be operational.

The 6-kW WECS was then installed at San Nicolas Island. In August 1983, after about 45 days of operation, one blade was broken, but the rotor was still turning and producing power. A later investigation indicated that the yaw shaft had fatigued and cracked, resulting in one blade hitting the tower. The WECS was removed from San Nicolas Island in January 1984 and is currently stored at NCEL.

Maintainability and Maintenance

The maintainability features of the 6-kW WECS were such that the entire unit required lowering prior to performing any major corrective maintenance. Preventive maintenance requirements included replacing oil in the gearbox every 6 months and providing periodic inspection for: (1) tower vibration, (2) rust condition, (3) instrumentation operation, and (4) synchronous inverter operation.

Availability

The availability of the 6-kW WECS between December 1979 and June 1981 was 0.965. This was based on a total of 578 days, 558 days of which the WECS was capable of operating. Ten days were allocated for each of the two critical failures.

DISCUSSION

The RAM characteristics of the four WECS tested at four different locations are summarized in Table 4. The 2-kW WECS at Port Hueneme has shown the highest availability (1.0) of all the four systems. This is attributed primarily to the regular inspections and care the system receives because of its location at NCEL. The lowest availability was demonstrated by the 5-kW system at San Nicolas Island. The system experienced numerous failures of its components because of highly corrosive environmental conditions at the site. Further, because of the remoteness of the site, the WECS did not receive proper care on a regular basis. The 6-kW WECS tested at Treasure Island for 21 months, basically with the same design features as the 5-kW system, showed good availability (0.965). The failures of the yaw sliprings experienced by the 6-kW system were mainly due to poor design. Finally, during 13 months of testing the 12.5-kW WECS at Kaneohe has shown only two failures, which were due to environmental corrosion and fluctuations in grid voltage.

It must be noted that all four WECS require scheduled or preventive maintenance every 3 to 6 months depending upon the environmental conditions at the site. Another feature noticed during the testing of the four WECS is that to facilitate unscheduled maintenance and repairs, the wind turbine generator atop the tower must be readily accessible. None of the systems discussed in this report are easily accessible for repairs; thus, the cost of repairing the systems during breakdown was high. Future WECS installations must use some type of a tilt-down tower design to reduce repair costs and downtime.

All four WECS showed excellent performance on a instantaneous basis, but long-term performance in some cases was affected dramatically because of numerous failures (e.g., the 5-kW WECS at San Nicolas). However, wind power technology is advancing rapidly to develop reliable and cost-effective WECS.

CONCLUSIONS

1. Small wind energy conversion systems (SWECS) in the 1- to 50-kW range are starting to become a viable source of alternative energy, but for most Navy applications they must be conditioned to operate in a highly corrosive marine environment. Based upon the tests of four SWECS

(2, 5, 6, and 12.5 kW), it is concluded that a majority of reliability problems experienced by the systems were due to environmental conditions and design configurations.

2. SWECS system performance was good on a instantaneous basis, but long-term performance suffered in some cases (e.g., the 5-kW WECS at San Nicolas Island) because numerous system failures. Most of these failures can be attributed to poor design features of the SWECS.

3. System availability varied, depending on the system size and site location. For instance, the 2-kW WECS at Port Hueneme showed an availability of 1.0, whereas the 12.5-kW WECS being tested at Kaneohe, Hawaii, demonstrated an availability of 0.897. It must be concluded here that a single unit availability of 0.90 is achievable with the present technology.

4. Each SWECS is unique and requires different preventive maintenance schedules. The results show that corrosion control should be performed, as a minimum, every 3 months, although as new materials and coatings for this material become available, corrosion control could be extended to 6 months in the future.

RECOMMENDATIONS

The lessons learned from these SWECS evaluations will assist greatly in future procurements of SWECS. The results of these lessons provide the following recommendations:

1. Do not use yaw sliprings.

2. All bearings used in a WECS must be sealed and self-lubricating.

3. For ease of maintenance, a hinged tilt-down type tower for WECS is desirable.

4. Special attention must be paid to design configurations, including material selection, to enable the SWECS to withstand a marine environment.

5. All controls for the SWECS must be passive and fail safe.

Table 1. 2-kW WECS Operating and Site Wind Characteristics Data, Port Hueneme

Month	Wind Speed			Duration (hr) at Wind Speeds Between--							WECS Output (kW-hr)	
	Average (mph)	Peak (mph)	Longest Lull (hr)	0-8 mph	8-12 mph	12-16 mph	16-20 mph	20-24 mph	24-26 mph	26 or greater mph	Computed	Measured
Dec[a] 1983	6.91	41.0	64	525	113	42	28	19	7	10	115.4	89.7
Jan 1984	7.65	49.5	24	471	146	64	31	16	5	11	125.7	76.1
Feb	7.69	44.5	18	429	125	72	40	18	4	8	128.0	75.1
Mar	7.49	51.5	27	469	128	76	39	14	4	14	135.6	110.4
Apr	9.93	45.5	14	344	132	93	64	42	15	30	254.0	241.7
May	7.13	43.5	18	461	148	67	37	18	5	8	128.8	80.1
Jun	7.03	28.0	14	394	201	102	20	3	0	0	91.2	60.48
Jul	6.43	28.0	71	464	187	75	16	2	0	0	73.7	b
Aug	6.21	25.5	16	474	186	72	11	1	0	0	66.9	b
Average	7.39											
Total				4,031	1,366	663	286	133	40	81	1,119.3	733.6

[a]Interpolation.

[b]No measurement because wattmeter being repaired.

Table 2. 12.5-kW WECS Operating and Site Wind Characteristics Data, MCAS Kaneohe

Month	Wind Speed			Duration (hr) at Wind Speeds Between--								WECS Output (kW-hr)		Remarks
	Average (mph)	Peak (mph)	Longest Lull (hr)	0-8 mph	8-12 mph	12-16 mph	16-20 mph	20-24 mph	24-26 mph	26-28 mph	28 or greater mph	Computed	Measured	
Jul 1983	16.42	41.0	0	7	84	242	267	118	17	6	3	2,612.4	773.8	New blades and brake assembly installed on 25 Jul. Power monitor started on 13 Jul 1984.
Aug	14.80	36.5	3	32	152	265	195	86	10	3	1	2,036.8	1,543.8	2-3 Aug, WECS secured due to tropical storm.
Sept	13.64	39.5	11	83	166	218	182	62	6	2	1	1,685.5	1,053.6	
Oct	16.00	36.5	5	21	86	257	247	105	16	8	5	2,502.2	2,871.5	
Nov	10.27	41.0	19	258	180	144	95	36	5	2	1	1,045.3	0	WECS down.
Dec	7.53	37.0	30	417	189	84	35	14	3	1	1	5,32.1	0	WECS down.
Jan 1984	11.16	39.5	38	282	114	114	137	74	12	6	5	1,580.5	1,715.0	WECS repaired on 4 Jan 1984.
Feb	6.25	45.5	45	491	79	50	38	23	6	3	6	616.1	612.3	
Mar	11.78	40.5	21	221	131	158	152	72	7	2	1	1,545.8	868.0	
Apr	15.91	46.5	15	32	80	242	245	105	8	6	2	2,396.4	2,664.0	
May	12.83	38.5	25	64	245	311	110	11	2	1	0	1,243.2	1,242.5	
Jun	14.97	34.0	0	7	99	342	229	41	3	1	0	1,802.1	798.0	Found Master Mind down on 25 Jun. Master Mind repaired on 28 Jun.
Jul	12.27	48.5	11	58	257	320	98	9	1	0	0	1,090.8	457.0	
Average	12.6													
Total			-	1,773	1,782	2,747	2,030	756	96	41	26	20,689	14,599.5	

Table 3. Treasure Island WECS Performance
(December 1979 through June 1981)

Month	DC (kW-hr)	AC (kW-hr)	Inverter Efficiency (%)
Dec 79	16.733	0.906	0.05
Jan 80	14.168	0.426	0.03
Feb 80	24.582	1.171	0.05
Mar 80	18.199	0.671	0.04
Apr 80	19.096	0.687	0.04
May 80	18.199	0.671	0.04
Jun 80	19.096	0.687	0.04
Jul 80	75.619	46.389	0.61
Aug 80	273.214	217.361	0.80
Sep 80	155.697	120.012	0.77
Oct 80	96.764	73.671	0.76
Nov 80	39.916	30.311	0.76
Dec 80[a]	109.962	85.683	0.78
Jan 81	159.893	124.632	0.78
Feb 81	61.771	48.206	0.78
Mar 81	54.845	19.339	0.35
Apr 81	105.297	5.017	0.05
May 81	173.133	59.164	0.34
Jun 81	228.185	114.076	0.50
TOTAL	1,664.369	949.086	
AVERAGE			0.57

[a]New blades installed.

Table 4. Summary of RAM Results on the Four WECS

WECS	Test Location	Test Period	Number of Failures	Nature of Failures	Availability	Maintainability
2-kW	Port Hueneme	Dec 83 to Aug 84	None	None	1.0	Preventive maintenance every 6 months.
5-kW	San Nicolas Island	Nov 79 to Feb 83	Numerous	Corrosion of bearings, electrical terminals, feathering controls, moisture, and salt in the air resulted in arcing at yaw sliprings.	Not calculated	Preventive maintenance every 45 days.
6-kW	Treasure Island	Sep 79 to Jun 81	Two	Moisture and salt in the air resulted in arcing at the yaw sliprings.	0.965	Proper programming of synchronous inverter.
12.5-kW	Kaneohe, Hawaii	Jul 83 to Jul 84	Two	Corrosion of brake assembly. Line fuses shown.	0.897	Preventive maintenance every 3 months due to harsh corrosive environment.

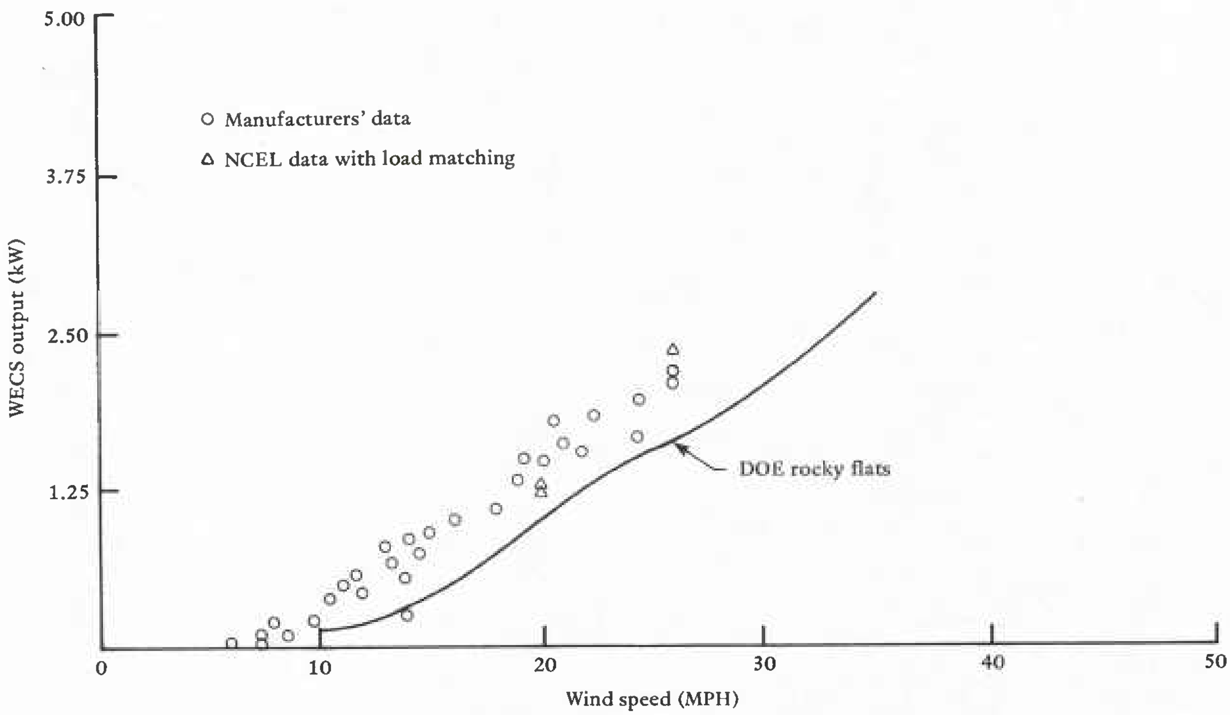


Figure 1. Performance curve for 2-kW WECS at NCEL, Port Hueneme.

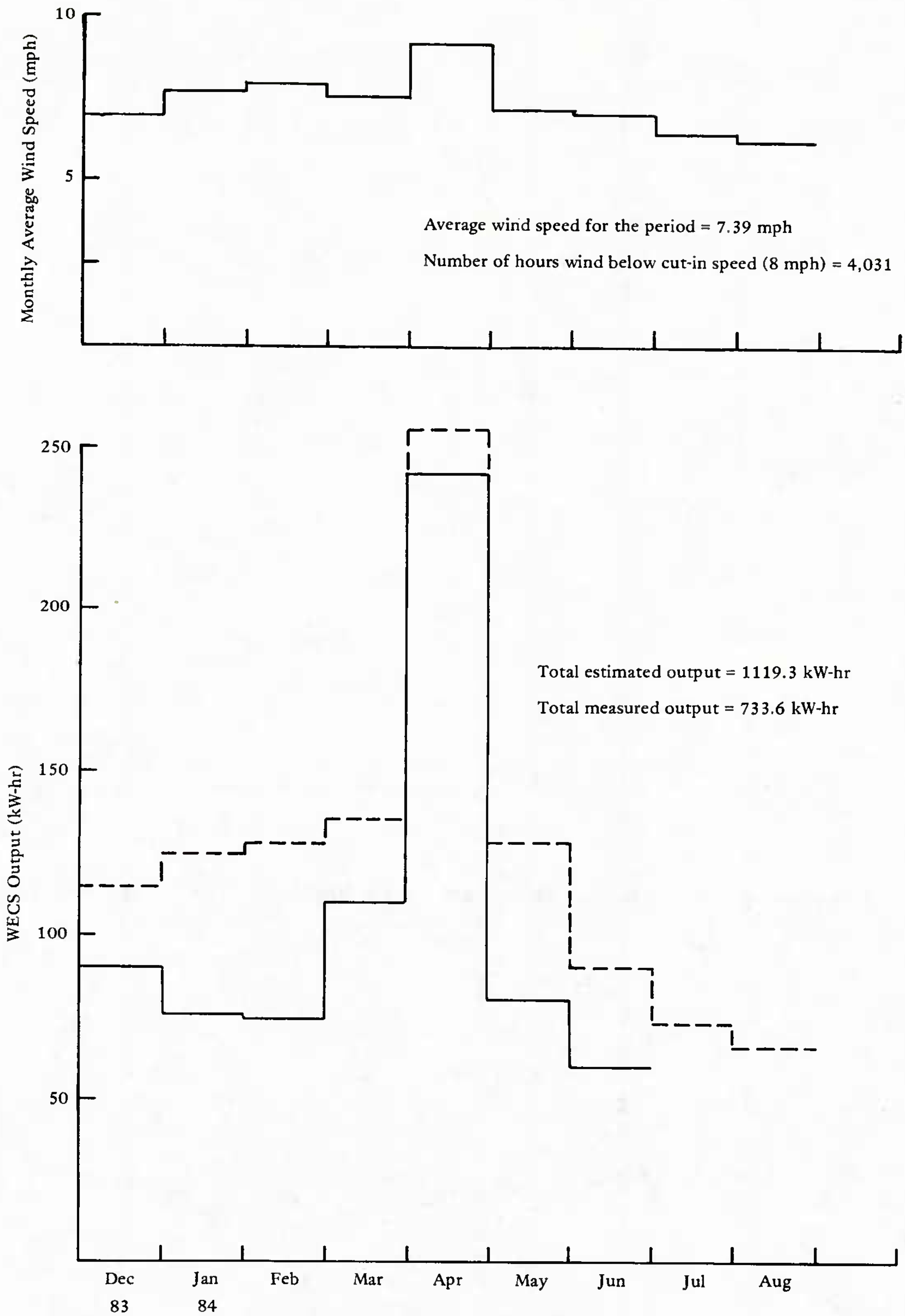
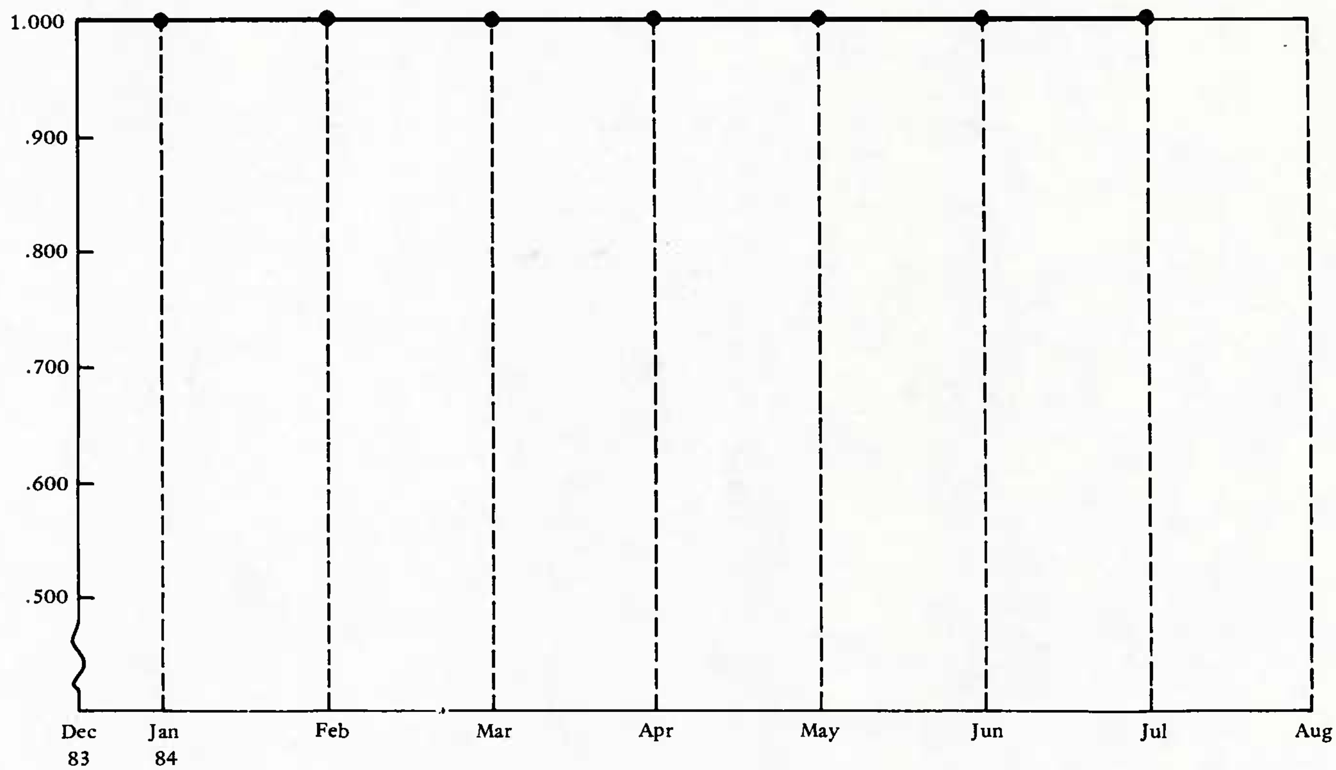


Figure 2. Output histogram for 2-kW WECS at Port Hueneme for the 9-month period between Dec 1983 and Aug 1984.



$$\text{Availability} = \frac{\text{Uptime + Available Time to Operate (ATTO)}}{\text{Uptime + Downtime + ATTO}} = \frac{6000}{6000} = 1.0$$

Figure 3. Availability of NCEL 2-kW WECS during 9-month period.

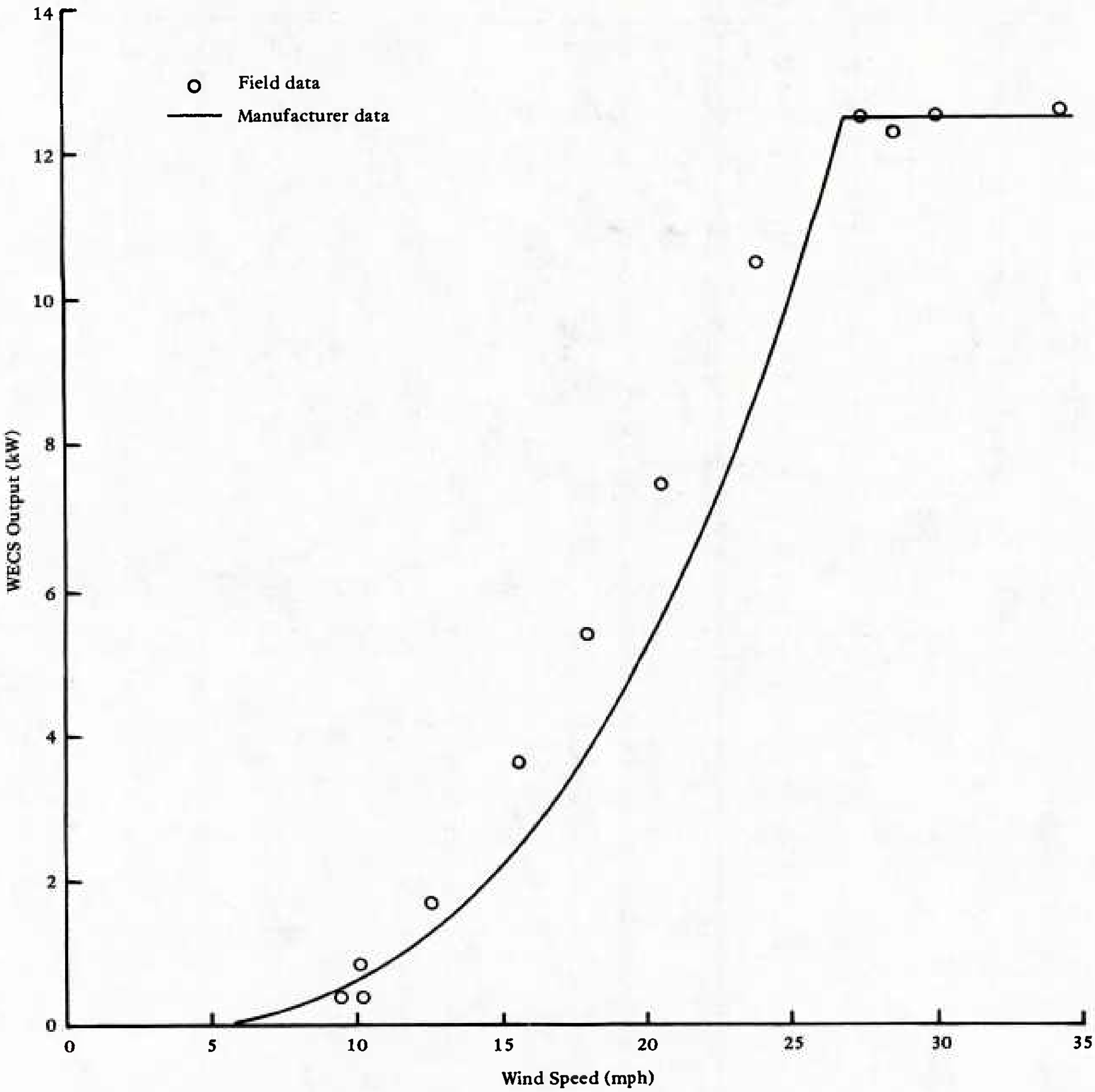


Figure 4. Output versus wind speed characteristics of the 12.5-kW WECS at Kaneohe Bay, Hawaii.

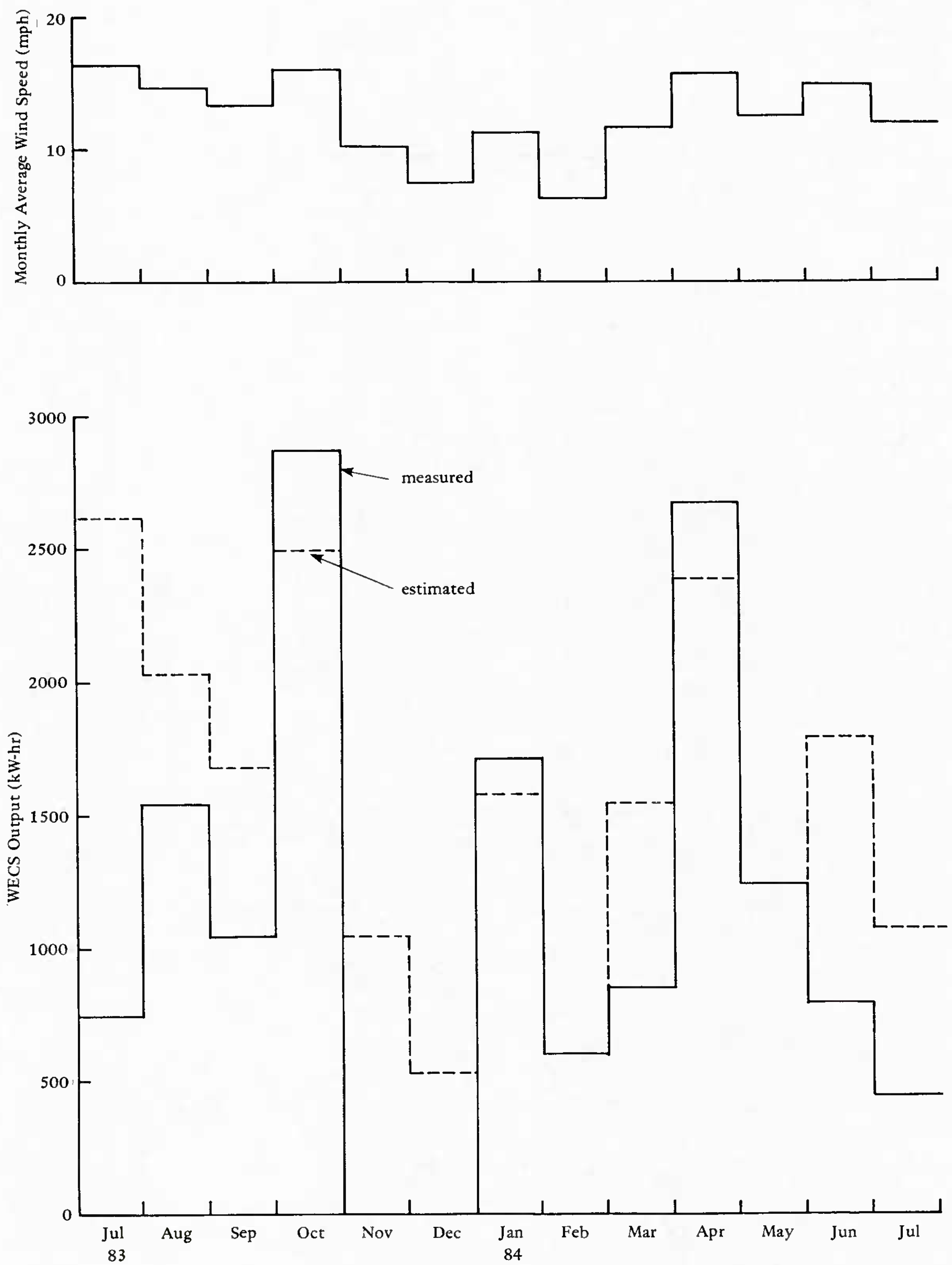
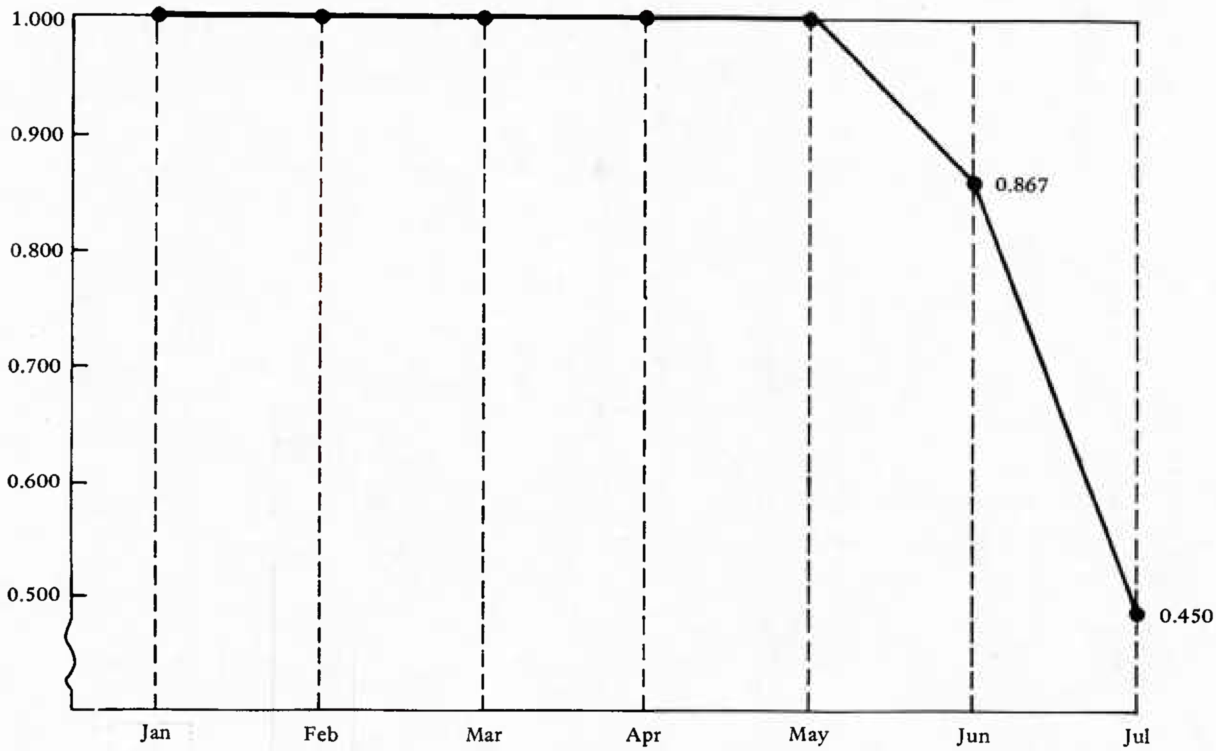


Figure 5. Output histogram for 12.5-kW WECS at MCAS Kaneohe Bay, Hawaii, for the 13-month period between Jul 1983 and Jul 1984.



$$\text{Availability} = \frac{\text{Uptime + available time to operate (ATTO)}}{\text{Uptime + downtime + ATTO}} = \frac{4594}{4594 + 518} = 0.897$$

Figure 6. Availability of Kaneohe Bay 12.5-kW WECS during first 7 months of 1984.

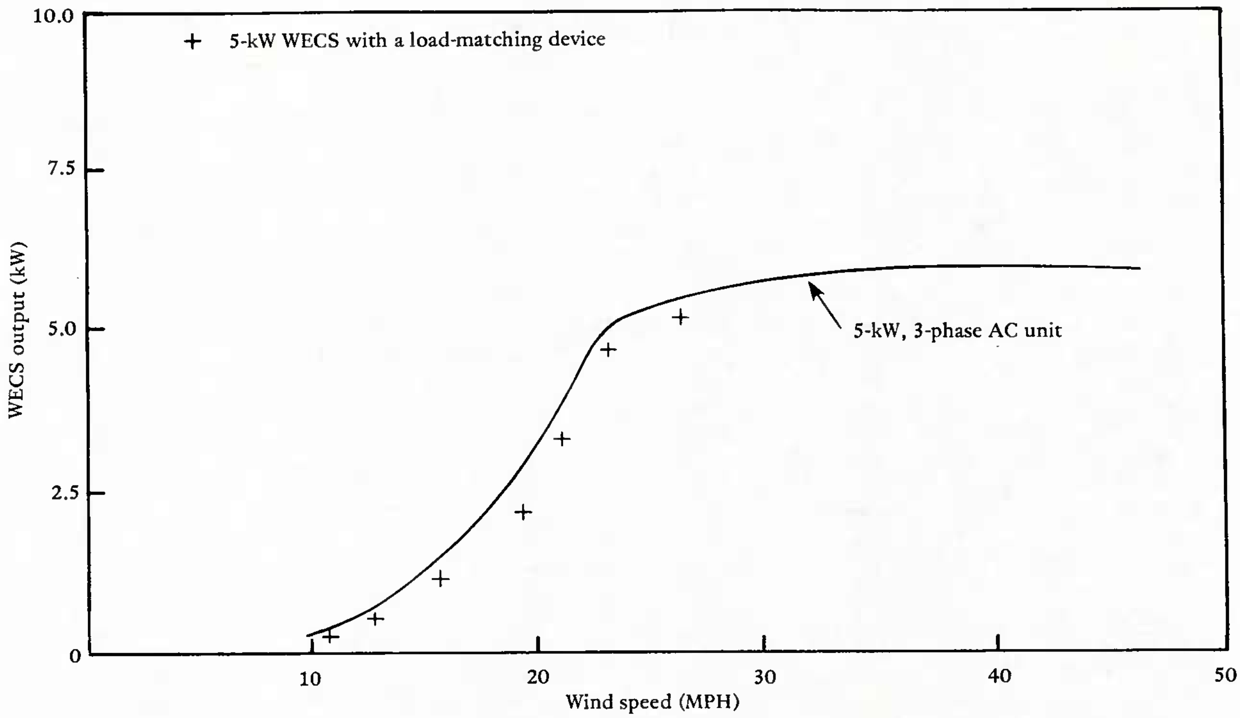


Figure 7. Performance curve for 5-kW WECS at San Nicolas Island.

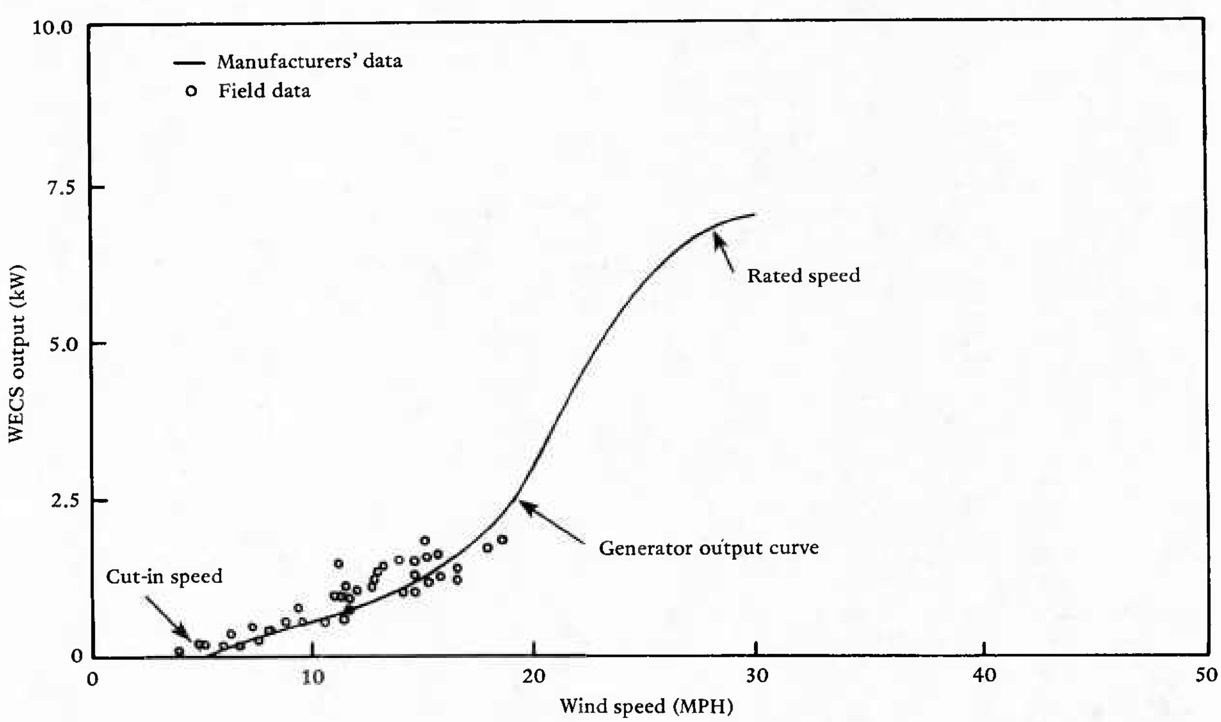


Figure 8. Performance curve for 6-kW WECS with a synchronous inverter.

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