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Costa de Cocos 11-kW Wind-Diesel Hybrid System

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ABSTRACT

Costa de Cocos is a small resort located in the state of Quintana Roo, Mexico. Using the existing diesel generator, the resort's power system was retrofitted to a wind-hybrid diesel system. The reason for this retrofit was to supply 24-hour power, to reduce diesel fuel by using wind energy, and to reduce diesel air and noise emissions in order to promote ecotourism. The wind system was installed in October 1996 with cost-shared funding from the U.S. Department of Energy/U.S. Agency for International Development renewable energy program in Mexico. The National Renewable Energy Laboratory (NREL) supplied technical assistance to the project. Discussed in this paper are the system design, installation, and initial performance.

BACKGROUND OF COSTA DE COCOS RESORT PROJECT

Costa de Cocos is a small scuba diving and fishing resort located in southern Mexico in the state of Quintana Roo, about three kilometers from the isolated town of Xcalak. Prior to the installation of the wind system, the owner used a diesel generator for part-time power. The owner would charge batteries with the diesel during the day and use the batteries to power small loads in the cabanas and restaurant during the evening. This had the benefit of not having to run the diesel all night long. However, the owner found that this system did not supply enough power to meet the evening loads. In addition, the owner was interested in installing a reverse osmosis machine to desalinate seawater for use by the resort. This was significant because desalination requires high energy input.

A major reason for installing the wind system was to save diesel fuel and reduce maintenance costs. Fuel costs about $0.50 per liter (including fuel transport costs) and the fuel savings over the life of the project are substantial. In addition, maintenance of the diesel is a continuous burden for the owner and reducing diesel run-time would result in less maintenance and less overall reliance on the diesel. The displacement of diesel emissions and diesel noise is appealing and especially attractive to customers who identify with "green" low-impact tourism. The surrounding area is full of natural ecological attractions and the owner anticipates that business will improve by making the facility more environmentally friendly.

Cost-shared funding for the project was available through a program sponsored jointly by the U.S. Agency for International Development (AID) and the U.S. Department of Energy (DOE), which is promoting the use of renewable energy in Mexico. This program is especially interested in renewable energy projects that promote "productive uses" of renewables, i.e., uses of energy that bring income to the end-user.

WHY ECOTOURISM HOTELS FOR WIND-HYBRIDS?

There are a number of reasons why ecotourism hotels are a good place to install wind-diesel hybrid systems: the owner has an ability to pay for the system with cash flow from the business; financing is often available because the owner has equity; there are usually good technical skills available at the site from previous experience with the existing diesel system that are important for operation and maintenance (O&M) of the hybrid system; there are good winds at coastal ecotourism sites because of trade winds and coastal sea-breeze effects; energy conservation and load management are easier to implement than with a larger village system; and the idea of "green marketing" appeals to many small resort owners and their customers. With larger mini-grid renewable systems for villages, such as the nearby Xcalak wind-PV hybrid system, the institutional arrangements of running a small utility service, including metering energy use and billing customers, can be challenging. This is not the case with a small wind-hybrid system for a private resort. If done correctly village mini-grids are sustainable, but they are a different market and can be harder to implement than small ecotourism resorts, hence it makes sense to commercialize systems in less difficult applications so that a good track record is achieved early on.

TECHNICAL DESIGN OVERVIEW OF THE COSTA DE COCOS SYSTEM

The following steps were taken in the implementation of the system.

1) Estimate existing and future loads and analyze types of loads.
2) Estimate wind resource and existing diesel fuel consumption.
3) Preliminary sizing of generation system based on available commercial equipment and budget.
4) Computer modeling of the system, including sensitivity analysis of battery storage, loads, diesel run time and dispatch, load management, and estimate diesel fuel savings.
5) Develop bid specifications.
6) Install system (October 1996).

Several different load scenarios were developed, based on seasonal variations and inclusion of a reverse osmosis (RO) machine (it was unclear whether the owner would buy the RO machine until the end of the project design phase). Besides the RO load, other major loads were the clothes washer and dryer, lighting, refrigeration and two freezers, kitchen appliances, an icemaker, and miscellaneous workshop tools. Figure 1 shows a peak season load profile with and without the RO system; note the large energy requirement of the RO system.

As can be seen from the load profiles, the peak energy use is in the middle of the day. This was defined by the owner because some of the loads could be turned on at any time in the day (i.e., deferrable loads). If the diesel is needed to meet the load, it will usually be during this peak load time. Having the peak load in the day allows for the diesel to be run when the noise will be less bothersome. In reality, the owner could manage the deferrable loads from the morning through the night so as to have the peak load coincide with the highest daily wind speeds, should the wind speed vary during the day. During peak seasonal load the diesel would meet the RO load during the midday peak because there would not be enough wind energy available. All the loads in the resort are single phase, requiring a single phase distribution system. All loads are 120 volts except the RO load, which is 240 volts.

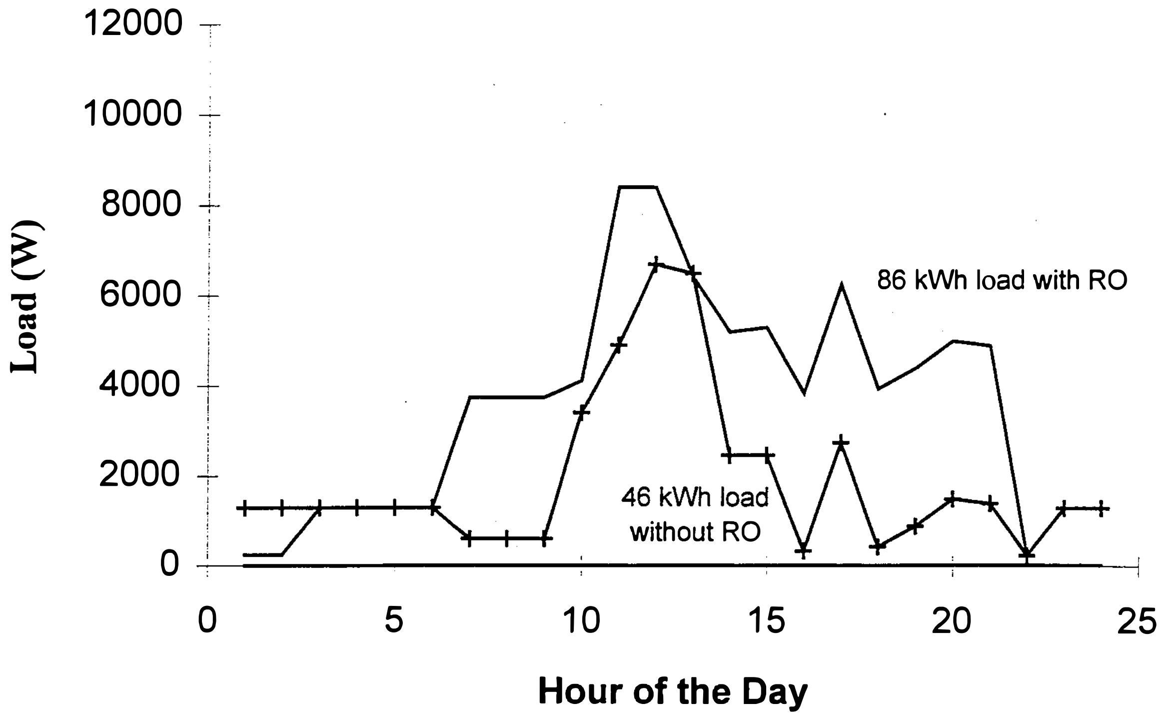

FIGURE 1. DAILY LOAD PROFILE - 46 KWH/DAY NO REVERSE OSMOSIS AND 86 KWH/DAY WITH REVERSE OSMOSIS AT PEAK SEASON

After estimating the load, the next task was to estimate the wind resource. Available wind speed data from the Xcalak anemometer indicated an annual average wind speed of 6.1 m/s at a 30 meter anemometer height. Low wind season is usually during October and November (average monthly wind speed about 4.9 m/s), which coincides nicely with the load demand because low tourist season for the resort is September thru November.

SYSTEM ANALYSIS

The NREL Hybrid2 simulation code (Baring-Gould et al., 1993) was used to model the system and calculate appropriate turbine and battery sizes. Hybrid2 is a time-series/probabilistic model that uses time-series resource and load information, along with manufacturer's data for hybrid system equipment, to predict the performance and cost of hybrid power systems. The basic system architecture modeled was an AC permanent magnet alternator turbine connected to a 48-volt DC bus via a wind turbine charge controller/rectifier for charging flooded lead acid batteries. The DC bus, consisting primarily of lead-acid batteries, is then connected to an inverter system to power the AC loads. The load profiles shown in Figure 1, adjusted for seasonal variations, were used as inputs along with hourly average wind speed data for Xcalak.

The largest recurring cost in a wind-hybrid system with energy storage is battery replacement. Different types of batteries were analyzed and lifetime for the batteries was calculated for a given battery bank capacity. For example, a battery bank comprising 350 amp-hour lead acid batteries (6 volt cells) was compared with the same capacity battery bank comprising tubular 500 amp-hour batteries (2 volt cells). Lifetime estimates were developed for the batteries by dividing the manufacturer's data on energy throughput by the annual energy cycled through the batteries as estimated by Hybrid2 (the load scenarios were the same for each battery type) to calculate battery lifetime in years. This lifetime was then reduced by 25% to account for accelerated lifetime degradation because of higher temperature. (Manufacturers' data for battery life is for 25 degrees C and the average annual temperature at the site is about 10 degrees C higher; a rule of thumb is that battery life can degrade from 25%-50% for every 10 degrees C above 25 degrees C, with calcium lead-acid batteries being affected more by this phenomena than antimony lead-acid batteries as used here). Based on the Hybrid2 modeling, the costs for the less expensive, lower amp-hour capacity batteries (i.e., 350 amp-hour) were found to have a lower life cycle cost even though they had to be replaced more often.

Modeling results indicated higher fuel savings with 20 kW of wind power; however, project funding was only available for a maximum of 10 kW of wind power. Base case modeling consisted of a diesel-only system, with inputs for diesel O&M and overhauls estimated based on current experience and costs. Fuel costs were estimated at $0.50/liter including transport.

Based on the computer modeling and the preliminary system design, bid specifications were developed for the system and included in a competitive request for proposal (RFP). The bid was awarded to Bergey Windpower Company of Norman, Oklahoma. Costs for the equipment are listed below. A simplified system schematic is shown in Figure 2.

TABLE 1. CAPITAL COSTS FOR EQUIPMENT AND INSTALLATION

7 kW Wind Turbine	$12750
Tower	$7626
Charge Controller	$1700
2 -5.5 kW Inverters	$6800
Battery System	$4992
Misc. Hardware	$450
AC Load Center	$714
System Wiring	$1370
DC Source Center	$1200
Installation and System Testing	$6600
System Documentation	$300
Shipping and Insurance	$3750
Travel Expense	$1953
Warrantee	$1250
Battery/Inverter Structure	$950
Customs	$4224
TOTAL	$58,315

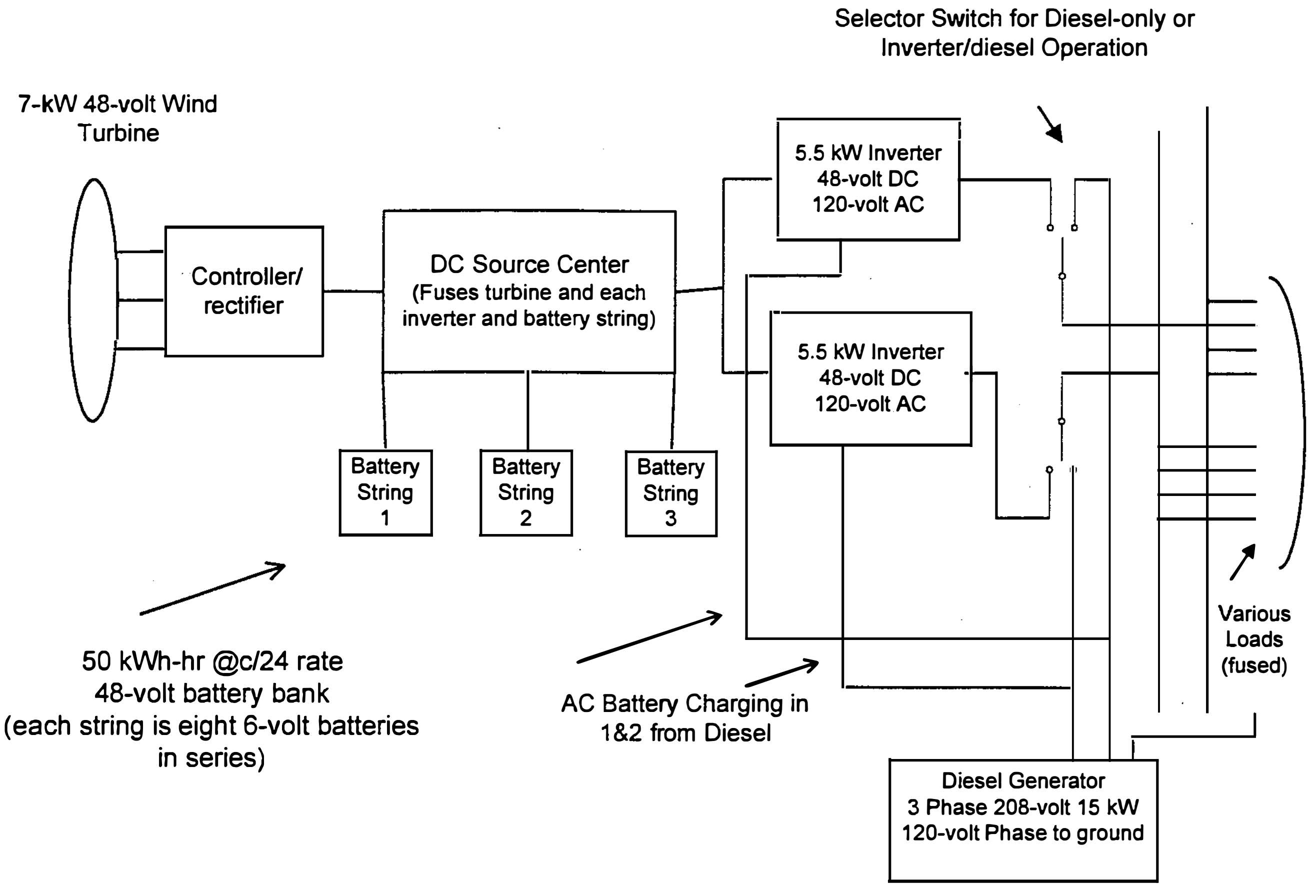

FIGURE 2. GENERAL HYBRID SYSTEM SCHEMATIC

EQUIPMENT DESCRIPTION

A Bergey EXCEL wind turbine was selected for the project. A unique feature of this turbine, which is different from previous EXCEL turbines, is that it has a 48-volt winding, so there is no need for a step-down transformer that is required for the more common 240-volt winding when the turbine is connected to a 48-volt DC bus. The 48-volt winding can be used in this application because the wire run from the turbine to the DC source center is short and thus resistive wire losses are within acceptable limits; usually wire runs are longer and a higher voltage winding is needed to prevent excessive wire losses. In this case not having a step-down transformer saved about $1000. However, the main reason for going to the 48-volt winding was to provide a better match between rotor output power and generator impedance for the given wind regime, thereby increasing the power output. (The Bergey EXCEL turbine produces about 10 kW when connected to a utility grid but only about 6.5 kW when connected to a fixed voltage load such as a battery bank. The stator winding can be changed to provide for better maximum power in high wind speeds, but this results in the turbine cutting in at a higher wind speed and hence energy is lost at low wind speeds. As will be discussed in a subsequent section, the maximum turbine output appears to be about 7 kW, although more information still needs to be collected.)

A problem with the Bergey EXCEL turbines at the nearby hybrid power system in Xcalak was their vulnerability to the high salt spray environment. Substantial improvements were made to the Costa de

Cocos turbine to prevent saltwater corrosion. These improvements included stainless steel fasteners and pitch weights; special inorganic zinc coatings to the blade bolts (i.e., mounting studs); epoxy encapsulated stator winding; hot dipped galvanized tower bolts; and a petroleum-based corrosion inhibitor for the guy wires. These important improvements are expected to mitigate the adverse effects that corrosion had on the Bergey turbines in Xcalak resulting in lower O&M costs for this system.

The wind turbine tower is a lattice, tilt-up tower. This tower is easier to install than a non-tilt-up tower that is erected using a gin pole because all the installation work is done on the ground, including both tower construction and attaching the turbine to the tower. Compared to a tubular tilt-up tower, the lattice tower is easy to climb for inspection and most O&M tasks can be performed without lowering it to the ground, making it easier to do maintenance than with a tubular tilt-up tower. It is estimated that using a tilt-up tower saved two days of installation time compared to using a non-tilt-up tower. Also, the Xcalak region is prone to hurricanes and a tilt-up tower can be lowered in about a half hour should the site be at risk for a direct hit from a hurricane. A tilt-up tower does take more space than a non-tilt tower because the guy wires have to be raised from an angle during the tilt-up.

As can be seen from the system schematic in Figure 2, the variable voltage AC power from the wind turbine is rectified by the controller. The controller also regulates the current above a high voltage regulation limit of about 56 volts using SCR (silicone controlled rectifier) switching. As a result of the current regulation, the turbine becomes unloaded in proportion to the amount of current being regulated, and turbine RPM increases as a result.

The DC source center in Figure 2 provides an enclosure where the battery, wind turbine, and inverter connections to the DC bus can be properly fused and safely interconnected. Three parallel strings of eight Trojan (Santa Fe Springs, California) L-16 batteries are used for energy storage. The Trojan L-16 is a 6-volt flooded lead-acid battery, with a nominal 350 amp-hour capacity at a discharge rate of C/24 (i.e., the total battery capacity is discharged over a period of 24 hours). Because discharge rates used in the system are appreciably higher, the real battery capacity is about 300 amp-hours, which corresponds to about 43 kW-hrs of energy storage. For the peak season daily load without the RO system of 46 kWh, this corresponds to about 14 hours of storage if the batteries are discharged to 60% depth of discharge. For the peak season daily load with the RO system the diesel is estimated to run about 4-6 hours per day, hence battery storage duration will vary depending on diesel run time.

The existing diesel in the system uses a three-phase generator. Although a three-phase RO system that would be compatible with the diesel could have been purchased, this would of required a three-phase inverter if the RO system was to ever be run off of the renewable system. A three-phase inverter is significantly more costly than the two single phase inverters and was outside of the project budget, hence a single phase RO system at 240 volts was purchased. This could be powered by the two inverters or the three-phase diesel using only two phases of the diesel distribution system. (The three-phase diesel current would be 120 degrees out of phase and the RO motor would like to see a 180 degree phase angle because it's single phase at 240-volts, but this was not a concern as it would only lower the efficiency of the motor a little and would not significantly affect diesel fuel consumption).

Because of the presence of both 120- and 240-volt loads (i.e., the RO system), two 120-volt Trace (Arlington, Washington) inverters were "stacked" together to provide power at both voltages. Using two 5.5 kW inverters together doubled the total inverter capacity to 11.0 kW and also doubled the surge or start-up capability of the inverters. The electrical surge requirement for the RO machine was estimated based on the locked rotor torque of the motor and was very close to the combined surge power rating of the two inverters, so close that it was impossible to discern without testing if the inverters could start the RO system without the diesel. Because the system start-up could not be tested before installation, it was decided to install the RO system and use the diesel to start it in parallel with the inverters if the inverters could not start it alone. However, because the diesel is three phase and the inverters are single phase, parallel operation would require rewinding the diesel to have two phases which would be 180 degrees out of phase and hence be compatible with the inverters which are 180 degrees out of phase.

In summary, the approach to integrating the single phase 240-volt RO load into the three phase diesel system without first being able to test the inverters during RO startup was to 1) try a switched system whereby either the diesel or the inverters power the RO load, providing the inverters can start the system, and if the inverters could not start the RO then, 2) rewind the diesel for two-phase operation so that the inverters could run in parallel with it and the diesel could start the RO and then let the inverters power it after it is started.

Because of the high energy requirements for the RO desalination system, it was not intended to run the RO system extensively from the inverter system during high water demand months with no rain (rainwater will still be collected during the rainy season for water supply). This is primarily because the battery bank is undersized to continually cycle all the energy required to power the RO (a cost constraint from the project and a drawback to RO systems). (Future improvements in energy requirements [i.e., kWh/liter] for small-scale water desalination systems could significantly reduce the costs of renewable energy desalination systems.)

SYSTEM INSTALLATION

The system was installed during a rainy, four-day period in October 1996. Two of the days were dedicated to rewiring the AC load center, as the previous load center was wired poorly and several short circuits occurred. Installation time for the wind turbine system was two days. The concrete for the wind turbine tower anchors was poured several weeks prior to allow for it to dry completely.

Tower and wind turbine assembly was easy because the system was installed on the ground and tilted up. The use of a tractor simplified installation significantly, as it was used to move large parts (e.g., tower sections and the wind turbine rotor) as well as to actually raise the tilt-up tower by pulling it up via a winch and gin-pole assembly. Bergey Windpower engineered a custom, integrated battery rack/DC source center whereby the batteries were housed on a rack, and the back side of the rack was used to mount the two inverters, DC source center, and wind turbine controller. This simplified the installation and wiring of these components and minimized the space requirements for the equipment.

SYSTEM MONITORING AND INITIAL PERFORMANCE RESULTS

A data acquisition system was installed in February 1997 to monitor performance of the system. The system consists of a tower mounted anemometer and wind direction sensor, transducers for measuring DC current from the wind turbine and DC current to the batteries and to the inverter, DC bus voltage, battery temperature, AC watts and power factor, and diesel on/off status.

To date the system has been characterized by low loads. This is because the RO system is not is use yet and because the system was designed for 20% higher loads to allow for future load growth. In addition, the icemaking load is lower than originally estimated because the owner has decided not to sell ice. The RO system was not ready for operation during the commissioning of the renewable energy system. Months after commissioning of the renewable energy system, the RO system was installed by the owner, but it was damaged during its installation and has yet to be repaired; hence, the RO system has not been powered to date.

Figure 3 shows the hourly turbine output during May. Much of the energy is dumped because the load is small (the average load for April/May is 1.1 kW as compared to the estimated future load shown in Figure 1) and the batteries are charged above the high-voltage cut-off much of the time, so the turbine charge controller limits the current to the batteries (this can be seen by the points on the graph below the top of the power curve).

Average inverter efficiency from March through June is about 80%. Although the loads are well below rated inverter capacity, the inverter efficiency does not drop at the lower loads. The battery charging efficiency is about 63% for the same time period, which is low, primarily because the batteries spend much of their time between 85% and 100% state-of-charge (SOC) due to the low loads. Continuous battery charging at high SOC is very inefficient because of the battery's inability to accept as much current compared to a lower SOC (below 80% SOC is where efficient battery charging occurs, but batteries are given an equalize charged every month to prevent premature aging). Based on the above efficiencies, the combined battery/inverter efficiency for energy cycled through the batteries is about 50%, which is low. Of course energy produced from the wind turbine will go directly towards meeting the load when loads are present and hence not be subject to battery losses. Therefore, better load management, i.e., more load during high winds, would improve overall system efficiency because it would use more of the wind energy directly without cycling it through the batteries. In addition, a higher overall load on the system would result in more efficient battery charging because the batteries would be cycled below 80% SOC more often.

Figure 4 shows the power output of the turbine for one second averages and no current regulation (i.e., voltages below the high voltage set point for current regulation). There is little data above about 14 m/s, which is the wind speed that corresponds to rated power, so maximum power output cannot be determined; however, it appears that wind turbine power would reach about 7 kW at rated wind speed. (Note that this data should not be compared to published power curve data because it was taken at 1 hertz, and the anemometer is tower-mounted below the turbine; however, it is typical of field installation data where an approximate indication of power output is useful.) The data logger will be reprogrammed in the future to record one-minute average data of turbine power output.

The wind system has supplied more than 95% of the resort's energy since installation. The diesel was started a total of 22 times during the months of March through June for 162 hours of run-time, which is 5.5% of the time. Twelve of these starts occurred during the beginning of June, which was a low-wind resource period.

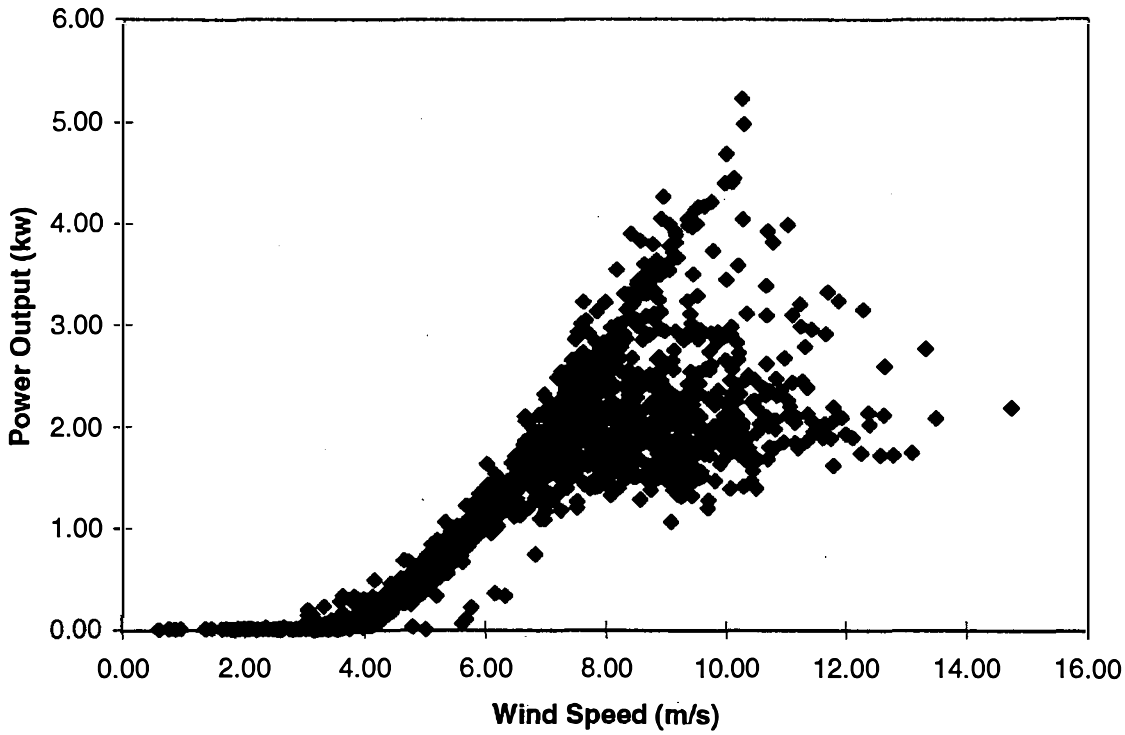

FIGURE 3. TURBINE POWER VERSUS WIND SPEED
10 MINUTE AVERAGE WITH VOLTAGE REGULATION

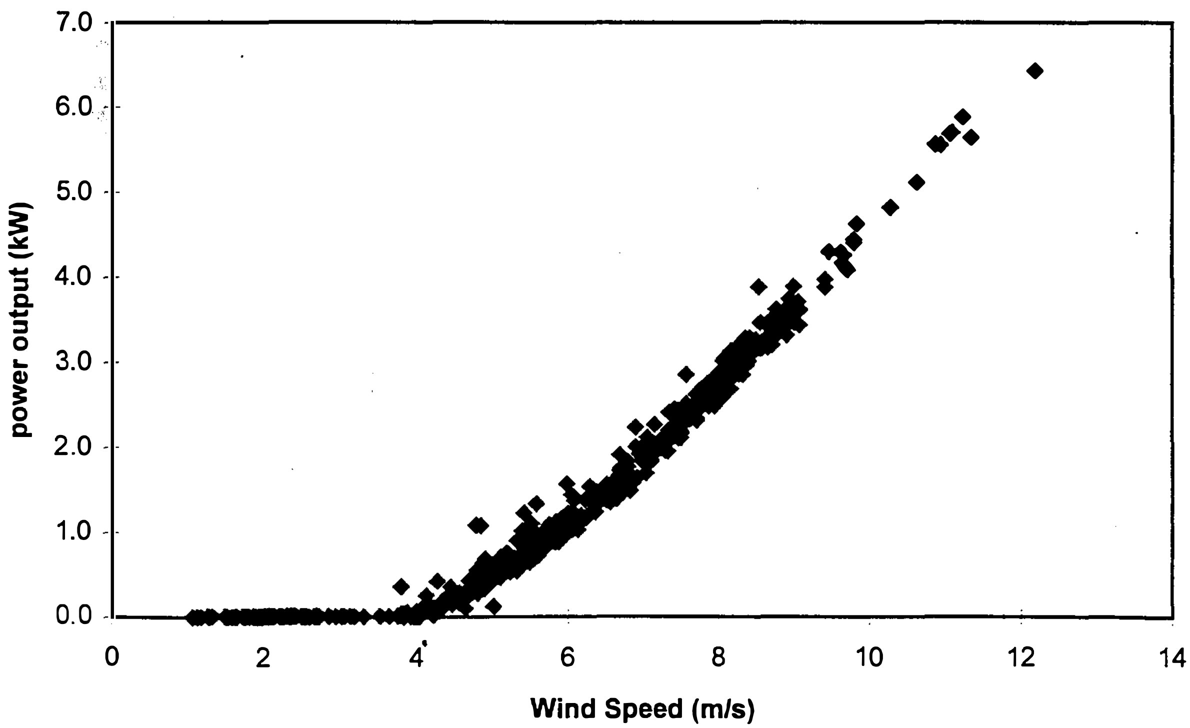

FIGURE 4. ONE SECOND POWER OUTPUT WITHOUT VOLTAGE REGULATION

OPERATIONS AND MAINTENANCE

Providing for good future O&M support is a key part of any remote power system program. In this case, Bergey Windpower trained the owner of the system, who is technically capable of system maintenance, as a first step in system diagnosis and maintenance. Should a problem arise and the owner could not fix the system, Bergey Windpower offered a three-year warranty on the system. A lack of a local technician/wind turbine representative in the area made a local three-year maintenance contract difficult, although in many installations this is a preferred alternative.

LESSONS LEARNED

The design, bidding, installation and commissioning of the system resulted in several useful "lessons learned." Turbine noise has been a small problem with some of the guests staying at the resort, and future installations should take note of this and locate the turbine farther away from residences (greater than 50 meters is a rule of thumb). The 48-volt winding required that the turbine be located close to the DC source center, but since the 48-volt winding does not seem to result in a higher power output, there is no reason to locate the turbine so close to the DC source center in future installations. Significant problems occurred with the existing diesel after system commissioning, but none of these problems were related to the renewable energy system. Because of the low cost of a new diesel, future installations should consider purchase of a new diesel.

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