NREL/TP-440-21120 • UC Category: 1213 • DE96007949

Hybrid Energy System Cost Analysis: San Nicolas Island, California

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A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Prepared under Subcontract No. CAK-6-15387-01

July 1996

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FOREWORD

This report was prepared as an account of work for others funding contract, sponsored by the Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP) under Department of Energy (DOE) Contract # DE-AC02-83CH10093.

The objective of this joint DOE and National Renewable Energy Laboratory (NREL) SERDP project is to determine whether wind turbines can reduce costs by providing power to US military facilities in high wind areas. In support of this objective, one year of data on the wind resources of San Nicolas Island was collected and presented in the report NREL/TP 44-20231 "Wind Resource Assessment: San Nicolas Island, California" [1]. The wind resource data was used as input to economic and feasibility studies for a wind-diesel hybrid installation for San Nicolas Island (SNI). The results of this hybrid system study are presented here.

Timothy L. Olsen, an engineering consultant, was contracted by NREL to provide data reduction analysis, research historical wind resource data, perform wind-diesel hybrid analysis, and generate this report.

ACKNOWLEDGMENTS

The authors wish to acknowledge major contributions to the success of this project by Bob Keller and Bill Gage of Mountain Valley Energy, who helped to install, commission, and operate the meteorological test equipment. Sherwin West also helped process large quantities of wind resource data. Neil Kelley of NREL shared his meteorological advice and guidance in presentation and interpretation of the wind resource data. Dennis Elliott and Mark Schwartz of NREL helped us track down historical site data. Ron Vincent of NFESC, the SNI project manager, advised on all aspects of SNI facilities, costs, and operations, and Carrie Eller, the Head of Utilities Management at Point Mugu, helped to ferret out detailed cost breakdowns for the whole SNI energy system. Lieutenant Commander Egeln, USN Officer in Charge for San Nicolas Island and USN Point Mugu Energy and Public Works Center (PWC) office made the site available for study and arranged travel to and from SNI. Scott Miller of NFESC assisted with instrumentation, and the rest of the SNI Navy support staff assisted with this project in countless ways. Curt Jonas executed the details of developing the spreadsheet-based hybrid system and economics models. Kristin Olsen of KO Consulting developed and refined the numerous graphs in the report. Al Miller of Problem Solvers International provided substantial advice on understanding hybrid system modeling and interpreting the pertinent data. Ian Baring-Gould and Vincent van Dijk of NREL provided training in the use of the HYBRID2 computer program and guidance in developing, troubleshooting, and interpreting the hybrid system models. Each of these people deserves special thanks for their role in bringing this project together.

EXECUTIVE SUMMARY

San Nicolas Island has an excellent wind resource, with an annual average wind speed of 7.2 m/s (14.0 knots) as measured by the National Renewable Energy Laboratory (NREL) at 30.5 m (100 ft) at Facility No. 186 in the August 1994 - July 1995 data collection period. Recognizing this, a hybrid energy system was modeled to examine the merits of supplementing the existing diesel generators with a modest portion of wind energy generation. Using conservative assumptions (unfavorable to wind energy) at every step in the spreadsheet model, the hybrid system displayed favorable operation and economics. The levelized cost of energy (COE) for the hybrid case using four 225 kW wind turbines is $0.338/kWh vs. $0.358/kWh for the baseline case. This would create a COE savings of 5.6%. The payback period is 6.97 years, the internal rate of return 13.1%. The two-turbine case had a COE of $0.342/kWh, saving 4.5%, with a payback period of 5.29 years, and an internal rate of return of 18.2%. The COE for this case is relatively insensitive to annual average wind speed, varying 1% for a 10% change in wind speed. But the payback period is quite sensitive to wind speed, varying 11% to 17% for a 10% change in wind speed.

This work presented a preliminary study of a hybrid system using between 1 and 4 wind turbines. For the conditions examined here, it appears wind energy will be cost effective in this application. We believe these conditions are realistic. But certainly many alternatives to these cases merit consideration. For instance, it appears that the wind penetration could be increased, thus producing further, yet diminishing, savings. If greater redundancy is required, larger numbers of smaller turbines could be used. Smaller wind turbines would have similar relative performance as those machines examined here, with slightly higher per-energy costs and a somewhat limited selection.

Moreover, excess electrical energy should not be curtailed or wasted on dump loads; rather, it should be used for beneficial purposes, provided those purposes make economic sense. Within the San Nicolas Island electrical grid, such benefits may be realized by using excess wind energy for deferrable loads such as the SNI reverse osmosis water system, water heating, or space heating.

Different economic assumptions, such as higher and lower inflation, do not appear to have much impact on the results, but they also should be examined. Because cost and savings components are well distributed, there does not appear to be a dominant factor affecting the economic results. Factors that could affect the results include the actual capital and installation costs of the wind equipment, diesel fuel costs, and diesel system operations and maintenance and overhaul costs.

As a preliminary review, this study used 1 hour average wind and load data for the hybrid system modeling, which can give only a general sense of economic tradeoffs. Before making any final decisions about a wind-diesel hybrid electrical generation system, a more detailed analysis is recommended. Dynamic load management should be addressed using load and wind data at shorter intervals (2 minute or less) to grasp a more realistic picture of load and wind dynamics. 2 minute wind resource data is available from the NREL 1994-1995 measurements. However, 2 minute load data would need to be obtained.

1.0 INTRODUCTION

This report analyzes the local wind resource and evaluates the costs and benefits of supplementing the current diesel-powered energy system on San Nicolas Island, California (SNI), with wind turbines. In Section 2.0 the SNI site, naval operations, and current energy system are described, as are the data collection and analysis procedures. Section 3.0 summarizes the wind resource data and analyses that were presented in NREL/TP 442-20231 [1]. Sections 4.0 and 5.0 present the conceptual design and cost analysis of a hybrid wind and diesel energy system on SNI, with conclusions following in Section 6. Appendix A presents summary pages of the hybrid system spreadsheet model, and Appendix B contains input and output files for the HYBRID2 program.

2.0 BACKGROUND

2.1 San Nicolas Island

SNI is the site of the US Navy Range Instrumentation Test Site, which relies on an isolated diesel-powered grid for its energy needs. As shown in Figure 1, the island is located in the Pacific Ocean 137 km (85 miles) southwest of Los Angeles, California, and 105 km (65 miles) south of the Naval Air Weapons Station (NAWS), Point Mugu, California. SNI is situated on the continental shelf at latitude N33°14' and longitude W119°27'. It is approximately 15 km (9 miles) long and 5.8 km (3.6 miles) wide and encompasses an area of 54.10 sq km (13,370 acres) of land owned by the Navy [2].

The island, generally treeless, is relatively flat on top and drops sharply off on the south side with a more gradual slope to the ocean on the north side. The island's shoreline is formed by cliffs. The interior terrain is a rolling mesa, extensively eroded with little vegetation, mostly coarse grasses and few large shrubs. Its highest point is 276 m (907 ft) high. The western end contains large shifting sand dunes, and the eastern end has a large sand spit extending eastward. Cliffs on the southern side of the island rise sharply from the sea to 213 m (700 ft) within a mile of shore; cliffs on the northern side of the island rise to the mesa at 91 - 122 m (300 - 400 ft) above sea level [2]. A topographic map of the island is shown in Figure 2.

The average mean monthly temperature on SNI is 15°C (59°F). In general, daily maximum temperatures vary from 16 to 21°C (60 to 70°F), and daily minimum temperatures vary from 9 to 14°C (48 to 58°F). The coolest month is usually January, and the warmest month is usually September. No freezing temperatures have been recorded on SNI, but temperatures above 38°C (100°F) have been recorded several times. Precipitation averages only 20.1 cm (7.91 in.) per year, and 86% of the rain falls from November through February. The relative humidity ranges from 57% to 100%.

Winds on SNI are prevailingly northwest and are strong most of the year. The average wind speed is 7.2 m/s (14 knots) and seasonal variation is small. The windiest months, March through July, have wind speeds averaging 8.2 m/s (16 knots). The least windy months, August through February, have wind speeds averaging 6.2 m/s (12 knots).

Much of SNI is used as the Navy Range Instrumentation Test Site. The island is equipped with facilities supporting metric radar, telemetry, Extended Area Test System, optics, communications, microwave, missile launching, drone launching, surveillance radar, and target control. The main support facilities include a runway, an air terminal, housing, a power plant, a fuel farm, a reverse osmosis water system, and a public works and transportation building [2].

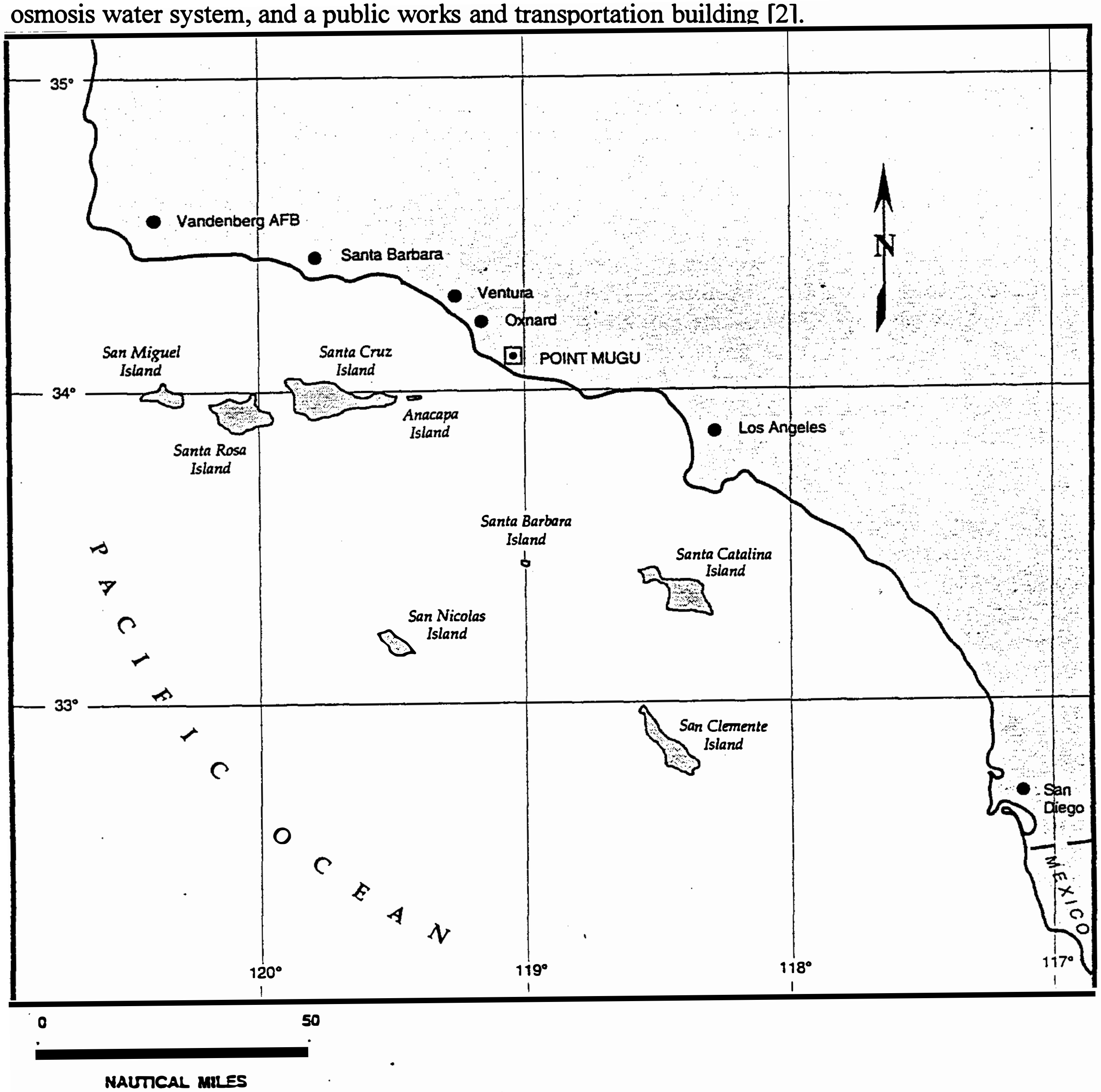
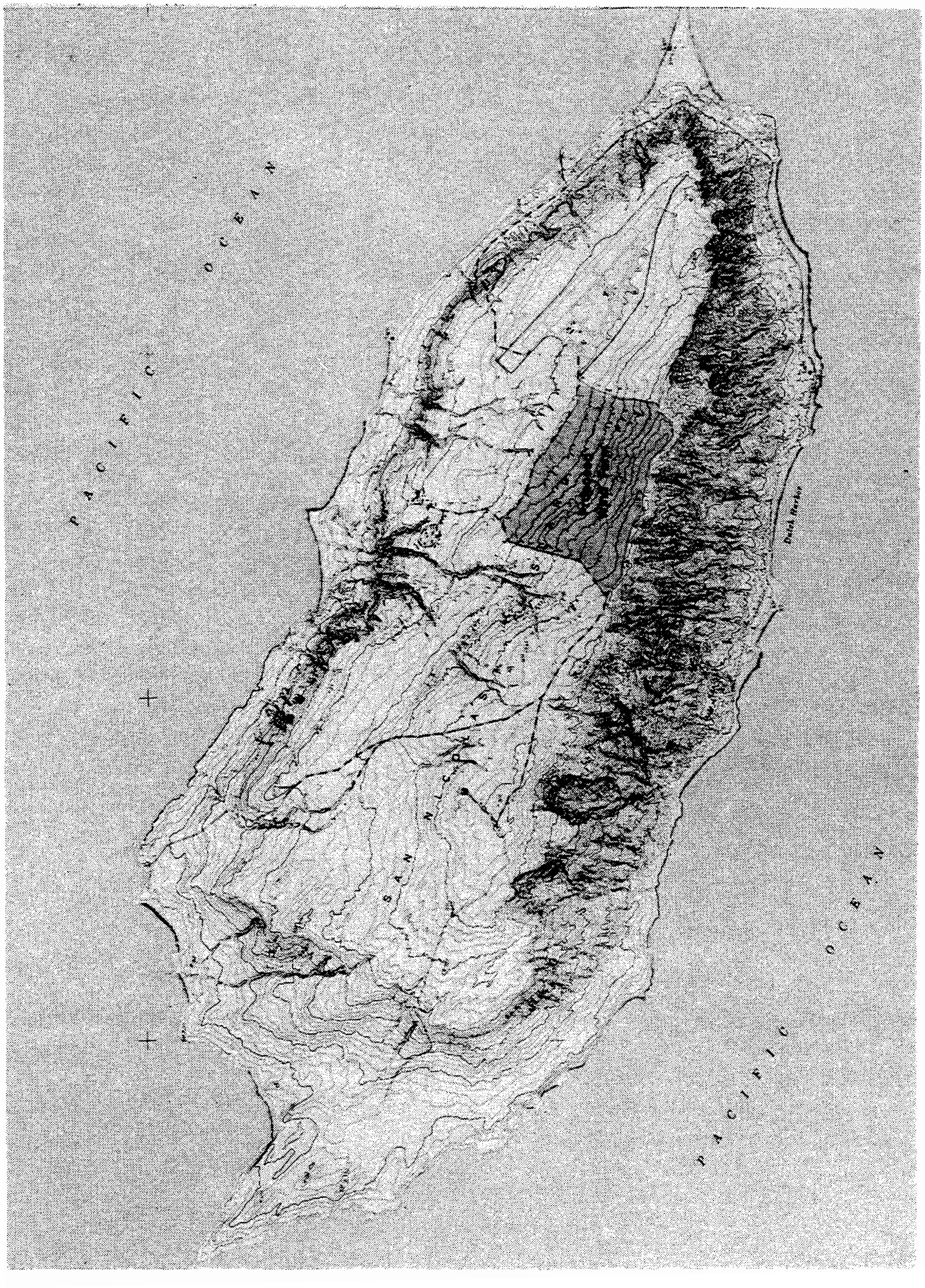


Figure 1: SNI Location Map
Source: San Nicolas Island Site Manual

Figure 2: SNI Topographical Map
Source: San Nicolas Island Site Manual



2.2 Wind Energy Site Description

The proposed wind energy site is located east-southeast of the center of the island, west of the airport, and along the island's crest, as shown in Figure 3. About 1.7 sq km (0.7 sq mi) in area, the site is the west portion of the quadrant bounded by Harrington Road, Owens Road and Monroe Drive. The highest elevation, 249 m (818 ft), occurs along Harrington Road toward Owens Road, from which the terrain slopes down to the north and northeast to 168 m (550 ft) near Monroe Drive.

There are no trees or other wind obstructions on the site, just light vegetation including grasses and cacti. Several low water tanks and buildings, including the Power Plant Island Utilities, are located upwind. The nearness of the power plant minimizes power line distances to the wind energy site.

Parts of the site are very eroded and would require some fill and stabilization. This site has energetic winds throughout the year. Although more optimal wind site locations may exist on the island, this particular site was selected because it is the only site that does not interfere with radar, communications, or other naval operations, and does not pose environmental or cultural constraints.

2.3 Existing Energy System

Diesel Generator Sets: Electrical power at SNI is presently supplied by five Navy-owned, 3-phase, 4160 V, diesel driven electric generators that are operated by the Public Works Department located at Point Mugu. The diesel plant on the island was rebuilt in 1986 as building N114 on Owens Road. Operating data for 1995 shows an average diesel fuel consumption rate of 3.382 kWh/liter (12.802 kWh/gal). Online diesel capacity typically exceeds average demand by some margin to ensure enough capacity to cover excursions and to avoid switching between diesels too often. More frequent switching causes the diesels to run below their ratings most of the time, causing a lower energy conversion efficiency. Lacking any better information on fuel consumption rates, we have assumed a no-load rate equal to 25% of the full-load rate. Then, adjustment of the baseline model for the average rate of 3.382 kWh/liter (12.802 kWh/gal) requires a full-load fuel consumption rate of 3.840 kWh/liter (14.534 kWh/gal). The resulting fuel rate estimates are shown in Table 1.

Table 1: Power Rating and Fuel Consumption

	Power Rating, kW		Fuel Consumption, l/hr (gal/hr)	
Manufacturer & Model	Manuf.	Navy	No Load	Full Load
1. CAT 3516 (1800 rpm)	825	750	48.8 (12.9)	195.3 (51.6)
2. EMD 8-645-E1 (720 rpm)	500	500	32.6 (8.6)	130.2 (34.4)
3. EMD 8-645-E1 (720 rpm)	500	500	32.6 (8.6)	130.2 (34.4)
4. CAT model N/A (1800 rpm)	830	750	48.8 (12.9)	195.3 (51.6)
5. EMD 16-645-E1 (720 rpm)	1,000	1,000	65.1 (17.2)	260.4 (68.8)

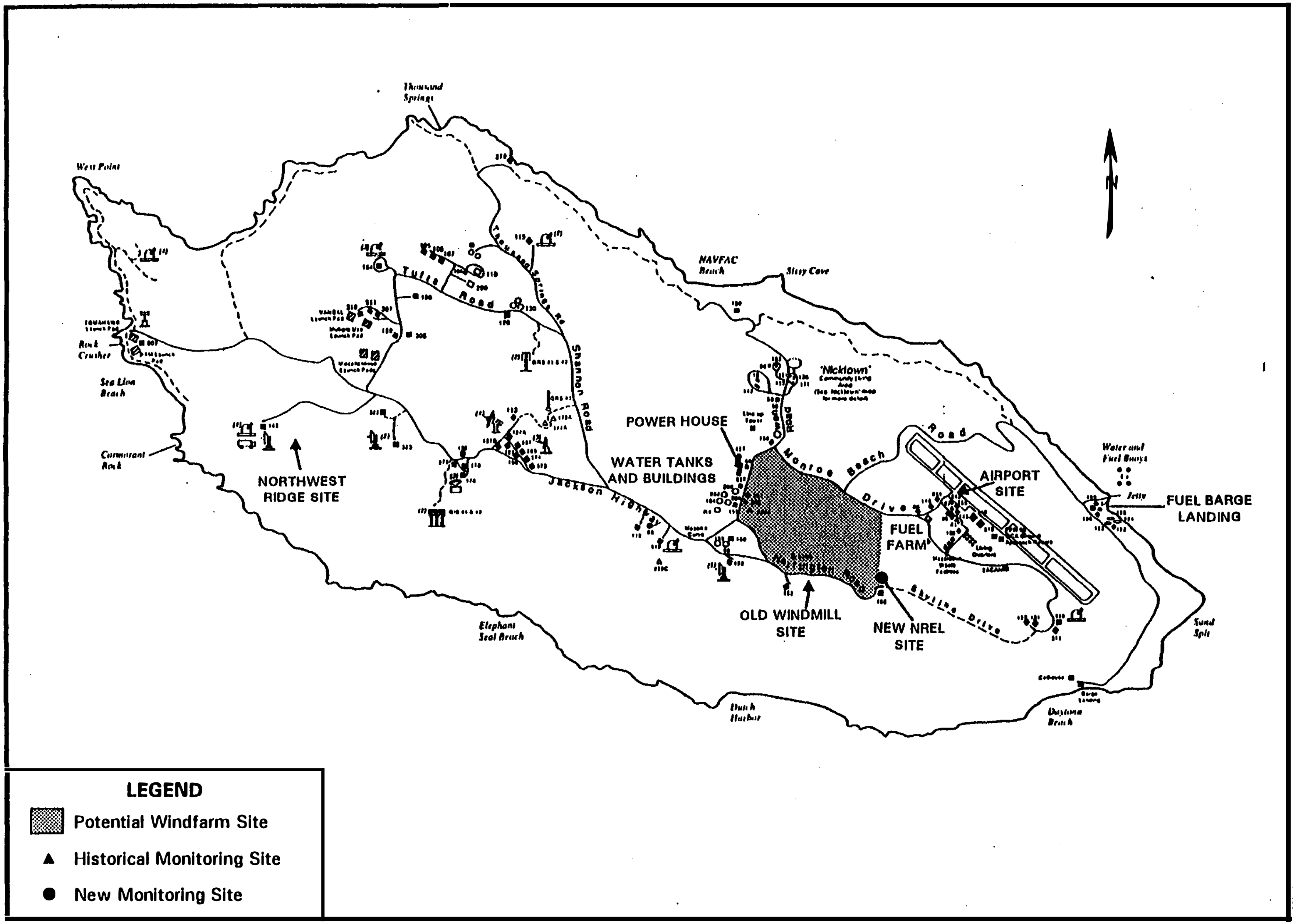


Figure 3. San Nicolas Island Naval Facilities and potential windfarm area
Source: San Nicholas Island Site Manual.

Fuel Supply System: JP-5 fuel is stored in a 37,850 liter (10,000 gallon) above-ground tank located to the south of Building N114. Fuel flows by gravity from this tank to pumps that fill the day tanks located just outside Building N114. From the day tanks, fuel flows by gravity to each operating engine's driven fuel pump. There is a plan to replace the outdoor day tanks with tanks located inside the building. The 37,850 liter (10,000 gallon) fuel tank is cleaned and refilled via trucks every 6 weeks.

An 11,355 liter (3,000 gal) lubrication oil tank is located within a double containment wall, adjacent to Building N114. An 18,925 liter (5,000 gal) truck trailer is parked adjacent to the lubrication oil tank. A quick-disconnect hose from the truck is connected to the pipe serving the permanently installed lubrication oil tank. A pump, mounted next to the lubrication oil tank, allows the transfer of oil to the engines as needed.

The plant is also provided with a waste-oil collection system. This system consists of two 11,355 liter (3,000 gal) holding tanks, two 1,893 liter (500 gal) sump tanks, and two sump pumps. The tanks and pumps are located immediately outside the power plant and are equipped with secondary containment interconnecting piping [2].

Balance of Plant: The plant is operated 24 hours per day. Operators observe equipment operation, make hourly log entries, and start and stop the generators as required. The control room has been recently upgraded and is enclosed by sound-reducing insulation and double doors leading to the engine room.

The station auxiliary equipment includes one 150 kVA, three-phase, 4160-120/208 V station service transformer, a 120/208 V distribution panel board, a 125 V DC station battery, and two 225 kVA, three-phase, grounded-wye-delta-connected grounding transformers, one for each bus in the switchgear to provide a neutral for single-phase, 2400 V loads.

The power plant switchgear, installed in 1990, has two buses with a vacuum circuit breaker tie. The circuit breaker tie will trip automatically in the event of a fault on either bus.

In addition to the 4160 V generators, local emergency generators provide back-up power for critical loads. The power is generated at utilization voltage (120/208V or 480V) and is applied to the load through manual or automatic transfer switches.

Distribution: Electricity is distributed throughout the island by three 12.4-kVA, 4160 V feeders. Feeder #1 serves most of the western half of the island; feeder #2 serves the north-central area of the island, including personnel living facilities, administration and recreational facilities, and the public works buildings; feeder #3 serves the air terminal and associated hangars and maintenance facilities, and two loads in the western part of the island.

The western portion of the distribution (feeder #1 and part of feeder #3) is completely underground [2]. Feeders #2 and #3 use mostly overhead lines, consisting of wood poles supporting bare copper conductors.

2.4 Energy Demand

Energy production information is sparse, but some statistics follow in Table 2. The current (1995) average hourly electrical demand at SNI is 771 kW; the hourly average peak is estimated to be 1230 kW. The SNI grid supplies about 6.8 GWh annually, up from 5.5 GWh in past years.

Table 2: SNI Available System Demand Statistics

Year		1987	1989-1990	1993	1995
Peak demand	(kW)	950	1030	1050	
Low demand	(kW)		300		
Average demand	(kW)	628	644	627	771
Annual energy production	(kWh)	5,500,000	5,643,600	5,488,714	6,753,000
Annual fuel consumption	(l)	1,498,860	1,862,648	1,768,587	1,996,584
Annual fuel consumption	(gal)	396,000	492,113	467,262	527,499
Energy / Fuel ratio	(kWh/l)	3.67	3.04	3.09	3.38
Energy / Fuel ratio	(kWh/gal)	13.9	11.5	11.7	12.8
Source		TM No. 74-88-06 [3]	Graphical Data Set	Power Plant Process Data Table, & [4]	Carrie Eller FAX

One full year of graphical load data was digitized for input to the hybrid system model. It consists of hourly power readings from 1 October 1989 through 30 September 1990. These readings were taken from copies of the SNI power plant written log sheets and hand entered on a computer spreadsheet. All load data graphs presented in this report use the original 1989-90 data, but for hybrid system modeling these load values will be inflated 19.66 % to match 1995 demand.

The load frequency distribution follows in Figure 4 with a bimodal shape, centered around 580 kW and 780 kW. Annual diurnal loads are shown in Figure 5. These figures are based on the original 1989/90 loads data. Included with the data set are daily energy production and monthly fuel consumption. Annual records of monthly energy production and fuel consumption are shown in Figures 6 and 7. The plot of these two quantities in Figure 8 shows poorer correlation than expected. We don't know whether the anomalous data points result from problematic Navy record keeping, significant differences or fluctuations in diesel fuel rates, or changes in operating procedures.

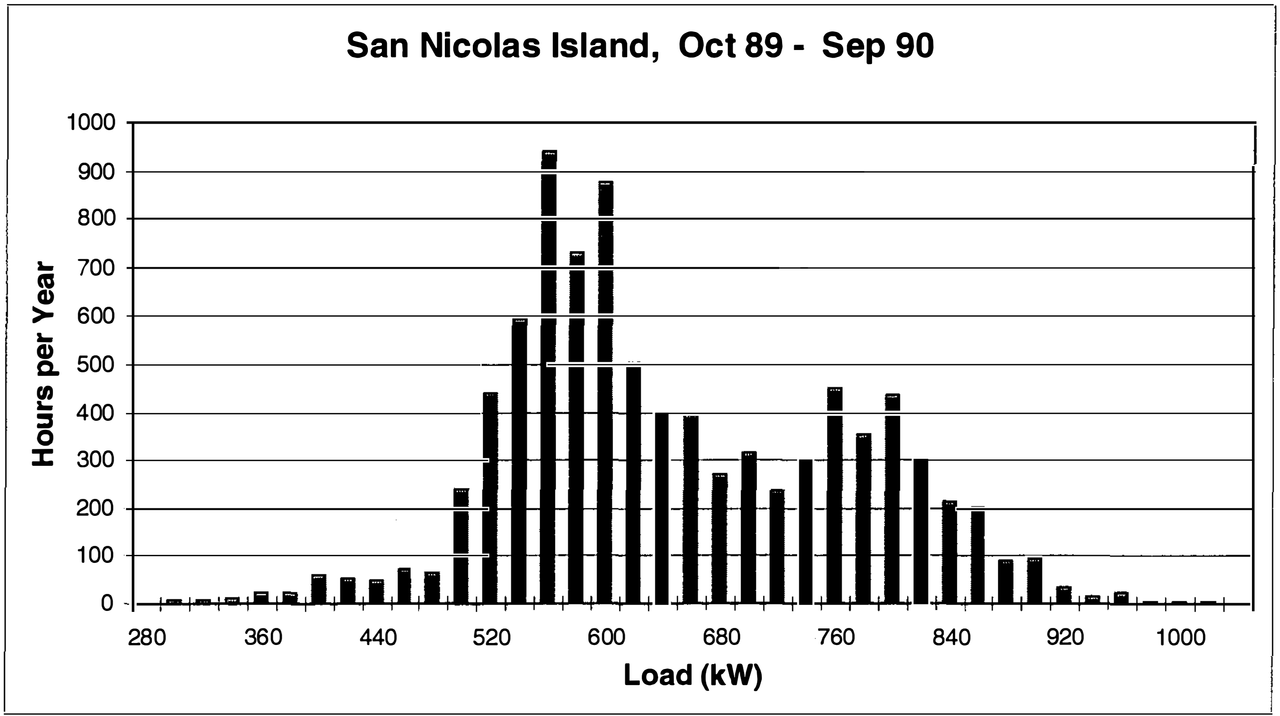


Figure 4: SNI Load Frequency Distribution

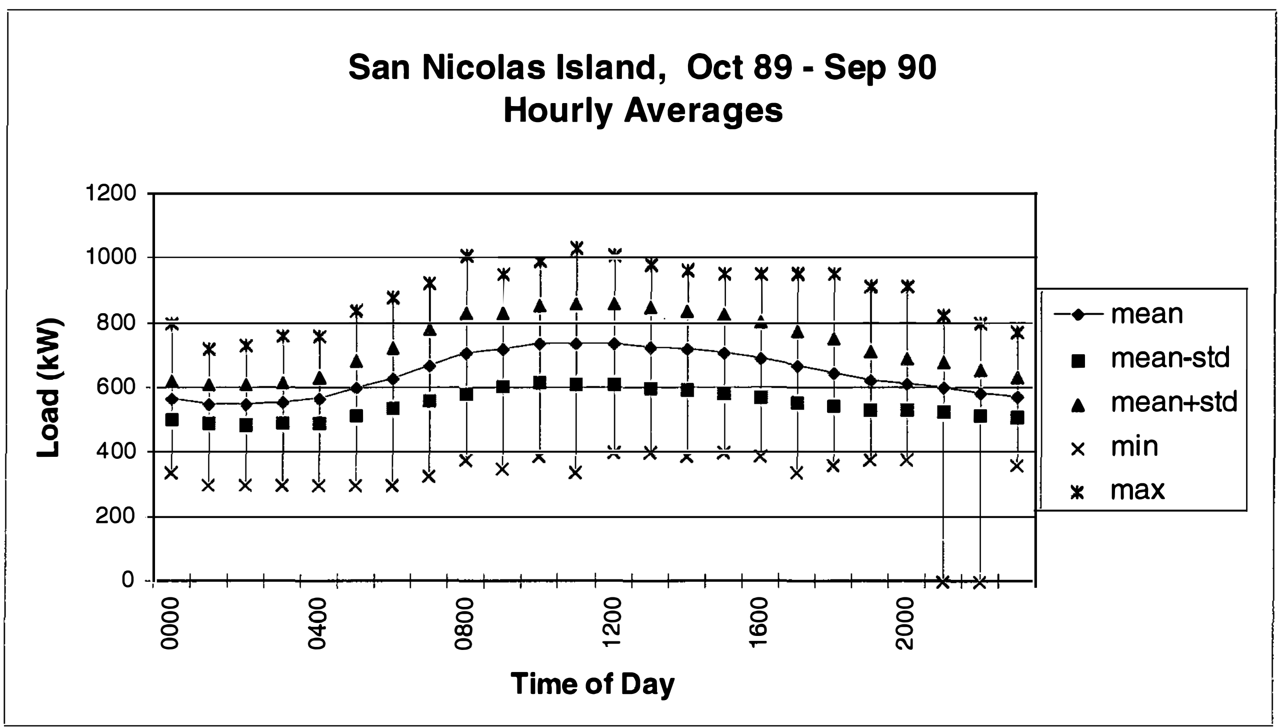


Figure 5: SNI Annual Average Diurnal Load

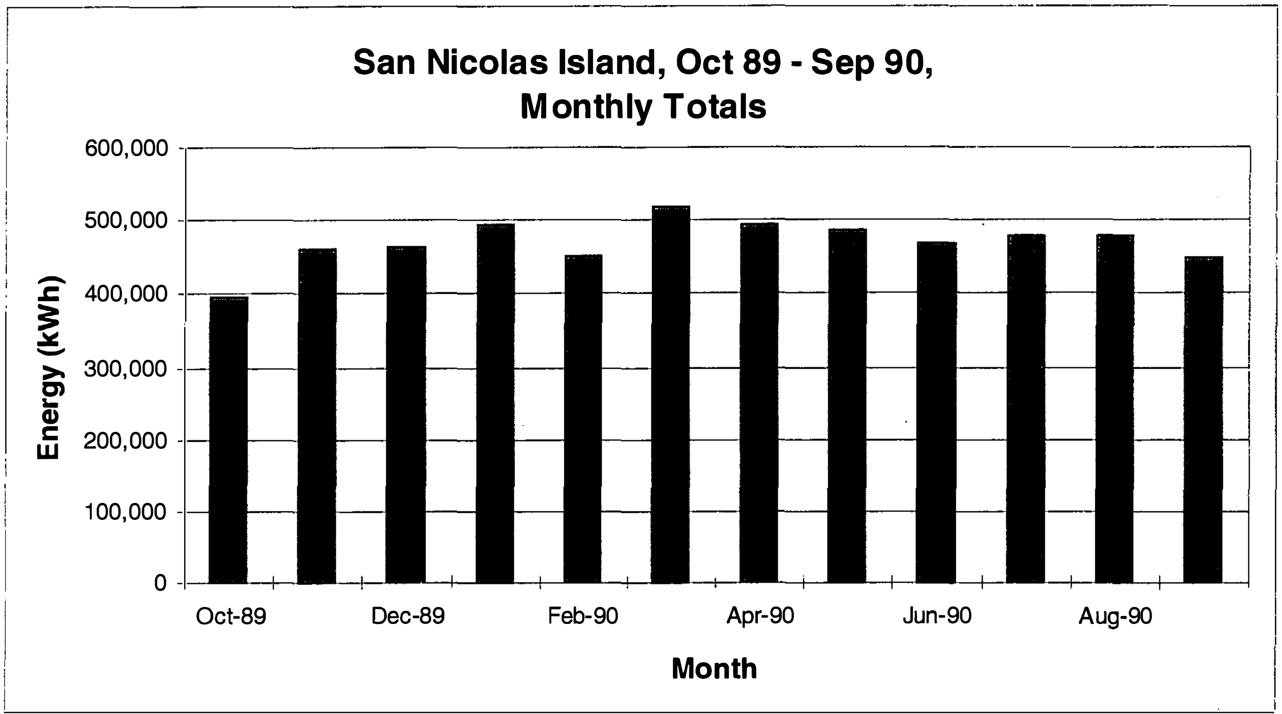


Figure 6: SNI Annual Energy Production Record

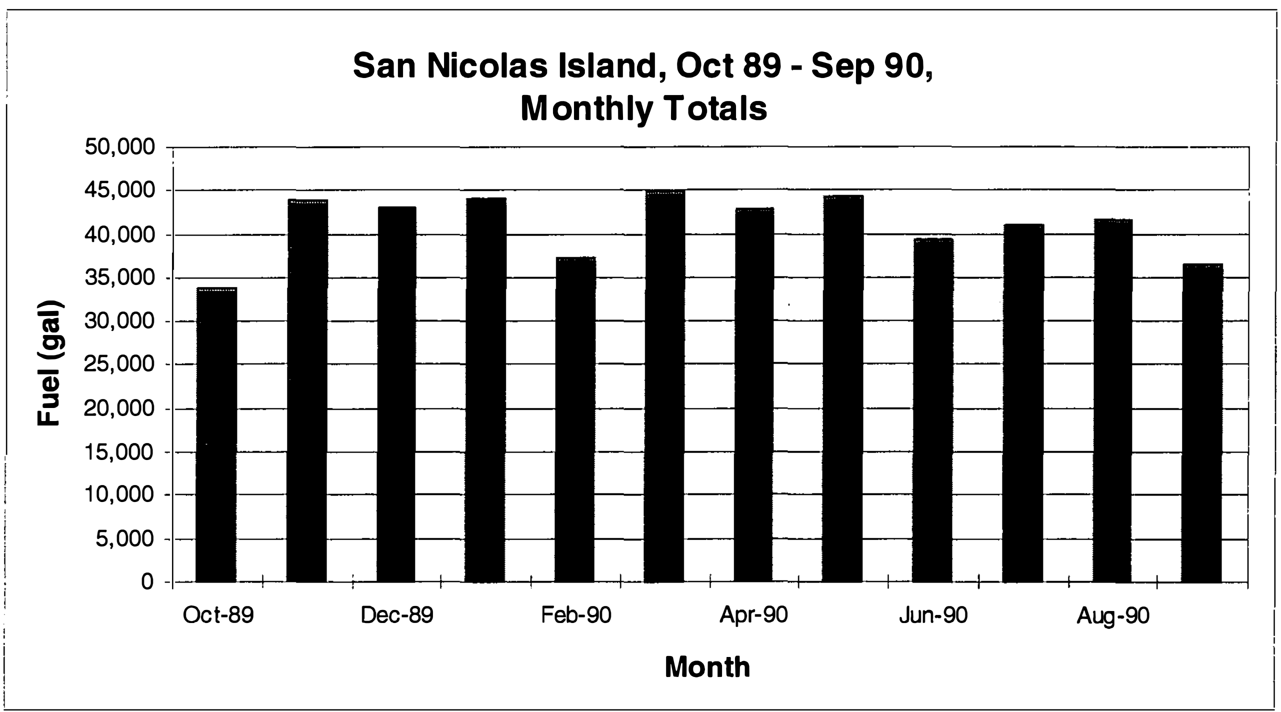


Figure 7: SNI Annual Fuel Consumption Record

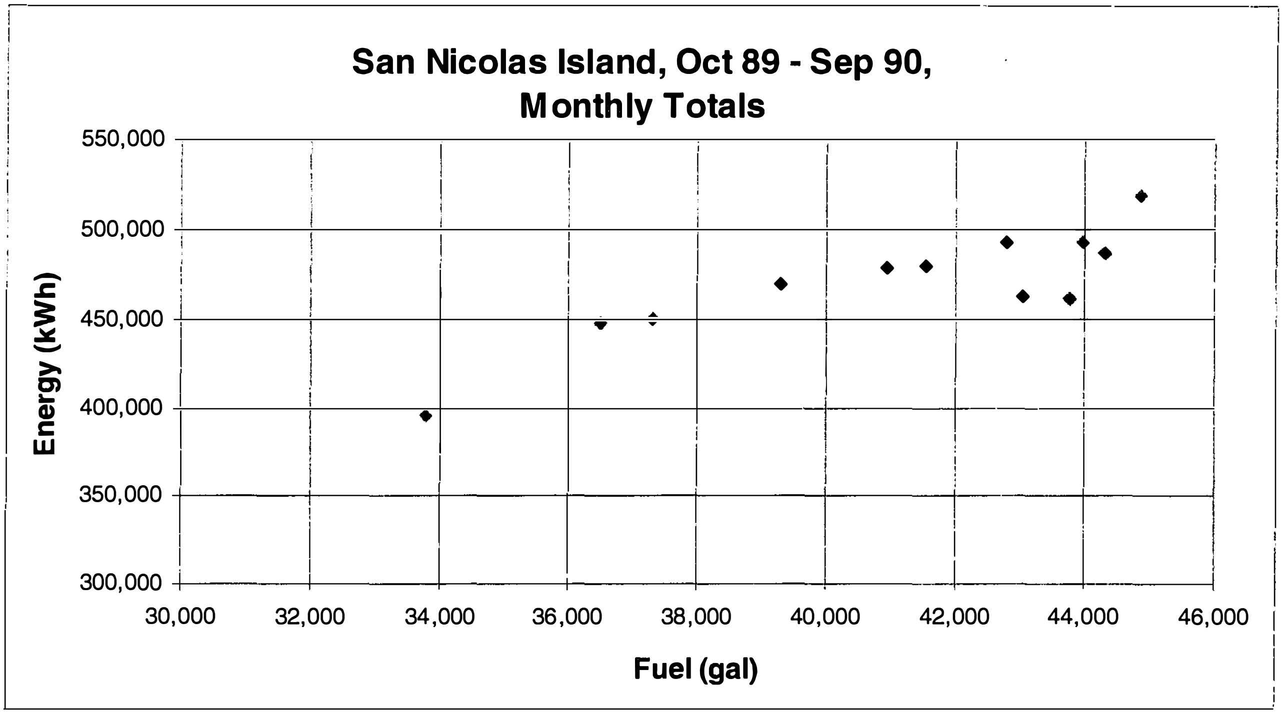


Figure 8: SNI Energy Production vs Fuel Consumption

3.0 THE WIND RESOURCE

In July 1994, the National Renewable Energy Laboratory (NREL) entered into a cooperative agreement with the Naval Facilities Engineering Service Center (NFESC) to collect one full year of high quality wind energy resource data at SNI Facility 186 at 30.5 m (100 ft) height. We examined this data in detail, and reviewed historical summary data to describe long-term behavior. Details of the data collection and analysis can be found in McKenna [1].

3.1 Historical Wind Data

This section begins with a review of 32 years of wind speed data (1947-1978) at SNI station number 93116, compiled by Pacific Northwest Laboratories and managed by the National Climatic Data Center [5]. Historical annual average wind speeds follow in Figure 9 and details of the analysis are presented in McKenna [1].

The average 32 year wind speed at SNI adjusted to the 30.5 m height is 6.1 m/s (11.8 knots) based on annual averages of hourly data, and the average of the annual standard deviations is 3.8 m/s (7.4 knots). The standard deviation of the annual averages is 0.6 m/s, giving a variability of 0.6 / 6.1 = 0.10, or 10%. Although confidence in the average wind speed is low, this variability implies that the annual average wind speed will fall within +/- 30% (3 standard deviations) 99% of the time, assuming these values are normally distributed.

The historical 32 year anemometer locations changed several times for this collection of historical wind data; therefore, there were different sensors, mountings, heights, exposures, and possibly drifting calibrations. The heights varied from 4.6 m to 19.8 m, so each year's data was adjusted to the NREL study's measurement height (30.5 m) using the 1/7 power law. These low heights are more susceptible to the effects of obstructions.

Readings on the historical data generally were made 12-18 times a day -- more often in the daytime -- thereby raising the possibility of skewing the averages with non-uniform intervals. Some bias toward lower wind speed measurements might be expected if more readings occurred in daytime, if unknown obstructions were present, or if old anemometers began to bind. Because these factors are not tractable, no attempt is made to account for them. Therefore, the averages found here will not be used for the hybrid system modeling later in this report, but the interannual variability of 10% will be used for a sensitivity analysis.

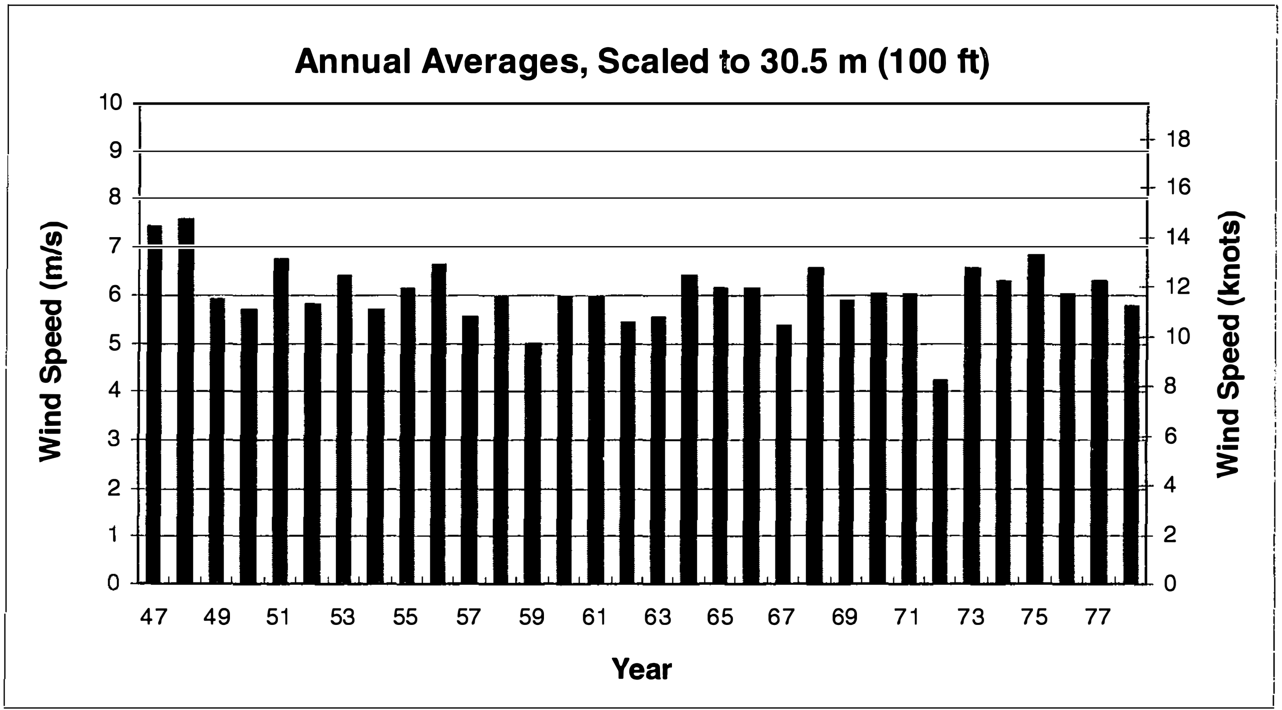


Figure 9: SNI Historical Wind Speeds

3.2 Current Wind Data

Statistical analysis of the full year of NREL 10 minute data yielded the results shown in Table 3, and a full wind speed distribution is presented in Figure 10. Collected at 30 m height under highly controlled conditions, this data will be used in hourly form for the subsequent hybrid system modeling.

Table 3: Summary of Current SNI Meteorological Data

Channel	Units	Average	Standard Deviation	Minimum	Maximum
Wind Speed	m/s	7.2	4.8	0.0	28.5
Wind Speed	knots	14.0	9.3	0.0	55.4
Ambient Temperature	°C	14.5	3.9	6.4	33.4
Ambient Pressure	mbar	983	4.6	965	997
Air Density	kg/m^3	1.20	0.02	1.14	1.22
Power Density	W/m^2	473	759	2.3	4010

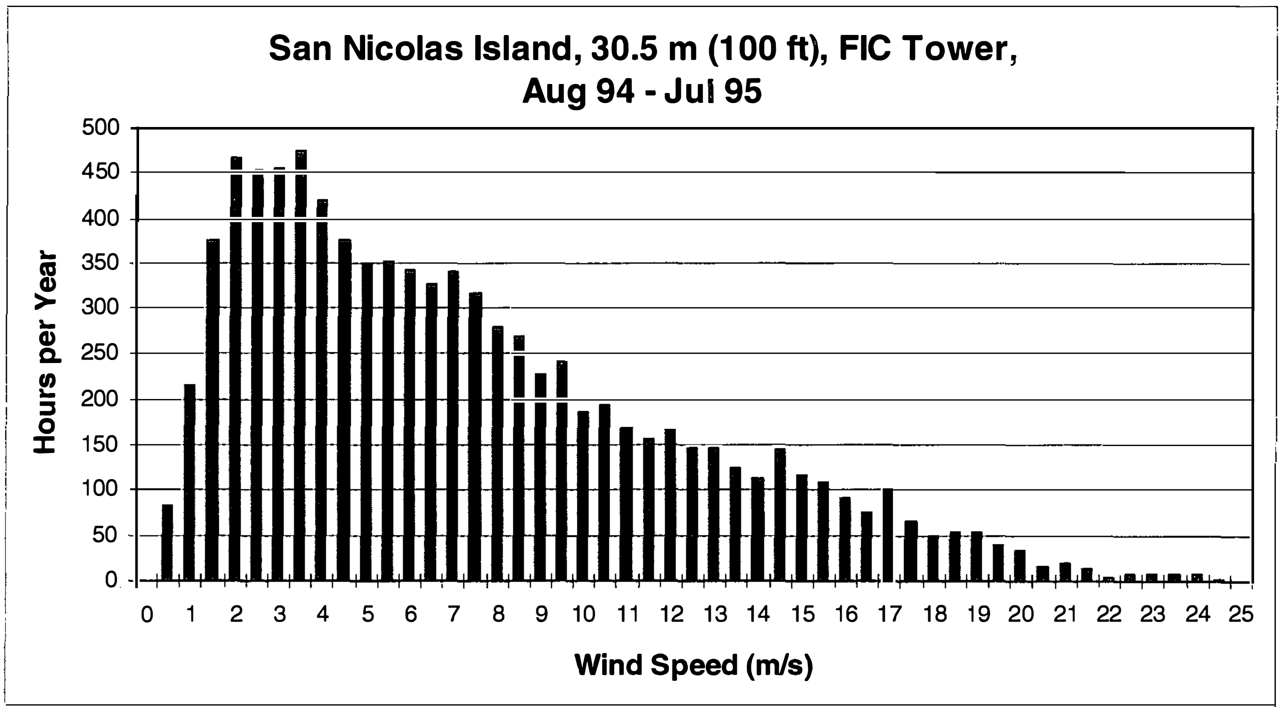


Figure 10: SNI Wind Speed Frequency Distribution

An annual record using monthly average wind speeds is plotted in Figure 11. February appears to be the low month, with a high month in April just two months later. The rest of the year is between 6 and 8 m/s more consistently. The source data was derived from NREL testing on SNI at 30.5 m at Facility 186 for the period 1 August 1994 through 31 July 1995. The annual average diurnal given in Figure 12 shows a stable pattern, with wind speeds falling between 6 and 8 m/s. However, these are averages, any specific day could be quite different. For reference, the column labeled "0000" refers to the first hour of the day, 0000 to 0100.

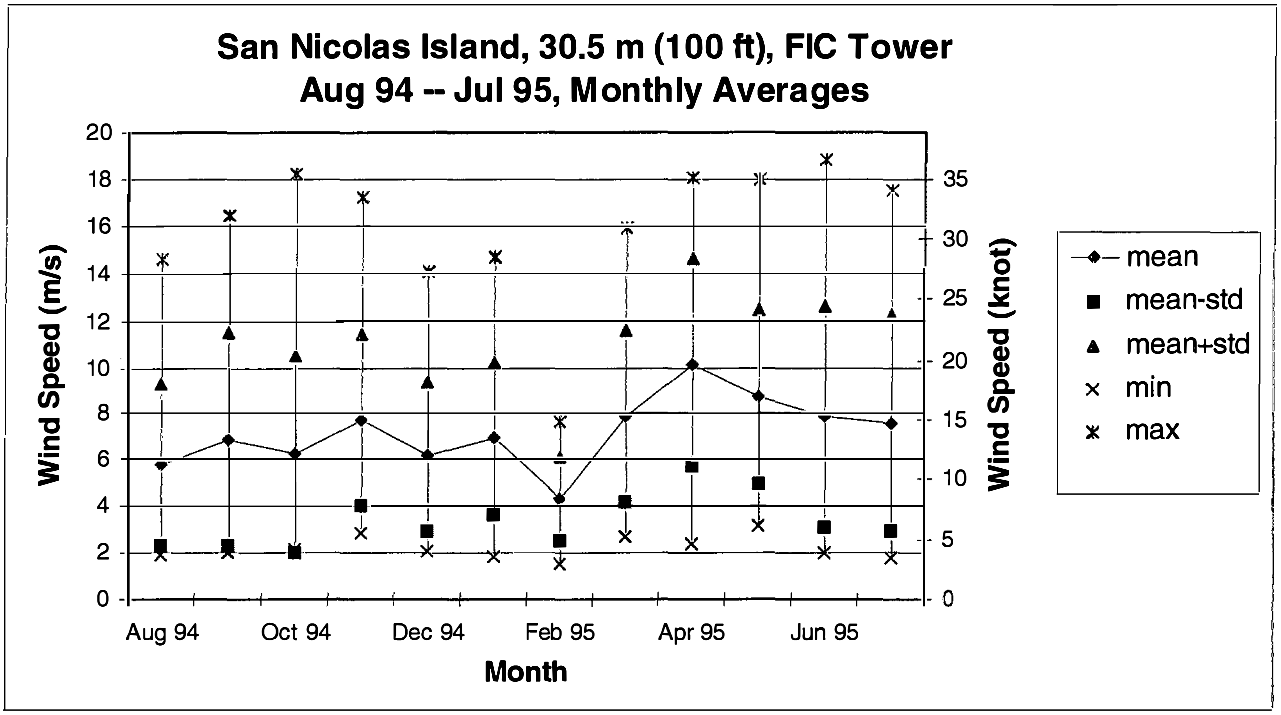


Figure 11: SNI Annual Wind Speed Record

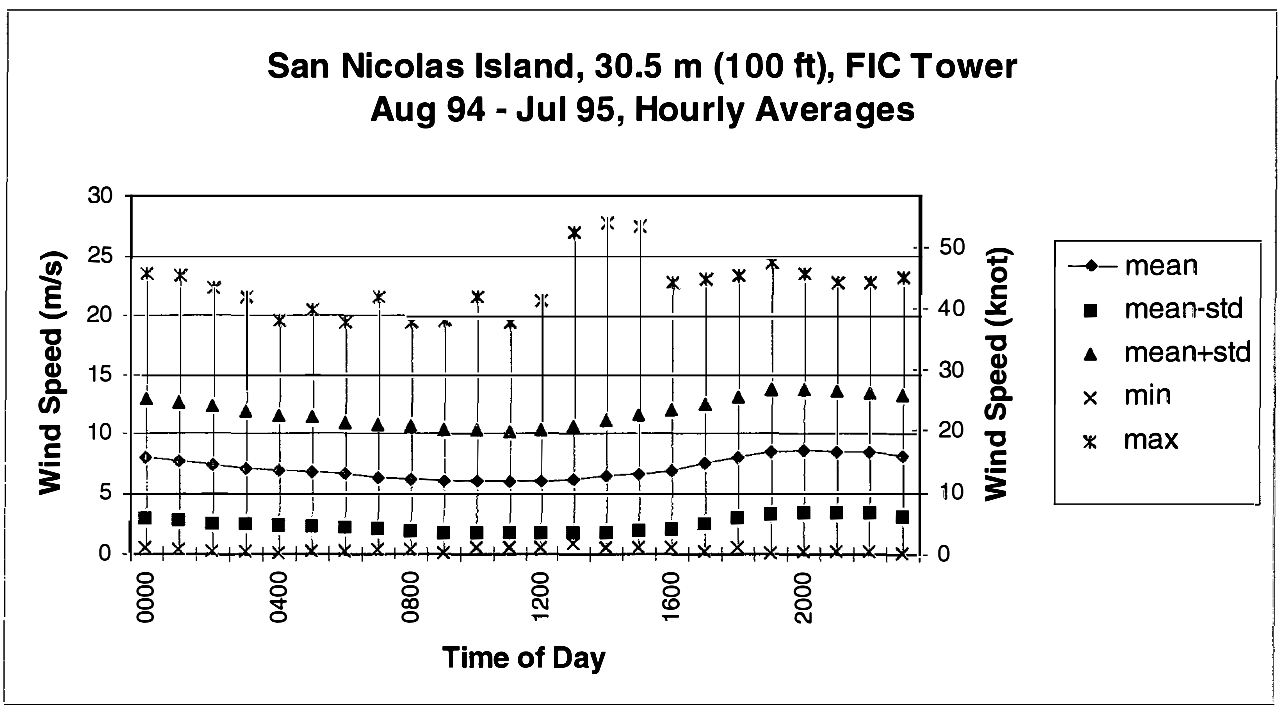


Figure 12: SNI Annual Average Diurnal Wind Speed

4.0 PROPOSED ENERGY SYSTEM AND ANALYSIS

A hybrid energy system consisting of combined wind and diesel generators may be economically and environmentally advantageous for SNI and surrounding areas. A preliminary study of such a system was conducted using a spreadsheet program to compare the cost of power generation for the current baseline (diesel only) to several hybrid cases. The hybrid cases were compared to determine the most cost-effective number of wind turbines to purchase.

4.1 Hybrid System

The proposed hybrid system is relatively simple. Between one and four commercially available wind turbines (each with a capacity of 225 kW) would be combined with the existing 3500 kW diesel generation capacity. With a demand peak of 1230 kW, no more than 1500 kW of diesel is on line at any time. Therefore, wind penetration of "on-line" capacity with four wind turbines is 900/1500 = 60%. Based on instantaneous power, wind penetration can range from 0 % when there is no wind to 250% when peak wind power of 900 kW is combined with a minimum load of 360 kW.

Power storage, photovoltaic generation, dump load, and advanced load management were not included in this preliminary analysis. Their consideration in future analyses may be useful.

Several assumptions were made regarding the power that can be generated by the wind. First, at least 200 kW must always be generated by the existing diesel generators even if there is excess wind capacity. Second, it is assumed that only the necessary number of turbines will be generating power at any given time, with the remaining turbines idled. Third, a minimum diesel run time is required to hold the number of diesel starts on the order of 100. To simulate this in real operation, the diesel rating is selected to cover the maximum demand of the previous 30 hours, thereby preventing the diesel from being started too often.

4.2 Diesel Generation

As mentioned in Section 2.3, there are five diesel generator sets, two generators rated by the Navy at 500 kW, two at 750 kW, and one at 1000 kW. One generator of each size is included in the hybrid system model. The generator fuel/energy curves were given in Section 2.3. Typically, only one diesel is run at a time, unless a special naval exercise requires 1250 kW capacity.

The power demand for 1 year ranges from a minimum of 360 kW to a maximum estimated at 1472 kW. The fuel needed (with no wind energy input) is calculated based on minimizing the number and rating of operating diesel generators. The power demand can be met by configuring the diesels to produce 500, 750, 1000, 1250 or 1500 kW.

The diesel generators follow the load automatically through speed and frequency monitoring and fuel rate regulation. The diesels have no specific selection priority, but there are other constraints. At least one diesel must be on line at all times to ensure reliable capacity and system stability; the minimum operating load is 200 kW, or 40% rated power for the smallest unit.

Also, according to SNI power system operating data from 1989/90, the manual operating scheme tends to favor running the larger engines for long periods of time, so that the actual number of diesel starts was about 127 for the year, as estimated from the Navy-supplied data. An optimized operating scheme alone could provide significant fuel savings, but it would require many more diesel starts and some form of automated system control. For this study, the spreadsheet model follows the actual manual operating scheme for all cases, wind and baseline. The hybrid wind systems likely would show even greater savings than the baseline system with such an optimizer.

4.3 Wind Generation

The wind generation system modeled consists of between 1 and 4 commercial wind turbines rated at 225 kW each. The sea level power curve for this turbine is shown in Figure 13. A fifth-order polynomial was fit to the curve for use in the spreadsheet model. No density correction was made to the power curve, as the proposed wind site is only 700 to 800 ft above sea level. The wind turbines can be curtailed (shut down) as necessary when excess wind energy is available.

The net annual energy production (AEP) can be computed by multiplying the power production level by the number of hours for each wind speed level and summing the results. If P_i is power and N_i is number of hours at each wind speed, then:

$$AEP = \text{sum}\,(P_i * N_i),\quad i = 0.0,\ 0.5,\ 1.0,\ \ldots\ 100.0\ \text{m/s}.$$

Actual AEP is often lower because of various system losses. Assessment of the wind site showed that there are not any significant obstructions to the prevailing wind flow. Also, there is plenty of room for one to four wind turbines, so array losses should be mitigated with proper siting. However, other sources of loss cannot be avoided as easily. Such losses include 1 - 5% availability loss for operation and maintenance, possibly 5% for blade soiling losses, 2% for turbulence losses, and 3% for control, grid, and collection system losses. Using 97% availability, the combination of these sources is significant, having a net loss of 11.5%. To account for these losses, the wind turbine power curves have been penalized by 11.5% throughout their range.

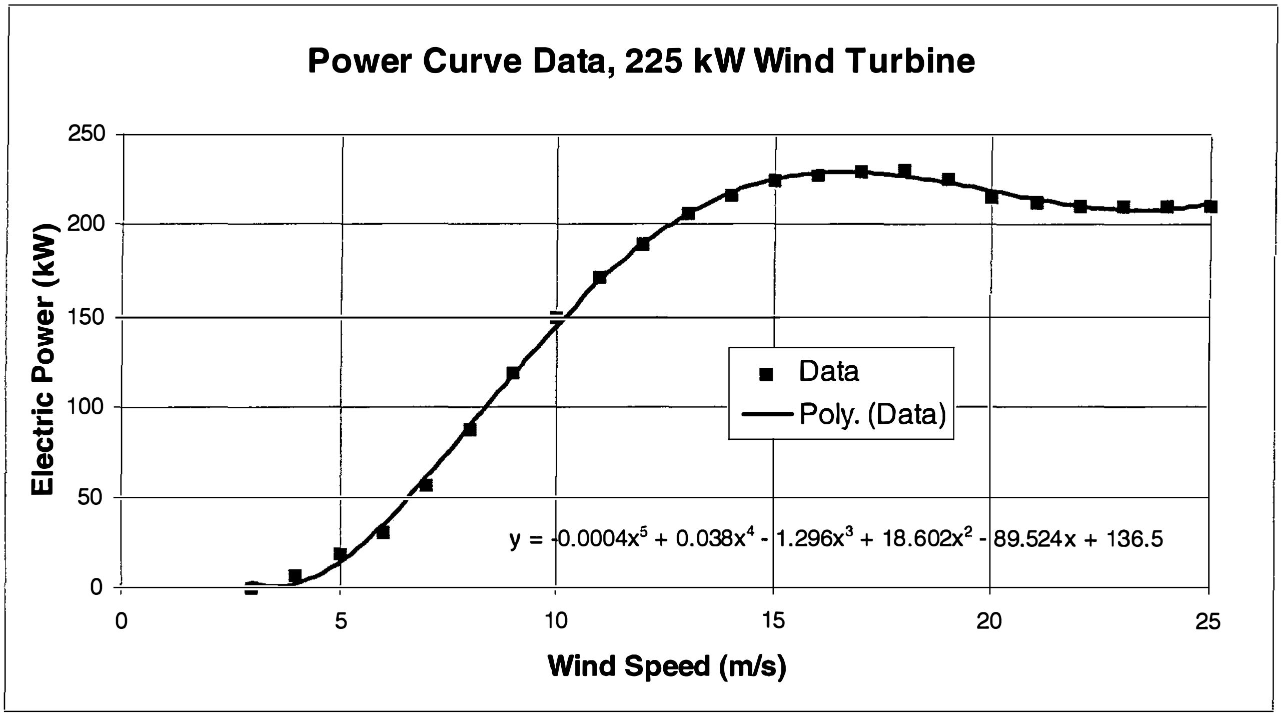


Figure 13: Power Curve, 225 kW Wind Turbine

4.4 Load Profile

The hourly SNI load data mentioned in Section 2.4 was used in the hybrid system model. The evidence of the power production statistics in Section 2.3 indicates that the loads at SNI had grown 19.66% from the 1989/90 load data year to 1995, so these values were inflated accordingly and rearranged to a calendar year for the hybrid modeling. The uninflated load frequency distribution was shown earlier in Figure 4.

Short-term load variability is defined as 0.044 based on the following rationale: The average load, 771 kW, gives 1 sigma = 34 kW and 3 sigma = 102 kW. These fluctuations coincide with operating experience, which has demonstrated a 20 - 30 kW normal fluctuation and an occasional 100 kW spike during a motor start. The hybrid spreadsheet model accommodates this fluctuation by reserving a 100 kW margin of diesel capacity above the net demand for each 30 hour period.

4.5 Wind Profile

The hourly wind speed averages from 1 August 1994 through 31 July 1995 (from the new NREL / SNI data set) were used in the hybrid system model. As with load, this data was rearranged to a calendar year to assure proper synchronization with the load profile. The wind frequency distribution was presented earlier in Figure 10. Annual and monthly diurnal wind speed and load are overlaid in Figure 14. Although in the same range, they appear to be inversely correlated through the day.

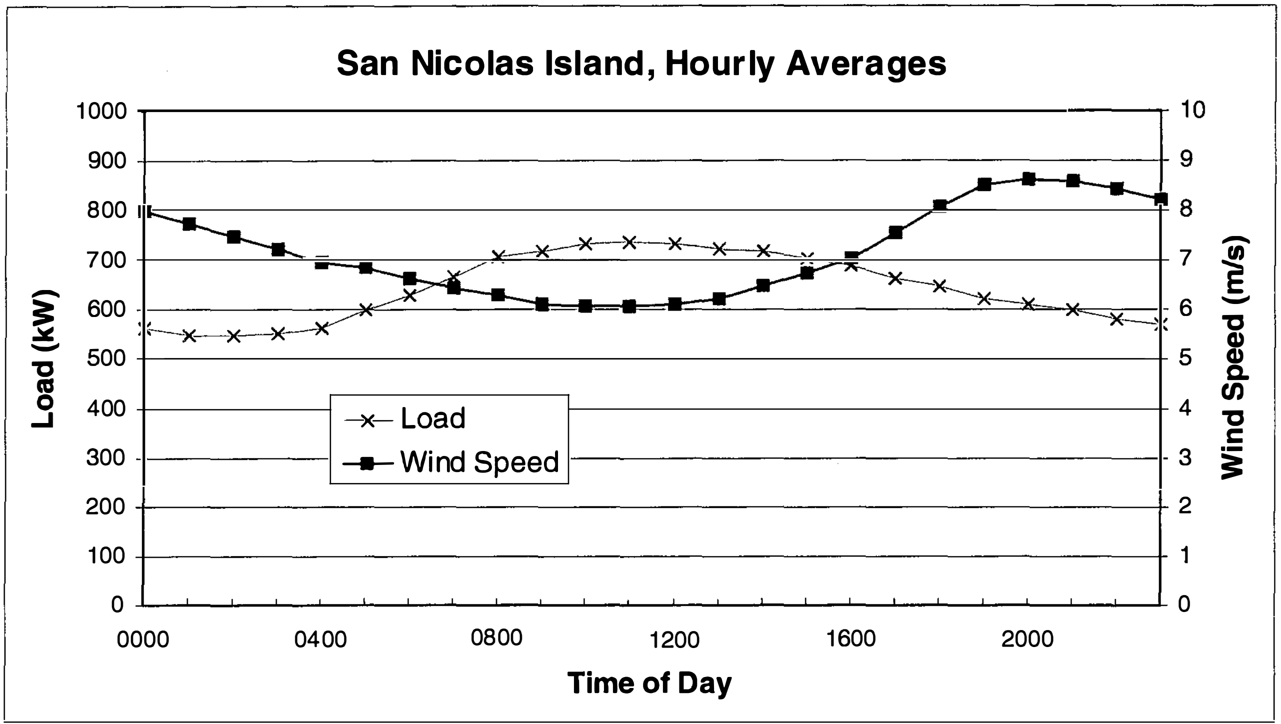


Figure 14: SNI Diurnal Load and Wind Speed Overlay

4.6 Hybrid System Spreadsheet Model

The hybrid system model uses the existing diesel system plus new wind generation; the load data is scaled to 1995 and the wind data is from the NREL/SNI 1994-1995 measurements. The spreadsheet model starts by calculating a diesel rating that covers the demand with sufficient margin to ensure a minimum diesel run time of 30 hours and handle 100 kW excursions. The minimum run time holds the number of starts to less than 130 per year. Diesel consumption, based on demand and efficiency, is calculated next. Finally, the number of diesel starts and run time are computed.

The wind-hybrid section follows by calculating the power produced by a single wind turbine at each hour of the year. Then it calculates the optimal wind power usage by choosing the greatest number of turbines to operate, without exceeding demand, while maintaining at least 200 kW of diesel energy online. This wind power, when subtracted from the demand, reduces the amount of power required from the diesel generators. Only in very low or very high winds is the diesel power demand unchanged. Diesel fuel consumption is then calculated from this net demand and fed into the fuel savings over the diesel-only system.

Four different cases of the hybrid system were examined. The results are summarized in Table 4. In the first case, just one 225 kW wind turbine was added to the existing (baseline) diesel set-up, in the second case two 225 kW turbines, and so on, up to four 225 kW wind turbines. The minimum and maximum net loads (demand minus wind power) are 0 kW (loss of grid) and 1472 kW for all cases. The number of diesel starts is determined by incrementing a counter every time the diesel capacity changes. The diesel run time is 8760 hours (1 diesel all year), plus the number of hours at 1250 kW capacity (2 diesels on). The diesel-only case required 100 starts and 15,491 hours of total run time for the year.

Table 4: 1995 Hybrid Systems vs. Baseline: Spreadsheet Model Results

Hybrid Results Parameter	Units	Baseline Diesel Only	1 Wind Turbine 225 kW	2 Wind Turbines 225 kW	3 Wind Turbines 225 kW	4 Wind Turbines 225 kW
Average WS, 1 yr.	m/s	7.2	7.2	7.2	7.2	7.2
Average Load, 1 yr.	kW	771	771	771	771	771
Run Duration	hour	8,760	8,760	8,760	8,760	8,760
Avg. Net Diesel Load	kW	771	704	638	595	569
Energy Demand, 1yr	MWh	6753	6753	6753	6753	6753
Diesel Energy, 1yr	MWh	6753	6166	5593	5216	4983
Wind Energy, 1yr	MWh	0	588	1160	1538	1770
Unused Wind Energy	MWh	0	1	17	228	584
Diesel Energy	%	100.0	91.3	82.8	77.2	73.8
Wind Energy	%	0.0	8.7	17.2	22.8	26.2
Wind Energy Incremental Turbine	%	0.0	8.7	8.5	5.6	3.4
Wind System Capacity Factor	%	n/a	29.8	29.4	26.0	22.5
Wind Sys Inctl Turbine Cap Fac	%	n/a	29.8	29.0	19.2	11.8
Fuel Usage	kltr	1997	1882	1770	1696	1651
Fuel Usage	% of base	0.0	94.2	88.6	84.9	82.7
Fuel Saving	kltr	0	151	311	417	482
Inctl Wind-produced COE,	$/kWh	n/a	0.266	0.265	0.270	0.282
Levelized COE	$/kWh	0.358	0.350	0.342	0.338	0.338
COE Saving	$/kWh	0.000	0.008	0.016	0.020	0.020
COE Saving	% of base	0.0	2.2	4.5	5.6	5.6
Payback Period	year	n/a	5.22	5.29	6.00	6.97
Internal Rate of Return,	%	n/a	18.5	18.2	15.8	13.1

Notes: (1) "Net Load" means net power required from the diesels, or system load minus useable wind power.
(2) Wind System Capacity Factor = Wind Energy [MWh] / (#turbines*rating[0.225MW]*8760[h]).
(3) Inctl wind-produced Cost of Energy (COE) = (hybrid COE*energy demand - baseline COE*diesel energy) / wind energy.
(4) All other values derived from spreadsheet model results, Appendix A.

Four 225 kW wind turbines reduce diesel energy production by 26.2% and fuel consumption by 17.3%. Two 225 kW wind turbines reduce diesel energy production by 17.2% and fuel consumption by 11.4%. Fuel savings fall below energy savings because the high wind variability necessitates greater diesel capacity running at somewhat less efficient conditions. However, these fuel savings could be improved significantly if the diesel usage was optimized, but at the cost of starting and stopping the engines much more frequently.

4.7 HYBRID2 Model

The hybrid system was also modeled using HYBRID2, a software package for operational and economic modeling of complex hybrid energy systems. The same input data was used in both the spreadsheet and HYBRID2 models. A description of the software package follows.

The HYBRID2 code was developed by the University of Massachusetts and the NREL to elucidate the performance of a variety of wind/diesel and hybrid power system configurations. HYBRID2 is a combined probabilistic/time series model designed to study a wide variety of hybrid power systems. The hybrid systems may include diesel generators, wind turbines, battery storage, different power conversion devices and a photovoltaic array. Systems can be modeled on the AC, DC or multiple buses. A variety of different operating strategies have been allowed.

Of two types of simulation models for hybrid systems that are widely used, the first are known as "logistic" models. These models are used primarily to predict long-term performance and to provide input to economic analyses. Historically, most of these logistic models have been of the time series type. The second type of models are called "dynamic" models and consider very rapid fluctuations and system responses to changes in system parameters. HYBRID2 is a logistic model that uses statistical analysis to more accurately model what occurs during a given time step. The HYBRID2 code can model systems with time series input data ranging from 5 minutes to 2 hours. The original version of the model, HYBRID1, is described in Manwell, et al. [7]. Briefly, HYBRID2 was designed to provide a consistent platform for comparing a variety of wind/diesel hybrid power systems, a means of performance estimation for feasibility studies, a baseline for comparison with other models, and insight into control system options.

The types of systems that can be modeled include those with (1) up to seven different types of diesel generators, (2) up to 60 wind turbines of different types, (3) storage batteries, (4) four types of power conversion, (5) dump load, (6) solar photovoltaics. The model uses a statistical approach to account for the effect of short term fluctuations in wind power and load, and to consider the power smoothing effect of multiple wind turbines. The spacing between turbines in a multi-turbine system is also considered. Many different control strategies and options are included that allow for minimum diesel operating power levels, diesel "back drive" using the diesel as a limited dump load, minimum diesel run time, as well as other specialized control and dispatching options. Outputs include, where applicable, useful wind and solar energy, diesel energy, diesel operating hours and start/stops, diesel fuel use, storage system energy losses, and battery life. A very detailed economic analysis is also available that considers new or retrofit systems, operation and maintenance costs, equipment overhaul costs, installation costs, taxes, and system salvage value [8]. Economic module outputs include, but are not limited to, life-cycle costing, project cash flow, and investment payback. The verification of the HYBRID2 code is ongoing, but very positive. Comparisons are being made to a number of operational hybrid power systems as well as to independent testing. The HYBRID2 code is also heavily based on its predecessor, HYBRID1, which has been validated [9]. HYBRID2 instructions are available in Manwell, et al [10].

5.0 ENERGY COST ANALYSIS

5.1 Methodology

After estimating 1995 operating costs for the four cases of the hybrid system and for the baseline diesel-only system, the resulting levelized costs of energy (COE) were compared. Also, payback periods were computed for the four cases of hybrid system investment. COE is derived using

$$COE = NPV * CRFI / AEP,$$

where NPV is the total net present value of all system costs, CRFI is the capital recovery factor for system income, and AEP is annual energy production (system load). A simple payback period is calculated by dividing the total initial capital cost by the annual savings from system operation, which includes the difference in fuel, overhaul, and operations and maintenance (O&M) costs between the hybrid and baseline systems [6].

Economic assumptions included 3% general inflation, 4% fuel inflation, 6.9% discount rate, 20 year system life, and 100% down payment on new investment. These values have been confirmed by NFESC personnel as reasonable. Although new wind turbines will start with a 20 year life, the existing diesel systems have been in service for several years and have limited lives of their own. This is covered by a fund for major diesel overhauls. It was further assumed that no additional labor would be required to operate the hybrid plant beyond that already assigned to operate the existing diesel power plant.

5.2 Existing System Costs

Since the baseline system is already in place, it has no initial costs. Its main operating costs are $1.14/gal for fuel, $250,000 per year for the diesel overhaul fund, and about $0.14 / kWh for O&M, based on the Navy-provided actual cost items listed in Table 5. These costs are treated in two separate categories. Fixed costs are annual costs that are independent from the amount of diesel usage. Variable costs scale up or down with the amount of diesel energy produced in the year. Fuel costs $0.3012 per liter ($1.14 / gal). The SNI Public Works Center schedules major overhauls and covers these in the Navy budget by setting aside a fixed $250,000 each year, regardless of diesel usage.

Table 5: Diesel Operations and Maintenance Costs

Item	Cost	Type	Totals
Fixed O&M Costs:			
Operations (labor)	$298,043	Fixed	
Maintenance	166,909	Fixed	464,952
Variable O&M Costs:			
Maintenance	166,909	Variable	
Barge cleaning	250,000	Variable	
O&M materials	75,000	Variable	491,909
O&M Rate	$0.1417/kWh	Total:	$956,861

5.3 Hybrid System Costs

Hybrid system costs include the baseline costs as given above, plus new costs associated with the wind turbines and interconnect and control equipment. The interconnect and control equipment are included with the wind turbine balance of station (BOS) costs, along with foundations, installation, spare parts inventory, site surveying and preparation, O&M facilities and equipment, permits and licenses, project management and engineering, and construction insurance and contingency. BOS costs are detailed in Table 6. (Note: It may be possible to further reduce installation and operation costs by adding Department of Defense excess heavy equipment (e.g., a crane) to SNI inventory.)

Each sample wind turbine costs $250,000. An additional $87,500 is required to cover BOS costs. Thus, the total capital cost required for four wind turbines is $1.35 M. Overhaul costs are fixed at an annual $1000 per wind turbine, regardless of turbine usage. Actual wind turbine O&M costs of $0.01/kWh are doubled to $0.02/kWh to account for the small system size and the extra burden SNI represents with its remote setting. As implied by its units, this O&M cost is variable, or fully dependent on wind turbine usage. These amounts are based on working systems using the sample 225 kW wind turbine.

Table 6: Balance of Station for Four 225 kW Wind Turbines

Item	Estimate (Source)	Additional SNI Cost	1995 Cost
Electrical Collection System	34,000 (NREL [6])		$34,000
Control & Monitoring Equipment	12,000 (NREL)	10,000	22,000
Foundations	30,000 (NREL)	6,000	36,000
Installation	20,000 (NREL)	4,000	24,000
Spare Parts	1 % turbine (NREL)		13,500
Site Survey & Preparation	9,000 (NREL)	2,500	11,500
Permits & Licenses	10,000 (SNI add on)		10,000
Environmental Assessment	10,000 (SNI add on)		10,000
Project Management & Engr.	9 % (3-15% NREL, mfg.)		121,500
Construction Ins & Contingency	5 % (3-10% NREL, govt.)		67,500
Total			$350,000

5.4 Hybrid System Spreadsheet Model Savings

Once all of the engineering and cost data were ready, an economic assessment was performed. Figure 15 shows the resulting COE decreasing as the number of wind turbines increases. The trend has leveled off with four turbines, and it will probably reverse and start to increase, as each additional wind turbine would be less efficiently utilized because of the growing wind energy penetration combined with a lack of system storage. For this same reason, Figures 16 and 17 show the payback period growing and the internal rate of return declining after similar values for one and two wind turbines. The complete economic tables can be found in Appendix A. These results are provided for those who need data points to check their own simulations. Copies of the spreadsheets used here can be obtained from the authors.

The $1.35 M capital investment in the four-turbine-hybrid system was easily offset by savings in fuel, overhaul, and O&M costs for diesel operation of $194,000 annually, giving a 6.97 year simple payback period with 13.1% internal rate of return and dropping the COE from $0.358/kWh to $0.338/kWh. This would give net savings of $0.020/kWh, or $135,000 in 1995. Two 225 kW wind turbines have annual operating savings of $128,000, and would give a 5.29 year payback period, 18.2% internal rate of return, and $0.342/kWh COE, with net savings of $0.016/kWh, or $108,000 in 1995.

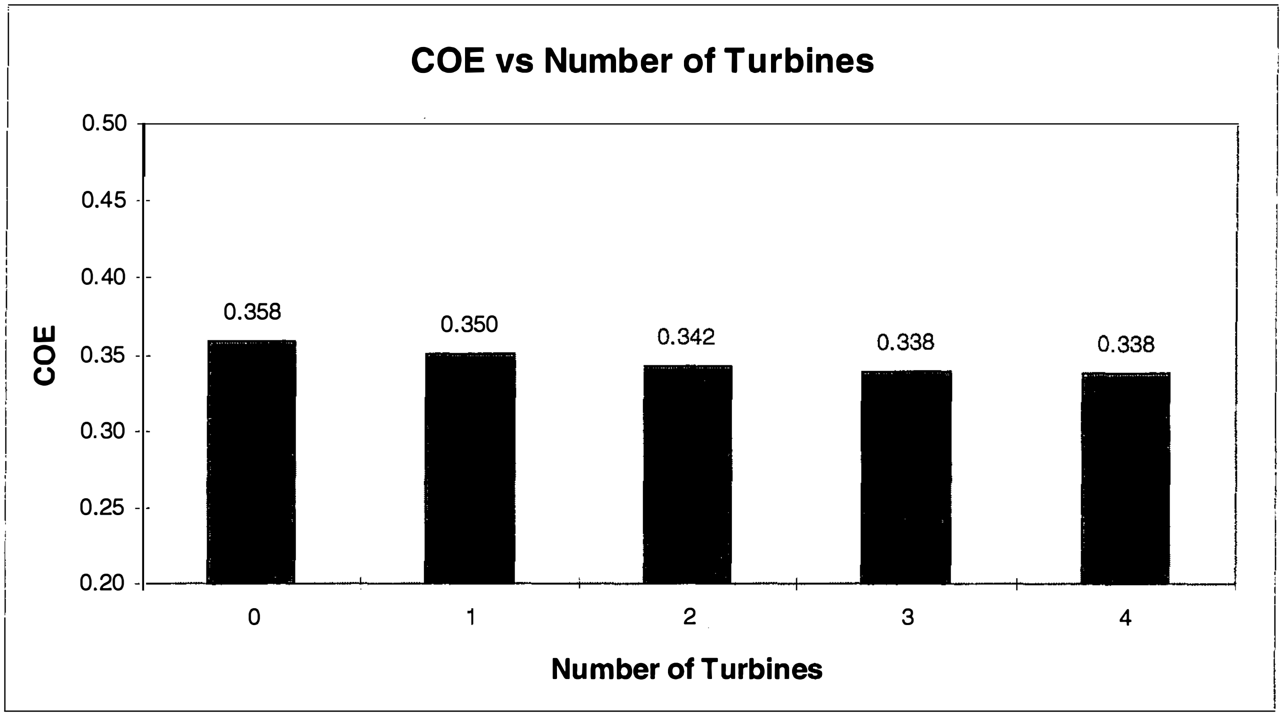


Figure 15: COE vs. Number of Wind Turbines

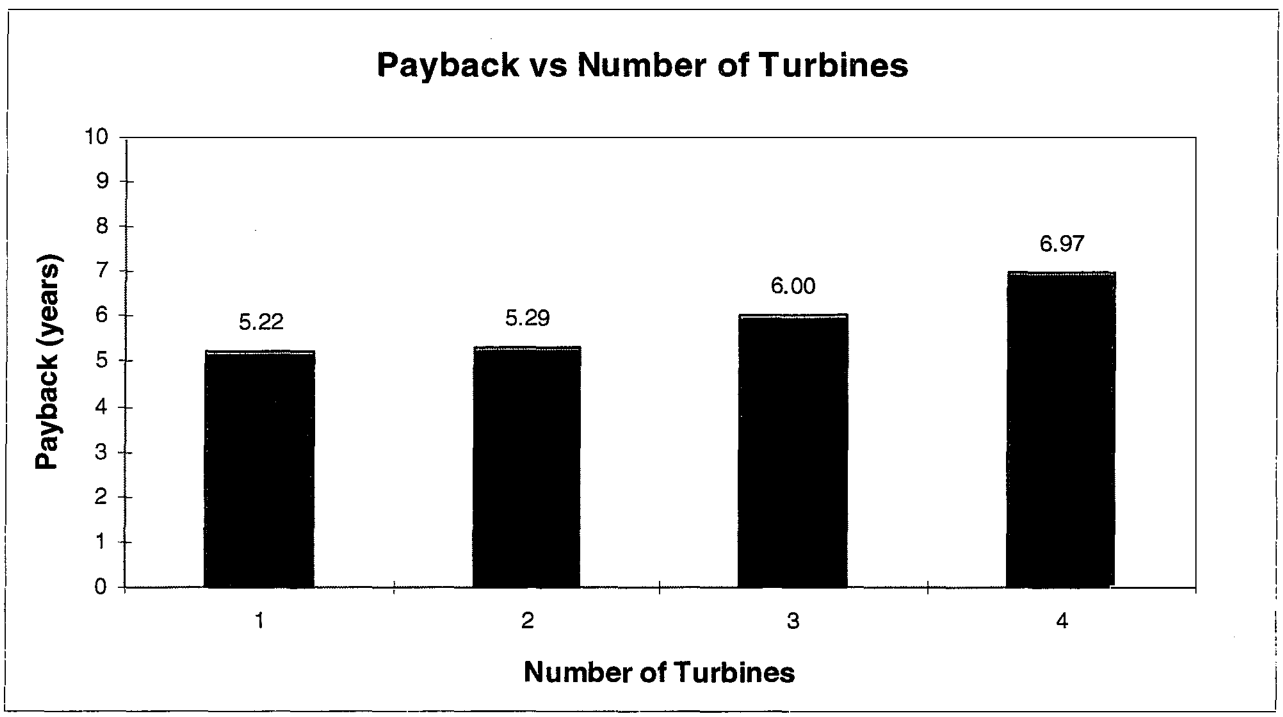


Figure 16: Payback Period vs. Number of Wind Turbines

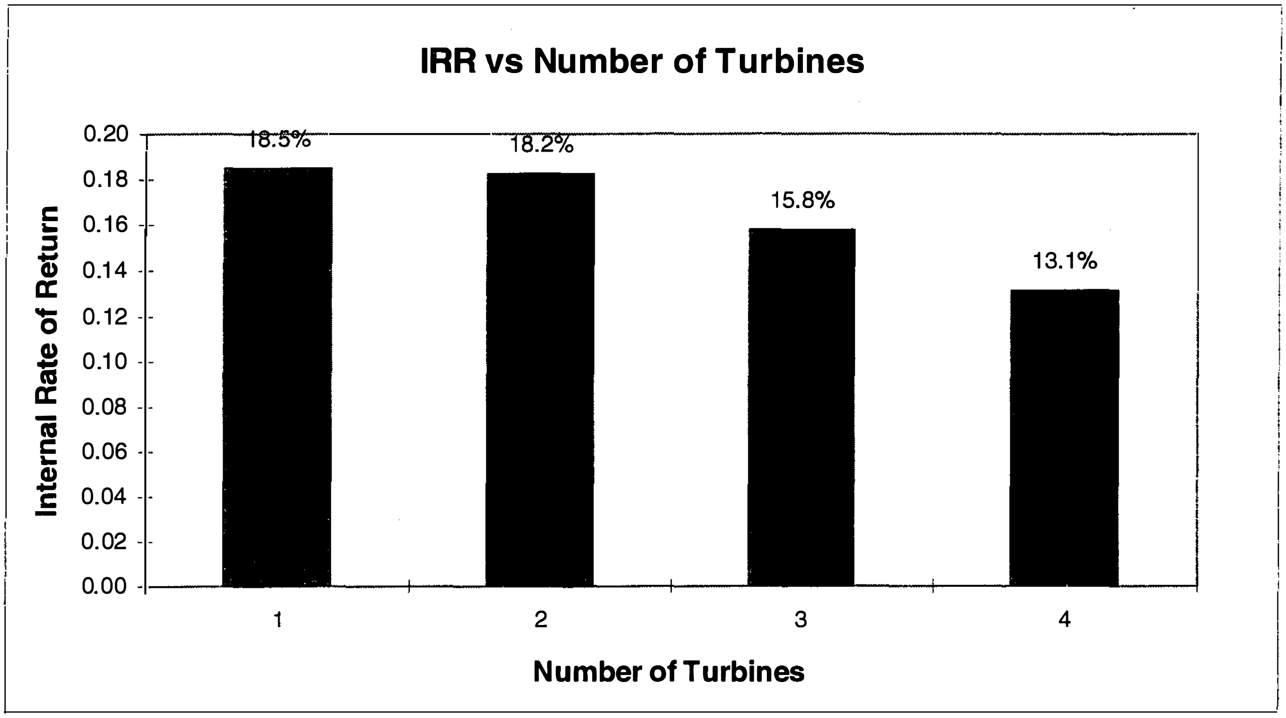


Figure 17: Internal Rate of Return vs. Number of Wind Turbines

5.5 Wind Speed Sensitivity

To check the sensitivity of the results to variations in average wind speed from year to year, the two-turbine case was run with the wind speeds adjusted upward and downward by 10%, which is the interannual variability found in the historical wind measurements. The results are shown in Table 7. With the wind speed 10% lower than the NREL measurement year, COE and payback period rose by 1% and 17%. With the wind speed 10% higher, COE and payback period dropped by 1% and 11%.

Table 7: Economic Sensitivity to Wind Speed Variations
Spreadsheet Model for 2 Turbines

Case	Wind Speed	Diesel Saving (kltr)	Cost of Energy ($/kWh)	Payback Period (years)	Internal Rate of Return (%)
minus 10%	6.5 m/s	195	0.346	6.2	15.2
baseline	7.2 m/s	227	0.342	5.3	18.2
plus 10%	7.9 m/s	256	0.339	4.7	20.9

5.6 HYBRID2 Model Savings

Results from the HYBRID2 model generally are consistent with the spreadsheet model used for this study. With two 225 kW turbines, HYBRID2 gives a simple payback period of 4.43 years; with four 225 kW turbines, the payback is 7.21 years. The shorter payback time with two turbines (4.43 instead of 5.29 in the spreadsheet model) likely results from using automatic operation of the diesel generation system in HYBRID2, whereas the spreadsheet model simulates manual operation. Indeed, the HYBRID2 model results in 394 diesel starts; the spreadsheet model 100 starts, which is slightly below the 127 starts reported in the actual 1989/90 SNI Navy data. The longer payback time with four turbines (7.21 instead of 6.97 in the spreadsheet model) is likely caused by HYBRID2's lack of a provision for curtailing excess wind energy, which increases the O&M costs attributed to wind turbine operation. Complete Hybrid2 model spreadsheet results are available on request from the authors, and can be obtained through NREL.

6.0 CONCLUSIONS

SNI has an excellent wind resource, with an annual average wind speed of 7.2 m/s (14.0 knots) as measured by NREL at 30.5 m (100 ft) at Facility No. 186 in the August 1994 - July 1995 data collection period. Recognizing this, a hybrid energy system was modeled to examine the merits of supplementing the existing diesel generators with a modest portion of wind energy generation. Using conservative assumptions (unfavorable to wind energy) at every step in the spreadsheet model, the hybrid system displayed favorable operation and economics. The levelized COE for the hybrid case using four 225 kW wind turbines is $0.338/kWh vs. $0.358/kWh for the baseline case. This would create a COE savings of 5.6%. The payback period is 6.97 years, the internal rate of return 13.1%. The two turbine case had a COE of $0.342/kWh, saving 4.5%, with a payback period of 5.29 years, and an internal rate of return of 18.2%. The COE for this case is relatively insensitive to annual average wind speed, varying 1% for a 10% change in wind speed. But the payback period is quite sensitive to wind speed, varying 11% to 17% for a 10% change in wind speed.

This work presented a preliminary study of a hybrid system using between 1 and 4 wind turbines. For the conditions examined here, it appears wind energy will be cost effective in this application. We believe these conditions are realistic. But certainly many alternatives to these cases merit consideration. For instance, it appears that the wind penetration could be increased, thus producing further, yet diminishing, savings. If greater redundancy is required, larger numbers of smaller turbines could be used. Smaller wind turbines would have similar relative performance as those machines examined here, with slightly higher per-energy costs and a somewhat limited selection.

Moreover, excess electrical energy should not be curtailed or wasted on dump loads; rather, it should be used for beneficial purposes, provided those purposes make economic sense. Within the San Nicolas Island electrical grid, such benefits may be realized by using excess wind energy for deferrable loads such as the SNI reverse osmosis water system, water heating, or space heating.

Different economic assumptions, such as higher and lower inflation, do not appear to have much impact on the results, but they also should be examined. Because cost and savings components are well distributed, there does not appear to be a dominant factor affecting the economic results. Factors that could affect the results include the actual capital and installation costs of the wind equipment, diesel fuel costs, and diesel system O&M and overhaul costs.

As a preliminary review, this study used 1 hour average wind and load data for the hybrid system modeling, which can give only a general sense of economic tradeoffs. Before making any final decisions about a wind-diesel hybrid electrical generation system, a more detailed analysis is recommended. Dynamic load management should be addressed using load and wind data at shorter intervals (2 minute or less) to grasp a more realistic picture of load and wind dynamics. 2 minute wind resource data is available from the NREL 1994-1995 measurements. However, 2 minute load data would need to be obtained.

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APPENDIX A: Hybrid Model and Economic Summary Tables

SAN NICOLAS ISLAND HYBRID SYSTEM MODEL

Maximum number of wind turbines: 1

Date	Time (hr)	Demand (kW)	Diesel Rating (kW)	Percent of Rating Used	Litres of Diesel Consumed	starts counter	Diesel run time (hours)	Wind Speed (m/s)	Single Turbine Wind Power (kW)	Maximum Allowed Wind Demand (kW)	Number of Turbines	Net Demand (kW)	Percent of Rating Used	Litres of Diesel Consumed	litres saved
		diesel only						wind hybrid							
Average		770.9	1188.1	65%	227.9			7.2	67.2	570.9	0.8	703.8	0.6	214.8	13.1
Standard Deviation		141.5	116.8	10%	32.0			4.8	73.7	141.5	0.4	164.2	0.1	35.8	14.4
Maximum		1232.5	1250.0	99%	322.1			27.7	203.0	1032.5	1.0	1232.5	1.0	322.1	39.6
Minimum		0.0	750.0	0%	48.8			0.1	0.0	-200.0	0.0	0.0	0.0	48.8	0.0
Total		6753132			1996559	100	15491		588626	5001132		6165512		1881789	114770

587620 Wind Energy Used
588626 Wind Energy Available
1006 Wind Energy Curtailed

Maximum number of wind turbines: 2

Date	Time (hr)	Demand (kW)	Diesel Rating (kW)	Percent of Rating Used	Litres of Diesel Consumed	starts counter	Diesel run time (hours)	Wind Speed (m/s)	Single Turbine Wind Power (kW)	Maximum Allowed Wind Demand (kW)	Number of Turbines	Net Demand (kW)	Percent of Rating Used	Litres of Diesel Consumed	litres saved
		diesel only						wind hybrid							
Average		770.9	1188.1	65%	227.9			7.2	67.2	570.9	1.6	638.5	0.5	202.1	25.9
Standard Deviation		141.5	116.8	10%	32.0			4.8	73.7	141.5	0.8	208.2	0.2	43.5	28.4
Maximum		1232.5	1250.0	99%	322.1			27.7	203.0	1032.5	2.0	1232.5	1.0	322.1	79.3
Minimum		0.0	750.0	0%	48.8			0.1	0.0	-200.0	0.0	0.0	0.0	48.8	0.0
Total		6753132			1996559	100	15491		588626	5001132		5593287		1770027	226532

1159845 Wind Energy Used
1177[illegible] Wind Energy Available
17408 Wind Energy Curtailed

Maximum number of wind turbines: 3

Date	Time (hr)	Demand (kW)	Diesel Rating (kW)	Percent of Rating Used	Litres of Diesel Consumed	starts counter	Diesel run time (hours)	Wind Speed (m/s)	Single Turbine Wind Power (kW)	Maximum Allowed Wind Demand (kW)	Number of Turbines	Net Demand (kW)	Percent of Rating Used	Litres of Diesel Consumed	litres saved
		diesel only						wind hybrid							
Average		770.9	1188.1	65%	227.9			7.2	67.2	570.9	2.2	595.4	0.5	193.6	34.3
Standard Deviation		141.5	116.8	10%	32.0			4.8	73.7	141.5	1.2	231.9	0.2	47.6	36.5
Maximum		1232.5	1250.0	99%	322.1			27.7	203.0	1032.5	3.0	1232.5	1.0	322.1	118.9
Minimum		0.0	750.0	0%	48.8			0.1	0.0	-200.0	0.0	0.0	0.0	48.8	0.0
Total		6753132			1996559	100	15491		588626	5001132		5215503		1696241	300318

1537629 Wind Energy Used
1765878 Wind Energy Available
228250 Wind Energy Curtailed

Maximum number of wind turbines: 4

Date	Time (hr)	Demand (kW)	Diesel Rating (kW)	Percent of Rating Used	Litres of Diesel Consumed	starts counter	Diesel run time (hours)	Wind Speed (m/s)	Single Turbine Wind Power (kW)	Maximum Allowed Wind Demand (kW)	Number of Turbines	Net Demand (kW)	Percent of Rating Used	Litres of Diesel Consumed	litres saved
		diesel only						wind hybrid							
Average		770.9	1188.1	65%	227.9			7.2	67.2	570.9	2.8	568.8	0.5	188.5	39.5
Standard Deviation		141.5	116.8	10%	32			4.8	73.7	141.5	1.6	243.4	0.2	49.6	40.5
Maximum		1232.5	1250	99%	322.1			27.7	203	1032.5	4	1232.5	1	322.1	158.6
Minimum		0	750	0%	48.8			0.1	0	-200	0	0	0	48.8	0
Total		6753132			1996559	100	15491		588626	5001132		4983013		1650833	345726

1770119 Wind Energy Used
2354505 Wind Energy Available
584386 Wind Energy Curtailed

ECONOMIC ANALYSIS

Site: San Nicolas Island, CA
Turbine: 225 kW, Commercial
Quantity: 1

Input Values

System load, (kWh/y)	SL	6,753,132
Diesel energy (kWh/y)		6,165,512
Wind energy (kWh/y)		587,620
Diesel fuel usage, no wind (l/yr)	FL	1,996,559
Diesel fuel usage, with wind (l/yr)	FL	1,881,789
Diesel fuel cost, ($/l)	FC	0.3012
System life, (yrs)	L	20
General inflation	i	3.0%
Fuel inflation	e	4.0%
Discount rate	d	6.9%
Interest	b	10.0%
Term of loan, (yrs)	N	10

Economic Factors

	a variable	n variable	Y(a,n)
Present worth factor of fuel costs, PWFF, a=(1+e)/(1+d)	0.97287184	20	15.17266
Present worth factor of O&M costs, PWFO, a=(1+i)/(1+d)	0.96351731	20	13.85103
Present worth factor of interest payments, PWFP, a=1/(1+b)	0.9354537	10	7.05616

	a variable	n variable	X(a,n)
Capital recovery factor for system income, CRFI, a=1/(1+d)	0.9354537	20	0.09366054
Capital recovery factor for interest payments, CRFP, a=1/(1+b)	0.90909091	10	0.16274539

Calculated Values for Both Systems

		Diesel Only	Hybrid System Diesel Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	337,500	337,500
Initial payment on system	Ad	0	0	337,500	337,500
Loan	Al = C - Ad	0	0	0	0
Annual payment	Ap = Al * CRFP	0	0	0	0
NPV of annual payment	Apnpv = Ap*PWFP	0	0	0	0
Fuel cost per annum	Af = FL * FC	601,364	566,795	0	566,795
NPV of fuel costs	Afnpv = Af * PWFF	9,124,287	8,599,787	0	8,599,787
Overhaul cost per annum	Ao	250,000	250,000	1,000	251,000
NPV of overhaul costs	Aonpv = Ao * PWFO	3,462,757	3,462,757	13,851	3,476,608
O&M costs per annum	Am	956,861	914,058	11,752	925,810
NPV of O&M costs	Amnpv = Am*PWFO	13,253,507	12,660,639	162,783	12,823,422
Total annual costs	At = Ap+Af+Ao+Am	1,808,225	1,730,853	12,752	1,743,605
Total system NPV, TNPV	= Ad+sum(NPVs)	25,840,551	24,723,183	514,134	25,237,317
Annual savings	Sv = dsl At - hbd At				64,619
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.358	0.376	0.082	0.350
Payback period, years					5.22
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P =		0.000		18.5%

(NPV = net present value; ICC = initial capitol cost; BOS = balance of station = 26% ICC; O&M = operations and maintenance)

Sniecon1, 7/3/96

ECONOMIC ANALYSIS

Site: San Nicolas Island, CA, 7.2 m/s avg
Turbine: 225 kW, Commercial
Quantity: 2

Input Values

System load, (kWh/y)	SL	6,753,132
Diesel energy (kWh/y)		5,593,287
Wind energy (kWh/y)		1,159,845
Diesel fuel usage, no wind (l/yr)	FL	1,996,559
Diesel fuel usage, with wind (l/yr)	FL	1,770,027
Diesel fuel cost, ($/l)	FC	0.3012
System life, (yrs)	L	20
General inflation	i	3.0%
Fuel inflation	e	4.0%
Discount rate	d	6.9%
Interest	b	10.0%
Term of loan, (yrs)	N	10

Economic Factors

	a variable	n variable	Y(a,n)
Present worth factor of fuel costs, PWFF, a=(1+e)/(1+d)	0.97287184	20	15.17266
Present worth factor of O&M costs, PWFO, a=(1+i)/(1+d)	0.96351731	20	13.85103
Present worth factor of interest payments, PWFP, a=1/(1+b)	0.9354537	10	7.05616

	a variable	n variable	X(a,n)
Capital recovery factor for system income, CRFI, a=1/(1+d)	0.9354537	20	0.09366054
Capital recovery factor for interest payments, CRFP, a=1/(1+b)	0.90909091	10	0.16274539

Calculated Values for Both Systems

		Diesel Only	Hybrid System Diesel Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	675,000	675,000
Initial payment on system	Ad	0	0	675,000	675,000
Loan	Al = C - Ad	0	0	0	0
Annual payment	Ap = Al * CRFP	0	0	0	0
NPV of annual payment	Apnpv = Ap*PWFP	0	0	0	0
Fuel cost per annum	Af = FL * FC	601,364	533,132	0	533,132
NPV of fuel costs	Afnpv = Af * PWFF	9,124,287	8,089,034	0	8,089,034
Overhaul cost per annum	Ao	250,000	250,000	2,000	252,000
NPV of overhaul costs	Aonpv = Ao * PWFO	3,462,757	3,462,757	27,702	3,490,459
O&M costs per annum	Am	956,861	872,376	23,197	895,573
NPV of O&M costs	Amnpv = Am*PWFO	13,253,507	12,083,304	321,301	12,404,605
Total annual costs	At = Ap+Af+Ao+Am	1,808,225	1,655,508	25,197	1,680,705
Total system NPV, TNPV	= Ad+sum(NPVs)	25,840,551	23,635,094	1,024,003	24,659,097
Annual savings	Sv = dsl At - hbd At				127,519
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.358	0.396	0.083	0.342
Payback period, years					5.29
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P =		0.000		18.2%

(NPV = net present value; ICC = initial capitol cost; BOS = balance of station = 26% ICC; O&M = operations and maintenance)

Sniecon1, 7/3/96

ECONOMIC ANALYSIS

Site: San Nicolas Island, CA
Turbine: 225 kW, Commercial
Quantity: 3

Input Values

System load, (kWh/y)	SL	6,753,132
Diesel energy (kWh/y)		5,215,503
Wind energy (kWh/y)		1,537,629
Diesel fuel usage, no wind (l/yr)	FL	1,996,559
Diesel fuel usage, with wind (l/yr)	FL	1,696,241
Diesel fuel cost, ($/l)	FC	0.3012
System life, (yrs)	L	20
General inflation	i	3.0%
Fuel inflation	e	4.0%
Discount rate	d	6.9%
Interest	b	10.0%
Term of loan, (yrs)	N	10

Economic Factors

	a variable	n variable	Y(a,n)
Present worth factor of fuel costs, PWFF, a=(1+e)/(1+d)	0.97287184	20	15.17266
Present worth factor of O&M costs, PWFO, a=(1+i)/(1+d)	0.96351731	20	13.85103
Present worth factor of interest payments, PWFP, a=1/(1+b)	0.9354537	10	7.05616

	a variable	n variable	X(a,n)
Capital recovery factor for system income, CRFI, a=1/(1+d)	0.9354537	20	0.09366054
Capital recovery factor for interest payments, CRFP, a=1/(1+b)	0.90909091	10	0.16274539

Calculated Values for Both Systems

		Diesel Only	Hybrid System Diesel Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	1,012,500	1,012,500
Initial payment on system	Ad	0	0	1,012,500	1,012,500
Loan	Al = C - Ad	0	0	0	0
Annual payment	Ap = Al * CRFP	0	0	0	0
NPV of annual payment	Apnpv = Ap*PWFP	0	0	0	0
Fuel cost per annum	Af = FL * FC	601,364	510,908	0	510,908
NPV of fuel costs	Afnpv = Af * PWFF	9,124,287	7,751,832	0	7,751,832
Overhaul cost per annum	Ao	250,000	250,000	3,000	253,000
NPV of overhaul costs	Aonpv = Ao * PWFO	3,462,757	3,462,757	41,553	3,504,310
O&M costs per annum	Am	956,861	844,858	30,753	875,610
NPV of O&M costs	Amnpv = Am*PWFO	13,253,507	11,702,146	425,955	12,128,100
Total annual costs	At = Ap+Af+Ao+Am	1,808,225	1,605,765	33,753	1,639,518
Total system NPV, TNPV	= Ad+sum(NPVs)	25,840,551	22,916,734	1,480,008	24,396,742
Annual savings	Sv = dsl At - hbd At				168,707
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.358	0.412	0.090	0.338
Payback period, years					6.00
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P =		0.000		15.8%

(NPV = net present value; ICC = initial capitol cost; BOS = balance of station = 26% ICC; O&M = operations and maintenance)

Sniecon1, 7/3/96

ECONOMIC ANALYSIS

Site: San Nicolas Island, CA
Turbine: 225 kW, Commercial
Quantity: 4

Input Values

System load, (kWh/y)	SL	6,753,132
Diesel energy (kWh/y)		4,983,013
Wind energy (kWh/y)		1,770,119
Diesel fuel usage, no wind (l/yr)	FL	1,996,559
Diesel fuel usage, with wind (l/yr)	FL	1,650,833
Diesel fuel cost, ($/l)	FC	0.3012
System life, (yrs)	L	20
General inflation	i	3.0%
Fuel inflation	e	4.0%
Discount rate	d	6.9%
Interest	b	10.0%
Term of loan, (yrs)	N	10

Economic Factors

	a variable	n variable	Y(a,n)
Present worth factor of fuel costs, PWFF, a=(1+e)/(1+d)	0.97287	20	15.17266
Present worth factor of O&M costs, PWFO, a=(1+i)/(1+d)	0.96352	20	13.85103
Present worth factor of interest payments, PWFP, a=1/(1+b)	0.93545	10	7.05616

	a variable	n variable	X(a,n)
Capital recovery factor for system income, CRFI, a=1/(1+d)	0.93545	20	0.09366
Capital recovery factor for interest payments, CRFP, a=1/(1+b)	0.90909	10	0.16275

Calculated Values for Both Systems

		Diesel Only	Hybrid System Diesel Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	1,350,000	1,350,000
Initial payment on system	Ad	0	0	1,350,000	1,350,000
Loan	Al = C - Ad	0	0	0	0
Annual payment	Ap = Al * CRFP	0	0	0	0
NPV of annual payment	Apnpv = Ap*PWFP	0	0	0	0
Fuel cost per annum	Af = FL * FC	601,364	497,231	0	497,231
NPV of fuel costs	Afnpv = Af * PWFF	9,124,287	7,544,317	0	7,544,317
Overhaul cost per annum	Ao	250,000	250,000	4,000	254,000
NPV of overhaul costs	Aonpv = Ao * PWFO	3,462,757	3,462,757	55,404	3,518,161
O&M costs per annum	Am	956,861	827,923	35,402	863,325
NPV of O&M costs	Amnpv = Am*PWFO	13,253,507	11,467,579	490,359	11,957,939
Total annual costs	At = Ap+Af+Ao+Am	1,808,225	1,575,154	39,402	1,614,556
Total system NPV, TNPV	= Ad+sum(NPVs)	25,840,551	22,474,653	1,895,763	24,370,416
Annual savings	Sv = dsl At - hbd At				193,669
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.358	0.422	0.100	0.338
Payback period, years	P = C / Sv				6.97
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P = 0.000				13.1%

(NPV = net present value; ICC = initial capitol cost; BOS = balance of station = 26% ICC; O&M = operations and maintenance)

Sniecon1, 7/3/96

SAN NICOLAS ISLAND HYBRID SYSTEM MODEL (SENSITIVITY STUDY)

Maximum number of wind turbines: 2; Average wind speed: 6.5 m/s (10 % low)

		diesel only						wind hybrid							
Date	Time (hr)	Demand (kW)	Diesel Rating (kW)	Percent of Rating Used	Litres of Diesel Consumed	starts counter	Diesel run time (hours)	Wind Speed (m/s)	Single Turbine Wind Power (kW)	Maximum Allowed Wind Demand (kW)	Number of Turbines	Net Demand (kW)	Percent of Rating Used	Litres of Diesel Consumed	litres saved
Average		770.9	1188.1	65%	227.9			6.5	57.7	570.9	1.5	657.2	0.6	205.7	22.2
Standard Deviation		141.5	116.8	10%	32.0			4.3	69.3	141.5	0.9	201.5	0.2	42.3	26.7
Maximum		1232.5	1250.0	99%	322.1			24.9	203.0	1032.5	2.0	1232.5	1.0	322.1	79.3
Minimum		0.0	750.0	0%	48.8			0.1	0.0	-200.0	0.0	0.0	0.0	48.8	0.0
Total		6753132			1996559	100	15491		505328	5001132		5756721		1801947	194612

996411 Wind Energy Used
1010656 Wind Energy Available
14245 Wind Energy Curtailed

Maximum number of wind turbines: 2; Average wind speed: 7.2 m/s (baseline)

		diesel only						wind hybrid							
Date	Time (hr)	Demand (kW)	Diesel Rating (kW)	Percent of Rating Used	Litres of Diesel Consumed	starts counter	Diesel run time (hours)	Wind Speed (m/s)	Single Turbine Wind Power (kW)	Maximum Allowed Wind Demand (kW)	Number of Turbines	Net Demand (kW)	Percent of Rating Used	Litres of Diesel Consumed	litres saved
Average		770.9	1188.1	65%	227.9			7.2	67.2	570.9	1.6	638.5	0.5	202.1	25.9
Standard Deviation		141.5	116.8	10%	32.0			4.8	73.7	141.5	0.8	208.2	0.2	43.5	28.4
Maximum		1232.5	1250.0	99%	322.1			27.7	203.0	1032.5	2.0	1232.5	1.0	322.1	79.3
Minimum		0.0	750.0	0%	48.8			0.1	0.0	-200.0	0.0	0.0	0.0	48.8	0.0
Total		6753132			1996559	100	15491		588626	5001132		5593287		1770027	226532

1159845 Wind Energy Used
1177252 Wind Energy Available
17408 Wind Energy Curtailed

Maximum number of wind turbines: 2; Average wind speed: 7.9 m/s (10 % high)

		diesel only						wind hybrid							
Date	Time (hr)	Demand (kW)	Diesel Rating (kW)	Percent of Rating Used	Litres of Diesel Consumed	starts counter	Diesel run time (hours)	Wind Speed (m/s)	Single Turbine Wind Power (kW)	Maximum Allowed Wind Demand (kW)	Number of Turbines	Net Demand (kW)	Percent of Rating Used	Litres of Diesel Consumed	litres saved
Average		770.9	1188.1	65%	227.9			7.9	75.8	570.9	1.6	621.4	0.5	198.7	29.2
Standard Deviation		141.5	116.8	10%	32.0			5.3	76.7	141.5	0.8	212.8	0.2	44.3	29.6
Maximum		1232.5	1250.0	99%	322.1			30.4	203.0	1032.5	2.0	1227.0	1.0	321.0	79.3
Minimum		0.0	750.0	0%	48.8			0.1	0.0	-200.0	0.0	0.0	0.0	48.8	0.0
Total		6753132			1996559	100	15491		664307	5001132		5443858		1740841	255717

1309274 Wind Energy Used
1328613 Wind Energy Available
19340 Wind Energy Curtailed

ECONOMIC ANALYSIS

Site:	**San Nicolas Island, CA, 6.5 m/s avg**
Turbine:	**225 kW, Commercial**
Quantity:	**2**

Input Values

System load, (kWh/y)	SL	6,753,132
Diesel energy (kWh/y)		5,756,721
Wind energy (kWh/y)		996,411
Diesel fuel usage, no wind (l/yr)	FL	1,996,559
Diesel fuel usage, with wind (l/yr)	FL	1,801,947
Diesel fuel cost, ($/l)	FC	0.3012
System life, (yrs)	L	20
General inflation	i	3.0%
Fuel inflation	e	4.0%
Discount rate	d	6.9%
Interest	b	10.0%
Term of loan, (yrs)	N	10

Economic Factors

	a variable	n variable	Y(a,n)
Present worth factor of fuel costs, PWFF, a=(1+e)/(1+d)	0.97287184	20	15.17266
Present worth factor of O&M costs, PWFO, a=(1+i)/(1+d)	0.96351731	20	13.85103
Present worth factor of interest payments, PWFP, a=1/(1+b)	0.9354537	10	7.05616

	a variable	n variable	X(a,n)
Capital recovery factor for system income, CRFI, a=1/(1+d)	0.9354537	20	0.09366054
Capital recovery factor for interest payments, CRFP, a=1/(1+b)	0.90909091	10	0.16274539

Calculated Values for Both Systems

		Diesel Only	Hybrid System Diesel Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	675,000	675,000
Initial payment on system	Ad	0	0	675,000	675,000
Loan	Al = C - Ad	0	0	0	0
Annual payment	Ap = Al * CRFP	0	0	0	0
NPV of annual payment	Apnpv = Ap*PWFP	0	0	0	0
Fuel cost per annum	Af = FL * FC	601,364	542,746	0	542,746
NPV of fuel costs	Afnpv = Af * PWFF	9,124,287	8,234,909	0	8,234,909
Overhaul cost per annum	Ao	250,000	250,000	2,000	252,000
NPV of overhaul costs	Aonpv = Ao * PWFO	3,462,757	3,462,757	27,702	3,490,459
O&M costs per annum	Am	956,861	884,281	19,928	904,209
NPV of O&M costs	Amnpv = Am*PWFO	13,253,507	12,248,197	276,026	12,524,224
Total annual costs	At = Ap+Af+Ao+Am	1,808,225	1,677,027	21,928	1,698,955
Total system NPV, TNPV	= Ad+sum(NPVs)	25,840,551	23,945,863	978,728	24,924,591
Annual savings	Sv = dsl At - hbd At				109,269
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.358	0.390	0.092	0.346
Payback period, years					6.18
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P =		0.000		15.2%

(NPV = net present value; ICC = initial capitol cost; BOS = balance of station = 26% ICC; O&M = operations and maintenance)

SNIECON1.XLS, 7/2/96

ECONOMIC ANALYSIS — **Site:** San Nicolas Island, CA, 7.2 m/s avg
Turbine: 225 kW, Commercial
Quantity: 2

Input Values

System load, (kWh/y)	SL	6,753,132
Diesel energy (kWh/y)		5,593,287
Wind energy (kWh/y)		1,159,845
Diesel fuel usage, no wind (l/yr)	FL	1,996,559
Diesel fuel usage, with wind (l/yr)	FL	1,770,027
Diesel fuel cost, ($/l)	FC	0.3012
System life, (yrs)	L	20
General inflation	i	3.0%
Fuel inflation	e	4.0%
Discount rate	d	6.9%
Interest	b	10.0%
Term of loan, (yrs)	N	10

Economic Factors

	a variable	n variable	Y(a,n)
Present worth factor of fuel costs, PWFF, a=(1+e)/(1+d)	0.97287184	20	15.17266
Present worth factor of O&M costs, PWFO, a=(1+i)/(1+d)	0.96351731	20	13.85103
Present worth factor of interest payments, PWFP, a=1/(1+b)	0.9354537	10	7.05616

	a variable	n variable	X(a,n)
Capital recovery factor for system income, CRFI, a=1/(1+d)	0.9354537	20	0.09366054
Capital recovery factor for interest payments, CRFP, a=1/(1+b)	0.90909091	10	0.16274539

Calculated Values for Both Systems

		Diesel Only	Hybrid System Diesel Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	675,000	675,000
Initial payment on system	Ad	0	0	675,000	675,000
Loan	Al = C - Ad	0	0	0	0
Annual payment	Ap = Al * CRFP	0	0	0	0
NPV of annual payment	Apnpv = Ap*PWFP	0	0	0	0
Fuel cost per annum	Af = FL * FC	601,364	533,132	0	533,132
NPV of fuel costs	Afnpv = Af * PWFF	9,124,287	8,089,034	0	8,089,034
Overhaul cost per annum	Ao	250,000	250,000	2,000	252,000
NPV of overhaul costs	Aonpv = Ao * PWFO	3,462,757	3,462,757	27,702	3,490,459
O&M costs per annum	Am	956,861	872,376	23,197	895,573
NPV of O&M costs	Amnpv = Am*PWFO	13,253,507	12,083,304	321,301	12,404,605
Total annual costs	At = Ap+Af+Ao+Am	1,808,225	1,655,508	25,197	1,680,705
Total system NPV, TNPV	= Ad+sum(NPVs)	25,840,551	23,635,094	1,024,003	24,659,097
Annual savings	Sv = dsl At - hbd At				127,519
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.358	0.396	0.083	0.342
Payback period, years					5.29
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P =		0.000		18.2%

(NPV = net present value; ICC = initial capitol cost; BOS = balance of station = 26% ICC; O&M = operations and maintenance)

SNIECON1.XLS, 7/2/96

ECONOMIC ANALYSIS

Site:	San Nicolas Island, CA, 7.9 m/s avg
Turbine:	225 kW, Commercial
Quantity:	2

Input Values

System load, (kWh/y)	SL	6,753,132
Diesel energy (kWh/y)		5,443,858
Wind energy (kWh/y)		1,309,274
Diesel fuel usage, no wind (l/yr)	FL	1,996,559
Diesel fuel usage, with wind (l/yr)	FL	1,740,841
Diesel fuel cost, ($/l)	FC	0.3012
System life, (yrs)	L	20
General inflation	i	3.0%
Fuel inflation	e	4.0%
Discount rate	d	6.9%
Interest	b	10.0%
Term of loan, (yrs)	N	10

Economic Factors

	a variable	n variable	Y(a,n)
Present worth factor of fuel costs, PWFF, a=(1+e)/(1+d)	0.97287184	20	15.17266
Present worth factor of O&M costs, PWFO, a=(1+i)/(1+d)	0.96351731	20	13.85103
Present worth factor of interest payments, PWFP, a=1/(1+b)	0.9354537	10	7.05616

	a variable	n variable	X(a,n)
Capital recovery factor for system income, CRFI, a=1/(1+d)	0.9354537	20	0.09366054
Capital recovery factor for interest payments, CRFP, a=1/(1+b)	0.90909091	10	0.16274539

Calculated Values for Both Systems

		Diesel Only	Hybrid System Diesel Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	675,000	675,000
Initial payment on system	Ad	0	0	675,000	675,000
Loan	Al = C - Ad	0	0	0	0
Annual payment	Ap = Al * CRFP	0	0	0	0
NPV of annual payment	Apnpv = Ap*PWFP	0	0	0	0
Fuel cost per annum	Af = FL * FC	601,364	524,341	0	524,341
NPV of fuel costs	Afnpv = Af * PWFF	9,124,287	7,955,654	0	7,955,654
Overhaul cost per annum	Ao	250,000	250,000	2,000	252,000
NPV of overhaul costs	Aonpv = Ao * PWFO	3,462,757	3,462,757	27,702	3,490,459
O&M costs per annum	Am	956,861	861,491	26,185	887,677
NPV of O&M costs	Amnpv = Am*PWFO	13,253,507	11,932,540	362,696	12,295,236
Total annual costs	At = Ap+Af+Ao+Am	1,808,225	1,635,833	28,185	1,664,018
Total system NPV, TNPV	= Ad+sum(NPVs)	25,840,551	23,350,951	1,065,398	24,416,349
Annual savings	Sv = dsl At - hbd At				144,206
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.358	0.402	0.076	0.339
Payback period, years					4.68
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P =		0.000		20.9%

(NPV = net present value; ICC = initial capitol cost; BOS = balance of station = 26% ICC; O&M = operations and maintenance)

SNIECON1.XLS, 7/2/96

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1.

2. REPORT DATE
July 1996

3. REPORT TYPE AND DATES COVERED
Subcontract Report

4. TITLE AND SUBTITLE

Hybrid Energy System Cost Analysis: San Nicolas Island, California

5. FUNDING NUMBERS

C: CAK-6-15387-01

TA: WF234401

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

TP-440-21120

DE96007949

11. SUPPLEMENTARY NOTES

NREL Technical Monitor: Ed McKenna

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

UC-1213

13. ABSTRACT *(Maximum 200 words)*

San Nicolas Island has an excellent wind resource, with an annual average wind speed of 7.2 m/s (14.0) knots) as measured by the National Renewable Energy Laboratory (NREL) at 30.5 m (100 ft) at Facility No. 186 in the August 1994 - July 1995 data collection period. Recognizing this, a hybrid energy system was modeled to examine the merits of supplementing the existing diesel generators with a modest portion of wind energy generation. Using conservative assumptions (unfavorable to wind energy) at every step in the spreadsheet model, the hybrid system displayed favorable operation and economics. The levelized cost of energy (COE) for the hybrid case using four 225 kW wind turbines is $0.338/kWh vs. $0.358/kWh for the baseline case. This would create a COE savings of 5.6%. The payback period is 6.97 years, the internal rate of return 13.1%. The two-turbine case had a COE of $0.342/kWh, saving 4.5%, with a payback period of 5.29 years, and an internal rate of return of 18.2%. The COE for this case is relatively insensitive to annual average wind speed, varying 1% for a 10% change in wind speed. But the payback period is quite sensitive to wind speed, varying 11% to 17% for a 10% change in wind speed.

14. SUBJECT TERMS

wind energy; hybrid energy systems

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

UL