Wind Resource Assessment and Wind Energy System Cost Analysis: Fort Huachuca, Arizona

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EXECUTIVE SUMMARY

This report presents the results of meteorological testing at three different sites on Fort Huachuca, followed by an economic assessment of a small wind energy project at the best site.

Fort Huachuca has a marginal wind resource, with annual average wind speeds of 3.9 to 5.1 m/s (8.7 to 11.5 mph) as measured by the Fort Huachuca meteorological team at 13.7 m (45 ft) height at three collection sites on the base between 1 July 1995 and 30 June 1996. Somewhat helpful, though, are strong positive vertical wind shears, which could scale wind speeds up to 7.0 m/s (15.7 mph) at a wind turbine hub height of 36 m (118 ft) with 0.35 scaling coefficient.

A wind energy system was evaluated to examine the merits of supplementing grid energy with eight 225 kW wind turbines. Using conservative assumptions (unfavorable to wind energy) throughout the analysis, the wind energy system displayed marginal economics. The levelized cost of energy for the wind and grid energy case using eight 225 kW wind turbines is $0.100 / kWh, nearly unchanged from the baseline case without wind ($0.101 / kWh). The payback period is 14.3 years, the internal rate of return 5.7%.

More substantial benefits of wind energy would require a site with stronger winds or lower equipment prices, perhaps from the used-turbine market. Tall towers may present another means of gaining favorable wind economics, provided the high wind shears can be verified at higher measurement levels.

1.0 INTRODUCTION

This report analyzes the local wind resource and evaluates the costs and benefits of supplementing the current purchased grid energy at Fort Huachuca, Arizona with wind turbines. In Section 2.0 the Fort Huachuca site, operations, and current energy system are described, as are the data collection and analysis procedures. Section 3.0 summarizes the measured wind resource data and analyses. Section 4.0 presents the conceptual design and cost analysis of a wind energy system at Fort Huachuca, with conclusions following in Section 5.0. Appendix A presents summary sheets from the economics spreadsheet model.

2.0 BACKGROUND

2.1 Fort Huachuca

Fort Huachuca is a United States Army fort with a variety of divisions and functions, the foremost being the US Army Intelligence Center and School. It also includes the US Army Signal Command, the US Army Eleventh Signal Brigade, the US Army Electronic Proving Ground, the Department of Defense Joint Interoperability Test Command, Arizona Army National Guard, Army Reserve, the Missouri Air Guard, and an air field shared by the Sierra Vista airport and A10's and fighter jets from Davis Monthan Air Force Base in Tucson. As shown in Figure 1, the fort is located in southeast Arizona, approximately sixty miles southeast of Tucson. Fort Huachuca is situated just east of the Huachuca Mountains, at latitude 31.4N, longitude110.2W and elevation 1423 m (4667 ft). The base is approximately 15 miles east to west, 11 miles north to south, minus a southeast corner, and encompasses an area of 114 square miles of land owned by the US Army.

The base, with scattered trees, slopes down gently to the northeast in the developed eastern portion, with rugged mountains to the west. With 2100 to 2300 m (7000 to 7500 ft) ridgelines and a peak at 2560 m (8400 ft), the Huachuca mountains may have significant weather interaction with the 1300 m (4300 ft) valley floor. Some Fort Huachuca personnel expect daily heating and cooling drainage wind flows to amplify in several of the large canyons. An aerial photograph of the base is shown in Figure 2.

In general, daily maximum temperatures vary from 4 to 38 C (40 to 100 F), and daily minimum temperatures vary from -9 to 24 C (15 to 75 F). The coolest months are December and January, and the warmest months are June and July. The lowest temperature recorded at Fort Huachuca between 1961 and 1990 is -13 C (9 F), the highest 40 C (104 F). Precipitation averages 0.38 m (14.8 in) per year; snowfall averages 0.22 m (8.7 in) per year. Most of the rain falls from July through September. The relative humidity ranges from 7% to 97%, with an average of 28%.

Winds at Fort Huachuca primarily blow from the West and are stronger in spring. Average wind speeds vary from 3.9 to 5.1 m/s (8.7 to 11.5 mph) at 13.7 m (45 ft) height, and seasonal variation is small. The windiest months, March through May, have wind speeds averaging 5 to 6 m/s. The least windy months, July through December, have wind speeds averaging 3 to 4 m/s.

Fort Huachuca is a complete community which houses 8700 people and has a working population of 15,800. The base includes a 30 bed hospital, library, schools for 1680 students, golf course, airfield with 3660 m (12,000 ft) runway, several government and private businesses and an assortment of military facilities for electronic warfare training, testing, and general operations. A map of the base including measurement sites appears in Figure 3.
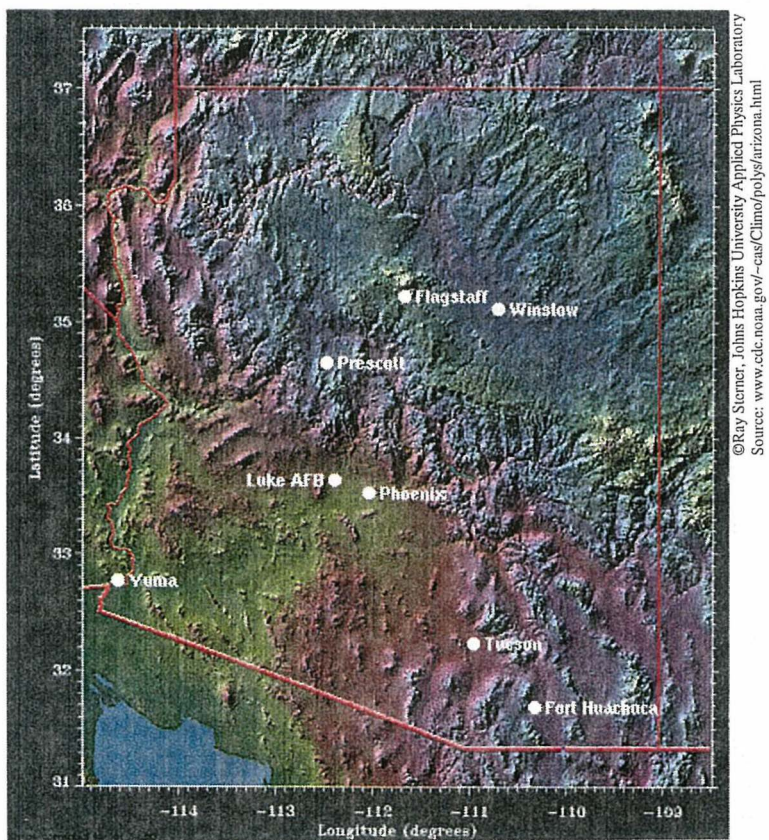
Figure 1: Fort Huachuca Location Map

Figure 2: Aerial View of Fort Huachuca

▲ DCP 16   TV Hill 7003 ft elev.

● DCP 13   Bore Site/Scotts Peak
            5932 ft elev.

▪ DCP 2/18 West Gate 5020 ft elev.

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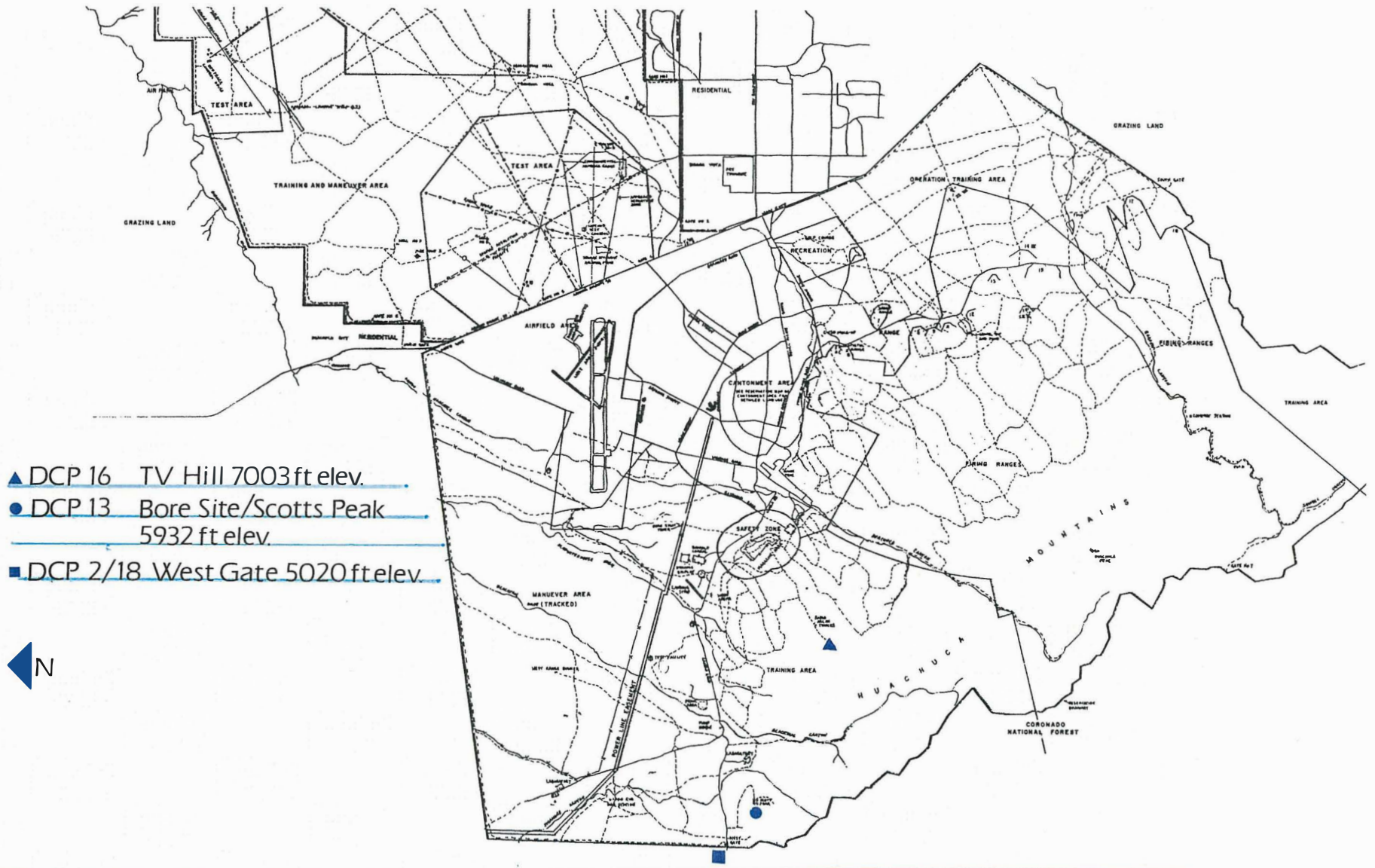
Figure 3: Fort Huachuca Measurement Sites

2.2 Existing Energy System and Demand

Fort Huachuca consumes approximately 9 million kWh per month at a cost near $ 0.07 / kWh for a monthly bill of $630,000. Electric power at Fort Huachuca is supplied by Tucson Electric Power (TEP) through their grid. Figures 4 through 7 show the monthly energy consumption, peak demand, cost of energy (based on TEP charges), and power factor. The annual demand cycle peaks in summer time as expected in a hot climate. Cost of energy rose significantly in the late eighties, but nearly leveled off in the nineties. Power factor improvements give some reduction in energy costs.

The Fort Huachuca Energy Manager has been conducting ongoing base resource use improvements, both for energy and water. The energy improvements include a variety of efficiency measures and supplemental and experimental renewable energy systems: solar water heating, solar photovoltaics, and solar thermal Stirling engine electricity generation. A 30 kW photovoltaic array and inverter bank are operating on the thrift shop near the main gate. The solar thermal system consists of an array of mirrors focused on a 11 kW Stirling engine. Currently, wind generation is under study.
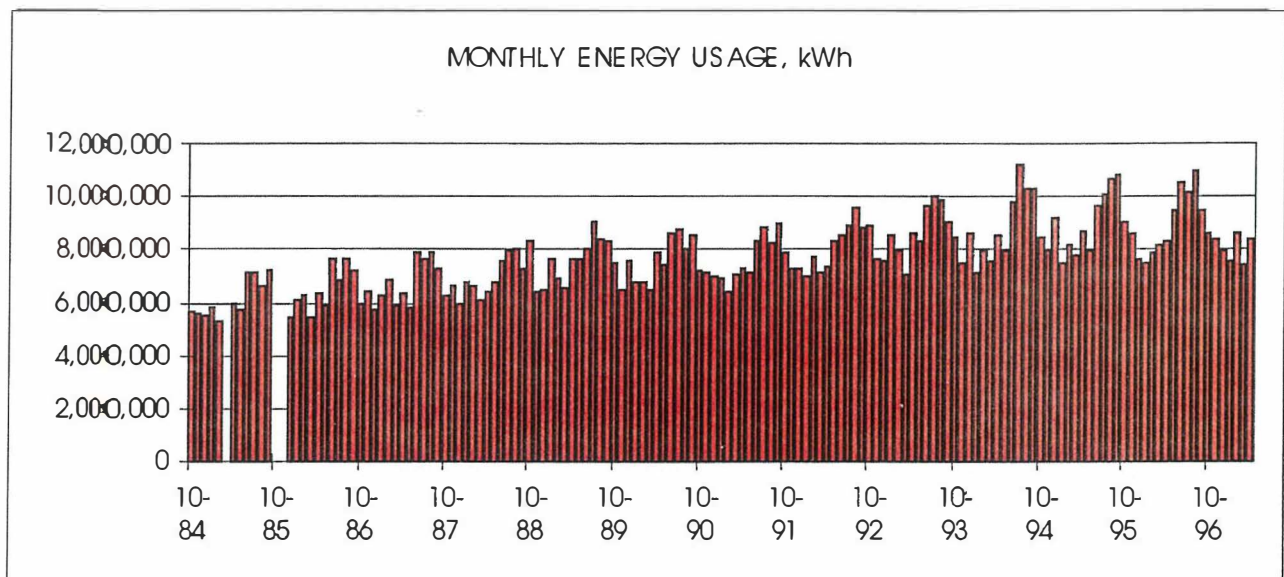
Figure 4: Fort Huachuca Monthly Energy Consumption
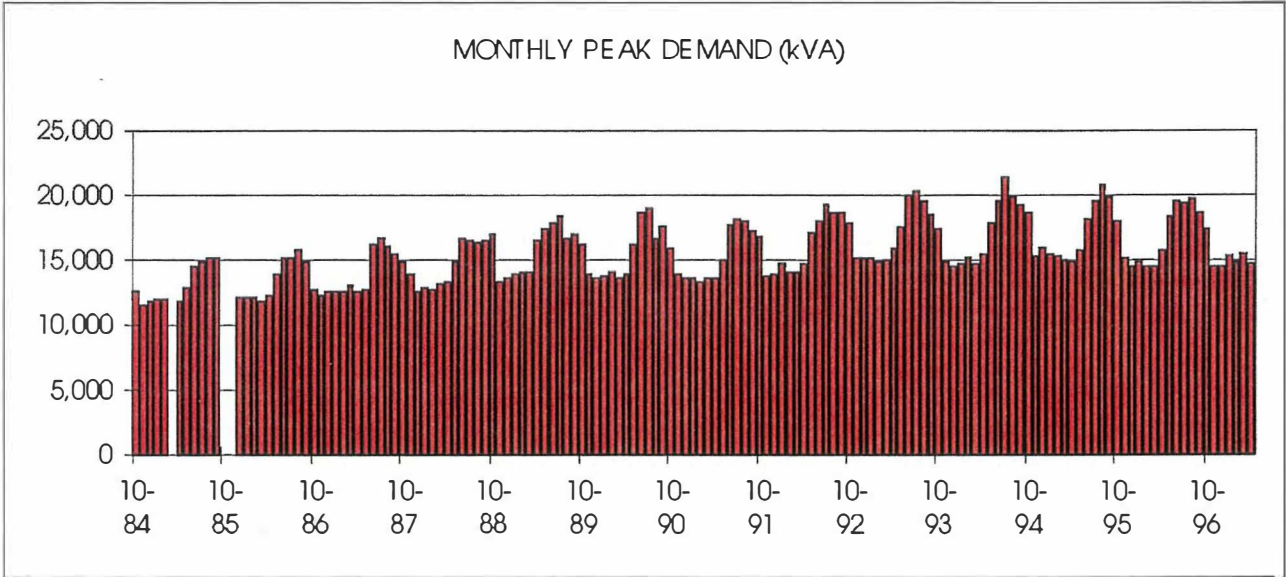
Figure 5: Fort Huachuca Monthly Peak Demand
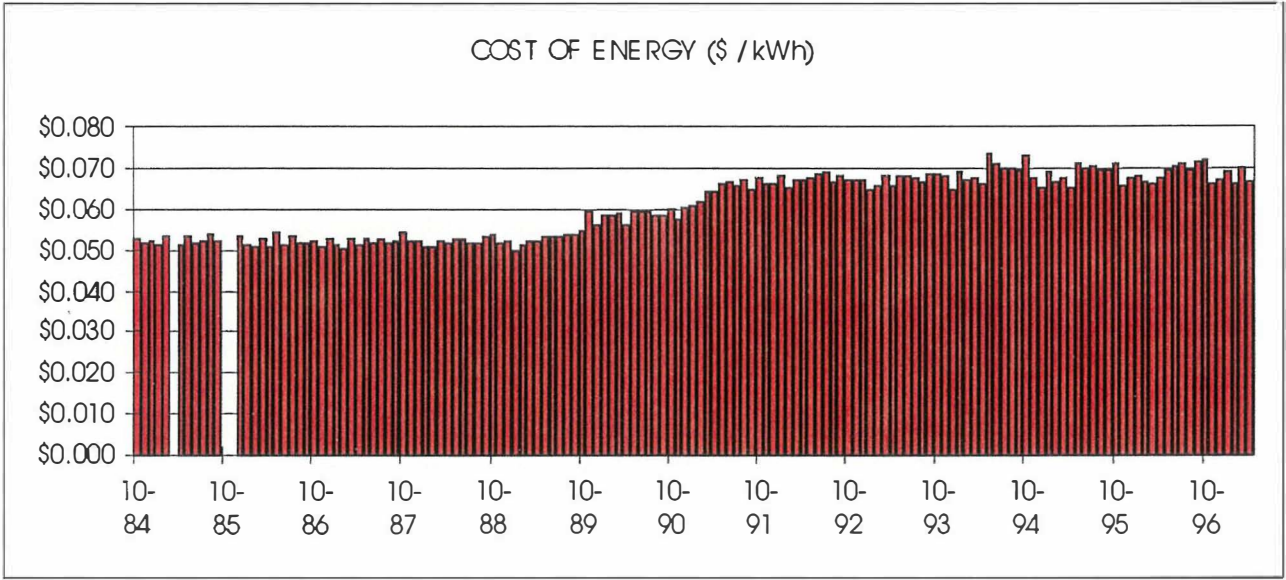
Figure 6: Fort Huachuca Monthly Cost of Energy
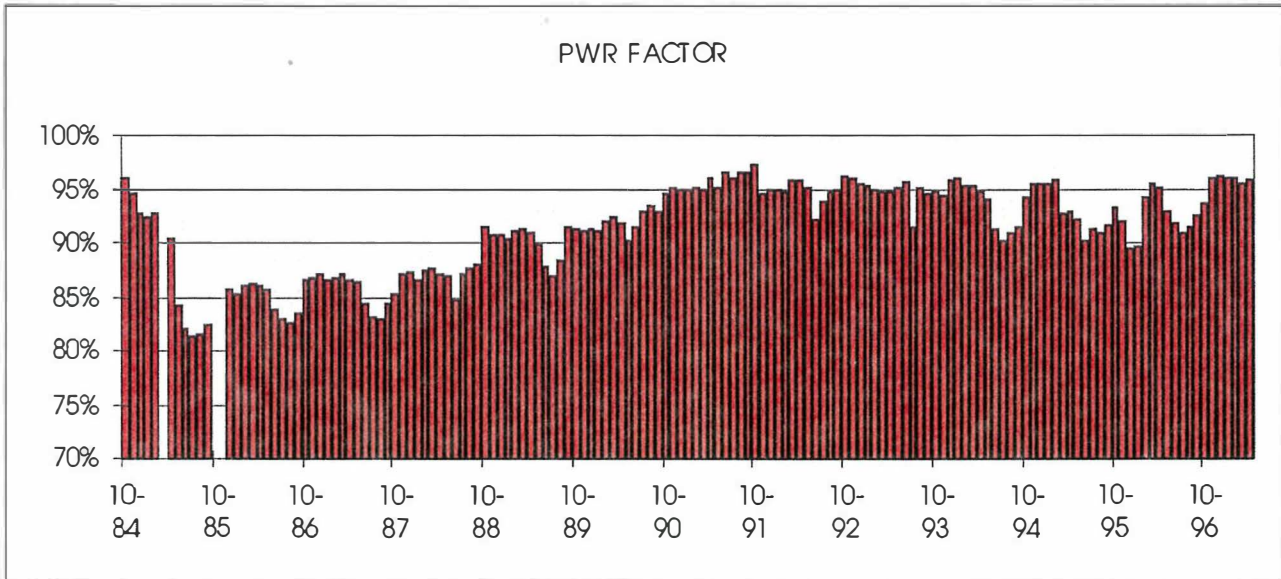
Figure 7: Fort Huachuca Monthly Power Factor

2.3 Wind Measurement Site Descriptions

Three sites have been monitored at Fort Huachuca: Data Collection Points (DCP) 2, 13, and 16. A separate data set labeled DCP 18 contains an extra level of (30.5 m; 100 ft) data at DCP 2. Shown in Figure 3, their locations are:

DCP 2/18: "West Gate," elevation 1530 m (5020 ft), toward the northwest end of the base and the north end of the Huachuca Mountains with possible influence from, but not in direct alignment with, Blacktail Canyon.

DCP 13: "Bore Site," elevation 1814 m (5952 ft), a topographically complex site near Scott Peak and near the northwest edge of the Huachuca Mountains.

DCP 16: "TV Hill," elevation 2135 m (7003 ft), a peak near the center of the Huachuca Mountains between the south and west Fort Huachuca base ranges and southeast of Bore Site.

These sites are either southeast or northwest of the base buildings by a half mile or more. They are on the edge of the valley floor, which has scattered low trees. The trees thicken in the rugged mountains to the southwest.

These sites all have mild to moderate winds, with marginal energy production potential. Stronger wind may exist along the ridgelines, but accessibility is severely limited. Some local terrain-induced wind amplification could be found with sufficient prospecting. Fort Huachuca staff view the

canyons as likely amplification sites, but acknowledge potential problems with space and protected bat territory.

2.4 Wind Data Collection and Analysis

The wind data was collected by the Fort Huachuca meteorological team using a standardized acquisition system they developed in previous years. This system produces the data in a daily report format in ASCII files. The data includes temperature, relative humidity, pressure, average wind direction, average wind speed, and peak wind speed at 2 to 3 heights, every 15 minutes. Unfortunately, the report format stripped all decimal information in its presentation of the data, displaying mean wind speeds with only one significant digit. However, statistics will help mitigate this problem, as most of our analyses will look at averages of collections of these values.

The measurements heights were 7.6 m (25 ft) and 13.7 m (45 ft) at all sites, plus 30.5 m (100 ft) at DCP 2/18. The period of measurement was July, 1995 through June, 1996. All comparisons of meteorological data in this report will refer to the evaluation height of 13.7 m (45 ft), unless otherwise noted.

Analysis of this data required several steps for each data set (DCP):
1. Assemble all data into a single file, using a MS Excel spreadsheet macro to import each daily report and strip out header and summary information.
2. Visually scan these files for a variety of data errors, noting omissions, text values and other anomalies, and repairing data segments with incorrect time shifts.
3. Perform a series of statistical analyses on each data set, including summary statistics, frequency distributions, annual and seasonal records, and annual and seasonal average diurnals.

3.0 WIND RESOURCE

In November, 1994, NREL entered into a cooperative agreement in which the Fort Huachuca meteorological team would collect one year of high quality wind resource data at several sites and an NREL team would analyze the data and evaluate the sites for wind energy production in cooperation with the Fort Huachuca Energy Manager. We examined this data in detail, and reviewed available historical data summaries in order to describe a long-term behavior.

3.1 Historical Wind Data

The wind resource at most sites varies from year to year and, in fact, it can vary widely. For this reason, it is prudent to review long-term data at the nearest site available. Therefore, this section begins with a review of 17 years of wind speed data (1954 -1971) at the Fort Huachuca station number 03124, compiled by Pacific Northwest Laboratories and managed by the National Climatic Data Center [5]. Newer data is not yet available. Located at 31.35 deg latitude and -110.20 deg longitude, this station measured hourly wind speed at 4 m height 24 times per day.

Information is not available on quality control of these measurements; they carry risks such as wind obstruction and drifting calibrations. Some bias toward lower wind speed measurements might be expected because of ground drag, obstructions, or binding anemometers, but no attempt is made to account for such bias in this study. Therefore, the averages found here will not be used for the wind energy modeling later in this report, but the interannual variability found will be used for a sensitivity analysis.

Historical annual average wind speeds follow in Figure 8. The average 17 year wind speed at Fort Huachuca at the 4 m data collection height is 3.0 m/s (6.7 mph) based on annual averages of hourly data, and the average of the annual standard deviations is 2.3 m/s (5.1 mph). The standard deviation of the annual averages is 0.27 m/s (0.61 mph), giving a coefficient of variation of 0.27 / 3.0 = 0.090, or 9%. The interannual variability of 9% is relatively low indicating reasonably stable year-to-year conditions.
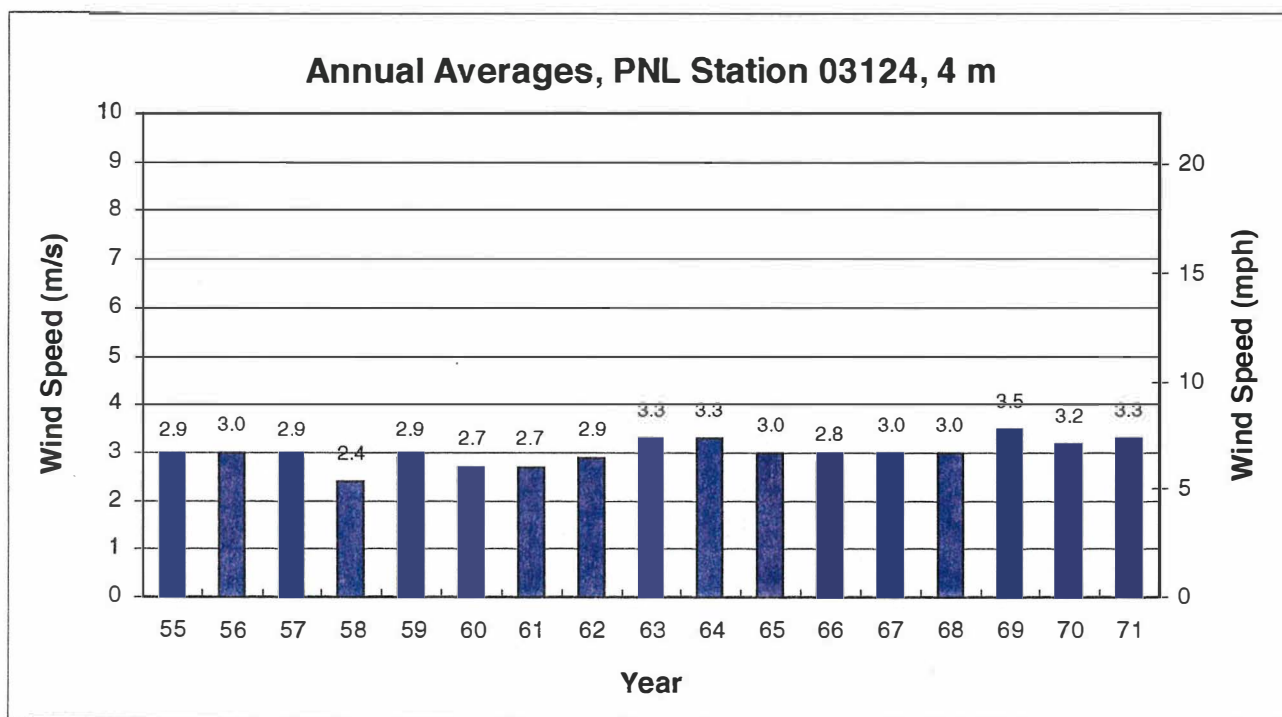
Figure 8: Fort Huachuca Historical Wind Speeds

3.2 Current Wind Data

Statistical analysis of the full year of Fort Huachuca 15-minute data yielded the results shown in Table 1, and a full wind-speed distribution is presented in Figure 9. Collected at 7.6, 13.7, and 30.5 m heights, the data revealed rather modest wind speeds, with the best average of 5.0 m/s occurring at 13.7 m at DCP16. However, these are somewhat low measurement levels. Wind turbine tower heights typically range from 24 m (79 ft) to 50 m (164 ft). Although canyon "drainage" flows were expected (winds amplified by terrain funneling low in the canyons), it was

not clearly demonstrated, as accurate wind direction data was not available. However, significant positive wind shears were found. The wind shear exponents varied from 0.22 to 0.49, all higher than the typical 1/7 power law (0.143).

Table 1: Summary of Current Fort Huachuca Meteorological Data

West Gate, DCP 2, 13.7 m:

Channel	Units	Average	Standard Deviation	Minimum	Maximum	Coefficient of Variation
Wind Speed	m/s	3.9	2.3	0.0	16.1	0.59
Wind Speed	mph	8.7	5.2	0.0	36.0	0.60
Ambient Temperature	°C	18.9	8.0	-2.2	51.7	0.42
Ambient Pressure	mbar	843	2.8	817	866	0.00
Air Density	kg/m^3	1.01	0.00	0.93	1.05	0.00
Power Density	W/m^2	49	11	1	3201	0.22
Wind Shear Exponent	(25' to 45')	0.49				
Wind Shear Exponent	(45' to 100')	0.22				
Wind Shear Exponent	(25' to 100')	0.33				
Mean Diurnal Variation	m/s	+/- 1.1				

Bore Site, DCP 13, 13.7 m:

Channel	Units	Average	Standard Deviation	Minimum	Maximum	Coefficient of Variation
Wind Speed	m/s	4.1	2.4	0.0	19.7	0.59
Wind Speed	mph	9.2	5.4	0.0	44.0	0.59
Ambient Temperature	°C	17.8	8.0	-3.9	37.2	0.45
Ambient Pressure	mbar	820	3.0	808	827	0.00
Air Density	kg/m^3	0.99	0.00	0.93	1.05	0.00
Power Density	W/m^2	34	7	0	3751	0.21
Wind Shear Exponent	(25' to 45')	0.27				
Mean Diurnal Variation	m/s	+/- 0.4				

TV Hill, DCP 16, 13.7 m:

Channel	Units	Average	Standard Deviation	Minimum	Maximum	Coefficient of Variation
Wind Speed	m/s	5.0	3.4	0.4	23.2	0.68
Wind Speed	mph	11.2	7.5	1.0	52.0	0.67
Ambient Temperature	°C	14.9	7.6	-6.1	36.7	0.51
Ambient Pressure	mbar	791	3.4	771	799	0.00
Air Density	kg/m^3	0.96	0.00	0.90	1.01	0.00
Power Density	W/m^2	61	18	0	6037	0.30
Wind Shear Exponent	(25' to 45')	0.35				
Mean Diurnal Variation	m/s	+/- 1.1				
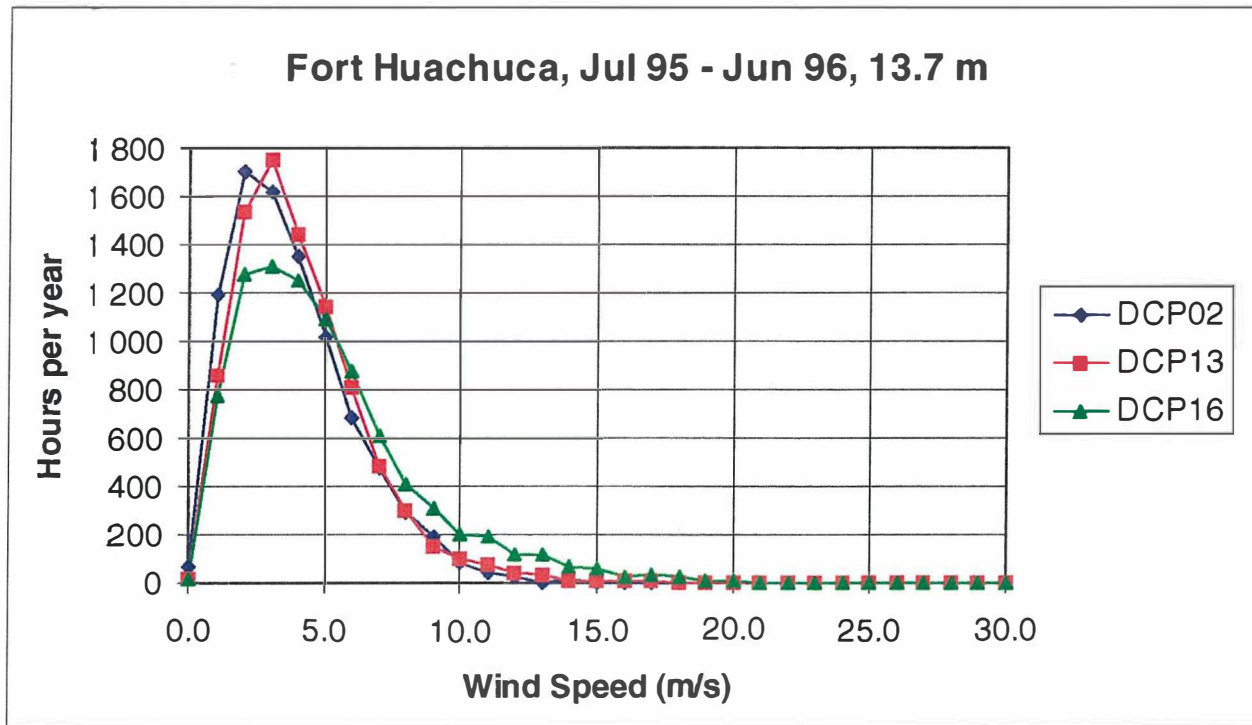
Figure 9: Fort Huachuca Wind Speed Frequency Distribution

Annual records using monthly average wind speeds are plotted in Figure 10. The whole year falls between 3.5 and 6.0 m/s (7.8 and 13.4 mph) at all three sites measured, with lower winds in the fall and higher winds in spring. Fifteen-minute average highs reach 16.0 m/s (35.8 mph) in January at DCP16, indicating winter storms. The source data was derived from Fort Huachuca testing as described in section 2.4. The most energetic site of the three examined is DCP16.

The annual average diurnals given in Figure 11 show stable patterns, with hourly mean wind speeds again falling between 3.5 and 6.0 m/s (7.8 and 13.4 mph). However, these are averages; any specific day could be quite different. When reading x-axis (time of day), the column labeled "0000" refers to the first hour of the day, 0000 to 0100. Site DCP02 tends to lull in the morning with higher winds following in the afternoon, while site DCP16 follows with a midday lull and nighttime surge. Site DCP13 tends to hold steady throughout the day.

Additional meteorological data and power density records are given for DCP02 in Figure 12. Ambient temperature and pressure data are used to derive air density, which in turn is used with wind speed to derive wind power density.
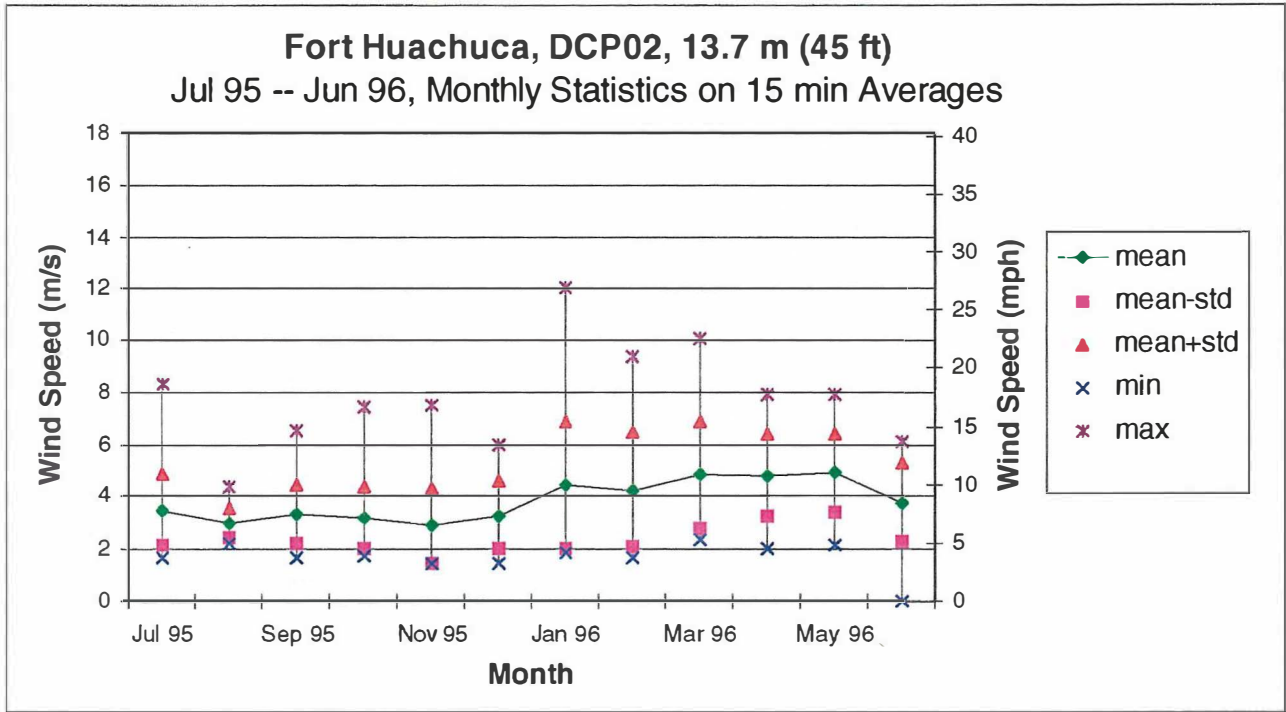
Figure 10a: Fort Huachuca Annual Wind Speed Record, West Gate, DCP02
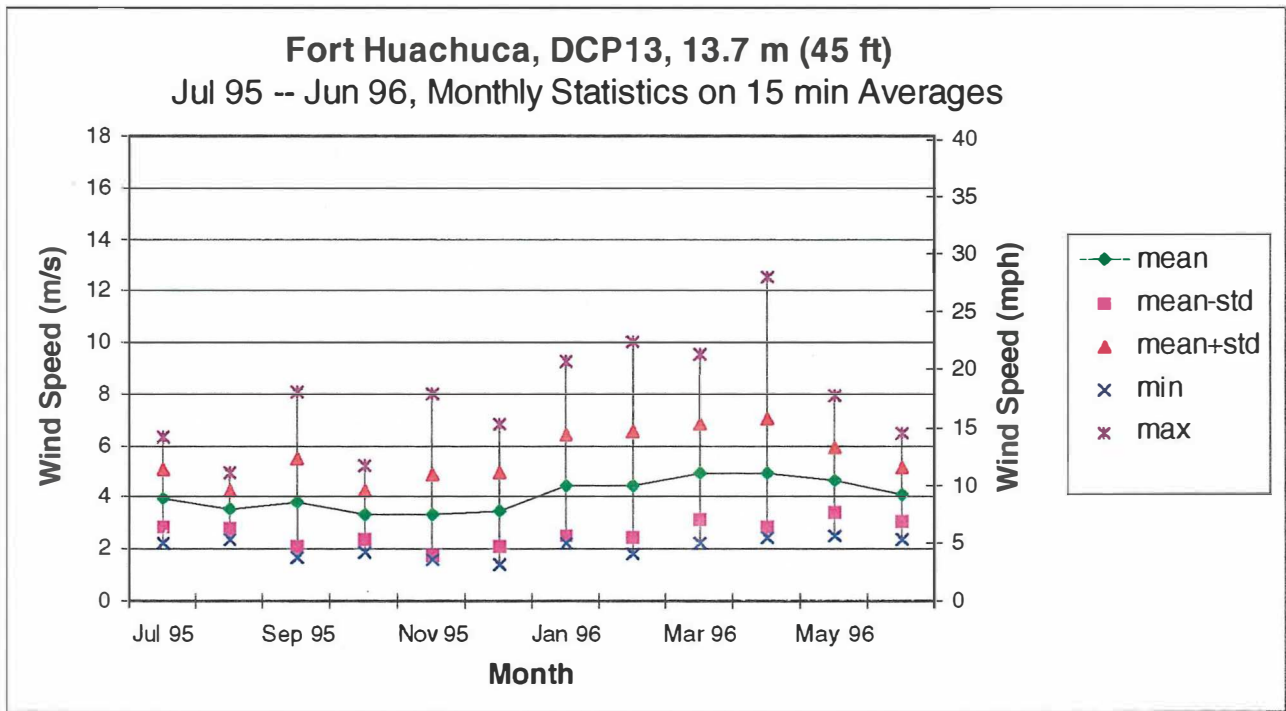
Figure 10b: Fort Huachuca Annual Wind Speed Record, Bore Site, DCP13
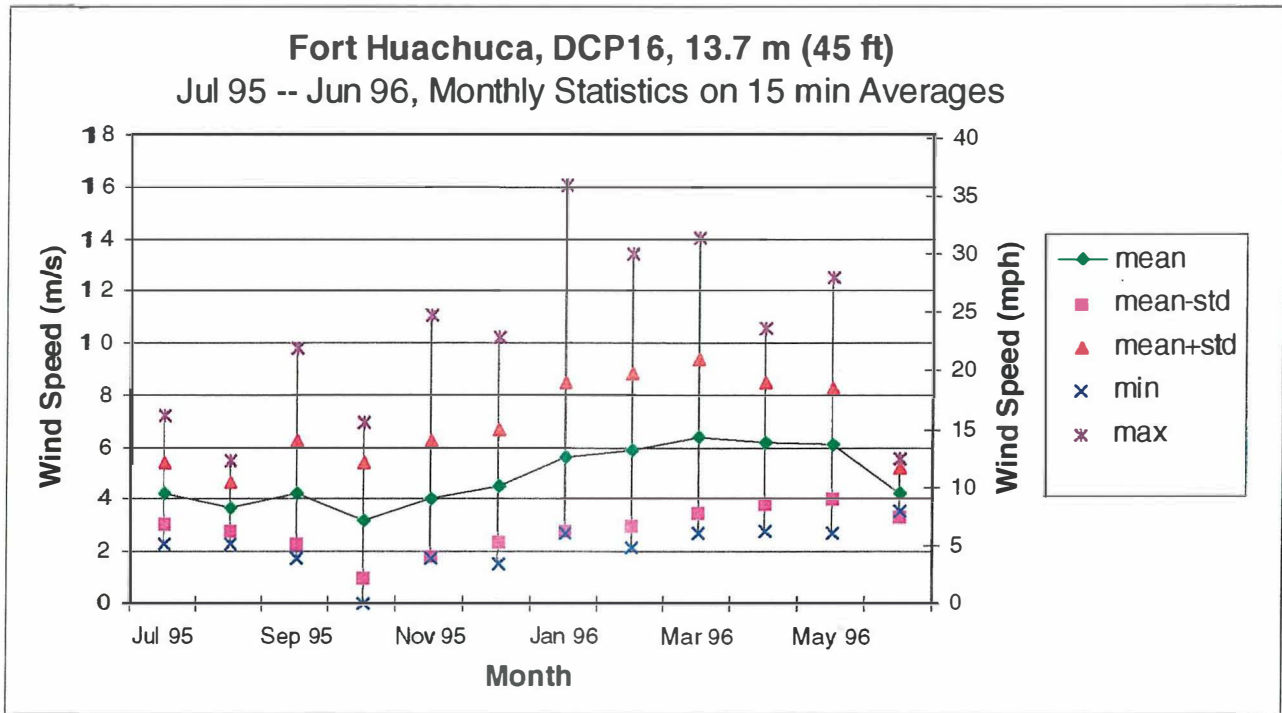
Figure 10c: Fort Huachuca Annual Wind Speed Record, TV Hill, DCP16
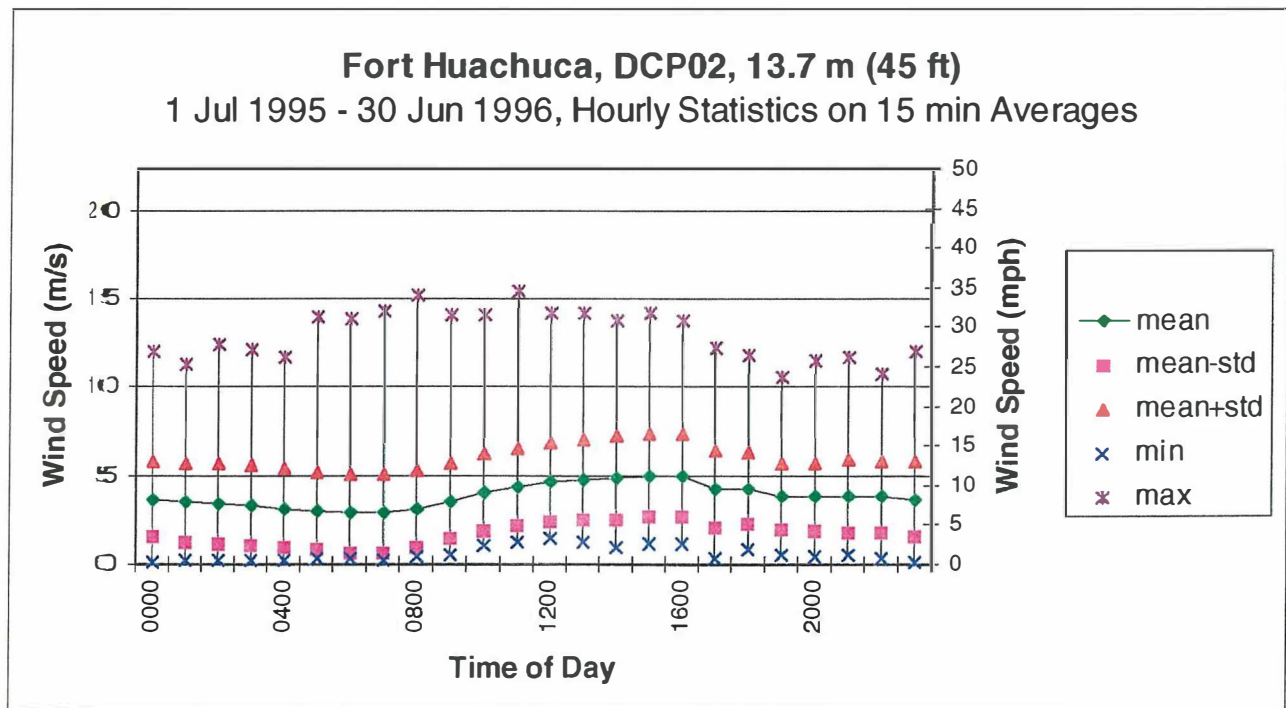
Figure 11a: Fort Huachuca Annual Average Diurnal Wind Speed, West Gate, DCP02

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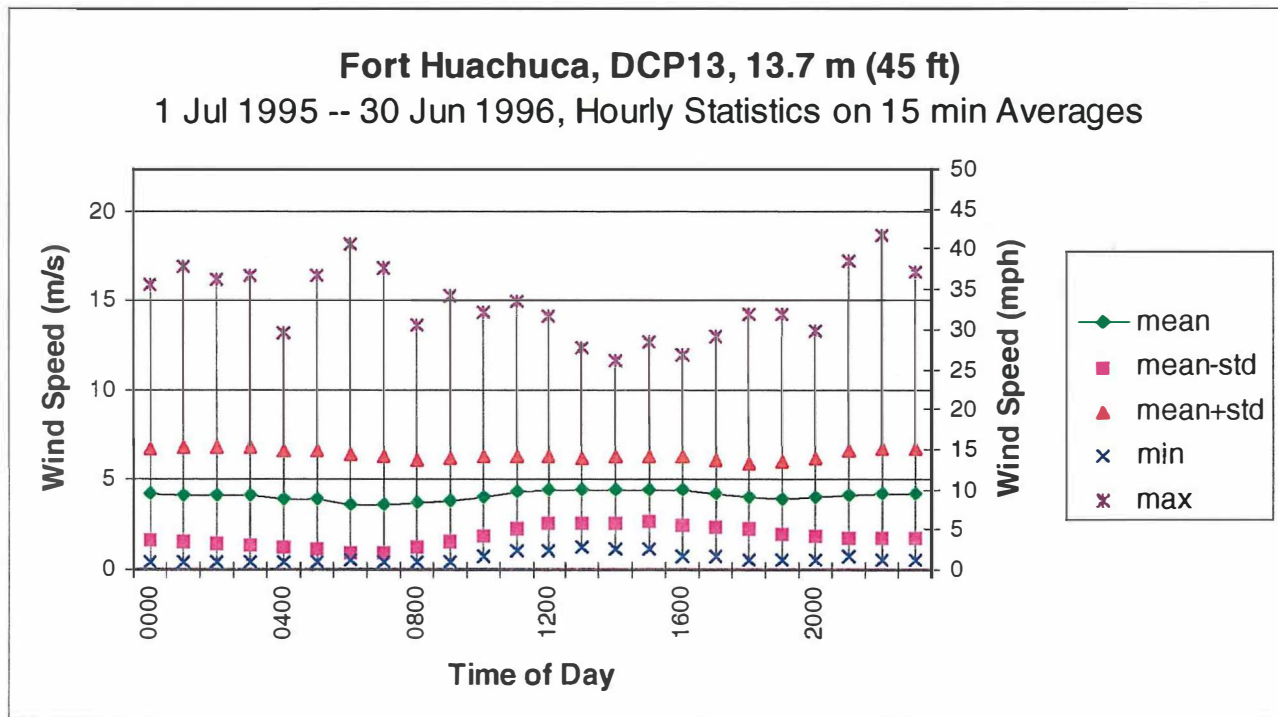
Figure 11b: Fort Huachuca Annual Average Diurnal Wind Speed, Bore Site, DCP13
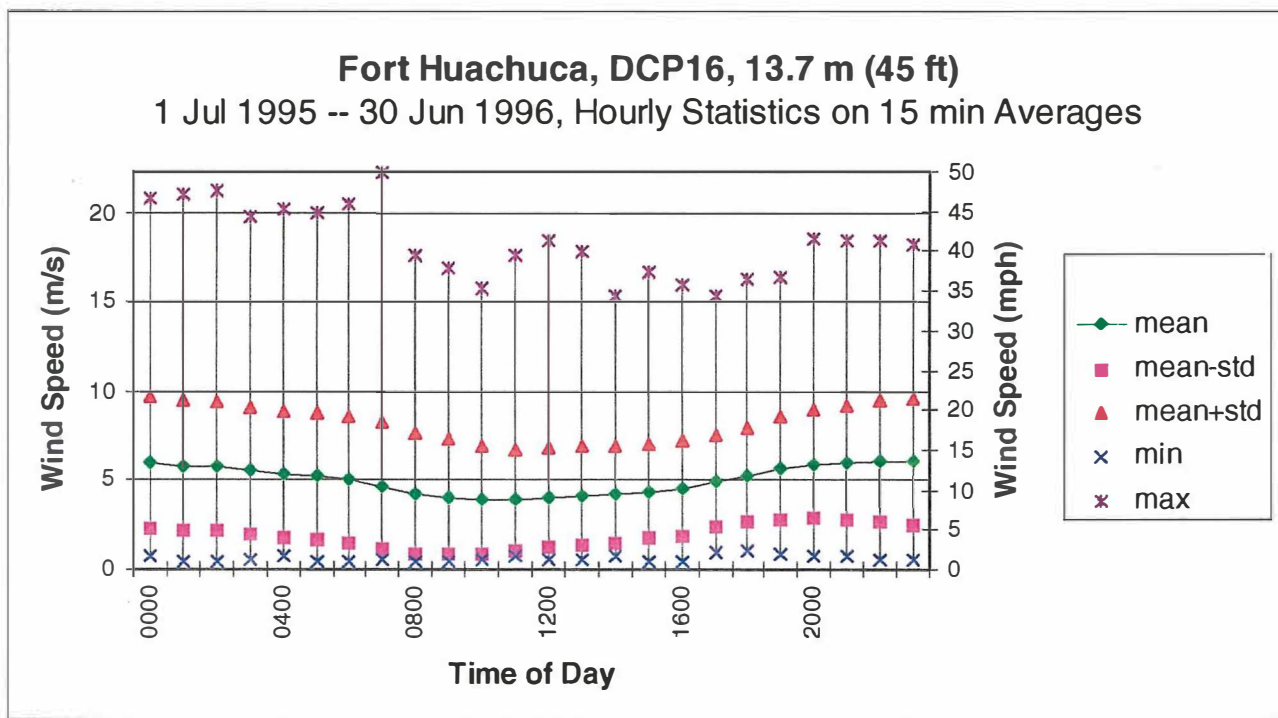
Figure 11c: Fort Huachuca Annual Average Diurnal Wind Speed, TV Hill, DCP16
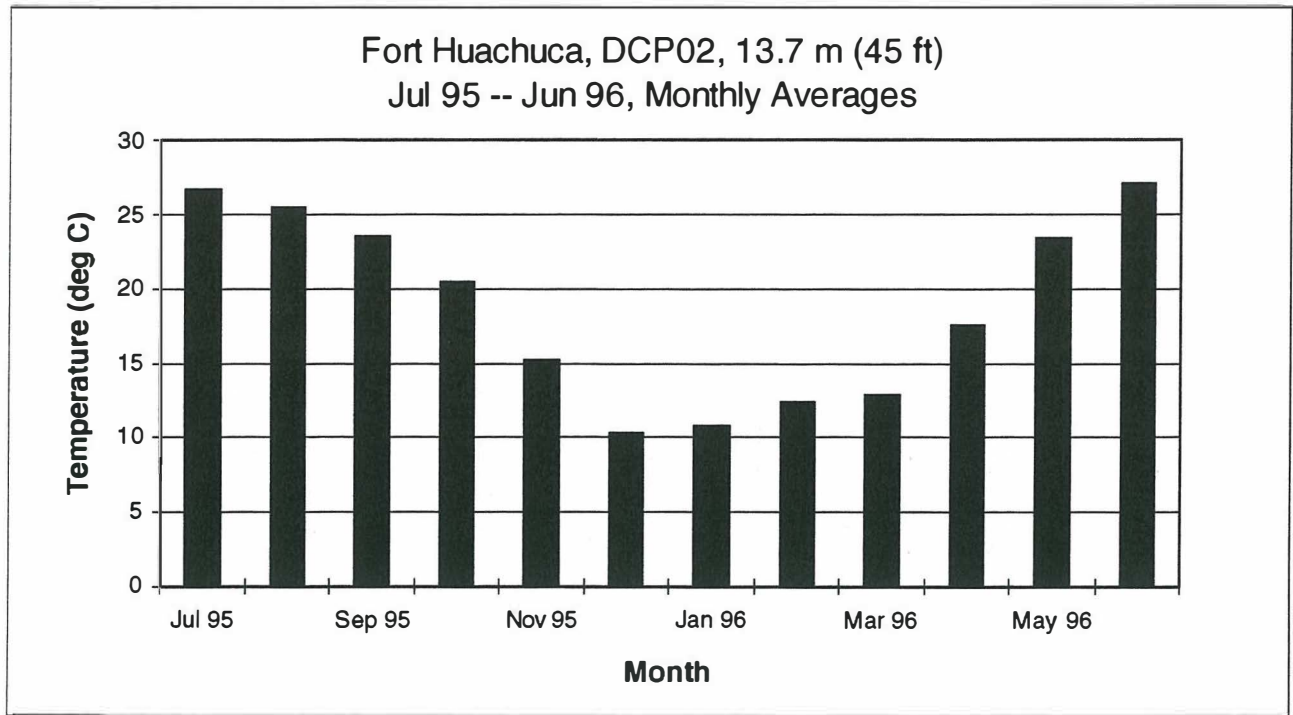
Figure 12a: Other Fort Huachuca West Gate DCP2 Annual Average Data: Temperature
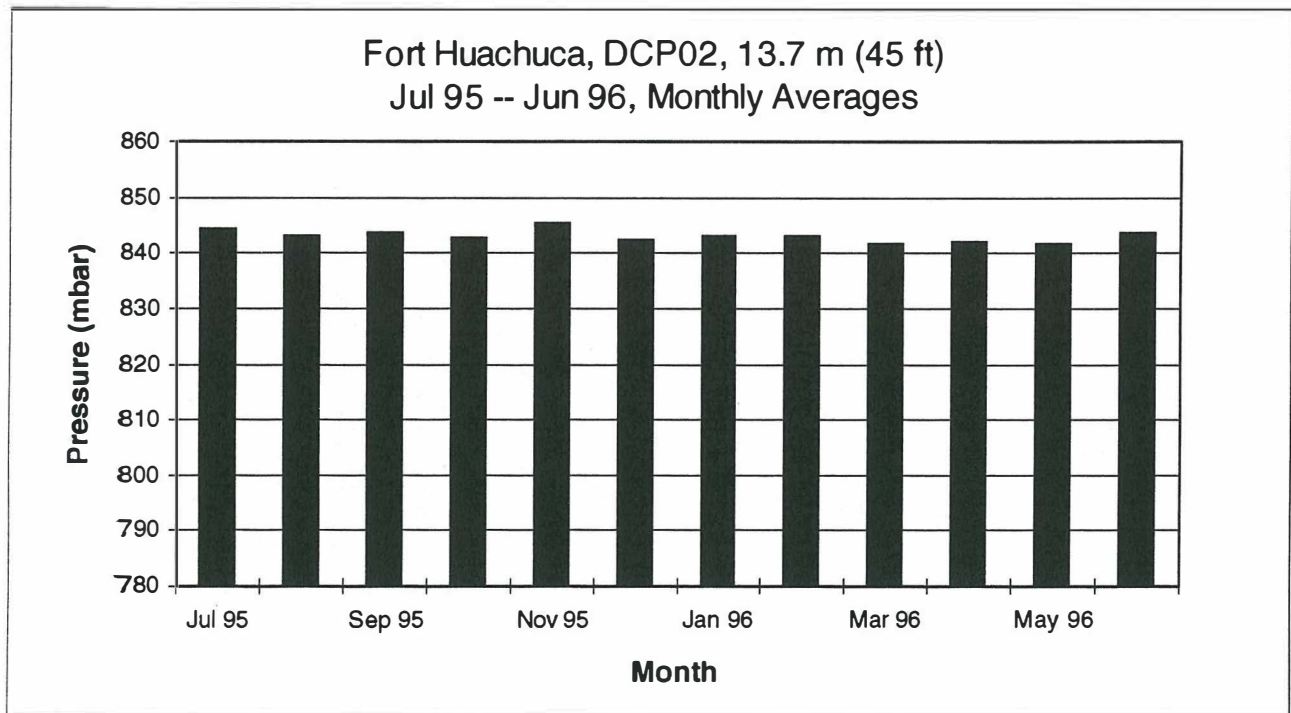
Figure 1 2b: Other Fort Huachuca West Gate DCP2 Annual Average Data: Pressure

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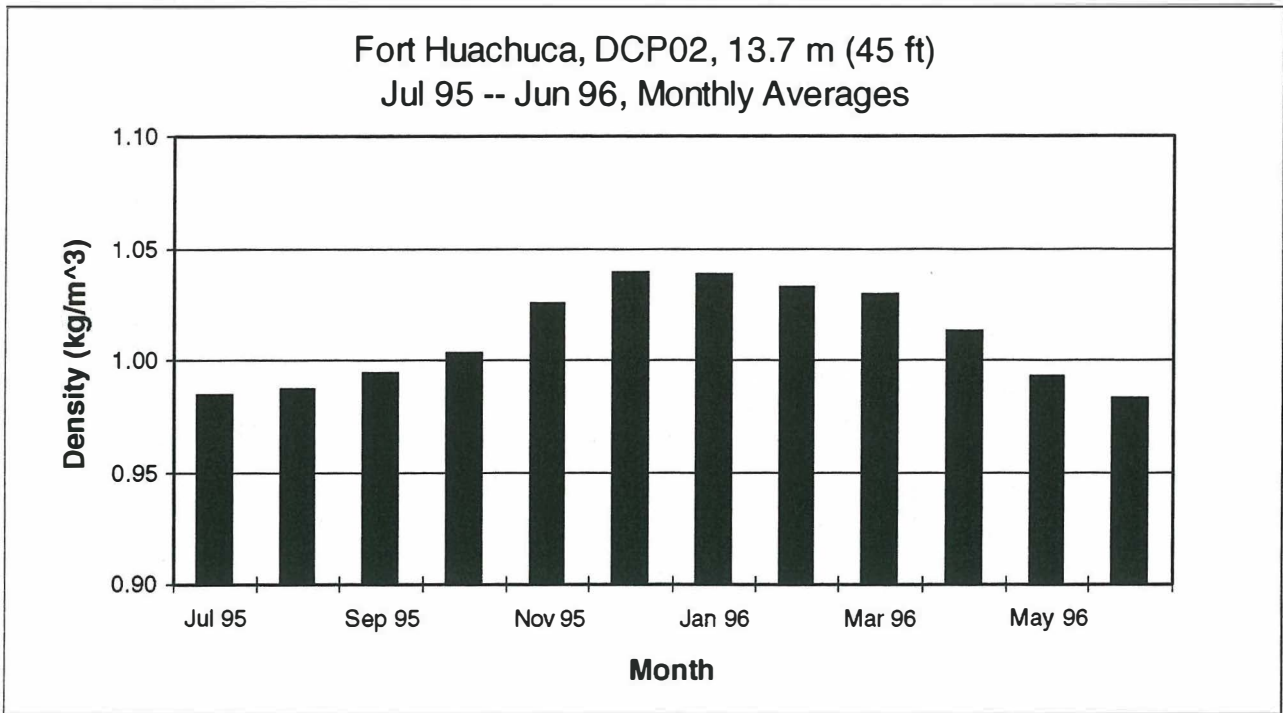
Figure 12c: Other Fort Huachuca West Gate DCP2 Annual Average Data: Air Density
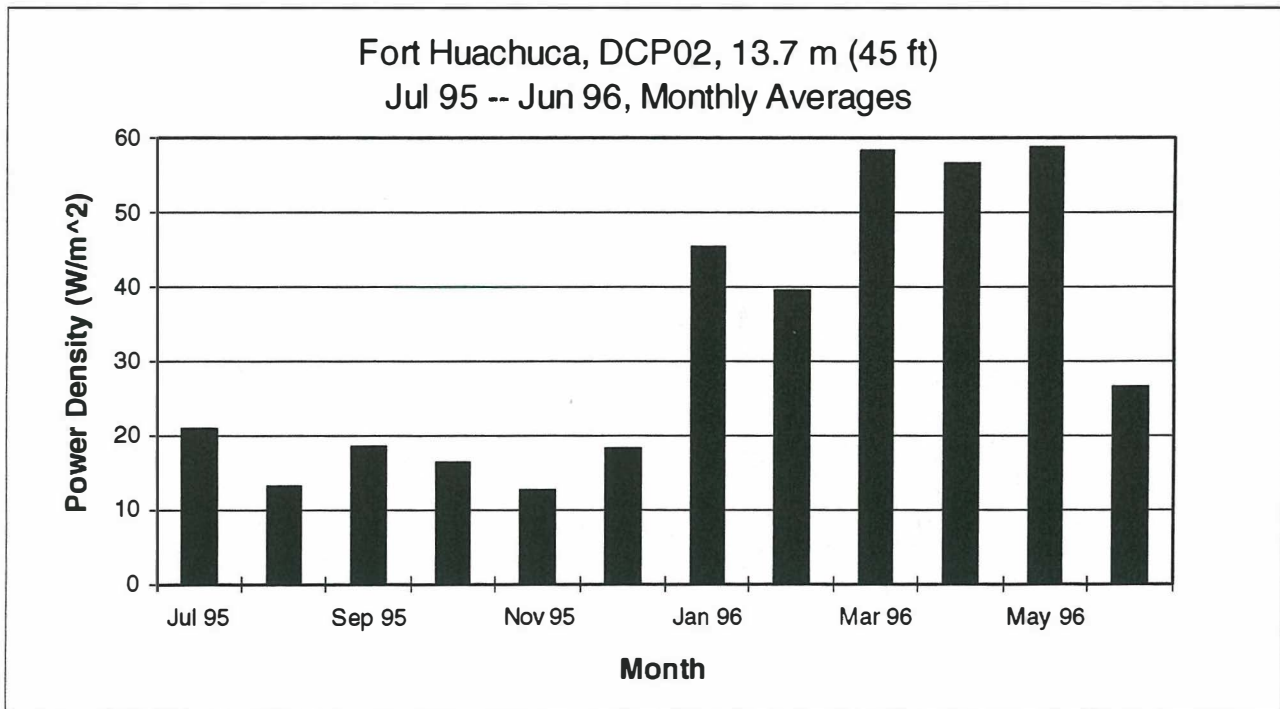
Figure 12d: Other Fort Huachuca West Gate DCP2 Annual Average Data: Wind Power Density

4.0 WIND ENERGY COST ANALYSIS

A wind energy system may be economically and environmentally advantageous for Fort Huachuca and surrounding areas. A preliminary study of such a system was conducted using the author's "WindEcon" spreadsheet program based on the Hunter and Elliott [6] formulation to evaluate the potential energy cost savings from wind generation. Several wind energy cases were compared to help determine the most cost-effective wind farm size.

4.1 Methodology

After estimating 1996 operating costs for the wind energy system, the resulting levelized costs of energy (COE), annual energy cost savings and payback periods were estimated. COE is derived according to the National Renewable Energy Laboratory Request for Proposal formulation:

$$COE = [(FCR * ICC) + LRC / AEP] + O\&M,$$

Where:

COE = Levilized Cost of Energy ($ / kWh)
FCR = Fixed Charge Rate (1 / yr) = 0.109, consists of 8.0% Capital Recovery Factor
　　　　(CRF) plus 2.9% insurance costs
ICC = Initial Capital Cost ($)
LRC = Levelized Replacement Cost ($ / yr)
AEP_{net} = Net Annual Energy Production (kWh/yr)
O&M = Annual Operation and Maintenance Cost ($ / kWh)

A simple payback period is calculated by dividing the total initial capital cost by the annual savings from system operation.

Economic assumptions included 3% general inflation, 3% energy inflation, 10.9% fixed charge rate (FCR), 6.9% discount rate, 10% interest rate, 30-year system life, and 100% down payment on new investment [NREL RFP]. It was further assumed that no additional labor would be required to operate the wind energy system beyond that already assigned to operate the extensive base facilities.

4.2 Existing Energy Costs

Fort Huachuca consumed 107.6 million kWh of electricity in 1996, at a cost of $7.4 million. Consumption grew at an average of 3.3% per year over the last decade but just 1% over the previous year. The energy bill grew a little faster, with 6.6% annual average for the decade and 1.4% in the past year. Peak demand grew from 16,400 kW in 1987 to 21,300 kW in 1994, and then dropped to 19,360 kW in 1997. Both the slowed consumption growth and the reduced peak demands are a tribute to the success of the ongoing energy conservation program at Fort Huachuca.

Currently, Tucson Electric Power (TEP) Company bills Fort Huachuca at the rate of 0.047457 per kWh plus a demand charge of $10.28 per kW based on the peak demand for the month. Using May 1996 as a sample month, the peak demand of 18,392 kW and energy consumption of 9,254,400 kWh give base costs of $628,257. Adding a power factor adjustment and taxes raise the total bill up 5.3% to $661,586, or about $0.0715 per kWh. Details of the demand profile are not available.

4.3 Wind Generation System

The wind generation system modeled consists of eight commercial wind turbines rated at 225 kW each. The sea level power curve for this turbine is shown in Figure 13. An elevation correction was made to adjust the power curve to 2135 m (7003 ft) above sea level, to match the elevation of a proposed wind site at TV Hill (DCP 16). This correction is applied by reducing the power at low winds by 21% (for 2134 m, or 7000 ft elevation), and then fairing in the power to level off at 210 kW at higher winds. The wind turbines can be curtailed (shut down) as necessary when excess wind energy is available.

Power Curve Data, 225 kW Wind Turbine

$$y = -0.0002x^5 + 0.0186x^4 - 0.7047x^3 + 11.023x^2 - 53.111x + 79.404$$
$$R^2 = 0.9995$$

Legend: Sea Level; 2134 m; Poly. (2134 m)

X-axis: Wind Speed (m/s). Y-axis: Electric Power (kW).
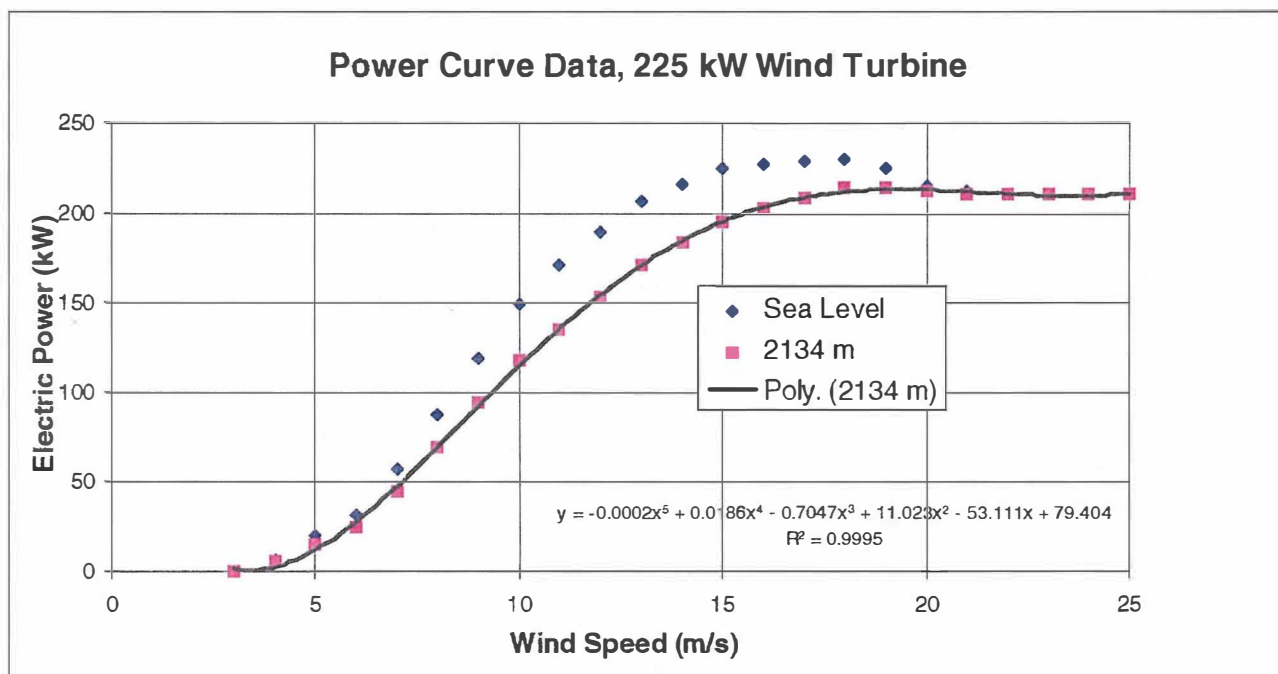
Figure 13: Power Curve, 225 kW Wind Turbine

The proposed wind energy system is relatively simple. Eight commercially available wind turbines (each with a capacity of 225 kW) would be interconnected with the existing TEP grid, for a total rating of 1.8 MW. With a demand peak of 19,600 kW and eight wind turbines, this would constitute wind penetration of peak capacity of 1800 kW / 19,600 kW = 9.2%. Based on a capacity factor of 25% and annual energy consumption of 108 million kWh, wind penetration

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would be 0.25 * 1800 kW * 730 hrs / 108 kWh = 3.0%. Such low penetration allows the assumption that all available wind energy is utilized.

4.4 Wind Profile and Energy Production

The 13.7 m (45 ft) wind data for DCP16, TV Hill, was scaled to 36 m (118 ft) hub height using the power law exponent of 0.35. This raises the average wind speed from 5.00 m/s (11.1 mph) to 7.03 m/s (15.7 mph). The new distribution appears in Figure 14.
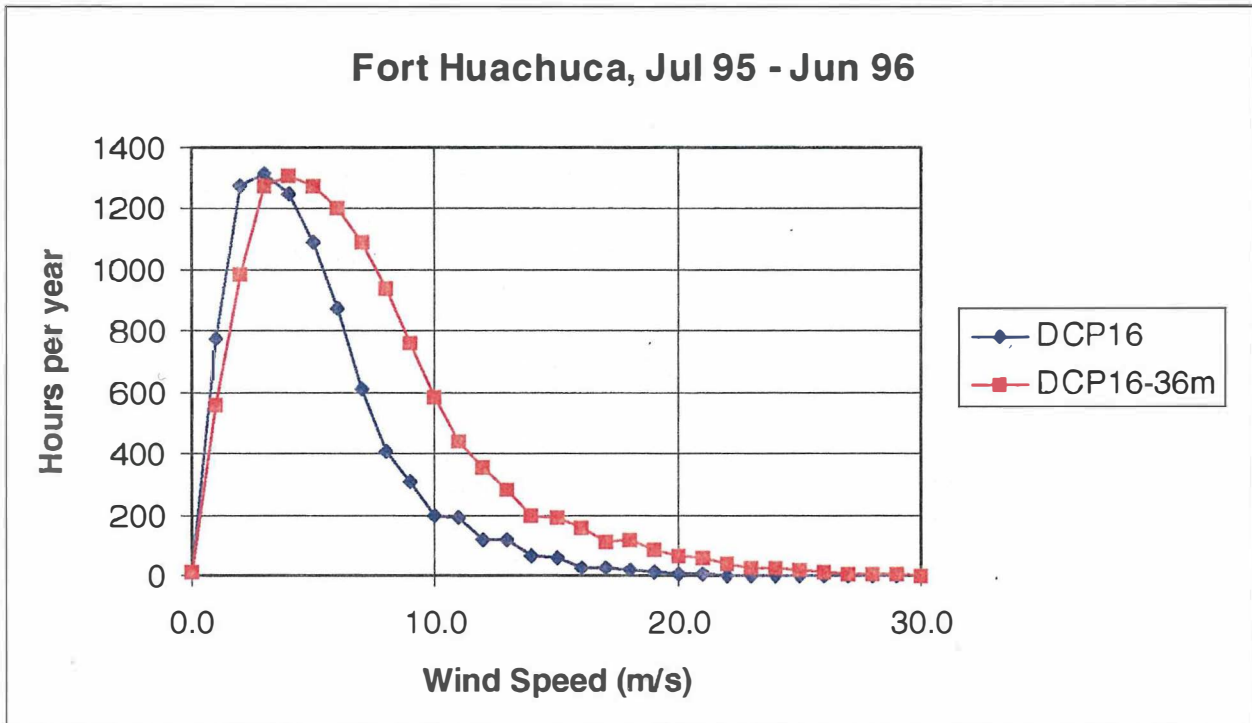
Figure 14: TV Hill, DCP16 Wind Distribution Scaled to 36 m

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:

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

Actual AEP is often lower because of various system losses. The 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 eight wind turbines, so array losses should be mitigated with proper siting. However, other sources of loss cannot be avoided as easily. They 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%.

Convolving the power curve shown in Figure 13 with the 36 m wind distribution shown in Figure 14 gives an AEP of 498,727 kWh per year per turbine. After 11.5% losses, net AEP is 441,373 kWh per turbine.

4.5 Wind Generation System Costs

Wind energy system initial capital costs (ICC) include all 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 2. (Note: It may be possible to further reduce installation and operation costs by adding DoD excess heavy equipment [e.g. a crane] to Fort Huachuca inventory.)

Table 2: Balance of Station Costs for Eight 225 kW Wind Turbines

Item	1995 Cost
Electrical Infrastructure	$100,000
Control & Monitoring Equipment	30,000
Foundations	100,000
Installation	250,000
Spare Parts	19,000
Site Survey & Preparation	50,000
Permits & Licenses	10,000
Environmental Assessment	10,000
Project Management & Engineering	200,000
Construction Insurance & Contingency	67,000
Training	11,000
Shipping	40,000
Total	$888,000

Meteorological Instrumentation System (optional) $34,000

Each 225 kW wind turbine, including a 24.4 m (80) ft tower, costs approximately $250,000. An additional $111,100 has been allotted to cover BOS costs. BOS costs are highly site dependent and can vary by an order of magnitude. The total ICC required then for each wind turbine is $361,100.

Levelized parts replacement costs (LRC) are fixed at an annual $1000 per wind turbine, regardless of turbine usage.

Actual wind turbine O&M costs are expected to be $40,000 for eight turbines, giving a per-energy rate of $0.0115/kWh. As implied by its units, this O&M cost is variable, or fully dependent on wind turbine usage. These estimates are based on working systems using the sample 225 kW wind turbine and are fairly conservative.

4.6 Wind Energy Cost Comparison

The NREL RFP calculation gives an uncompetitive COE result for a small wind system at this site:

$$COE = [(FCR * ICC) + LRC] / AEP + O\&M$$

$$COE = [(0.109 * \$361,100) + \$1000] / 441,373 \text{ kWh} + \$0.0115/\text{kWh}$$

$$COE = \$ 0.103 / \text{kWh}.$$

However, it is likely the US Army would pay the initial capital costs in cash rather than through financing, in which case the fixed charge rate is not accurate. So a net present value formulation is used instead (Appendix A). This approach actually gives a higher COE for the grid energy payments. Because of the 3% inflation and 30 year life assumptions, levelized grid energy COE is $ 0.101 / kWh, while the wind energy COE is $ 0.085 / kWh and the combined system COE is $ 0.100 / kWh. This reduction in system COE is minimal. The $2.89 M capital investment in the eight wind turbine system was offset by energy bill savings of $202,000 annually, giving a 14.3 year simple payback period with 5.7 % internal rate of return (IRR). These results also are presented in Table 3.

Fort Huachuca probably could handle a much larger wind farm and fully utilize wind energy with penetrations up to 30%. However the economic benefit is marginal at this point, and would require lower wind system costs or higher grid energy rates to improve. Currently available used wind generating equipment may be the key to much more beneficial economics.

Table 3: 1996 Wind Energy System Economics

Parameter	Units	Baseline Grid Only 0 kW	+8 Wind Turbines 1800 kW
Average WS, 1 yr	m/s	6.65	6.65
Average Load, 1 yr	kW	12,290	12,290
Avg Net Grid Load	kW	12,290	11,880
Energy Demand, 1yr	GWh	107.6	107.6
Grid Energy, 1yr	GWh	107.6	104.1
Wind Energy, 1yr	GWh	0	3.5
Unused Wind Energy	MWh	0	0
Grid Energy	%	100.0	96.7
Wind Energy	%	0.0	3.3
Wind System Capacity Factor	%	n/a	22.4
Levelized COE	$/kWh	0.101	0.100
COE Saving	$/kWh	0.000	0.001
COE Saving	% of base	0.0	1.0
Wind COE	$/kWh		0.085
Payback Period	year	n/a	14.3
Internal Rate of Return	%	n/a	5.7

Notes: (1) "Net Grid Load" means net power required from the grid, or system load minus useable wind power.
(2) Wind System Capacity Factor = Wind Energy [MWh] / (#turbines*rating[0.225MW]*8760[h]).
(3) All other values derived from spreadsheet model results, Appendix A.

4.7 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 9%, which is the interannual variability found in the historical wind measurements. The results are shown in Table 4. With the wind speed 9% lower than the NREL measurement year, wind energy COE and payback period rose by 13% and 17%. With the wind speed 9% higher, COE and payback period dropped by 11% and 13%. In both cases, the total system COE is nearly unchanged, because of the low wind energy penetration.

Table 4: Economic Sensitivity to Wind Speed Variations
Spreadsheet Model for 8 Turbines

Case	Wind Speed	Energy bill Saving ($1000)	Wind COE ($/kWh)	Payback Period (years)	Internal Rate of Return (%)
minus 9%	6.4 m/s	173	0.096	16.7	4.3
baseline	7.0 m/s	202	0.085	14.3	5.7
plus 9%	7.7 m/s	231	0.076	12.5	6.9

Case	Wind Speed	Energy bill Saving (delta %)	Wind COE (delta %)	Payback Period (delta %)	Internal ROR (delta %)
minus 9%	6.4 m/s	-14	13	17	-25
baseline	7.0 m/s	0	0	0	0
plus 9%	7.7 m/s	14	-11	-13	21

5.0 CONCLUSIONS

Fort Huachuca has a marginal wind resource, with annual average wind speeds of 3.9 to 5.0 m/s (8.7 to 11.2 mph) as measured by the Fort Huachuca meteorological team at 13.7 m (45 ft) height at three collection sites on the base between 1 July 1995 and 30 June 1996. Somewhat helpful, though, are strong positive vertical wind shears with exponents of 0.22 to 0.49. The wind speed at DCP16 had a shear factor of 0.35, which scales the wind speeds up to 7.0 m/s (15.7 mph) at a wind turbine hub height of 36 m (118 ft). Recognizing this, a wind energy system was evaluated to examine the merits of supplementing grid energy from Tucson Electric Power (TEP) with a modest portion of wind energy generation: 1.8 MW, or 3% energy penetration or 9% peak capacity penetration. Using conservative assumptions (unfavorable to wind energy) throughout the analysis, the wind energy system displayed favorable operation and marginal economics. The levelized cost of energy for the wind and grid energy case using eight 225 kW wind turbines is $0.100 / kWh, essentially unchanged from the baseline case without wind ($0.101 / kWh). The payback period is 14.3 years, the internal rate of return 5.7%. The system COE is relatively insensitive to annual average wind speed, varying less than 1% for a 9% change in wind speed. But the wind portion of the COE is more sensitive to wind speed, varying 13% for a 9% change in wind speed. The same 9% change in wind speed causes payback period to change up to 17%, and the internal rate of return to change 25%.

This work presented a preliminary study of a wind energy system using eight 225 kW wind turbines. For the application and conditions that were examined, it appears wind energy would be essentially cost neutral. We believe these conditions are realistic. But certainly many alternatives to these cases merit consideration. For instance, used wind generation equipment with installed costs below $500 per kW (half the price of new equipment) might lead to further savings. For example, the market currently offers 10-year old 60 kW wind turbines for about $8000, which may need an additional $8000 for refurbishment and handling, plus installation and balance of station costs. Alternatively, larger wind turbines on tall towers might reap significant benefits from the strong positive vertical wind shears measured. It would be extremely helpful to measure wind speeds at 50 m. If wind energy is considered beneficial for non-economic reasons in addition to the slight savings shown, much larger systems (and greater penetration) would be possible. Quantities of scale would tend to favor the economics of larger wind turbines and farms.

We have not tried to examine the relationship between wind energy and the grid demand costs. Large wind energy savings may do little to reduce demand costs, unless the wind shows consistency and strong correlation with demand loads. Although the concept of demand side management (DSM) may be overused, it could lead to significant savings in demand costs, and merits further study.

Different economic assumptions, such as higher and lower inflation, also can have significant impacts on such borderline results, and also should be examined further. Other factors that could impact the results include the actual capital and installation costs of the wind equipment and future TEP energy prices.

REFERENCES

1.   Olsen, T. and McKenna, E. (1996). *Hybrid Energy System Cost Analysis: San Nicolas Island, California.* NREL/TP-440-21120. Golden, CO: National Renewable Energy Laboratory.

2.   McKenna, E. and Olsen, T. (1996). *Wind Resource Assessment: San Nicolas Island, California.* NREL/TP-442-20231. Golden, CO: National Renewable Energy Laboratory.

4.   McKenna, E. (1993). *Review of Initial Feasibility of Wind Energy for Fort Huachuca, Arizona - SERDP Project.* Interoffice Memorandum. National Renewable Energy Laboratory.

5.   Elliott, D.L. et al. (1987). *Wind Energy Resource Atlas of the United States.* DOE/CH10093-4. Richland, WA: Pacific Northwest Laboratory.

6.   Hunter, R., and Elliott, G. (1994). *Wind Diesel Systems*, Cambridge University Press.

7.   NREL (1996). *Request For Proposals: Product Improvement Project.* No. RAT-6-16477. Golden, CO: National Renewable Energy Laboratory.

APPENDIX: Economic Summary Tables

ECONOMIC ANALYSIS   Site: Fort Huachuca, AZ, DCP16, 36 m, 7.0 m/s
Turbine: 225 kW, Commercial
8

Input Values

			Economic Factors			
				a variable	n variable	Y(a,n)
System load, (kWh/y)	SL	107,634,800	Present worth factor of fuel			
Grid energy (kWh/y)		104,103,816	costs, PWFF, a=(1+e)/(1+d)	0.96352	30	17.74945
Wind energy (kWh/y)		3,530,984	Present worth factor of O&M			
Diesel fuel usage, no wind (l/yr)	FL		costs, PWFO, a=(1+i)/(1+d)	0.96352	30	17.74945
Diesel fuel usage, with wind (l/yr)	FL		Present worth factor of interest			
Grid energy cost ($/kWh)	FC	0.071	payments, PWFP, a=1/(1+b)	0.93545	10	7.05616
System life, (yrs)	L	30				
General inflation	i	3.0%		a variable	n variable	X(a,n)
Grid energy inflation	e	3.0%	Capital recovery factor for system			
Discount rate	d	6.9%	income, CRFI, a=1/(1+d)	0.93545	30	0.07978
Interest	b	10.0%	Capital recovery factor for interest			
Term of loan, (yrs)	N	10	payments, CRFP, a=1/(1+b)	0.90909	10	0.16275

Calculated Values for Both Systems

		Grid Energy Only	Hybrid System Grid Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	2,888,800	2,888,800
Initial payment on system	Ad	0	0	2,888,800	2,888,800
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
Grid energy cost per annum	Af = FL * FC	7,642,071	7,391,371	0	7,391,371
NPV of energy costs	Afnpv = Af * PWFF	135,642,573	131,192,788	0	131,192,788
Overhaul cost per annum	Ao	0	0	8,000	8,000
NPV of overhaul costs	Aonpv = Ao * PWFO	0	0	141,996	141,996
O&M costs per annum	Am	0	0	40,606	40,606
NPV of O&M costs	Amnpv = Am*PWFO	0	0	720,740	720,740
Total annual costs	At = Ap+Af+Ao+Am	7,642,071	7,391,371	48,606	7,439,977
Total system NPV, TNPV	= Ad+sum(NPVs)	135,642,573	131,192,788	3,751,536	134,944,323
Annual savings	Sv = dsl At - hbd At				202,094
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.101	0.101	0.085	0.100
Payback period, years	P = C / Sv				14.29
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P =		0.000		5.7%

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

Average Wind Speed	Wind COE	System COE	Payback	IRR
6.4	0.096	0.100	16.70	4.3%
7.0	0.085	0.100	14.29	5.7%
7.7	0.076	0.100	12.48	6.9%

Wind Energy COE vs Average Wind Speed

System COE vs Average Wind Speed

COE ($ / kWh)

Average Wind Speed (m/s)	COE
6.4	0.100
7.0	0.100
7.7	0.100

Payback vs Average Wind Speed

Payback (years)

Average Wind Speed (m/s)	Payback
6.4	16.70
7.0	14.29
7.7	12.48

IRR vs Average Wind Speed

Internal Rate of Return

Average Wind Speed (m/s)	IRR
6.4	4.3%
7.0	5.7%
7.7	6.9%

ECONOMIC ANALYSIS   **Site:** Fort Huachuca, AZ, DCP16, 36 m, 6.4 m/s
                            Turbine: 225 kW, Commercial
                            Quantity: 8

Input Values

			Economic Factors			
				a variable	n variable	Y(a,n)
System load, (kWh/y)	SL	107,634,800	Present worth factor of fuel			
Grid energy (kWh/y)		104,592,474	costs, PWFF, a=(1+e)/(1+d)	0.96352	30	17.74945
Wind energy (kWh/y)		3,042,326	Present worth factor of O&M			
Diesel fuel usage, no wind (l/yr)	FL		costs, PWFO, a=(1+i)/(1+d)	0.96352	30	17.74945
Diesel fuel usage, with wind (l/yr)	FL		Present worth factor of interest			
Grid energy cost ($/kWh)	FC	0.071	payments, PWFP, a=1/(1+b)	0.93545	10	7.05616
System life, (yrs)	L	30				
General inflation	i	3.0%		a variable	n variable	X(a,n)
Grid energy inflation	e	3.0%	Capital recovery factor for system			
Discount rate	d	6.9%	income, CRFI, a=1/(1+d)	0.93545	30	0.07978
Interest	b	10.0%	Capital recovery factor for interest			
Term of loan, (yrs)	N	10	payments, CRFP, a=1/(1+b)	0.90909	10	0.16275

Calculated Values for Both Systems

		Grid Energy Only	Hybrid System Grid Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	2,888,800	2,888,800
Initial payment on system	Ad	0	0	2,888,800	2,888,800
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
Grid energy cost per annum	Af = FL * FC	7,642,071	7,426,066	0	7,426,066
NPV of energy costs	Afnpv = Af * PWFF	135,642,573	131,808,600	0	131,808,600
Overhaul cost per annum	Ao	0	0	8,000	8,000
NPV of overhaul costs	Aonpv = Ao * PWFO	0	0	141,996	141,996
O&M costs per annum	Am	0	0	34,987	34,987
NPV of O&M costs	Amnpv = Am*PWFO	0	0	620,996	620,996
Total annual costs	At = Ap+Af+Ao+Am	7,642,071	7,426,066	42,987	7,469,052
Total system NPV, TNPV	= Ad+sum(NPVs)	135,642,573	131,808,600	3,651,791	135,460,391
Annual savings	Sv = dsl At - hbd At				173,018
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.101	0.101	0.096	0.100
Payback period, years	P = C / Sv				16.70
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P =		0.000		4.3%

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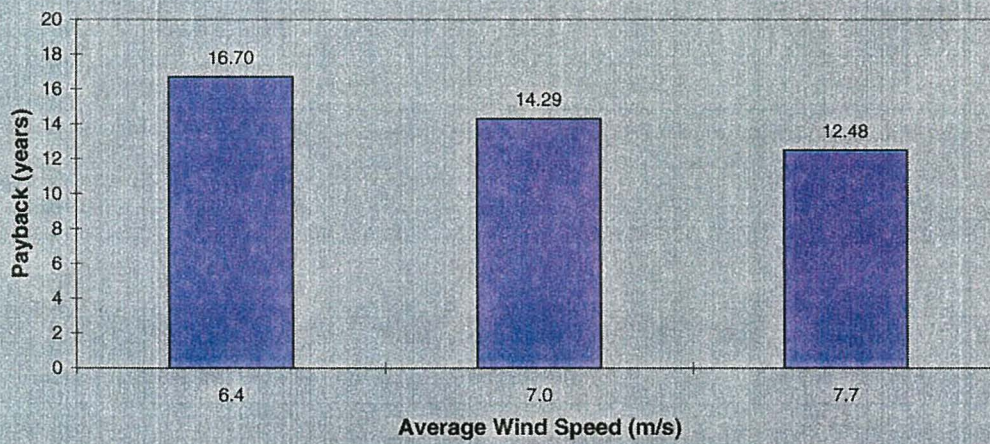
ECONOMIC ANALYSIS

Site: Fort Huachuca, AZ, DCP16, 36 m, 7.7 m/s
Turbine: 225 kW, Commercial
Quantity: 8

Input Values

System load, (kWh/y)	SL	107,634,800				
Grid energy (kWh/y)		103,609,969				
Wind energy (kWh/y)		4,024,831				
Diesel fuel usage, no wind (l/yr)	FL					
Diesel fuel usage, with wind (l/yr)	FL					
Grid energy cost ($/kWh)	FC	0.071				
System life, (yrs)	L	30				
General inflation	i	3.0%				
Grid energy inflation	e	3.0%				
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)	0.96352	30	17.74945
Present worth factor of O&M costs, PWFO, a=(1+i)/(1+d)	0.96352	30	17.74945
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	30	0.07978
Capital recovery factor for interest payments, CRFP, a=1/(1+b)	0.90909	10	0.16275

Calculated Values for Both Systems

		Grid Energy Only	Hybrid System Grid Part	Hybrid System Wind Part	Hybrid System Total
Capital cost	C = ICC+BOS	0	0	2,888,800	2,888,800
Initial payment on system	Ad	0	0	2,888,800	2,888,800
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
Grid energy cost per annum	Af = FL * FC	7,642,071	7,356,308	0	7,356,308
NPV of energy costs	Afnpv = Af * PWFF	135,642,573	130,570,436	0	130,570,436
Overhaul cost per annum	Ao	0	0	8,000	8,000
NPV of overhaul costs	Aonpv = Ao * PWFO	0	0	141,996	141,996
O&M costs per annum	Am	0	0	46,286	46,286
NPV of O&M costs	Amnpv = Am*PWFO	0	0	821,543	821,543
Total annual costs	At = Ap+Af+Ao+Am	7,642,071	7,356,308	54,286	7,410,593
Total system NPV, TNPV	= Ad+sum(NPVs)	135,642,573	130,570,436	3,852,339	134,422,775
Annual savings	Sv = dsl At - hbd At				231,477
Levelized cost of energy, COE	= TNPV*CRFI/SL	0.101	0.101	0.076	0.100
Payback period, years	P = C / Sv				12.48
Internal rate of return, IRR, (x)	[(1+x)^L-1]/[x*(1+x)^L] - P =	0.000			6.9%

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

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The objective of this joint DOE and National Renewable Energy Laboratory (NREL) Strategic Environmental Research and Development Program (SERDP) project is to determine whether wind turbines can reduce costs by providing power to U.S. military facilities in high wind areas. In support of this objective, one year of data on the wind resources at several Fort Huachuca sites was collected. The wind resource data were analyzed and used as input to an economic study for a wind energy installation at Fort Huachuca. The results of this wind energy feasibility study are presented in the report.

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