WIND ENERGY ASSESSMENT OF THE PALM SPRINGS-WHITewater REGION,
CALIFORNIA, U.S.A.

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Summary

In 1978 and 1979, sponsored by the California State Energy Commission and the Southern Californian Edison Company, AeroVironment Inc. conducted a major survey of the wind energy in the Palm Springs-Whitewater region, an area dominated by the San Gorgonio Pass. The pass, of about 8 km width and 50 km in E-W extent is 130 km East of Los Angeles, connecting the coastal plains with the inland desert. Ground level is at 460 m MSL with steep escarpments rising to 2,700 m MSL to North and South. Continuous strong Westerlies prevail. The survey identifies a major energy resource in the area. A large region has an annual average wind energy flux at 50 m height exceeding 600 W/m² with parts of this area exceeding 1,200 W/m². Detailed measurements include diurnal, seasonal and annual wind characteristic at 19 sites. These include wind duration curves, turbulence, speed variation with height and expected storm statistics.

Wind data was collected from historical and existing meteorological records, from vegetation flagging studies, and from the field stations erected for this program providing continuous records at the 10 m level. High altitude surveys (150 m) were conducted using a new kite anemometer system. Geographical, seismic, geological, and environmental surveys were also made. All of these, coupled with the intense winds, indicate an outstanding energy potential. Arrays of 4 MW wind turbines could be located in the San Gorgonio Pass providing an equivalent annual average power of 2,300 MW.

The methodology described represents a reliable and cost-effective method of assessing the wind potential of a region. From insights developed in Palm Springs-Whitewater Study, new techniques for rapid initial screening using readily available short-term data were developed. These were utilized and examined in an associated study in the Tehachapi Mountains, an area quite different from the Palm Springs-Whitewater region. This coastal range is located about 130 km north-northwest of Los Angeles and consists of rolling, grassy terrain of about 1400 m MSL. The techniques proved very effective, and were validated by detailed measurements. The monitoring in the Tehachapis identified significant areas having wind energy flux of 400 W/m² at 50 m height with portions at 500 W/m².
1. Introduction

The State of California is making a significant effort to promote the development of mainline power by wind energy (Ginosar, 1979; Lerner, 1979). As a part of this program, the California Energy Commission (CEC) and the Southern California Edison Company (SCE), a major electrical utility for the Los Angeles area, commissioned AeroVironment Inc. to make a wind energy resource assessment of the Palm Springs-Whitewater region (PSWR), an area which has been shown by preliminary studies to have an excellent wind energy potential.

The prominent topographic feature of this region is the San Gorgonio Pass, which has traditionally been regarded as a "windy" area. It is a narrow east-west pass of about 8 km in width, situated about 130 km east of Los Angeles, California, and connecting the coastal plain with the Coachella Valley and the inland desert. The floor of the pass (460 m MSL) is typical desert terrain (Figure 1-1), with the southern wall the San Jacinto Range (about 2750 m MSL) and the northern wall the San Gorgonio Range of comparable height. The study area (Figure 1-2), centered east of the pass itself, is of about 36 km east-west extent and about 16 km wide.

With its strong prevailing winds, closeness to the large metropolitan Los Angeles power system, and good topography and accessibility for construction, it is an extremely attractive site for installation of large multi-megawatt wind energy systems.

Wind turbines represent a solar energy technology which is available in the short (five- to ten-year) time frame. Current estimates of large units (2 to 4 MW) indicate that their plant cost will make them competitive with fossil- or nuclear-fired plants, provided they are sited in areas of strong continuous winds. Although many factors enter into this cost evaluation, a rule of thumb is that a site with an effective average annual continuous wind (the energy wind) of about 7.5 m/s will be cost effective with modern wind turbine units. In this study, energy winds of 9.9 m/s have been measured in a significant area of the Pass, with portions of this area recording seasonal wind exceeding 12.5 m/s.

In order to estimate the annual energy output of wind turbines it is necessary to determine the wind speed characteristics of the site and to couple these with the turbine performance characteristics. The most important wind characteristic is the wind duration curve, which defines the fraction of time that each wind speed occurs, determined over a monthly, quarterly, or annual period. For the turbine characteristics, the major features are the cut-in wind speed (at which the turbine starts operating), and the rated speed (at which full power is delivered), and the cut-out speed (at which the turbine shuts down to prevent overloads). These characteristics affect not only the energy capture, but also the cost of the wind turbine unit. The magnitude and character of the wind turbulence is also of interest to the turbine designer, while the spatial correlation of wind energy at different sites is of interest to the energy planner.

This report describes the salient features of the wind resources in the PSWR. Extensive details may be found in the five volume final report submitted to SCE and the CEC (Zambrano et al., 1980). The above-referenced report was designed to present a framework from which others could study wind energy policy could make rational analytical estimates. The present decisionmakers in wind energy assessment program. An improved technique, based on the knowledge Southern California, the Tehachapi Mountain Range (Figure 1-2), and the present report also Zambrano (1980).

The basic goal of the program was to determine the amount of power available from the winds of the PSWR. There are at least three levels of precision for such a study. The first is a regions of significant wind energy flux; that is, good areas for wind turbines. Such studies have Whitewater region as one of the more promising wind energy development locations in resolution, identifying particular places -- for example, the crest of a long ridge, the side of a valley -- where the wind energy flux is maximum, and characterizing the isovents (lines of
constant wind speed) in sufficient detail that the effects of local topographic features are recognized. This level of resolution was the goal of this wind assessment of the PSWR.

The final level consists of the specific definition of the wind turbine tower foundations and, in complex terrain, would involve a resolution of about 100 m. In more regular terrain, the wind uniform plain, it might be expected that the exact placement of units would not be too important. In this case, though, it will be necessary to consider an array of turbines, constituting the boundaries of the uniform field -- that is, at the edge of the plain.

The above level of definition is the objective of a current SCE/CEC-sponsored study of the PSWR, being conducted by AeroVironment Inc.

2. Field Assessment Studies

The field program was conducted over a one-year period, starting in June 1978. Initially, wind measurements were taken at 32 locations throughout the PSWR using hand-held Gill propeller anemometers when the wind was from the west, the prevailing direction. These data were reduced to give average wind speed and turbulence intensity, and were correlated with measurements recorded at the Department of Energy tower at Devers, located northeast of the San Gorgonio Pass. These surveys indicated areas of high, moderate, and low wind speeds.

An initial field survey study was made to investigate wind-deformed vegetation, and the general accessibility and exposure throughout the region. Numerous well-defined areas of vegetation flagging and wind-induced effects were observed and are described. An example of vegetation flagging is given in Figure 2-1.

As a result of this survey, 19 sites for permanent wind instrumentation were selected and automatic anemometer stations installed there. These stations measure wind at 10 m from the local ground level. However, wind turbines are likely to have rotors of up to 100 m in diameter. To determine the winds and turbulence at heights of 75 m from the ground, special kite anemometers (TALA system) were used (Figure 2-2). Wind profiles measured at several locations indicated a slight increase in wind speed with height. The power law exponents calculated from the TALA measurements between 10 m and 100 m heights were between 0.07 and 0.09; while those measured with anemometers between 2 m and 10 m heights gave a value of 0.13. For this study, a power law of 0.10 was chosen to reflect a conservative estimate based on these preliminary measurements.

The permanent wind instruments consisted of cup anemometers, provided by the Weather-Measure Corporation, mounted on 10-m high masts. Wind speed was recorded on single-channel Rustrak strip recorders with signal conditioning circuitry designed and built by AeroVironment. For some stations, wind direction also was recorded using Meteorology Research Inc. (MRI) Model 1074 mechanical weather stations.

Performance and data acquisition of the wind stations were excellent, although it is of interest that there were a number of anemometer cup bracket fractures due to excessive wind loads and also a heavy incidence of damage to stations by vandalism. The remote and hostile pass area is frequented principally by hunters in off-road vehicles and it appears that the stations were damaged by rifle shots.

3. Data Analysis

The wind station data was recovered every three weeks and the wind characteristics were analyzed. Monthly summaries were prepared for each site giving, for each day and month:

- average hourly wind speed and direction,
- diurnal average wind speed and direction variation,
- hourly peak wind speed.

In addition, the important wind speed frequency distribution analysis was made, generating the wind speed duration curves for each site. Such data is necessary to calculate wind turbine
performance. These curves are given for each site and for monthly, seasonal, and annual periods. A typical set of such curves is shown in Figure 3.1.

Extensive methods of computer automated data processing were developed, making it possible to go directly (that is, without human processing) from digitized field data to automatically plotted wind speed frequency distribution (WSFD) curves of the type shown in Figure 3-1. To guard against computer processing errors, additional human-interpretable charts were automatically printed, showing for each station the wind speed and direction for every hour logged. These could be studied to check that reasonable data was being logged.

Much other processing of data was done. For example, joint frequency distributions of wind speed and wind direction were prepared, while the WSFD curves were least-square fitted to Weibull parameters determined (Zambrano, et al., for Weibull probability distributions) and the Weibull curves provided good fits for all the data obtained (1980). It is of interest that the Weibull curves provided good fits for all the data obtained, although as can be inferred from Figure 3-1, the Weibull parameters differ seasonally and by site. An example of this is shown in Figure 3-2, which displays the WSFD for Site 2, a station at the western end, in one of the narrower defiles of the Pass.

Other processing included the determination of diurnal speed variation, as well as the mean wind speed and peak hourly wind speeds, all presented by month, season, and site. This information is not extractable from the energy data integrated in the form of a WSFD, but is of extreme importance to the turbine designer, who requires the turbulence and the gust data to assure satisfactory structural and mechanical operation. Analyses of the extreme wind speeds, (of interest for survival design) were also made, although the study was not long enough to obtain valid long term extremes. Some tentative results of interest have been obtained. These are that, in the study region, significant wind speeds above 20 m/s (normal turbine cut-out speed) occur every year, but speeds greater than 27 m/s do not occur for significant times. However, it may be expected that at least once every year there will be a five second gust exceeding 45 m/s.

Cross-correlation of every site pair was also made. This is of interest to planners of wide spread turbine arrays. The significance of these correlations indicates the extent to which the wind blows as a unified flow in the area. For example, a high negative correlation would indicate that the wind is strong at one site when it is weak at the other. Such a situation never occurred and all correlation coefficients were positive and of the order of 0.5. An interesting conclusion of this data, coupled with that described in the previous paragraph, is that every day of the year there is at least one surveyed site where a turbine would be generating power, and further that the probability exceeds 50% that the turbine will be developed full rated power.

As a final input, the synoptic patterns of each season are given, with meteorological descriptions of the flow system in the pass. The general pattern is dominated by the location and strength of the semi-permanent eastern Pacific high and the desert low in the southwest desert region. Throughout the year, these cause westerly air mass movements through the Pass. Eight basic flow patterns were observed in the study period. Figure 3-3 shows the westerly airflow of a spring afternoon. The Santa Ana, a strong hot, mistral-like, northeasterly wind, blowing in late fall and the subject of much Californian legend, adds significantly to the wind energy flux.

An important point in applying this data is the extent to which the study year is representative of a long-term average year. This issue is studied and discussed using historical data, and it is apparent that the study year is, indeed, a representative year.

4. Descriptive Geography and Environmental Analysis

It is of cultural interest that the PSWR has long been known for its winds. In the 1850s, William P. Blake, surveying the area for a railroad from the Mississippi to the Pacific, reported (Blake, 1857)

"... the wind is not an ordinary shifting breeze, but is a constant and powerful current of air sweeping through the pass from the west. It pours in from the Pacific in an apparently unbroken, unvarying stream, passing over the surface with such violence that all the fine grains of sand are lifted from the dry channels of the streams and are driven along the slope of San Jacinto... the pass is a great draught channel from the ocean to the interior..."
through which air flows with peculiar uniformity and persistence thus supplying the partial
vacuum caused by the ascent of heated air from the surface of the parched plains and
deserts... It is very desirable that meteorological observations should be made at this
pass."

These observations were not made, and in a later study of the PSWR, R. J. Russell, the
geologist, noted (Russell, 1932) that "few regions of such unusual climate interest are still so
little known from the standpoint of precise meteorological information." The present report
finally gives some of this needed data.

In general terms, the PSWR is a depressed trough filled to an unknown but very great depth
by recent sediments. Considering only the floor, it appears to be an elongated depression of the
earth's crust between two parallel faults. Annual precipitation in the PSWR is low, about 0.38 m
per year, falling mainly from December to March. Snow is very rare. Generally, the area is arid
with no major streams or water wells.

The San Andreas and San Jacinto faults are near the region; the latter is the most active.
In 1948 a strong earthquake of 6.5 magnitude occurred with its epicenter half a mile east of Site
16 of the present survey.

Between 1920 and 1957, eight petroleum exploration wells were drilled in the study area;
all were dry and geological reports assert there is little possibility of commercial strikes in this
region. Sand and gravel for aggregate and decorative stone are the only commercial mineral
commodities produced in the PSWR.

The PSWR contains the classic California Desert flora. The most common plants are the
Creosote bush, the Bigelow cholla, and Mesquite. Yucca, Juniper, and Cottonwood trees, and
Ocotilla are found, as well as America's only native palm, the Washingtonia, which graces several
oases.

Big Horn Sheep, White Pelicans, and Golden Eagles have been observed in the San Jacinto
Range to the south, while the rare fringe-toed lizard is to be found in the eastern portion.
However, there are no endangered species in the study area, and any bird kill possibility due to
turbines is believed to be minimal.

Possible wind turbine effects on microwave interference and the aesthetic effects (both
visual and noise) have been studied. Because of the small population and limited activity in the
region, these are not considered critical. The region is not regarded today as being of
spectacular scenic attraction.

5. Power Availability Estimation

Using the wind duration curves determined from the analysis, wind energy flux at 50 m
height (approximately the hub height of a large multi-megawatt wind turbine) was determined
and regions of different energy levels for each season plotted. The annual energy flux level is
shown in Figure 5-1. It is noted in this figure that there is a region centered in the PSWR of
about 12 km east-west and 8 km north-south extent where this annual wind energy flux exceeds
600 watts per square meter. This is a very significant amount, corresponding to a constant
average wind (the energy wind) of 9.9 m/s. Within this region, energy winds of 12.5 m/s have
been measured.

The actual capture of this energy depends upon wind turbine size and operating character-
istics. For the study, three hypothetical turbines, based on designs by the Boeing Engineering &
Construction Company, have been used. These are in the class of the NASA MOD-2 unit, and are
all 91 m diameter, two-blade propeller-type machines, but designed for different wind speeds,
and thus of different ratings, as is shown in Figure 5-2.

Using the characteristics of these turbines and the wind duration curves for specific sites,
the annual energy output can be determined by season and year. These outputs, for six actual
the annual energy output can be determined by season and year. These outputs, for six actual
the annual energy output can be determined by season and year. These outputs, for six actual
sites, are shown in Table 5-1. The capacity factor is defined as the ratio of the average power
site, annual capacity factors of about 0.40 are obtained, with seasonal
example, at the Devers site, annual capacity factors of about 0.40 are obtained, with seasonal
values as high as 0.57 during the windiest quarter, spring. These are remarkable when compared with capacity factors for fossil-fired power plants, which are generally about 0.65.

Energy cost estimates have not been made since these depend upon turbine cost and are currently not well-defined.

Additional studies have been made to determine the mutual interference of arrays of wind turbines. It is estimated that the shielding, due to a close array, would reduce the turbine output by about 10%. On this basis, about 650 MOD-2-type units could be placed in the prime wind area of the PSWR, providing an annual average power of about 740 MW.

An analytical development of methods appropriate to define the wind loads for structural design has also been given. This includes discussion of single point and two point statistics for rotor loadings, as well as methods of establishing the various appropriate turbulent length scales. From these techniques design loads, extreme or survival loads and endurance loadings can be determined. Actual figures for such results depend upon specific turbine designs and are not part of this analysis.

6. Techniques for Rapid Initial Screening of Wind Energy Sites

As a consequence of the extensive PSWR study, new insights into the technique of site selection were developed and an improved procedure was proposed. This procedure was tested in the Tehachapi Mountains, a range about 130 km north-northwest of Los Angeles, comprised of rolling, mountainous country at elevations of about 1400 m MSL and vegetated mainly by grass and sagebrush with California oak at lower elevations (Figure 6-1). The project was conducted by AeroVironment Inc. under funds provided by the U.S. Department of Energy (Contract No. B-23453-A-H) and is reported by Zambrano (1980).

The methodology essentially involved selecting promising wind sites by preliminary screening of available data, by overflying and closely examining the topography, by examining natural wind indicators, and by conducting, during potential site visits short-term wind measurements (check anemometry) using the TALA system. Anemometry stations were then installed so that accuracy of the preliminary assessment could be validated. The results showed that a site survey involving short-term field measurements, ecological surveys, and wind monitoring can be a very effective and economical tool for preliminary evaluation, provided it is conducted by a properly qualified team.

The first step involved an initial screening of the site using available data, and a tour of the area. Of the 240 square km of the region, only the 50 square km area which contained the major ridgelines was considerable suitable. A preliminary site investigation showed that in this remaining area there would most probably be one orographic feature every 2.5 square km which would make a local area suitable. Due to land access problems, wind monitoring instrumentation was installed at 16 of the 20 areas, or candidate sites.

The second step investigated those 16 sites in a detailed field assessment survey conducted during a one-week period when winds were from the dominant northwest direction. The aim of disadvantages of wind monitoring techniques to judge the merits and technique -- namely, ecological features, check anemometry, and accessibility and serviceability of the monitoring equipment. For each wind energy assessment station, each site was ranked with respect to the other 15 in order of merit. This was a three sets of rankings into a matrix to obtain, from best to worst, the sites most suitable for TALA kites proved to be a versatile field instrument and continually indicated there was no involvement of the development of a correlation between annual wind speed and the deformation indexes this study application, were shown to be satisfactory low-cost field instruments.

In the third step, 9 sites from the original 16 candidate sites were equipped with 10 m monitoring stations. Wind speed and direction were continuously recorded over a six-month period. As a result of cost constraints, only two of the nine stations included wind direction
monitoring capabilities. However, for future surveys it is recommended that the importance of continued for an additional six months with the support of the CEC.

Using the recorded six-month data, results from the field assessment survey, and continued TALA measurements, a wind field analysis, power availability estimate, and a comparison of wind energy assessment techniques were made. The wind field analysis identified four basic wind patterns and their detailed characteristics are described by Zambrano (1980).

The wind frequency distribution plots for each site were determined and the wind energy flux plotted on seasonal (summer and fall) and annual (estimated) basis. There is a ridge line area of approximately 11 km in length where the annual wind energy flux is estimated to exceed 400 watts/m², corresponding to an average wind of about 9 m/sec at the 50 m level, with some portions showing seasonal wind energy flux exceeding 500 watts/m² (an energy wind of 9.8 m/s).

Comparisons of the six-month recorded data to field assessment survey results showed that the wind energy assessment techniques used were able to identify sites which were most immediate and reliable for turbine installation, and also those with marginal development potential.

7. Conclusions

The general goals of the work were to make detailed wind measurements of the PSWR with a view to determining its potential as an area for a wind energy farm, and to adapt the methods to a different region (Tehachapi) and check their validity there. An additional goal was to make preliminary studies of other areas of concern in a wind turbine energy farm, specifically environmental issues and engineering details related to turbine spacing, power outputs, and structural loads due to atmospheric turbulence. These goals were accomplished.

A summary of the conclusions is:

1. The development of a number of large scale wind energy arrays for electricity production in the Palm Springs-Whitewater Region is a realistic goal.

2. An annual energy output of $6.5 \times 10^9$ kWh could be obtained from the most promising subregion of the PSWR, using 650 turbines rated at 4 MW each.

3. At this level of analysis there do not appear to be significant environmental or institutional issues which would impede turbine installation in the PSWR.

4. The data collection, logging, and reduction methods employed represent reliable and cost-effective techniques to assess wind potential.

5. Results of the Tehachapi study indicate that it is possible to make an initial selection of good wind sites rapidly and economically.

As with any large scale engineering project, there are more specific questions which need to be addressed as the program matures. Because of this, the California Energy Commission and Southern California Edison Company are currently funding AeroVironment for additional site-specific and machine performance oriented wind energy projects. A new project in the PSWR includes the erection of a 100 m meteorological tower system with full wind assessment capabilities to monitor wind speed and direction, temperature, pressure, and turbulence. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity. The system will monitor at four levels above the ground and thereby provide accurate intensity.
8. **Acknowledgements**

A program of this magnitude and complexity involves many intricate interactions and problems; technical, administrative, and political. The authors express their warm appreciation and gratitude to the sponsor agencies for the outstanding fashion in which their staff responded with imagination and flexibility to every situation, thus freeing AeroVironment to concentrate on getting the job done.

The authors acknowledge the outstanding efforts of Dr. Matania Ginosar of the California Energy Commission, technical director and program manager for the work and of Dr. James Lerner of CEC. Their skill, enthusiasm, and encouragement was matched by that of Mr. Robert Scheffler, program manager, and Mr. Robert Yinger of Southern California Edison. We express our gratitude to the above individuals, whose efforts made the long task always a pleasant exercise. Numerous specialists cooperated on the AeroVironment team and we would like to make special mention of the sterling contribution of John Wade, Robert Baker and Melvin Smith.

9. **References**

Blake, W. P.: "Geological report of Lieutenant R. S. Willilamson on explorations and surveys to ascertain the most practical and economic route for a railroad from the Mississippi River to the Pacific Ocean," 1853:33rd Congress, 2nd Session, Senate Executive Doc. 78, Vol. 5 (1857).


Fig. 1-1 Typical desert terrain of the Palm Springs-Whitewater Region

Fig. 1-2 Wind energy study regions in Southern California. Outlined are two major areas of wind energy research.
Fig. 2-1 Wind-flagged Juniper tree near Whitewater, in the PSWR

Fig. 2-2 TALA kite used in field survey
Fig. 3-1 Wind speed duration curves for selected sites
Fig. 3-2 Seasonal wind speed frequency distribution for Site 2 (dotted line is Weibull fit with $C$ and $K$ the Weibull parameters, $\bar{V}$ is the actual mean wind speed)
Spring Afternoon - 22 April 1979

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<td>1800</td>
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Site

1 | 7 | 13 | 16 | 18
---|---|----|----|----
| W | S  | WNW| WSW| WSW|
| W | SSW| NW | W  | W  |
| W | WSW| WNW| WSW| W  |
| W | WSW| W  | W  | W  |
Table 5-1 Estimate of MOD-2 type average seasonal power and total energy output for specific sites of interest, August 1978 to July 1979
Fig. 5-1 Wind energy density flux distribution in the PSWR
Fig. 5-2 Wind turbine configurations

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Fig. 6-1 Typical terrain of the Tehachapi region