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# PACIFIC NORTHWEST REGIONAL ASSESSMENT*

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## INTRODUCTION

Rapid commercial utilization of wind as a source of electric power is the principal goal of the Federal Wind Energy Program. Assessments of the wind resource play an important role in achieving this goal, because utility planning, wind turbine manufacturing and marketing of wind energy conversion systems depend on detailed wind resource assessments. However, previous national-scale assessments and their synthesis (Elliott 1977) have not displayed the geographical and temporal detail needed to effectively plan a strategy for tapping wind as a viable source of energy.

The wind energy resource of the United States and its territories must be described in adequate detail to meet the needs of a variety of users. To meet these needs, the Wind Characteristic Program Element, managed for the U.S. Department of Energy (DOE) by Pacific Northwest Laboratory (PNL), developed, applied and tested techniques using existing wind information to assess the wind energy potential of the Northwest region. This assessment included Idaho, Montana, Oregon, Washington and Wyoming.

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Assessments in eleven other regions covering the United States will be patterned after the Northwest assessment. This standardization will result in regional assessments with compatible data resources and analysis methods and comparable presentation formats.

## APPROACH

Existing wind data provided the primary basis for assessing the Northwest's wind energy resource. Techniques were developed for identifying, screening and analyzing these data. However, in data-sparse areas, techniques using various indicators of wind energy, such as supplemental information on regional climatology, meteorology, topography, vegetation and eolian landforms, were developed and applied to deduce the wind energy. The wind data and qualitative indicators of wind power were combined to analyze the geographical distribution of wind energy in the region. During the analysis, methods were developed for treating variations in terrain, evaluating the representativeness of the wind power estimates and adjusting vertically the wind power throughout the region. The final phase in the assessment was to prepare a Northwest wind-energy atlas containing maps and graphs for describing the geographical distribution of the wind resource on a regional and state scale and for detailing wind characteristics for selected stations.

## TECHNIQUES

### Wind Data Screening

Table I indicates the sources and format of wind data that are available in the Northwest. However, not all of these data need to, or should, be used in a wind resource assessment.

Screening procedures were developed to identify stations with the most useful data and to eliminate stations that would not significantly contribute information on the distribution of the wind resource.

TABLE I. Number of Stations with Wind Data in the Northwest Region and Peripheral Area

| Source and Type | Available | Used in Assessment |
|---|---|---|
| National Climatic Center (NCC) | | |
| Summarized | 205 | 173 |
| Digitized | 97 | 61 |
| Unsummarized | 207 | 80 |
| U.S. Forest Service | 685 | 63 |
| Canadian Summarized | 34 | 34 |
| Other | 200 | 51 |

The index compiled by Changery et al. (1977) aided the screening of summarized data to find the most useful format. Stations were selected on the basis of summary format, length of record, changes in anemometer location and frequency of observation. Digitized data were acquired for some stations with wind summaries if they had moderate to strong winds and, when available, for stations located in areas with inadequate summarized data. Stations with nonsummarized wind data were selected for visual inspection of station records when they were found in areas of limited summarized or digitized data. The U.S. Forest Service data were selected for use if more than 70% of the once-daily observations exceeded 8 mph (3.5 m/s) (Marlatt et al. 1979). Data from Canada, ships, power plants and university research were incorporated if they were summarized and if the locations added to the understanding of the geographical distribution of the resource.

## Evaluating Wind Power

The average wind power density $\bar{P}$ (watts/m$^2$) in a vertical plane perpendicular to the wind direction for stations with one- or three-hourly digitized data was calculated, using:

$$\bar{P} = \frac{1}{2n} \sum_{i=1}^{n} \rho_i V_i^3$$

where n is the number of observations in the averaging period, $\rho_i$ is the density computed from the station pressure and temperature, and $V_i$ is the wind speed at the $i^{th}$ observation time. For stations with wind summaries, $\bar{P}$ was calculated from:

$$\bar{P} = \tfrac{1}{2} \bar{\rho} \sum_{j=1}^{c} f_j V_j^3$$

where $\bar{\rho}$ is the mean air density, c is the number of wind speed classes, $f_j$ is frequency of occurrence and $V_j$ is the median wind speed of the $j^{th}$ class. When an observed frequency distribution was not available, a Rayleigh distribution was applied to the mean speed to estimate the mean wind power.

## Adjusting The Wind Power

The power law equation, $V_r/V_a = (Z_r/Z_a)^{\alpha}$, was used to adjust average wind speed ($V_a$) from anemometer height ($Z_a$) to wind speed ($V_r$) at a reference height ($Z_r$) above the ground. For wind power, the exponent is $3\alpha$. An evaluation of tower sites throughout the United States and of airport stations, where the anemometer height had changed, revealed that an $\alpha$ of 1/7 is reasonable for adjusting mean wind speed and power at low roughness sites. Because the annual and seasonal wind power estimates represent well-exposed sites with low roughness in the direction(s) of the prevailing power-producing winds, an $\alpha$ of 1/7 was used to obtain the 10-m and 50-m values of annual and seasonal average wind power.

## Use of Indirect Indicators

In data-sparse areas, techniques using various indicators of wind energy may be applied to infer the wind energy potential available. These techniques include the use of meteorological and topographical features, vegetation features, eolian landforms, public surveys and model estimates. Of these, the meteorological and topographical indicators were of greatest benefit to the Northwest regional assessment. The following combinations of meteorological and topographical features were found to be indicative of high wind-energy potential: corridors in areas of frequently strong pressure gradients; long valleys parallel to prevailing winds aloft; high elevation plains and plateaus, and exposed ridge crests in areas of strong winds aloft; plains with persistent downslope winds from mountainous areas; and exposed coastal sites in areas of strong winds aloft and/or strong thermal/pressure gradients.

### Synthesis of Wind Data and Indicators

Annual and seasonal wind power maps for each state and the region, of the form shown in Figures 1 and 2, were constructed through a synthesis of the following: annual and seasonal wind power estimates for the surface stations and ridge crests, descriptions of site locations and qualitative indicators of wind power. Topographic relief maps were used to identify and outline the mountainous areas and significant terrain features.

## RESULTS

The analysis of the wind resource is presented in the atlas as a series of maps and graphs on various space and time scales. As the spatial resolution increases from region to state to individual station, the temporal resolution improves from annual average to seasonal averages to diurnal variations. The structure of the atlas is such that these scales are presented sequentially from region to individual station. Unfortunately, space limits each type of map or graph from being shown in this paper.

### Regional Features

Regional features of the wind resource are described by a set of maps that show: the cultural and physical geography, and annual average wind power and season of maximum wind power. The regional map of the annual average available wind power density (Figure 1) is a composite of the individual state maps. The classes of wind power density are defined in Table II. The width of the wind power classes is indicative of the accuracy to which the wind power density can be estimated. In some areas, the interannual variability of the wind power density may be even larger than the class interval suggests.

### State Features

The maps and graphs for each state are placed together. In addition, a grid one-third degree longitude by one-fourth degree latitide overlays these maps to facilitate locating a particular place on subsequent maps of wind power density. The map of annual average wind power density is followed by four maps depicting the winter, spring, summer, and autumn seasonal average wind power density. Figure 2 shows the seasonal maps for the state of Oregon. Class intervals of wind power density for the state maps are the same as for the regional map.

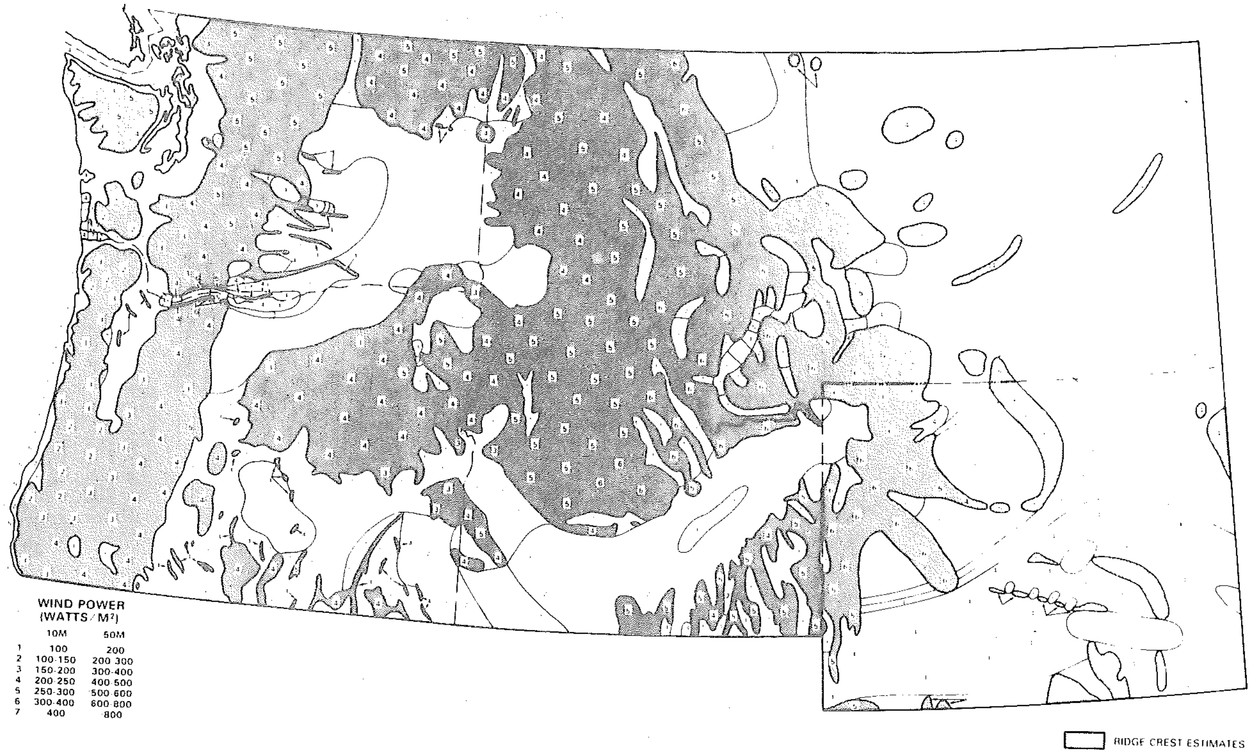



FIGURE 1. Northwest Annual Average Wind Power

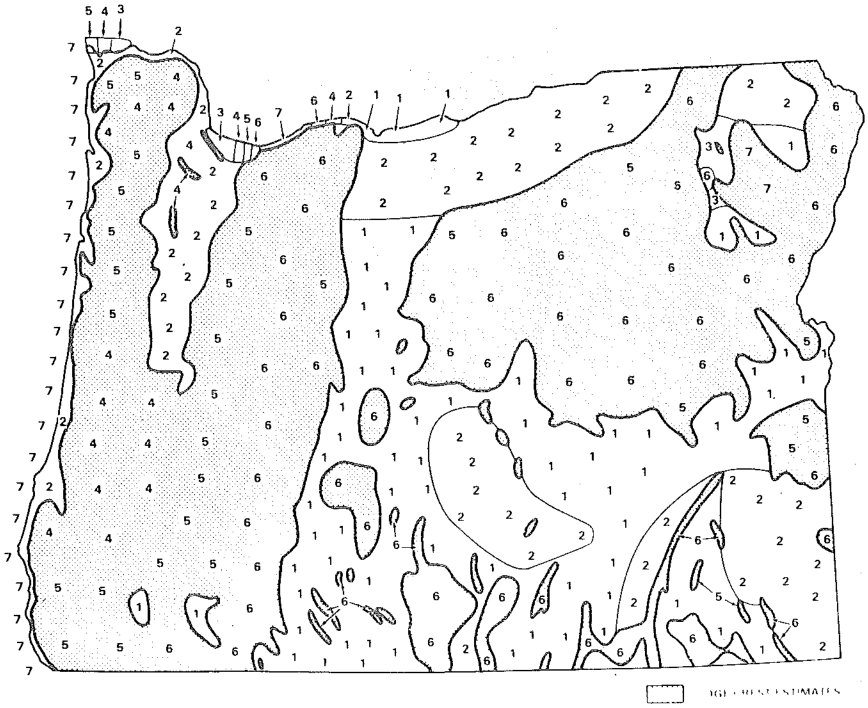
TABLE II. Average Wind Power Density and Speed[a] Classes

| Wind Power Class | Reference Level 33 ft (10 m) Wind Power Density, watts/m² | 33 ft (10 m) Speed,[b] mph (m/s) | 164 ft (50 m) Wind Power Density, watts/m² | 164 ft (50 m) Speed,[b] mph (m/s) |
|---|---|---|---|---|
| | 0 | 0 | 0 | 0 |
| 1 | | | | |
| | 100 | 9.8 (4.4) | 200 | 12.5 (5.6) |
| 2 | | | | |
| | 150 | 11.5 (5.1) | 300 | 14.3 (6.4) |
| 3 | | | | |
| | 200 | 12.5 (5.6) | 400 | 15.7 (7.0) |
| 4 | | | | |
| | 250 | 13.4 (6.0) | 500 | 16.8 (7.5) |
| 5 | | | | |
| | 300 | 14.3 (6.4) | 600 | 17.9 (8.0) |
| 6 | | | | |
| | 400 | 15.7 (7.0) | 800 | 19.7 (8.8) |
| 7 | | | | |
| | 1000 | 21.1 (9.4) | 2000 | 26.6 (11.9) |

a. Mean speed based on Rayleigh speed distribution of equivalent mean wind power density.

b. Wind speed for standard sea-level conditions; to maintain same power density, speed increases 5%/5000 ft (3%/1000 m) as elevation increases.

OREGON
WINTER AVERAGE WIND POWER



OREGON
SPRING AVERAGE WIND POWER

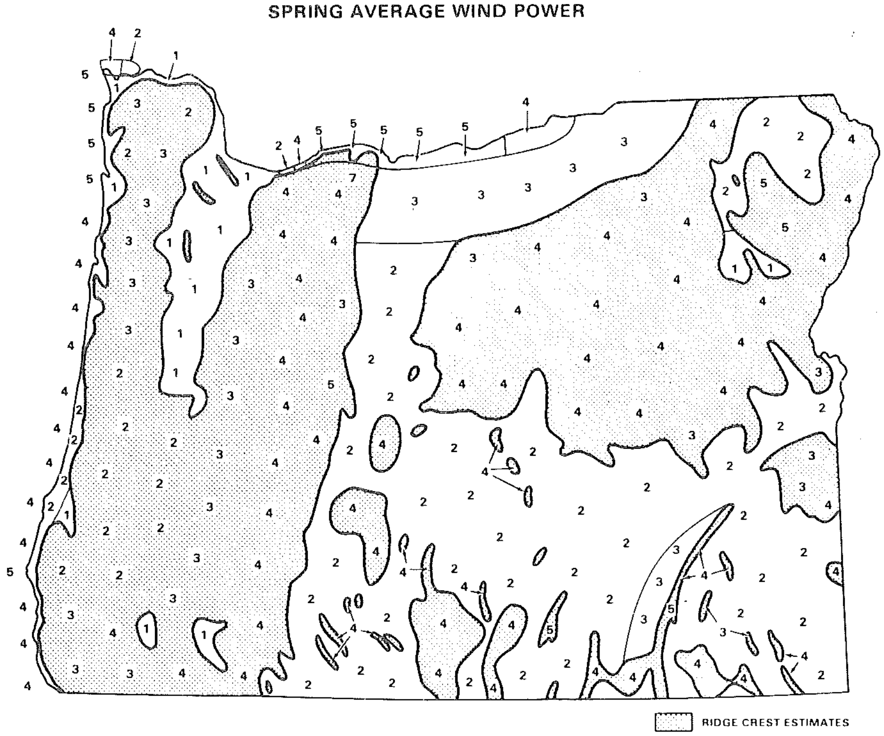
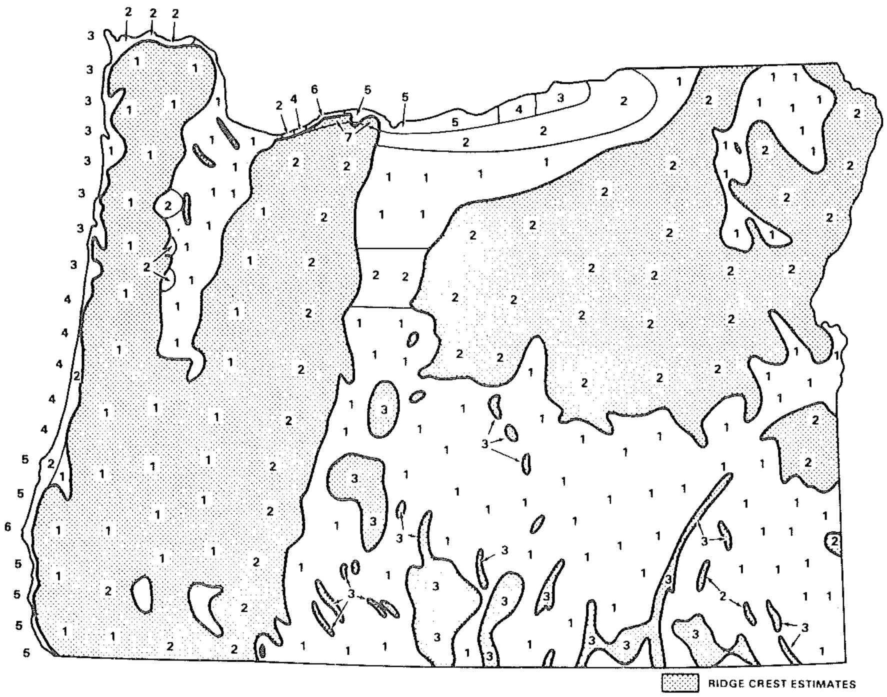



FIGURE 2. Seasonal Average Wind Power for Oregon

### OREGON
### SUMMER AVERAGE WIND POWER




### OREGON
### AUTUMN AVERAGE WIND POWER

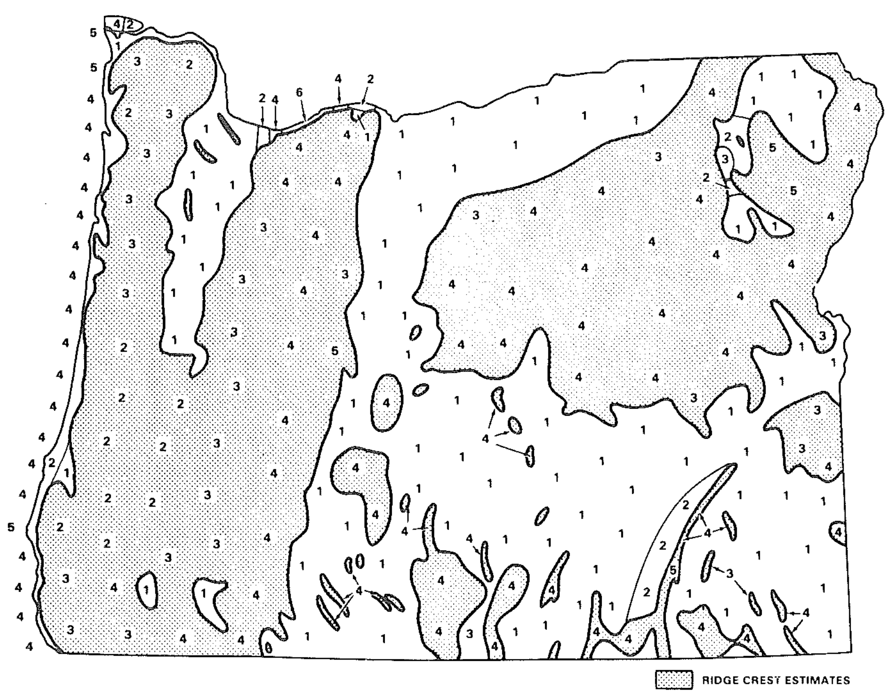



FIGURE 2. (continued)

## Station Features

The analysis of the wind resouce maps on a state and regional basis depends on information from individual stations. For those stations with one- or three-hourly data on NCC magnetic tapes, a very detailed presentation of the temporal variation and character of the wind resource can be obtained. However, the geographical area represented by a station may well be very small and, in many cases, not representative of the windiest or best-exposed sites in a particular area.

Figure 3 presents selected examples of the wind characteristics at one station. In the atlas, up to 18 graphs of the same type may appear on one page allowing convenient station-to-station comparison. The interannual graph (Figure 3a) illustrates the range of annual wind power density that can be expected. The seasonal variation of the wind resource is shown in the graph of monthly average wind-power density (Figure 3b). The variation of the wind resource during the course of an average day is given by the diurnal graphs for the four seasons (Figure 3c). A Rayleigh wind speed distribution based on the mean speed is shown (Figure 3d) along with the observed wind speed frequency distribution. The coincidence of the two peaks in the speed-direction graph (Figure 3e) indicates the highest wind speeds occur from the prevailing wind directions.

The numeric data from which these graphs are plotted, along with various other tables presenting relevant wind statistics, are included in the atlas as a set of microfiche cards, with one for each state.

# DISCUSSION

## Exposed Locations

The estimates of mean wind power, given in Figures 1 and 2, generally represent local terrain features that are favorably exposed to the wind. Exposed locations include mountain summits, ridge crests, hilltops, uplands, etc. In forested or wooded areas, the estimates are representative of large clearings with good exposure to the prevailing power-producing winds. In mountainous regions, the analyses also reflect major valleys.

## High Wind Resource Areas

Where are the good wind areas? The answer depends on many factors, one of which is the annual average available wind power density. Even with this single parameter, what is good to one user may not be adequate to another. For the purpose of this discussion, an average wind power density in excess of 200 watts/$m^2$ at 33 ft (10 m) or 400 watts/$m^2$ at 164 ft (50 m) will identify areas with an adequate wind energy resource. Areas in the Northwest satisfying this criterion (see Figure 1) are identified and described below.

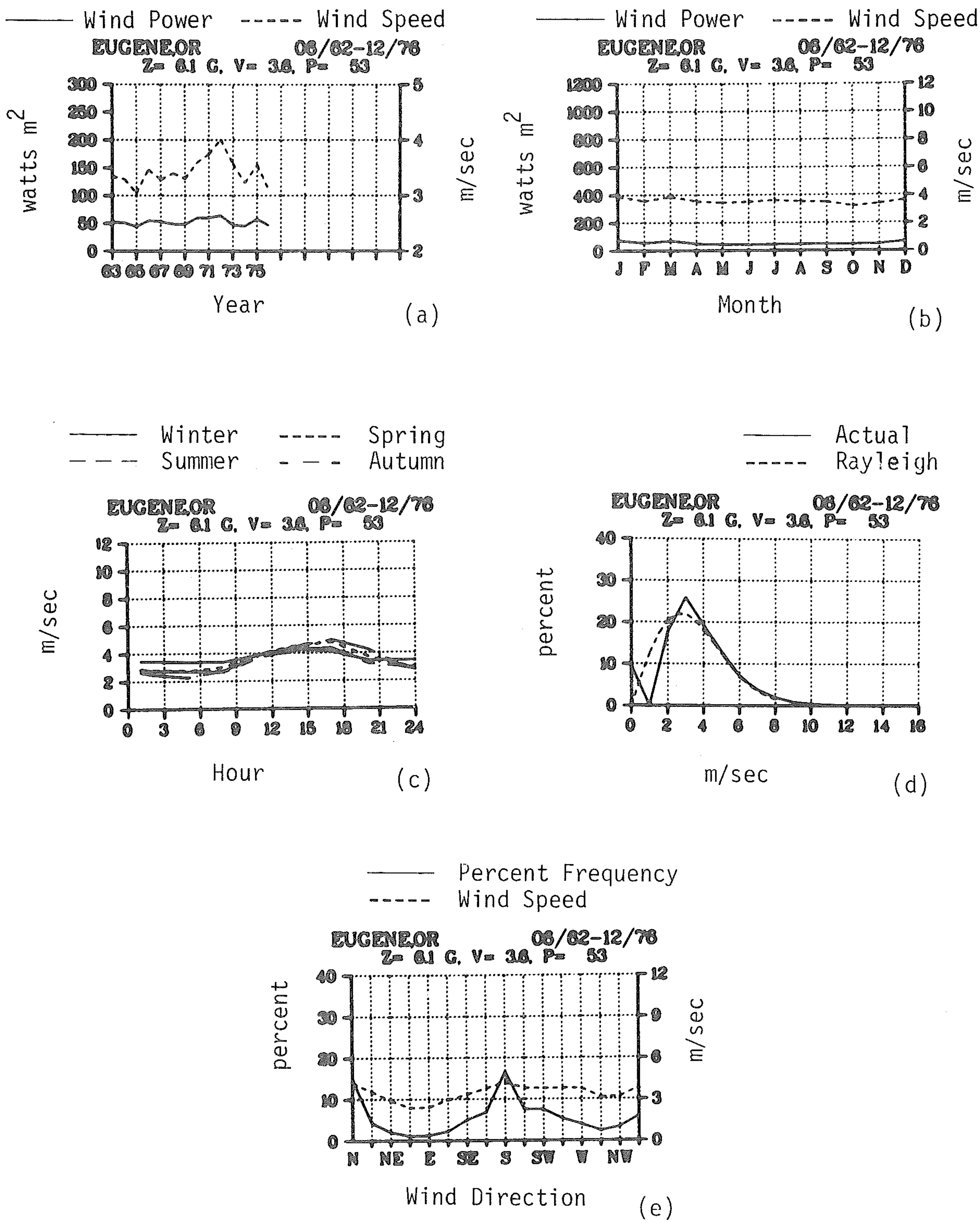



FIGURE 3. Wind Characteristics for Eugene, Oregon from 6/62 to 12/76. Anemometer at 20 ft, Average Speed 12.6 mph and Average Power 230 watts/$m^2$: (a) Interannual, (b) Monthly, (c) Daily, (d) Speed Frequency, and (e) Directional Frequency.

The Oregon and Washington coastal wind resource extends seaward farther than it is likely to be utilized. The abrupt increase in surface roughness, because of vegetation and topography inland from the beach, rapidly attenuates the wind resource landward of the beach. The seasonal variation of the coastal wind resource is linked to the seasonal displacement of the belt of prevailing westerly winds and storm tracks making winter the season of maximum wind speeds. However, during the summer, wind power is also high along the central and southern Oregon coast and is associated with the strong surface pressure gradients created by the cold water and hot interior.

The Columbia River corridor straddles the Oregon-Washington state border from just east of Portland, Oregon, to just west of Boardman, Oregon. The Columbia River gorge provides a low-elevation connection between continental air masses in the interior of the Columbia River Basin east of the Cascade Mountains and the maritime air of the Pacific Coast. Especially strong pressure gradients develop along the Cascades and force the air to flow rapidly eastward or westward through the gorge. Summer winds blow eastward from the cool, dense maritime air west of the Cascades to the hot, less-dense air in the Columbia Basin. In winter, the air in the Columbia Basin is cold in comparison to the maritime Pacific air, and the wind blows westward through the gorge. The windiest locations change with the season and are near the downwind end of the gorge.

The Central Washington corridor, near Ellensburg, Washington, is the location of another breech in the Cascade Mountain barrier between maritime and continental air. Unlike the Columbia River gorge, this gap is a mountain pass. As a result, in winter the cold, dense air to the east of the pass rarely becomes deep enough to spill westward into the Puget Sound area. However, in late spring and summer, the cool, marine air entering northwestern Washington is usually deep enough to flow over the pass and eastward through the corridor into the Columbia Basin. As a result, the wind resource in the upper Yakima valley and ridges to the east of Ellensburg is high during these two seasons. At Ellensburg, wind speeds are highest in early evening; the time of maximum wind is earlier or later to the west or east, respectively.

The Northwest Montana plains, eastward from the abrupt rise of the Rocky Mountains to about Cut Bank, Montana, experience strong winds in response to intense pressure gradients along the Rocky Mountains. The greater winter intensity of high-pressure systems over the mountains and low-pressure storm systems over the Canadian Great Plains gives this area a maximum wind resource during the winter. However, downslope winds during all seasons make the wind resource along the mountains greater than it is farther eastward on the Montana plains. A mid-afternoon wind speed maximum is typical of this area.

The Southwest Montana corridors, associated with the Jefferson River valley above Whitehall, Montana, and the Yellowstone River valley near Livingston, Montana, are high wind resource areas because strong pressure gradients occur in this area, and the channeling effect of the valley intensifies the winds set in motion by the pressure gradients. Both of these valleys have a very pronounced maximum winter, wind power density. Neighboring valleys and basins lacking the appropriate orientation show a rather poor wind resource. The data from Livingston show a diurnal pattern that depends more on the season than that found for Whitehall, although the wind speed shows an early- to mid-afternoon maximum for both.

The Southern Wyoming corridor marks a major gap in the north-south barrier of the Rocky Mountains through which the prevailing westerly and southwesterly winds can blow with little resistance. As a result, this area is one of the largest regions of non-mountainous terrain with a high wind resource in the Northwest. Winter is the season of maximum wind speed and the daily wind speed typically occurs in mid-afternoon.

Exposed mountain ridges and summits are widely distributed among the states of the Northwest region. Exposed locations on high-elevation terrain can tap the wind resource of large-scale atmospheric pressure systems with a minimal influence of surface roughness. Winter is again the season of highest wind speeds. However, at many summit and crest locations the daily wind speed maximum may occur at night.

### Distribution of the Resource

Wind speed and power can vary dramatically over distances of less than one mile, the degree of variation being strongly dependent on the topography. A map of land surface form (National Atlas 1970), such as in Figure 4 for the state of Oregon, provided information on the type of land surface. For each type of surface landform, the percentage of land area suitable to wind turbine siting was determined. Table III illustrates the variation of land surface area suitable to siting on different surface landform types. For example, the percentage of land area varies from 96% in smooth plains to less than 6% in very mountainous areas. The landform classification and average wind power were evaluated and processed for a grid one-fourth degree latitude by one-third degree longitude for all states in the region. The grids of terrain-adjusted wind power were used to determine the percentage of land area, by state and region, over which the wind power exceeds a given value. Figure 5 shows the distribution of wind power density with land area for the state of Oregon. Table IV summarizies similar curves for the states of the Northwest region by giving the percentage land area over which the wind power density at 50 (m) equals or exceeds 400 watts/$m^2$.

The land areas given in Table IV are sizable and many thousands of large wind turbines could theoretically be sited on these lands. However, such factors as land availability, access to roads and transmission lines or the presence of hazardous environments such as turbulence, icing or extreme winds have not been considered in this assessment of the wind resource. A determination of the electrical energy likely to be generated by wind turbines within a region will have to address these issues which go beyond assessing the meteorological status of the wind resource.

## CONCLUSIONS

Techniques developed by PNL appear to yield reasonable wind resource assessments when applied to the Northwest. Maximal use of available wind data and the use of various indirect indicators of wind speed allow the space and time resolution to be much improved over previous national-scale assessments. Furthermore, a wider audience of users can benefit from an atlas form of presenting the assessment.

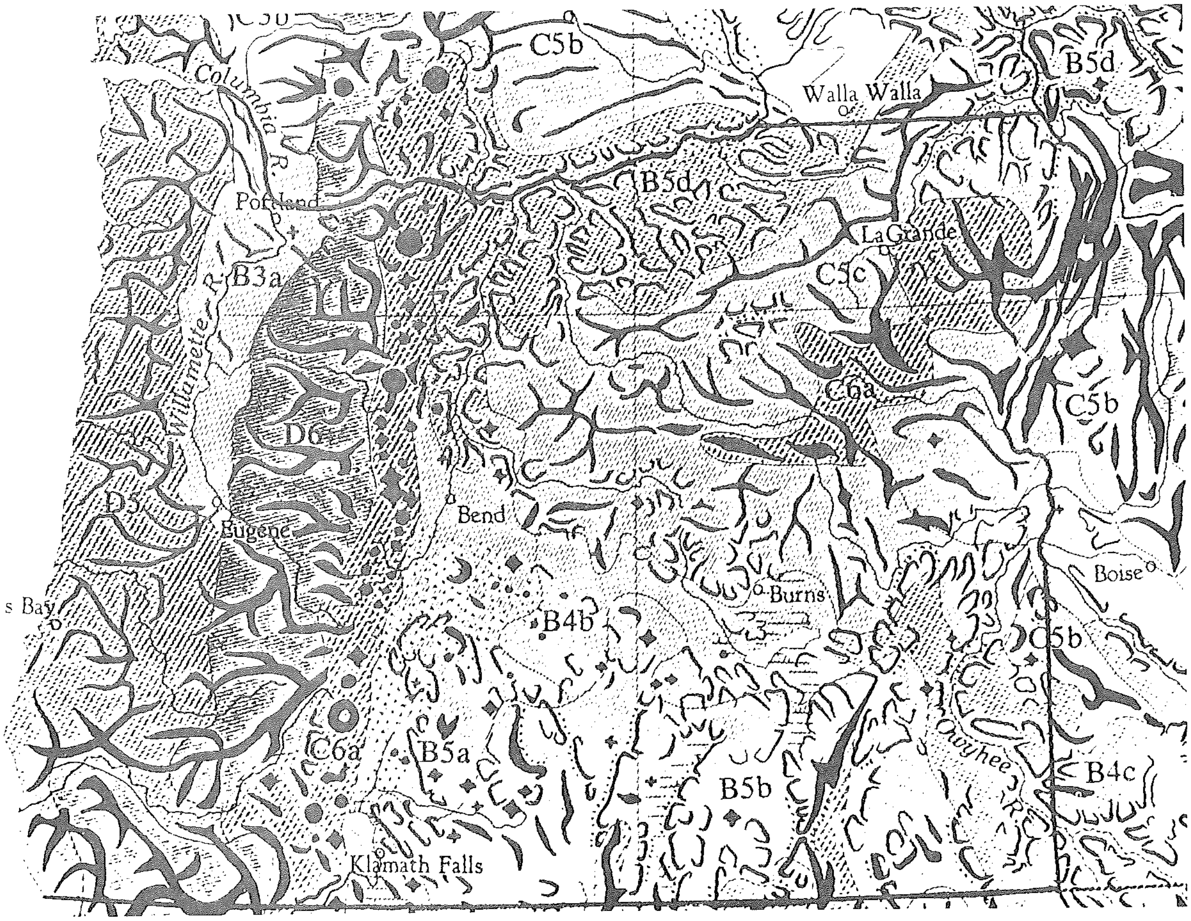



FIGURE 4. Land Surface form Map for the State of Oregon (National Atlas 1970)

TABLE III. Percentage of Land Area Exposed to Wind in Different Land Surface Forms

| Landsurface Form | Class | Area Exposed Percent |
|---|---|---|
| Flat Plains | A | 96 |
| Tablelands | B c,d | 65 |
| Hilly Plains | B a,b | 52 |
| Open Mountains | C | 23 |
| Mountains | D | 6 |

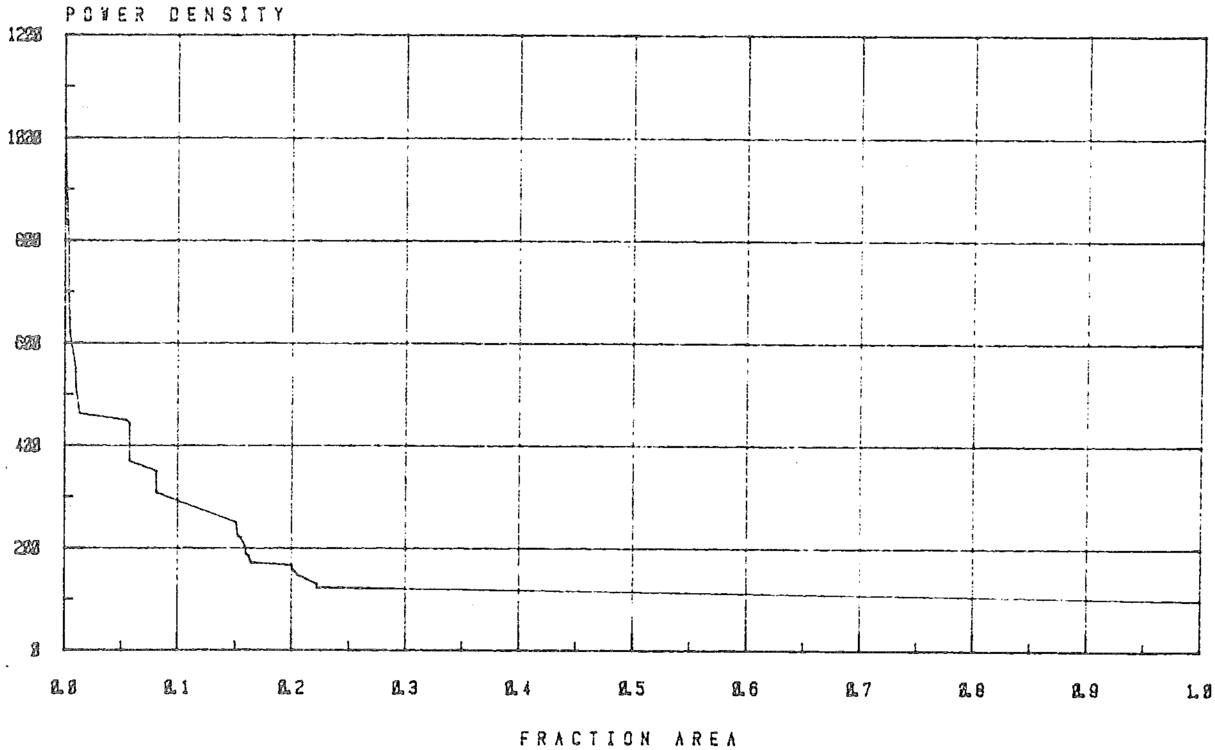



FIGURE 5 . Percentage of Land area of state of Oregon Over Which Wind Power Density (Watts/$m^{-2}$) at 50 meters Equals or Exceeds Given Value

TABLE IV. Land Area With $\geq$400 Watts/$m^2$ at 50 m

| State | Percentage | Area ($km^2$) |
|---|---|---|
| Idaho | 7.7 | 11900 |
| Montana | 9.5 | 24700 |
| Oregon | 5.7 | 10300 |
| Washington | 3.8 | 4600 |
| Wyoming | 26.6 | 49100 |
| Northwest | 11.2 | 100600 |

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DISCUSSION

C. Mazzola: Which of the power law coefficients did you use to calculate the 50-meter wind speed from the 10-meter winds?

ELLIOTT: We applied the one-seventh power law for all sites.

D. Neill: What other sources of data were used if existing long-term data were based primarily on airports, which may be non-windy areas (e.g., in Hawaii our airport locations have quite low "wind power" versus our windy areas which have 1000 to 1800 $w/m^2$)?

BARCHET: We deleted other sources that may have higher winds (e.g., forest station).

H. Panofsky: You did not comment on available wind power at sea coasts; yet some of the biggest numbers are found there. Would you comment?

BARCHET: The regions of available wind power on the coasts (especially West Coasts) are very narrow, and therefore contribute little to state-wide statistics. But, they are locally very important.