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WIND POWER

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OREGON STATE UNIVERSITY

Department of Atmospheric Sciences

REPORT NO. BPA 79-4
1979

OCTOBER

NETWORK WIND POWER OVER THE
PACIFIC NORTHWEST

PROGRESS REPORT, OCTOBER 1978-SEPTEMBER 1979,
INCLUDING A LIMITED COMPARISON
WITH PREVIOUS WORK

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prepared by

E. WENDELL HEWSON and ROBERT W. BAKER
PRINCIPAL INVESTIGATORS

Submitted to

BONNEVILLE POWER ADMINISTRATION

Portland, Oregon

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I. INTRODUCTION AND CONCLUSIONS

INTRODUCTION AND CONCLUSIONS

In 1975 the Bonneville Power Administration (BPA) contracted with Oregon State University (OSU) to perform a feasibility study of the wind power potential in a portion of the Columbia River Gorge. Since that initial assessment the research at OSU has expanded to investigate the wind power potential in the rest of the BPA service area which covers Washington, Oregon, Idaho, western Montana, and northern Nevada. Previous BPA Reports 76-1, 77-2, and 78-3 have documented the progress of this research.

The objectives and conclusions of the research during FY 79 are summarized below. The data analyzed were for the period June 1978 through May 1979. The details of the research are contained in the rest of the report. There are also two separate appendices: Appendix 1, Wind Prospecting Site Survey Reports; and Appendix 2, Wind Data Summaries.

Objectives of the Research

The research had the following objectives:

1. To locate, obtain, compile, and analyze existing sources of wind data and to establish new data stations in locations with promising wind power potential.
2. To analyze the wind energy potential of a simulated network of wind turbine generators (WTGs).
3. To investigate the use of the TALA kite anemometer as a wind prospecting tool.
4. To analyze the pressure gradient force that governs the wind flow using a case study approach.

Conclusions

1. The wind data that have been collected and analyzed indicated that strong and persistent winds occurred over many well exposed areas

in the Northwest during the 12-month period. The wind flow during the summer and fall of 1978 appeared to be near typical over most of the region. However, during December 1978 the wind flow was about 25% weaker than normal in western Oregon. January 1979 was colder than usual over the Northwest, and winds were 20-30% lighter than normal over most of the region. During the spring the winds were 15-35% lighter than normal in March, but were near or slightly above normal in April or May.

2. The wind characteristics investigated at seven selected wind power stations indicated that the mean wind speed for the 12-month period varied between 14 and 21 mph, moderate to strong winds tended to be channeled in one or two prevailing directions at most of the locations, and wind power density values exceeded 300 watts/m^2 (a minimum value for utility scale development) for the 12-month period at most of the stations. The diurnal variation in the wind speed was greatest in the summer and least in the winter except at Kennewick, where little seasonal diurnal variations were noticed. The Cape Blanco station reported the highest number of hours of winds ≥ 50 mph and measured gusts near 100 mph on several occasions during the winter.
3. A study of the fit of the Weibull theoretical wind speed distribution to the actual wind speed distribution at several sites in the Northwest revealed that the shape parameter was usually between 1.0 and 2.0. The site topography appears to be a dominant factor in influencing the shape parameter, and this influence is as large as the diurnal and seasonal influences. It appears unlikely that one can estimate the shape parameter at one site given its value at another site.

4. The estimated energy generated by a single 2.5 MW WTG at seven selected sites for the 12-month period June 78 to May 79 varied from 10600 to 6000 MWH. The period capacity factors varied from 0.27 to 0.48. Goodnoe Hills, Cape Blanco, Juniper Point, and Sevenmile Hill were the top four energy producers.
5. The interannual variation in the estimated WTG output at four selected stations varied from about 2% to 20% for the two 12-month periods analyzed: December 76 - November 77, and June 78 - May 79. The interannual energy variation at Cape Blanco and Goodnoe Hills was about 2%, while the difference at Kennewick and Pequop Summit was about 12% and 20% respectively.
6. A study was made concerning the optimum placement of WTGs at six selected sites in the Northwest based on the site energy potential and accessibility and WTG costs. The results indicated that Cape Blanco was the best location for a 4.5 MW WTG and Goodnoe Hills was the top choice for a 2.5 MW turbine in terms of annual energy and peak-period energy generation. For the assumptions used in this study, the 30-year levelized cost of energy was about 6.5¢ and the cost per installed kilowatt was about \$670.
7. The kite anemometer has been calibrated against several tower-mounted anemometers and appears accurate to within 2%. The most accurate wind profile sampling technique appears to be making two consecutive profiles and averaging the data to filter out the small-scale turbulent fluctuations in the lowest 350 feet.
8. Kite anemometer measurements over various types of terrain at several wind power sites indicated that individual profiles within the family

of wind profiles taken at each site show close similarity, especially those taken with the same wind direction; over the top of a dense tree canopy, the turbulent boundary layer extends upward at least two tree heights; turbulence intensity generally decreases with height except over very rough terrain; for a given wind direction the change in wind speed with height decreases as the wind speed increases in moderately smooth terrain; and at most of the sites tested in the Columbia Gorge there is little change in wind speed with height above the 150-foot level when the wind speed exceeds 25 mph.

9. Wind prospecting field surveys located promising new areas to investigate, and also further defined the wind energy potential in known high wind areas. The western Washington coast and the northwest Washington coast mountains below 3000 feet appear to have good wind power potential, based on the degree of wind-deformed vegetation and limited spot wind measurements. The areal extent of good winds in the Cape Blanco area appears to be quite large. Due to the rugged topography and the dense, high forest canopy in the central part of the Columbia River Gorge near Augspurgen Mountain, the spatial extent of good winds in the lowest 350 feet is somewhat limited. The areal extent of good winds over the Columbia Hills near KCIV appears to cover most of the ridge and portions of the valley floor near the Columbia River. The strength of the winds at Goodnoe Hills may change as much as 20% within a mile of the proposed WTG site. Wind profile measurements taken at and near the Kennewick station in the Horse Heaven Hills indicated the strongest winds occurred on the crest of the hills. The wind speed difference between slope and

crest measurement locations varied from 20-40%, and of the crest sites the Kennewick station location measured the strongest flow. Spatial variations in the wind profiles taken at the Kennewick station within 350 feet of each other indicated a 10% difference in wind speed. This spatial variation was about twice as great as that measured in the vertical.

10. A case study of the relationship of the wind flow over the Northwest to the horizontal pressure gradient revealed that where winds exceed 6 mph there tends to be a good correlation between the pressure gradient force and the wind direction. During the first half of the three-day study period the u - component of the wind speed at five sites corresponded well with the pressure gradient force, but a more random pattern occurred during the latter half of the period. In complex terrain, using the altimeter correction to determine the pressure gradient force is more accurate than using the reduction of station pressures to sea level.

II. WIND DATA ANALYSIS

Wind Data Network

Anemometer Failure

Climatological Wind Analysis for the Period June 1978-May 1979

Wind Characteristics at Selected Wind Power Sites

Investigation of the Weibull Shape Parameter for Sites in Complex Terrain

Wind Data Network

Wind data have been collected from 69 data stations throughout the Pacific Northwest. These stations are located on the map in Figure 1 and pertinent station data are listed in Tables 1a and 1b. The analysis of the data from 63 of these sites is contained in this report. Five new data stations were installed in August and the data have not been received yet. Wind data from the Valmy Nevada meteorological tower were recently received and are being processed.

Hourly wind speed and direction data were analyzed for 17 of the sites; four to 6 hourly data were investigated at nine of the locations; monthly wind speed frequency distribution data were available at seven of the sites; and monthly average wind speeds were available at 30 of the sites.

The wind summaries for these data stations are contained in Appendix 2 for the period July 1978 to May 1979. These wind summaries include wind roses, diurnal speed distributions, monthly power densities, annual wind speed frequency distributions, high wind summaries, monthly wind speed frequency distributions, and monthly mean wind speeds.

FIGURE 1. Anemometer station locations.

Table 1a. Anemometer site data

	Station Elevation MSL (ft)	Anemometer Height	Period of Record	Remarks*		Station Elevation MSL (ft)	Anemometer Height	Period of Record	Remarks*
1. Gold Beach	720	40	8/76-current	5	19. Mt. Hood Meadows	6600	30	1975-current	6
2. Hill Top	600	8	1/79-current	4	20. Wind Mtn.	960	40	6/76-5/79	4
3. Cape Blanco CGLS	200	20	1968-72	3	21. Augspurgen Mtn.	2880	60, 150	12/76-1/78	1
4. Cape Blanco BPA	200	40	10/76-current	1	22. Mosier	640	40	4/75-4/78	1
5. Wahl Ranch	100	30	8/79-current	4	23. Thunderbird Ranch	1000	30	7/78-current	4
6. Knapp Ranch	20	30	8/79-current	4	24. KCIV	3120	45	6/74-current	1
7. Langlois Mtn.	1200	30	10/76-current	4	25. Robbins Farm	2050	30	9/78-current	4
8. Prairie Mtn.	3200	100	10/77-current	1	26. Seven Mile Bell	1840	40	3/77-current	4, 5
9. Mary's Peak	4000	30	9/78-12/78	1	27. Seven Mile Tower	1880	50, 150	10/78-current	1
10. King's Valley	400	30	9/78-current	4	28. Ortle Point	2040	30	4/77-current	4
11. Bunker Hill	900	30	7/79-current	4	29. Sauter Ranch	1360	30	4/77-current	4, 5
12. Newberg Ridge	1530	60	8/77-current	4	30. Biggs	650	30	10/77-4/79	4
13. Columbia River Jetty	15	40	12/77-current	7	31. Goldendale Bell	2000	40	10/77-10/78	4
14. Pioneer Airport	250	40	4/78-current	1	32. Juniper Pt.	3100	100	8/78-current	1
15. Queets Hill	300	30	8/79-current	4	33. Goodnoe Hills	2565	45	4/76-current	1
16. Cheeka Peak	1200	30	8/79-current	4	34. Roosevelt	1706	75	10/78-current	1
17. Biddle Butte	1465	40	11/77-1/79	1	35. Wasco	1800	30	9/76-current	4
18. Mt. Hood Meadows (yellow chair)	5916	40	2/78-current	4	36. Shutler Flats	1200	40	9/76-current	4

*Remarks:

1. Hourly average velocities taken from strip charts.
2. Five-minute average velocity observations taken hourly.
3. Velocity observations taken every four hours.
4. Monthly average speed data (wind run anemometer).
5. Wind spectrum analyzer data.
6. Six-hour average velocities taken from strip charts.
7. Instantaneous hourly value.

Table 1b. Anemometer site data

	Station Elevation MSL (ft)	Anemometer Height	Period Record	Remarks*		Station Elevation MSL (ft)	Anemometer Height	Period Record	Remarks*
37. Hurlburt Flats	603	50	9/76-5/79	5	54. Stinkingwater Pass	5000	30	6/78-10/78	4
38. Boardman	320	130	12/76-5/79	1	55. Burns Butte	5307	35	12/76-current	4
39. Irrigon	300	30	2/78-current	4	56. Juniper Ranch	4200	30	6/78-current	4, 5
40. Kennewick	2050	105	6/76-current	1	57. Prineville Airport	3246	30	3/78-current	1
41. Sunnyside	3000	45	4/76-3/78	1	58. Coyote Hills	6700	35	9/76-current	4
42. Wanapum Dam	520	40	5/78-current	4	59. Adel	6571	50	8/76-4/78	4
43. Vantage Farms	890	30	6/74-current	2				4/78-current	1
44. Mission Ridge	6730	30	4/78-12/78	5	60. Ashland	1300	30	12/77-8/78	4
45. Steven's Pass	5100	30	1968-current	6	61. Valmy Tower	4700	33, 330	10/76-11/78	1
46. Crystal Mtn.	6870	30	1968-current	6	62. Ruby Station	5700	60	6/78-8/78	4
47. Mt. Baker	5040	40	1968-current	6	63. Wells West	6400	35	3/77-current	4
48. Bridger Bowl	8650	30	1967-current	6	64. Radio Hill	5800	30	6/78-current	4
49. Jackson Hole	10,300	20	1968-current	6	65. Pequop Summit	7538	40	4/76-current	1
50. Sun Valley	9100	30	1968-current	6	66. Haines	4000	30	10/77-current	4
51. La Grande Elevator	3149	20	1968-current	6	67. Hot Lakes	4400	30	9/78-current	4
52. La Grande (Andrews)	3149	136	10/77-current	1	68. Pumpkin Ridge	3200	30	10/78-current	4
53. John Day Airport	3665	50	10/77-current	4	69. Sheridan	500	30	11/78-current	4
		40	1/77-4/78	1					

*Remarks

1. Hourly average velocities taken from strip charts.
2. Five minute average velocity observations taken hourly.
3. Velocity observations taken every four hours.
4. Monthly average speed data (wind run anemometer).
5. Wind spectrum analyzer data.
6. Six hour average velocities taken from strip charts.
7. Instantaneous hourly value.

Anemometer Failure

Data losses during the twelve month period, June 1978 through May 1979, were primarily due to the mechanical failure of the wind system or failure of the system due to icing of the sensors. There were also two cases of vandalism of the equipment. A summary of the number of stations that experienced losses due to system mechanical failure, icing, or vandalism is given in Table 2.

Table 2. Number of stations that experienced data losses due to mechanical problems, icing, or vandalism.

<u>Type of System</u>	<u>Mechanical</u>		<u>Icing</u>	<u>Vandalism</u>
	Recorder	Sensor		
Real Time (Strip chart)	8	7	3	1
Wind-run	7	1	2	1

Equipment at eleven of the real time monitoring sites that recorded hourly data experienced some problems due to the mechanical failure of the recorder or sensor. Data losses occurred at four of these eleven sites owing to the failure of both the recorder and sensor. The recorder problems often involved a faulty chart drive or the clogging of the ink pens. Sensor problems varied from electrical failures to worn-out bearings. The greatest data losses occurred at Adel, KCIV, Augspurgen Mountain, and La Grande.

Most of the problems at the wind-run anemometer sites involved the mechanical failure of the odometer. The sensor failure was due to the cups blowing away.

Icing of the sensor prevented data from being gathered at five of the sites. Ice loading combined with high winds (>50 mph) resulted in the

complete loss of the sensor at Biddle Butte in January. There were intermittent problems with the icing of the sensor at Augspurger Mountain and Prairie Mountain. Both of these sensors were heated, keeping the data losses to a minimum. Local residents at Sevenmile Hill and Pumpkin Ridge reported that the wind-run cups iced up frequently during the winter and would remain frozen for extended periods in 10-20 mph winds. Undoubtedly, this may have been the case during the winter at many of the other inland wind-run anemometer stations at higher elevations.

Considering the number of anemometer installations, many in remote areas, the occurrence of vandalism was minimal. However, the Mary's Peak sensor was destroyed twice before the station was abandoned. The anemometer at Wind Mountain had been operating satisfactorily for over two years before it was stolen.

CLIMATOLOGICAL WIND ANALYSIS FOR THE PERIOD
JUNE 1978 TO MAY 1979

Wind speed and direction data were gathered from several National Weather Service stations throughout the Pacific Northwest for the 12 month period beginning in June 1978 and ending in May 1979. The mean monthly wind speeds were compared to the long-term, usually 30 year, monthly averages to determine any significant (i.e., greater than 10%) departures from the climatological norm. The prevailing wind direction was also investigated to determine wind flow changes. The mean monthly wind speed data for these stations along with data from several wind power data stations are summarized in Table 3. The data station locations are shown in Figure 2.

FIGURE 2. Wind power data stations (solid stars) and the nearest long term data stations (open stars).

Table 3. Mean monthly wind speeds (mph) at several long-term data stations and wind power data stations for the period June 1978 to May 1979. Long-term averages are also given.

Station	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	AVG
Columbia River Jetty	M	8.7	9.2 ¹	M	M	M	13.9 ¹	19.2 ¹	M	M	M	M	12.4 ¹
Astoria	7.8	8.1	8.5	7.4	7.4	8.1	8.4	7.2	10.2	9.0	8.1	9.5	8.3
Astoria 1941-70	8.3	8.4	7.8	7.4	7.5	8.4	9.1	9.5	8.9	8.9	8.6	8.4	8.4
Cape Blanco BPA	14.5	20.2 ¹	19.4 ¹	17.1 ¹	17.8	19.1	17.0	15.7	28.5	17.7	13.9	21.4	18.5
Cape Blanco CGLS	11.5	14.7	12.4	11.2	12.0	M	16.0	13.1	21.5	11.7	14.4	17.4	14.4
Cape Blanco CGLS 1968-72	14.7	16.0	14.9	13.7	14.8	16.9	20.9	19.9	17.8	18.5	17.6	15.5	16.8
Prairie Mountain	8.3	7.0	17.9	21.1	12.8	19.2	17.4	21.9 ¹	17.4	15.4	12.4	15.5	15.3
Eugene	7.2	7.4	7.8	6.7	6.6	7.8	7.0	6.7	8.9	7.2	7.1	8.1	7.4
Eugene 1941-70	7.4	8.0	7.5	7.4	6.6	7.1	7.7	8.3	7.9	8.6	7.7	7.4	7.8
Portland	7.8	7.7	8.0	6.8	6.0	8.7	7.4	11.1	10.3	7.5	7.3	8.0	8.1
Portland 1941-70	6.9	7.4	7.0	6.4	6.4	8.4	9.6	10.1	8.8	8.3	7.2	6.9	7.8
Augsburger Mountain	M	21.6	16.8	16.5 ¹	19.2 ¹	18.2	21.1	27.0 ¹	M	M	M	M	19.1 ³
Goodnoe Hills	19.8 ¹	17.6	18.3	16.6	13.5 ¹	7.5 ¹	15.6 ¹	6.9 ¹	14.3	15.1	16.7 ¹	19.1	15.6 ¹
Kennewick	17.7	16.3	13.7 ¹	15.8 ¹	13.2	17.1 ¹	18.1	6.6	18.8 ¹	12.0	13.3	16.4	14.8
Pendleton	M	M	M	M	7.9	7.3	8.9	5.6	8.9	9.2	10.7	10.4	8.6 ² (9.1) ²
Pendleton 1941-70	10.5	9.5	9.1	8.9	8.1	7.9	8.4	8.5	9.0	10.0	10.6	10.2	9.2
Pequop Summit (Wells)	14.4	11.6	12.7	12.4 ¹	10.6 ¹	12.5	21.8 ¹	14.4	16.8 ¹	12.1 ¹	17.1	15.2 ¹	13.9
Elko	6.5	5.6	5.6	4.8	4.1	5.3	5.1	5.5	5.7	5.6	6.8	6.6	5.6
Elko 1941-70	6.7	6.2	6.0	5.5	5.2	5.1	5.1	5.4	5.9	6.7	7.2	6.9	6.0

¹ Data recovery less than 85%

² The average was computed from eight months of data.

³ The average was computed from seven months of data.

M Missing data.

It should be noted that this comparison gives only a gross estimate of any basic flow changes from normal at the lower elevation long-term stations. The monthly departures from normal and the similarities with the normal do follow definite trends at most of the long-term stations. However, until longer term data, say five years, are gathered from the wind power stations, determining the monthly velocity deviations from normal at these high wind sites based on the National Weather Service station departures is difficult because of the spatial variations among stations. This is particularly true for the wind power sites in the Columbia River Gorge and in the Wells area shown in Figure 2. The Coast Guard station at Cape Blanco is adjacent to the BPA wind power station so monthly comparisons are meaningful there.

In the summer of 1978 the wind flow was nearly normal along the northern Oregon coast; the winds reported at Astoria agreed quite closely with the climatological norm. However, the prevailing north winds along the southern Oregon coast were lighter than normal in June and August; the Coast Guard station recorded a 16-22% departure of the mean from normal. The winds at the Portland Airport were slightly stronger than normal (12-14%) in June and August. Unfortunately, wind data were not available from Pendleton during the summer to determine if the prevailing westerly flow was stronger there also. The prevailing southwest wind flow recorded at the Elko Airport was nearly normal during the summer. The Pequop Summit (Wells) winds averaged 12-14 mph.

During September the wind flow was about normal in speed and direction at most of the National Weather Service stations. The only significant departure was a 12% decrease in the mean monthly wind speed at Elko. Most of the long-term data stations show the lowest winds on a climatological basis in October and this was generally the case for October 1978. However, the

strength of the wind was about 20% less than normal along the southern Oregon coast and in northeast Nevada as north winds prevailed at both locations. Southerly and southwesterly flow which usually produces stronger winds did not occur very often over the Northwest. In November storm passages through the region occurred more frequently than in October and monthly wind speed and direction averages closely approximated the climatological normal for the month.

Lighter than normal winds were reported for December at the Cape Blanco Coast Guard Station, Astoria, Portland, and Eugene. The most significant departures occurred at Cape Blanco and Portland where the difference was nearly 25%. A few winter storms did move through western Oregon but their intensity appeared to be weaker than normal. However, the wind flow over northeast Nevada was normal for December as southwest winds prevailed. January was a cold month as a high pressure center persisted over the Northwest. East winds often approaching gale force were common through the Columbia River Gorge. The winds measured at Portland were 11% higher than normal. Conversely, most of the other Northwest areas experienced much lighter than normal flow since the high pressure center prevented storms from passing over the region. The coastal stations at Astoria and Cape Blanco reported 25 and 33% decreases in the strength of the wind respectively as east to northeast winds prevailed. Eugene recorded a 19% decrease under prevailing north flow and Pendleton reported a 34% decrease as southeast winds were common. Although the mean wind speed at Elko was nearly normal for January, the prevailing wind direction was northwest rather than the usual southwest. A reversal in the weather pattern occurred in February as storm passages and steady and brisk winds occurred often over the region. Wind speeds along the Oregon coast were 15-20% higher than normal and the strength of wind flow in the Willamette Valley was about 15% above average. Nearly normal winds were reported at

Pendleton and Elko for the month.

March, which has the reputation of being a 'windy' month, was not as windy as usual: the departure from normal at Cape Blanco was about 30%, and that at Eugene was 16%; at Portland and Pendleton there was about a 10% decrease; and at Elko there was over a 15% difference. Storms did move over the region but they were weaker than usual. Nearly normal winds were recorded at most of the long-term data stations in April. The only significant difference was a 20% decrease from normal at Cape Blanco. Steady and brisk northwest winds persisted along the Oregon coast in May resulting in a 15% increase above average. North flow also prevailed in the Willamette Valley. The mean monthly wind speed at Eugene and Portland exceeded normal by about 10-15%. Near typical flow was recorded at Pendleton and Elko for May.

In summary, during the summer of 1978 nearly normal winds were recorded over most of the Northwest. The only significant departure from normal was a 15-20% decrease measured at Cape Blanco. Nearly normal wind flow was recorded during the fall at most of the long-term National Weather Service Stations. However, in October the mean monthly wind speeds were about 20% lighter than average at Cape Blanco and Elko. During the first two months of the winter the winds over much of the region were lighter than normal; a 25% decrease was experienced in western Oregon in December 1978. In January 1979 a cold high pressure center persisted over the Northwest producing light north to northeast winds over much of the region; departures from normal at most of the long-term data stations were 20-30%. However, strong east winds were common in the western part of the Columbia Gorge. In February the winds were 15-20% above average in western Oregon. During the spring the winds were 15-35% lighter than normal in March, but were near or slightly above normal in April and May.

Wind Characteristics at Selected Wind Power Stations

The wind characteristics are examined at seven stations where hourly wind speed and direction data have been gathered for the one year period June 1978 - May 1979. These stations have been selected for analysis based on the strength of the wind and on the percent of data recovery for the period. The data recovery ranges are from 66-94%. It is assumed that the partial record is a reasonable representation of a full year of data. An analysis is also made of the difference in the estimated WTG output for two separate years of record at four of the locations. The site locations are shown in Figure 3.

FIGURE 3. Selected potential wind power sites.

Mean Monthly Wind Speed Analysis

The mean monthly wind speeds at the seven sites are given in Table 4. The annual mean wind speed for the one year period, June 1978-May 1979, varied from 13.8 mph at Sevenmile Hill to 20.7 mph at Juniper Point. The instruments at Cape Blanco, Prairie Mountain, and Pequop Summit recorded the highest overall mean wind speeds during the winter (November through February). However, there were some months during the rest of the year where the monthly mean wind speed exceeded 15 mph at all three locations.

The wind data gathered at the Sevenmile Hill meteorological tower indicated that the strongest winds occurred in the spring and summer. However, the data base is somewhat limited from this site since the tower was installed in October 1978. The partial data from July through September 1978 were from a 30 ft high recording anemometer that was in place prior to the tower installation.

The Juniper Point area appears to experience strong winds most of the year as the mean monthly wind speed exceeded 18 mph in nine out of the ten months when data were taken. The wind flow recorded at the Goodnoe Hills site was lighter than that measured at Juniper Point but the mean monthly wind speeds still averaged 15-20 mph in 8 of the 12 months. The strongest and most persistent winds at Goodnoe Hills occurred in the spring and summer.

The winds recorded on top of the Horse Heaven Hills at the Kennewick site were strongest during the spring and summer. However, mean monthly wind speeds did exceed 15 mph in November, December, and February.

Table 4. Mean monthly wind speeds (mph) at seven wind power sites for the period June 1978 - May 1979.

Station	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	AVG
Cape Blanco BPA	14.5	20.2 ¹	19.4 ¹	17.1 ¹	17.8	19.1	17.0	15.7	28.5	17.7	13.9	21.4	18.5
Prairie Mountain	8.3	7.0	17.9	21.1	12.0	19.2	17.4	21.9 ¹	17.4 ¹	15.4	12.4	15.5	15.3
Pequop Summit	14.4	11.6	12.7	12.4 ¹	10.6 ¹	12.5	21.8 ¹	14.4	16.8 ¹	12.1 ¹	17.1 ¹	15.2	13.9
Sevenmile Hill 50'		15.7 ¹	14.6 ¹	12.2	12.2 ¹	10.0	15.5	8.4	11.8 ¹	12.7	18.8	23.4 ¹	13.8 ¹
Sevenmile Hill 150'					15.7	12.3	17.4	9.9	10.3	15.0	24.6 ¹	23.3 ¹	15.3
Juniper Point			22.5	21.5	18.2	18.2	24.0	14.0	24.6	20.2	23.9	21.0 ¹	20.7
Goodnoe Hills	19.8 ¹	17.6	18.3	16.6	13.5 ¹	7.5	15.6	6.9 ¹	14.3	15.1	16.7 ¹	19.1	15.6 ¹
Kennewick	17.7	16.3	13.7 ¹	15.8 ¹	13.2	17.1 ¹	18.1	6.6	18.8 ¹	12.0	13.3	16.4	14.8 ¹

¹ - Data recovery less than 85%

Wind Rose Analysis

The frequency of occurrence of the wind speed by direction is given for 16 compass points in Table 5. The mean wind speed for each direction is also listed. The wind rose for the Cape Blanco BPA station indicates that power-producing winds, those exceeding 10 mph, are found under north to northeast (47%) and south-southeast to southwest (40%) flow. The strongest winds occur during the winter under south flow and average over 27 mph for about 30% of the time.

The mean wind speeds at Prairie Mountain exceed 12 mph for all directions except north. South to southeast winds prevail about 35% of the time and average over 15 mph.

South-southwest through northeast winds appear to be the power-producing wind directions at Pequop Summit; the strongest and most persistent flow occurs about 42% of the time from the west through west-northwest direction and the mean speed is nearly 18 mph.

The wind flow at Sevenmile Hill is strongest under west to northwest winds. The mean wind speed under this prevailing flow (56%) is about 19 mph.

The Juniper Point records indicate that this site experiences moderate to strong winds from nearly all directions. The most persistent and strongest winds are from the west to northwest (48%) and average about 28 mph.

The Goodnoe Hills site experiences most of its strong winds for west to north-northwest directions about 65% of the time. The average speed for these directions is over 19 mph.

Most of the power-producing winds at Kennewick occur with south to southwest winds which persist about 52% of the time. The mean wind speed from these directions is nearly 20 mph.

Table 5. Wind rose summary for the period June 1978 - May 1979.

		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Cape Blanco BPA	% Time	11.0	30.2	6.1	1.9	2.0	1.8	1.5	5.5	29.5	4.2	1.4	.6	.7	.9	.5	1.7
	V	17.6	18.7	13.0	7.1	7.4	6.3	6.5	10.1	27.2	13.9	12.1	7.5	6.0	7.6	7.7	8.1
Prairie Mountain	% Time	11.2	2.9	9.6	3.7	5.7	6.1	11.2	8.0	17.0	6.4	3.1	2.3	3.7	2.8	3.1	1.6
	V	8.5	17.0	14.0	15.7	14.3	20.8	15.2	14.4	16.5	17.0	12.1	12.5	13.9	13.9	14.6	12.4
Pequop Summit	% Time	6.0	3.2	1.3	1.4	3.2	2.5	6.3	6.5	4.5	3.9	3.2	6.8	19.9	22.5	4.3	4.0
	V	12.3	17.7	13.3	6.2	8.8	7.0	8.8	7.8	8.2	10.6	14.0	12.4	16.6	19.5	14.7	12.7
Sevenmile Hill 50'	% Time	.4	.6	.1	.6	9.4	15.1	4.4	3.9	1.1	.5	.3	1.2	5.6	29.1	20.9	3.1
	V	5.6	6.5	5.6	5.1	7.9	8.6	7.6	5.3	4.2	9.2	10.6	9.2	13.7	20.1	19.5	7.8
Juniper Point	% Time	1.0	2.2	1.7	5.5	12.5	6.4	1.1	2.0	3.1	3.3	3.7	6.8	22.5	19.6	5.9	2.1
	V	18.5	13.8	18.2	14.2	12.5	9.1	8.4	7.7	14.2	11.4	15.7	16.2	29.8	28.3	26.2	17.2
Goodnoe Hills	% Time	2.3	.7	.7	1.4	3.8	2.6	4.2	5.1	6.2	2.7	1.6	2.2	10.1	13.3	22.1	19.6
	V	11.3	9.4	12.1	10.4	11.3	10.0	6.9	6.8	6.6	6.3	6.3	5.9	13.2	17.6	22.6	22.2
Kennewick	% Time	.1	.3	.4	.3	.6	.5	.3	.9	9.4	32.5	10.4	2.5	5.1	15.3	13.6	3.1
	V	7.2	9.3	8.1	6.7	6.9	7.5	7.1	10.4	16.7	22.6	19.1	10.2	9.1	10.6	10.5	8.3

Power Density Analysis

The mean monthly and annual power density (watts/m^2) for each of the seven sites is given in Table 6. The mean annual values range from nearly 300 watts/m^2 at Pequop Summit to over 1000 watts/m^2 at Juniper Point. However, anemometer height and site elevation differences are important. The power density is proportional to the air density and the cube of the wind speed. The air density decreases about 10% per 3000 ft change in altitude so site elevation differences can be significant. The site elevations and anemometer heights are noted in Table 6. Since the power density is proportional to the cube of the wind speed, minor changes in the wind speeds, say 10%, due to anemometer height differences can result in over a 30% difference in the power density value. Therefore, comparing the site data in Table 6 can be misleading when there are anemometer height differences of more than 20 or 30 ft and elevation differences of 2000 ft or more. The anemometer height effect is readily apparent when comparing the data from the 150 ft Sevenmile Hill meteorological tower. When a full month of data were available from each level the 100 ft difference in anemometer heights resulted in power density differences from 25 to 60%. Due to air density changes the power density would decrease about 25% from that calculated at sea level for a given wind speed at the 7500 ft Pequop Summit site.

Power density values exceeding 300 watts/m^2 at the 40 ft level represent good wind power potential. As noted in Table 6, the monthly power density values equalled or exceeded 300 watts/m^2 at Cape Blanco every month and the annual average was over 900 watts/m^2 . Power density values at Prairie Mountain exceeded 300 watts/m^2 in eight out of the twelve months. The light winds during the summer resulted in a significant decrease in the power density values.

Table 6. Mean monthly densities (watts/M²) for the period June 1978 - May 1979.

Station	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	AVG	Site Anem. Height (ft.)	Site Elevation (ft.) MSL
Cape Blanco BPA	300	645 ¹	1040 ¹	810 ¹	490	830	740	800	3310	860	490	870	930	40	200
Prairie Mountain	70	50	460	620	260	700	635	850 ¹	1020	490	270	370	460	100	3200
Sevenmile Hill 50'					245 ¹	220	490	100	300 ¹	300	615	1005 ¹	385	50	1880
Sevenmile Hill 150'					490	345	610	140	205	470	1120 ¹	1140 ¹	565	150	1880
Juniper Point			1020	925	775	945	1505	445	1490	910	1315	875 ¹	1025	100	3100
Goodnoe Hills	685 ¹	530	545	430	370 ¹	150 ¹	435	80 ¹	380	345	460 ¹	655	435	45	2565
Kennewick	595	505	215 ¹	535 ¹	400	1000	1010	75	615 ¹	215	280	470	495	105	2050
Pequop Summit	260	135	145	195 ¹	125 ¹	225	780	310	470	170	450	260	270	40	7538

¹ Data recovery less than 85%

The limited data from the Sevenmile Hill meteorological tower indicated good wind power potential for 5 of the 8 months. The ten months of data collected at Juniper Point showed good wind power potential throughout the period as monthly values ranged from nearly 450 watts/m² to over 1500 watts/m². The mean wind power density at this site for the period of record exceeded 1000 watts/m². At the Goodnoe Hills site wind power potential was good 10 out of the 12 months and the mean annual power density was 435 watts/m². The mean annual power density at Kennewick was nearly 500 watts/m² and mean monthly values exceeded 300 watts/m² for 8 of the 12 months. Good wind power potential was measured for only four months at Pequop Summit and the annual average was 270 watts/m².

Diurnal Wind Speed Analysis

The mean hourly wind speeds were investigated for a 'typical' winter and summer month at the seven locations to detect diurnal variations. December was chosen as representative of the winter months since storm passages were frequent through the Northwest. July was chosen as the typical summer month at five of the locations. Data were not available for July 1978 at the Sevenmile Hill tower and Juniper Point so May 1979 was selected for analysis. The diurnal variations are plotted in Figures 4-10.

All of the sites except Kennewick show the greatest diurnal variations during the summer. Minimum wind speeds at most of these sites occurred during the morning and daily speed maxima occurred in the late afternoon and early evening. The most notable summer diurnal fluctuations were found at Sevenmile Hill, Juniper Point, Goodnoe Hills, and Pequop Summit where morning and afternoon speeds differed by about 10 mph. There was very little diurnal variation of the wind speed at Kennewick in July as noted in Figure 7.

The wind speed change during the day was not as great in December at most of the sites as that measured in the summer. The random nature of storm passages brings high winds through the region independently of the time of day and greatly reduces the effect of the thermally induced pressure gradient. This pressure gradient is weak in the winter but is the dominant controlling factor in regulating the wind flow in the summer. Daily wind speed maxima occurred about mid-day at Cape Blanco whereas the daily maximum wind developed near sunset at Pequop Summit and Seven Mile Hill. The wind speeds peaked in intensity during the late evening and early morning hours at Juniper Point and Kennewick during the winter. There was very little diurnal variation in the wind speed at Goodnoe Hills as indicated in Figure 6. However, a relative minimum in the wind speed did occur around noon.

Figure 4. Diurnal wind speed variation at Sevenmile Hill for December 1978 and May 1979.

Figure 5. Diurnal wind speed variation at Juniper Point for December 1978 and May 1979.

Figure 6. Diurnal wind speed variation at Goodnoe Hills for December and July 1978.

Figure 7. Diurnal wind speed variation at Kennewick for December and July 1978.

Figure 8. Diurnal wind speed variation at Cape Blanco BPA station for December and July 1978.

Figure 9. Diurnal wind speed variation at Prairie Mountain for December and July 1978.

Figure 10. Diurnal wind speed variation at Pequop Summit for December and July 1978.

High Wind Analysis

The frequency of occurrence of wind speeds greater than or equal to 50 mph was investigated at each of the seven sites for the one year period. The number of hours of high wind observations is categorized by speed class in Table 7. A detailed breakdown of each observation is contained in Appendix 2. As can be seen, the Cape Blanco and Juniper Point sites experienced the highest frequency of occurrence and the former site experienced the strongest winds. There were four hours when the mean hourly wind speed was 80 mph at Cape Blanco. Gusts during these high winds approached 100 mph. These strong winds at Cape Blanco occurred with south flow whereas west to northwest winds were the common wind direction at Juniper Point.

Table 7. Number of hours of observations where the mean hourly wind speed equalled or exceeded 50 mph for the period June 1978 - May 1979.

	Speed Class (mph)						Total
	50-55	56-60	61-65	66-70	71-75	76-80	
Cape Blanco BPA	126	80	19	21	15	6	267
Prairie Mtn	48	3					51
Sevenmile Hill 50'	6	1					7
Sevenmile Hill 150'	11	1	1				13
Juniper Point	142	25	5	6	0	2	180
Goodnoe Hills	8	2	2				12
Kennewick	17	20	2	1			40
Pequop Summit	6	1					7

High winds at Prairie Mountain occur with east to southeast flow whereas west to northwest winds are common with high winds at Sevenmile Hill, Goodnoe Hills, and Pequop Summit. At Kennewick, south southwest is the prevailing direction for high winds.

2.5 MW Wind Turbine Generator (WTG) Annual Energy Output

The wind speed duration data for the 12 month period June 1978 - May 1979 were used to estimate the normalized annual energy output of a single 2.5 MW WTG at each of the seven sites. Complete data for this period were not available at any of the locations. It was assumed that the partial record, which varied from 66-94% of a full record, was representative of the annual speed distribution. This analysis was not done for the Augspurger Mountain and KCIV data because the data recovery was less than 60%.

The 2.5 MW WTG, MOD-2, is a two bladed upwind system with a hub height of 200 ft and a blade diameter of 300 ft. The cut-in speed is 11 mph, the rated speed is 28 mph, and the cut-out speed is 45 mph as shown in Figure 11. Also shown in Figure 11 is the performance curve for the 4.5 MW WTG.

Figure 11. WTG output curve (sea level/hub height)

The sea level/hub height performance curve for the 2.5 MW WTG was adjusted for the site anemometer height and station elevation as described in BPA Report 78-3. The energy output was calculated assuming a power law[†] exponent, α , of 0.2.

[†] See the glossary

The annual speed duration curves for the seven sites are shown in Figures 12 and 13. Winds exceeding 10 mph occurred at least 60% of the time at all of the locations and those exceeding 25 mph occurred at least 15% of the time at most of the sites. Both Cape Blanco and Juniper Point recorded winds exceeding 45 mph about 5% of the time.

The estimated annual energy output for a single 2.5 MW WTG at each of the seven sites is presented in Table 8. The annual capacity factor and mean wind speed are also given. The highest energy output occurred at Goodnoe Hills where the value exceeded 10,500 megawatt hours and the annual capacity factor was 0.48. The Cape Blanco output exceeded 10,000 megawatt hours and that at Juniper Point approached 9500 megawatt hours. The annual capacity factor at Sevenmile Hill was 0.39 and the energy output neared 9500 MWH. The estimated annual energy output at Prairie Mountain, Pequop Summit, and Kennewick was between 6000 and 7000 megawatt hours.

Table 8. Estimated annual energy output of a single 2.5 MW WTG at seven sites

Site	Period of Record	% Data Recovery	Megawatt Hours ²	Capacity Factor	$\bar{V}$ (mph) ¹	Site Anem. Height (ft)
Cape Blanco BPA	6/78-5/79	90.4	10039	0.46	18.5	40
Prairie Mtn	6/78-5/79	94.1	6998	0.32	15.3	100
Sevenmile Hill	7/78-5/79	66.3	8561	0.39	13.8	50
Juniper Point	8/78-5/79	75.2	9462	0.43	20.7	100
Goodnoe Hills	6/78-5/79	78.8	10597	0.48	15.6	45
Kennewick	6/78-5/79	82.4	6182	0.28	14.8	105
Pequop Summit	6/78-5/79	86.6	6015	0.27	13.9	45

¹ Mean wind speed at the site anemometer level

² Assumes 100% availability.

Figure 12. Speed duration curves at four wind power sites for the period June 1978 - May 1979.

Figure 13. Speed duration curve at three wind power sites for the period 6/78 - 5/79.

Interannual Variation in the Estimated WTG Output

Estimates of the annual energy output for an array of wind turbine generators at six sites in the Northwest have been made by the authors in BPA Reports 78-3 and 77-2. The data base for these estimates was for the period December 1976 through November 1977.

Sufficient wind data have been gathered at four of the six sites during the past 12 months, June 1978 through May 1979, to estimate the annual energy output for this period. A comparison of the annual energy outputs for the two separate periods is given in Table 9. These values are for a single WTG. However, these two 12-month period variations may not represent the true interannual variations on a long-term basis.

TABLE 9. Comparison of the estimated WTG output for two separate 12-month periods at four sites (assumes 100% availability).

Site	WTG Size (MW)	<u>Jun 78-May 79</u>			<u>Dec 76-Nov 77</u>			% Diff Megawatt Hours	% Diff $\bar{V}$
		Megawatt Hours	Capacity Factor	$\bar{V}$ (mph)	Megawatt Hours	Capacity Factor	$\bar{V}$ (mph)		
Cape Blanco	4.5	13460	0.34	18.5	13654	0.35	18.1	-1.4	-2.2
Goodnoe Hills	4.5	11994	0.30	15.6	12276	0.31	17.2	-2.3	-9.3
Kennewick	2.5	6182	0.28	14.8	7040	0.32	16.7	-12.2	-11.4
Pequop Summit	2.5	6015	0.27	13.9	7494	0.34	15.8	-19.7	-12.0

Little difference was observed at Cape Blanco, as the annual energy outputs differed by less than 2%. The mean annual wind speed differences varied by about the same amount. The Goodnoe Hills interannual variation was about 2% although the mean annual wind speed decreased by 9%. It appears that the wind speed distribution at both of these locations is a good match with the performance curve of the 4.5 MW WTG shown in Figure 11. Somewhere between 15 and 30% additional energy production is possible if 4.5 MW units are used at Cape Blanco and Goodnoe Hills in lieu of the 2.5 MW site.

Noticeable interannual energy variations occurred at Kennewick and Pequop Summit with differences in the estimated annual energy output varying from 12 to 20% respectively. The decrease in the annual mean wind speed was about 12% at both Kennewick and Pequop Summit.

Investigation of the Weibull Shape Parameter for Sites in Complex Terrain

Introduction

To determine the average wind power, one needs the wind speed distribution. The average wind speed alone is not sufficient to determine the average power since different wind speed distributions having the same average speed will result in different average power. A popular model of wind speed distributions is the Weibull function. It exhibits many of the characteristics of observed wind speed and may be fit to observed winds to obtain a shape parameter. The shape parameter describes the distribution of wind speeds and in conjunction with the average wind speed can be used to estimate the average power (Hennessey, 1977).

The shape parameter is found for distributions of hourly average wind speed at seven sites in complex terrain: Yaquina Tower, Yaquina Communications Station, Cape Blanco Airport, Goodnoe Hills, Kennewick, Augspurger Mountain, and KCIV Radio Station (see Table 10 and Figure 14a.) It is then examined to determine its variability with time of day, season, and wind direction.

The Weibull Model

The Weibull distribution function is given by

$$f(x) = \frac{c}{b} \left(\frac{x}{b} \right)^{c-1} \exp \left[- \left(\frac{x}{b} \right)^c \right]$$

where c is the shape parameter and b is the scale parameter. For $c = 2$ the Weibull reduces to the Rayleigh distribution. In Figure 14b the Weibull distribution is given for several values of the shape parameter.

Figure 14a. Station numbers and locations

Figure 14b. The Weibull distribution function for various values of the shape parameter c . (from Hennessey, 1977)

Results

Using all available data, all but one station (KCIV) had a shape parameter less than 2.0 (see Table 11), the value obtained for a site with resultant wind of zero and equal variance in all directions. The lowest value was at Yaquina Tower which had a value of 0.99. When only data from early morning (0300) were used, it dropped to an average value for all the sites studied of about 1.3, while for the afternoon (1500) it averaged about 1.6.

Table 10. Site Information

No.	Station	Site Elev. (ft)	Anem. Ht. (ft)	Period of Record	No. Obs.
1.	Cape Blanco Airport	200	55	7/ 1/76- 6/30/77	7893
2a	Yaquina Tower	240	33	1/15/76- 6/30/77	12523
2b	Yaquina Communications Station	371	33	1/13/73- 9/24/76	26910
3	Augspurgen Mountain	2880	40	5/ 5/75- 6/30/77	16049
4	KCIV Radio Station	3120	45	1/ 1/76-11/30/77	13856
5	Goodnoe Hills	2565	45	4/ 2/76- 6/30/77	9542
6	Kennewick	2050	105	7/ 1/76- 6/30/77	7521

Table 11. Shape Parameters

Shape parameter as related to time of day and time of year.

No.	Station	All Data	0300	1500	January	July
1	Cape Blanco Airport	1.15	1.04	1.48	1.07	1.45
2a	Yaquina Tower	.99	--	1.72	1.33	.80
2b	Yaquina Communications Station	1.32	.91	1.77	1.49	1.07
3	Augspurgen Mountain	1.73	1.52	1.70	1.75	1.87
4	KCIV Radio Station	2.06	1.83	2.13	1.80	2.66
5	Goodnoe Hills	1.08	1.14	1.34	--	2.29
6	Kennewick	1.22	1.09	1.32	.61	1.89
	Average	1.36	1.26	1.64	1.34	1.72

The winds at all seven stations had larger shape parameters during the afternoon than during the early morning. Similarly the shape parameter was computed for just winter or summer winds (January and July). On the average, the shape parameter was larger in summer than in winter although taken individually some sites had a higher value in winter. Different prevailing wind directions also yielded different shape parameters (see Table 12). The three coastal sites, Yaquina Tower, Yaquina Communications Station and Cape Blanco Airport, had an average shape parameter for northerly winds of about 2.0 whereas for southerly winds it was about 1.5. The Gorge sites had shape parameters ranging from about 1.6 to 3.2 for westerly winds and 2.4 to 2.7 for easterly winds. However, at Augspurger Mountain the two directions had nearly the same value. The directions used were the maxima of the wind direction frequency distributions. For the coastal sites there were maxima for approximately northerly winds and southerly winds. The Gorge sites had maxima for easterly and westerly winds except for Goodnoe Hills which had only a westerly maximum and Kennewick which had two maxima with westerly components.

Discussion and Conclusion

For the winds at the sites studied the shape parameter was usually between about 1.0 and 2.0. This range of values could be used to calculate a possible range of wind speed distributions which may prove to be more useful than just assuming a shape parameter of 2. In addition, the apparent diurnal variation -- and possibly seasonal variation -- of the shape parameter may be used to give a rough estimate of the variability of the shape parameter with time. On the other hand, it appears unlikely that one can estimate the shape parameter at one site given its value at another site. The uniqueness of topography at each site appears to be a dominant factor influencing the shape parameter. The variability of terrain is on a small

scale compared to the distance between sites. Although there are large scale diurnal and seasonal influences on the shape parameter, the smaller scale terrain influence is at least as large. Even for stations in close proximity significant differences in shape parameter can occur. For example, for all data the range between shape parameters for Yaquina Tower and Yaquina Communications Station was 0.99 to 1.32 whereas the range for all seven sites studied was 0.99 and 2.06. A study of a large number of sites in various terrain types is needed before conclusions can be made regarding the influence of topography on the shape parameter.

Table 12. Shape parameter in relation to prevailing wind direction.

No.	Station	Prevailing Wind Direction (degree)	Shape Parameter	% of Time Wind from Prevailing Direction
1.	Cape Blanco Airport	010 - 030	2.29	18
		170 - 190	1.41	13
2a	Yaquina Tower	020 - 040	1.75	16
		180 - 200	1.47	13
2b	Yaquina Communications Station	320 - 340	1.90	14
		160 - 180	1.55	8
3.	Augspurger Mountain	060 - 080	2.68	11
		260 - 280	2.70	22
4.	KCIV Radio Station	120 - 140	2.36	7
		270 - 290	3.20	21
5.	Goodnoe Hills	280 - 300	2.52	18
6.	Kennewick	210 - 230	1.85	20
		300 - 320	1.65	14

III. WIND PROFILE MEASUREMENTS

Kite Anemometer Calibration and Testing

Wind Profile Measurement Techniques

Wind Profile Measurements at Several Potential Wind Power Development Areas

Kite Anemometer Calibration and Testing

Large wind turbine generators to be constructed in the near future will have rotors as large as 300 ft in diameter. Strong and persistent winds are needed if these aerogenerators are to be cost effective. Good winds are often found in mountainous terrain so inexpensive, portable and reasonably accurate methods for measuring winds up to 300 ft or more above ground are needed in site surveying.

Presently available methods for making profile measurements such as pilot balloon tracking, observation of smoke trails released from a vertically rising rocket, construction of instrumented towers, acoustic sounding, and laser scattering have been found to be unsatisfactory due for the most part to either high cost, low accuracy or poor reliability. However, the recently developed Tethered Aerodynamically Lifting Anemometer (TALA)* has been tested and found to be a most satisfactory tool for making wind profile measurements.

The TALA system has been used by Oregon State University (OSU) scientists for two years with encouraging results. This system consists of a sled-type kite with tail, tethering line, reel, and either a spring scale or a recording strain gauge for direct measurement of line tension. Atmospheric density corrections are applied to the measured data.

BPA and OSU have pioneered the use of the TALA system in wind energy siting. This section describes the calibration of the kite anemometer against tower mounted anemometers and the development of a valid wind profile sampling method.

* U.S. Patent No. 4,058,010. Manufactured by Approach Fish, Inc., Route 1, Box 620B, Ringgold, VA 24586.

The performance of the kite has been calibrated by the manufacturer in the National Bureau of Standards and NASA-Langley wind tunnels and was found to be within 1-2% agreement with the true wind speed. The manufacturer calibrated the wind force measurement versus wind speed using a strain gauge system. Using the wind tunnel results, the tension for 8-40 mph winds was calculated and an appropriate coil spring was then manufactured.

We have conducted field calibration of the TALA kite as near as possible to tower mounted anemometers. Three different TALA models have been tested and the calibration results are documented in Table 13. The basic kite is used in all models but the data acquisition system is different in each. The model T-150 uses a hand held spring scale to measure the wind speed; the model T-151 uses a strain gauge connected to a strip chart recorder for the wind speed. An air density correction must be made to the data gathered by both the T-150 and T-151 models to note departures from the standard atmospheric pressure and temperature for which the kite has been calibrated. The models T-152 and T-152P are similar to the model T-151 except the ambient correction can be dialed directly into the wind speed measurement. The T-152 and T-152P models can also record the wind direction and elevation angle of the line. The T-152P unit is the prototype of the T-152 model, the latter having a redesigned strain gauge and circuitry system.

There are a number of possible sources of error which could result in differences between the kite and tower anemometers. These include:

- inherent error in the kite
- errors in reading kite wind speeds

Table 13. Calibration results of four TALA models.

Location	Sampling Time (min.)	Altitude (ft)	Unit Model	Kite Speed (mph)	Tower Speed (mph)	Error (%)
Cape Blanco Airport, OR	5	55	T-150	17.5	17.0	+2.9
Cape Blanco BPA, OR	5	40	T-150	19.3	19.5	-1.0
	5	40	T-150	17.6	17.0	+3.5
Sevenmile Hill, OR	5	50	T-152	28.2	28.0	+0.7
	5	50	T-152P	28.9	32.5	-11.1 ^{1/}
	5	150	T-152	35.4	37.0	-4.3
	5	150	T-152P	33.2	38.0	-12.6 ^{1/}
Roosevelt, WA	15	75	T-150	39.2	39.0	+0.5
Juniper Pt., WA	5	100	T-150	21.7	22.0	-1.4
	5	100	T-150	15.8	16.0	-1.3
Hanford 1, WA	5	400	T-150	26.7	25.0	+6.8 ^{2/}
	5	300	T-150	28.5	26.0	+9.6 ^{2/}
	5	200	T-150	32.7	29.0	+12.8 ^{2/}
	5	100	T-150	29.3	28.0	+4.6 ^{2/}
Kennewick, WA	5	105	T-150	35.4	34.5	-0.3
Erie, CO	10	660	T-152 P	19.0	18.8	+1.1
	3	330	T-152 P	26.2	26.6	-1.5

1 Recording strain guage out of calibration.

2 See discussion, page 46-47.

- inherent error in the tower anemometer
- errors in reading the tower anemometer chart record
- errors due to line loss over the distance from the tower sensor to its recorder
- errors due to wake or other wind interference effects around the tower
- errors due to spatial distance between the tower and the kite anemometers

The first four sources of error are errors of precision and likely to result in random deviations between the measured and true speed. The inherent error of the kite and tower anemometers may be as great as $\pm 5\%$. Reading errors arise because the chart recorders and kite measurement tube can only be read to the nearest 1 mph which will result in errors $\pm 2-11\%$ over the range of speeds measured by the kite.

However, errors such as those due to line loss and tower wake effects are likely to cause systematic differences between the true wind speed and the measured wind speed. Fortunately, line loss due to tower cable resistance is usually a small error, often less than -0.1% but can exceed -1% over a distance of 1500 ft. Errors due to interference effects around the tower may result in tower anemometers reading as much as 40% low on the lee side of a tower and 30% high when the wind is blowing toward the anemometer at an angle 20 to 40° with respect to the sides of tower the anemometer is mounted on (see Moses and Daubek - 1961 and Gill and Olsson - 1967).

The last source of error may be either systematic or random error. We have found differences on the order of 10% in the wind speed in the horizontal over distances of less than 300 ft. In turbulent conditions large temporal variations of wind speed may result in discrepancies between tower and kite speeds averaged over a short interval of less than five minutes.

The most notable of the field calibration investigations was done at the 1000 ft Boulder Atmospheric Observatory tower in Erie, Colorado, with the prototype analog recorder model T-152P. The kite was flown at the 330 ft and 660 ft levels next to the tower. Simultaneous 10 min samples of wind speeds at 330 ft were made from kite anemometer line measurements and from strip chart records; the approach of thunderstorms made it necessary to reduce the sampling period for winds at 660 ft to 3 min. In both cases the average wind speeds were near the 2% accuracy claimed by the manufacturer for the analog system. The lack of systematic errors over this height range suggests that wind drag on the line of varying lengths does not introduce significant error. It appears that, as would be expected, more accurate and representative measurements of the mean flow are obtained with a greater averaging period.

The sampling time for most of the calibrations was for a 5 min period. This period was chosen to see if short-term measurements of the wind flow by the TALA anemometer were reasonably close to the true wind speed. Most of the 5 min samples indicated good agreement with the tower speeds. The average error of the hand held spring scale measurements (model T-150) was $\pm 4\%$. Excluding the calibrations from the Hanford 1 Tower, the average error was $\pm 1.5\%$. A longer sampling time reduced the average error to $\pm 1\%$ or less. The model T-152 agreed quite closely with the tower speed at Sevenmile Hill. The errors ranged from 1-4%. Initially the T-152 prototype model calibrated very closely with tower anemometers (i.e., Erie Tower) but after continued use over a 6 month period the recording strain gauge in this unit lost accuracy and read consistently low, about 12%.

The winds measured by the TALA anemometer near the 400 ft Hanford 1 meteorological tower read consistently higher than the tower at all four levels.

The errors ranged from about 5 to 13%. Two kites were flown next to each other during this test and both indicated the same deviations from the tower. It appears that the consistently low readings by the tower anemometers at Hanford were due to: cable resistance errors of -0.4 to -1.3% for cable length of 1500 ft; and an error of -5 to -8% due to interference effects on the strong northwest winds by the large triangular tower that is 15 ft on each side. The anemometers are positioned 8 ft out horizontally on the northwest side of the tower. Wind tunnel tests by Gill and Olsson (1967) on the disturbance of the wind flow around towers indicate that an anemometer should be located at least one tower width out from the tower to measure the true wind flow; the decrease in the wind flow closer to the tower could be as much as 5 to 8%.

In two instances the kite anemometer detected gross errors in the accuracy of tower anemometers. In February 1979 the T-151 unit was flown near the 50 ft level anemometer on the Sevenmile Hill tower. Measurements were made for 20 min under northwest flow and the results indicated the tower anemometer read about 33% higher than the kite anemometer. The anemometer was subsequently removed and calibrated. The laboratory tests indicated about a 30% error. In July 1979 it was discovered upon arriving at the Kennewick substation that the existing anemometer was recording inaccurately. The kite anemometer was flown next to the cup anemometer mounted on the tower. The tower sensor recorded a wind speed of 16.5 mph while that measured by the kite anemometer was 23.3 mph. The measurement period was for 5 min and the ratio between the kite and tower anemometer speed was 1.41. Owing to this discrepancy a recording anemometer (Climatronics) was installed next to the regular unit to make a longer term comparison of the difference. Comparisons of the hourly average wind speeds over a 2 day period gave a ratio of 1.44 between the Climatronics unit and the regular anemometer.

Wind Profile Measurement Techniques

The kite anemometer has been used to measure the wind velocity profile over several different terrain types in potential wind power development areas. Measurements were made at several levels up to 400 ft above the ground. An instantaneous profile can not be taken by a single kite anemometer since the kite is raised or lowered to a desired level. Thus, the kite samples the wind flow at each level, say at 50, 150, 250, and 350 ft, but at different times. A 5 min sampling period was selected to use at each level based on Van der Hoven's work (1957) which concluded that there are mainly random speed fluctuations with time scales in the range of 5-60 min. About 25 to 30 minutes are needed to complete a profile where measurements are taken at four levels.

A valid criticism of taking a single profile at four levels in this manner is the possibility that the wind flow may change in strength due to turbulent fluctuations while the profile is taken. The results would give values of the wind speed change with height (wind shear) that are not real but are a result of the temporal change.

Two different techniques were tested to correct for any such temporal variations. The first was to use a base station anemometer mounted on a portable 16-20 ft mast to record the mean wind speed during each 5 min sampling period. The 5 min mean speeds for the four sampling levels were compared and the TALA data for the 150, 250, and 350 ft levels were normalized based on the mean base station anemometer speed taken during the 50 ft level measurement. This technique seemed to work satisfactorily in smooth terrain at Sevenmile Hill and Juniper Point. However, it did not fare so well in measurements taken at Cape Blanco. The 5 min wind-run anemometer speeds taken from the 16 ft high anemometer were compared to the 5 min average winds taken

at the 150 ft level. The results indicated that there was little correlation between the near ground wind speed changes and the 150 ft level changes. Even the changes in the 5 min mean wind speeds at the 150 ft level did not correlate well with the changes at the other higher levels. This non-correlated flow indicates that there is small scale eddy movement below the 350 ft level, perhaps related to erratic patterns of flow separation at this site, which prevents the use of this normalizing technique.

Another sampling technique was tested over irregular terrain at KCIV on top of the Columbia Hills. Two wind profiles were made by a single spring scale TALA unit taking 5 min samples at four levels (50, 150, 250, and 350 ft). Three recording TALA units were flown simultaneously at the 150, 250, and 350 ft levels. The two profiles taken by the single TALA unit were averaged and compared to the profile taken by the stationary TALA units. These data are summarized in Table 14. The average of the two profiles compared quite closely with the profile taken by the stationary TALA anemometers. The agreement was within 1 mph. It appears that taking the average of two consecutive profiles with one kite anemometer is a reasonable method of approximating the true wind profile; the effects of the small scale turbulent fluctuations in the lowest 350 ft are filtered out. Five to 15 minute sample periods with data recorded every 15 seconds during the sample periods appears to produce adequate accuracy.

Table 14. Wind profiles obtained with hand-held spring scale TALA units compared to those from stationary TALA units at KCIV on 28 June 1979. Wind speed is in mph. Five minute sample period at each level, 15 second data sampling intervals.

0830-0913 PST:	<u>Altitude (ft)</u>			
	<u>50</u>	<u>150</u>	<u>250</u>	<u>350</u>
Hand-held Spring Scale	14.9	17.9	18.0	18.5
TALA 152 Prototype		17.6		
TALA 152			18.6	
TALA 151				19.5

0922-0956 PST:	<u>Altitude (ft)</u>			
	<u>50</u>	<u>150</u>	<u>250</u>	<u>350</u>
Hand-held Spring Scale	13.2	18.7	20.7	19.6
TALA 152 Prototype		17.4		
TALA 152			20.2	
TALA 151				20.5

<u>Average of the two Profiles</u>				
	<u>50</u>	<u>150</u>	<u>250</u>	<u>350</u>
Hand-held Spring Scale	14.0	18.3	19.3	19.1
Recording TALA's		17.5	19.4	20.0

Wind Speed Profile Measurements at Several Potential Wind Power Development Areas

The wind flow is measured at most of the wind power data stations at levels of 30 to 50 ft above the ground. But large wind machines with rotor blades up to 300 ft in diameter are now in the design stage and will be constructed and operated soon. Thus, the significant winds are those from 50 to 350 ft. Measurements at high wind sites in the Pacific Northwest of winds at the 30 to 50 ft levels have been presented by Hewson and Baker in BPA Reports 77-2 and 78-3. Extrapolations of wind speeds to rotor hub heights have been attempted, but are subject to considerable uncertainty in the absence of measurements at these greater heights.

The 'power law' is often used to extrapolate the winds to higher levels from a base reference height. The simple equation reads:

$$(1) \quad V_U = V_L \left(\frac{Z_U}{Z_L} \right)^\alpha$$

where V_U is the desired upper level wind speed, V_L is the known lower level wind speed, Z_U is the upper level height, Z_L is the lower level height, and α is the power law exponent. Many studies of this relationship have been done over flat terrain where the power law exponent has been found to be "1/7th" (0.14). Over rugged terrain the wind shear increases due to frictional retardation of the wind flow in the lowest several hundred feet and the power law exponent can be 0.20 or greater.

The TALA kite anemometer has been used to measure the wind speed profile in the vertical over several different terrain types in potential wind power development areas. Measurements were taken at several levels up to 400 ft above the ground. The winds were commonly measured at heights of 50, 150, 250, and 350 ft. Five minute readings were taken at each level either on

the analog strip chart recorder or on the spring scale readout. The data collected over the five minute sampling period were used to obtain the mean and standard deviation of the speed. The turbulence intensity value I , defined as the standard deviation divided by the mean speed, was calculated to determine the degree of gustiness which exerts stresses of varying amounts on a wind turbine rotor and its supporting tower. Turbulence intensity values less than 0.10 occur in stable, smooth flow; those between 0.10 and 0.20 are representative of moderately turbulent flow; and higher values characterize very turbulent flow.

Numerous wind profiles have been taken at Cape Blanco, Sevenmile Hill, KCIV, Juniper Point, Goodnoe Hills, and at the Kennewick anemometer site. The topography in these areas varies from smooth grass covered ridges to forested coastal headlands. The wind shear at each site is analyzed with respect to the variation in the α value noted in Equation 1 from the 50 to 200 ft levels. The turbulence characteristics are also discussed. Although limited measurements are available from most of these sites, the individual profiles in the family of profiles plotted appear to show close similarity, especially those taken with the same wind direction.

Cape Blanco

Several wind profile measurements have been taken at two locations on the headland of Cape Blanco. One location is on the well exposed tip of the Cape at the BPA anemometer site and the other is at the Cape Blanco Airport which is surrounded by a 40 ft high tree canopy. The wind speed profiles are plotted in Figures 15 and 16 and the site locations are shown in Figure 17.

The Cape Blanco BPA wind station is located on the tip of the Cape about 200 ft above the water. It is barren except for a few buildings. The wind profile data are shown in Figure 15 and summarized in Table 15. The north-northwest winds measured on 1 June 1979 during a four hour period indicated a wind speed increase in the lowest 150 ft and little change above this level. Moderately turbulent winds were measured at the 50 ft level and relatively smooth flow was measured at higher levels. It appears the rugged topography of the Cape had little affect on the wind flow in the lowest 150 ft under northwest winds. The average α value for the five profiles was 0.11.

Table 15. Wind shear data giving wind speed in mph and turbulence intensity values measured by the TALA anemometer at the Cape Blanco BPA site. The 200 ft speed data were estimated by interpolation of the graphs in Figure 15.

<u>Run No.</u>	<u>Date</u>	<u>Time (PST)</u>	<u>50 ft</u>	<u>200 ft</u>	α <u>(50-200 ft)</u>	<u>Mean wind</u> <u>Direction</u>
1	2-23-79	1445-1505	15.7/0.07	19.5/0.06	0.16	200°
2	8-22-79	1033-1119 ¹	18.5/0.05	18.8/0.03	0.01	190°
3	6-1-79	1227-1605 ²	22.6/0.14	26.2/0.05	0.11	330°

1. Average of two profiles
2. Average of five profiles

Figure 15. Cape Blanco BPA profile measurements

Figure 16. Cape Blanco airport profile measurements

Figure 17. Cape Blanco wind profile locations showing the BPA station, A, and the airport, B.

The wind profiles measured under south to south-southwest winds at the BPA station are different, especially below the 200 ft level. The α value calculated for direction 200° was 0.16 while that for direction 190° was only 0.01. The wind flow measured above the south end of the steep bluff where the BPA station is located indicated little turbulence. However, this may not be the case in stronger south winds where flow separation and turbulence may be common. The strip chart traces from the BPA anemometer indicate very gusty south winds for speeds in excess of 20-26 mph.

In contrast to the flow measured at the tip of Cape Blanco, much more turbulent and separated flow has been measured at the Airport about 4 miles northeast of the Cape. The southwest to south-southwest winds measured show a noticeable increase in the wind speed with height, especially in the lower levels (see Figure 16). The α values exceeded 0.40 as noted in Table 16 and the turbulence levels were moderate to high. The effect of the heavy tree canopy is very apparent in retarding the wind flow. The northwest winds measured were also moderately turbulent but the wind shear was not as great as that measured under the southwest flow. The airport runway is oriented in the northwest direction and the trees are cleared out along the flight line. This opening in the tree canopy allows the airflow in the vertical to remain fairly uniform as noted by the low α value, 0.06.

Table 16. Wind shear data giving wind speed in mph and turbulence intensity values measured by the TALA anemometer at the Cape Blanco airport. The 200 ft level speed data were estimated by interpolation of the graphs in Figure 16.

Run No.	Date	Time (PST)	50 ft	200 ft	α (50-200 ft)	Mean Wind Direction
1	2-23-79	1300-1335	10.0/0.20	18.1/0.10	0.42	220°
2	6-13-79	1203-1236	17.4/0.20	18.8/0.19	0.06	320°
3	11-22-77	1300-1325	17.0/0.22	31.0/0.20	0.43	200°

Sevenmile Hill

The six wind profiles shown in Figure 18 were taken at the Sevenmile Hill site under westerly flow. The area is grass covered and the 150 ft meteorological tower is located on a well exposed hill as noted in Figure 19. The greatest wind speed change with height measured was with west-northwest flow as α values ranged from 0.20 to 0.29 (see Table 17). The shear measured by the meteorological tower between the 50 and 150 ft levels resulted in an α value of 0.25 for a wind direction of 300° . The flow at the 50 ft level was also moderately turbulent. Much smoother flow at the 50 ft level was measured for wind directions $260-280^\circ$ and the wind shear was not as great as α values ranged from 0.07 - 0.13. All of the profiles taken indicated smooth flow at the 200 ft level as indicated by turbulence intensity values from 0.05 - 0.07.

Table 17, Wind shear data giving wind speed in mph and turbulence intensity values measured by the TALA anemometer at the Sevenmile Hill site. The 200 ft speed data were estimated by interpolation of the graphs in Figure 18.

<u>Run No.</u>	<u>Date</u>	<u>Time (PST)</u>	<u>50 ft</u>	<u>200 ft</u>	α <u>50-200 ft)</u>	<u>Mean Wind Direction</u>
1	4-10-79	2224-2303	9.0/0.13	13.3/0.06	0.28	300°
2	4-11-79	1700-1727	16.6/0.13	24.7/0.07	0.29	300°
3	5-17-79	0641-0658	19.5/0.13	25.7/0.07	0.20	310°
4	8-17-78	1955-2020	29.3/0.08	32.1/0.05	0.07	260°
5	5-16-79	1753-1911	31.1/0.05	35.1/0.05	0.09	280°
6	5-16-79	2217-2248	33.5/0.07	40.2/0.07	0.13	280°

Figure 18. Profile measurements at Seven-mile Hill.

Figure 19. Sevenmile Hill profile location.

KCIV

The wind speed profiles shown in Figure 20 were taken at the KCIV anemometer site (see Figure 21). They indicate a noticeable difference in wind shear measured for directions 260° and 280° (see Table 18). The wind speed change with height was slight for winds coming from 260° (almost parallel to the ridge). The α value was 0.02 as noted in Table 18. However, α values of 0.16 and 0.29 were calculated from the flow measurements made for wind direction 280° . The difference in wind shear measured for the same wind direction is a result of a separation of the wind flow as it passes over a knoll about 1000 ft west of KCIV. It appears that the separation zone develops when the 50 ft level wind speed over KCIV exceeds 15 mph. This has been documented in a comparison of wind measurements taken at KCIV and at this knoll. Real time measurements of the wind speed were made from an anemometer mounted on a 25 ft mast on top of the knoll (see Figure 22). The hourly average wind speed from this anemometer and that from the KCIV anemometer at the 45 ft level are plotted in Figure 22 for a 34 hr period. The differences between the speeds are significant under the west northwest flow exceeding 15 mph. The knoll wind speeds are noticeably higher and indicate the presence of flow separation. The winds measured by the KCIV anemometer were also very turbulent. This turbulence was also noted at the 50 ft level from the TALA measurement (see Table 18).

Table 18. Wind shear data giving wind speed in mph and turbulence intensity values measured by the TALA anemometer at KCIV. The 200 ft speed data were estimated by interpolation of the curves in Figure 20.

Run No.	Date	Time (PST)	50 ft	200 ft	α (50-200 ft)	Mean Wind Direction
1	6-28-79	0836-1439 ¹	14.0/0.13	17.4/0.07	0.16	280°
2	8-1-79	1342-1440 ²	16.1/0.25	24.0/0.15	0.29	280°
3	8-3-79	0945-1046 ²	28.7/0.20	29.4/0.12	0.02	260°

1. Average of six profiles

2. Average of two profiles

Figure 20. KCIV wind profile measurements.

Figure 21. KCIV, (A), and the Knoll location, (B), 1000 ft west of KCIV.

Figure 22. Comparison of the mean hourly wind speed between KCIV and site B, 1000 ft west of KCIV under 280° flow. (The KCIV anemometer was at 45 ft while the knoll site anemometer was at 25 ft.)

Juniper Point

The four wind profiles taken at Juniper Point show little change of wind speed with height from the 50 to 200 ft level as noted in Figure 23 and in Table 19. In fact, the wind speed decreased slightly with height in two of the profiles. The Columbia Hills drop off sharply to the south but the grass covered north slope is smooth and descends gradually (see Figure 24). The wind flow from directions $290-360^{\circ}$ was smooth as indicated by turbulence intensity values between 0.03 to 0.09. The most notable wind shear and turbulence measured were for winds from 250° where the wind flows up and over the steep south slope.

Table 19. Wind shear data giving wind speed in mph and turbulence intensity values measured by the TALA anemometer at the Juniper Point site. The 50 and 200 ft speed data were estimated (when not available) by interpolation of the graphs in Figure 23.

<u>Run No.</u>	<u>Date</u>	<u>Time (PST)</u>	<u>50 ft</u>	<u>200 ft</u>	<u>α (50-200 ft)</u>	<u>Mean Wind Direction</u>
1	4-25-78	1130-1200	15.3/0.08	14.7/0.09	-0.03	360°
2	7-18-78	2045-2105	18.6/0.04	17.8/0.03	-0.03	300°
3	8-18-78	1218-1240	20.0/0.20	21.8/0.10	0.06	250°
4	6-29-79	0930-0957	49.0/0.08	51.0/0.08	0.03	290°

Figure 23. Wind profiles at Juniper Point.

Figure 24. The Juniper Point profile location.

Goodnoe Hills

Several wind profile measurements have been taken at the proposed Goodnoe Hills wind turbine generator site in moderate to strong west winds. The profiles are plotted in Figure 25 and the site location is noted in Figure 26. The site is grass covered and smooth and is located on the crest of a ridge. The measurements were made in wind flow from 260-300°. The α values varied from 0.05 to 0.20 as tabulated in Table 20 and averaged about 0.12 for all the directions. The wind flow measured was moderately turbulent at both the 50 and 200 ft levels. A very high turbulence intensity value of 0.43 was observed at the 50 ft level under west winds. A comparison of profiles 1 and 6 indicates that the winds above 150 ft tend to intensify more than those below.

Table 20. Wind shear data giving wind speed in mph and turbulences intensity values measured by the TALA anemometer at the proposed Goodnoe Hills WTG site. The 200 ft speed data were estimated by interpolation in the graphs of Figure 25.

<u>Run No.</u>	<u>Date</u>	<u>Time (PST)</u>	<u>50 ft</u>	<u>200 ft</u>	α <u>(50-200 ft)</u>	<u>Mean Wind Direction</u>
1	9-21-78	0900-0930	17.0/0.10	19.8/0.11	0.11	300°
2	4-11-79	1302-1339	20.1/0.17	24.3/0.14	0.14	260°
3	2-16-79	1525-1555	21.7/0.11	23.3/0.13	0.05	260°
4	6-06-79	0925-0957	24.8/0.20	28.3/0.13	0.10	250°
5	2-26-79	1250-1350	25.3/0.43	28.8/0.11	0.09	270°
6	10-20-78	1230-1300	28.1/0.23	37.2/0.12	0.20	290°

Figure 25. Wind profiles taken at Goodnoe Hills

Figure 26. The Goodnoe Hills wind profile location, A.

Kennewick

Kite anemometer measurements have been taken under moderate to strong southwest winds at the Kennewick anemometer site on the east end of the Horse Heaven Hills. The grass covered hills gradually slope to the south and west. All of the profiles shown in Figure 27 indicate little change in wind speed with height. The site location is shown in Figure 28. The α values given in Table 21 vary from -0.02 to 0.06. The turbulence intensity values varied from 0.05 to 0.13. Under stronger southwest flow the 100 and 200 ft winds tend to be relatively greater than winds above and below those levels as indicated in Figure 27. This tendency was also noted at Goodnoe Hills, Juniper Point, and Sevenmile Hill.

Table 21. Wind shear data giving wind speed in mph and turbulence intensity values measured by the TALA anemometer at the Kennewick site.

<u>Run No.</u>	<u>Date</u>	<u>Time (PST)</u>	<u>50 ft</u>	<u>200 ft</u>	α <u>(50-200 ft)</u>	<u>Mean Wind Direction</u>
1	9-14-78	1720-1755	20.0/0.05	19.4/0.06	-0.02	230°
2	7-12-79	0900-1000 ¹	22.6/0.12	24.5/0.09	0.06	220°
3	7-12-79	0800-0900 ¹	25.9/0.08	25.6/0.09	-0.01	210°
4	7-11-79	1122-1357 ²	29.9/0.13	30.3/0.11	0.01	240°
5	9-15-79	0811-0840	32.5/0.04	35.0/0.06	0.05	230°

1. Average of two profiles
2. Average of five profiles

Figure 27. Wind profiles taken at Kennewick

Figure 28. The Kennewick profile location, A.

Conclusions

The wind flow over various types of terrain at several wind power sites has been measured by the kite anemometer. From these measurements a few preliminary conclusions can be drawn. They are as follows:

1. Although a limited number of TALA measurements are available from most of the sites, individual profiles within the family of wind profiles show close similarity, especially those taken with the same wind direction.
2. The wind flow over a densely forested area (i.e., the Cape Blanco airport) is reduced significantly by the high surface roughness. This turbulent boundary layer extends at least two tree heights above the top of the tree canopy.
3. Turbulence intensity generally decreases with height except over very rough terrain (i.e., the Cape Blanco airport) where the turbulence level remains high 100 to 200 ft above the surface.
4. For a given wind direction the wind speed change with height, as represented by the value of the α coefficient in the power law, decreases as the wind speed increases in moderately smooth terrain such as that at Sevenmile Hill and Kennewick.
5. In winds exceeding 25 mph there is little change in wind speed with height above the 150 ft level at most of the sites in the Columbia River Gorge. However, at Goodnoe Hills the wind speed increased steadily through the 250 ft level when winds exceed 25 mph.

IV. WIND PROSPECTING FIELD SURVEYS

Northwest Washington

Central Columbia River Gorge

Cape Blanco

Columbia Hills

Goodnoe Hills

Horse Heaven Hills

Wind Prospecting Field Surveys

Wind prospecting field trips were made during the past year in two new areas, northwest Washington and the central Columbia River Gorge. The purpose of the trips was to define the geographical extent of the strong winds in each area and to locate several sites for installation of anemometers. Similar field trips were also made to the potential WTG development areas, Cape Blanco, the Columbia Hills, Goodnoe Hills, and the Horse Heaven Hills. The details of these site surveys are contained in Appendix 1; a summary of the findings follows.

Survey Technique Using Wind Deformed Vegetation

These areas were assessed in terms of their exposure, accessibility and wind deformed vegetation. Wind measurements were also taken with the kite anemometer at several locations. The vegetation survey gave valuable information on the overall strength of the wind at each location. An external deformation classification developed by Hewson et al. (1977-1979) was used to relate the degree of wind deformed vegetation to the mean annual wind speed. This index, based on the Griggs-Putnam analysis and shown in Figures 29 and 30, is accurate in predicting the mean annual wind speed to within $\pm 20\%$ (Wade and Hewson. 1979).

The Griggs-Putnam Index (G) is based on the pioneering work of R.F. Griggs, a botanist who collaborated with P.C. Putnam in the survey of wind power potential in New England prior to the installation of the Smith-Putnam wind turbine on Grandpa's knob in Vermont (see Putnam, 1948). This index, (shown in Figure 29), is a subjective scale based on the degree of response by the tree to the wind.

Figure 29. The Griggs-Putnam Index of wind deformation based on the degree of permanent bending of needles, twigs, branches and trunk of coniferous type trees. The mean annual wind speed that corresponds to the deformation is also given.

The degrees of response have been divided into the following seven classes:

Class 0 indicates *no effect*. Careful examination of needles, twigs and branches indicates that the wind had no noticeable influence on the tree.

Class I is *brushing*. The small branches and needles appear bent away from the prevailing wind direction. The tree crown may appear slightly asymmetric upon careful examination.

Class II is *light flagging*. The small branches and the ends of the larger branches are bent by the wind giving the tree a noticeably asymmetric crown.

Class III indicates *moderate flagging*. The large branches are bent toward the leeward side of the tree giving the tree a nearly one-sided crown.

Class IV is *strong flagging*. All the branches are swept to the leeward and the trunk is bare on the windward side. The tree resembles a banner.

Class V is *partial throwing*. A partially thrown tree is one in which the trunk and the branches are bent to the lee. The trunk may be bent concave or convex, but it rises vertically near the ground with the degree of bending increasing near the top of the trunk.

Class VI indicates *complete throwing*. The tree grows nearly parallel to the ground and along the path of the prevailing wind. The larger branches on the leeward side may extend beyond the tip of the trunk.

Class VII is *carpeting*. The wind is so strong or accompanying conditions so severe (i.e., ice particles) that the tree takes the form of a shrub. Upright leaders are killed, lateral growth predominates and the crown grows across the ground like a prostrate shrub.

The Griggs-Putnam Index was calibrated in terms of the mean annual wind speed, with the results as shown in Figure 30.

Figure 30. The relationship between the Griggs-Putnam Index and mean annual wind speed. Triangles indicate locations with more than 4 years of wind data. Closed circles indicate locations with more than a year but less than 4 years of wind data. Open circles indicate locations with more than one year of contact anemometer data. Douglas-firs and Ponderosa Pines were used in this analysis.

Note that the degree of deformation of individual trees is rounded to the nearest Griggs-Putnam Index number, whereas the deformation is actually a continuous function between index numbers. For example, the six data points identified as G-P 2.0 could range from G-P 1.5 to G-P 2.5.

Northwest Washington Survey

Two site survey trips were made to the coastal and mountainous areas of northwest Washington where twelve locations were visited. These locations are shown in Figure 31. The vegetation was inspected for wind deformation and wind profile measurements were made at several of these locations.

The spruce and fir trees along the Washington coast at sites 1, 12, and 8 indicate west to northwest wind flagging. The estimated mean annual wind speed from this deformation varies from 15 mph at site 8 to 12 mph at site 12. Deformation representative of these three sites is shown in Figure 32. East and southwest flagging were noted in the trees at sites 2, 3, 4, and 7 in the northwest coastal mountains (see Figure 33). The estimated mean annual wind speed based on the degree of deformation at these locations is 14-15 mph. South wind flagging is very apparent on the heavily forested ridges near Snider Peak, site 6. This deformation indicates a mean annual wind speed of about 15 mph. West wind flagging was observed at sites 5 and 11 along the Straits of Juan de Fuca. This deformation shows a mean annual wind speed of about 12-13 mph at site 5 and about 9 mph at site 11, the Port Angeles airport.

In August two of these sites were instrumented with wind-run anemometers mounted on 30 ft. masts. These sites are Cheeka Peak, site 4 and Queets Hills, site 12 in Figure 31. These two locations were chosen based on their good exposure to the wind flow, tree deformation and accessibility. Wind data will be recorded frequently by the FAA personnel who have a facility near site 4 and by the Queets Indian tribe who have a communications facility at site 12. The accessibility to the higher elevation locations at sites 6 and 7 is marginal to poor during the winter when strong winds prevail.

Figure 31. Northwest Washington wind survey locations (1 - Kalalock, 2 - Sekiu Mtn., 3 - Bahokus Peak, 4 - Cheeka Peak, 5 - Striped Peak, 6 - Snider Peak, 7 - Ellis Mtn., 8 - North Head, 9 - Mt. Octopus, 10 - Mt. Pleasant, 11 - Port Angeles Airport, 12 - Queets Hills). Location 13 is Tatoosh Island, the long-term data station.

Figure 32. Northwest wind flagged trees on the hills east of Queets.

Figure 33. East wind flagged Hemlocks and Pacific Silver Fir at Cheeka Peak.

Central Columbia River Gorge Survey

A three day wind prospecting field survey was made in the vicinity of the Augspurgen Mountain wind data station in the central Columbia River Gorge. The area surveyed is shown in Figure 34; it extends approximately 15 mi north and south of the Augspurgen Mountain site and about the same distance east and west. The Augspurgen Mountain wind station has been in operation for over three years and the mean annual wind speed is over 16 mph. Strong and persistent west winds are common throughout most of the year, but brisk east winds also are measured especially during the winter.

The area visited west of Augspurgen Mountain at sites 1 and 1A shows east wind flagging in the trees. The estimated mean annual wind speed is 12-13 mph. The area north of Augspurgen Mountain is also heavily forested. Some of the well exposed ridges shows moderate west wind flagging in the trees (see Figure 35). The deformation indicates mean annual wind speeds in the 13-15 mph range. South of Augspurgen Mountain in the Hood River Mountain area trees deformed by the west wind (sites 9-11 in Figure 34) also show 13-15 mph flagging as indicated in Figure 36. Most of this well exposed ridge is heavily wooded in 100 ft firs and pines. The area west of Hood River Mountain, sites 13-16 in Figure 34, generally indicates less wind deformation in the trees, on the order of 11-13 mph for the mean annual wind speed. However, the well exposed top of Mount Defiance, at 5,000 ft, shows good wind flagging (15-18 mph) along with limb breakage due to ice and severe winds.

The overall conclusion reached after site surveying this area of the Columbia River Gorge is that there are a few well exposed areas north and south of Augspurgen Mountain that show good wind deformation in the trees. However, most of the area is too heavily forested with trees extending above 100 ft in height and is too difficult to get into, especially during the winter months when most of the roads are impassible. Possible anemometer

sites where wind data could be gathered for 8-9 months out of the year are locations 7, 9, and 11 in Figure 34.

Figure 34. Topography map of the central part of the Columbia River Gorge showing the wind power site survey areas.

Figure 35. West wind flagged trees at Peterson Ridge, Site 7.

Figure 36. West wind flagged trees at site 10.

Cape Blanco Survey

Several wind prospecting field trips were made in the Cape Blanco area to assess the strength in the winds under north and south flow. Strong winter and summer winds have been measured by the Cape Blanco BPA anemometer for the past 2½ yrs. The mean annual wind speed there is over 18 mph. The locations investigated are shown in Figure 37. Wind profile measurements and ground based measurements of the wind flow were made at these locations and related to the wind flow measured at the Cape Blanco BPA station.

In February wind measurements were made under gusty southwest to west winds at locations 1, 5, 6, and 8 in Figure 37. Southwest winds at 18-20 mph were measured at the Cape Blanco BPA station and at Langlois Mountain. West winds were measured at Langlois, site 6, and were about 30 percent stronger than the southwest to west winds measured at site 1. At the Cape Blanco airport the winds were too erratic and weak to fly the kite anemometer below the 150 ft level, while 18-20 mph southwest winds were measured at the 150 ft level and above. The southwest winds weaken considerably and also are quite turbulent immediately above the 40 ft high tree canopy that surrounds the airport. A similar effect was observed in November 1977 where the winds increased with height by nearly a factor of two in the lowest 200 ft in south-southwest flow.

South winds at 15-20 mph were also measured by the kite anemometer in August at sites 1, 9, and 10. The flow measured at site 9 was moderately turbulent and was about 70% as strong as that measured at site 1. The winds measured at sites 1 and 10 were relatively smooth. The strength of the south wind measured at site 10 was about 90 percent of the strength measured at site 1.

However, the south wind regimes measured in February and August were not the typical persistent and strong south to southwest flow that frequently occurs

CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FOOT INTERVALS

Figure 37. TALA wind measurement locations in the Cape Blanco area. The starred sites are those that have anemometers (site 1 - Cape Blanco BPA, site 8 - Langlois Mountain, site 9 - Knapp Farm (Langlois), and site 10 - Wahl Farm).

from the fall through spring. Wind speeds exceeding 30 mph are common with storm passages. Field trips are planned in the future to measure the typical storm winds over the Cape area.

Wind profile measurements were made in June under typical summer north winds at sites 1-8 in Figure 37. Wind velocity profiles were taken on the hour from 1100-1500 PST near the Cape Blanco BPA station, site 1. The five profiles are tabulated in Table 22 along with the average of all of the profiles. The most notable increase in the wind speed under the moderate north flow was from the 50-150 ft levels. The general increase above the 150 ft level was slight. The power law coefficient α averaged 0.13 between the 50 and 150 ft levels. Also, the 50 ft level experienced the most turbulence, $I = 0.14$, and relatively smooth flow was measured aloft.

The wind profiles taken at sites 2-8 are compared to those taken at the base station, site 1. The site profile data are given in Table 22. A relative ranking is also given for each site compared with site 1. The ratio V_n/V_1 is the average of the ratio of the speeds at all four levels at each site to those at site 1. Sites 2 and 3 south of the Cape Blanco BPA station had the strongest relative flow. The north winds measured at the Knapp Farm, site 2, were stronger in the lower levels than those measured at the BPA station. The sharp cliff just north of site 2 caused considerable acceleration of the flow. Turbulence intensity values varied from 0.12 at the 50 ft level to 0.08 at the 350 ft level. Site 3, the Wahl Farm, also appears to have very good winds. The wind profile at the Cape Blanco BPA station was estimated. The general wind flow measured by the BPA anemometer decreased from an afternoon steady 16 mph to 12 mph at 1730 PST, the time the site 3 profile was taken. The site 1 profile was multiplied by a factor of 0.75 to obtain the estimated profile. Turbulence intensity values were quite high at the Wahl Farm and varied from 0.27 at 50 ft to 0.12 at 350 ft. The wind flow at sites

4, 6, and 8 was about 80% of that at site 1. Site 4 had high turbulence intensity values at the 50 and 150 ft levels where the averages were 0.29 and 0.20 respectively. Moderate turbulence intensity values were measured at sites 6 and 8. The wind flow measured at sites 5 and 7 was very turbulent below the 200 ft level and averaged about 70% of that measured at site 1.

Table 22. Comparison of the wind speeds (mph) at each site to that at the base station, Site 1, for the same time period. (13 June 1979)

Site No.	50	150	250	350	$\frac{V_n}{V_1}$	Relative Ranking
2	26.0	25.8	25.9	27.1	1.03	1
1	21.9	24.5	27.2	28.5		
3	15.1	15.6	18.6	21.1	.92	2
1 (estimated)	17.0	19.5	19.7	20.4		
4	20.0	20.5	23.9	22.5	.81	3
1	23.9	26.9	28.0	28.3		
5	17.4	17.9	20.0	23.2	.71	6
1	23.9	26.9	28.3	28.3		
6	19.1	20.2	18.0	20.0	.77	5
1	23.2	27.9	24.4	24.8		
7	13.8	17.1	20.5	20.7	.71	7
1	21.0	26.5	26.7	26.7		
8	19.0	18.8	19.9	20.9	.79	4
1	23.2	27.9	24.4	24.8		

To better define the wind flow in the high wind area, wind-run anemometers were installed in August on 30 ft masts at sites 9 and 10 in Figure 37. The tree cover is sparse and the land area is well exposed to north and south flow from sites 2 to 4 south of the Cape. There are also many large, well exposed open fields north of the Cape Blanco airport between sites 6 and 7. The winds measured at these two new locations will be related to those at the longer term wind data stations at sites 1 and 8.

Columbia Hills Survey

Wind measurements were made over a 4 mi by 6 mi area in the vicinity of KCIV at nine locations in June. The site locations are shown in Figure 38. West winds prevailed, being in the 10-15 mph range on the first day and increasing to 15-25 mph on the second day.

A recording anemometer was installed at the start of the survey at site 1, about 3 mi southwest of KCIV. This is the only location of those surveyed that has trees. The west wind flagging is shown in Figure 39 and indicates a mean annual wind speed in the 14-16 mph range. The wind speed and direction sensor was mounted on a 25 ft mast on a well exposed knoll, at the same location at which TALA measurements were made on 13 October 1977 and reported in BPA Report No. 77-2. Anemometer records from KCIV and the Dallesport airport were also gathered to use as base station measurements. The Dallesport facility is closed during the night so wind observations were not available for a continuous 24 hr period. The hourly plots of wind speed at these three sites are shown in Figure 40.

On 27 June the west wind flow was shallow and variable in The Dalles area. Moderate west winds were recorded on the floor of the Columbia River Gorge at sites 5, 6, and 10. The west winds decreased with elevation and were generally less than 10 mph at sites 1 and 2 on top of the Columbia Hills. TALA measurements were made at sites 5 and 6. Two profiles were taken at each site at four levels, 50, 150, 250, and 350 ft. The west winds measured were nearly the same at both sites. The wind speed increase with height was slight, from about 15 mph at the 50 ft level to 17 mph at the 350 ft level. Turbulence intensity values varied from 0.14 to 0.07. Winds measured at the Dallesport airport, site 10, by the 15 ft high anemometer were northwest at 15 mph.

On 28 June the west wind flow deepened during the early morning hours and was felt at KCIV and at site 1, as noted in Figure 40. The west winds probably decreased to less than 10 mph at the Dallesport airport during this time owing to the low level inversion that formed under clear skies. Wind profile measurements were taken at sites 1, 3, 4, 5, and 7 while hourly kite profile measurements were made at the base station KCIV. The wind profile at KCIV was estimated when the profile was taken at site 8 at 1730 PST. The wind speed recorded by the KCIV anemometer at 1730 PST was 15 mph and at 1400 PST when the last wind profile was taken there it was 12 mph. Therefore, a multiplication factor of 15/12 or 1.25 was used to correct the 1400 PST profile speed observations to give the estimated 1730 PST profile.

The results of this site survey are presented in Table 23. The overall strength of the wind over the entire profile was higher at all but one of the sites compared to that at KCIV as noted by the ratio V_s/V_{KCIV} . The overall wind speed measured at site 1 was about 7% higher than that measured at KCIV. The most notable difference was that of 2.8 mph at the 50 ft level. TALA measurements at site 3 along the ridge southeast of KCIV indicated about a 6% difference in the overall wind speed. At this site a significant speed difference from KCIV occurred at the 350 ft level where a 3.6 mph difference was measured. The wind profile taken at site 7, about a half a mile south of KCIV, indicated about 14% stronger winds than those found at KCIV. Higher winds were measured at the 50, 150, and 250 ft levels, and the most significant departure, a 4.9 mph difference, occurred at the 50 ft level. The wind flow measured at site 4, a well exposed ridge line about 2 miles southeast of KCIV was much lighter than that found at KCIV. The west winds were very gusty and decreased with height. The kite anemometer could not be flown at the 350 ft level owing to the light and turbulent flow. The wind speed at this level was estimated at 8 mph. The ratio of the wind speeds at this site to those at KCIV was 0.77.

Figure 39. West wind deformed trees at site 1.

Figure 40. Hourly mean wind speed (mph) at KCIV (site 2), Dallesport (site 10), and site 1.

Table 23. Comparisons of the wind speed (mph) and turbulence intensity measurements at six sites with those at KCIV for 28 June 1979.

Site	Time (PST)	Mean Dir.	Altitude (ft)				Ratio V_s/V_{KCIV}
			50	150	250	350	
1	1100-1158	290°	15.5/0.11	16.1/0.11	19.1/0.04	20.3/0.02	1.07
KCIV	1100-1158	290°	12.7/0.14	16.7/0.06	17.5/0.05	20.2/0.03	
3	1300-1401	280°	14.2/0.08	14.7/0.10	16.8/0.08	19.4/0.09	1.06
KCIV	1300-1401	290°	13.8/0.08	15.1/0.09	16.5/0.05	15.8/0.07	
4	1301-1355	280°	14.8/0.19	11.6/0.28	12.4/0.24	8.0 (est)	.77
KCIV	1301-1355	280°	13.8/0.08	15.1/0.09	16.5/0.05	15.8/0.07	
5	1431-1534	290°	23.3/0.12	20.4/0.13	20.6/0.10	19.6/0.12	1.22
KCIV	1431-1534	280°	15.9/0.19	16.3/0.09	18.6/0.03	18.5/0.05	
7	1108-1209	290°	17.6/0.11	17.9/0.10	19.8/0.09	19.7/0.07	1.14
KCIV	1108-1209	290°	12.7/0.14	16.7/0.06	17.5/0.05	20.2/0.03	
8	1653-1733	300°	38.1/0.19	41.2/0.07	43.7/0.03	45.4/0.04	1.95
KCIV*	1653-1733	280°	19.8	20.4	23.2	23.1	

* The KCIV profile was estimated

The overall strength of the wind increased farther down the slope. Wind speeds at site 5 were 1.22 times as high as those measured at KCIV. The differences ranged from 7.4 mph at the 50 ft level to a 1.1 mph difference at the 350 ft level. The west wind measured at site 8 on the floor of the valley near the Columbia River was almost twice as strong as that estimated at KCIV for all four levels.

After leaving the Smith Ranch, site 8, a wind profile was taken at Murdock, site 9 in Figure 38. This is a proposed site for a small WTG unit. The wind flow measured at the 100 ft level averaged 43 mph and the turbulence intensity was 0.09. The kite broke twice at the 50 ft level owing to gusts over 50 mph so measurements were not made.

Although the results of this survey on 28 June indicated stronger flow on the valley floor than at KCIV, more kite anemometer measurements should be made to determine spatial variations on a seasonal basis. Previous comparison of the winds at KCIV with those at the Dallesport airport indicated stronger flow at KCIV, especially during the winter. (see BPA Report 77-2). The winds at Dallesport and KCIV are similar in the summer. However, the side of the valley just north of the Dallesport airport does experience much stronger west winds than those measured at the more sheltered airport. In fact, on June 28 the winds were twice as strong at site 8 as they were at the airport. It may be that summer west winds in this well exposed area of the valley are stronger than those higher on the ridge. Wind-run anemometers should be installed at sites 8, 5, and 1 to learn if this is so. Site 3 should also be instrumented since it is easily accessible and there is a Washington State Patrol communications station there with a 100 ft tower.

Goodnoe Hills Survey

Wind profile measurements made at and near the proposed WTG site in June and August at Goodnoe Hills showed an increase in wind speed with height at the three locations noted in Figure 41. The proposed WTG location is at site 1 while sites 2 and 3 are 0.5 mi west and east of site 1 respectively. West winds in the 20-30 mph range were measured on both occasions.

In June single profiles were taken at each site but at different times. The data are shown in Table 24. However, determining the true spatial variation in the wind field in the one mile distance is difficult since the strength of the wind increased during the measurement period. The average wind speed during each measurement period as recorded by the Goodnoe Hills anemometer, 45 ft above the ground, increased from 20 mph when the profile was taken at site 1 to 28 mph when TALA measurements were made at site 3. The strongest winds were measured at sites 1 and 3 and the winds at site 2 were about 15% lighter.

In August wind profile measurements were made at these three sites, simultaneously. Two consecutive profiles were taken at four levels at sites 2 and 3 while the recording TALA 152 unit measured the wind flow at the 150 ft level at site 1. The two profiles at each site were averaged. The data are tabulated in Table 25. As in the previous survey the wind flow increased from west to east across the top of the ridge and there was also a wind direction change of about 20° . The wind flow in the lowest 350 ft increased about 10% from site 2 to site 3. The wind flow at site 1 at the 150 ft level was about 1 mph faster than that measured at site 2. The winds were strongest at the 150 ft level at site 3 where the speed exceeded 29 mph. Both of the wind profiles taken at site 3 indicated the maximum speed to be at the 150 ft level.

Figure 41. Wind power site survey locations in the Goodnoe Hills area. Site 1 is the proposed WTG location and site 4 is the anemometer site.

Table 24. Wind profile measurement data taken at three locations in the Goodnoe Hills area on 6 June 1979. Wind speed $\bar{V}$ (mph) and turbulence intensity I data are given for the four levels.

	Altitude (ft)				Goodnoe Hills (Strip Chart)
	<u>50</u>	<u>150</u>	<u>250</u>	<u>350</u>	
<u>Site 1</u> (0925-0958 PST)					
$\bar{V}$	24.8	26.7	29.8	30.0	20.0
I	0.20	0.14	0.12	0.18	
Direction	230-260°	240-250°	260°	250°	
<u>Site 2</u> (1030-1100 PST)					
$\bar{V}$	20.6	21.5	24.3	25.7	24.0
I	0.19	0.14	0.17	0.16	
Direction	230-280°	270°	260°	260°	
<u>Site 3</u> (1132-1201 PST)					
$\bar{V}$	25.8	25.9	28.3	31.6	28.0
I	0.16	0.17	0.14	0.20	
Direction	260-300°	250-280°	280°	270°	

Table 25. Wind profile measurement data taken at three locations in the Goodnoe Hills area on 1 August 1979. Wind speed $\bar{V}$ (mph) and turbulence intensity I data are given.

	Altitude (ft)			
	<u>50</u>	<u>150</u>	<u>250</u>	<u>350</u>
<u>Site 1</u> (0630-0720 PST)				
$\bar{V}$		25.5		
I		0.10		
Direction		250°		
<u>Site 2</u> (0630-0720 PST)				
$\bar{V}$	21.3	24.4	26.7	27.4
I	.13	0.10	0.07	0.05
Direction	240°	240°	240°	240°
<u>Site 3</u> (0630-0720 PST)				
$\bar{V}$	26.1	29.3	26.7	27.7
I	0.10	0.09	0.19	0.13
Direction	260°	260°	260°	270°

Horse Heaven Hills Survey

Wind flow measurements were taken in the eastern part of the Horse Heaven Hills near the Kennewick BPA anemometer site to investigate the spatial and temporal changes in the wind field. A survey team composed of four OSU personnel performed the survey; the area surveyed is shown in Figure 42. The area surveyed covers about 100 mi² and encompasses the estimated WTG potential area described in BPA Report 77-2.

Figure 42. Horse Heaven Hills wind profile site locations and also the possible area for WTG development documented in BPA Report 77-2. Base stations are noted by the stars.

Kite anemometer measurements were made at the six sites on 11 and 12 July. Profile data were taken continuously at the two base stations, sites 1 and 2, while kite measurements were made at sites 4 to 6. These data are contained in Tables 26 and 27. The wind velocity at the 50, 200, and 350 ft

levels was measured every 10 sec for a 5 min period using the spring scale hand-held TALA units. Two profiles were measured at each site and the data for each level were averaged to reduce errors due to temporal variations in the speed while the profile was being taken. The technique was suggested from earlier studies investigating proper measurement techniques.

On 11 July a wind survey was made in the middle of the day under 20 to 30 mph southwest winds. A comparison of the profile data at site 1 to those at sites 2 to 6 is given in Table 26. A ratio of the average of the speeds at all three levels at site 1 to the average at sites 2 to 6 is also given. The overall strength of the wind at sites 2 to 6 was about 73 - 84% of that measured at the Kennewick site on the east edge of the Horse Heaven Hills. The flow at sites 2, 3, and 4 was about 77 to 84% as strong as that measured at site 1. The wind flow at site 5 was about 73% of that at site 1. The strength of the wind at site 6 on top of the ridge was about 78% as strong as that measured on the ridge crest at site 1, about 4 mi north of site 6. The turbulence intensity values at all of the sites were moderate, ranging from 0.08 to 0.15.

During the morning of the next day a similar survey was taken at the six sites. These data are tabulated in Table 27. The wind flow was lighter at the sites than that measured the previous day. Also the overall wind speed decreased during the morning. The mean wind direction was 210° . Winds from 230° were measured the day before. As noted in Table 27 the strength of the flow measured on this morning at sites 2 to 6 was about 54 to 78% of that measured at site 1. Sites 3 and 6 on the ridge crest experienced flow about 77% as strong as that at site 1 while the lower elevation sites west of site 1 experienced much lighter winds.

Table 26. Comparisons of the wind speed (mph) and turbulence intensity measurements at five sites with those at Kennewick, site 1, on 11 July 1979.

Site	Time (PST)	Mean Dir.	Altitude (ft)			v_s/v_1
			50	200	350	
1	1140-1230	230°	28.9/0.13	29.4/0.13	29.9/0.13	1.00
2	1140-1230	230°	20.2/0.13	22.8/0.12	26.4/0.12	0.79
4	1140-1230	220°	22.0/0.15	21.6/0.14	24.2/0.13	0.77
1	1140-1230	230°	28.9/0.13	29.4/0.13	29.9/0.13	1.00
2	1140-1230	230°	20.2/0.13	22.8/0.12	26.4/0.12	0.79
5	1140-1230	240°	20.1/0.13	22.6/0.13	21.4/0.15	0.73
1	1300-1340	230°	31.0/0.12	31.3/0.08	30.3/0.11	1.00
2	1300-1340	230°	25.3/0.10	24.8/0.14	26.3/0.09	0.83
3	1300-1340	240°	24.6/0.12	25.9/0.11	27.6/0.12	0.84
1	1340-1430	230°	30.9/0.11	31.6/0.08	31.2/0.11	1.00
2	1349-1430	230°	26.9/0.10	24.7/0.12	25.7/0.11	0.83
6	1340-1430	270°	23.5/0.15	24.1/0.14	25.4/0.13	0.78

Table 27. Comparisons of the wind speed (mph) and turbulence intensity measurements at five sites with those at Kennewick, site 1, on 12 July 1979.

Site	Time (PST)	Mean Dir.	Altitude (ft)			v_s/v_1
			50	200	350	
1	0820-0900	210°	25.9/0.08	25.6/0.09	24.9/0.09	1.00
2	0820-0900	230°	15.9/0.25	12.6/0.32	12.6/0.26	0.54
4	0820-0900	230°	14.7/0.24	14.5/0.18	14.1/0.17	0.57
1	0820-0900	210°	25.9/0.08	25.6/0.09	24.9/0.09	1.00
2	0820-0900	230°	15.9/0.25	12.6/0.32	12.6/0.26	0.54
5	0820-0900	240°	15.1/0.10	16.2/0.11	16.0/0.14	0.62
1	0950-1030	210°	20.3/0.08	22.1/0.09	22.3/0.09	1.00
2	0950-1030	230°	$v < 10$	12.3/0.20	12.6/0.18	0.56
3	0950-1030	240°	15.9/0.12	16.7/0.15	16.9/0.14	0.77
1	0950-1030	210°	20.3/0.08	22.1/0.09	22.3/0.09	1.00
2	0950-1030	230°	$v < 10$	12.3/0.20	12.6/0.18	0.56
6	0950-1030	270°	18.9/0.15	16.5/0.27	14.5/0.24	0.78

In summary, the wind profile measurements taken over the two-day period revealed some interesting relationships on the spatial variation in the wind field. These include:

1. Under south to southwest flow, stronger winds occur along the ridge crest from sites 6 to 3 than along the gently rising slope to the west. Highest winds occur near the Kennewick anemometer site 1.
2. Under the stronger wind field measured on 11 July the wind speed differences between sites 2 to 6 were not large, being less than 10%, and the difference between these sites and site 1 was about 20%.
3. Under the lighter southwest winds of July 12 the wind speed difference between the sites was more pronounced. The difference between the ridge sites 1, 3, and 6 and the slope sites 2, 4, and 5 was between 20 and 45%. Of the ridge sites the winds were about 25% stronger at site 1.

However, more measurements should be made in this area to verify the conclusions derived from the two days of testing. The other prevailing wind direction as measured by the Kennewick anemometer is northwest. This flow should also be investigated to determine the spatial variation in the wind field.

On the morning of 13 July wind profiles were taken to investigate the spatial variation in the wind flow immediately adjacent to the Kennewick anemometer. Two kites were flown 300 ft apart with the Kennewick anemometer half way between the two TALA units. Two profiles were measured at each site at 50, 200, and 350 ft levels and the data were averaged and are summarized in Table 28. The difference in the strength of the winds in the profiles at sites A and B was about 10%. The wind speed differences were greatest near the ground, at the 50 ft level, and had the closest agreement at the 350 ft level. The surface roughness upwind of site B was greater than that near

site A; the turbulence intensity values were correspondingly larger at site B. The Kennewick anemometer at the 105 ft level recorded a wind speed of about 15 mph. The spatial variations in the horizontal thus appear to be as great as or greater than the wind variation in the vertical at this site. More investigations of the wind variation in the horizontal within 300 ft will be made at other potential WTG sites.

Table 28. Comparison of kite wind profiles taken next to the Kennewick tower on 13 July 1979 from 0715-0900 PST. Site A is 150 ft north of the tower and site B is 150 ft south of the tower. Wind speed (mph) and turbulence intensity data are given.

<u>Altitude (ft)</u>	<u>50</u>	<u>200</u>	<u>350</u>	<u>DIR.</u>
Site A	17.4/0.09	17.6/0.07	17.8/0.09	200°
Site B	15.2/0.11	16.6/0.11	17.0/0.10	200°

Conclusions

The wind prospecting field surveys yielded the following conclusions:

1. The northwest Washington coast and the coastal mountains appear to have good wind power potential based on the degree of wind deformed vegetation and spot wind measurements.
2. There appear to be many well exposed areas in the lowland adjacent to Cape Blanco that experience good winds.
3. The wind power potential in the central Columbia River Gorge near Augspurger Mountain is limited due to the rough topography and the vast extent of the high forest canopy that often extends 100 ft or more above the ground.
4. There appears to be good wind power potential over much of the ridge top area near KCIV and also over some of the valley land at the base of the Columbia Hills near the Columbia River.
5. The strength of the winds at Goodnoe Hills may change as much as 20% within a mile of the proposed WTG site.
6. The wind flow over the Horse Heaven Hills appears to be strongest on the crest of the ridge. The wind speed difference between the slope and crest measurements varied from 20-40% and of the crest sites, the Kennewick location measured the strongest flow.
7. Spatial variations in the wind profiles taken at the Kennewick station within 300 ft of each other indicated a 10% difference in wind speed. This spatial variation was about twice as great as that measured in the vertical.

V. NETWORK WIND ENERGY ANALYSIS

Optimal Placement of Wind Turbine Generators at Selected Sites in
the Pacific Northwest

Optimal Placement of Wind Turbine Generators at Selected Sites in the Pacific Northwest

Introduction

In BPA Report 77-2(1978) researchers identified several prime potential sites in the Pacific Northwest for the placement of wind turbine generators (WTGs). This report performs a network analysis in order to find the optimal placement of WTG units among six of these sites using several different objectives.

Background

The six sites with sufficient wind data for inclusion in this study are Augspurgen Mountain, Columbia Hills (KCIV), Goodnoe Hills, Kennewick, Cape Blanco and Wells. The site locations are shown in Figure 43.

Figure 43. Sites for possible WTG network.

Hourly wind data for these sites were used from the 12-month period beginning 1 March 1976. There were several times during this period in which data from one or more of the sites were not recorded. The amount of available data per site is summarized in Table 29.

Table 29. Summary of available wind data.

Number of Hourly Wind Speed Observations Per Week	Augspurger Mountain	Columbia Hills	Goodnoe Hills	Kennewick	Cape Blanco	Wells
0	1	2	1	0	2	12
1-56	1	4	1	1	1	2
57-112	4	4	1	1	1	2
113-167	6	9	4	3	7	4
168(Maximum)	40	33	45	47	41	32

Entries in the table indicate the number of weeks where the number of hourly observations recorded at that site fell within the range indicated. For example, at the Augspurger Mountain site there were 4 weeks during the 12-month period where the number of hourly wind speed measurements observed per week ranged between 57 and 112 (out of the 168 maximum). From this table, we can see that the most complete information was obtained at the Kennewick and Goodnoe Hills sites, and the least complete information is from the Wells and Columbia Hills areas.

From the characteristics of the terrain at these sites, a maximum allowable number of WTGs that could be placed at each site was estimated. These limits are:

<u>Site</u>	<u>Maximum Number of Units</u>
Augspurger Mountain	15
Columbia Hills	60
Goodnoe Hills	90
Kennewick	400
Cape Blanco	200
Wells	200

Assumptions Used in the Study

Several assumptions were made to facilitate the network analysis of this study, including:

1. The wind speed data collected for the 12-month period beginning 1 March 1976 represent a typical year at each of the six sites. Thus, the potential power generated from a WTG at any of these sites for the 12-month period of data collection is representative of future power output.
2. In order to account for the missing observations in the wind speed data, a normalized energy production was obtained using the recorded data. That is, it was assumed that the recorded values were representative of the missing values.
3. The WTGs considered in this study include both 2.5 MW and 4.5 MW units.
4. Only one size of WTG is installed at any one site.
5. At any site, each 4.5 MW unit costs \$3 million installed (plus an additional \$300,000 for the integrating facilities) and each 2.5 MW WTG cost \$2 million installed (plus \$250,000 for integrating facilities). Operating and maintenance costs for the 4.5 MW WTG are \$150,000 per unit per year, whereas those for the 2.5 MW WTG are \$130,000.
6. The maximum installed cost of all WTG units must not exceed \$45 million.
7. Each WTG unit can be expected to produce power for 30 years.
8. The cost of energy was calculated using the following equation:

$$\text{cost of energy} = \frac{(\text{PIC} \times \text{AFCR}) + (\text{OM} \times \text{PWLF})}{(\text{GEP} \times \text{AF})}$$

where PIC is the plant investment cost (installed unit cost

plus integrating facilities charges); AFCR is the annual fixed charge ratio (assumed to be 0.15); OM is the first year's operating and maintenance costs; PWLF is the present worth leveling factor (assumed to be 2.0); GEP is the (normalized) annual gross energy production per WTG unit; and AF is the availability factor (assumed to be 0.90).

Objectives Used in the Study

Several objectives were to be considered in determining the optimal placement of WTGs among the six sites. These are:

1. The maximization of the total annual energy output.
2. The maximization of the total peak-use period (November through February) energy output.
3. The minimization of the total cost per KWH generated by the WTG network.
4. The minimization of the cost per installed KW of the WTG network.

The Network Analysis

The first step in the analysis involved the calculation and normalization of the total annual and peak period output for each size of WTG at each site, based on the hourly wind speed data and the known power curves of the two sizes of WTGs considered in this study as adjusted for individual site conditions. Results of this analysis are presented in Tables 30 and 31 below.

Table 30. Total annual and peak period energy output from a single 2.5 MW WTG at each site, MWHs

	<u>Augspurger Mountain</u>	<u>Columbia Hills</u>	<u>Goodnoe Hills</u>	<u>Kennéwick</u>	<u>Cape Blanco</u>	<u>Wells</u>
Annual	10851	7345	9494	6432	9774	7579
Peak Period	3066	1643	2103	1781	2518	2684

Table 31. Total annual and peak period energy output from a single 4.5 MW WTG at each site (MWHs)

	<u>Augspurger Mountain</u>	<u>Columbia Hills</u>	<u>Goodnoe Hills</u>	<u>Kennewick</u>	<u>Cape Blanco</u>	<u>Wells</u>
Annual	13605	9155	12136	8927	13552	9288
Peak Period	3603	2058	2518	2695	3513	3422

From these results, the six sites can be ranked according to the WTG size and the total annual and peak period energy generated. These rankings are given in Tables 32 and 33.

Table 32. Ranking of the sites using a single 2.5 MW WTG

<u>Annual Energy Output</u>	<u>Peak Period Energy Output</u>
1. Augspurger Mountain	1. Augspurger Mountain
2. Cape Blanco	2. Wells
3. Goodnoe Hills	3. Cape Blanco
4. Wells	4. Goodnoe Hills
5. Columbia Hills	5. Kennewick
6. Kennewick	6. Columbia Hills

Table 33. Ranking of the sites using a single 4.5 MW WTG

<u>Annual Energy Output</u>	<u>Peak Period Energy Output</u>
1. Augspurger Mountain	1. Augspurger Mountain
2. Cape Blanco	2. Cape Blanco
3. Goodnoe Hills	3. Wells
4. Wells	4. Kennewick
5. Columbia Hills	5. Goodnoe Hills
6. Kennewick	6. Columbia Hills

Using the cost of energy equation and the annual energy production figures in Tables 30 and 31, the cost per KWH is calculated for the six sites and the two sizes of WTGs, as given in Table 34.

Table 34. Cost of energy at each of the six sites (\$/KWH)

	<u>Augspurger Mountain</u>	<u>Columbia Hills</u>	<u>Goodnoe Hills</u>	<u>Kennewick</u>	<u>Cape Blanco</u>	<u>Wells</u>
2.5 MW	.061	.090	.069	.103	.067	.087
4.5 MW	.065	.096	.072	.098	.065	.095

The conclusions that can be drawn from the results presented in Tables 32, 33, and 34 are as follows:

1. The Augspurger Mountain, Goodnoe Hills and Cape Blanco sites are the best of the sites included in this study, in terms of energy output and the cost of energy. The actual energy generation potential at Cape Blanco may be reduced somewhat due to the decrease in wind flow over the inland area of the Cape compared to that over the well exposed point of the Cape where the winds were measured.
2. While the Wells site could produce well during the peak-use period, it's overall energy production was quite low, resulting in the higher cost of energy at this site. It should also be recalled that Wells was one of the sites with fairly incomplete wind speed data (Table 29), and a review of the data indicates that much of the missing data was during the peak-use season. This could be the reason for the high peak-use production of the Wells site, and raises some question as to the confidence of these figures for that site.
3. The Columbia Hills and Kennewick sites rank poorly in comparison to the others.

Based on these results, and because the Augspurger Mountain and Cape Blanco sites were the two top-rated sites (see Tables 32 and 33), these two sites were selected for the placement of any WTGs in the network. (Recall that only one size of WTG can be installed at any one site, hence two sites should be considered.) From the cost of energy figures in Table 34 it was decided that any 2.5 MW WTGs used in the network would be placed at Augspurger Mountain, whereas 4.5 MW WTGs would be placed at Cape Blanco.

The next step of the analysis involved the determination of the maximum allowable number of 2.5 MW and 4.5 MW WTGs which could be used in combination and not exceed the \$45 million limit. The results are given in Table 35.

Table 35. Maximum allowable numbers of 2.5 MW and 4.5 MW WTGs in combination.

<u>Maximum Number of 4.5 MW WTG</u>	<u>Maximum Number of 2.5 MW WTG</u>	<u>Total Cost</u>
15	0	\$45 million
14	1	44 million
13	3	45 million
12	4	44 million
11	6	45 million
10	7	44 million
9	9	45 million
8	10	44 million
7	12	45 million
6	13	44 million
5	15	45 million
4	16	44 million
3	18	45 million
2	19	44 million
1	21	45 million
0	22	44 million

With these results we could now address the various objectives. Since Augspurgen Mountain was the optimal site for any 2.5 MW units with respect to annual and peak period energy, and Cape Blanco was the optimal site for 4.5 MW units in terms of the same objectives, an analysis was made to determine the optimal combination of 2.5 MW WTGs at Augspurgen Mountain and 4.5 MW WTGs at Cape Blanco in terms of annual and peak energy. The results of this analysis are given below.

NUMBER OF 2.5 MW UNITS AT AUGSPURGER MOUNTAIN = 15

NUMBER OF 4.5 MW UNITS AT CAPE BLANCO = 5

TOTAL ANNUAL ENERGY = 230525 MWH

TOTAL PEAK PERIOD ENERGY = 63555 MWH

COST PER INSTALLED KW = \$750

COST PER KWH = \$.0623

Therefore, we would be able to generate maximum energy (both annually and during the peak-use season) by installing 5 4.5-MW units at Cape Blanco and 14 2.5-MW units at Augspurgen Mountain.

The third objective, that of minimizing the cost per KWH, was achieved by the following straightforward procedure. From Table 34, we see that the lowest cost per KWH figure for the 2.5 MW WTG is Augspurgen Mountain. Furthermore, the figure of \$.061 per KWH is independent of the number of 2.5 MW WTGs installed at Augspurgen Mountain, since each additional WTG would (under the assumptions) generate an equal amount of energy at an equal cost. Also notice that if any 2.5 MW units were installed at any of the other sites, the total costs would be the same, but we would get less energy from these units, and hence raise the overall cost per KWH. Therefore, any 2.5 MW units used in the network must again be installed at Augspurgen Mountain in order to minimize the cost per KWH.

Now consider the 4.5 MW units. Using similar reasoning to that above for 2.5 MW WTG, we see that any 4.5 MW units in the network must be installed at either Augspurgen Mountain or Cape Blanco, where the cost per KWH is \$.065. Since Augspurgen Mountain was selected as the site for any 2.5 MW units, Cape Blanco was chosen for any of the 4.5 MW WTGs. But notice that the cost per KWH for the 4.5 MW units at Cape Blanco is \$.065, which is higher than the \$.061 cost per KWH for the 2.5 MW units at Augspurgen Mountain. Therefore, the installation of any 4.5 MW units at Cape Blanco will increase the overall cost per KWH. Hence, the optimal solution in terms of minimizing the cost per KWH is:

NUMBER OF 2.5 MW UNITS AT AUGSPURGER MOUNTAIN	= 15
NUMBER OF 4.5 MW UNITS AT CAPE BLANCO	= 0
TOTAL ANNUAL ENERGY	= 162765 MWH
TOTAL PEAK PERIOD ENERGY	= 45990 MWH
COST PER INSTALLED KW	= \$800
COST PER KWH	= \$.0612

To achieve the fourth objective, that of minimizing the cost per installed KW, notice that each 2.5 MW WTG cost \$2 million, giving us a cost per installed KW of \$800, whereas each 4.5 MW WTG costs \$3 million, or \$666 per installed KW. Thus the optimal solution in terms of this objective is:

NUMBER OF 2.5 MW UNITS AT AUGSPURGER MOUNTAIN = 0
 NUMBER OF 4.5 MW UNITS AT CAPE BLANCO = 15
 TOTAL ANNUAL ENERGY = 203280 MWH
 TOTAL PEAK PERIOD ENERGY = 52695
 COST PER INSTALLED KW = \$666
 COST PER KWH = \$.065

The optimal solutions for the different objectives when the Augspurger Mountain and Cape Blanco sites are used for the 2.5 MW and 4.5 MW units, respectively, are summarized in Table 36.

Table 36. Summary of the analysis using the Augspurger Mountain and Cape Blanco sites.

<u>Objective</u>	<u>Number of 2.5 MW Units</u>	<u>Number of 4.5 MW Units</u>	<u>Total Annual Energy (MWH)</u>	<u>Total Peak Period Energy (MWH)</u>	<u>Cost Per KWH</u>	<u>Cost/ Installed KW</u>
Maximum Annual Output	15	5	230525	63555	\$.0623	\$750
Maximum Peak Period Output	15	5	230525	63555	\$.0623	\$750
Minimum Cost Per KWH	15	0	162765	45990	\$.0612	\$800
Minimum Cost per Installed KW	0	15	203280	52695	\$.0652	\$666

Several important points are displayed in Table 36. Notice that while there is great fluctuation in the number of 2.5 MW and 4.5 MW units among the various solutions, the cost per KWH for the solution to the objectives of maximizing annual and peak energy production is close to the minimal cost per KWH. In fact, all of the cost per KWH figures are fairly close. It should also be pointed out that the limit of 15 WTGs for the Augspurger Mountain site was very influential in the analysis of the first three objectives. For example, had we been able to place 22 of the 2.5 MW units at Augspurger Mountain (the maximum number subject to the budget constraint), and none of the 4.5 MW units at Cape Blanco, we could have produced 238722 MWH annually and 67452 MWH during the peak-use season. Furthermore, this would have also minimized the cost per KWH at \$.0612.

Further Analysis

Owing to the potential difficulty of installing any WTGs at the Augspurger Mountain site because of poor accessibility, additional analysis was performed using an alternate site for the location of any 2.5 MW units in the network. The Cape Blanco area was ranked second in terms of annual power generation for the 2.5 MW WTG (see Table 32); however, it has already been selected as the site for any 4.5 MW units. Therefore, the third best site in terms of total annual energy generated from a 2.5 MW WTG—the Goodnoe Hills site—was chosen for this analysis.

The analysis performed with the Cape Blanco and Goodnoe Hills sites as the locations for any 4.5 MW and 2.5 MW WTGs, respectively, proceeds exactly as the previous analysis. Therefore, only the results are given in Table 37.

Table 37. Summary of the analysis using the Goodnoe Hills and Cape Blanco sites.

<u>Objective</u>	<u>Number of</u> <u>2.5 MW</u> <u>Units</u>	<u>Number of</u> <u>4.5 MW</u> <u>Units</u>	<u>Total</u> <u>Annual</u> <u>Energy (MWH)</u>	<u>Total</u> <u>Peak Period</u> <u>Energy (MWH)</u>	<u>Cost</u> <u>Per</u> <u>KWH</u>	<u>Cost</u> <u>Installed</u> <u>KW</u>
Maximum Annual Output	21	1	212926	47676	\$.0696	\$789
Maximum Peak Period Output	0	15	203280	52695	\$.0652	\$666
Minimum Cost Per KWH	0	15	203280	52695	\$.0652	\$666
Minimum Cost Per Installed KW	0	15	203280	52695	\$.0652	\$666

In this situation we see a slight increase in the cost per KWH when attempting to maximize total annual energy production, a direct result of the substitution of Goodnoe Hills for Augspurgen Mountain as the location of any 2.5 MW units in the network. Notice also that this substitution resulted in a loss of approximately 18000 MWH of annual energy production.

Conclusions

It appears as if the placement of 15 of the 2.5 MW units at Augspurgen Mountain and five of the 4.5-MW WTGs at Cape Blanco is the best of the alternatives investigated in this study. Again, the difficulty with this recommendation is the present undesirability for other reasons of installing any WTGs at Augspurgen Mountain. In light of this, the Goodnoe Hills site appears to be a worthwhile location for the placement of the 2.5 MW WTGs in the network.

VI. WIND FLOW ANALYSIS

Wind Flow Analysis

Introduction

Forecasting the winds, especially in complex terrain, is a difficult procedure. The main force driving the winds is the pressure gradient force so that the accurate determination of this force is essential for the improvement of these forecasts.

The simplest way to determine the pressure gradient between two stations at the same elevation is to subtract the two station pressures and divide by the distance between them (the pressure gradient force is the negative of this quantity). On the earth's surface, stations are not generally at the same elevation so reduction of the station pressure to a common level, usually taken to be sea level, is performed. There is no exact way for this to be calculated and reduction of pressures to sea level has long been known to yield erroneous results in regions of high elevation.

Standard methods of reduction are a function of both station pressure and temperature. Consider the following example: the two stations, Spokane, WA and Great Falls, MT at about the same elevation but separated by the Rocky Mountains, often have the same pressure but greatly differing temperatures, so that the reduction of pressures by identical procedures results in a fictitious horizontal pressure gradient between the two stations.

Bellamy (1945) introduced a new method for determining the pressure gradient force. It was based on the difference between height above mean sea level and the height in a reference atmosphere of the observed pressure at the observed height. This was found to work well in the upper levels of the atmosphere and over flat or moderately sloping terrain. In mountainous regions a correction term was included by Sangster (1960) to improve the analysis. He used a smoothed topography in which pressures were reduced (up or down) to the level of the smoothed surface.

This study develops a technique similar to Sangster's except that the terrain is not smoothed so that all calculations and analyses are performed at the station elevation. The case study approach is used to analyze data for the period 17 - 19 November 1978.

The objective of this study is to more accurately determine the pressure gradient force and, thus, explore the potential for prediction of winds at wind energy conversion sites, and in particular in the Columbia River Gorge.

2. THEORY

The basis for the following development is the D-system where

$$(1) \quad D = z - z_r$$

with z as the surface elevation (or any other height above mean sea level) and z_r as the height in a reference atmosphere at which the station pressure (or pressure at the indicated height) would be observed.

Bellamy (1945) first introduced the D-system, referring to D as the altimeter correction. He also used z_p in place of z_r and called it the pressure altitude. In addition he employed the U. S. Standard Atmosphere tables (1926 edition).

The horizontal pressure gradient force, $(F_p)_n$, on a constant pressure (or p) surface was derived to be

$$(2) \quad (F_p)_n = -g \left(\frac{\partial D}{\partial n} \right)_p$$

with n as the horizontal coordinate in the direction of the total horizontal pressure gradient (see Figure 44).

Bellamy used D to express the pressure field on upper air charts and then later extended the development to surface charts. Figure 45 is an example of Bellamy's D-analysis compared to the reduction to sea level.

Figure 44. The horizontal pressure gradient force, $(F_p)_h$; vertical pressure gradient force, $(F_p)_z$; total pressure gradient force, F_p . The angle α between z_p , a constant pressure surface, and z , a constant height surface, is exaggerated (Bellamy, 1945).

Figure 45. Surface chart comparing Bellamy's results with the reduction of station pressures to sea level (Bellamy, 1945).

In general he found that the D-analysis represented the (gradient) wind more closely than the sea level pressure analysis.

As indicated earlier, Bellamy's methods were applied mainly to the upper air for forecasting and aviation operations. His analysis did not take into account wide variations in topography.

The development by Sangster (1960) did take into consideration complex surface terrain by introducing a second, or correction, term. He defined a new independent vertical coordinate system that combined the best features of the p- and sigma- coordinate systems, the latter as defined in Equation 5. Using Bellamy's (1945) results and this newly defined vertical coordinate, Sangster derived an equation for the horizontal pressure gradient force

$$(3) \quad \nabla_p D = \nabla_p z = \nabla_{pp^1} D - S^* \nabla_{pp^1} z_p$$

where ∇_{pp^1} is the horizontal gradient operator in the new coordinate system and S^* is a specific virtual temperature anomaly. Both D and z_p have the same definitions as before.

He then defined a smoothed representation of the earth's surface to which pressures were then reduced (either up or down). In addition a variable reference atmosphere was defined such that a new pressure variable was introduced,

$$(4) \quad D' = D - S_r (z_p - \hat{z}_p)$$

where $\hat{z}_p$ is an arbitrary base level and S_r a specific temperature anomaly in the reference atmosphere.

By computing the geostrophic stream and potential functions for the lowest coordinate surface (i.e. the earth's surface) and comparing them to charts of pressure reduced to sea level, Sangster found that much of the distortion of the geostrophic wind field could be avoided. Figure 46 shows some of his results. On the sea level charts the isobars are packed along the Rocky

Mountains of Canada and Montana whereas the stream function (which is analogous to the sea level isobars) shows much less concentration of isopleths. This is in much better agreement with the observed surface winds.

Figure 46. Surface chart based on Sangster's analysis. The upper panels are the geostrophic stream (solid lines) and potential (dashed lines) functions; lower panels are the station pressures reduced to sea level. Wind symbols point in the direction the wind is flowing at the surface. (Sangster, 1960)

In the current study we define D by

$$(1) \quad D = z - z_r$$

and introduce the sigma coordinate system in the following manner

$$(5) \quad \sigma = p/p_s$$

where p is the pressure at any height above the surface and p_s is the surface pressure.

For A, an arbitrary scalar, and s, a horizontal direction, a coordinate transformation from σ to p takes the form

$$(6) \quad \left(\frac{\partial A}{\partial s} \right)_p = \left(\frac{\partial A}{\partial s} \right)_\sigma + \frac{\partial A}{\partial \sigma} \left(\frac{\partial \sigma}{\partial s} \right)_p$$

Noting that

$$(7) \quad \begin{aligned} \left(\frac{\partial \sigma}{\partial s} \right)_p &= p \frac{\partial}{\partial s} (1/p_s)_p = \frac{p}{p_s^2} \left(\frac{\partial p_s}{\partial s} \right)_p \\ &= - \frac{\sigma}{p_s} \left(\frac{\partial p_s}{\partial s} \right)_p \end{aligned}$$

replacing A by D and substituting equation (7) into equation (6) yields

$$(8) \quad \left(\frac{\partial D}{\partial s} \right)_p = \left(\frac{\partial D}{\partial s} \right)_\sigma - \frac{\partial D}{\partial \sigma} \frac{\sigma}{p_s} \left(\frac{\partial p_s}{\partial s} \right)_p$$

Extending (8) to a two-dimensional operator gives an equation similar to equation (3), i.e.,

$$(9) \quad \nabla_p D = \nabla_\sigma D - \frac{\partial D}{\partial \sigma} \frac{\sigma}{p_s} \nabla_p p_s$$

If we note that

$$(10) \quad \frac{\partial D}{\partial \sigma} = \frac{R}{g\sigma} (T_r - T)$$

we obtain the final form of the equation for the horizontal pressure gradient force on a p-surface

$$(11) \quad \nabla_p D = \nabla_\sigma D - \frac{R}{g} \frac{T_r - T}{p_s} \nabla_p p_s$$

where R is the gas constant for dry air, g the acceleration due to gravity, T the station temperature, and T_r a reference atmosphere temperature. For an observed station pressure p, T_r is defined by

$$T_r = 15.0000 + 51.2523 \ln(p/1013.25).$$

By first combining equations (8) and (11) and integrating along a straight line from s_1 to s_2 (for a constant $T_r - T$ along s) we can obtain an equation showing the difference in D values between two points.

or (12) $(D_{s_2} - D_{s_1})_p = (D_{s_2} - D_{s_1})_\sigma - \frac{R}{g} (T_r - T) (\ln (p_s)_{s_2} - \ln (p_s)_{s_1})$

and (13) $(\Delta D)_p = (\Delta D)_\sigma - \frac{R}{g} (T_r - T) \Delta \ln p_s.$

With equation (13) the error per degree of the difference $T_r - T$ can easily be seen, as illustrated in Table 38. The error can become very significant even for small differences when $(p_s)_{s_2} / (p_s)_{s_1}$ is near 0.8.

Table 38. Error per degree of difference between reference atmosphere temperature and observed station temperature. The first column is the ratio of observed surface station pressures.

$(p_s)_{s_2} / (p_s)_{s_1}$	$-\frac{R}{g} (T_r - T) \ln \left\{ (p_s)_{s_2} / (p_s)_{s_1} \right\}$ [per °K of $(T_r - T)$]
0.9	3.09
0.8	6.53
0.7	10.45

3. SYNOPTIC SITUATION, DATA, INTERPOLATION TECHNIQUE

a. Synoptic situation

The period 17 - 19 November 1978 was investigated for the current study. The National Meteorological Center (NMC) analyses showed that low pressure located at 49° N, 149° W on the 17th 1000 PST moved south-eastward to 45° N, 126° W by 1000 PST on the 19th. A cold front associated with this low moved to a line extending from NW Nevada through the San Francisco Bay area. A trough line in eastern Oregon, analyzed on the 17th, was dropped from the analysis at 0400 PST on the 18th after moving eastward to central Idaho. A stationary front in southwestern Canada and extending through Montana slowly migrated southward to a

position just north of the Oregon/Washington border during the same period. Low pressure associated with this front on the 17th was not evident in later periods. Figure 47 shows the situation for the entire period. The NMC analyses are not detailed enough to show some of the small scale phenomena we are currently investigating.

Figure 47. Location of surface features based on the National Meteorological Center's analyses for the period 17 - 19 November 1978 at 1000 PST. The small numbers represent the day on which the feature was observed at that position; the arrows indicate the motion of each feature.

b. Data

The data used in this study are the hourly reports of aviation and supplementary aviation weather observation stations. In addition, wind observations at potential BPA wind energy sites and barograph traces of the aviation station pressures supplemented the wind and pressure data respectively. The aviation observations and barograph traces are available from the National Climate Center in Asheville, North Carolina.

c. Interpolation technique

To compute gradients of pressure, data are interpolated to a regular grid network. To interpolate the data to a grid we employed a Barnes (1973) scheme that varied the weighting functions according to the station density. The number of stations in a 3° by 3° box centered on the station under consideration was used to modify the weights, i.e.

$$(14) \quad y = \frac{1}{\alpha} \exp (-d^2/4k)$$

where d is the station-to-grid point distance, k a weight parameter and α the number of stations in the box. The Barnes scheme was developed on the assumption of equal station spacing. However, this assumption is not valid for all cases and the above modification (14) eliminated the bias resulting from unequal station spacing. With these weights the station data were interpolated to a grid from 40° N to 49° N and from 115° W to 126° W. The grid point spacing was 1° in both directions. Gradients were computed using a 2° centered differencing scheme.

4. RESULTS

From our analyses the wind direction at most stations are in very good agreement with the direction of the horizontal pressure gradient force (HPGF). Where variations do occur, the winds are usually light (about 5 knots).

At time period 16* (1600 PST/17th) the winds in the Columbia River Gorge have a westerly component as does the HPGF at nearby grid points (Figure 48a). Mountain winds, at Stampede Pass WA and Sexton Summit OR, also agree with the local pressure gradient force even though the wind speed is very light.

Twenty-four hours later (period 40, 1600 PST/18th) a significant wind shift occurred at nearly all stations. By this time the low pressure and associated cold front (see Figure 47) moved closer to the Oregon coast. Hence, the winds responded to the larger-scale changing surface pressure pattern. Figure 48b shows the pressure gradient force and winds for this time period. The winds in the mountains were much stronger; Gorge wind speeds remained nearly the same as in period 16; and the eastern one-third of Washington continued to show a westerly HPGF component. The Gorge winds were being funneled down the Gorge which would account for the slight north/south discrepancy (at Portland and The Dalles) between the HPGF and the observed wind direction.

By period 58 (1000 PST/19th) the low was just off the Oregon coast. The gradient was much stronger along the western half of the Oregon/Washington border and there was an increase in wind speed at most stations (Figure 48c).

At this time the winds at Salem were northerly and did not correspond to the pressure gradient. This was due to a shallow cold air mass moving from north to south through the Willamette Valley, having passed Salem and reaching Eugene a few hours later. With the passage of this feature, Eugene's temperature fell 12° in one hour and Salem had a 5° decrease. The Mary's Peak (elev. 4097 ft) and Prairie Mountain (elev. 3200 ft) winds did not show any evidence of the shift in wind that occurred at Salem and Eugene with the passage

* Time periods were numbered consecutively, 1 through 72, beginning with 0100 PST on the 17th and continuing hourly until 2400 PST on the 19th.

Figure 48a. The horizontal pressure gradient force, $-g(\nabla D)_P$, at each of the grid points, selected wind observations^P from aviation weather stations (o), and winds from BPA wind energy sites (*) (in knots). The length of each HPGF vector is proportional to its magnitude according to the scale shown ($\times 10^{-5}$). Each full line on the flagged tail indicates 10 knots; each half line indicates 5 knots. Time period 16 is 17 Nov 78, 1600 PST.

Figure 48b. The horizontal pressure gradient force, $-g(\nabla D)_p$, at each of the grid points, selected wind observations^p from aviation weather stations (o), and winds from BPA wind energy sites (*) (in knots). The length of each HPGF vector is proportional to its magnitude according to the scale shown ($\times 10^{-5}$). Each full line on the flagged tail indicates 10 knots; each half line indicates 5 knots. Time period 40 is 18 Nov 78, 1600 PST.

Figure 48c. The horizontal pressure gradient force, $-g(\nabla D)_p$, at each of the grid points, selected wind observations from aviation weather stations (o), and winds from BPA wind energy sites (*) (in knots). The length of each HPGF vector is proportional to its magnitude according to the scale shown ($\times 10^{-5}$). Each full line on the flagged tail indicates 10 knots; each half line indicates 5 knots. Time period 58 is 19 Nov 78, 1000 PST.

of this air mass. It is concluded that the disturbance was very shallow and was not associated with the cold front that NMC had analyzed.

With weights used in the Barnes interpolation scheme and station spacing, this small scale feature could not be resolved to account for the wind direction at Salem. Smaller weights would have introduced too much noise and severely distorted the larger scale picture. Thus, careful manual analysis is necessary to resolve features such as this cold air mass.

The Mary's Peak wind direction at periods 40 and 58 were not in the same direction as the HPGF. Pressure data were not available from the top of the mountain; had it been available, the HPGF pattern might have been modified and been in better agreement with the observed wind. Also, for a station that is much higher than the surrounding topography, such as Mary's Peak, the winds tend to be more nearly geostrophic, i.e., flowing parallel to the isobars at that level. The 850 mb (approx. 5000 ft) flow at 1600 PST/18th was in nearly the same direction as the observed wind direction on Mary's Peak.

Figure 49 shows the east-west (u) component of wind at five sites* in the Columbia River Gorge plotted as a function of time (in hours). $(\Delta D)_\sigma$, curve 2, was computed by subtracting the Pendleton D from the Portland D value at each time period; $(\Delta D)_p$, curve 1, was determined by first computing the 2nd right-hand side term in equation 11 (again between Portland and Pendleton) and adding this to $(\Delta D)_\sigma$.

* (The Dalles, Sevenmile Hill, Boardman, Roosevelt, Augspurgen Mountain)

Figure 49. The east-west (u) wind component at five sites in the Columbia River Gorge (dots), (ΔD)_P (solid curve 1), and (ΔD) _{σ} (solid curve 2) for the 72 hr study. The points at the top of the graph represent missing wind observations.

The u-component is positive (westerly) in the early periods and negative (easterly) in the later periods almost without exception. $(\Delta D)_O$ and $(\Delta D)_P$ both correlate well with this direction change and seem to correlate well with wind speed, especially in the early time periods. The u-component increased from an average of 10 knots at period 1 to 20 knots at period 10, falling to zero near period 30. After this time the wind had an easterly component (negative u value) for the remainder of the 3-day period with no discernible trend as in earlier periods. Values ranged from 2 knots to 20 knots with an average value of 10 knots. If stations are plotted separately (i.e., one station per graph) similar to Figure 49, the u-component for each station remains nearly constant for the last half of the period.

5. Conclusions and Future Work

Where winds are above 5 knots there tends to be good correlation between the horizontal pressure gradient force and the wind direction. Early in the 3-day period the u-component of the wind at five sites corresponded well with $(\Delta D)_P$, with a more random pattern occurring in the latter part of the study.

While the interpolation scheme works well and is potentially useful with numerical weather prediction model output, the winds at Salem at time 58 show the existence of a small scale feature that cannot be resolved with the current weighting factors. Careful hand analysis is necessary to distinguish such phenomena. In addition, the depth of such disturbances might be smaller than the height of surrounding topography, so a vertical analysis might also be necessary. Also, the lack of pressure data at higher elevations such as Marys Lake contributes to model inaccuracy.

This study has shown the usefulness of using the altimeter correction D in determining the horizontal pressure gradient force in place of the reduction of station pressures to sea level. The results obtained using the two procedures may not be vastly different in the region covered in this study,

especially in moderately sloping terrain, whereas large differences can be expected in areas of extremely complex terrain such as the Rocky Mountains. We propose to extend the use of this technique to a larger area in the future. In addition, geostrophic stream functions should be determined so that analyses similar to those of Bellamy (see Figure 45) and Sangster (see Figure 46) can be performed. This will allow easy visual correlation between wind speed and contour spacing (since wind speed is inversely proportional to the stream function spacing).

A statistical analysis correlating the pressure gradient force, stability and winds aloft to the actual winds is also planned. This analysis would concentrate on the Columbia River Gorge region and be expanded to include stations with three or more years of data. The case study approach, while being very revealing, is impractical when the period of investigation is much longer than a few days in studies such as this. The feasibility of using the National Meteorological Center Limited-Area Fine Mesh (LFM) prog in giving reasonably accurate forecasts of the Gorge winds is also planned.

GLOSSARY

Geostrophic Wind - the horizontal wind, blowing parallel to the isobars, representing a balance between the pressure gradient force and the Coreolis force.

Gradient Wind - the wind represented by the Coreolis force and centrifugal force exactly balancing the horizontal pressure gradient force.

Power Law - the power law is often used to extrapolate the winds to higher levels from a base reference height. The equation reads:

$$V_U = V_L \left(\frac{Z_U}{Z_L} \right)^\alpha$$

where V_U is the desired upper level wind speed, V_L is the known lower level wind speed, Z_U is the upper level height, Z_L is the lower level height, and α is the power law exponent.

Virtual Temperature - the temperature a sample of dry air would have at the pressure and density of a sample of moist air.

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