Wind Energy Resource Atlas: Volume 2 - The North Central Region

Prepared for Pacific Northwest Laboratory
Under Agreement B-87926-A-L

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$____; Microfiche \$3.00

*Pages	NTIS
	Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

3 3679 00053 7631

PNL-3195 WERA- 2
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WIND ENERGY RESOURCE ATLAS:
Volume 2 - The North Central Region

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February 1981

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PREFACE

For the purpose of assessing the national wind resource, the United States and its possessions have been divided into twelve regions. For each region, wind resource assessments are presented in the form of an atlas. The atlases depict in graphic, tabular and narrative form, the wind resource on a regional and state level. The information presented in the atlases will help guide homeowners, utilities and industry in decisions concerning the use of the wind as a source of energy.

This atlas of the wind energy resource is composed of introductory and background information, a regional summary of the wind resource, and assessments of the wind resource in each state of the region. Chapter 1 provides background on how the wind resource is assessed and on how the results of the assessment should be interpreted. A description of the wind resource on a regional scale is then given in Chapter 2. The results of the wind energy assessments for each state are assembled in this chapter into an overview and summary of the various features of the regional wind energy resource. Chapter 3 provides an introduction and outline to the descriptions of the wind resource given for each state. Assessments for individual states are presented as separate chapters beginning with Chapter 4. The state wind energy resources are described in greater detail than is the regional wind energy resource, and features of selected stations are discussed. This preface outlines the use and interpretation of the information found in the state chapters.

Much of the information in the state chapters is given in graphic or tabular form. As is discussed in Section 3.1, the sequence of maps, tables, and graphs is the same in each state chapter. References to these figures and tables are made here with an asterisk (*) in place of the chapter number (e.g., Figure *.1, Table *.2). Similar maps and tables are found in Chapter 2 on the regional wind resource. References to the regional maps and tables are made in brackets, [].

Figure *.1 shows the major geographical (mountains, rivers) and cultural (cities, towns) features in the state [Figure 2.1]. This map can be used to orient the reader to the state. Figure *.2 portrays the topography of the state in shaded relief [Figure 2.2]. The shaded relief allows the reader to visualize the character of the terrain surrounding locations of special interest. Superimposed on these state maps (but not the regional maps) is a grid of dashed lines one-third degree (20') longitude by one-quarter degree (15') latitude. This grid is repeated on nearly all subsequent maps to give the reader an adequate frame of reference for locating the same feature on different maps.

Figure *.3 is a map of the land-surface form [Figure 2.3]. The information presented in Sections 1.6 and 1.8 indicates how the land-surface form is used to designate the terrain features considered to have a typical good exposure to the wind. Awareness of what constitutes well-exposed terrain features is crucial to the proper interpretation of the maps of wind power density.

Figures *.4 and *.5 identify and locate wind data sites relevant to the assessment. All locations in each state for which the National Climatic Center (NCC) has wind data in its archives are shown and named in Figure *.4. However, this assessment is based on a subset of NCC data augmented by data from other sources (see Sections 1.1 and 1.2).

Figure *.5 shows the location of all wind data sites used in the assessment. Sections 1.3 through 1.5 briefly describe the methods used to analyze the wind data and evaluate the wind power.

The wind energy resource for a state is illustrated using several maps. The wind power maps represent a careful synthesis of quantitative wind data guided by state-of-the-art concepts on air flow near the earth's surface. Section 1.6 describes how the analysis of the wind data is transformed into the map of annual average wind power density found in Figure *.6 [Figure 2.4]. This map gives the annual average wind power density at typically exposed sites. A discussion of the classes of wind power density in Section 1.7 gives the relationship between mean wind power density (watts/m^2) and mean wind speed (m/s or mph).

A certainty rating is used to provide a measure of the ability to objectively evaluate the wind resource in a grid cell. The certainty ratings are given in the maps of Figure *.7. The degree of certainty with which the wind power can be estimated depends on the quality and quantity of wind data, the complexity of the terrain and concern over the variability of the wind resource over short distances. How these factors are combined to assign a certainty rating is discussed in Section 1.9.

The terrain feature with typical good exposure to the wind in a particular land-surface form provides a convenient and essential reference point on which to base the analyses of the wind resource shown in Figure *.6. However, a substantial portion of the terrain may have poorer than typical exposure to the wind and will have a lower wind resource than shown on the wind power maps. The maps of Figure *.8 provide an estimate of the percentage of area in each grid cell that may experience at least each of four different wind power classes. Section 1.10 discusses the assumptions underlying the evaluation of the areal distribution of the wind resource. The area of the state estimated to have a particular wind power class is given in Table *.1 [Table 2.2]. This table summarizes the contribution made by each grid cell to the areal distribution of wind power for the state.

The annual average wind power density compresses into a single statistic time-varying trends on several time scales, e.g., annual, seasonal, monthly, and daily. In this atlas, the seasonal evolution of the geographical distribution of wind power is shown at the state level. The maps of Figure *.9 give the average wind power density for winter, spring, summer, and autumn. The interpretation of the seasonal average wind power maps is identical to that for the annual average wind power map. [For the region, Figure 2.5 shows only the season of maximum power.]

Additional information on the time variation and other characteristics of the wind resource in each state is presented for selected locations for which the National Climatic Center placed 1-hourly or 3-hourly time-series data on magnetic tape. Descriptions of the characteristics of the wind resource presented for these stations are given in Section 3.2. The urge to consider information pertaining to one of these sites as representative of some other location must be tempered with the realization that wind characteristics are extremely site-dependent. The degree of correspondence between the wind characteristics at one site and those at another site depends on the similarity between the topographical setting of the sites, the weather patterns that affect the sites and the obstructions to the wind in the vicinity of the sites.

Table *.2 identifies the stations, and gives their location (see also Figures *.4 and *.5) and annual average wind speed and power density. Figure *.10 shows how the yearly mean speed and power varied during the period of record. The monthly mean wind speed and power over the course of a year are shown in Figure *.11. The hourly mean wind speed over the course of a day is shown in Figure *.12 with a separate curve for each season. Figures *.11 and *.12 indicate the variation by time of year and time of day, respectively, of the wind resource. Figure *.10, on the other hand, indicates the year-to-year variability that might be expected in the yearly mean resource.

The frequency of occurrence of winds from a particular direction and of winds with a particular speed is shown in Figures *.13 and *.14, respectively. The information on wind direction may be important in assessing the availability of the wind resource relative to surrounding terrain or nearby obstructions. However, it is also important to realize that the wind direction statistics are highly dependent on the location of the instrument site relative to obstructions and major terrain features, e.g., valleys, ridges, and mountain ranges.

Figures *.15 and *.16 portray speed and power frequency statistics in the form of speed and power exceedance curves, respectively. The fraction of the total period of record during which the speed equals or exceeds a given value is shown in Figure *.15. The power exceedance curve in Figure *.16 gives the fraction of the total period of record during which the power exceeds a given value.

As has been shown in the preceding discussion, the order of presentation of the wind resource in this atlas proceeds from a regional perspective in Chapter 2, to a state perspective in the first part of each state chapter, to individual station descriptions in the last part of the state chapters. Attention given to Chapter 1 and Chapter 3 will make it possible for the reader to properly interpret the wind resource presentations.

ACKNOWLEDGEMENTS

We wish to extend our thanks to all those who assisted in the compilation of this atlas. Special thanks to personnel in the Applied Meteorology Division of ERT/Western Scientific Services, especially Stephen Andersen for this never-failing support, and Nick Klemm for his support and follow-through during the compilation of data. We are also especially grateful to Loren Crow for his advice, wisdom and knowledge which he unselfishly shared; to Lanette Moore and Bob Newsham for their patience through seemingly endless modifications of text and graphics; to Sophie Sawyer of ERT and Betsy Owzarski of PNL for their editing; and to all public agencies and private industries who cooperated with us during the search for data. Finally, special acknowledgement is due to L. Divone and G. Tennyson, for their support and encouragement as well as their understanding of the many technical aspects and associated difficulties in producing this atlas.

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CHAPTER 1: REGIONAL WIND ENERGY RESOURCE ASSESSMENT

Rapid development of wind as a source of commercial electric power is the principal goal of the Federal Wind Energy Program. Utility planning, wind turbine manufacturing and marketing of wind energy conversion systems all depend on detailed wind resource assessments. This atlas of the wind resource in the North Central region, a product of the Wind Characteristics Program Element of the Federal Wind Energy Program, represents a major source of information for meeting these various needs.

This wind energy resource atlas is the second of twelve such atlases that will be assembled. The other atlases will describe the potential wind resource in eleven other regions of the United States (see Figure 1.1). The spatial and temporal resolution of the wind resource in these regional assessments will be depicted in considerably greater detail than that in existing national assessments (Reed 1975, Coty 1976, Garate 1977, Elliott 1977). To produce the North Central atlas in a timely fashion, only existing relevant data were used. The other atlases will use comparable data sets, analysis techniques and presentations to ensure the comparability of the wind resource assessments.

The North Central atlas assimilates six collections of wind resource data: one for the region and one for each of the five states that compose the North Central region (Iowa, Minnesota, Nebraska, North Dakota, and South Dakota). At the state level, features of the climate, topography and wind resource are discussed in greater detail than is provided in the regional discussion, and the data locations on which the assessment is based are mapped. Variations, over several time scales, in the wind resource at selected stations in each state are shown on graphs of monthly average and interannual wind speed and power, and hourly average wind speed for each season. Other graphs present speed, direction and duration frequencies of the wind at these locations.

The methods used to identify, screen, evaluate, and analyze the various types of data, and to produce the wind energy resource maps and graphs will only be described briefly. [For more detail see Elliott and Barchet (1980), and Freeman (1980).] However, this discussion will provide the reader with useful background information for interpreting the wind energy resource maps for the North Central region.

FIGURE 1.1. Geographic Divisions for Regional Wind Energy Assessments

1.1 IDENTIFICATION OF WIND DATA SOURCES

The surface wind data on which this atlas has been based were obtained from several sources: the National Climatic Center (NCC), the U.S. Forest Service, university research projects, nuclear and fossil-fuel power plants and their proposed sites, DOE candidate wind turbine sites, the Atmospheric Environment Service of Canada, and other government and private organizations. The National Climatic Center offers the largest collection of wind data. Surveys and indices of wind data archived at the NCC (Changery 1975, 1978; Changery et al. 1977) are extremely helpful in locating available wind data. The Index of Original Surface Weather Records, published for each individual state by the NCC, provides additional information about stations at which wind data have been taken.

The wind data available from the NCC may be in one or more of three formats: summarized, digitized, and unsummarized. Initially, all wind data are in the unsummarized format consisting of the original station weather records. For many stations, the collection of individual observations has been condensed into wind summaries. Changery et al. (1977) present examples of the various summary formats used and indices of the stations for which wind summaries are available. For still fewer stations (primarily airport stations) the NCC has put the original one- or three-hourly weather observations on magnetic tape to create a digitized time series of weather (and wind) observations. [TDF-14 (NCC 1975) describes the data on these tapes.] In the remainder of this Atlas, "digitized data" will refer to hourly averaged data in computer-accessible format, such as magnetic tape or computer cards. Table 1.1 indicates the number of stations with wind data in these various formats in the North Central region.

A detailed study of digitized wind data from three NCC sites in Iowa (Takle et al. 1978) suggests the possibility that one minute wind speed averages estimated by observers from watching instantaneous wind speed indicators may lead to over-estimates of wind speed and wind power. Nevertheless, these data, described in TDF-14, were the primary reference data on which this analysis was based. If subsequent studies show that there is a consistent bias so introduced, then these data, and hence the regional analysis, can be adjusted uniformly.

In contrast to the NCC data, which are primarily from inhabited areas, U.S. Forest Service data in the National Fire Weather

Data Library (Furman and Brink 1975) are from remote sites in mountainous and forested areas under the jurisdiction of the Federal government (i.e., national forests, national parks, Indian reservations, or Bureau of Land Management areas). Sixty-two stations with wind data are reported in the National Fire Weather Data Library for the North Central region (Marlatt et al. 1979). However, only one afternoon observation, at about 2 p.m., is digitized per day during the local fire weather season.

Wind data from 7 nuclear or fossil-fuel power plants or potential plant sites (Verholek 1977) were examined. Many other wind data sets collected by university research projects, state and local air pollution control agencies, or in support of environmental impact statements have also been identified.

1.2 WIND DATA SCREENING

Table 1.1 indicates the quantity of wind data available in the North Central region and peripheral area. However, not all of these data need to, or should, be used in a wind resource assessment. Screening procedures were developed to identify stations with the most useful data and to eliminate stations that would not significantly contribute information on the distribution of the wind resource.

TABLE 1.1. Stations with Wind Data Screened for the North Central Region Wind Energy Resource Assessment

Source and Type	Screened	Retained
National Climatic Center		
Digitized	124	76
Summarized	40	39
Unsummarized	76	32
National Fire Weather Data Library	62	18
Nuclear and Fossil-Fuel Power Plant	7	7
Canadian	12	12
Other	48	28

Wind data in summarized or digitized format were chosen over unsummarized data. When stations had both summarized and digitized data, the digitized data were used for selected stations to prepare a more extensive characterization of the wind resource.

Unsummarized data were used only when no summarized or digitized data were available, and only if the data constituted a representative sample. Many of the NCC stations with unsummarized data were intermittently reporting stations, some of them having observations as infrequently as once or twice per month. A few of the NCC unsummarized data stations were omitted from the analysis because of poor anemometer exposure.

In areas with a high density of stations with wind summaries, those stations appearing to have the best exposure to the wind, greatest number of daily observations, longest period of record, and longest period of unchanged anemometer height and location were usually selected over other nearby stations. When more than one type of summary (see Changery et al. 1977) was available for a given station, the summary covering the longest period of record with constant anemometer height and location, with the greatest number of wind speed and direction classes, and with the highest frequency of daily observations was chosen.

1.3 TIME SCALES IN REGIONAL ASSESSMENTS

Several time scales are encountered in the following discussions of the wind resource: annual, seasonal, monthly and diurnal. Annual mean values are generally based on an average of the one- or three-hourly observations of wind speed or power in the period of record; however, a complete calendar year's data (covering January 1 to December 31) is used for calculating individual yearly means. At stations with less than 24 hourly observations or 8 three-hourly observations per day, the values are only representative of the times of day for which the data were taken.

The four seasons are defined as:

- winter - December, January and February
- spring - March, April and May
- summer - June, July and August
- autumn - September, October and November.

The phrase "seasonal trends" refers to the change in monthly mean values over the course of the four seasons.

Monthly mean values are based on as many hours of data as are available for that month in each year of the period of record.

The daily or diurnal cycles of variation in the hourly mean wind power or speed are referenced to local standard time on a 24-hour clock. Midnight is both 00 and 24.

1.4 EVALUATION OF WIND DATA

For the purpose of mapping the geographical variation of the wind resource, wind power density was chosen over wind speed since the power density incorporates in a single number the combined effect of the distribution of wind speeds and the dependence of the power density on air density and on the cube of the wind speed. Quantitative wind data in three formats were evaluated for mean wind power density: digitized, summarized, and unsummarized. The average wind power density $\bar{P}$ (watts/m²) in a vertical plane perpendicular to the wind direction for stations with one- or three-hourly digitized data was calculated from:

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

where

n = the number of observations in the averaging period

ρ_i = the density (in kg/m³) computed from the station pressure and temperature at the i th observation time

V_i = the wind speed (in m/s) at the i th observation time.

For stations with wind summaries, $\bar{P}$ was calculated from:

$$\bar{P} = \frac{1}{2} \bar{\rho} \sum_{j=1}^c f_j V_j^3 \quad (2)$$

where

$\bar{\rho}$ = the mean air density, approximated by using the National Advisory Committee for Aeronautics (NACA) standard atmosphere at station elevation

c = the number of wind speed classes

f_j = frequency of occurrence of wind in the j th class

V_j = The median wind speed of the j th class.

In those cases for which unsummarized wind data were assessed, the seasonal and annual average speeds, $\bar{V}$, were estimated from a visual examination of one year's original weather records. The wind power density, $\bar{P}$, was then estimated by assuming that the speed frequency distribution followed a Rayleigh distribution. For a wind speed frequency distribution that

follows a Rayleigh distribution, wind power density is given by (Cliff 1977):

$$\bar{P} = 0.955 \bar{\rho} \bar{V}^3 \quad (3)$$

where

$\bar{\rho}$ = mean air density, approximated by using the NACA standard atmosphere and station elevation

$\bar{V}$ = mean wind speed for the period being analyzed

It should be noted that the Rayleigh distribution is a good approximation of the natural distribution of windspeed for high windspeeds only. Cliff (1977) suggests a lower limit to $\bar{V}$ of 4.5 m/sec. At this mean speed, mean power density approximated by equation (3) is near 100 W/m², or near the upper limit of the 10 meter class 1 wind power density category. Consequently, equation (3) provides a good approximation of wind power density for class 2 wind power density and higher, especially in the simple terrain characteristic of much of the North Central region.

For most of the NCC stations with unsummarized data, the mean wind speed was estimated by a visual examination of one year of original weather records, and the average wind power density estimated by equation (3). For a few stations with unsummarized hourly data, primarily stations in areas otherwise void of data (e.g., Brookings and Mitchell, South Dakota), the average seasonal and annual cubed speed, $\bar{V}^3$, was estimated by manually averaging all V^3 every third day for one year. Wind power density for these stations was then estimated by:

$$P = \frac{1}{2} \bar{\rho} \bar{V}^3 \quad (4)$$

1.4.1 Vertical Adjustment

The anemometer height above the surface rarely was at either the 10-m or 50-m reference levels chosen for the presentation of the wind resource. A power law was used to adjust the long-term mean wind speed or power density to the reference level:

$$\frac{\bar{V}_r}{\bar{V}_a} = \left(\frac{Z_r}{Z_a} \right)^\alpha \quad \text{or} \quad \frac{\bar{P}_r}{\bar{P}_a} = \left(\frac{Z_r}{Z_a} \right)^{3\alpha} \quad (5)$$

where

$\bar{V}_{a,r}$ and $\bar{P}_{a,r}$ = the mean wind speed or wind power density at heights $Z_{a,r}$ (the anemometer, and reference level, respectively)

α = the power law exponent.

An examination of long-term mean wind speeds at airport locations at which the anemometer height was changed and at tower sites with multiple levels of anemometry, including towers at five Great Plain sites, indicates an $\alpha \sim 1/7$ to be widely applicable to low surface roughness and well exposed sites from which conventional NCC data are available (Elliott 1979b).

1.4.2 Estimates for Mountainous Areas

The quantitative estimation of wind power over the Black Hills made use of the northern hemisphere upper-air wind climatologies for the 850, 700 and 500 mb constant pressure levels by Crutcher (1959). Since earlier studies had shown a strong correlation between mountaintop and free-air wind speeds (Wahl 1966), the free air wind speed at mountain summit or ridge crest height was extrapolated (or interpolated) from the mean scalar speeds on the constant pressure surfaces. Estimates of the mountaintop wind speeds were made on a grid one-fourth degree latitude by one-third degree longitude. In each such cell of the grid over the mountains, the mean ridge crest or mountain summit elevation and appropriate constant pressure surface mean wind speeds were estimated. Linear extrapolation provided the mean free-air wind speed at the terrain elevation and the application of a Rayleigh speed distribution gave the mean free-air wind power. The mean wind power at the 10-m and 50-m reference heights was taken to be one-third and two-thirds of the free-air value, respectively, to account for the frictional slowing of the wind near the surface.

Wind power estimates for the Black Hills are considered to be lower limits for exposed ridge crests and mountain summits. Local terrain features in mountainous regions can enhance the wind power considerably. However, a major uncertainty in any mountainous terrain is the representativeness of some of the data upon which the free air estimates are based (e.g., sheltering by nearby mountains can bias rawinsonde winds).

1.5 QUALITATIVE WIND INDICATORS

Although more than 200 stations provided quantitative data used in the North Central regional wind resource assessment, these stations were not uniformly distributed. The station location figures for each state show many large areas in the North Central region that are devoid of any form of quantitative wind data suitable for this assessment, such as eastern North Dakota and much of South Dakota. To evaluate the distribution of the wind resource in data-sparse areas, qualitative indicators of the wind speed or power were used in the assessment.

The most widely used technique depended on certain combinations of topographical and meteorological features (Elliott 1979a) that were associated with high or low wind speeds. Those features indicative of high mean wind speeds include:

- high elevation plains and plateaus
- exposed ridges and mountain summits in areas of strong upper-air winds
- exposed coastal sites in areas of:
 - 1) strong upper-air winds, or
 - 2) strong thermal/pressure gradients.

Features that signal rather low mean wind speeds include:

- valleys perpendicular to the prevailing winds aloft
- sheltered basins
- short and/or narrow valleys and canyons
- areas of high surface roughness, e.g., forested terrain.

In addition, it was assumed that areas of flat terrain that have no data, but that have the same exposure as stations with data and are in the same general land feature, will have nearly the same wind characteristics. Examples of this are eastern North Dakota and eastern South Dakota between the Missouri River and the Prairie Coteau.

Areas in which the appropriate features occur were determined by examining topographic contour and shaded relief maps and synoptic and climatological maps of sea-level pressure patterns and air flow.

1.6 WIND POWER MAPS

The production of mean wind power density maps, such as those presented for each state, depended on the coherent synthesis of several pieces of information. The goal of the synthesis process was to present wind power density values representative of sites well exposed to the prevailing strong winds. Hilltops, ridge crests, mountain summits, large clearings and other locations free of local obstructions to the wind are expected to have good exposure to the wind (see Table 1.2). In contrast, locations in narrow valleys and canyons, downwind of hills and obstructions, or in forested or urban areas are likely to have poor exposure. The wind power density shown on the maps in this atlas will not be representative of poorly exposed locations. Estimates for ridge crests and summits of the Black Hills (shaded) are lower limits to the wind power expected at exposed sites. In this area, local terrain features can enhance the wind power considerably (e.g., by a factor of 2 or 3). By specifying the type of wind exposure to which the map values of wind power pertain, we avoid the ambiguity that typical-location or average-for-the-terrain values might introduce. In this atlas, the terms wind energy, wind power and wind power density are used synonymously.

To represent the wind resource at well-exposed sites, it was necessary to become extremely familiar with the land-surface form and topography in the vicinity of every data site. Maps were prepared showing the location of stations, the mean wind speed and mean wind power at the reference level, the character of anemometer exposure, and the land-surface form for each state. On these maps, areas with the appropriate combinations of topographical and meteorological features were identified. A great deal of attention was given to the orientation of topographic features with the prevailing wind directions. Only after all this information was assembled were the maps analyzed. The annual maps for each state were merged into a regional mosaic.

1.7 WIND POWER DENSITY CLASSES

The analysis of wind power maps departs from conventional isopleth analyses by showing the boundaries of wind power density classes. Each wind power class represents the range of wind power densities likely to be encountered at exposed sites within an area designated as having that wind power class. Table 1.3 gives the

power density limits for the wind power classes used in the atlas for the 10-m (33-ft) and 50-m (164-ft) reference levels. The definitions of the wind power density classes are repeated with the annual wind power map for the region and for each state as a convenience for the reader.

Wind power density is proportional to the third moment of the wind speed distribution and to air density; therefore, a unique correspondence between power density and mean wind speed (the first moment of the speed distribution) does not exist. However, by specifying a Rayleigh wind speed distribution and a standard sea level air density (1.22 kg/m^3) a mean wind speed can be determined for each wind power class limit. The decrease of air density with elevation requires the mean Rayleigh speed to increase by about 3%/1,000 m elevation (1%/1,000 ft) to maintain the same power density. If the wind speed distribution is more sharply peaked than the Rayleigh distribution, the equivalent mean speed will be slightly higher than the value in Table 1.3. Conversely, a broader distribution of wind speeds will slightly reduce the equivalent mean speed.

1.8 CLASSES OF LAND-SURFACE FORM

The physical characteristics of the land-surface form affect the number of wind turbines that can be sited in exposed places. For example, over 90% of the land area in a flat plain may be favorably exposed to the wind; whereas in mountainous terrain only the ridge crests and passes, which may be only a small percentage (<5%) of the land area, may represent exposed sites. The map of classes of land-surface form by Hammond (1964) provided information on the distribution of plains, tablelands, hills and mountains in the North Central region. Several characteristics are coded on this map:

- percentage of land area occupied by surfaces of gentle inclination (less than 8% slope)
- local relief, the maximum difference in elevation within a unit square six miles across
- percentage of gently inclined surfaces that lie in the lower half of the local relief
- land area covered by sand, ice, and standing water
- pattern of major crests, peaks, and escarpments.

The first three characteristics are used in the classification scheme (see Table 1.4); the latter two have been omitted from the maps presented here. A three-character code, for example B3a, designates each class of land-surface form. In this example the "B" indicates that 50% to 80% of the area is occupied by gentle slopes; the "3" that the maximum local difference in elevation is 100 to 150 m (300 to 500 ft); and the "a" that more than 75% of the gently sloping land is in the lowland. In areas of very little gentle slope (D) or very low relief and great smoothness (A1), the third designator is omitted.

For each land-surface form, the percentage of land area that is representative of well exposed, moderately exposed, and poorly exposed sites has been estimated. These percentages were determined subjectively as a function of the slope, local relief, and profile type. Table 1.2 gives the average percentage of land area that is designated as exposed terrain for the different classes of land-surface form. For simplicity, the percentages shown for each class of land-surface form have been averaged over the range of categories in local relief and profile type found in the North Central region. For example, the 43% for open hills is an average for C2 through C4. The average percentage of land area that is designated as exposed terrain ranges from 91% in smooth plains to 5% in the Black Hills where the exposed areas are usually the ridge crests and mountain summits.

1.9 CERTAINTY RATING

The analyses of wind power density at exposed sites shown on the wind power maps depend on the subjective integration of several factors: quantitative wind data, qualitative indicators of wind speed or power, the characteristics of exposed sites in various terrain, and familiarity with the meteorology, climatology and topography of the region. As a result, the degree of certainty with which the wind power class can be specified depends on

- the abundance and quality of wind data
- the complexity of the terrain
- the geographical variability of the resource.

A certainty rating from 1 (low) to 4 (high), of the wind energy resource estimate has been made for each cell of a

one-quarter degree latitude by one-third degree longitude grid on a state-by-state basis by considering the influence of the above three factors on the certainty of the estimate of the wind power class for each cell. The definitions for the certainty ratings are adopted from those used by Voelker et al. (1979) in a resource assessment of U.S. Forest Service tracts. The certainty ratings for the wind resource assessment are defined as follows:

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: <ul style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	A low intermediate degree of certainty. One of the following conditions exists: <ul style="list-style-type: none"> 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	A high-intermediate degree of certainty. One of the following conditions exists: <ul style="list-style-type: none"> 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data.

Rating	Definition
2)	Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.

The assignment of a certainty rating requires subjective evaluation of the interaction of the factors involved.

1.10 AREAL DISTRIBUTION OF THE WIND RESOURCE

As noted above, the wind power density class values shown on the maps apply only to sites well exposed to the wind. Therefore, the map area designated as having a particular wind power class does not indicate the true land area having this wind power. Instead, there is a complicated and difficult-to-quantify relationship among the class of land-surface form, the land-surface area and the map value of wind power density. For each land-surface form, the fraction of land area that would be favorably exposed to the winds, i.e., have the wind power density indicated on the map, was estimated (see Table 1.2 for averages in various land-surface forms). Furthermore, to be able to establish a wind power density for the remaining area, it was also necessary to specify a factor by which the wind power shown on the map is reduced in the less exposed areas. As an additional complication, some land-surface forms, isolated hills and ridges that rise above a nearly flat landscape may even have a higher power density than the map indicates.

To accommodate these various situations, the land area represented by a given land-surface form was divided into four exposure categories: 1) better exposure than typical for the terrain, 2) exposure typical for that land-surface form, 3) partially sheltered exposure, and 4) very sheltered exposure. The partitioning of the land-surface forms into the four categories was based on the parameters used to classify the land-surface forms.

In order to adjust the wind power density from the map value to the various exposure categories, the power density was scaled to be 1) greater than, 2) equal to, 3) slightly less than, and 4) much less than the map value power density. The factor by which the map value was adjusted to represent the wind power density in each category was determined by the magnitude of elevation relief given by the middle character of the land-surface form code. (The minimum power density allowed for a category was the median value of wind power density class 1). The scaling factors for the wind power density were based on a conservative application of a power-law type vertical adjustment with the height change specified by the terrain relief code.

In each cell of a grid one-third degree longitude by one-quarter degree latitude, the land-surface form was specified and the wind power class associated with a typically exposed site in that land-surface form was determined. By partitioning the area of the cell into the four exposure categories, and by scaling the wind power class to each category, the contribution of that cell to the areal distribution was determined.

A cell-by-cell representation of the areal distribution is given in a map that indicates the percentage land area in a cell over which the wind power class equals or exceeds a threshold value. Four maps are shown in the chapters on the state wind

resources for threshold values of classes 2, 3, 4 and 5.

A summary table of the areal distribution that combines the contributions by each cell is provided for the region and for each state. For each power class, the sum of the area contributed by each exposure category is determined for each state and the region. Summing the area associated with each power class in each cell gives the area of the state or region over which the power class exceeds a given value. The table gives the estimated land area (km²) and the percentage of land area associated with each power class.

Both of these presentations of the areal distribution of the wind resource are highly dependent on the estimates used to partition the land area into the four exposure categories and on the scaling of the power density for each category of exposure. Therefore, the areal distribution derived from the wind power and land-surface form maps must be considered only an approximation. The quantity and quality of wind data and topographic information required to make a highly accurate cell-by-cell appraisal of the wind resource goes far beyond the scope of this regional wind resource assessment. However, as wind information becomes available through new measurement programs or through the discovery and processing of existing data sets, the evaluation of the areal distribution of the wind resource can be improved on a cell-by-cell basis.

TABLE 1.2. Land-Surface Form Terrain Features Representative of Exposed Locations

Land-Surface Form	Exposed Feature (Map Value)	Percentage Area ^(a)
Plains: A1,2; B1,2	Plains	91
Plains with Hills: A, B3a,b	Open Plains	82
Tablelands: B3-6c,d	Tablelands, uplands	80
Open Hills: C2-4	Hilltops and Uplands	43
Open Mountains: C5-6	Broad Valleys (not shaded)	80
Mountains: D5-6	Ridge Crests and Mountain Summits (shaded) ^(b)	5

(a)Percentage represents an average over the land-surface forms found in the North Central region.

(b)Shaded areas on the wind maps emphasize that map values are estimates for ridge crests and mountain summit locations.

TABLE 1.3. Classes of Wind Power Density at 10 m and 50 m^(a)

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

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 1.4. Scheme of Classification

Slope (1st item)

- A >80% of area gently sloping
- B 50 to 80% of area gently sloping
- C 20 to 50% of area gently sloping
- D <20% of area gently sloping

Local Relief (2nd item)

- 1 0 to 30 m (0 to 100 ft)
- 2 30 to 90 m (100 to 300 ft)
- 3 90 to 150 m (300 to 500 ft)
- 4 150 to 300 m (500 to 1000 ft)
- 5 300 to 900 m (1000 to 3000 ft)
- 6 900 to 1500 m (3000 to 5000 ft)

Profile Type (3rd item)

- a >75% of gentle slope is in lowland
- b 50 to 75% of gentle slope is in lowland
- c 50 to 75% of gentle slope is on upland
- d >75% of gentle slope is on upland

CHAPTER 2: REGIONAL FEATURES

In this chapter, the geography, climate, annual average wind power and seasonal variations in the wind power are described for the North Central region. Assessments of the wind resource for each state of the North Central region were performed using the methods described in Chapter 1. These assessments were then combined to depict the wind energy potential for the region. Major areas in the North Central region that are estimated to have the greatest wind resource are also described in this chapter.

2.1 GEOGRAPHY AND TOPOGRAPHY

The North Central region, shown in Figure 2.1, consists of Iowa, Minnesota, Nebraska, North Dakota, and South Dakota and covers nearly 950,000 km² (367,000 mi²). The region's total population in 1977 was 9,761,000 (see Table 2.1). Two-thirds of the population live in the states of Iowa and Minnesota. The region is largely rural. About 3,000,000 people live in the largest population centers of Minneapolis-St. Paul, Minnesota; Omaha and Lincoln, Nebraska; and Des Moines, Iowa. Of these, nearly 2,000,000 live in the largest population center, the Minneapolis-St. Paul metropolitan area.

TABLE 2.1 Land Area and Population of the North Central Region.

State	Area (a)		Population in 1977	Population Per km ² (mi ²)	
	km ²	(mi ²)			
Iowa	145,865	(56,290)	2,888,000	19.8	(51.3)
Minnesota	217,847	(84,068)	3,980,000	18.3	(47.3)
Nebraska	200,119	(77,227)	1,555,000	7.8	(20.1)
N. Dakota	183,115	(70,665)	650,000	3.6	(9.2)
S. Dakota	199,653	(77,047)	688,000	3.5	(8.9)
N. Central	946,599	(365,297)	9,761,000	10.3	(26.7)

(a) 1977 World Almanac

(b) Statistical Abstracts, 100th edition, 1979

The topography of the region is generally flat plains to rolling hills and uplands, with the exception of the mountainous Black Hills area of western South Dakota (Figures 2.1 through 2.3). Topographic features in the North Central region, especially in the eastern Dakotas, Minnesota, and parts of Iowa, are largely the result of glaciation, with flat areas that are the beds of ancient lakes. Consequently, a large fraction of the land area is well exposed to the wind.

When the glaciers receded, a large area of low relief and relatively low elevation was left. This region of glaciated plains has a western boundary in the vicinity of the Missouri Coteau of North and South Dakota, and an eastern boundary in the area of the east slope of the shallow Red River Valley (see Figures 2.1, 7.1).

The western Dakotas and much of Nebraska consist of older strata that have been carved over millions of years into hilly plains and tablelands. The fertile open hills and plains in Iowa are the result of glacial deposition of soil from Canada.

Areas of highest relief are found in the Sand Hills area of Nebraska, the Little Missouri River Badlands of western North Dakota, and the Black Hills mountain range.

2.2 CLIMATE

The North Central region has a climate typical of continental regions at mid-latitudes, characterized by well-defined seasons and changeable weather.

Mean 500 mb charts show prevailing winds aloft to be generally westerly in the summer and northwesterly in the winter. Summer mean sea-level pressure charts indicate low pressure most frequently centered in the southwestern United States and high pressure most frequently centered over the Atlantic Ocean. This produces generally southerly surface flow over the North Central region. Winter mean sea-level pressure charts indicate the frequent presence of a high pressure system over the northwestern U.S. and western Canada and a low over Greenland. These produce generally northwesterly surface flow in the region.

In the summer, southerly winds bring warm maritime air from the Gulf of Mexico, resulting in hot, humid weather. Thunderstorms and hailstorms occur frequently, especially in the southern states of Nebraska and Iowa.

In the winter, a shallow high pressure system frequently becomes established over the western Canadian plains. The surface pressure gradient thus induced causes periodic surges of arctic air to flow southeastward toward Iowa. In conjunction with frequent migratory low pressure systems, this situation brings strong northwesterly surface winds, extreme cold, and occasional blizzards to the northern states of Minnesota, North Dakota, and, less frequently, South Dakota. Westerly

winds from the Rocky Mountains can bring about occasional warmer and drier weather in the western parts of Nebraska and the Dakotas.

Spring and autumn are transition periods. Spring in particular can be very active with severe thunderstorms and tornados. These occur most frequently in the southern states of Nebraska and Iowa, and sometimes southern Minnesota.

Summer average high temperatures range from about 22°C (70°F) in northern Minnesota to 30°C (85°F) in Iowa and Nebraska. Average temperatures are about 5°C (10°F) cooler in the Black Hills area and along the north shore of Lake Superior. Winter average low temperatures range from near -18°C (0°F) in North Dakota and Minnesota to -8°C (18°F) in southeastern Iowa.

Annual average precipitation decreases from southeast to northwest and varies from 89 cm (35 in.) in southeastern Iowa to 36 cm (14 in.) in northwestern North Dakota. Most of this precipitation occurs as convective showers in the summer months when the moist southerly flow dominates.

2.3 WIND POWER IN THE NORTH CENTRAL REGION

The annual average available wind power density in the North Central region is shown in Figure 2.4. The analysis of mean wind power applies to terrain features that are favorably exposed to the wind. In general, most of the central part of the North Central region is low-relief terrain and is thus well exposed to the wind. However, parts of the region with higher relief will have a smaller percentage of the land area actually exposed to the wind, and a larger percentage of sheltered terrain. Such areas are found on the Missouri Plateau of the western Dakotas, in the Nebraska Sand Hills and the hilly plains of Iowa, and, in an extreme case, the Black Hills of South Dakota. In such areas, available wind power can vary significantly over a short distance. In forested areas such as northeastern Minnesota, the wind power analysis applies to cleared areas with good exposure to the wind, such as at airports where many of the data used in the analysis were taken. Table 1.2 presents the percentage of area exposed to the wind for different land-form types.

In the North Central region, the highest wind resource areas are found in two large class 4 sub-regions: the high plains of the Missouri Plateau, a region that

includes the western Dakotas and, for wind power assessment purposes, extends into the Sand Hills of northwestern Nebraska; and the flat open plains that extend south-eastward from the Canadian border through the center of the region.

In the Missouri Plateau sub-region, high annual average wind power is primarily the result of strong surface winds driven by synoptic scale pressure gradients.

In the flat plains sub-region, strong surface winds are also synoptically driven, but average wind speeds also appear to be enhanced, partly by channeling of cold surface air as it flows southeastward across the glaciated plains during the cold months, and partly because of the low surface roughness in this broad area. Because of this enhancement of average wind speeds, this area will be referred to as the Canadian Wind Corridor. It has a western boundary defined approximately by the Missouri Escarpment and Coteau and an eastern boundary in the area east of the Red River.

2.3.1 Certainty Rating of the Wind Resource

Certainty ratings for the wind power resource estimates were assigned to each grid cell as described in Section 1.9. Maps of the certainty rating in each state accompany the descriptions of that state's wind resource.

Certainty ratings throughout the North Central region range from low (1) to high (4). A high certainty rating is assigned to areas with adequate long-term data and simple terrain. Such areas are found primarily in southern and eastern Nebraska, eastern Iowa, and along the Red River between North Dakota and Minnesota. The Red River valley has both high certainty and high (class 4) annual average wind power.

Most of the rest of the region is assigned certainty ratings of 2 or 3. Ratings of 3 are found in areas where data exist, but are for a short (<2 years) period of time. Areas in which no data were found are assigned class 2 certainty ratings, except for areas that contain complex terrain. Areas with no data and that contain complex terrain are assigned a certainty rating of 1. These low certainty areas are found in parts of the Missouri Plateau, in the Sand Hills of Nebraska, and in the hills of western Iowa.

Although year-round data from exposed sites on ridge crests of the Black Hills does not exist, wind power estimates in

this area have certainty ratings of 2 because upper-air wind data were used to approximate the wind power.

2.3.2 Areal Distribution

Through the superposition of a grid one-third degree longitude by one-quarter degree latitude over the region, the areal distribution of wind power was computed as described in Section 1.10. The results of the computation of the areal distribution for the states of the North Central region are summarized in Table 2.2.

The low relief of the terrain in the region is indicated by the number of grid cells in the three land-surface form categories. Of 1,365 grid cells in the region, 383 have slope class A (flat) and 729 have slope class B (gently sloping). One hundred and ninety have local relief class 1 (0 to 30 m), 758 have local relief class 2 (30 to 90 m), and 363 have local relief class 3 (90 to 150 m). Only 53 have local relief greater than 150 m. These areas are found in the Black Hills, in the Badlands of western North Dakota, and on the bluffs near the Lake Superior shore of Minnesota. Fifty-eight percent, or 786, are defined by profile type C, with 50 to 75% of gentle slope on upland. This last figure indicates that even in moderately complex terrain, such as that found on the Missouri Plateau and Coteau, and in the Sand Hills of Nebraska, most of the land is upland, and therefore has good exposure to strong winds.

Consequently, in the North Central region, the percentage of map area that has a given wind power class (i.e., the percentage of area that would be indicated on a flat map by assuming that all areas have uniform exposure) is a good estimate of the percentage of exposed land-surface area that has that class (i.e., the percentage of land-surface area with exposure to wind power of that class that is indicated by considering the complexity of terrain). For example, 610 of the 1,365 grid cells, or 45% of the map area, has class 4 wind power. The percentage of exposed land-surface area with this wind power, as calculated by methods outlined in Chapter 1, is about 37%. Percentages of map area and exposed land-surface area for class 3 are 39% and 32% respectively.

This map area approximation is most realistic for North Dakota, Minnesota, and Iowa, and less realistic for South Dakota and Nebraska because of the high relief terrain of the Black Hills and the Sand Hills.

2.4 SEASONAL VARIATIONS IN THE WIND RESOURCE

Winter is the season of maximum wind power in northern North Dakota (Figure 2.5). During the winter, stagnating air in a shallow layer over the Canadian plains frequently causes a shallow high pressure system, or cold dome, to develop with a resulting surface pressure gradient that causes periodic drainage of cold surface air into the Canadian Wind Corridor. Frequently, migratory low pressure systems originate on the lee side of the Rocky Mountains and move across the region to the east or northeast. When these migratory lows come near the east edge of this surface high, severe storms and blizzards with high speed northwest winds can develop. Such short-term storms contribute significantly to the seasonal and annual wind power.

Extending through the Canadian Wind Corridor into northern Iowa, winter average wind power and spring average wind power are nearly the same, with slightly greater winter wind power in the north and slightly greater spring wind power in the south. There is evidence that the area in the vicinity of Lake Traverse on the Minnesota-South Dakota border may also have a winter maximum in some years (see Section 8.1).

Winter is also the season of maximum wind power on the high ridge crests and summits of the Black Hills in western South Dakota. These sites are well exposed to upper-air winds that are strongest during the winter.

Spring is a transition season, with upper-level wind speeds decreasing and average upper-air wind speeds consequently not as strong as in winter. However, with the increased solar insolation of spring, the surface is warmed and stable surface air that restricts vertical mixing during the winter is not as prevalent in the spring. Consequently, surface wind speeds, and thus wind power, are at their maximum in spring throughout the North Central region, outside of the north portions of the Canadian Wind Corridor and the ridges and summits of the Black Hills.

In summer, upper-air wind speeds are at a minimum and surface wind speeds are consequently lowest. This is the season of minimum wind power throughout the North Central region.

Autumn, like spring, is a season of transition, with upper-air and surface average wind speeds increasing as they

approach their wintertime maximum. Because of the increasing surface stability, surface wind speeds are in general not as strong as in spring. On ridge crests and summits of the Black Hills, autumn wind power is estimated to be greater than spring wind power.

2.5 MAJOR WIND RESOURCE AREAS

The terrain comprising much of the North Central region, especially the windiest areas, is of very low relief. Consequently, there are few areas with moderate to small-scale terrain features that can cause large acceleration of wind speeds. For example, there are no deep gaps in the terrain that can create isolated small areas of high wind power such as the Columbia River Gorge in the Northwest region. However, there may be less well-defined areas where local terrain features such as hilltops and low ridges may enhance the wind power. These areas may have greater wind power than is indicated by the wind power maps, but because of the absence of representative wind data for most of these areas, they are not delineated on the maps.

This section will briefly describe some of the major (class 4 or greater) wind resource areas in the region. For the locations of place names mentioned in this section, refer to the individual state maps.

2.5.1 Canadian Wind Corridor and the Red River Valley

The Canadian Wind Corridor is a wide, flat area that comprises most of the central part of the North Central region (see Section 2.3). It is characterized by low relief and low surface roughness and is thus well-exposed to the strongest winds which are mostly northerly to northwesterly in all seasons except summer. This area appears to have a significant effect in channeling cold arctic air from the Canadian interior southeastward into the United States during the winter. Strongest winds occur in conjunction with the passage to the east of migratory low pressure systems which originate in the lee of the Rocky Mountains. This entire area is estimated to have class 4 annual average wind power.

Within this general area is the Red River valley. The Red River forms much of the boundary between North Dakota and northern Minnesota. This valley slopes downward to the north, the Red River flowing northward into Hudson Bay. Data from stations near the Red River indicate some

channeling effect, prevailing winds being split between north and south directions. Although strongest winds in this area are northerly, and hence up-valley, the slope is so gentle and the terrain so flat that it is questionable whether this has any significant wind acceleration effects. Nevertheless, data from Pembina and Grand Forks indicate annual wind power averages that are near the borderline between class 4 and class 5, and that are among the highest in the North Central region. Also, old long-term (28 years) data from Fargo indicate that average height-adjusted wind speeds may be 25 to 30% higher than height-adjusted wind speeds indicated by old long-term (57 years) data from Devils Lake, on the west side of the Pembina Escarpment and outside of the Red River valley (Jensen 1972). However, precise anemometer heights and exposure characteristics for these periods are uncertain.

2.5.2 Missouri and Pembina Escarpments and Turtle Mountains

The Missouri Escarpment is an area of abrupt east-to-west rise of about 200 m (600 ft.) in the otherwise flat terrain of eastern and central North Dakota, and eastern South Dakota. Left by receding glaciers, this feature is near the approximate western boundary of the Canadian Wind Corridor. The Pembina Escarpment is similar to the Missouri Escarpment and is located west of the Red River, forming the approximate western boundary of that valley. The Turtle Mountains are located on the Canadian border in north-central North Dakota, with elevations of about 200 m (600 to 700 ft.) higher than the flat terrain to the south.

Although no wind data could be found that are representative of these three areas, it is possible that there is some acceleration of strong north and northwest winds as they impinge on these features. Such acceleration may be enough to increase the average wind power beyond the class 4 shown on the annual average wind power map (Figure 2.4).

2.5.3 Prairie Coteau and Lake Traverse Area

The Prairie Coteau is a basin-like plateau, rising about 200 to 250 m (700 to 800 ft) above the surrounding flat terrain (see Figures 2.1, and 8.1), and containing numerous small moraine lakes. It is bounded on the east by an extension of the Missouri Escarpment and on the west by a similar though lower ridge. Sloping downward to the south, its north end appears on topographic maps as a wedge pointed north

into the Canadian Wind Corridor. As with the Missouri and Pembina Escarpments, there may be sufficient acceleration of wind speeds as winds impinge upon the rim of the Prairie Coteau to increase wind power beyond that shown on the annual average wind power map (Figure 2.4).

To the east of the Prairie Coteau, near the Minnesota-South Dakota border formed by Lake Traverse, is an area that forms a divide between the Red River and Minnesota River drainages. Limited data in the area suggest that wind power to the east of the Prairie Coteau is slightly greater than to the west, possibly the result of some acceleration of surface winds as they flow over this low divide. Again, more data are needed to verify this.

2.5.4 Missouri Plateau

Hilltops and uplands of the Missouri Plateau of the western Dakotas and the Sand Hills of northwestern Nebraska that are well exposed to strong north and northwest winds are estimated to have class 4 wind power. Many of the drainages in this area are oriented west to east, and are frequently sheltered from prevailing winds. These valleys will probably have a lower wind power class, especially in winter and autumn when these valleys tend to fill with cold air. The resulting high stability restricts vertical mixing so that winds in these valleys are not as strong as on the uplands and better exposed areas.

2.5.5 Black Hills Ridge Crests

Ridge crests and summits in the Black Hills that are well exposed to prevailing winds are estimated to have at least class 4 annual average wind power. Average speed at any particular location is dependent upon the elevation, orientation with respect to strong westerly winds, and proximity to other ridges and mountains. Wind power should be greatest at high elevations of the Black Hills that have wide open exposure to the open plains to

the west. However, this may not be true at lower elevations near the foothills. For example, wind power is probably greater at Rapid City on the east side of the Black Hills than at a similar site on the west side. This is because of the diversion and constriction of northerly and northwesterly winds as they flow around the mass of the Black Hills. Sheltered canyons and basins in the Black Hills should be mostly class 1.

2.5.6 Open Hills and Plains of Southern Minnesota and Iowa

As on the Missouri Plateau, exposed elevated sites in southern Minnesota and northwestern Iowa are estimated to have at least class 4 wind power. Lower and more sheltered locations will have significantly less wind power, especially in winter and autumn when stable air in these lowlands restricts vertical mixing, causing wind speeds to be less than at higher locations.

2.5.7 Mesabi Range and Lake Superior Shore

Although the Mesabi Range and Lake Superior shore are estimated to have less annual average wind power than those areas already discussed, they are mentioned here because they are surrounded by areas in northeastern Minnesota that have class 1 annual average wind power.

The Mesabi Range is oriented perpendicular to the strongest winds in the area. Because of acceleration of winds blowing over this ridge, it is estimated to have wind power at least one class higher than the surrounding terrain.

The Lake Superior shore is exposed to the strong easterly winds from Lake Superior and is estimated to have class 3 annual average wind power. Strong easterly winds in this area may penetrate inland up to 25 km (15 mi), depending on the exposure at any particular location.

FIGURE 2.1. Geographic Map of the North Central Region

FIGURE 2.2. Topographic Map of the North Central Region

FIGURE 2.3. Classes of Land-Surface Form in the North Central Region

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

FIGURE 2.4. Annual Average Wind Power in the North Central Region

Classes of Wind Power Density at 10 m and 50 m (a)

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

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 2.2. Areal Distribution of Wind Power Classes in the North Central Region

Power Class	Land Area (km ²) Equal or Exceeding Power Class					
	North Central	Iowa	Minnesota	Nebraska	N. Dakota	S. Dakota
1	934,442	145,964	209,718	200,384	181,216	197,159
2	788,779	132,889	149,723	169,184	163,911	173,071
3	650,476	91,249	109,440	139,100	156,866	153,821
4	350,051	22,055	62,527	40,626	119,820	105,023
5	1,395	0	0	0	912	483
6	0	0	0	0	0	0
7	0	0	0	0	0	0

Power Class	Percentage Land Area Equal or Exceeding Power Class					
	North Central	Iowa	Minnesota	Nebraska	N. Dakota	S. Dakota
1	100.0	100.0	100.0	100.0	100.0	100.0
2	84.4	91.0	71.4	84.4	90.5	87.8
3	69.6	62.5	52.2	69.4	86.6	78.0
4	37.5	15.1	29.8	20.3	66.1	53.3
5	0.2	0.0	0.0	0.0	0.5	0.2
6	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0

FIGURE 2.5. Seasonal Maximum Wind Power in the North Central Region

CHAPTER 3: STATE FEATURES

The wind resource for each state is described in Chapters 4 through 8. The text of each description is followed by maps, graphs and tables that identify features of the geography and the wind energy resource and summarize the data collected from the observation stations. The sequence of maps, tables and graphs used to depict these features is presented in Table 3.1. In the state descriptions, these illustrations are presented so that related information is on facing pages and can be viewed simultaneously.

To avoid repetition in the following chapters, the general format and content of the various maps, tables and graphs used to describe the wind resource for each state are summarized here.

3.1 MAPS OF STATE FEATURES

The maps of cultural geography show the locations of major cities, rivers and terrain features for each state. The maps of shaded topographic relief for Nebraska, North Dakota, and South Dakota are reproductions of the 1:500,000 scale U.S. Geological Survey maps. The maps of shaded topographic relief for Minnesota and Iowa are reproductions from the U.S. shaded-relief map contained in the National Atlas of the United States. The land-surface form maps are reconstructions of portions of the map of classes of land-surface form by Hammond (1964; this is also available at a scale of 1:17,000,000 on Plate 62 in the National Atlas of the United States). The

use of the land-surface form map was described in Section 1.8.

Two maps are used to show the locations of stations with wind data. The first map gives the locations and names of the NCC stations with wind data in any form. The other map shows the locations of NCC, fire weather and other data stations that were utilized in this assessment of the wind resource.

The map of annual average wind power is accompanied by maps of the certainty rating of the estimated annual average wind power by grid cell, and of the areal distribution of the wind resource by grid cell. The certainty rating, which ranges from 1 (low) to 4 (high), indicates the level of confidence in the estimates of the wind resource in each cell of the grid. The certainty rating is based on the availability of wind data, the complexity of the terrain, and the inherent geographical variability of the wind resource (see Section 1.9). The maps of areal distribution give the percentage of land area in each cell estimated to have an annual average wind power class equal to or exceeding power classes 2, 3, 4, and 5 (see Section 1.10).

Maps of the average wind power are presented for each season: winter (December, January, February); spring (March, April, May); summer (June, July, August); and autumn (September, October, November). The legend for the power classes is found with the annual average wind power map.

TABLE 3.1. Maps, Tables, and Graphs Used to Depict the Wind Resource

Maps	
Left Hand	Right Hand
Cultural Geography	Topographic Shaded Relief
Land-Surface Form	Legend to Land-Surface Form
NCC Station Locations	Location of Stations Used in Wind Assessment
Annual Average Wind Power	Legend to Wind Power Classes and Table on Areal Distribution
Certainty Rating	Legend for Certainty Rating
Areal Distribution (Power Classes 2 & 3)	Areal Distribution (Power Classes 4 & 5)
Seasonal Average Wind Power (Winter, Summer)	Seasonal Average Wind Power (Spring, Autumn)
Graphs	
Summary Table of Selected Stations	Interannual Speed and Power
Monthly Speed and Power	Diurnal Speed
Directional Frequency	Speed Frequency
Speed Duration	Power Duration

3.2 FEATURES OF SELECTED STATIONS

The analysis of the wind resource on a state and regional basis depends on information from individual stations. For those stations with one- or three-hourly data on NCC magnetic tapes, a very detailed presentation of the temporal variation and character of the wind resource can be obtained. Graphs portraying various features of the wind resource have been prepared for selected stations in each state and are presented in the state chapters. For each station presented, a brief description of the station's topographical setting and unique features is given in the text preceding the maps and graphs. The geographical area represented by a station varies, depending on the complexity of the local terrain and variability of the wind resource.

A table listing the stations for which graphs and summaries of the features of the wind resource are presented precedes the series of graphs. Height adjustments were made only to obtain estimates of the average wind speed and power at 10 m and 50 m given in this table. No attempt was made to adjust to a reference height any of the other wind characteristics (e.g., diurnal wind speeds, frequency distributions of wind speed, wind direction, speed and power duration, etc.) presented in the graphs for selected stations. Caution should therefore be used in comparing and interpreting station plots.

In the plots of interannual wind power and speed, the first line of each graph contains the station name and state. The second line contains the WBAN number.

In all other plots, the first line on each station graph contains the station identification that corresponds to the name and location listed in the table and the month and year of the selected period of record. Even though some stations had several periods of record, only one period of record with constant anemometer height was plotted. Usually, periods when the anemometer was located on a mast mounted directly on the ground were preferred to periods when the anemometer was located on the roof of a building.

The second line of each station graph contains the WBAN number, the anemometer height (Z) in m and location, and the annual average wind speed (V) in m/s and wind power (P) in watts/m². V and P are adjusted to 10 m for the graphs of interannual and monthly average wind power and speed and are at anemometer height (Z) for all other graphs.

The coded information listed with the anemometer height is one of the following (Changery 1978):

- R - indicates the anemometer was located on the roof of a control tower, operations building, hangar or other similar structure. Normal mast heights were 2 to 4 m (6 to 12 ft) above roof line; however, many inner-city locations used considerably taller masts. The listed height is elevation above ground level, not roof level; the "R" indicates an exposure type.
- G - indicates the anemometer was located on a mast attached directly to the ground. Most anemometers at airport locations changed from a roof to ground exposure by the early 1960s.
- B - indicates a beacon tower exposure. For these locations, neither R nor G was considered satisfactory.
- UNK - indicates that documentation on instrument heights was not available.

If information on exposure was unavailable, no exposure code is given.

On a few station plots, an E follows the annual average wind power. If a pressure or temperature observation is missing, the wind power for that observation is computed using an air density based on station elevation. If the number of missing observations exceeds 25% of the total, then an E is used to designate that the wind power is an estimated value.

Up to 18 graphs of the same type may appear on one page to allow for station-to-station comparison. The scale of each set of plots was determined by the maximum range of values found for all stations in the region.

3.2.1 Interannual Wind Power and Speed

The plots of interannual wind speed and power portray the variations of the yearly average over all periods of record. The beginning and ending of each period of record with constant anemometer height and location are designated by a "plus" symbol on the wind power curve and by a "diamond" symbol on the wind speed curve. If the anemometer height was unknown, a height of 10 m was assumed. Only yearly mean wind speeds based on 12 months' data (January through December) were plotted.

Year-to-year deviations from the long-term annual average may not be a reliable indicator of the deviations at nearby sites or areas (Elliott 1979b). Changes in instrument exposure from local development and other factors can affect interannual variations in wind speed and power.

3.2.2 Monthly Average Wind Power and Speed

Graphs of the monthly average wind power and speed portray the monthly and seasonal trends of the wind. Stations with less than five years of observations may not show reliable seasonal trends. Also, stations in complex terrain may not represent the seasonal trends in nearby areas because of the influence of nearby terrain. Most of the station curves are within the 0 to 400 watts/m² range.

3.2.3 Diurnal Wind Speed by Season

The diurnal variation in wind speed according to season is plotted on graphs containing four curves, one for each season. Local Standard Time (LST) is used with hour 24 as midnight and hour 1 as the beginning hour. For National Weather Service and Federal Aviation Administration stations, the diurnal curves are based on 24 observations daily for periods ending before 1965, and on 8 observations daily for periods ending after 1964. For Air Force stations the diurnal curves are usually based on 24 observations daily regardless of the period.

3.2.4 Directional Frequency and Average Speed

Graphs of the annual average frequency of occurrence show the percentage of time that the observed wind direction was from each of 16-point compass sectors and the average wind speed of all observations in each sector. Some stations show a definite bias toward 8-point compass observations.

The coincidence of peaks in the two curves indicates that the highest wind speeds occur from the prevailing directions. Caution should be used in applying these data to other sites, because nearby terrain and obstructions strongly influence the wind directions. Some of the directional data presented may not be reliable or representative because of the anemometer location.

3.2.5 Annual Average Wind Speed Frequency

Graphs of the annual average frequency of observed wind speeds are shown in 1 m/s intervals about each whole m/s wind speed. Along with the observed distribution, a Rayleigh wind speed distribution based on the annual mean speed is shown. Some of the stations show pronounced peaks in the observed distribution; these peaks reflect observer bias toward certain wind speeds, such as 2, 5, and 8 m/s (5, 10, and 15 knots). This bias occurs more frequently in records prior to 1960. Because many of the wind instruments used had a threshold velocity of about 1.5 m/s (3 knots), the frequency of observations in the 1 m/s class is often lower than the frequency of the calm and 2 m/s classes.

3.2.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in two sets of graphs. Abrupt changes in the slope of the duration curves for speed and power usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity. Points are plotted at 1 m/s intervals for the speed duration curves. Points are plotted every 50 watts/m² up to 500 watts/m² and every 100 watts/m² up to 1,000 watts/m² in the power duration curves.

IOWA

CHAPTER 4: IOWA

Iowa covers an area of 145,865 km² (56,290 mi²) and had a population in 1977 of about 2,888,000 (Statistical Abstracts, 100th edition, 1979). The population is largely rural, with 400,000 people living in the three largest cities: Des Moines, Cedar Rapids, and Davenport (Figure 4.1). The rest of the population is evenly distributed throughout the state.

The terrain in Iowa ranges from smooth plains in the north-central part of the state to irregular plains throughout most of the rest of the state (see Figures 4.2, 4.3). Southwestern Iowa and parts of Iowa near the Missouri border are rolling hills. Highest local relief is found in the bluffs area near the Mississippi River in north-eastern Iowa.

Wind data are most abundant in the eastern half of the state and near the western border along the Missouri River (Figures 4.4, 4.5). Data are sparse in the western half of the state, especially in the northwest quarter.

4.1 ANNUAL AVERAGE WIND POWER

The annual average wind power map for Iowa is shown in Figure 4.6. This analysis of mean wind power applies to terrain features that are favorably exposed to the wind, such as hilltops and uplands. However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as ± 50 to 100% from the assessment value (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy). The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

Except for areas along the Missouri River in western Iowa, there is a general northwest to southeast decrease in the annual average wind power in the state. This is due primarily to the corresponding decrease in elevation with the consequent decrease in wind speed during northwesterly flow periods. It is also partly attributable to the lower frequency of low pressure system passages as compared to locations farther north within the North Central region.

Much of northwest Iowa is class 4. This estimate is based primarily on summarized data from Adair (1934 to 1938), Ft. Dodge (1963 to 1967) and Worthington, Minnesota (1959 to 1961). These data consist of 24, 16, and 14 observations per day,

respectively, and all indicate class 4 to class 5 annual average wind power. Class 3 wind power extends eastward almost to the eastern border. Parts of Iowa close to the Mississippi and Missouri Rivers are estimated to have class 2 annual average wind power.

Although the wind power gradient is from northwest to southeast, local terrain differences can cause larger differences in average wind power than would be indicated by geographic position. For example, Cedar Rapids and Duane Arnold Nuclear Power Plant are both located in the class 3 area in east-central Iowa. Duane Arnold Nuclear Power Plant is about 32 km (20 mi) north of the Cedar Rapids airport. Yet 5 years of data at Duane Arnold, located in the low-land by the Cedar River, show an annual average wind power density at 10 m of about 60 watts/m², while 4 years of data from the Cedar Rapids airport, located 11 to 12 km (7 to 8 mi) from the river at a well-exposed upland site, show a 10 m annual average wind power density of 174 watts/m². Wind power class boundaries shown in Figures 4.6 and 4.9 show indentations near the major rivers in Iowa. This is to indicate that near these rivers there may be sheltering by higher terrain, as is evident from this example.

The annual wind power map may be more accurate for 10 m wind power than for 50 m wind power because of the frequent occurrence of a nocturnal wind maximum in the lower levels of the atmosphere. This phenomenon is known to occur frequently in the summer in the central U.S. and could result in wind speeds at 50 m that are higher than predicted by the 1/7 power law (see Section 4.2.3).

4.1.1 Certainty Rating of the Wind Resource

Certainty ratings for the annual average wind power density map for Iowa are shown in Figure 4.7. In general, high certainty ratings are given to grid cells in eastern Iowa and low certainty ratings are given to grid cells in western Iowa, a consequence of the relative abundance and scarcity of data in these respective areas. Certainty ratings of 4 were given to cells that contain, or are adjacent to cells that contain, reliable data sites that indicate the same wind power class that is assigned to the cell. Certainty ratings are lower for cells that contain terrain of moderate relief than for cells that contain terrain of low relief. Certainty ratings are also lower for cells that are traversed by wind

power class boundaries. Because of the relatively gentle wind power gradient that exists in Iowa, the exact location of wind power class boundaries cannot be known. (Also, see Section 2.3.1.)

4.1.2 Areal Distribution

The areal distribution of wind power in Iowa is illustrated in Figure 4.8. Numbers identify the percentage area in each cell of the grid in which the wind power is equal to or exceeds some threshold value. It is seen from this figure that most of the class 4 grid cells in the northwest part of the state are predicted to have 88% of their actual land-surface area exposed to class 4 or greater winds.

Table 4.1 presents the areal distribution of wind power classes in Iowa. Land-surface area with class 4 wind power is about 15% of the total land-surface area. The amount that would be predicted on the basis of map area alone (i.e. the number of class 4 grid cells, 35, as a percentage of all grid cells, 213) is 16%. Thus the actual class 4 land-surface area is slightly over-predicted by the class 4 map area (see Section 2.3.2).

4.2 SEASONAL WIND POWER

Wind power maps of Iowa for each season are shown in Figure 4.9. Spring is generally the season of maximum wind power throughout the state, although in northern Iowa there is less difference in wind power between winter and spring than in the rest of the state.

4.2.1 Winter

In winter, class 4 wind power is found over most of northwestern Iowa. Eastern, southern, and extreme western Iowa near the Missouri River flood plain are estimated to be class 3.

Winds are mostly northwesterly during winter, and the strongest winds are also northwesterly. Southern parts of the state show a higher frequency of southerly winds than do the northern parts, and stations near the Mississippi River show a nearly even split between north and south as the directions of strongest winds. This is probably the result of some channeling by the Mississippi River drainage.

As in other states in the North Central region, Iowa is subject to episodes of high winter winds over short periods of time, especially northern Iowa. A large part of the annual average wind power in the state occurs during these periods.

4.2.2 Spring

Spring is the season of maximum wind power throughout Iowa, and most of the state is rated at class 4 in this season. The highest wind power occurs in April. Class 3 areas are found in eastern and southeastern Iowa and at more sheltered locations near the Mississippi and Missouri Rivers.

Prevailing surface winds are shifting to a more southerly direction during this period and strongest winds are more westerly than in the winter. For this reason, sites on the narrow Missouri River flood plain are more sheltered in the spring than in the winter. These surface winds are primarily driven by westerly winds aloft.

4.2.3 Summer

In summer, wind power is at a minimum. Lowest wind power usually occurs in August. Class 2 wind power density is found in the northwestern half of Iowa, and the rest of Iowa is rated at class 1. Prevailing winds are southerly and strongest winds are from the southwest and south-southwest. Strong winds of short duration frequently occur during summer thunderstorms.

The wind power map is based primarily on data from surface stations. However, during clear summer nights, radiational cooling at the surface and resultant low-level stability can cause a decoupling of low-level winds from higher-level winds. This can result in a wind speed maximum at relatively low levels, typically between 100 and 200 m (300 to 600 ft) based on a Central Plains study (Sisterson and Frenzen 1978). This study also indicated that even at 50 m, average wind speeds can be significantly higher than predicted by the 1/7 power law. Thus, the summer wind power map may be less reliable for 50 m than 10 m, and wind power classes at 50 m may be slightly higher than indicated.

4.2.4 Autumn

In autumn, prevailing surface winds shift from southerly to the more northerly regime typical of winter. Strongest winds are split between southerly and northwesterly, with a slight dominance of strong northwesterly winds in the northern parts of the state.

A class 3 wind power area is found in northwestern Iowa and wind power generally decreases in a southeastward direction across the state. Most of southern and eastern Iowa, as well as the more sheltered

areas near the Missouri and Mississippi Rivers, are estimated to have class 2 wind power.

4.3 FEATURES OF SELECTED STATIONS

Table 4.2 gives the location and annual wind speed and power density of nine stations in Iowa. Graphs of other features of the wind resource at these stations are shown in Figures 4.10 to 4.16. Except for Sioux City Airport, these stations are located in central and eastern Iowa.

Burlington Airport is located south of Burlington at an elevation of 60 m (200 ft) higher than the Mississippi River. This station is representative of sites in southeastern Iowa on the bluffs above the Mississippi River floodplain.

Des Moines Airport is located on the southwestern edge of Des Moines in central Iowa, near the Des Moines River. Wind and wind power characteristics at this site are representative of exposed sites in the irregular plains country of central Iowa.

Dubuque Airport is located 10 to 11 km (6 to 7 mi) south of Dubuque in eastern Iowa. It is well removed from the Mississippi River, which is 10 km (6 mi) to the northeast, and is representative of well-exposed areas in the hilly areas of eastern Iowa near the Mississippi River. However, only 12 to 18 observations per day were made during most of the period of record (except 1951). Consequently, annual and seasonal average wind power and speed shown in Table 4.2 should be adjusted downward.

Iowa City SAWR (Supplementary Aviation Weather Reporting Station) is located at the Iowa City Airport, south of Iowa City near the Iowa River. Because of its location in the lower terrain of the Iowa River it is not well exposed to prevailing winds, but may be representative of sites near the major rivers of eastern Iowa, the Des Moines, Iowa, and Cedar rivers.

Lamoni CAA (Civil Aeronautics Administration) is located at the Lamoni airport 1 mile northeast of Lamoni. Graphs for this site are based on only one year of data and therefore, may not be representative of long-term wind and wind power characteristics. However, this site and Ottumwa are essentially the only sites within Iowa that are representative of exposed locations in south-central Iowa.

Mason City Airport is located 8 km (5 mi) east of Mason City in north-central

Iowa. This site is generally representative of locations in the flat country of north-central Iowa. Two periods of record at this station show a marked difference in annual average wind speed and power. Although there was a movement of the anemometer between those periods, the exposure did not appear to change significantly in this flat area, and the base elevation changed by only 2 m. Data from the earlier period are based on hourly averages and data from the second period are based on 3-hour averages. However, average wind speed and power for this station for the first period of record are anomalously higher than any other in the state. In addition, the anemometer was mounted on a roof top rather than on a ground mast as in the later period of record. Consequently, the latter period of record (1/65 to 12/78) is regarded as being more reliable.

Ottumwa Airport is located 8 km (5 mi) north of Ottumwa in southeastern Iowa. It is situated in an exposed area on top of the bluffs east of the Des Moines River and is representative of exposed areas in the rolling hills of south-central and south-eastern Iowa.

Sioux City Airport is about 6 km (4 mi) south of Sioux City in the center of the Missouri River floodplain of western Iowa. Although the floodplain is significantly lower than the bluffs on either side of the river, it is about 16 km (10 mi) wide at this point and a comparison with other stations in the area indicates that wind speeds are not greatly reduced. Consequently, this site may be generally representative of western Iowa. It is possible that sheltering effects due to the lower elevation may be partially compensated for by some channeling and acceleration during northwest wind flow periods.

Waterloo Airport is located 3 to 5 km (2 to 3 mi) north of Waterloo in northeastern Iowa, near the Cedar River. Although it is at a lower elevation than most exposed sites in the surrounding hills, it should be representative of wind characteristics in northeastern Iowa. Wind speeds are lower here than at Mason City, 80 km (50 mi) northwest.

4.3.1 Interannual Wind Power and Speed

Six of the Iowa stations have periods of record longer than 10 years (Figure 4.10). Burlington is consistent throughout the period of record, while other stations show much variation. The most significant variations are attributable to changes in instrumentation. For example, in 1961 the sensor height at Des Moines was changed

from 21 m (69 ft) on a rooftop to 6.1 m (20 ft) on a ground mast, which may have changed the validity of the 1/7 power law extrapolation. Also, because of the questionably low wind speed and wind power in 1961, data for this year may not be valid. The anemometer at Dubuque Airport was at a rooftop location during the entire period of record but was lowered from 9.5 m (31 ft) to 7 m (23 ft) in 1965. The Mason City sensor was relocated in 1962. During the early period it was on a rooftop and later on a ground mast. Wind speed and power averages for this station prior to 1956 appear to be significantly higher than in later years (see Section 4.3, Mason City), and are therefore questionable. Between 1954 and 1958 the anemometer at Sioux City was at 31 m (103 ft) on a rooftop. After 1958 it was at 7.3 m (28 ft) on a ground mast.

In general, during periods of constant height and location, interannual variations are small. Wind characteristics should be more reliable during later periods when most sensors were on ground masts near the airport runway.

4.3.2 Monthly Average Wind Power and Speed

All stations except Mason City (65 to 78) show maximum wind power in the spring, with a slightly lower secondary maximum in the winter, and minimum wind power during the summer (Figure 4.11). Mason City (65 to 78) shows slightly higher wind power in winter than in spring, though class 4 wind power is estimated for both seasons. This could be a result of the flatter terrain in this area as well as a geographic location in northern Iowa which might be more sensitive to wintertime periods of strong northwesterly flow. Monthly average speeds and powers shown for Lamoni may not be representative because they are based on only one year of data.

4.3.3 Diurnal Wind Speed by Season

All stations show maximum wind speed during the afternoon from 1200 to 1500 LST, with nearly constant mean speeds between 1800 and 0600 (Figure 4.12). Diurnal variation is largest during spring and summer. Data for Dubuque are based on less

than 18 observations per day except for 1951. Consequently, the graph is probably not representative for nighttime hours. The slightly larger variation at Iowa City might be explained by the location of this station at a low elevation near the Iowa River. In this situation, cold air that drains into the valley can result in low level stability and a consequent decoupling of surface winds from winds aloft. This can result in a high frequency of nighttime calms and low nighttime mean wind speeds.

4.3.4 Directional Frequency and Average Speed

All stations show a bimodal directional frequency with the most frequent directions being southerly during the summer and northwesterly during winter and spring (Figure 4.13). This pattern is largely a response to synoptic-scale seasonal weather patterns.

Highest speeds generally occur with northwesterly wind directions, primarily during spring and winter. Spring is the season of maximum wind speeds for all stations except Mason City (65 to 78) which has its highest average wind speed and power during northwesterly flow periods in the winter.

4.3.5 Annual Average Wind Speed Frequency Distribution

Observer biases are apparent for Iowa City, Lamoni, Mason City (3/51 to 12/64) and Ottumwa (Figure 4.14). Otherwise, actual distributions appear to be reasonably approximated by a Rayleigh distribution. Most of the sites are at airports and wind speed distributions should show little terrain influence.

4.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 4.15 and 4.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 4.1. Geographic Map of Iowa

FIGURE 4.2. Topographic Map of Iowa

FIGURE 4.3. Land Surface Form Map for Iowa

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

FIGURE 4.4. NCC Station Locations in Iowa

FIGURE 4.5. Locations of Stations Used in Iowa Wind Resource Assessment

FIGURE 4.6. Iowa Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m^(a)

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

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 4.1. Areal Distribution (km²) of Wind Power Classes in Iowa

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	13,075	9.0	145,964	100.0
2	41,640	28.5	132,889	91.0
3	69,193	47.4	91,249	62.5
4	22,055	15.1	22,055	15.1
5	0	0.0	0	0.0
6	0	0.0	0	0.0
7	0	0.0	0	0.0

FIGURE 4.7. Certainty Rating of Iowa Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	<p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	<p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	<p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>

FIGURE 4.8. Areal Distribution of Wind Resource in Iowa (Power Classes 2 and 3); Percent of Land Area with or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 4.8 (Continued). Area Distribution of Wind Resource in Iowa (Power Classes 4 and 5); Percent of Land Area with or Exceeding Power Class Shown.

FIGURE 4.9. Seasonal Average Wind Power in Iowa (Winter, Summer)

FIGURE 4.9. Seasonal Average Wind Power in Iowa (Spring, Autumn)

TABLE 4.2. Iowa Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Lat (°N)	Long (°W)	Elevation of Station (m)	Period of Record (month/year)	Anem. Height (m)	Annual Average Speed (m/s)			Annual Average Power (watts/m ²)		
							At Anem Ht	At 10 m	At 50 m	At Anem Ht	At 10 m	At 50 m
Burlington, Iowa	Burlington Airport	40.78	91.12	212	3/50-12/64	10.1	4.7	4.7	5.9	118	118	235
Burlington, Iowa	Burlington Airport	40.78	91.12	212	1/65-12/78	6.1	4.5	4.8	6.0	99	122	244
Des Moines, Iowa	Des Moines Airport	41.53	93.65	295	6/55-6/61	21.0	5.3	4.8	6.0	161	117	233
Des Moines, Iowa	Des Moines Airport	41.53	93.65	295	6/61-12/78	6.1	4.6	5.0	6.3	115	142	283
Dubuque, ^(b) Iowa	Dubuque Airport	42.40	90.70	326	2/51-12/64	9.5	5.3	5.3	6.7	171	175	349
Dubuque, ^(c) Iowa	Dubuque Airport	42.40	90.70	326	6/65-12/78	7.0	5.2	5.5	6.9	146	170	339
Iowa City, Iowa	Iowa City SAWR	41.63	91.55	200	1/48-5/53	14.3	4.3	4.1	5.2	137	117	234
Lamoni, Iowa	Lamoni CAA	40.65	94.00	356	1/50-12/50	7.3	4.9	5.2	6.5	154	176	351
Mason City, Iowa	Mason City Airport	43.15	93.33	367	3/51-12/64	6.1	5.5	5.9	7.5	198	245	488
Mason City, Iowa	Mason City Airport	43.15	93.33	367	1/65-12/78	6.1	4.9	5.3	6.6	138	171	340
Ottumwa, Iowa	Ottumwa Airport	41.10	92.45	258	1/48-12/54	18.6	5.7	5.2	6.6	216	166	330
Sioux City, Iowa	Sioux City Airport	42.38	96.37	339	6/58-12/64	7.3	4.8	5.1	6.4	141	161	321
Sioux City, Iowa	Sioux City Airport	42.38	96.37	339	1/65-12/78	7.3	4.9	5.1	6.5	140	160	319
Waterloo, Iowa	Waterloo Airport	42.55	92.40	270	4/60-12/78	6.1	4.7	5.1	6.4	132	163	325

(a) SAWR - Supplementary Aviation Weather Reporting (Station); CAA - Civil Aeronautics Administration Facility

(b) Station had less than 18 observations/day except in year 1951.

(c) Station had less than 18 observations/day.

FIGURE 4.10. Interannual Wind Power and Speed for Iowa

FIGURE 4.11. Monthly Average Wind Power and Speed for Iowa

FIGURE 4.12. Diurnal Wind Speed by Season for Iowa

— PERCENT FREQUENCY LEFT ORDINATE — PERCENT
 - - - WIND SPEED RIGHT ORDINATE -- M/S
 PNL-3195 WERA-2
 ABSCISSA — WIND DIRECTION

FIGURE 4.13. Directional Frequency and Average Wind Speed for Iowa

— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 --- RAYLEIGH DISTRIBUTION ABSCISSA - M/S

PNL-3195 WERA-2

FIGURE 4.14. Annual Average Wind Speed Frequency for Iowa

ORDINATE - PERCENT
ABSCISSA - M/S

PNL 3195 WERA-2

FIGURE 4.15. Annual Average Wind Speed Duration for Iowa

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WERA-2

FIGURE 4.16. Annual Average Wind Power Duration for Iowa

MINNESOTA

CHAPTER 5: MINNESOTA

Minnesota had a population of 3,980,000 in 1977 (Statistical Abstracts, 100th edition, 1979) and covers a total land area of 217,847 km² (84,068 mi²). Nearly 2,000,000 live in the Minneapolis-St. Paul metropolitan area (see Figure 5.1). Most of the remaining population live in south-eastern Minnesota. The northern half of the state is relatively sparsely populated.

Most of Minnesota is flat, the result of glaciation (Figures 5.2, 5.3). The north-western part of the state is the flat bed of ancient Lake Agassiz and includes the Red River valley. The Red River flows north from here into the Hudson Bay. The northeastern tip of the state is classified as open plains. The Mesabi Range, also called the Laurentian Divide, is a west-southwest to east-northeast oriented ridge, rising 60 to 70 m (200 ft) above the surrounding terrain. Another area of high relief is located adjacent to the north shore of Lake Superior.

The east-central part of Minnesota consists of low-lying open plains. The vicinity of Minneapolis and St. Cloud is a large area of relatively low elevation. The land rises gradually in all directions from here, except for the Mississippi River valley, with the Mississippi River flowing southeastward from Minneapolis. Southern Minnesota is composed of flat to irregular plains. High relief terrain is found in the bluffs along the Mississippi River in southeastern Minnesota. Southwestern Minnesota includes part of the Prairie Coteau that is a major land feature of South Dakota.

Most of the northern two-thirds of the state is composed of lakes and swampland. Northeastern Minnesota is heavily wooded.

Wind data are fairly abundant in the southern half of the state where the population is most dense (Figures 5.4, 5.5). Fire weather stations are abundant in the forested northeastern part of the state, but data from almost all of those stations show very low wind speeds, lower in general than data from other sources in the area. This may be an exposure problem, as forest covers most of this area. Data in north-western Minnesota are sparse.

5.1 ANNUAL AVERAGE WIND POWER

The annual average wind power density in Minnesota is shown in Figure 5.6. This analysis of mean wind power applies to terrain features that are favorably exposed

to the wind, such as ridge crests, hill-tops, and uplands (see Section 1.6). However, nearby terrain features may interact with the windfield to cause the wind power at some exposed sites to vary as much as ± 50 to 100% from the assessment value. (See Wegley et al., 1980, for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, such as northeastern Minnesota, the assessment values are representative of large clearings, such as airports, with good exposure to the prevailing strong winds. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The annual average wind power class map shows that the wind power generally decreases in a west to east direction in central and northern Minnesota and in a south-southwest to north-northeast direction in southern Minnesota. This is probably the result of several factors, including the higher terrain and surface roughness found in northeastern Minnesota, which is largely forested land; the eastward decrease in elevation in central Minnesota which tends to decrease synoptically driven western downslope surface winds; and the synoptic-scale climatology of surface pressure patterns.

Highest annual average wind power is found in the belt of class 4 wind power that extends down the length of western Minnesota. Data from stations in the Red River valley of northwestern Minnesota, in particular, indicate wind power that is almost in the class 5 wind power category.

A narrow belt of class 3 wind power is found along the north shore of Lake Superior. Strongest winds here are generally east-northeast. This is apparently a result of the frequent passage of storm systems to the south with their associated east winds in this area, and the long smooth fetch over the open water under these east wind conditions. There is also a small area of class 2 wind power in the middle of the class 1 area of northeastern Minnesota. This is the Mesabi Range, which is oriented roughly perpendicular to strong northerly and northwesterly winds.

Lowest wind power is found in the low-land area of east-central Minnesota, and in northeastern Minnesota. The wind power classification in northeastern Minnesota is based on wind data from surface stations, primarily airport stations. Because of the

high surface roughness of this forested area, wind speeds at other locations might be lower than at these well-exposed sites. In general, wind power will probably be greatest at locations with a wide-open northerly fetch, such as at the southern shores of the larger lakes.

The wind power gradient across northern Minnesota is a trend only. Because of the flatness of the area, this trend is gradual, and wind power class boundaries should be considered only approximate.

5.1.1 Certainty Rating of the Wind Resource

Certainty ratings for the annual average wind power estimates are shown in Figure 5.7. Lowest ratings are found in northern and northwestern Minnesota where data are sparse. A certainty rating of 2 was assigned to most of the grid cells in this area. Certainty ratings of 1 were not generally given to this area because of its low relief. Low certainty ratings were also given to grid cells that are traversed by wind power class boundaries. In low-relief areas typical of most of Minnesota, the precise location of wind power class boundaries cannot be known.

Highest certainty ratings were given to grid cells that contain or are adjacent to cells that contain good data sites. This includes most of east-central and southern Minnesota. A certainty rating of 4 was given to grid cells that contain, or are adjacent to grid cells that contain stations with representative long-term data. A certainty rating of 3 was given to grid cells that contain stations with short-term data or data based on less than 24 observations per day. (Also, see Section 2.3.1.)

5.1.2 Areal Distribution

The areal distribution of wind power in Minnesota is illustrated in Figure 5.8. Numbers identify the percentage area in each cell of the grid in which the wind power equals or exceeds some threshold value. Because of the low relief in the state, the percentage of actual land-surface area of each cell that has wind power equal to or exceeding the wind power class assigned to that cell is large.

Table 5.1 presents the areal distribution of wind power classes in Minnesota. The actual land-surface area with exposure to class 4 wind power is about 30% of the total land area. The amount that would be predicted on the basis of map area alone is 31% (see Section 2.3.2). Thus, the actual

class 4 land-surface area is reasonably approximated by the class 4 map area.

5.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 5.9. The season of maximum wind power is spring throughout the state, although seasonal variation is minimal at low wind power sites (e.g., International Falls and St. Cloud). Summer is the season of lowest wind power throughout the state.

5.2.1 Winter

The winter seasonal wind power map shown in Figure 5.9 is almost identical to the annual wind power map, except for the inclusion of a class 5 wind power area around the Red River valley. Although upper-air winds are generally northwesterly during this season, surface winds in this area have a more northerly component.

The belt of class 4 in western Minnesota is the result of prevailing northwest winds aloft, and periodic northwesterly surface winds that occur as a result of southward Canadian air mass movements that frequently occur in this season.

A narrow belt of class 3 wind power is found along the northern shore of Lake Superior. Strongest winds in this area are from the east, although there is also a high percentage of northwesterly winds in this season.

The Mesabi Range ridge is estimated to have class 2 wind power, one class higher than the surrounding area, because of its orientation which is perpendicular to strong northerly winds.

Minnesota wind power generally decreases from west to east across the state in the winter. The lowest wind power is found in the lowlands of east-central Minnesota and in the forested country of northeastern Minnesota.

During the winter, western Minnesota is subject to high wind episodes that are of relatively short duration. The most severe such episodes occur when migratory storm systems move through this region during periods when a surface high pressure system is well established over the Canadian plains. The resulting surface pressure gradient causes strong northwesterly winds, which often have average speeds of 15 to 20 m/s (30 to 40 mph) over short (2 to 3 days) periods of time. Two or three times each year these develop into blizzards. Much of the winter wind power in western Minnesota is the result of these episodes.

5.2.2 Spring

Spring is the season of maximum wind power throughout the state except for extreme northwestern Minnesota, where maximum wind power occurs in the winter. Although upper winds are stronger in winter than in spring, surface winds are lower because of more stable conditions near the cold surface. The seasonal difference is less pronounced in the western half of the state than in the east. In the western half, winter winds are nearly as strong as spring winds, and in extreme northwestern Minnesota, data indicate that winter wind power is slightly higher than spring wind power. This is also a season of transition, when northerly prevailing winds are shifting to the more southeasterly summer directions.

A belt of class 5 wind power extends down the western length of Minnesota but is cut off near the Iowa border. Within this class 5 area, highest wind power appears to occur in the Red River valley of northwestern Minnesota.

Areas along the ridge crests of the Mesabi Range and along the northern shore of Lake Superior are estimated to have class 3 wind power. Strongest winds near Lake Superior are from the east-northeast and wind power is greatest in this season. These winds may penetrate inland up to 25 km (15 mi), depending upon the local exposure.

Wind power is low (class 2) in the lowlands of east-central Minnesota and the forested area of northeastern Minnesota.

5.2.3 Summer

Prevailing surface winds are southerly in the summer; upper-level winds are westerly. Winds are generally lighter so that this is the season of minimum wind power throughout the state.

Summer wind power throughout Minnesota is estimated to be class 1 and 2, although data from the Red River valley indicate that wind power in this area is almost class 3. Wind directions in this valley are about evenly split between north and south during the summer. Wind power along the Lake Superior shore and on the Mesabi Range ridge crest is not significantly different from surrounding areas.

5.2.4 Autumn

Autumn is a season of transition in which prevailing surface winds are shifting back to the more northerly, high-speed regime characteristic of winter.

A class 4 belt extends down the western length of Minnesota, but does not extend as far south as in winter and spring. As before, data from the Red River valley indicate that wind power may be greater in this area, almost class 5. Prevailing winds are split between north and south in the Red River valley, but strongest winds occur slightly more frequently from the north in this season.

Class 3 wind power is estimated for the Lake Superior shore. Strongest winds near Lake Superior are easterly, although there is an increasingly frequent occurrence of strong winds from the northwest. The Mesabi Range ridge crest is estimated to have class 2 wind power, one class greater than surrounding terrain. Lowest wind power is found in the lowlands of east-central Minnesota and in the forested areas of northeastern Minnesota.

5.3 FEATURES OF SELECTED STATIONS

Table 5.2 gives the location and annual wind speed and power density of ten stations in Minnesota. Graphs of other features of the wind resource at these stations are shown in Figures 5.10 to 5.16. Of these stations, one is in extreme northern Minnesota near the Canadian border, one is near Lake Superior, three are in the upland area of central Minnesota, three in the lowland area of central Minnesota, and two are in extreme southeastern Minnesota.

Alexandria FAA (Federal Aviation Administration) is located about 1.5 km (1 mi) southwest of Alexandria in the lake country of west-central Minnesota. This site appears to be representative of exposed sites in this flat area.

Duluth Airport is located north of Duluth about 3 km (5 mi) from the shore of Lake Superior. Although inland, the site is 250 m (820 ft) higher than the lake and, with no intervening topography, has good exposure to easterly winds. It should be representative of sites near the Lake Superior shore.

International Falls Airport is located south of International Falls near the Canadian border. This area is very flat so that data from this site should be representative of low-relief sites in northern Minnesota that have good exposure. Much of this region is wooded.

Minneapolis-St. Paul International Airport is located in south Minneapolis near the confluence of the Minnesota and Mississippi Rivers. Along with St. Paul Downtown Airport, this site should be

representative of well-exposed sites near the Minneapolis area. High surface roughness of the nearby urban area could have an effect on winds, especially from the northwest.

Redwood Falls FAA is located just east of Redwood Falls on a bluff overlooking the Minnesota River to the north. The airport is about 50 m (150 ft) above the Minnesota River floodplain. The site has good exposure in all directions and data from this site should be representative of exposed sites in southwestern Minnesota.

Rochester WBAS (Weather Bureau Airport Station) is located in southeast Rochester. The exposure here is not as good as at Rochester Airport, 10 km (6 mi) southwest and 85 m (280 ft) higher in elevation, and may not be truly representative of exposed sites in the area. However, comparison of this site with Rochester Airport provides a good example of how wind characteristics can change over a short distance. The Rochester site is somewhat sheltered by low hills while Rochester Airport is on the crest of a broad ridge.

Rochester Airport is located on top of a broad ridge about 8 km (5 mi) south of Rochester. This site is unrepresentative for southerly winds (Changery 1978). With the Rochester site, it provides an example of how local terrain features can enhance wind speeds on a geographic scale too small to appear on low resolution areal wind energy maps, even in regions with relatively low relief. (This area is classified as B2c, upland plains, and C3b, hilltops and uplands. See Section 1.8.)

St. Cloud Airport is located on the north side of St. Cloud by the Mississippi River. This station has recorded the lowest average speeds of all the Minnesota sites listed in this section. Also, because data for the period from 1972 to 1978 is based on only 12 to 18 observations per day, wind speeds should probably be adjusted downward even more for this period. These low wind speeds may be partially the result of sheltering by higher terrain to the west. Winds from the northwest through southwest are considered to be unrepresentative for the period from 1946 to 1949 (Changery 1978).

St. Paul Downtown Airport is located in West St. Paul, by the Mississippi River. See the discussion for Minneapolis-St. Paul International Airport.

Willmar CAA (Civil Aeronautics Administration) is just west of Willmar in east-central Minnesota. The site has a short period of record (less than 2 years)

but, along with Alexandria Airport, should be representative of exposed sites in western and southwestern Minnesota.

5.3.1 Interannual Wind Power and Speed

Only five Minnesota stations have periods of record longer than 10 years with no anemometer change, and these cover different periods so that any comparison of interannual variability is difficult (Figure 5.10). Duluth and International Falls both show peak years in 1956. The decreasing wind power trend at Duluth, International Falls, and St. Cloud should be treated with caution. This trend is not necessarily correlated among these stations because of the high individual variability. The change in wind power between the two Rochester sites is apparent.

5.3.2 Monthly Average Wind Power and Speed

All stations show peak wind power and speed during spring and early winter (Figure 5.11). St. Paul and Rochester (9/60 to 12/78) show slightly higher wind power in winter, though the figures for St. Paul are based on a short period of record. Except for Minneapolis, Redwood Falls, and St. Cloud, winter and spring peaks are nearly equal. The high variability at Willmar could be misleading because of the very short period of record.

5.3.3 Diurnal Wind Speed by Season

All stations show approximately the same diurnal trend, with maximum winds occurring between 1200 and 1600 LST, slightly later in the spring and summer (Figure 5.12). Highest variability occurs in the summer and lowest in the winter. These trends are nearly uniform throughout the state. Again, the irregular curve at Willmar is probably a result of the short period of record at this site.

5.3.4 Directional Frequency and Average Speed

Duluth shows a high frequency of easterly winds from Lake Superior with the highest wind speeds from the east-northeast (Figure 5.13). This trend should be representative of sites near Lake Superior. Otherwise, all stations show directional frequencies biased toward south to southeasterly directions (summer regime) and west-northwest to northwesterly directions (winter regime). Spring and fall are transition seasons. Highest wind speed, with the exception of Duluth, occurs during northwesterly flow periods in winter and spring. This variability of speed with direction is small at International Falls, which shows nearly uniform mean wind speeds for all directions.

5.3.5 Annual Average Wind Speed Frequency

Observer biases are seen at Alexandria, Rochester (1/48 to 9/60), St. Cloud (1/48 to 4/56), St. Paul, Redwood Falls, and Willmar at wind speeds of 2, 5, and 8 m/s. (Figure 5.14). Later periods of record show more uniformity and reasonably good correlation with the Rayleigh distribution at all stations.

5.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 5.15 and 5.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 5.1. Geographic Map of Minnesota

FIGURE 5.2. Topographic Map of Minnesota

FIGURE 5.3. Land-Surface Form Map for Minnesota

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

FIGURE 5.4. NCC Station Locations in Minnesota

FIGURE 5.5. Locations of Stations used in Minnesota Resource Assessment

FIGURE 5.6. Minnesota Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m^(a)

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

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 5.1 Areal Distribution (km²) of Wind Power Classes in Minnesota

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	59,995	28.6	209,718	100.0
2	40,283	19.2	149,723	71.4
3	46,913	22.4	109,440	52.2
4	65,527	29.8	62,527	29.8
5	0	0.0	0	0.0
6	0	0.0	0	0.0
7	0	0.0	0	0.0

FIGURE 5.7. Certainty Rating of Minnesota Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	<p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	<p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	<p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>

FIGURE 5.8. Areal Distribution of Wind Resource in Minnesota (Power Classes 2 and 3); Percent of Land Area with or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 5.8 (Continued). Areal Distribution of Wind Resource in Minnesota (Power Classes 4 and 5); Percent of Land Area with or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 5.9. Seasonal Average Wind Power in Minnesota (Winter, Summer)

FIGURE 5.9 (Continued). Seasonal Average Wind Power in Minnesota (Spring, Autumn)

TABLE 5.2. Minnesota Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Lat (°N)	Long (°W)	Elevation of Station (m)	Period of Record (month/year)	Anem. Height (m)	Annual Average Speed (m/s)			Annual Average Power (watts/m ²)		
							At Anem Ht	At 10 m	At 50 m	At Anem Ht	At 10 m	At 50 m
Alexandria, Minnesota	Alexandria FAA	45.87	95.38	435	12/48-12/54	8.5	5.3	5.4	6.8	179	191	382
Duluth, Minnesota	Duluth Airport	46.83	92.18	434	4/50-6/61	16.2	5.6	5.2	6.6	200	162	325
Duluth, Minnesota	Duluth Airport	46.83	92.18	434	6/61-12/78	6.4	4.7	5.0	6.3	111	134	268
International Falls, Minnesota	International Falls Airport	48.57	93.38	359	9/53-9/63	7.0	4.0	4.2	5.3	91	105	211
International Falls, Minnesota	International Falls Airport	48.57	93.38	359	8/65-12/78	6.1	4.0	4.3	5.4	78	96	192
Minneapolis, Minnesota	Minneapolis-St. Paul International Airport	44.88	93.22	262	9/58-12/64	6.4	4.6	4.9	6.1	119	144	287
Minneapolis, Minnesota	Minneapolis-St. Paul International Airport	44.88	93.22	262	1/65-12/78	6.4	4.5	4.8	6.0	101	122	244
Redwood Falls, Minnesota	Redwood Falls FAA	44.55	95.08	315	11/49-12/54	7.9	4.8	5.0	6.3	158	174	348
Rochester, Minnesota	Rochester WBAS	44.00	92.45	315	1/48-9/60	19.2	4.5	4.1	5.1	125	94	188
Rochester, Minnesota ^(b)	Rochester Airport	43.92	92.50	393	9/60-12/78	6.1	5.7	6.1	7.7	187	231	461
St. Cloud, Minnesota ^(c)	St. Cloud Airport	45.58	94.18	316	1/48-4/56	11.0	3.7	3.6	4.6	78	74	149
St. Cloud, Minnesota ^(d)	St. Cloud Airport	45.58	94.18	316	2/72-12/78	6.1	3.6	3.9	4.9	60	74	148
St. Paul, Minnesota	St. Paul Downtown Airport	44.93	93.07	220	1/48-5/51	19.5	5.0	4.6	5.7	157	117	235
Willmar, Minnesota	Willmar CAA	45.12	95.05	347	12/48-9/50	12.2	5.8	5.6	7.1	300	275	549

^(a) FAA-Federal Aviation Administration Facility; WBAS-Weather Bureau Airport Station; CAA-Civil Aeronautics Administration Facility

^(b) Winds from the south are considered to be unrepresentative.

^(c) Winds from the northwest through southwest are considered to be unrepresentative.

^(d) Station had only 12 to 18 observations/day.

FIGURE 5.10. Interannual Wind Power and Speed for Minnesota

FIGURE 5.11. Monthly Average Wind Power and Speed for Minnesota

FIGURE 5.12. Diurnal Wind Speed by Season for Minnesota

..... PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-2
 ABSCISSA - WIND DIRECTION

FIGURE 5.13. Directional Frequency and Average Wind Speed for Minnesota

— ACTUAL DISTRIBUTION ORDINATE — PERCENT
 RAYLEIGH DISTRIBUTION ABSCISSA — M/S
 PNL-3195 WERA-2

FIGURE 5.14. Annual Average Wind Speed Frequency for Minnesota

ORDINATE -- PERCENT
ABSCISSA - M/S

PNL-3195 WERA-2

FIGURE 5.15. Annual Average Wind Speed Duration for Minnesota

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WERA-2

FIGURE 5.16. Annual Average Wind Power Duration for Minnesota

NEBRASKA

CHAPTER 6: NEBRASKA

Nebraska covers an area of 200,199 km² (77,227 mi²) and had a population in 1977 of 1,555,000 (Statistical Abstracts, 100th edition, 1979). Most of the residents live in the farmland country of eastern Nebraska. One-third of the population lives in the two largest cities, Omaha and Lincoln (see Figure 6.1). Western Nebraska is sparsely populated.

The terrain in Nebraska ranges from relatively flat plains in the east to open hills in the west (see Figures 6.2 and 6.3). Highest relief is found in the Sand Hills area of north-central and northwestern Nebraska and in the White River area north of the Niobrara River in extreme northwestern Nebraska. In general, elevations increase from east to west across the state.

Wind data are abundant at stations near the Platte River in southern Nebraska and sparse in the northern parts of the state, especially in the Sand Hills area (Figures 6.4 and 6.5). Only one station with NCC unsummarized data, Mullen, is located in the Sand Hills, and data from this station indicate wind speeds that are anomalously low. The site is located on a hillside and is not representative of well-exposed sites in the area.

6.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density for Nebraska is shown in Figure 6.6. This analysis of mean wind power applies to terrain features that are favorably exposed to the wind, such as ridge crests, hilltops, and uplands (see Section 1.6). However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as ± 50 to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the assessment values are representative of large clearings, such as airports, with good exposure to the prevailing strong winds. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The annual average wind power is estimated to be class 4 or higher on exposed hilltops in northwestern Nebraska and the Sand Hills area. This area is near the east end of the southern Wyoming wind corridor. Prevailing winds are generally westerly and associated with strong winds aloft. Strongest winds are from the west-

northwest in the winter and from the south-southeast in the summer.

Another class 4 area exists in the extreme southwestern part of the state, near the Colorado and Kansas borders. This marks the approximate northern boundary of a large class 4 area occupying much of western Kansas and Oklahoma.

The rest of Nebraska is predominantly class 3 except for sheltered locations along the Missouri River in eastern Nebraska. The general eastward decrease in wind power is a consequence of the eastward decrease in elevation. The influence of the southerly flow regime is obvious as most stations in the east part of the state show south to be the prevailing direction. However, strongest winds are generally north to northwest.

An area of class 2 is found along the Missouri River in extreme eastern Nebraska. Surface winds here are, on the average, lower because of sheltering by bluffs near the river, and because of periodic episodes of low-level air stagnation that decouples surface winds from winds aloft. Similar conditions may exist in the bottom of other broad river valleys, e.g., along the Platte River near North Platte and Scottsbluff, and in the vicinity of Lewis and Clark Lake in northeastern Nebraska. Here, annual wind power availability may be less than shown in Figure 6.6.

6.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for Nebraska are shown in Figure 6.7. In general, certainty ratings of 3 and 4 were assigned to grid cells that contain or are adjacent to cells that contain stations with representative data. Certainty ratings of 2 were given to grid cells with no representative data but that are composed of simple terrain. Grid cells that are composed of more complex terrain and that have no representative data were assigned a certainty rating of 1 (see Section 2.3.1).

The areas with class 4 wind power have generally low certainty ratings. In particular, the low (1) certainty ratings in the Sand Hills are a consequence of the scarcity of data and the moderately complex terrain in this area.

Low certainty ratings were also assigned to grid cells that are traversed by wind power class boundaries. In the low-relief terrain of the southeastern part of the

state, an exact boundary cannot be known because of the gentle average wind speed gradient.

Most of the grid cells in the class 3 area of southern and eastern Nebraska have high certainty ratings. Data in this region are abundant.

6.1.2 Areal Distribution

The areal distribution of wind power in Nebraska is illustrated in Figure 6.8. Numbers identify the percentage area in each cell of the grid in which the wind power equals or exceeds some threshold value. In southern and eastern Nebraska where the terrain is relatively flat, and which is estimated to have mostly class 3 wind power, most (88 to 100%) of the land area in each cell is actually class 3. However in the Sand Hills, a class 4 area, only about 40% of the land area in each cell is actually class 4. This is because of the higher relief of the Sand Hills terrain.

Table 6.1 presents the areal distribution of wind power classes in Nebraska. Land-surface area with class 4 wind power is about 20% of the total land area. The amount that would be predicted on the basis of map area alone is 35%. Thus, using map area alone, the actual class 4 land-surface area would be significantly over-predicted. Again, this is a consequence of the higher relief terrain in western Nebraska, particularly the Sand Hills area. (Also see Section 2.3.2).

6.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 6.9. Spring is the season of maximum wind power throughout the state. In the extreme northwestern to north-central parts of the state (near Chadron, Alliance, and Valentine), winter and summer both have low average wind power. For the rest of the state, summer is the season of lowest wind power.

6.2.1 Winter

In winter, most of Nebraska is estimated to have class 3 wind power (see Figure 6.9). Parts of western Nebraska, most notably the Sand Hills area, have class 4. Sheltered areas along the Platte and North Platte Rivers are estimated to have class 3 wind power. These areas, in addition to being sheltered by higher terrain, are subject to periodic stagnation of low-lying stable air that shields them from strong winds at higher altitudes.

Eastern Nebraska has predominantly class 3 wind power except for areas near the Missouri River that may be sheltered from the prevailing northwesterly winds by low-lying stable air, such as the class 2 areas in extreme eastern and northeastern Nebraska.

6.2.2 Spring

In spring, the season of maximum wind power throughout Nebraska, most of the western two-thirds of the state is estimated to have class 5 wind power (see Figure 6.9).

There is some indication, based on data from one fire weather station and one station with unsummarized data, that exposed areas in the Sand Hills may have class 6 wind power in spring. However, the fire weather station, on Scott Lookout, has daytime-only data. Wind power at the other station, Broken Bow, is an estimate based on samples taken from two years and is anomalous with other similarly exposed sites. Consequently this area was designated as having class 5 wind power.

Extreme eastern Nebraska is estimated to have class 4 wind power except for low-lying areas along the Missouri River, which are estimated to be class 3. This is a consequence of the shift of winds in this season to a more westerly direction than in winter. Because the Missouri River valley is oriented north to south, these areas are more subject to sheltering by high terrain.

6.2.3 Summer

In summer, Nebraska is estimated to have mostly class 2 or lower wind power. Exceptions are a large class 3 area that encompasses most of the Sand Hills, and a small area in extreme southwest Nebraska that was assigned class 3 on the basis of data from Akron, Colorado, and Goodland, Kansas.

6.2.4 Autumn

In autumn, most of Nebraska is estimated to have class 3 wind power. Winds during this season are shifting from predominantly southerly to predominantly northerly. Strongest winds are northerly. Extreme eastern Nebraska and low-lying areas near the Platte River are estimated to have class 2 wind power. During this season, low areas are becoming increasingly subject to low-lying stable air conditions.

6.3 FEATURES OF SELECTED STATIONS

Table 6.2 gives the location and annual wind speed and power density of fourteen

stations in Nebraska. Graphs of other features of the wind resource are shown in Figures 6.10 through 6.16. Four of these stations are located along the North Platte and Platte rivers, two are near the South Dakota border in northwestern Nebraska, three are near the Colorado and Kansas borders of southwestern Nebraska, two are in the flat country of eastern Nebraska, and two are on the Missouri River in eastern Nebraska.

Chadron Airport is located about 8 km (5 mi) west of Chadron, near the South Dakota border in northwestern Nebraska. A ridge about 300 m (1,000 ft) higher and oriented west-southwest to east-northeast is located 12 to 15 km (7 to 9 mi) southeast. It appears that this ridge may channel light winds to the southwest. There also may be some sheltering effects during northerly and southerly flow situations. It should be noted that 1/7 power law extrapolations of data from Chadron shown on the graphs in Figures 6.10 and 6.11 were based on an anemometer height of 17.7 m (58 ft). The true anemometer height was 12.2 m (40 ft) as shown in Table 6.2.

Grand Island Airport is located 5 km (3 mi) northeast of Grand Island and about 8 km (5 mi) north of the North Platte River. The surrounding terrain is level and this station should be representative of the flat country of east-central Nebraska.

The Hayes Center site is located 5 km (3 mi) east of Hayes Center and 24 km (15 mi) north of the Republican River in southwest Nebraska. The site is near a ridge top bordering Skunk Creek and appears to have had good exposure. However, because of the short period of record, the reliability of data from this site as being representative is uncertain.

Imperial Airport is located 3 km (2 mi) southeast of Imperial and about 25 km (15 mi) east of the Colorado border. The site is at an airport surrounded by level terrain so that the exposure is good and, because of its longer period of record, should be more representative than Hayes Center of southwestern Nebraska.

Lexington Airport is located just west of Lexington on the Platte River in south-central Nebraska. The river valley here, as at North Platte, is somewhat sheltered by bluffs 50 to 80 m (160 to 260 ft) higher to the north and south. Wind characteristics at these two sites should be representative of areas along the Platte River in south-central Nebraska.

Lincoln Airport is located 5 km (3 mi) northwest of Lincoln. The terrain is low rolling hills and the airport is at a lower elevation than better-exposed sites on hilltops nearby. However, the relief of the area is low and this site should be representative of sites in southeastern Nebraska.

Norfolk (Stefan Memorial Airport) is located in the valley of the Elkhorn River in northeastern Nebraska. The surrounding terrain is rolling hills, with some hills up to 60 m (200 ft) higher 8 km (5 mi) east. Because the relief is low, this site should be representative of the rolling hills country in this part of the state. However, data for the period shown on Table 6.2 is based on less than 18 observations per day. Consequently, average wind speed and power shown on Table 6.2 should be adjusted downward, as data were not taken during the low-wind speed nighttime hours.

North Platte (Lee Bird Airport) is located on the Platte River near the confluence of the North and South Platte Rivers. As at Lexington, the Platte River valley in this area is somewhat sheltered from prevailing winds by bluffs about 100 m (300 ft) higher to the north and south. At Lee Bird Airport the Platte River valley is only 6 to 8 km (4 to 5 mi) wide. This site should be representative of sites near the Platte River in south-central Nebraska.

Omaha/Eppeley Field is located by the Missouri River in extreme eastern Nebraska. As Eppeley Field is located on the Missouri River floodplain which at this point is 6 km (4 mi) wide and sheltered by bluffs on either side rising about 100 m (300 ft) higher, the site is not representative of stations at more-exposed locations away from the river. This site provides an indication of wind characteristics at low elevations along the Missouri River between Nebraska and Iowa.

Omaha/Offutt AFB (Air Force Base) is located on a bench near the Missouri River floodplain at the southern edge of Bellevue, Nebraska, and about 15 km (10 mi) south of Eppeley Field. Because of sheltering from northerly winds by higher terrain immediately north of the air field, average wind speed and wind power is lower than at Eppeley Field. Consequently, this site is less representative than Eppeley Field of wind characteristics along the Missouri River in eastern Nebraska.

Scottsbluff Airport is located 5 km (3 mi) east of Scottsbluff in the North Platte River Valley of the western Nebraska

panhandle. Although the valley is about 30 km (20 mi) wide at this point, hills to the north and south that rise up to 300 m (1,000 ft) and 100 m (300 ft) higher, respectively, may cause some sheltering from prevailing winds. Wind characteristics here are representative of sites at relatively low elevations along the North Platte River of western Nebraska.

Sidney FSS (Flight Service Station) is located about 15 km (9 mi) north of the Colorado border in the Nebraska panhandle. The terrain in the vicinity is gently rolling hills. This station is representative of the higher ground between the North and South Platte rivers of southwestern Nebraska and northeastern Colorado.

Valentine (Miller Field) is located at the northern edge of the Sand Hills about 16 km (10 mi) south of the South Dakota border in north-central Nebraska. Data from this site, as shown in the wind and wind power graphs in Figures 6.10 through 6.16, are based on a two-year period of record, from 9/76 to 12/78. Wind speed frequency data from the five-year period 4/56 to 3/61 show significantly higher speeds and wind power averages (about twice as high), even though the data were taken from the same site. This is partly because data from 4/56 to 3/61 were based on only 12 to 18 observations per day. However, because the 5-year data agree well with other sites nearby (Chadron, Alliance), it is considered to be more reliable and representative. Consequently, data from the two-year period, including graphs in Figures 6.10 to 6.16, are considered to be unrepresentative.

6.3.1 Interannual Wind Power and Speed

Five stations have periods of records of 10 years or more at constant anemometer height (Figure 6.10). Omaha/Eppeley Field and Scottsbluff show high interannual variability, while Norfolk and North Platte have relatively constant wind speed and power during the 1960s. The correlation among all of these stations is poor, although all stations show a high annual average wind power in 1968. The peak in 1964 at Omaha/Offutt AFB does not correspond with data at Omaha/Eppeley Field, which shows a relatively low wind power for this year, even though these two stations are both located on the Missouri River floodplain about 10 miles apart. Similarly, there is no peak at North Platte in 1967 that corresponds to the obvious peak at Scottsbluff for that year. Consequently, these graphs should be interpreted with caution.

6.3.2 Monthly Average Wind Power and Speed

All stations show a pronounced seasonal wind power and speed maximum occurring in spring (Figure 6.11). The secondary maximum that occurs in winter is not as obvious for Nebraska stations as for the other states in the North Central region. This may be in part because Nebraska is less subject to high-speed wind episodes during the winter because of its more southerly location (i.e., it is south of major storm tracks).

Norfolk and North Platte (8/64 to 12/78) show slightly higher wind speed and wind power averages in the fall than in the winter. Chadron shows seasonal average wind power to be approximately the same in winter as in summer. This feature also appears in data from Valentine (4/56 to 3/61, not shown on graph) and Alliance (1/58 to 12/62, not shown on graph), indicating that this may be characteristic of northwestern Nebraska.

North Platte also shows a trend to low wind power in the winter, apparently the result of sheltering by bluffs to the north.

For all other stations, minimum wind power occurs in the summer.

6.3.3 Diurnal Wind Speed by Season

All stations show the same general pattern of diurnal wind speed, with maximum wind speed occurring in the afternoon between 1200 and 1600 LST (Figure 6.12). Largest diurnal variation occurs in spring and summer and smallest in winter. The graph for Norfolk is incomplete because observations were only made between 0600 and 2100.

6.3.4 Directional Frequency and Average Speed

Generally, stations in Nebraska show south to be the most frequently occurring wind direction (Figure 6.13). Some stations indicate channeling by river valleys e.g., Scottsbluff, North Platte, Omaha/Eppeley Field, and Omaha/Offutt AFB. (The latter two lie in valleys already nearly parallel to the prevailing winds. The sharper spikes in the southerly direction for Omaha/Eppeley Field, as compared to Omaha/Offutt AFB, are probably due to a more wide open exposure to southerly winds. Omaha/Offutt AFB is located on a bench above the river. See station descriptions.)

Data from Chadron also indicate some channeling of light winds to the southwest, but not enough to channel the strongest winds, as indicated by the high average wind speeds for south-southeast and north-west winds, even though southwest is the prevailing direction.

The irregular curves of earlier station periods of record (late 1940s and early 1950s) indicate some observer bias to an eight-point compass.

Though north-to-northwest winds are not as frequent in Nebraska as in the other North Central region states, maximum wind speeds still occur from this direction with a secondary maximum from southerly winds.

6.3.5 Annual Average Wind Speed Frequency

Observer biases are evident at 2, 5, and 8 m/s at sites with older periods of

record, e.g., Chadron, Grand Island (5/48 to 12/61), Hayes Center, Imperial, Lexington, and Sidney (Figure 6.14). Stations with more recent records show little evidence of this observer bias.

Most stations show the wind speed frequency distribution to be reasonably well approximated by the Rayleigh distribution with the possible exceptions of Lincoln and Omaha/Offutt AFB.

6.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 6.15 and 6.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 6.1. Geographic Map of Nebraska

FIGURE 6.2. Topographic Map of Nebraska

FIGURE 6.3. Land-Surface Form Map of Nebraska

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

FIGURE 6.4. NCC Station Locations in Nebraska

FIGURE 6.5. Locations of Stations used in Nebraska Wind Resource Assessment

FIGURE 6.6. Nebraska Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m^(a)

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

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 6.1 Areal Distribution (km²) of Wind Power Classes In Nebraska

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	31,200	15.6	200,384	100.0
2	30,084	15.0	169,184	84.4
3	98,474	49.1	139,100	69.4
4	40,626	20.3	40,626	20.3
5	0	0.0	0	0.0
6	0	0.0	0	0.0
7	0	0.0	0	0.0

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	<p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	<p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	<p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>

Class 2

Class 3

FIGURE 6.8. Areal Distribution of Wind Resource in Nebraska (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.

Class 4

Class 5

FIGURE 6.8 (Continued). Areal Distribution of Wind Resource in Nebraska (Power Classes 4 and 5); Percent of Land Area with or Exceeding Power Class Shown.

FIGURE 6.9. Seasonal Average Wind Power in Nebraska (Winter, Summer)

FIGURE 6.9 (Continued). Seasonal Average Wind Power in Nebraska (Spring, Autumn)

TABLE 6.2. Nebraska Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Lat (°N)	Long (°W)	Elevation of Station (m)	Period of Record (month/year)	Anem. Height (m)	Annual Average Speed (m/s)			Annual Average Power (watts/m ²)		
							At Anem Ht	At 10 m	At 50 m	At Anem Ht	At 10 m	At 50 m
Chadron, Nebraska	Chadron Airport	42.83	103.08	1007	1/48-12/54	12.2	5.2	5.1	6.4	222	204	407
Grand Island, Nebraska	Grand Island Airport	40.97	98.32	567	5/48-12/61	14.5	5.6	5.3	6.6	183	156	313
Grand Island, Nebraska	Grand Island Airport	40.97	98.32	567	12/61-12/78	6.1	5.2	5.6	7.1	153	189	377
Hayes Center, Nebraska	Hayes Center	40.52	100.97	924	1/48-10/50	20.4	5.8	5.2	6.6	254	187	373
Imperial, Nebraska	Imperial Airport	40.52	101.62	998	12/50-12/54	7.9	4.6	4.7	5.9	133	146	293
Lexington, Nebraska	Lexington Airport	40.80	99.77	734	5/50-12/54	7.9	5.2	5.4	6.7	165	182	363
Lincoln, Nebraska	Lincoln AFB	40.85	96.75	360	1/59-6/64	4.0	3.6	4.1	5.2	88	130	261
Lincoln, Nebraska	Lincoln Airport	40.85	96.77	365	9/72-12/78	6.1	4.7	5.0	6.3	133	164	328
Norfolk, ^(b) Nebraska	Stefan Memorial Airport	41.98	97.43	472	1/65-5/75	15.6	5.6	5.2	6.6	211	174	348
North Platte, Nebraska	Lee Bird Airport	41.13	100.68	848	2/52-8/64	9.8	4.9	4.9	6.2	156	157	314
North Platte, Nebraska	Lee Bird Airport	41.13	100.68	848	8/64-12/78	6.1	4.3	4.6	5.8	106	131	261
Omaha, Nebraska	Eppley Field	41.30	95.90	304	9/54-3/63	22.6	5.2	4.6	5.8	172	121	242
Omaha, Nebraska	Eppley Field	41.30	95.90	304	4/63-12/78	6.1	4.4	4.7	6.0	111	137	274
Omaha/Offutt, Nebraska	Offutt AFB	41.12	95.90	312	5/60-12/70	3.7	3.4	4.0	5.0	75	115	230
Scottsbluff, Nebraska	Scottsbluff Airport	41.87	103.60	1204	3/54-8/64	15.2	5.1	4.8	6.1	164	136	273
Scottsbluff, Nebraska	Scottsbluff Airport	41.87	103.60	1204	8/64-12/78	6.1	4.6	5.0	6.2	123	152	303
Sidney, Nebraska	Sidney FSS	41.13	103.03	1231	12/49-12/54	7.9	5.3	5.5	6.9	167	184	368
Valentine ^(b)	Miller Field	42.87	103.55	789	9/76-12/78	9.2	4.0	4.0	5.1	101	104	209

(a) AFB-Air Force Base; FSS-Flight Service Station

(b) Station had less than 18 observations/day.

FIGURE 6.10. Interannual Wind Power and Speed for Nebraska

FIGURE 6.11. Monthly Average Wind Power and Speed for Nebraska

FIGURE 6.12. Diurnal Wind Speed by Season for Nebraska

PERCENT FREQUENCY LEFT ORDINATE - PERCENT
WIND SPEED RIGHT ORDINATE - M/S
PNL-3195 WERA-2
ABSCISSA - WIND DIRECTION

FIGURE 6.13. Directional Frequency and Average Wind Speed for Nebraska

----- ACTUAL DISTRIBUTION ORDINATE - PERCENT
 RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3195 WERA-2

FIGURE 6.14. Annual Average Wind Speed Frequency for Nebraska

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WERA-2

FIGURE 6.16. Annual Average Wind Power Duration for Nebraska

ORDINATE - PERCENT
ABSCISSA - M/S

PNL-3195 WERA-2

FIGURE 6.15. Annual Average Wind Speed Duration for Nebraska

NORTH DAKOTA

CHAPTER 7: NORTH DAKOTA

North Dakota covers an area of 183,115 km² (70,665 mi²) and had a population in 1977 of 650,000 (Statistical Abstracts, 100th edition, 1979). The population is mostly rural. The largest cities, Fargo and Grand Forks, have populations of 53,000 and 43,000, respectively (Figure 7.1). The hills and Badlands areas of southwestern North Dakota are sparsely populated.

The terrain in North Dakota varies from flat plains in the east to the hilly plains and tablelands in the southwest (Figures 7.2 and 7.3). The highest relief is found in the Badlands of the Little Missouri River and on the Missouri Plateau in western North Dakota. The elevation generally increases gradually from east to west, with steeper rises in elevation along the Pembina and Missouri Escarpments (see Figure 7.1). The general area which is bounded approximately on the west by the Missouri Coteau and which has a less well-defined eastern boundary east of the Red River, appears to be significant in channeling dense arctic air that periodically pours southward from Canada toward Iowa during the winter.

The Red River valley in eastern North Dakota is bounded on the west by the Pembina Escarpment and has a south-to-north decrease in elevation, with the Red River flowing north to the Hudson Bay.

Data are fairly abundant along the Missouri and Red rivers and in the southwestern part of the state except for the Little Missouri River Badlands (Figures 7.4 and 7.5). Most of the data in the southwest are from sources other than the National Climatic Center (NCC). Data are extremely sparse throughout the northeastern quadrant of the state. Except for stations near the Red River, there is only one NCC station in this area, Devil's Lake, that has data for a representative period of time, and this station has only unsystematized data. However, because of the flatness of this area, variability of the wind resource should be small.

7.1 ANNUAL AVERAGE WIND POWER

The annual average wind power density in North Dakota is shown in Figure 7.6. This analysis of mean wind power applies to terrain features that are favorably exposed to the wind, such as ridge crests, hilltops and uplands (see Section 1.6). However, nearby terrain features may interact with the windfield to cause the wind power at some exposed sites to vary as much as ± 50

to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The annual average wind power for most of North Dakota is estimated to be class 4 (Figure 7.6). The eastern half of the state is all class 4. Although this classification is based upon extremely meager data, the low variability of the terrain in eastern North Dakota makes the variability of the wind resource small. Data from stations near the Red River indicate that this area may have almost class 5 annual average wind power.

Strongest surface winds in this entire region are primarily north to northwest, with occasional strong southerly winds in the Red River valley, and are driven by strong winds aloft. Because of the low surface roughness of this area, which comprises much of the Canadian Wind Corridor (Section 2.3), surface wind speeds are high.

Within this class 4 area, certain terrain features may accelerate winds and increase the wind power. In particular, wind power may be higher on the higher elevations of the Missouri and Pembina Escarpments, and on hilltops of the Turtle Mountains. More wind data are needed to determine the degree of wind speed enhancement by these features.

The class 4 area on the Missouri Plateau of southwestern North Dakota consists of hilly plains and tablelands. Sites at the crests of these hills and uplands are well exposed to strong northwesterly surface winds, which are driven by strong winds aloft.

The class 3 area consists of lower elevation areas near the Missouri River and the Badlands of the Little Missouri River. These areas are subject to sheltering by uplands and to shielding from strong upper-air winds by low-lying stable air during cold months.

7.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for North Dakota are shown in Figure 7.7. The low (2) certainty ratings in the northeastern part of the state were assigned because of the lack of data in

this area. These grid cells were not assigned certainty ratings of 1 because of the flatness of the terrain and the consequent small spatial variability of the winds.

The group of cells with a certainty rating of 1 in the western part of the state consist mostly of the Badlands of the Little Missouri River. These cells have low certainty ratings because of the lack of data at well-exposed locations and because of the relatively complex terrain in this area.

Other low certainty ratings were assigned to grid cells that are traversed by wind power class boundaries. A precise wind power class boundary can not be known in low relief areas where average wind power gradients are slight.

High certainty ratings were assigned to cells near stations with high quality data. The southwestern uplands and hills generally have high certainty ratings because of the abundance of data in this area. Certainty ratings of 4 were assigned to grid cells that contain or are adjacent to grid cells that contain stations with representative long-term data. Certainty ratings of 3 were assigned to grid cells with representative data for short (< 2 years) periods of record. (Also, see Section 2.3.1.)

7.1.2 Areal Distribution

The areal distribution of wind power in North Dakota is illustrated in Figure 7.8. Numbers identify the percentage area in each cell of the grid in which the wind power equals or exceeds some threshold value. The Missouri Plateau in southwestern North Dakota and the flat plains of northern and eastern North Dakota are estimated to have class 4 annual average wind power. In the flat plains area, it was estimated, using methods outlined in Section 1.10, that 88 to 100% of the land-surface area in each cell is actually class 4 while in the moderately more complex terrain of the Missouri Plateau it was estimated that only 80% of the land-surface area in each cell is actually class 4 or greater (Figure 7.8). However, it is also estimated that in the high plains of the Missouri Plateau, 5% of the land-surface area actually has class 5 or greater wind power.

Table 7.1 presents the areal distribution of wind power classes in North Dakota. Land-surface area with class 4 wind power is estimated, using methods detailed in Section 1.10, to be about 66% of the total land area. The amount that

would be predicted on the basis of map area alone is 71%, a slight overestimate of the true land-surface area. This slight overestimate is due to the moderately complex terrain of the Missouri Plateau, where some sheltering will occur at low elevations. For the flat terrain of eastern North Dakota, the map area estimate should be a reasonable approximation. (Also, see Section 2.3.1).

7.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 7.9. As with the annual average wind power map, wind power class boundaries are approximate only. Because of the low complexity of the terrain, wind power will vary only slightly over the area of eastern and northeastern North Dakota. Lack of data in this area prevents a more precise delineation of the wind resource than is shown on these maps. Small scale terrain features such as the Missouri and Pembina Escarpment and the Turtle Mountains may increase the wind power on a very local scale.

Although wind power is almost the same for spring and winter throughout the state, winter wind power is slightly greater at locations in the northern part of the state in the Canadian Wind Corridor. Spring has slightly greater wind power throughout the rest of the state. Summer is the season of lowest wind power throughout all of North Dakota.

7.2.1 Winter

During the winter, class 5 average wind power is estimated for northern portions of the Canadian Wind Corridor, and for the hills and uplands of southwestern North Dakota (Figure 7.9). The precise boundary of the large class 5 area in the northeastern part of the state is not certain, although areas close to the Canadian border appear to be more sensitive to periodic southward surges of cold surface air from the Canadian plains. This phenomenon occurs frequently during the winter, when radiational heat loss from these plains causes a shallow high pressure system to develop, with a resulting strong surface pressure gradient.

Class 4 wind power is estimated for areas further southeast and east in the Canadian Wind Corridor. A class 4 area also exists in the transition zone between the class 5 area of southwestern North Dakota and the class 3 areas of the Missouri River and the Little Missouri River Badlands.

During the winter, North Dakota is subject to strong wind episodes that are of relatively short duration. Such episodes can occur when migratory low pressure systems that originate on the lee side of the Rocky Mountains move through this region to the northeast. The surface pressure gradient established is particularly strong when this occurs in conjunction with a surface high pressure system over the Canadian plains, as described above, and two or three times each year this can create blizzards. Consequently, much of the wind power in North Dakota is the result of high winds over short periods of time. One study showed that during one January, nearly 85% of the total output of a 3-kW generator at Grand Forks occurred during three days of blizzard (Krueger 1976). Although this is an extreme example, this fact must be considered in any assessment of the wind resource.

7.2.2 Spring

Most of North Dakota is estimated to have class 4 or higher wind power in the spring. Class 6 areas are found at exposed locations on the Missouri Plateau in southwestern North Dakota. Strong surface winds are generally from the north to northwest during this period.

Class 5 wind power is estimated for most of eastern and northern North Dakota. Data from stations near the Red River indicate that this area may also have class 6 wind power in the spring of some years. Northerly flow is still significant in early spring, although it occurs less frequently than in the winter.

Areas along the Missouri River are estimated to have class 4 wind power, except in the west-central part of the state where the river runs more perpendicular to the strong north and northwesterly winds, and in the sheltered areas of the Little Missouri River Badlands. Class 3 average wind power is estimated for these areas.

7.2.3 Summer

In summer most of the state is estimated to have class 2 average wind power. Class 3 areas may be found at exposed locations on the Missouri Plateau of southwestern North Dakota. Northerly winds are slightly dominant in northwestern North Dakota, e.g., at Williston and Minot. Prevailing winds are south to southeast at most other stations, although strong winds are split between southerly and northerly in the Red River valley.

7.2.4 Autumn

In autumn, the wind pattern is in transition to the winter type of regime. Most of the state is class 4 except for regions of the Missouri River and the Little Missouri River Badlands where increased surface cooling causes cold stable air to collect in low areas. Monthly mean wind speeds are increasing during this season.

7.3 FEATURES OF SELECTED STATIONS

Table 7.2 gives the location and annual wind speed and power density of eleven stations in North Dakota. Graphs of other features of the wind resource are shown in Figures 7.10 to 7.16. These stations are distributed evenly throughout the state. Of the eleven, two are located near the Missouri River in northwestern North Dakota, two are in the north-central part of the state, one is in the rolling hills of southwestern North Dakota, one is near the Missouri River in south-central North Dakota, one is in the flat lands of southeastern North Dakota, one is in northeastern North Dakota away from the Red River, and three are along the Red River that forms the eastern boundary of North Dakota.

Bismarck Airport is located about 3 km (2 mi) southeast of Bismarck, on the east bank of the Missouri River. Hills 5 km (3 mi) to the north and 8 km (5 mi) to the southeast rise 70 to 80 m (230 to 260 ft) higher. Across the river to the west are rolling hills that rise 100 to 200 m (330 to 660 ft) higher than the airport. This site is representative of low elevations near the Missouri River in south-central North Dakota.

Dickinson FAA (Federal Aviation Administration) is located about 8 km (5 mi) south of Dickinson in the high plains of the Missouri Plateau of southwestern North Dakota. The site is on exposed upland well above the Heart River and is representative of exposed sites in southwestern North Dakota.

Fargo (Hector Airport) is located on the Red River in southeastern North Dakota. Although the surrounding terrain is flat, there are indications of mesoscale north-south wind channeling by the Red River Valley. Data from this site, with data from Grand Forks and Pembina, are representative of wind characteristics in this broad and shallow valley that forms the boundary of North Dakota and Minnesota.

Grand Forks FAA is located near the city of Grand Forks by the Red River, about 120 km (75 mi) north of Fargo. With Fargo and Pembina, this site is representative of sites in the Red River valley of eastern North Dakota.

Grand Forks AFB (Air Force Base) is located 15 km (9 mi) west of Grand Forks and the Red River but is still within the Red River valley. This site is representative of exposed locations in eastern North Dakota.

Jamestown FAA is located at the northeastern edge of Jamestown near the Jamestown Reservoir on the James River. About 15 km (9 mi) west of Jamestown the terrain rises gently to about 100 m (300 ft) higher elevation. Jamestown data are representative of the flat country in eastern North Dakota.

Minot AFB is located 20 km (12 mi) north of Minot. The terrain is flat and Minot AFB is most representative of sites in northern North Dakota with good exposure to strong northwesterly surface winds. Fifteen to 30 km (10 to 20 mi) southwest along the Missouri Escarpment, the terrain rises from 100 to 150 m (300 to 500 ft) higher.

Minot International Airport is located on the northern edge of Minot. Just to the southwest the terrain rises up the Missouri Escarpment. With Minot AFB, this site should be representative of locations on the northern North Dakota plains.

Pembina CAA (Civil Aeronautics Administration) is located south of Pembina and 5 to 6 km (3 to 4 mi) south of the Canadian border in extreme northeastern North Dakota. The period of record shown on Table 7.2 is short (less than 2 years). However, data for this period agrees well with summarized data for the period from 1932 to 1938. The site is by the Red River and with Grand Forks and Fargo is representative of sites in the Red River Valley.

Williston WBO (Weather Bureau Office) is located on the shore of Lake Sakakawea, a reservoir on the Missouri River in northwestern North Dakota. During the period from 3/50 to 12/61 this location was in downtown Williston and the low wind speeds recorded for the period shown on Table 7.2 are probably a result of the influence of nearby buildings. Consequently, data from this site is not representative.

Williston/Sloulin International Airport is located at the northwestern edge of Williston, near Lake Sakakawea on the Missouri River. Hills to the east rise 80

to 100 m (250 to 300 ft) higher at a distance of 8 to 10 km (5 to 6 mi). Six kilometers (4 mi) to the south across the Missouri River are bluffs 60 to 70 m (200 to 250 ft) higher. The immediate terrain is flat and although the surrounding rolling hill country may have some sheltering effect, data from this site should be more representative than data from Williston WBO of sites near the Missouri River in northwestern North Dakota.

7.3.1 Interannual Wind Power and Speed

Six stations have selected periods of record of 10 years or more at constant anemometer height and location (Figure 7.10). Because several winter and spring storms of a few days duration increase the average wind power significantly, wind power averages frequently show large variability from year to year and from station to station. All of the North Dakota stations show this large variability to some extent.

Correlation among stations is inconsistent. Grand Forks and Fargo, both located in the Red River Valley, show wind power maxima in 1950 and 1955 and, with Bismarck and Dickinson, show wind power minima in 1952. Bismarck and Minot show high wind power in 1975. On the other hand, Bismarck and Williston show 1977 to be a low wind power year, while Fargo shows 1977 to be a high wind power year. Inconsistencies could be the result of narrow storm tracks that pass over stations that are close together but miss stations farther away.

Conclusions based on interannual variability and trends at individual stations should be treated with caution. In particular, trends indicated for Dickinson, Grand Forks FAA, Grand Forks AFB, and Minot from 1948 to 1958, are questionable.

7.3.2 Monthly Average Wind Power and Speed

All stations show the same general trend to high wind power and speed in winter and spring and low wind power and speed in summer (Figure 7.11). Minot, Minot AFB, and Fargo (6/61 to 12/78) show slightly higher wind power and speed in the winter than in the spring. Data taken at Pembina from 1932 to 1938 (not shown in Figure 7.11) also show a winter maximum. This is possibly because these sites are closer to the northern border of North Dakota and are therefore more sensitive to southward surges of arctic air in the winter. Otherwise, all stations have highest wind power and speed in the spring.

7.3.3 Diurnal Wind Speed by Season

All stations show the same general diurnal trend (Figure 7.12). Maximum wind speeds occur in the afternoon, roughly between 1200 and 1700 LST. The maximum occurs slightly earlier in the winter than in the summer, with maximum variability in the summer and minimum variability in the winter. Uniform diurnal heating/cooling of this low-relief terrain makes this pattern uniform across the state.

7.3.4 Directional Frequency and Average Speed

Prevailing surface wind directions show some terrain influence (Figure 7.13). Fargo, Grand Forks, and Pembina show a tendency to a north-south flow pattern, indicating channeling by the broad, flat Red River valley.

Otherwise, the most frequent wind direction is northwest. Data from Dickinson show west-northwest to be the prevailing direction but shows a larger amount of south to south-easterly flow than is found at other stations, which may indicate that the Missouri Plateau area is more sensitive to the summer southerly flow regime.

Patterns at Williston and Bismarck are not as well defined, though both stations show a trend to northwesterly flow with south to south-easterly flow at Bismarck during the summer.

Bismarck, Dickinson, Minot, and Williston all have maximum wind speed, and hence maximum wind power, during periods of northwesterly winds, with a secondary maximum during south to southeasterly wind periods. Fargo and Pembina have higher average speeds during north wind periods and a sharp peak in the wind speed curve during south-southeasterly flow, again possibly the result of some low-level channeling by the Red River valley.

7.3.5 Annual Average Wind Speed Frequency

Observer biases are evident from peaks at 2, 5, and 8 m/s at stations with older periods of record, e.g., Bismarck (1/48 to 10/61), Dickinson, Fargo (11/53 to 6/61), Grand Forks (11/49 to 12/58), Jamestown, Minot (12/48 to 9/58), Pembina, and Williston WBO (Figure 7.14). Otherwise, wind frequency distributions appear to be reasonably well approximated by the Rayleigh distribution.

7.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed and power is exceeded is shown in Figures 7.15 and 7.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 7.1. Geographic Map of North Dakota

FIGURE 7.2. Topographic Map of North Dakota

FIGURE 7.3. Land-Surface Form Map of North Dakota

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

FIGURE 7.4. NCC Station Locations in North Dakota

FIGURE 7.5. Locations of Stations Used in North Dakota Wind Resource Assessment

FIGURE 7.6. North Dakota Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m^(a)

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

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 7.1 Areal Distribution (km²) of Wind Power Classes in North Dakota

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	17,305	9.6	181,216	100.0
2	7,045	3.9	163,911	90.5
3	37,046	20.4	156,866	86.6
4	118,908	65.6	119,820	66.1
5	<1,000	<1.0	<1,000	<1.0
6	0	0.0	0	0.0
7	0	0.0	0	0.0

FIGURE 7.7. Certainty Rating of North Dakota Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ul style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	<p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ul style="list-style-type: none"> 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	<p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ul style="list-style-type: none"> 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	<p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>

FIGURE 7.8. Areal Distribution of Wind Resource in North Dakota (Power Classes 2 and 3); Percent of Land Area with or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 7.8 (Continued). Areal Distribution of Wind Resource in North Dakota (Power Classes 4 and 5); Percent of Land Area with or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 7.9. Seasonal Average Wind Power in North Dakota (Winter, Summer)

FIGURE 7.9 (Continued). Seasonal Average Wind Power in North Dakota (Spring, Autumn)

TABLE 7.2. North Dakota Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Lat (°N)	Long (°W)	Elevation of Station (m)	Period of Record (month/year)	Anem. Height (m)	Annual Average Speed (m/s)			Annual Average Power (watts/m ²)		
							At Anem Ht	At 10 m	At 50 m	At Anem Ht	At 10 m	At 50 m
Bismarck, North Dakota	Bismarck Airport	46.77	100.75	507	1/48-10/61	13.1	4.9	4.8	6.4	161	154	370
Bismarck, North Dakota	Bismarck Airport	46.77	100.75	507	10/61-12/78	6.1	4.4	4.7	5.9	122	150	301
Dickinson, North Dakota	Dickinson FAA	46.78	102.80	792	12/48-7/64	9.1	6.1	6.2	7.8	250	259	518
Fargo, North Dakota	Fargo, Hector Airport	46.90	96.80	278	11/53-6/61	26.2	6.7	5.9	7.4	340	224	448
Fargo, North Dakota	Fargo, Hector Airport	46.90	96.80	278	6/61-12/78	6.1	5.3	5.6	7.1	165	203	407
Grand Forks, North Dakota	Grand Forks FAA	47.93	97.08	259	11/49-12/58	14.3	6.0	5.7	7.2	299	256	511
Grand Forks, North Dakota	Grand Forks AFB	47.97	97.40	276	5/60-11/68	4.6	4.6	5.1	6.4	139	194	387
Jamestown, North Dakota	Jamestown FAA	46.92	98.68	456	12/48-12/54	8.8	5.4	5.5	6.9	226	238	475
Minot AFB	Minot AFB	48.42	101.33	504	5/60-2/65	5.5	4.6	5.0	6.3	138	178	356
Minot AFB	Minot AFB	48.42	101.35	497	4/65-11/68	5.2 ^(b)	4.6	5.1	6.4	145	192	383
Minot, North Dakota	Minot International Airport	48.27	101.28	526	12/48-9/58	6.4	5.5	5.8	7.4	194	234	468
Minot, North Dakota	Minot International Airport	48.27	101.28	526	6/62-12/78	6.1	5.6	6.0	7.5	175	216	431
Pembina, North Dakota	Pembina CAA	48.95	97.25	242	12/48-9/50	13.7	6.0	5.8	7.2	279	243	486
Williston, North Dakota	Williston WBO ^(c)	48.15	103.62	581	3/50-12/61	15.2	3.8	3.6	4.5	68	56	113
Williston, North Dakota	Williston, Slioulin International Airport	48.18	103.63	581	8/67-12/78	6.1	4.5	4.8	6.1	117	144	288

(a) FAA-Federal Aeronautics Administration Facility; AFB-Air Force Base; CAA-Civil Aeronautics Administration Facility; WBO-Weather Bureau Office

(b) Anemometer height is approximate.

(c) Station had only 12 to 18 observations per day.

FIGURE 7.10. Interannual Wind Power and Speed for North Dakota

FIGURE 7.11. Monthly Average Wind Power and Speed for North Dakota

FIGURE 7.12. Diurnal Wind Speed by Season for North Dakota

FIGURE 7.13. Directional Frequency and Average Wind Speed for North Dakota

----- ACTUAL DISTRIBUTION ORDINATE -- PERCENT
 RAYLEIGH DISTRIBUTION ABSCISSA -- M/S
 PNL-3195 WERA-2

FIGURE 7.14. Annual Average Wind Speed Frequency for North Dakota

ORDINATE - PERCENT
ABSCISSA - M/S

PNL-3195 WERA-2

FIGURE 7.15. Annual Average Wind Speed Duration for North Dakota

ORDINATE -- PERCENT
ABSCISSA -- WATTS/M²
PNL-3195 WERA-2

FIGURE 7.16. Annual Average Wind Power Duration for North Dakota

SOUTH DAKOTA

CHAPTER 8: SOUTH DAKOTA

South Dakota covers an area of 199,653 km² (77,047 mi²) and had a population in 1977 of 688,000 (Statistical Abstracts, 100th edition, 1979). The population is mostly rural with only 72,488 people living in the largest city, Sioux Falls, and 43,836 people living in the second largest city, Rapid City. Western South Dakota, excluding Rapid City and the perimeter of the Black Hills, is very sparsely populated. A cultural geographic map of the state is shown in Figure 8.1.

Terrain in South Dakota varies from flat and irregular plains in the east to open hills and tablelands in the west (Figures 8.2, 8.3). The flat plains in the eastern half of the state are the result of glaciation. The Prairie Coteau in north-eastern South Dakota is an upland area of glaciated irregular plains that is bounded on the east and west by slightly higher ridges to form a low elevated basin. This feature appears on the topographic relief map (Figure 8.2) as a northward-pointing wedge. Just to the east of the northern tip of the Prairie Coteau, on the Minnesota border near Lake Traverse, is a flat area that divides the drainages of the north-flowing Red River and the southeast-flowing Minnesota River. The area around Aberdeen is the bed of an ancient lake, Lake Dakota.

Higher relief is found in western South Dakota west of the Missouri River on the Missouri Plateau (Figure 8.1). This high plains area is generally rolling to hilly plains, with the exception of the Badlands National Park area and the Black Hills. The Black Hills area is the only mountainous area in the North Central region, with elevations from 1,200 m (4,000 ft) to over 2,100 m (7,000 ft) on the highest peaks.

Wind data are sparse throughout South Dakota (Figures 8.4, 8.5). There are 17 fire weather stations in the state, most of these in and around the Black Hills. Only four of these show annual wind power averages greater than 100 watts/m². All of these have wind data for only one time of day, about 1400 LST. Three have no winter data and one has no summer data. Most of the data on which the South Dakota analysis is based were taken from the archives of the National Climatic Center (NCC).

8.1 ANNUAL AVERAGE WIND POWER

The average annual wind power density in South Dakota is shown in Figure 8.6. This analysis of mean wind power applies to terrain features that are favorably exposed to the wind, such as ridge crests, hill-

tops, and uplands (see Section 1.6). However, nearby terrain features may interact with the windfield to cause the wind power at some exposed sites to vary as much as ± 50 to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The annual average wind power is estimated to be class 4 throughout most of South Dakota (Figure 8.6). It should be noted that wind power class estimates for South Dakota are based on inferences made from very sparse data. Because of this, the delineation of wind power class boundaries shown in Figures 8.6 and 8.9 are tentative and, especially in the flat terrain of eastern South Dakota, somewhat arbitrary.

The large class 4 area in the western half encompasses most of rolling and hilly plains west of the Missouri River. Strongest winds in this area are primarily from the northwest to north-northwest and are associated with strong winds aloft. The class 4 designation refers to exposed sites on hill and ridge tops. There is probably less wind power in more sheltered river valleys along the Grand, Moreau, Cheyenne, and White rivers. The class 3 area just north of the Black Hills comprises the Belle Fourche River Valley.

At Rapid City and Philip, data show significantly higher average wind speeds during north and northwest flow periods, as compared to wind speeds during flow from other directions. Wind speeds during north and northwest flow periods are also higher than wind speeds during northerly flow periods at other sites farther east. This is apparently a result of acceleration of northwesterly flow as it is diverted to the east of the Black Hills.

The shaded area in the Black Hills represents ridge crest estimates. Class 4 wind power is assigned to this area but represents only sites at well-exposed locations, i.e. ridge crests and mountaintops. A small class 5 area exists in the center of this area where elevations are the highest.

Northeastern South Dakota is also mostly class 4. Winds in this area are largely driven by strong winds aloft, but are also enhanced because of the low surface roughness of the area.

There is some evidence, based on data from Milbank, Brookings, Huron, Aberdeen, Worthington, Minnesota, and Willmar, Minnesota, that annual average wind power increases in an easterly direction through northeastern South Dakota into western Minnesota. In the vicinity of Lake Traverse on the Minnesota border, there is a division between the northward drainage of the Red River and the southward drainage of the Minnesota River. Two years of data from a site near Milbank indicate that there may be some acceleration of air as it flows over this divide during northerly flow periods. This suggestion is based on limited data, and is therefore, highly tentative, and requires additional data for verification.

The inclusion of the area near Pierre, within the class 4 area, is based on the fact that this station shows a very high 10 m-adjusted mean wind speed for the longest and most recent period of record, although the mean annual wind power density is not as high as others in the state (see Table 8.2).

8.1.1 Certainty Rating of the Wind Resource

Certainty ratings for the annual average wind power estimates in South Dakota are shown in Figure 8.7. Lowest certainty ratings were given to grid cells in the western two-thirds of the state, where data are sparse. Certainty ratings of 2 were given to grid cells that have no stations with data but which have simple terrain. This includes most of the area of the state. Certainty ratings of 1 were given to grid cells that have no data and which are composed of more complex terrain.

Highest certainty ratings were given to grid cells that contain or are adjacent to grid cells that contain stations with representative data. In general, certainty ratings of 4 were given to cells with long-term representative data and certainty ratings of 3 were given to grid cells with short-term data or data based on less than 24 observations per day. Highest certainty ratings are found in the flat terrain of eastern South Dakota. (Also, see Section 2.3.1.)

8.1.2 Areal Distribution

The areal distribution of wind power in South Dakota is illustrated in Figure 8.8. Numbers identify the percentage area in each cell of the grid in which the wind power equals or exceeds some threshold value. Class 4 annual wind power is found in most of western South Dakota and in northeastern South Dakota. In the flat

terrain of northeast South Dakota, 80 to 100% of the land area in individual cells is estimated to have the wind power assigned to that cell, while in the relatively more complex terrain of western South Dakota outside of the Black Hills this value ranges from 35 to 92%. In the Black Hills, a class 4 area, only 5% of the total land area is actually class 4. This is because most of this mountainous terrain is on steep sheltered slopes. Near the western North Dakota border, 5% of the land area is estimated to have greater wind power than is typical for that area, i.e., wind power of class 5 or greater.

Table 8.1 presents the areal distribution of wind power classes in South Dakota. Land-surface area with class 4 wind power is about 53% of the total land area. The amount that would be predicted on the basis of map area alone is 71%. Thus, using map area alone, the amount of actual land-surface area having high wind power is over-estimated, a consequence of the high-relief terrain of the Black Hills and the moderately complex terrain of the Missouri Plateau. (Also, see Section 2.3.2.)

8.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 8.9. Winter is the season of maximum wind power on the ridge crests of the Black Hills where the windiest sites are those that are well exposed to strong winds at high elevations. One site in northeastern South Dakota near Milbank also shows maximum wind power in the winter, although this is not indicated on the seasonal maps (see Section 8.2.1). Otherwise, spring is the maximum wind power season throughout the state. Summer is the season of low wind power throughout all of South Dakota.

8.2.1 Winter

In winter, upper-air winds are generally from the northwest and upper-air mean wind speeds are the highest of the year. Black Hills ridge crests and mountain-tops are well exposed to these winds and have class 6 wind power with class 7 wind power at the very highest summits.

A class 5 area covers much of the west-central and northwestern part of the state and represents exposed sites, such as hilltops and uplands. Prevailing winds are northwesterly and strongest winds are west to north-northwest. Close to the Black Hills strong winds are more northerly than farther east. These winds are driven primarily by strong winds aloft.

Most of the rest of South Dakota west of the Missouri River is estimated to have class 4 wind power except for areas near the Missouri River and south of the Black Hills. Areas of low elevation are subject to periodic stagnation of low-lying stable air that shields them from the influence of strong winds at higher altitudes.

Most of eastern South Dakota is estimated to have class 4 wind power. Prevailing winds are north to west-northwest, and southerly winds are more frequent than in western South Dakota. Strongest winds are north to northwest, partly the result of strong winds aloft and partly the result of periodic southward surges of arctic air, although the main path of such air appears to cut eastward across southwestern Minnesota. Blizzards occur with less frequency in South Dakota than in North Dakota or western Minnesota.

Two years of wind data from the Big Stone Power Plant in northeastern South Dakota near Milbank show higher wind power in winter than in any other season, with strongest winds from the southwest to northwest. This site is located near the north-south divide between the Red River and Minnesota River drainages. Surface winds blowing over this divide may be subjected to some acceleration. Although this possible acceleration effect would be small because of the small elevation differences involved, it could be significant in terms of average wind power because of the sensitivity of wind power to small changes in wind speed at high speeds.

Southeastern South Dakota and areas near the Missouri River in north-central South Dakota are estimated to have class 3 wind power in the winter. There is a small area of class 2 wind power on the Missouri River where the river forms the border between South Dakota and Nebraska.

8.2.2 Spring

In spring, nearly all of South Dakota is estimated to have class 4 or higher wind power and most of this is class 5. Ridge crests of the Black Hills are estimated to be class 4. Exposed hill tops in western South Dakota, west of the Missouri River, are estimated to be class 5 and class 6 except for the protected areas near the Belle Fourche River and south of the Black Hills, which are estimated to have class 4 wind power. Except for extreme southeastern South Dakota and low areas near the Missouri River in north-central South Dakota, all of eastern South Dakota is estimated to have class 5 wind power in the spring.

Prevailing and strongest winds are still northwesterly in this season although there is an increasing frequency of south to southeast winds, particularly in the eastern half. Winds near the Black Hills foothills are mostly northerly. Surface winds in this season are driven primarily by strong winds aloft.

8.2.3 Summer

Almost all of South Dakota is estimated to have class 2 or lower wind power in the summer. Exceptions are found at exposed locations in the northwestern part of the state and near the Nebraska border in the southwestern part of the state. Prevailing surface winds in this season are generally south to southeast with a higher frequency of north winds in the west half of the state. Strongest winds are from the south in the east half of South Dakota and north-northwest in the west half.

8.2.4 Autumn

In autumn, class 4 wind power is found on exposed hill tops on the Missouri Plateau of western South Dakota and in extreme northeastern South Dakota. All of the rest of South Dakota is estimated to have class 3 wind power except for sheltered areas south of the Black Hills and along the Missouri River in southeastern South Dakota. In this season, low areas are becoming increasingly subject to stable surface conditions typical of winter.

Autumn is the season of transition from the southerly wind regime to the northerly winter regime. Surface winds are shifting from a south-prevailing direction to a north-prevailing direction. Strongest winds are west-northwest in eastern South Dakota and north-northwest in western South Dakota.

8.3 FEATURES OF SELECTED STATIONS

Table 8.2 gives the location and annual wind speed and power density of nine stations in South Dakota. Graphs of other features of the wind resource are shown in Figures 8.10 to 8.16. Three of these stations are located near the Black Hills of western South Dakota, one is on the hilly Missouri Plateau of western South Dakota, one is by the Missouri River in central South Dakota, two are in the flat country of eastern South Dakota, one is on the Prairie Coteau of northeastern South Dakota, and one is in the flat country in extreme southeastern South Dakota.

Aberdeen Airport is located 3 km (2 mi) east of Aberdeen at the northern edge of the ancient glacial Lake Dakota. Because of the flatness of this area, exposure at this site is excellent and appears to be representative of most of northeastern South Dakota.

Huron Airport is located north of Huron in east-central South Dakota. This area is also quite flat with excellent exposure. As with Aberdeen, data from this site should be representative of this part of the state. Huron is about 130 km (80 mi) south of Aberdeen and the two stations lie in the broad flat James River Valley.

Philip Airport is located 5 km (3 mi) east of Philip on the South Fork of the Bad River in western South Dakota. The terrain in this area is hilly plains, typical of the Missouri Plateau. The airport is located at a point well above the Bad River drainage and has good exposure, so that this site is representative of well-exposed sites in this area between the Black Hills and the Missouri River. There is evidence of some diversion of light southerly winds to a more easterly direction (see Section 8.3.4).

Pierre Airport is located 3 km (2 mi) northeast of Pierre near the Missouri River, near the exact center of the state. The site is on level terrain 80 m (270 ft) above the river bottom, with level land to the northeast and gradually rising land to the west and south across the river. It is representative of sites in South Dakota near and east of this part of the Missouri River.

Three sites in the Rapid City area were used in the assessment. Old Rapid City Municipal Airport is located near the present site of Ellsworth AFB (Air Force Base). Rapid City Regional Airport is located 8 to 10 km (5 mi) east-southeast of Rapid City on the north slope of the Rapid Creek valley. An east-west ridge some 50 m (150 to 200 ft) higher is located 3 km (2 mi) to the north and a comparison of this site with Ellsworth AFB 8 km (5 mi) north indicates there may be some shifting of light southerly winds to a more south-easterly direction. Otherwise, the two sites, Rapid City Regional Airport (11/65 to 12/78) and Rapid City/Ellsworth AFB (7/55 to 12/70), show no significant differences. Rapid City/Ellsworth AFB is located 8 km (5 mi) east-northeast of Rapid City on top of a ridge that slopes upward to the Black Hills foothills 15 (10 mi) west.

This area is unique in the North Central region because of its proximity to the

Black Hills mountain range. The three Rapid City sites are about 15 km (10 mi) from the foothills and Chinook winds appear to blow from the northwest in this local area. Data from these sites should be representative of exposed locations in the upland country to the east. These sites also show the highest wind power averages among the stations listed in this section.

Sioux Falls/Foss Field is located on the northern edge of Sioux Falls, in the Big Sioux River Valley of southeastern South Dakota. Although the airport is near the river, the surrounding terrain is level to gently rolling, with a gradual rise to the north and east. Local terrain effects are slight and this site should be generally representative of exposed sites in southeastern South Dakota.

Watertown Airport is located 3 km (2 mi) northwest of Watertown on the Prairie Coteau in northeast South Dakota. The terrain in the vicinity is irregular but generally level. This plateau area, roughly 80 km (50 mi) wide and 160 km (100 mi) long, is 100 to 150 m (300 to 500 ft) higher than surrounding country to the west and east. This site has good exposure and is representative of locations on the Prairie Coteau.

8.3.1 Interannual Wind Power and Speed

Six of the stations have periods of record of ten years or longer at constant anemometer height and location (Figure 8.10). Correlation among stations is good for some years, e.g., most stations with data show peaks in 1955, 1967, and 1975, and minima in 1952 and 1970. There are some contradictions, however. For example, 1967 was a peak year for all stations except Sioux Falls, which shows a minimum for this year. In general, stations in proximity show good correlation, e.g., Rapid City and Rapid City/Ellsworth, and Huron and Aberdeen.

Long-term trends such as the decreasing trend at Huron and the increasing trend at Sioux Falls should be treated with caution. In general, long-term averages appear to be nearly steady.

8.3.2 Monthly Average Wind Power and Speed

All stations show spring to be the season of maximum wind power and speed and summer the season of low wind power and speed (Figure 8.11). There is a trend to a secondary maximum in winter, although in most cases this maximum is not well defined. Watertown shows nearly equal wind power averages in fall (204 watts/m²) and winter (200 watts/m²).

8.3.3 Diurnal Wind Speed by Season

Diurnal wind speed patterns are consistent throughout the state (Figure 8.12). All stations show maximum wind speeds in the afternoon from 1200 to 1700 LST, earlier in the winter than in the spring and summer. Maximum diurnal variation occurs in the summer and minimum variation in the winter.

Because of the low relief of terrain in most of the state and uniform diurnal surface heating, there is little variation in this pattern. Exceptions may occur at locations in the Black Hills, e.g., locations having drainage winds, but data in this area are sparse. There is some evidence of drainage winds at Edgemont in the southern Black Hills but this site is sheltered. Data from this site are not representative of patterns at sites with high wind power potential.

8.3.4 Directional Frequency and Average Speed

Generally, there is a trend to bimodal wind direction frequencies, with northerly winds in winter and southerly winds in summer (Figure 8.13). Stations on the Missouri Plateau in the western part of the state (Rapid City, Philip, Pierre from 12/53 to 7/60) show a higher frequency of northerly winds than do stations in the eastern part of the state, especially Rapid City. Philip shows a higher frequency of easterly winds than southerly winds but has higher average speeds for southerly winds than easterly winds, indicating there may be some terrain diversion of light southerly winds to a more easterly direction, but no such diversion for high speed southerly winds.

Highest wind speeds tend to occur during northerly winds, especially at stations in the western part of the state. Rapid City in particular shows much higher speeds during northerly winds, possibly a result of compression of south-flowing air as it is diverted by the Black Hills.

8.3.5 Annual Average Wind Speed Frequency

Observer biases are apparent at 2, 5, and 8 m/s at stations with older periods of record, Aberdeen (6/50 to 12/54), Huron (1/40 to 1/62), Philip, Rapid City (1/48 to 10/50, 11/50 to 12/64), Sioux Falls (1/48 to 4/56) and Watertown (Figure 8.14).

Rapid City/Ellsworth AFB shows a high frequency of calms. If this is a real phenomenon, wind speed frequency distributions are not well approximated by the Rayleigh distribution at this site. However, data from the two other Rapid City sites contradict this high frequency of calms.

For all other stations, the Rayleigh distribution approximates the actual distribution reasonably well.

8.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 8.15 and 8.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 8.1. Geographic Map of South Dakota

FIGURE 8.2. Topographic Map of South Dakota

FIGURE 8.3. Land-Surface Form Map for South Dakota

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

FIGURE 8.4. NCC Station Locations in South Dakota

FIGURE 8.5. Locations of Stations Used in South Dakota Wind Resource Assessment

FIGURE 8.6. South Dakota Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m^(a)

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

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 8.1 Areal Distribution (km²) of Wind Power Classes in South Dakota

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	24,088	12.2	197,159	100.0
2	19,250	9.8	173,071	87.8
3	48,799	24.8	153,821	78.0
4	104,540	53.0	105,023	53.3
5	<500	<1.0	<500	<1.0
6	0	0.0	0	0.0
7	0	0.0	0	0.0

FIGURE 8.7. Certainty Rating of South Dakota Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	<p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	<p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	<p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>

FIGURE 8.3. Areal Distribution of Wind Resource in South Dakota (Power Class 2 and 3); Percent of Land Area with or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 8.8 (Continued). Areal Distribution of Wind Resource in South Dakota (Power Classes 4 and 5); Percent of Land Area with or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 8.9. Seasonal Average Wind Power in South Dakota (Winter, Summer)

FIGURE 8.9 (Continued). Seasonal Average Wind Power in South Dakota (Spring, Autumn)

TABLE 8.2. South Dakota Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Lat. (°N)	Long. (°W)	Elevation of Station (m)	Period of Record (month/year)	Anem. Height (m)	Annual Average Speed (m/s)			Annual Average Power (watts/m ²)		
							At Anem Ht	At 10 m	At 50 m	At Anem Ht	At 10 m	At 50 m
Aberdeen, South Dakota	Aberdeen Airport	45.45	98.43	396	6/50-12/54	10.7	5.5	5.4	6.8	222	215	430
Aberdeen, South Dakota	Aberdeen Airport	45.45	98.43	396	7/64-12/78	6.1	5.0	5.4	6.8	149	184	367
Huron, South Dakota	Huron Airport	44.38	98.22	392	1/40-1/62	12.5	5.5	5.3	6.6	201	182	364
Huron, South Dakota	Huron Airport	44.38	98.22	392	1/62-12/78	6.1	5.1	5.5	7.0	156	192	384
Philip, South Dakota	Philip Airport	44.05	101.60	673	1/48-12/54	8.2	5.1	5.2	6.6	186	202	403
Pierre, South Dakota	Pierre Airport	44.38	100.28	525	12/53-7/60	20.1	5.2	4.7	6.0	219	162	324
Pierre, South Dakota	Pierre Airport	44.38	100.28	525	6/62-12/78	6.1	5.2	5.6	7.0	162	200	399
Rapid City, South Dakota	Old Rapid City Municipal Airport	44.15	103.10	981	1/48-10/50	19.2	6.4	5.9	7.4	393	297	592
Rapid City, South Dakota	Rapid City Regional Airport	44.05	103.07	966	11/50-12/64	9.8	5.0	5.0	6.3	184	185	371
Rapid City, South Dakota	Rapid City Regional Airport	44.05	103.07	966	11/65-12/78	6.4	5.1	5.4	6.8	196	237	473
Rapid City, South Dakota	Rapid City/ Ellsworth AFB	44.15	103.10	980	7/55-12/70	4.0	4.2	4.8	6.1	149	221	442
Sioux Falls, South Dakota	^(b) Sioux Falls/ Foss Field	43.57	96.73	437	1/48-4/56	16.5	5.0	4.7	5.9	171	138	275
Sioux Falls, South Dakota	Sioux Falls/ Foss Field	43.57	96.73	437	11/61-12/78	5.2	5.0	5.5	7.0	140	185	370
Watertown, South Dakota	Watertown Airport	44.92	97.15	527	9/48-12/54	7.6	5.1	5.3	6.6	190	213	426

^(a) AFB-Air Force Base

^(b) Winds from the southeast through southwest are considered to be unrepresentative.

FIGURE 8.10. Interannual Wind Power and Speed for South Dakota

FIGURE 8.11. Monthly Average Wind Power and Speed for South Dakota

FIGURE 8.12. Diurnal Wind Speed by Season for South Dakota

FIGURE 8.13. Directional Frequency and Average Wind Speed for South Dakota

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FIGURE 8.14. Annual Average Wind Speed Frequency for South Dakota

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FIGURE 8.15. Annual Average Wind Speed Duration for South Dakota

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FIGURE 8.16. Annual Average Wind Power Duration for South Dakota

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