Wind Energy Resource Atlas: Volume 5 - The East Central Region

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WIND ENERGY RESOURCE ATLAS:
Volume 5 - The East Central Region

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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 experience 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 time of year and time of day, respectively, the wind resource is available. 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 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 period of record for 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.

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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 East Central region wind resource, 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 one of 12 such atlases that will be assembled. The other atlases will describe the potential wind resource in 11 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 East Central region atlas in a timely fashion, only existing relevant data were used. The other atlases use comparable data sets, analysis techniques, and presentations to ensure the comparability of the wind resource assessments.

The East Central region atlas assimilates eight collections of wind resource data: one for the region and one for each of the five states (Delaware, Maryland, North Carolina, Tennessee, and West Virginia) and two commonwealths (Kentucky and Virginia) that compose the East Central region. The assessments for Delaware and Maryland are presented together. 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 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 Brode and Stoner (1980).] However, this discussion will provide the reader with useful background information for inter-

FIGURE 1.1. Geographic Divisions for Regional Wind Energy Assessments

preting the wind energy resource maps for the East Central region.

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, existing and proposed nuclear and fossil-fueled power plant sites, DOE candidate wind turbine sites, and other government and private organizations. The NCC 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.] Table 1.1 indicates the number of stations with wind data in these various formats in the East Central region.

Conventional NCC surface weather data in coastal areas were supplemented by monthly mean wind speeds summarized over one-degree latitude by one-degree longitude squares for the East Coast in the Climatic Study of the Near Coastal Zone (National Weather Surface Detachment 1976). Wind summaries at the 150-m and 300-m levels above the surface (Wind Aloft Summaries, NCC 1970) for five sites in the East Central region supplemented the upper-air wind climatology compiled by Crutcher (1959) for the northern hemisphere.

In contrast to the NCC data, which are primarily from inhabited areas, U.S. Forest Service data in the National Fire Weather Data Library (NFWDL) (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). A total of 62 stations with wind data are reported in the NFWDL for the East 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. Additional problems with the data set have limited the number of stations for which data have been screened to 29. Elevations could not be obtained for several of the stations, and data for stations in Kentucky and Virginia could not be obtained because of damage to the data tape.

Annual wind data from 15 existing or potential nuclear power plant sites in the East Central region have been summarized by Verholek (1977). Wind data sets for numerous fossil-fueled power plants were also identified. A computer search was performed on the Environmental Data Base Directory (EDBD) of the National Oceanic and Atmospheric Administration (NOAA) which identified 66 sources of wind data in the East Central region. Data sets identified in the EDBD were mostly from university research projects and private organizations. Information for each entry included a description of the purpose for which the data were collected, data format and availability, frequency and amount of data, data location, and a contact for obtaining additional information. State and local air pollution control agencies and state climatology offices were also contacted as part of a telephone survey to identify additional sources of wind data.

1.2 WIND DATA SCREENING

Table 1.1 indicates the quantity of wind data available in the East Central region. However, not all of these data need to, or

TABLE 1.1. Stations with Wind Data in the East Central Region Screened in Assessment

Source and Type	Screened	Retained
National Climatic Center		
Digitized	86	82
Summarized	140	96
Unsummarized	142	35
National Fire Weather Data Library	29	2
Nuclear & Fossil-Fueled Power Plant	25	4
Other (University Research, etc.)	66	5

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 source.

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.

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. Consideration was also given to changes in a station's location from one summary period to another since substantial changes in exposure to the prevailing strong winds could occur in such cases.

The screening of unsummarized wind data available at the NCC identified those stations for which no digitized or summarized data were available. In order to maximize the usefulness of unsummarized data obtained from the assessment, these stations were assigned a priority rating based on the sparsity of digitized or summarized data in the area, the level of wind power potential expected for the area, and available information on anemometer height history, frequency of observations and instrument and site exposure. Only data for those stations receiving the highest priority rating were obtained for use in the assessment.

Data obtained from the NFWDL proved to be of only limited usefulness in the resource assessment for the East Central region. Seasonal and annual mean wind speeds for stations in the NFWDL were generally found to be less than 3.0 m/s (wind power less than 50 watts/m²). Detailed information on site and instrument exposures and measurement procedures for NFWDL stations is not available. However, it is thought that high surface roughness from trees in the vicinity of the wind instruments, is

likely to account for the low observed wind speeds.

A substantial number of wind data locations exist for the East Central region which are not reflected in Table 1.1. Data from university research projects, private organizations, and government agencies other than the NCC frequently exist in a format which is not suitable for an assessment of this scope, either as unreduced strip-chart records or as partial compilations of hourly data records collected for very specialized purposes. Quality assurance procedures, such as instrument maintenance and calibration and data verification, are often inadequate and not well defined for these projects, introducing additional limitations on their usefulness in assessing the regional wind energy resource. These considerations, as well as the exposure of sites to the prevailing strong winds and the availability of nearby NCC digitized or summarized data, were the major factors taken into account in screening these data sources.

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

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

c = the number of wind speed classes

f_j = frequency of occurrence of winds in the j class

V_j = the median wind speed of the j class.

In those cases for which unsummarized wind data were assessed, the seasonal and annual average speeds, V , were estimated from a visual examination of one year's original weather records. In certain cases, a more objective estimate of seasonal and annual average wind speeds was obtained to compute averages based on every third observation over a one-month period from each season. This was done only for those stations which showed high wind energy potential based on spot examination and which recorded at least eight observations per day distributed throughout the diurnal cycle. In

addition, some station records were on the Form 1001A, which often reports monthly mean wind speeds computed from all available hourly observations. In such cases, the seasonal and annual mean wind speeds were computed based on the reported monthly mean speeds. The wind power density, P , was then estimated by assuming the speed frequency distribution followed a Rayleigh distribution (Cliff 1977):

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

For stations with summarized or unsummarized wind data used in the assessment for the East Central region, the mean air density in Equations 2 and 3 was determined from climatological information on seasonal and annual mean station temperatures and mean sea-level pressure. Where appropriate climatological data were not available, the mean air density was calculated as a function only of station elevation, z , by

$$\bar{\rho} = 1.225 - (1.194 \times 10^{-4}) z \quad (4)$$

which approximates the U.S. Standard Atmosphere profile for density (NOAA 1976). The former method, while only an approximation of mean density, has the advantage of incorporating the seasonal variation of air density in the calculation of wind power.

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 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 mountains made use of the northern hemisphere upper-air wind climatologies for the 850- and 700-mb constant pressure levels by Crutcher (1959) and the climatology of pressure heights by Ratner (1958). 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 mountainous areas, the mean ridge crest or mountain summit elevation and appropriate constant pressure surface mean wind speeds and pressure heights were estimated. Seasonal mean wind speeds and pressure heights were estimated from the available climatologies and were used to calculate the annual mean wind speeds and pressure heights. 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.

These estimates are considered lower limits for exposed ridge crests and mountain summits. Local terrain features in these mountainous regions can enhance the wind power considerably. However, a major uncertainty in 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 low-level rawinsonde winds).

Wherever possible, these estimates were compared with surface data from ridge crests and mountain summits. Over some of the mountainous areas, the estimates were adjusted based on the location of the upper-air recording station and/or the surface data from ridge crests.

1.5 QUALITATIVE WIND INDICATORS

Although some 224 stations provided the wind resource assessment in the East Central region, these stations were not uniformly distributed. The station location figures for each state show that most NCC stations are located in populated areas and along transportation corridors. Large areas in the East Central region are devoid of any form of quantitative wind data suit-

able for this assessment, such as eastern Kentucky, south central Tennessee, central West Virginia, and central North Carolina. Furthermore, in areas of complex terrain, most observation sites are confined to valley locations, and the mesoscale features of the wind flow in coastal areas are not adequately described by the existing distribution of data locations. To evaluate the distribution of the wind resource in data-sparse areas, qualitative indicators of the wind speed or power were developed for, and employed 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 are:

- gaps, passes, and gorges in areas of frequent strong pressure gradients
- long valleys extending down from mountain ranges
- high elevation plains and plateaus
- plains and valleys with persistent strong downslope winds associated with strong pressure gradients
- 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 are:

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

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 (the shaded areas on the maps) are lower limits to the wind power expected at exposed sites. In such areas, 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 also 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%/1000 m elevation (1%/1000 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 East 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 six square 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" indicates that the maximum local

difference in elevation is 100 to 150 m (300 to 500 ft); and the "a" indicates 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 East Central region. For example, the 37% for open hills is an average for C2 through C4. The average percentage of land area that is designated as exposed terrain ranges from 92% in smooth plains to 3% in mountainous areas 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 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 rat-

ings for the wind resource assessment are defined as follows:

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: <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	A low-intermediate degree of certainty. One of the following conditions exists: <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	A high-intermediate degree of certainty. One of the following conditions exists: <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	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 experiencing 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 the 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 experience 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 (Elliott and Barchet 1980).

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 wind power density classes 2, 3, 4, and 5 (see Table 1.3).

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; B1,2	Plains	92
Plains with Hills: A, B3a,b	Open Plains	78
Plains with Mountains: B4-6a,b	Plains (not shaded) ^(b)	70
	Ridge Crests and Mountain Summits (shaded)	5
Tablelands: B3-6c,d	Tablelands, Uplands	82
Open Hills: C2-4	Hilltops and Uplands	37
Open Mountains: C5-6	Broad Valleys (not shaded)	68
	Ridge Crests and Mountain Summits (shaded)	10
Hills: D3-4	Hilltops and Uplands	5
Mountains: D5-6	Ridge Crests and Mountain Summits (shaded)	3

(a)Percentage represents an average over the land-surface forms found in the East Central region (Brode and Stoner 1980).

(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 ³	Speed, ^(b) m/s(mph)	Wind Power Density watts/m ²	Speed, ^(b) m/s(mph)
1	0	0	0	0
2	100	4.4(9.8)	200	5.6(12.5)
3	150	5.1(11.5)	300	6.4(14.3)
4	200	5.6(12.5)	400	7.0(15.7)
5	250	6.0(13.4)	500	7.5(16.8)
6	300	6.4(14.3)	600	8.0(17.9)
7	400	7.0(15.7)	800	8.8(19.7)
	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 Land-Surface Form 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

The features that are addressed in the description of the wind energy resource in the East Central region include geography, climate, and annual average and seasonal wind power. These features are considered for each state using the methods outlined in Chapter 1. Assessments for each state were combined to depict the wind energy resource potentially available in the East Central region. This regional assessment is summarized here. The descriptions of the regional features are followed by discussions of the areas of the East Central region that appear to have the greatest wind resource potential.

2.1 GEOGRAPHY AND TOPOGRAPHY

The East Central region, consisting of Delaware, Kentucky, Maryland, North Carolina, Tennessee, Virginia, and West Virginia covers 549,666 km² (212,227 mi²) and had a total population of 23,098,826 in 1970 (see Table 2.1). North Carolina, Virginia, and Maryland account for nearly 60% of the population of which most reside in the Mid-Atlantic Lowlands. The major cities, rivers, mountain ranges, and national parks are shown in Figure 2.1.

TABLE 2.1. Land Area and 1970 Population of the East Central Region

State	Area		Population in 1970	Population	
	km ²	(mi ²)		Per km ²	(mi ²)
Delaware	5,328	(2,057)	548,104	102.9	(266.5)
Maryland	27,394	(10,577)	3,923,897	143.2	(371.0)
Kentucky	104,623	(40,395)	3,220,711	30.8	(79.7)
N. Carolina	136,197	(52,586)	5,084,411	37.3	(96.7)
Tennessee	109,411	(42,244)	3,926,018	35.9	(92.9)
Virginia	104,084	(40,817)	4,651,448	44.7	(114.0)
W. Virginia	62,629	(24,181)	1,744,237	27.9	(72.4)
East Central	549,666	(212,227)	23,098,826	42.0	(108.8)

The topography varies from rolling hills in the west to forested mountain ridges in the central portion to relatively flat coastal plains in the east (see Figures 2.2, 2.3). The mountain ridges are oriented in a northeast-southwest direction.

2.2 CLIMATE

The mountain ridges are oriented approximately perpendicular to the mean wind flow over the area. The ridges affect the movement of weather systems but not as dramatically as do the mountains of the western United States.

The climate of the interior plains is predominantly of the continental type, varying with latitude. Cool to cold winters, hot summers and large extremes of temperature are characteristic of the interior plains. While weather conditions are generally pleasant, violent local storms are experienced during the warm seasons of the year. These local storms include thunderstorms, tornadoes, and hail storms. During the winter, cold polar outbreaks occur, bringing short periods of very cold weather.

The Appalachian Mountains have heavy rainfall on their western slopes during the summer months and heavy snow during the winter. Movement of large scale storm systems can be somewhat retarded by these mountains. When storms enter the Mid-Atlantic Lowlands, the eastern slopes of the Appalachian Mountains experience the same orographic enhancement of precipitation as the western slopes because of their altitude and orientation.

The Mid-Atlantic Lowlands extend from the mountains on the west to the coast of the Atlantic Ocean on the east. The mountains partially shelter the lowlands from the extreme temperatures that occur west of the mountains. The Atlantic Ocean modifies the lower layers of the atmosphere and winters in the coastal areas are generally warmer than in the west. Summer along the coast and in the mountains to the west is cooler than in the inland lowlands.

2.3 WIND POWER IN THE EAST CENTRAL REGION

The annual average available wind power density in the East Central region is shown in Figure 2.4. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Table 1.2). 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 the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). In mountainous regions, the analyses also reflect major valleys. In coastal areas, the estimates are representative of well-exposed land sites along the shoreline. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Table 1.2).

A brief description of the major (class 4 and higher) wind resource areas of the East Central region follows in Section 2.5. For more complete discussions of these wind resource areas, refer to the chapter on the individual states containing these areas.

2.3.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power resource 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.

The geographical distribution of the certainty ratings in the East Central region ranges from low (1) to high (4). Certainty ratings of 4 were limited to well populated areas where adequate surface wind data are available, but wind power values are usually low (class 1) in these areas. Certainty ratings for the assessment over exposed ridge crests and mountain summits vary from 1 in areas where abrupt changes in terrain occur, to 3 around the few areas where estimates from upper-air wind data were supplemented with representative surface data from exposed sites. Most of the ridge crest and mountain summit areas were assigned certainty ratings of 2 based on the use of upper-air wind data to estimate wind power. Most areas with nonmountainous terrain, including most coastal areas, were given certainty ratings of 2 or 3, depending on the proximity and representativeness of available surface wind data. However, an area in northeastern Kentucky and another in west-central Tennessee were given certainty ratings of 1 because of the sparsity of data and the complexity of the hilly terrain.

2.3.2 Areal Distribution

Through the superposition of a grid one-third degree longitude by one-fourth degree latitude over the region, the areal distribution of wind power can be estimated as described in Section 1.10. The estimates of areal distribution reported are based on annual average wind power.

Table 2.2 summarizes the results of the computation of the areal distribution for the states of the East Central region. Although the calculated values have more than two significant digits, the subjectivity underlying the assignment of exposure partitioning and power scaling warrants reporting the areas and percentages to only two significant digits. Thus, individual areas and percentages may not sum to their stated totals. Also, since large bodies of water were excluded from the calculation

of areal distribution, total areas for the region and for Delaware/Maryland and North Carolina reported in Table 2.2 are less than the areas given in Table 2.1.

Of the 741 grid cells that encompass the East Central region, 63 have exposed areas with class 4 or higher wind power. However, these power classes are predominantly assigned to ridge crests and mountain summits in mountainous areas (shaded areas on the wind power maps) with high topographic relief. As a result, the estimate of the actual fraction of land area that experiences class 4 and higher wind power (about 0.5%) is significantly less than the 10% suggested by the wind power map of Figure 2.4. In contrast to the effect of terrain on the area with high wind power, the land area estimated to have low power density of classes 1 and 2 (about 98% for the region) is much larger (78%) than the wind power maps suggest.

The highest annual average wind power found in the region is class 6. Only 0.01% of the land area of the region is estimated to have this level of wind power and it is limited to the high ridge crests and mountain summits of western North Carolina, where some of the highest terrain above sea level of the Appalachian Mountains is found.

2.4 SEASONAL VARIATIONS IN THE WIND RESOURCE

Throughout the East Central region, winter and spring are seasons of maximum wind power (see Figure 2.5). At exposed mountain summits and ridge crests (shaded areas), winter is the season of maximum wind power because mean upper-air wind speeds over 1500 m (4920 ft) above ground level are strongest during the winter (December, January, and February). However, mean winter wind speeds are generally low in sheltered basins and valleys. Cold air often drains into the basins and valleys from nearby ridges which experience strong radiational cooling during the long winter nights. The corresponding stable vertical temperature profile (i.e., inversion) may persist throughout the day because of low insolation. Under these stable atmospheric conditions, vertical mixing is restricted, and winds may be very light in a basin or valley even if the winds are strong on nearby ridges. An exception would be a valley oriented parallel to the winter prevailing wind direction since, in such a case, mechanical mixing from wind flow along the valley could break up the temperature inversion and overcome the stratification of wind flow associated with stable conditions. Most of the valleys in the East Central region are

oriented perpendicular to the winter prevailing wind direction, which is from the west through northwest, and are thus expected to experience relatively low wind power during the winter.

In spring (March, April, and May), the upper air flow remains quite strong over the East Central region, although its strength decreases as spring progresses from March to May. Because insolation is greater in spring than in winter, temperature profiles are less stable and more vertical mixing in the surface layer results. Therefore, near-surface wind speeds over the valleys and basins of the East Central region in spring are generally equal to or greater than winter wind speeds. An exception is the valley in western North Carolina around Asheville which is oriented in a northwest to southeast direction and is expected to experience some channeling of wind flow as described above. As a result, this valley has a maximum wind power during winter. The Tyghart Valley around Elkins, West Virginia, and the broad Tennessee River Valley in eastern Tennessee are not cross-hatched in Figure 2.5, indicating a maximum wind power in winter when, in fact, winter and spring wind powers are about equal in these two valleys. East of the Appalachian Mountains, the piedmont and coastal plains of Virginia and North Carolina experience maximum wind power in spring, with the exception of the near-coastal areas which experience a maximum wind power in winter. Surface pressure gradients east of the mountains tend to be strongest in spring. In addition, these lowlands are somewhat sheltered from the strong prevailing northwesterly winds during winter by the Appalachian Mountains to the west, but no such barrier exists to obstruct the winds from the southwest, which becomes the prevailing direction during the spring season. The western portion of the region also experiences a springtime maximum wind power in association with the strong surface pressure gradients and high upper-air wind speeds over the central plains during spring.

In summer (June, July, and August), mean wind powers are low over the entire East Central region. Only the higher mountain elevations, in western North Carolina and east central West Virginia, and exposed coastal sites experience higher than class 1 wind power during the summer. Upper-air wind speeds over the region during summer are about 60% of the winter values, indicating that summer mean free-air wind power is only about 20% of the winter values. In addition, the semipermanent Bermuda anticyclone, a large-scale feature of the late-summer circulation, influences much of the region with prolonged periods

of atmospheric stagnation associated with very low wind speeds.

During autumn (September, October, and November), upper-air wind speeds increase substantially, but remain less than the spring upper-air speeds over the East Central region. They range from about 80% of the spring values in the southern part of the region (50% of the mean free-air wind power) to about 90% (70% of the mean free-air wind power) in the north. This is related to the fact that the southward movement of the winter storm track (an area of high surface pressure gradients) affects the northern part of the region much earlier in autumn than it does the southern part. The Bermuda anticyclone, with its associated low surface wind speeds, can still influence the region well into autumn, but its position shifts southward during the autumn season.

Seasonal variations in atmospheric stability affect the variation of wind speed with height in the East Central region. As discussed above, upper-air winds are strongest during winter over the entire region, but the average surface speeds in the Mid-Atlantic lowlands are highest during the spring.

2.5 MAJOR WIND RESOURCE AREAS

Descriptions of major areas in the East Central region with high annual average wind power (class 4 and above) are briefly summarized in this section. For additional detail on these areas, refer to chapters on the state assessments. For the location of place names mentioned in this section, refer to the individual state maps (such as Figures 4.1 and 4.4 for the Delaware/Maryland assessment).

2.5.1 Atlantic Coastal Areas

The annual average wind power for exposed coastal areas of Delaware, Maryland, Virginia, and North Carolina is estimated to be at least class 3, with class 4 wind power likely in the better exposed areas. There is a steep gradient in the estimated wind power within several kilometers of the coastline due to the abrupt change in surface roughness between the land and open water, even though relatively flat, smooth plains extend far inland along the entire length of the East Central region coastline. While the majority of the coastline is oriented such that the prevailing wind direction (from the southwest across most of the region) is offshore, there is considerable variation in the orientation from one area to another.

The prevailing wind direction has a significant along-shore component for the Delmarva Peninsula and for the North Carolina coast south of Cape Hatteras. These areas have the highest wind potential since they are better exposed to the prevailing winds. Winter is the season of maximum power for the coastal areas of the region, since surface pressure gradients are strongest during the winter. However, the seasonal variability of the wind resource depends on the orientation of the coastline since the prevailing wind direction varies seasonally, being from the southwest quadrant during summer and from the northwest quadrant in winter. Coastal wind power also has a very definite variation with latitude, being higher in the north. This is related to the relative increase in surface pressure gradients with latitude.

2.5.2 Chesapeake and Delaware Bays

Exposed areas of the eastern shore of the Chesapeake Bay and Cape Henlopen at the mouth of the Delaware Bay are estimated to have class 4 wind power. This is because of the large fetch over open water for the prevailing strong winds out of the west through north directions in these areas. The complexity of the Chesapeake Bay shoreline, with its many islands and inlets, suggests a high variability of wind power in this area. Local interactions between terrain and wind flow may lead to enhanced wind power potential, but the level of possible enhancement is not expected to be large because of the relatively flat, simple terrain. The highest wind power potential is around the southern tip of the Delmarva Peninsula since it has the best exposure to winds from the north, which are

typically the strongest in this area, and it is well exposed to a broader range of wind directions.

2.5.3 Exposed Mountain Ridges and Summits

Class 4 or higher wind power is estimated for exposed mountain summits and ridge crests in western North Carolina, extreme eastern Tennessee, east central West Virginia, western Maryland (west of Cumberland), and portions of Virginia including the higher elevations of the Blue Ridge Mountain Range in Shenandoah National Park. The map analyses present lower limits to the wind resource expected for exposed terrain in the mountainous areas (shaded areas on the wind power maps). Average wind speeds may vary considerably from one ridge crest site to another, and are primarily influenced by the height and slope of the ridge, orientation to the prevailing winds, and the proximity and relative height of other mountains and ridges. A majority of the ridges in Virginia, West Virginia, and western Maryland are oriented perpendicular to the prevailing westerly winds, and as a result the higher ridges may experience considerably enhanced wind power from a venturi speed-up effect as wind flows are compressed as they are forced over the ridges. Winter is the season of maximum wind power over the mountain summits and ridge crests of the East Central region because mean upper-air wind speeds are highest during this season (see Section 2.4). In contrast to valley and plain locations, the daily maximum wind speed for mountain summits and ridge crests generally occurs at night because the frictional boundary layer is more shallow due to the absence of solar heating and associated vertical mixing.

FIGURE 2.1. Geographic Map of the East Central Region

FIGURE 2.2. Topographic Map of the East Central Region

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

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

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 ³	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 East Central Region

Power Class	Land Area (km ²) Equal or Exceeding Power Class						
	East Central	Delaware/Maryland	Kentucky	North Carolina	Tennessee	Virginia	West Virginia
1	530,000	30,000	100,000	130,000	110,000	100,000	63,000
2	57,000	8,800	2,400	12,000	17,000	12,000	3,900
3	10,000	1,400	77	1,600	400	4,800	2,100
4	3,200	220	0	850	170	1,000	940
5	760	2	0	410	46	48	250
6	75	0	0	57	18	0	0
7	0	0	0	0	0	0	0

Power Class	Percentage Land Area Equal or Exceeding Power Class						
	East Central	Delaware/Maryland	Kentucky	North Carolina	Tennessee	Virginia	West Virginia
1	100.	100.	100.	100.	100.	100.	100.
2	11.	29.	2.3	9.5	16.	12.	6.2
3	1.9	4.5	0.08	1.2	0.37	4.6	3.3
4	0.60	0.72	0.00	0.67	0.15	0.98	1.5
5	0.14	0.01	0.00	0.33	0.04	0.05	0.39
6	0.01	0.00	0.00	0.05	0.02	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00

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

CHAPTER 3: STATE FEATURES

The state wind resource descriptions are presented in Chapters 4 through 9, in alphabetical order beginning with Delaware/Maryland and ending with West Virginia. The state descriptions are presented in a consistent format. 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 below 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 are reproductions of the 1:500,000 scale U.S. Geological Survey maps. 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 gridded maps of the certainty rating of the estimated annual average wind power by grid cell, and gridded maps 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 and 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 experience 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 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 of any of the other wind characteristics (i.e., diurnal wind speeds, frequency distributions of wind speed and wind direction, speed and power duration) 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 directly on the ground were preferred to periods when the anemometer was located on the roof of a building.

The second line of each 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 terrain. Most of the station curves are within the 0 to 200 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 01 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. The diurnal curves for Navy stations are based on 24 observations daily for periods ending before March 1972 and on 8 observations for periods ending after February 1972.

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 observa-

tions. 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 1000 watts/m² in the power duration curves.

DELAWARE/MARYLAND

CHAPTER 4: DELAWARE/MARYLAND

Delaware covers an area of 5328 km² (2057 mi²) and had a population of 548,104 in 1970. Most of Delaware's population lives in Wilmington and Dover with the remainder spread evenly over the state. Delaware is bounded on the east by the Atlantic Ocean and the Delaware Bay; on the south and west by Maryland; and by Pennsylvania on the north. There are no major terrain reliefs within the state, the highest point being 24 m (80 ft) above mean sea level (MSL).

Maryland covers an area of 27,394 km² (10,577 mi²) and had a 1970 population of 3,923,897. The majority of Maryland's population is centered around Washington, D.C., and Baltimore with corridors of population between Washington and Baltimore and between Washington and Frederick to the northwest. Most of the remainder of the population is distributed in the state east of the mountainous area. The mountainous areas are sparsely settled, usually in small towns in the valleys. The largest of these are Cumberland and Hagerstown. Maryland is bounded on the north by Pennsylvania, on the west by West Virginia, the south by West Virginia and Virginia, and the east by Delaware and the Atlantic Ocean. The Chesapeake Bay separates the eastern part from the remainder of the state. The topography of the eastern section is similar to Delaware. The middle of the state (from the Chesapeake Bay to the mountains) consists of rolling hills gradually increasing in relief from the east to the first major ridge of the Appalachian Mountains, the Catoctin Mountains just west of Frederick. The rest of the state is of typical Appalachian terrain; river and stream-cut valleys rise to ridges averaging about 550 m (1800 ft) MSL and about 300 m (1000 ft) above the valley floors. The highest point in Maryland is 1024 m (3360 ft) MSL.

Figure 4.1 shows the locations of the major geographic features of Delaware and Maryland. Topographic relief is shown in Figure 4.2 and land-surface forms in Figure 4.3.

Available wind data from the National Climatic Center (NCC) are mostly located near the major population centers and along major highway routes (see Figure 4.4). Only limited data exist along the eastern shore of the Chesapeake Bay and in the mountains of western Maryland. No data are available in north central Maryland, roughly north of a line between Frederick and Baltimore. Most of the non-NCC data screened for this assessment were in areas where NCC data are abundant. Figure 4.5

shows the locations of data stations used in the assessment.

4.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in the Delaware and Maryland region is shown in Figure 4.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Table 1.2). 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, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). In mountainous regions, the analyses also reflect major valleys. In coastal areas, the estimates are representative of well-exposed land sites along the shoreline. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Table 1.2).

Annual average wind power for exposed ridge crests and mountain summits in the Appalachian Mountains of western Maryland varies from class 3 for the Catoctin Mountains in the east, to class 4 for the higher elevations west of Cumberland (Figure 4.6). Limited NCC data exist at two exposed sites in the mountains of western Maryland, and estimates from these surface data support the estimates based on Crutcher's (1959) climatology of upper-air winds (see Section 1.4.2). The ridges are cut by numerous valleys which are primarily oriented in a northeast-southwest direction. Some of these valleys are very broad (see areas not shaded on Figure 4.6), especially the northern extension of the Shenandoah Valley around Hagerstown. Based on available data, the wind power for these broad valleys was assessed as class 1. In addition, a region of lower elevation ridges just east of Cumberland (mean ridge crest elevations of less than about 550 m (1800 ft) MSL), is estimated to have class 2 wind power. This is based on estimates from upper-air climatology and the fact that these ridges are somewhat sheltered from the power-producing winds by the much higher ridges to the west.

The plains of central Maryland and western Delaware are estimated to have

class 1 annual average wind power. Based on available wind data and on previous studies of coastal zone wind energy (Garstang et al. 1978), the boundary between class 1 and class 2 wind power is estimated to vary from about 10 km inland around the northern portion of Chesapeake Bay to 20 km inland in southern Delaware. Class 3 wind power is estimated for portions of the eastern shore of Chesapeake Bay and for exposed Atlantic coastal sites. Cape Henlopen at the mouth of the Delaware Bay is estimated to have class 4 wind power. It is expected that well-exposed sites on the eastern shore of the Chesapeake Bay, and some of the islands in the Bay, also experience class 4 wind power, but surface wind data are too sparse and the shoreline too complex to resolve these features in an assessment of this scope. Qualitative indicators, such as the orientation of the shoreline to the main power-producing winds and the over-water fetch distance for these winds, were main factors in assigning assessment values in data-sparse areas.

The terrain for a large area of north central Maryland is classified as tablelands with moderate 100-150 m (300-500 ft) relief. No representative surface wind data exist in this area. Based on the nearest available data, from Frederick to the west, and from the Baltimore area to the southeast, class 1 wind power was assessed for this region. However, the wind power is expected to be near the boundary between class 1 and class 2, and the better exposed hilltops may experience class 2 wind power.

4.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for Delaware and Maryland vary from 1 to 4 (Figure 4.7). The areas around Washington, D.C., and non-coastal areas of the Delmarva Peninsula have certainty ratings of 4 based on availability of wind data at exposed sites and the low variability of the wind resource across the inland plains. Coastal areas have certainty ratings of 2 and 3. Some wind data are available for most coastal areas, but the higher variability of the resource due to the change in surface roughness between land and water and the complexity of the shoreline in some areas, indicated a lower certainty rating for the assessment in coastal areas.

Certainty ratings for the mountains of western Maryland vary from 3 in the far west, where wind data from exposed sites supplemented estimates based on upper-air climatology, to 1 in the Catoctin Mountains

and just west of Hagerstown. The low certainty rating in the latter areas is due to the absence of surface data for exposed ridges and summits, and the high variability of the resource associated with the changing terrain.

Ridge crest and mountain summit estimates were given a certainty rating of 2, even if data from well-exposed surface stations were not available, because upper-air wind data were used to approximate the power in these areas. However, sharp changes in terrain within a grid cell, or other topographical indicators of very high variability of the resource, were the basis for assigning a certainty rating of 1 in some mountainous areas.

4.1.2 Areal Distribution

Table 4.1 summarizes the areal distribution of annual average wind power for Delaware and Maryland. Only 0.72% of the land area experiences wind power of class 4 or higher. The largest contribution to class 4 or higher wind power is from exposed ridge crests and mountain summits in western Maryland, with only a small contribution from exposed coastal sites. However, because of the partitioning of wind power by exposure category and the scaling of wind power for sheltered exposures in mountainous terrain, the coastal areas make the largest contribution to the percent area with class 2 or higher wind power. This situation is depicted in Figure 4.8 which shows areal distribution for each grid cell giving percent area with wind power greater than or equal to classes 2, 3, 4 and 5.

Because of the scale of the grid cells used in the determination of the areal distribution the wind power, and the limited amount of quantitative data available in areas of complex terrain, it is difficult to represent the contribution to the areal distribution of wind power made by areas of topographically enhanced wind power (e.g., gaps between ridges and valleys extending down from mountain summits). For this reason, the estimates of areal distribution are considered to be lower limits which could be expected for the area.

4.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 4.9. Winter is the season of maximum wind power over the exposed ridge crests and mountain summits of western Maryland, and over most of the plains and coastal areas of Delaware and Maryland. The broad valley around Hagerstown, Maryland, and a small area lo-

cated roughly in the center of the Delmarva Peninsula are estimated to have maximum wind power during spring (see also Figure 2.5). The sparsity of data on the peninsula makes it difficult to accurately delineate the spring-maximum from the winter-maximum areas. Summer is the season of least wind power throughout Delaware and Maryland.

4.2.1 Winter

During the winter, class 7 wind power occurs in the extreme western tip of Maryland, where the highest mountain ridges are located. Class 6 wind power is estimated for the remainder of the ridge crest areas west of Cumberland. These estimates are based on mean upper-air wind data supplemented by surface data from two exposed sites in the area (one located across the border in West Virginia).

The wind power for exposed ridge crests and mountain summits east of Cumberland is estimated to be class 5 during winter.

The broad valley around Hagerstown, Maryland is estimated to have class 2 wind power, based on available surface data. Narrower valleys will be sheltered from the strong prevailing northwesterlies during the winter, and are expected to have only class 1 wind power. As discussed in Section 2.4, these valleys experience extremely stable atmospheric conditions during the long winter nights. This stable stratification can persist throughout the day, because of the low amount of insolation, and inhibit the normal increase in surface wind speeds during the daylight hours.

The coastal plains east of the mountains experience at least class 2 wind power during winter. Wind power for exposed coastal sites on the Chesapeake and Delaware Bays, and on the Atlantic Ocean, ranges from class 2 to class 5 during winter. Class 5 wind power is found around Cape Henlopen at the mouth of the Delaware Bay, and on the eastern shore of the Chesapeake Bay along the Maryland-Virginia border. Class 4 wind power is found along the Atlantic coast and portions of the Delaware and Chesapeake Bays.

4.2.2 Spring

Mean wind power over exposed ridge crests and mountain summits is considerably lower during spring than winter because upper-air wind speeds decrease significantly from March through May. The highest assessed wind power for spring is class 5 and occurs in the northwest portion of Maryland along the border with Pennsyl-

vania. Wind power over the eastern mountain ridges and summits is estimated to be class 3 during spring. Wind power in the Mid-Atlantic Plains is class 2 during spring, and remains at about the same level as during winter. Coastal areas experience somewhat lower wind power during spring than in winter, ranging from class 3 to class 4 for exposed land areas.

4.2.3 Summer

Summer is the season of lowest wind power for all of Delaware and Maryland. Even exposed ridge crests and mountain summits in western Maryland are estimated to have only class 1 wind power during the summer. This is because of low wind speeds aloft over the region. Class 2 wind power is experienced by exposed coastal sites on the Atlantic Ocean and on the Delaware and Chesapeake Bays, but appears to be attenuated to the class 1 level within 5 to 10 km inland. The land/sea breeze cycle may be a significant contributor to coastal wind power during the summer.

4.2.4 Autumn

The autumn map shows wind power for mountainous areas of Maryland varying from class 4 in the extreme northwest along the Pennsylvania border to class 2 for the lower elevation ridges in the east. Valleys and the inland plains experience class 1 wind power during the autumn. Autumn wind power values for exposed coastal sites are lower than spring and winter values, but are substantially higher than summer values. The exposed Atlantic coastal sites are expected to have class 3 wind power during autumn, while the Chesapeake Bay experiences class 2 and 3 wind power.

4.3 FEATURES OF SELECTED STATIONS

Table 4.2 gives the location and annual average wind speed and power density of twelve stations in Delaware and Maryland (2 in Delaware, 9 in Maryland and 1 in Washington, D.C.) for which digitized data are available from the NCC. Graphs of other features of the wind resource are shown in Figures 4.10 to 4.16. A brief description along with a discussion of the relative representativeness and reliability of the data is presented here for each station. Data for Washington National Airport and Dulles International Airport are presented with Virginia stations in Chapter 8.

Dover, Delaware, is located in the center of Delaware on the Atlantic Coastal Plain. There are no topographic reliefs exceeding about 25 m (80 ft) in this area, indicating good site exposure. Wind power

estimates may be unrepresentative because of the low anemometer height.

Wilmington, Delaware, is located in the northern end of the state at the boundary of the rolling hills which extend north and northwest into Pennsylvania and the Atlantic Coastal Plain to the south. The wind instruments are located at the airport on a ground mast and the exposure is excellent.

Aberdeen, Maryland, Aberdeen (Phillips Field), is located halfway between Wilmington, Delaware and Baltimore, Maryland, at the north end of the Chesapeake Bay. The unknown anemometer height indicates that wind power estimates based on these data should be used with caution.

Annapolis, Maryland, is located on the western shore of the Chesapeake Bay at the U.S. Naval Academy. The wind instruments are located on the roof of a building and may not be representative.

Baltimore/Dunkirk, Maryland, is located east of Baltimore City in a heavily urbanized area close to the Chesapeake Bay. The roof location of the anemometer and possible influence of other nearby buildings on wind flow make the wind power estimates questionable.

Baltimore-Washington International Airport (formerly Friendship Airport), Maryland, is located on the western side of the Chesapeake Bay. There is little land relief exceeding 30 m (100 ft) within a 10-mile radius of the field. The exposure of the wind instruments is excellent.

Camp Detrick, Maryland, is located to the north of Frederick, just east of the Catoctin Mountain ridges. The unknown anemometer height indicates that wind power estimates based on these data should be used with caution.

Fort Meade, Maryland, is located approximately 15 miles southeast of Baltimore-Washington International Airport. Wind power estimates may be unrepresentative because of the low anemometer height of 4.0 m (13 ft).

Patuxent River, Maryland, Naval Air Station, is located at the outlet of the Patuxent River into the Chesapeake Bay. Wind power estimates may be unrepresentative because of the low anemometer height of 4.0 m (13 ft).

Salisbury, Maryland, is located in the Atlantic Coastal Plain area and has similar local terrain to Dover, Delaware, located about 80 km (50 mi) to the north.

Data for the period used in the assessment, January 1968 to December 1972, were recorded on a ground mast, and the site and instrument exposure are considered excellent.

Andrews Air Force Base, Maryland, is located in the area where the Atlantic Coastal Plain is beginning to change into gently rolling hills to the west that lead to the Appalachian Mountains. The wind instruments are located on a 4.0 m ground mast, and may be affected by local obstructions. The interannual variations (Figure 4.10) show about a 60% increase in wind power from 1968 to 1969. Since data from nearby stations do not corroborate this increase, the data may be considered questionable for representing wind power.

Bolling Field, Washington, D.C., is located on the south side of Washington, D.C. at the outlet of the Anacostia River into the Potomac River. The wind equipment was mounted on a roof and the wind power estimates are considered low for exposed sites.

4.3.1 Interannual Wind Power and Speed

Interannual variations in wind power are not very large for most of the stations shown in Figure 4.10, with less than a 50% difference in power between the years of lowest and highest wind power. An exception is Andrews Air Force Base, which shows a sharp increase in wind power toward the end of the data period. As discussed above, the representativeness of these data is questionable.

Breaks which appear in the plots of interannual variability are associated with changes in anemometer height for a station. These changes frequently correspond to changes in anemometer location from a roof exposure to a ground mast, as the instrumentation and exposure at major airports became more uniform, and usually improved, during the late 1950s and early 1960s. The plots for Wilmington, Delaware and Baltimore-Washington International Airport illustrate the effect that changes in instrument locations can have on wind power estimates. The remaining plots in this section (Figures 4.11 to 4.16) are based on selected periods of constant anemometer height and location. When more than one period of data was available, the longest period with the best exposure of the wind instruments was selected for the assessment of wind power.

4.3.2 Monthly Average Wind Power and Speed

All of the stations presented in Figure 4.11 have maximum wind power during winter

or spring, and most show peak power during February or March. The minimum power occurs during July and August for all stations. This pattern is typical of locations in the lowlands of the region. The maximum monthly power at anemometer height level is 300 watts/m² and occurs at Baltimore/Dunkirk, Maryland, during February.

4.3.3 Diurnal Wind Speed by Season

All stations presented in Figure 4.12 indicate maximum wind speeds during the afternoon for all seasons. Peak speed occurs at about 1200 local standard time (LST) during winter and autumn for most stations, and at about 1500 LST during spring and summer. Diurnal variations are largest for spring and summer, being about equal for the two seasons. Winter and autumn variations also appear to be about the same at most stations.

The smallest diurnal variation of wind speed occurs at Annapolis. Indications are that diurnal variation is smaller for stations closer to the shoreline. The reason for this may be that at night the lower layer of the atmosphere is less stable for areas close to large bodies of water than for inland areas due to the difference in radiative cooling rates between land and water.

4.3.4 Directional Frequency and Average Speed

Frequencies and average speeds are lowest for wind from the east sectors for all of the stations depicted in Figure 4.13. Directional frequencies are usually bimodal with peak frequencies for south winds and for west through northwest winds. The maximum wind speeds are also for west through northwest winds, and average about 5 to 6 m/s (11 to 13 mi/hr) for those directions at most stations. There is some indication of a slight 8-point compass bias for the data from military installations.

4.3.5 Annual Average Wind Speed Frequency

Observer biases are evident in the actual distributions of wind speed for Aberdeen/Phillips Field, Baltimore/Dunkirk, and Camp Detrick, Maryland (Figure 4.14). This bias is reflected in the peaks at 2, 5, and 8 m/s (5, 10 and 15 knots) and is not uncommon at stations with periods of record in the 1940s and 1950s.

4.3.6 Annual Average Wind Speed and Power Duration

The percentage of time 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 usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 4.1. Geographic Map of Delaware and Maryland

FIGURE 4.2. Topographic Map of Delaware and Maryland

FIGURE 4.3. Land-Surface Form Map for Delaware and Maryland

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 Delaware and Maryland

FIGURE 4.5. Location of Stations Used in Delaware and Maryland Resource Assessment

FIGURE 4.6. Delaware and Maryland 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 ³	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 Delaware and Maryland

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	22,000	71.	30,000	100.
2	7,500	25.	8,800	29.
3	1,200	3.8	1,400	4.5
4	220	0.71	220	0.72
5	2	0.01	2	0.01
6	0	0.00	0	0.00
7	0	0.00	0	0.00

FIGURE 4.7. Certainty Rating of Delaware and Maryland 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>

Class 2

Class 3

FIGURE 4.8. Areal Distribution of Wind Resource in Delaware and Maryland (Classes 2 and 3)

Class 4

Class 5

FIGURE 4.8 (Continued). Areal Distribution of Wind Resource in Delaware and Maryland (Classes 4 and 5)

FIGURE 4.9. Seasonal Average Wind Power in Delaware and Maryland (Winter, Summer)

FIGURE 4.9 (Continued). Seasonal Average Wind Power in Delaware and Maryland (Spring, Autumn)

TABLE 4.2. Delaware and Maryland Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Annual Average Wind Speed, m/s				Annual Average Wind Power, watts/m ²		
						Anemometer Height, m	At Anemometer Height	At 10 m	At 50 m	At Anemometer Height	At 10 m	At 50 m
Dover, Delaware	Dover AFB	39.13	75.46	7	05/63-12/70	4.0	3.4	3.9	4.9	69	102	204
Wilmington, Delaware	Greater Wilmington/ New Castle Airport	39.66	75.59	29	01/65-12/78	6.1	4.2	4.5	5.7	90	112	223
Aberdeen, Maryland	Aberdeen Phillips Field	39.46	76.16	19	01/49-12/57	Unk ^(b)	3.6	3.6	4.5	86	86	171
Annapolis, Maryland	Annapolis Naval Air Facility	38.98	76.47	12	02/59-01/62	28.3	4.1	3.5	4.4	97	62	124
Baltimore, Maryland	Baltimore Dunkirk Airport	39.18	76.53	13	11/45-07/50	22.3	5.4	4.8	6.1	211	150	298
Baltimore, Maryland	Baltimore Friendship International Airport	39.18	76.66	60	01/65-12/78	6.1	3.9	4.2	5.3	76	94	187
Frederick, Maryland	Camp Detrick AF	39.43	77.44	100	01/49-12/53	Unk ^(b)	2.7	2.7	3.4	70	70	140
Fort Meade, Maryland	Fort Meade Tipton AAF	39.12	76.77	46	09/60-09/66	4.0	2.1	2.4	3.0	31	46	92
Patuxent River, Maryland	Patuxent River Naval Air Station	38.28	76.41	14	04/60-12/78	4.0	3.3	3.8	4.7	58	86	171
Salisbury, Maryland	Salisbury Wicomico County Airport	38.33	75.50	21	01/68-12/72	6.1	3.5	3.8	4.7	68	84	168
Wash/Andrews, Maryland	Washington, D.C. Andrews AFB	38.81	76.88	84	12/61-05/70	4.0	3.5	4.0	5.0	80	118	236
Wash/Bolling, Maryland	Washington, D.C. Bolling Field	38.83	77.02	18	04/55-12/65	21.3	3.2	2.9	3.6	77	56	111

^(a)AF - Air Force Facility; AFB - Air Force Base; AAF - Army Air Field.

^(b)Unk - Anemometer height is unknown. Height of 10 m was assumed for estimating wind speed and power at 10 and 50 m.

FIGURE 4.10. Interannual Wind Power and Speed for Delaware and Maryland

FIGURE 4.11. Monthly Average Wind Power and Speed for Delaware and Maryland

FIGURE 4.12. Diurnal Wind Speed by Season for Delaware and Maryland

FIGURE 4.13. Directional Frequency and Average Wind Speed for Delaware and Maryland

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

PNL-3195 WERA 5

FIGURE 4.14. Annual Average Wind Speed Frequency for Delaware and Maryland

ORDINATE - PERCENT
ABSCISSA - M/S

PNL-3195 WERA-5

FIGURE 4.15. Annual Average Wind Speed Duration for Delaware and Maryland

ORDINATE - PERCENT
ABSCISSA - WATTS/M²

PNL-3195 WERA-5

FIGURE 4.16. Annual Average Wind Power Duration for Delaware and Maryland

KENTUCKY

CHAPTER 5: KENTUCKY

Kentucky covers an area of 104,623 km² (40,395 mi²) and had a population of 3,220,711 in 1970. Most of Kentucky's population resides in the areas of Louisville and Lexington. The rest of the population is distributed throughout the state with the density decreasing to the east in the mountainous areas. The topography of Kentucky consists of rolling hills in the west becoming more mountainous in the east. The altitude varies from an average of less than 300 m (1000 ft) above mean sea level (MSL) in the west to about 900 m (3000 ft) in the east. The highest elevation in Kentucky is 1263 m (4145 ft) MSL.

Figure 5.1 shows the locations of the major geographic features of Kentucky. Topographic relief is shown in Figure 5.2 and land-surface form in Figure 5.3.

Available wind data from the National Climatic Center (NCC) are mostly located near the major population centers in Kentucky (see Figure 5.4). NCC wind data are very sparse in eastern Kentucky, with no digitized or summarized data available east of Lexington and Corbin. Moreover, the site exposures for locations with unsunmarized wind data are generally poor due to the hilly terrain and the tendency for most stations to be located in river valleys. Figure 5.5 shows the locations of data stations used in the assessment for Kentucky.

5.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in Kentucky is shown in Figure 5.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Table 1.2). 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, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). In mountainous regions, the analyses also reflect major valleys. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Table 1.2).

The highest annual average wind power in Kentucky is class 3, and is confined to the higher elevations in the Appalachian Moun-

tains in southeastern Kentucky (Figure 5.6). In the Pine Mountain area, mean ridge crest and mountain summit elevations are between 900 and 1100 m (3000 and 3600 ft) MSL, with no higher elevations to the west and north to obstruct the prevailing strong winds from those directions. These estimates are based solely on climatology of the upper-air wind speeds, as there are no surface data from exposed sites in the area. Class 2 wind power extends west and north from the Pine Mountains to within about 40 km (30 mi) of Lexington. The absence of data from exposed sites in this area and the gradual nature of changes in terrain elevation make it difficult to assess the location of the boundary between class 1 and class 2 wind power with any degree of accuracy. Additional uncertainty is introduced into the wind assessment for this area due to the fact that wind power estimates based on extrapolating down from upper-air data become less reliable as the vertical distance over which the extrapolation is carried increases. Over eastern Kentucky, the upper-air wind speeds were extrapolated down from the 850 mb level (about 1500 m MSL) to terrain elevations of about 500 m MSL.

Class 1 wind power covers the remainder of Kentucky with the exception of a small area around the Kentucky Lake in southwestern Kentucky. This area is estimated to have class 2 wind power based on available surface data located to the west and a qualitative assessment of the interaction of the wind flow with terrain features. In addition, an area in northeastern Kentucky is estimated to have class 1 wind power based on the nearest surface data from Huntington, West Virginia, and the presence of higher hills to the west of the area. It should be noted that the large area of class 1 wind power in western Kentucky is in the upper range of that wind power class. Average power densities are in the 75 to 90 watts/m² range at 10 m above ground for existing data locations with good exposure to the prevailing strong winds. Thus it is likely that the more prominent hills and uplands will experience class 2 wind power, although these features are too small and too widely dispersed to be resolved on the wind power maps.

5.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for Kentucky vary from 1 to 4 (Figure 5.7). Certainty ratings of 4 are limited to the few areas where representative surface data exist, around Paducah, Owensboro, Louisville, Covington (Cincinnati), Lexington, and Bowling Green. A

certainty rating of 2 was assigned for the hilly and mountainous areas of eastern Kentucky because upper-air wind data were used in assessing the wind power for that area. Some areas of western and northeastern Kentucky have a certainty rating of 1 because of the absence of any representative surface wind data and the complexity of the hilly terrain.

5.1.2 Areal Distribution

The areal distribution of wind power for Kentucky is summarized in Table 5.1 for the state and is shown in Figure 5.8 for each one-third degree longitude by one-fourth degree latitude grid cell. Only 2.3% of the land area in the state has class 2 or higher wind power, and the highest wind power assessed is class 3. However, as discussed above, the area that experiences class 2 wind power may be significantly larger than the 2.3% indicated by this assessment. Additional data for well-exposed hilltops in central Kentucky and, perhaps, more refined region-specific terrain partitioning schedules and scaling factors, would be needed to make a more accurate assessment of the areal distribution of wind power for Kentucky.

5.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 5.9. Winter is the season of maximum wind power and summer is the season of minimum wind power over the entire state, with the exception of extreme western Kentucky which experiences maximum wind power during spring.

5.2.1 Winter

The exposed ridge crests and mountain summits of southeastern Kentucky experience class 6 wind power during winter at elevations above about 800 m (2600 ft). Winter wind power decreases to the north and west as elevations decrease, but remains at least class 2 for exposed sites over the entire state. Sheltered valleys and basins are expected to experience low (class 1) wind power during winter.

5.2.2 Spring

Next to winter, spring is the season of highest wind power for Kentucky. Class 4 wind power is found over the highest ridges and mountain summits of southeastern Kentucky. The majority of the Pine Mountain area experiences class 3 wind power during spring. The remainder of the state experiences class 2 wind power, with the exception of the lowlands in northeastern Kentucky, which are estimated to have class 1 wind power.

5.2.3 Summer

The entire state, including exposed ridge crests and mountain summits, is estimated to have only class 1 wind power. The absence of strong surface pressure gradients and low upper-air wind speeds account for the low wind power during the summer.

5.2.4 Autumn

Wind power over the interior lowlands remains low (class 1) during autumn. The exposed ridge crests and mountain summits of southeastern Kentucky are estimated to have class 2 wind power.

5.3 FEATURES OF SELECTED STATIONS

Table 5.2 gives the location and annual average wind speed and power density of nine stations in Kentucky for which digitized data are available from the NCC and which were used in the assessment. Graphs of other features of the wind resource are shown in Figures 5.10 to 5.16. A brief description of each station including the relative reliability and representativeness of the data is presented here.

Bowling Green is located in the Green River Valley approximately 115 km (70 mi) south-southeast of Owensboro. The wind instrument exposure would be affected by valley winds and does not represent the winds on the surrounding plateau areas, which are about 90 to 120 m (300 to 400 ft) higher elevation than the airport.

Corbin is located on a plateau which rises from 300 m (1000 ft) in the northwest to 500 m (1600 ft) to the southeast, and then rapidly to the mountains. The area is surrounded by hills equal to or less than the height of the plateau. Because of the short period of record and the roof location of the wind instrument, the wind power may not be representative of this site.

Covington is located on a small plateau southwest of, and across the Ohio River from, Cincinnati, Ohio. The exposure of the anemometer is excellent, and the site is considered representative for estimating wind power for the surrounding plateau area of northern Kentucky.

Fort Campbell is located on the Kentucky-Tennessee border on a plain which slopes gently upward to the east. The exposure of the wind instruments is uncertain because of the low anemometer height of 4.0 m (13 ft).

Fort Knox is located on the west central Kentucky plains. The exposure of the wind

instruments is uncertain because of the low anemometer height of 4.0 m (13 ft.)

Lexington is located on a plateau of approximately 300 m (1000 ft) MSL elevation in the heart of the Blue Grass region. The wind instrument exposure is considered good for the data period used in the assessment.

London is located approximately 19 km (12 mi) north of Corbin, Kentucky, on the same plateau, but because of the roof location of the anemometer, the exposure is uncertain.

Louisville is located on the south bank of the Ohio River and is on the border of the Ohio flood plain to the west and rolling hills to the east. The wind instrument exposure is excellent. The site exposure is representative of areas on the flood plain, but some sheltering from the prevailing strong northerly and northwesterly winds occurs as a result of the high hills to the northwest on the other side of the flood plain.

Paducah is located on the flood plain of the Ohio River, with hills to the northwest and south. The wind power at this station may be slightly lower than the high terrain of the surrounding area.

5.3.1 Interannual Wind Power and Speed

Interannual variations of wind power and speed are generally small for those stations with more reliable instrument exposures (Figure 5.10). Stations with long periods of record and anemometers located on a ground mast show differences of less than 50% between years of lowest and highest wind power. Higher variability for other stations in Figure 5.10 may be attributed to the uncertainty of the instrument exposure. Also, development in urban areas may cause changes in instrument exposure with time. This may be particularly true on the plains, where construction of buildings can significantly change the surface roughness characteristics of an area.

5.3.2 Monthly Average Wind Power and Speed

Most of the stations show fairly uniform wind power for the months of December

through April, with a slight maximum for March or April (Figure 5.11). Corbin shows a maximum wind power for the month of January, but this is based on a relatively short period of record of five years. Power values begin to decrease after April, reaching a minimum during July or August, then increasing to near the winter level by November. The variation in the seasonal cycle is small across the state.

5.3.3 Diurnal Wind Speed by Season

The diurnal variations in wind speed are similar for all of the stations, showing maximum wind speeds during the afternoon hours between 1200 and 1500 local standard time (LST), and with winter showing the smallest diurnal variation of the four seasons (Figure 5.12).

5.3.4 Directional Frequency and Average Speed

Peak frequencies are for winds from the south through southwest directions for most of the stations in Figure 5.13. Lowest frequencies are generally for winds out of the east through southeast. These directions are also associated with the lowest mean wind speeds. The maximum wind speeds occur over a broad range of directions from south through southwest to north. There is some indication of an 8-point compass bias in the directional frequencies for Bowling Green.

5.3.5 Annual Average Wind Speed Frequency

Observer biases are evident in the actual distributions of wind speed for Bowling Green, Corbin, and Paducah (Figure 5.14). This bias is reflected in the peaks at 2, 5, and 8 m/s (5, 10, and 15 knots) and is not uncommon at stations with periods of record in the 1940s and 1950s.

5.3.6 Annual Average Wind Speed and Power Duration

The percentage of time 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 usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 5.1. Geographic Map of Kentucky

FIGURE 5.2. Topographic Map of Kentucky

FIGURE 5.3. Land-Surface Form Map for Kentucky

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 5.4. NCC Station Locations in Kentucky

FIGURE 5.5. Location of Stations Used in Kentucky Resource Assessment

FIGURE 5.6. Kentucky 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 ³	Speed, ^(b) m/s(mph)	Wind Power Density watts/m ²	Speed, ^(b) m/s(mph)
1	0	0	0	0
2	100	4.4(9.8)	200	5.6(12.5)
3	150	5.1(11.5)	300	6.4(14.3)
4	200	5.6(12.5)	400	7.0(15.7)
5	250	6.0(13.4)	500	7.5(16.8)
6	300	6.4(14.3)	600	8.0(17.9)
7	400	7.0(15.7)	800	8.8(19.7)
	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 Kentucky

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	99,000	98.	100,000	100.
2	2,300	2.3	2,400	2.3
3	77	0.08	77	0.08
4	0	0.00	0	0.00
5	0	0.00	0	0.00
6	0	0.00	0	0.00
7	0	0.00	0	0.00

FIGURE 5.7. Certainty Rating of Kentucky 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>

Class 2

Class 3

FIGURE 5.8. Areal Distribution of Wind Resource in Kentucky (Classes 2 and 3)

Class 4

Class 5

FIGURE 5.8 (Continued). Areal Distribution of Wind Resource in Kentucky (Classes 4 and 5)

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

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

TABLE 5.2. Kentucky Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s			Annual Average Wind Power, watts/m ²		
							At Anemometer Height	At 10 m	At 50 m	At Anemometer Height	At 10 m	At 50 m
Bowling Green, Kentucky	Bowling Green City-County Airport	36.96	86.43	162	01/48-12/54	11.0	3.1	3.1	3.8	63	60	121
Corbin, Kentucky	Corbin CAA	36.95	84.10	359	08/49-10/54	7.6	2.2	2.3	2.9	26	29	58
Covington/Cin., Kentucky	Greater Cincinnati Airport	39.06	84.66	270	02/62-12/78	6.1	3.9	4.2	5.3	71	88	175
Fort Campbell, Kentucky	Fort Campbell AFB	36.66	87.50	12	05/56-12/70	4.0	2.4	2.7	3.4	31	46	92
Fort Knox, Kentucky	Fort Knox Godman AAF	37.89	85.96	224	04/64-12/70	4.0	2.7	3.1	3.9	41	61	121
Lexington, Kentucky	Lexington Blue Grass Field	38.03	84.59	299	04/62-12/78	7.0	3.9	4.1	5.2	65	76	151
London, Kentucky	London Municipal Airport	37.08	84.08	368	04/62-12/64	6.1	2.5	2.7	3.4	28	35	69
Louisville, Kentucky	Louisville Standiford Field	38.18	85.73	149	05/60-12/78	6.1	3.7	4.0	5.0	61	75	150
Paducah, Kentucky	Paducah Barkley Airport	37.07	88.77	120	09/49-12/64	9.4	3.6	3.6	4.6	73	75	149

(a) CAA - Civil Aeronautics Administration; AFB - Air Force Base; AAF - Army Air Field.

FIGURE 5.10. Interannual Wind Power and Speed for Kentucky

FIGURE 5.11. Monthly Average Wind Power and Speed for Kentucky

FIGURE 5.12. Diurnal Wind Speed by Season for Kentucky

— PERCENT FREQUENCY LEFT ORDINATE — PERCENT
 - - - WIND SPEED RIGHT ORDINATE — M/S
 PNL-3195 WERA-5 ABSCISSA — WIND DIRECTION

FIGURE 5.13. Directional Frequency and Average Wind Speed for Kentucky

— ACTUAL DISTRIBUTION ORDINATE — PERCENT
 - - - RAYLEIGH DISTRIBUTION ABSCISSA — M/S
 PNL-3195 WERA-5

FIGURE 5.14. Annual Average Wind Speed Frequency for Kentucky

FIGURE 5.15. Annual Average Wind Speed Duration for Kentucky

ORDINATE - PERCENT
 ABSCISSA - WATTS/M²
 PNL-3195 WERA-5

FIGURE 5.16. Annual Average Wind Power Duration for Kentucky

NORTH CAROLINA

CHAPTER 6: NORTH CAROLINA

North Carolina covers an area of 136,197 km² (52,586 mi²) and had a population of 5,084,411 in 1970. The population is evenly distributed except for higher concentrations around the major cities, and decreased population densities in the mountains to the west and the coastal areas in the extreme eastern portions of the state. The topography varies from coastal in the east to mountainous in the far west, with elevations varying from an average of 9 m (30 ft) above mean sea level (MSL) to over 1,000 m (3,300 ft) MSL in the west. The highest point in North Carolina is Mount Mitchell at 2,037 m (6,684 ft) MSL.

Figure 6.1 shows the locations of the major geographic features of North Carolina. Topographic relief is shown in Figure 6.2 and land-surface forms in Figure 6.3.

National Climatic Center (NCC) wind data are available for stations in and around the major population centers of North Carolina, which are evenly distributed over the plains that cover about 80% of the state (Figure 6.4). Areas between existing stations are data-sparse, but the low variability of the wind resource over the plains lessens the impact of these data-sparse areas on the assessment. NCC data also exist at numerous locations distributed along the Atlantic coastal areas of the state, but the quality of much of these data is low for the purpose of assessing the wind resource. Estimates of wind power over exposed ridge crests and mountain summits based on upper-air climatology were supplemented by surface data from four exposed sites in the mountainous area of the state. All four sites, one from the NCC and three from other sources, are located in the mountains to the north of Asheville. Two stations from the National Fire Weather Data Library (NFWDL) provided limited data for the assessment, one located in central North Carolina, between Charlotte and Fayetteville, and the other located in the coastal area south of Cherry Point Naval Air Station. Figure 6.5 shows the locations of data stations used in the assessment.

6.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in North Carolina is shown in Figure 6.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Table 1.2). 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, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). In mountainous regions, the analyses also reflect major valleys. In coastal areas, the estimates are representative of well-exposed land sites along the shoreline. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Table 1.2).

Annual average wind power ranges from class 6 over some of the exposed ridge crests and mountain summits of western North Carolina, to class 1 over the Mid-Atlantic Lowlands, to class 3 and 4 over exposed sites in the coastal areas (Figure 6.6). The class 6 wind power estimates over the higher elevation summits and ridges of the Great Smoky and Blue Ridge Mountain ranges are the highest assessed for the East Central region. Summit elevations in this area are among the highest in the Appalachian Mountains, exceeding 1900 m (6,200 ft) MSL in many cases.

The French Broad River valley around Asheville is assessed as class 1 wind power. The area is sheltered by high mountain ranges to the southwest and northeast, with summits rising over 1,200 m (4,000 ft) above the valley floor. However, the ruggedness of the terrain along the sides of the valley, and the better exposure to the strong northwest winds, indicate that the variability of the resource will be high in this area, with significant local enhancement of wind power expected around certain terrain features. Even though the valley is oriented parallel to the prevailing northwest winds, it does not appear to experience the enhancement of wind speed of a true wind corridor because the entrance to the valley from the northwest is partially blocked by large ridges on either side of the river. A wind corridor is defined as a passageway of lower elevation than the surrounding terrain through which the winds are channeled and sometimes enhanced.

The ridge crest and mountain summit estimates from upper-air data are supported by existing surface data from four exposed sites. The elevations for the surface data range from 902 m (2,960 ft)

MSL at a ridge site just outside of Asheville, to 2,037 m (6,684 ft) MSL at the summit of Mount Mitchell. Annual wind power is estimated to be class 4 for elevations above about 1,200 m (4,000 ft) MSL, class 5 for elevations above 1,500 m (5,000 ft) MSL, and class 6 for elevations above 1,800 m (6,000 ft) MSL. Isolated areas around prominent summits and ridges may experience class 7 wind power.

Wind power estimates over exposed coastal sites in North Carolina range from class 2 in the south to class 4 along the Outer Banks around Cape Hatteras and Cape Lookout. The remainder of the Outer Banks, and most of the inner banks, are estimated to have class 3 wind power. Wind power estimates are based on digitized data at two different locations at Cape Hatteras on the Outer Banks, several stations with digitized data along the inner banks, and limited summarized and unsummarized NCC data at selected coast guard stations. However, the summarized coast guard data were used with caution due to the fact that data periods were in the late 1930s and early 1940s, before observing procedures were upgraded, and the fact that wind speed frequency distributions were provided for only five broad wind speed classes. Wind power over the near offshore areas varies between class 4 and class 5, with the higher value occurring around the major prominences of the Outer Banks.

The Mid-Atlantic Lowlands are sheltered from the main power-producing winds out of the west and north by the Appalachian Mountain ranges. Movement of large-scale storm systems, with high surface pressure gradients, into the lowlands is also retarded somewhat by the presence of the mountains. Hence, mean wind power is low (class 1) over this area.

6.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for North Carolina are shown in Figure 6.7. Most of the mountainous areas received a certainty rating of 2 since upper-air wind data were used to derive wind power estimates. A few grid cells in the mountains received a certainty rating of 3 because of the availability of seasonal and annual surface wind data from well-exposed sites to supplement the estimates from upper-air data. Most grid cells along the Tennessee-North Carolina border were assigned certainty ratings of 1 due to the abrupt change in topography that occurs between the Tennessee River Valley and the Great Smoky Mountain range, and the associated high variability of the wind resource in that area. Certainty

ratings for the plains east of the mountains range from 2 in data-sparse areas, to 4 around locations with representative wind data. Certainty ratings in the coastal areas are mostly 2 and 3, since limited data exist along most of the coast line, but the variability of the resource may be high due to changes in exposure associated with the orientation of the shoreline with respect to prevailing strong winds.

6.1.2 Areal Distribution

Table 6.1 summarizes the areal distribution of annual average wind power for North Carolina. It shows that 0.73% of the land areas experience wind power of class 4 or higher. The effects of scaling the wind power for exposure categories in mountainous terrain, and of the large expanse of class 1 wind power over the lowlands, are evident in the fact that only 9.5% of the land area experiences class 2 or higher wind power. Figure 6.8 shows the areal distribution of wind power for each grid cell of one-third degree longitude by one-fourth degree latitude, giving percent area with wind power greater than or equal to classes 2, 3, 4, and 5. This figure illustrates that exposed ridge crests and mountain summits account for most of the class 4 or higher wind power in the state.

6.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 6.9. Winter is the season of maximum wind power over the ridge crests and mountain summits and over the exposed coastal areas. Spring is the season of maximum wind power over the lowlands between the mountains and the coast, and probably in most sheltered valleys, although the latter features are too small to be depicted on the wind power maps for this area. The French Broad River valley around Asheville is better exposed to the prevailing strong winds because of its northwest to southeast orientation, and experiences maximum wind power during the winter based on surface data located in the valley.

6.2.1 Winter

During the winter, class 7 wind power occurs over most of the exposed ridge crests and mountain summits in western North Carolina. The eastern-most area of mountains is somewhat sheltered by the higher elevations to the west, and thus experiences lower wind power, classes 5 and 6. The foothills and eastern slopes are estimated to experience class 2 wind power, but higher values may be expected

in some of the narrow valleys extending down from the higher ridges and summits. The French Broad River valley experiences class 3 wind power during the winter.

The lowlands are estimated to have class 1 wind power, due to the sheltering effect of the mountains. Surface data from well-exposed sites indicate wind power values approaching class 2, but the uniformity of the terrain and the variability of exposures for existing data locations make it difficult to determine the boundary between class 1 and class 2 wind power, or even to determine if any areas actually do experience class 2 wind power.

Well-exposed coastal sites are estimated to have class 4 and class 5 wind power along the Outer Banks, with classes 2 and 3 extending well inland. The highest wind powers are along the Outer Banks north of Cape Hatteras, due to better exposure to strong prevailing north to northwest winds.

6.2.2 Spring

Class 6 wind power occurs over most of the ridge crest and mountain summit areas during spring. Lower elevation ridges in the northern and eastern portion of the mountainous area experience class 4 and 5 wind power, with class 3 wind power found in the exposed foothills to the east of the main mountain range. Class 2 wind power extends east from the mountains to about Winston-Salem, and is also found in the French Broad River valley around Asheville. The Mid-Atlantic Lowlands experience class 1 wind power during the spring, with the boundary for class 2 wind power varying from about 20 to 40 km (12 to 25 mi) inland in the north to about 10 km (6 mi) inland in the south along the Atlantic coast. Wind power along the Outer Banks is estimated to be class 4 during the spring. The inner banks of the Pamlico and Albemarle Sounds experience class 3 wind power.

6.2.3 Summer

The highest wind power assessed for exposed ridge crests and mountain summits is class 2, and is confined to a relatively small area around Mount Mitchell and the higher elevations in the northwest part of the state. Well-exposed coastal sites are also estimated to have class 2 wind power during summer. The remainder of the state experiences class 1 wind power during summer.

6.2.4 Autumn

The autumn mean wind power for exposed ridge crests and mountain summits ranges from class 2 to class 4. The Mid-Atlantic

Lowlands and valleys experience class 1 wind power. Wind power for exposed coastal sites varies between class 2 and class 3. Due to the prevailing winds from the northeast during autumn, coastal areas north of Cape Hatteras are better-exposed and have higher wind power during this season than areas south of Cape Hatteras. The level of wind power for autumn is difficult to assess for this area due to the limited amount of representative digitized data available, and the possibility that strong winds associated with hurricanes, which are most common during autumn, may have biased the available summarized data.

6.3 FEATURES OF SELECTED STATIONS

Table 6.2 gives the location and annual average wind speed and power density for 18 stations in North Carolina for which digitized data are available from the NCC. Graphs of other features of the wind resource are shown in Figures 6.10 to 6.16. A brief description of each station along with a discussion of the relative representativeness and reliability of the data is presented here.

Asheville is located in the French Broad River valley, which cuts through the Great Smoky and Blue Ridge Mountain ranges, and is oriented northwest-southeast near the Tennessee border and becomes more north-south at the southern end of the valley. Ridge crests and mountain summits rise about 1,200 m (4,000 ft) above the valley floor within about 25 km (15 mi) on either side of the valley. The wind-measuring instruments are located at the airport about 20 km (12 mi) south of the city of Asheville, and their exposure is excellent.

Cape Hatteras is on the easternmost island of the Outer Banks off the coast of North Carolina. Wind measurements are taken at the Weather Office in Buxton, within about 1 kilometer (0.6 mi) of the shoreline. The wind power estimates should be representative of most of the coastal islands, with the instruments mounted on a ground mast at 9.8 m (32 ft). However, obstruction from trees growing around the anemometer may have affected data recorded from approximately 1972 to 1978 (see Section 6.3.1).

Charlotte is located in the southern Piedmont. The wind power estimates should be representative of the surrounding area.

Cherry Point Naval Air Station is located in the Atlantic coastal area at the southern end of Pamlico Sound about 20 km (12 mi) from the shoreline. Wind power estimates may be unrepresentative (low) because of the low anemometer height of 3.7 m (12 ft).

Elizabeth City is located on the tide-water plain in the northeastern part of North Carolina. The wind power estimates may be unrepresentative because of the roof location of the anemometer.

Fayetteville is located on the edge of the Coastal Plain, with the Piedmont Plateau just a few miles to the west. Wind power estimates may be unrepresentative (low) because of the low anemometer height of 4.0 m (13 ft).

Fort Bragg is located north of Fayetteville on the Coastal Plain; with the Piedmont Plateau just to the west. Wind power estimates may be unrepresentative (low) because of the low anemometer height of 4.0 m (13 ft).

Goldsboro is located in the middle of the Coastal Plain. Wind power estimates may be unrepresentative (low) because of the low anemometer height of 4.0 m (13 ft).

Greensboro is located in the northern Piedmont section of North Carolina. The wind power evaluation should be representative of the surrounding areas.

Hatteras, located about 16 km (10 mi) southwest of Cape Hatteras, is the previous location for the Weather Bureau Office now located at Cape Hatteras. Site exposure is considered good, but instrument exposure is unknown. The instruments were located within about 1 km (0.6 mi) of the shoreline on the Pamlico Sound side of Hatteras Island.

Hickory is located in the western part of the state, in the foothills of the Appalachian Mountains. Higher terrain surrounds the airport in all directions but east, and therefore the wind resource at exposed sites is not represented by these data.

Jacksonville is located about 20 km (12 mi) from the Atlantic coast, midway between Wilmington to the southwest and Cherry Point to the northeast. The low anemometer height of 4.0 m (13 ft) makes the representativeness of these data for assessing the wind resource questionable.

Lumberton is located on the Coastal Plain approximately half way between the coast and the Piedmont Plateau. The wind power estimates may be unrepresentative because of the roof location of the anemometer.

New Bern is located on the south banks of the Neuse River, in the tide water plain area. The wind power estimates may be unrepresentative because of the roof location of the anemometer.

Raleigh is located on the border of the Coastal Plain and the Piedmont Plateau. The wind power rating should be representative of the surrounding area. The wind data are recorded at the Raleigh-Durham Airport.

Rocky Mount is located in the northern part of the state on the western edge of the tide water plain. The wind power estimates may be unrepresentative because of the roof location of the anemometer.

Wilmington is located in southeastern North Carolina on the tide water land area with small topographic relief. The wind power classification should be representative of the surrounding inland area.

Winston-Salem is located on the Piedmont Plateau in the north central portion of the state. The wind power estimates may be unrepresentative because of the roof location of the anemometer.

6.3.1 Interannual Wind Power and Speed

Interannual variations of wind power and speed are generally small for those stations with more reliable instrument exposures (Figure 6.10). Stations with long periods of record and anemometers located on a ground mast, away from obstructions, show differences of less than 50% between years of lowest and highest wind power. The effect of anemometer location on wind power estimates is clearly evident in the interannual variations of wind power for Asheville. Data for periods beginning in the late 1950s and early 1960s are generally considered more reliable since observation procedures and anemometer locations were upgraded and made more consistent at most major airports during that time.

The interannual variability for Cape Hatteras is the highest of the stations presented, showing a steep decline in wind power after 1972. Information obtained from the meteorologist at the National Weather Service suggests that the more recent data are unreliable. The anemometer was relocated in early 1978 due to growth of trees around the earlier location. This increase in surface roughness could account for the decline observed in wind power values. Data from Cherry Point Naval Air Station also indicates a steady decline in wind power throughout the data period. The low anemometer height of 3.7 m (12 ft) is an indication of a greater susceptibility of wind power estimates to the influence of changes in surface roughness characteristics.

6.3.2 Monthly Average Wind Power and Speed

All of the stations show a maximum wind power during the months of February and March and minimum power during July and August (Figure 6.11). Peaks of mean wind speed do not always coincide with peaks of wind power, indicating the dependence of wind power on seasonal variations in the wind speed frequency distributions.

6.3.3 Diurnal Wind Speed by Season

Most of the inland stations show similar patterns of diurnal wind speed variations (Figure 6.12). Maximum speeds are during the afternoon between 1200 and 1500 local standard time (LST). The amount of variation appears to be largest during spring and smallest during winter. The two locations near Cape Hatteras on the Outer Banks show much smaller diurnal variation than the inland locations. This is probably due to the fact that the coastal areas experience less stable nighttime conditions in the lower atmosphere due to the difference in radiative cooling rates between land and water. The nighttime land breeze, light to moderate winds blowing offshore, may also contribute to the higher nighttime wind speeds observed for exposed coastal sites.

Data for Asheville show the largest difference between winter and spring diurnal wind speed ranges of all the stations presented. Diurnal data for exposed ridges and summits (not shown) indicate that maximum wind speeds occur at night, in contrast to the pattern for valleys and plains. This was discussed further in Section 2.5.3. The degree of diurnal variation is less for ridges and summits than for lowlands.

6.3.4 Directional Frequency and Average Speed

Most locations show maximum frequencies for wind from the south through southwest directions, with a secondary maximum for north to northeast winds. The high frequency of north and northeast winds for the coastal sites receives its largest contribution from the autumn and winter seasons. Southwest winds prevail during the summer.

Two stations show evidences of channeling of wind flow, Asheville for winds from the north and south, and Hickory for northwest winds. The north and south peaks for Asheville correspond to the orientation of the valley in the vicinity of the airport. The northwest wind direction peak for Hickory appears to be related to a nighttime drainage flow from the mountains northwest of the airport.

6.3.5 Annual Average Wind Speed Frequency

Observer biases are evident in the actual distributions of wind speed for the Hatteras Weather Bureau Office (old location), Hickory, Lumberton, New Bern, and Rocky Mount (Figure 6.14). This bias is reflected in the peaks at 2, 5, and 8 m/s (5, 10, and 15 knots) and is not uncommon at stations with periods of record in the 1940s and 1950s.

6.3.6 Annual Average Wind Speed and Power Duration

The percentage of time 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 usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 6.1. Geographic Map of North Carolina

FIGURE 6.2. Topographic Map of North Carolina

FIGURE 6.3. Land-Surface Form Map for North Carolina

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 6.4. NCC Station Locations in North Carolina

FIGURE 6.5. Location of Stations Used in North Carolina Resource Assessment

FIGURE 6.6. North Carolina 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 ³	Speed, ^(b) m/s(mph)	Wind Power Density watts/m ²	Speed, ^(b) m/s(mph)
0	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 North Carolina

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	110,000	90.	130,000	100.
2	11,000	8.3	12,000	9.5
3	730	0.57	1,600	1.2
4	440	0.34	850	0.67
5	360	0.28	410	0.33
6	57	0.05	57	0.05
7	0	0.00	0	0.00

FIGURE 6.7. Certainty Rating of North Carolina 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 6.8. Areal Distribution of Wind Resource in North Carolina (Classes 2 and 3)

FIGURE 6.8 (Continued). Areal Distribution of Wind Resource in North Carolina (Classes 4 and 5)

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

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

TABLE 6.2. North Carolina Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Annual Average Wind Speed, m/s				Annual Average Wind Power, watts/m ²		
						Anemometer Height, m	At Anemometer Height	At 10 m	At 50 m	At Anemometer Height	At 10 m	At 50 m
Asheville, North Carolina	Asheville Municipal Airport	35.43	82.53	659	09/64-12/78	6.1	3.5	3.8	4.7	69	86	171
Cape Hatteras, North Carolina	Cape Hatteras WBO	35.26	75.54	8	01/65-12/78	9.8	5.1	5.1	6.4	136	137	273
Charlotte, North Carolina	Charlotte Douglas Municipal Airport	35.23	80.93	226	11/60-12/78	6.1	3.3	3.5	4.5	44	54	108
Cherry Point, North Carolina	Cherry Point Marine Corps Air Station	34.89	76.88	11	10/59-12/70	3.7	2.9	3.3	4.1	41	63	126
Elizabeth City, North Carolina	Elizabeth City FSS	36.26	76.18	4	01/65-06/69	8.8	4.1	4.2	5.3	77	81	162
Fayetteville, North Carolina	Fayetteville Pope AFB	35.18	79.02	61	05/60-12/70	4.0	2.1	2.4	3.0	27	40	80
Fort Bragg, North Carolina	Fort Bragg Simmons Field	35.13	78.93	93	03/68-12/70	4.0	1.9	2.2	2.7	19	28	56
Goldsboro/S/J, North Carolina	Seymour-Johnson AFB	35.33	77.96	27	03/65-12/70	4.0	2.5	2.8	3.6	33	49	97
Greensboro, North Carolina	Greensboro-High Point Airport	36.08	79.94	275	04/60-12/78	6.1	3.3	3.5	4.5	44	55	109
Hatteras, North Carolina	Hatteras WBO	35.25	75.66	8	01/48-04/55	14.3	5.6	5.3	6.7	192	165	328
Hickory, North Carolina	Hickory Municipal Airport	35.73	81.38	349	01/49-12/54	10.1	2.6	2.6	3.3	35	35	69
Jacksonville, North Carolina	New River Marine Corps Air Field	34.69	77.41	5	05/68-12/78	4.0	2.5	2.8	3.6	31	46	92
Lumberton, North Carolina	Lumberton CAA	34.61	79.06	39	01/49-12/54	13.7	2.8	2.7	3.4	39	34	68
New Bern, North Carolina	New Bern FSS	35.07	77.03	6	01/49-09/53	17.1	4.0	3.7	4.7	70	56	111
Raleigh/R-D, North Carolina	Raleigh-Durham Airport	35.86	78.78	135	06/63-12/78	6.1	3.6	3.9	4.9	55	68	136
Rocky Mount, North Carolina	Rocky Mount Municipal Airport	35.96	77.79	26	01/49-12/54	18.9	3.4	3.1	3.9	63	48	96
Wilmington, North Carolina	Wilmington-New Hanover Airport	34.26	77.91	14	03/63-12/78	6.1	3.6	3.9	4.9	60	75	149
Winston-Salem, North Carolina	Smith Reynolds Airport	36.13	80.23	303	12/55-12/62	19.2	4.0	3.6	4.6	103	78	155

(a) WBO - Weather Bureau Office; FSS - Flight Service Station; CAA - Civil Aeronautics Administration; AFB - Air Force Base.

FIGURE 6.10. Interannual Wind Power and Speed for North Carolina

FIGURE 6.11. Monthly Average Wind Power and Speed for North Carolina

FIGURE 6.12. Diurnal Wind Speed by Season for North Carolina

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-5 ABSCISSA - WIND DIRECTION

FIGURE 6.13. Directional Frequency and Average Wind Speed for North Carolina

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

PNL-3195 WERA-5

FIGURE 6.14. Annual Average Wind Speed Frequency for North Carolina

ORDINATE - PERCENT
ABSCISSA - M/S
PNL-3195 WERA-5

FIGURE 6.15. Annual Average Wind Speed Duration for North Carolina

ORDINATE - PERCENT
ABSCISSA - WATTS/M²

PNL-3195 WERA-5

FIGURE 6.16. Annual Average Wind Power Duration for North Carolina

TENNESSEE

CHAPTER 7: TENNESSEE

Tennessee covers an area of 109,411 km² (42,244 mi²) and had a population of 3,926,018 in 1970. The population is distributed evenly across the state with the exception of concentrations around the four largest cities (Memphis, Nashville, Knoxville, and Chattanooga), and a decrease of population densities in the mountainous areas in the eastern part of the state. The topography of Tennessee consists of coastal plains in the west, with rolling hills and dissected plateaus in the central portion, rising to the Appalachian Mountains in the east. The elevation varies from an average of 90 m (300 ft) above mean sea level (MSL) in the west to 300 m (1,000 ft) MSL for the central plateaus to over 1,500 m (4,900 ft) MSL in the extreme east.

Figure 7.1 shows the locations of the major geographic features of Tennessee. Topographic relief is shown in Figure 7.2 and land-surface forms in Figure 7.3.

National Climatic Center (NCC) data are available for stations in and around the major population centers of Tennessee, but large areas in the mountainous regions of the east and the hilly areas of south central Tennessee (west of Nashville and east of the Tennessee River) are without any identified surface data (Figure 7.4). Data from the Tennessee Valley Authority (TVA) network screened for this assessment were mostly located in river valleys that are not well-exposed to the strong prevailing winds, or near existing NCC data locations. Figure 7.5 shows the locations of data stations used in the assessment.

7.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in Tennessee is shown in Figure 7.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Table 1.2). 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, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). In mountainous regions, the analyses also reflect major valleys. The percentage of land area that is favorably exposed to the wind strongly

depends on the land-surface form (Table 1.2).

The highest annual average wind power in Tennessee is found on exposed ridge crests and mountain summits in the Great Smoky Mountains in the extreme eastern part of the state, where wind power based on upper-air wind speeds ranges from class 3 to class 6. The higher elevations in the Cumberland Mountains to the west of the Tennessee River Valley are associated with class 3 wind power. The remainder of the state experiences class 1 or class 2 wind power (Figure 7.6). The broad Tennessee River Valley experiences low (class 1) wind power due to the sheltering effect of the mountains to the east and west of the valley.

The hilly area between Nashville and the Tennessee River to the west was assigned class 2 wind power based on the nearest available surface data and a qualitative assessment of the interaction of the wind flow with terrain features. However, the absence of any representative surface data from exposed sites in the area reduces the reliability of this assessment. The area to the south and east of Nashville, known as the Nashville Basin, was assigned class 1 wind power, based primarily on NCC data from the Nashville area and on the sheltering effect of the surrounding hills and plateaus of higher elevation.

7.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for Tennessee vary from 1 to 4 (Figure 7.7). Based on the existence of representative wind data and the simplicity of the terrain, most grid cells along the Mississippi River in the western part of the state received certainty ratings of 3 or 4. Elsewhere, the highest certainty rating (4) was assigned to small areas around the large cities where wind data were adequate. Most grid cells along the Tennessee-North Carolina border were assigned certainty ratings of 1 due to the abrupt change in topography that occurs between the Tennessee River Valley and the Great Smoky Mountain range, and the associated high variability of the wind resource in that area. Also, the hilly areas between Nashville and the Tennessee River and south to the Alabama border received certainty ratings of 1 due to the absence of any representative surface data. Other areas of the state were assigned certainty ratings of 2 or 3 depending on the combined factors of data availability, complexity of terrain, and variability of the wind resource.

7.1.2 Areal Distribution

The areal distribution of wind power for Tennessee is summarized in Table 7.1 for the state, and is shown in Figure 7.8 for each one-third degree longitude by one-fourth degree latitude grid cell. Figure 7.8 gives the percent area with wind power greater than or equal to class 2, 3, 4, and 5 for each grid cell.

Less than 0.5% of the land area in Tennessee has class 3 or higher wind power (Table 7.1), and this is confined to the mountainous areas northwest of Knoxville and along the border with North Carolina. The variety of topographic regimes that are found east of the Tennessee River (from its western passage through the state), combined with the subjectivity of the exposure partitioning schedules and power scaling factors assigned for the various land form types, make it difficult to assess the areal distribution of wind power for Tennessee.

7.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 7.9. Winter is the season of maximum wind power over the exposed ridge crests and mountain summits of Tennessee, as well as over the interior plateaus. Wind power levels in the Tennessee River Valley around Knoxville and Chattanooga are about equal for winter and spring, but remain low throughout the year. A small area along the Mississippi River has maximum wind power during the spring, but levels are only slightly higher than during winter, and the precise extent of this area of spring maximum power is difficult to determine. Summer is the season of lowest wind power potential over the entire state.

7.2.1 Winter

Wind power during winter varies from class 1 in the Tennessee River Valley around Knoxville and Chattanooga, and the Sequatchie River Valley just west of Chattanooga, to class 7 in the Blue Ridge and Great Smoky Mountains along the border with North Carolina. The exposed ridge crests, mountain summits and higher hilltops are estimated to experience at least class 4 wind power during winter. The interior plains and plateaus experience class 2 wind power during winter.

7.2.2 Spring

Class 6 wind power is found over the higher elevations, above about 1,400 m (4,600 ft), of the Blue Ridge and Great Smoky Mountains during spring. Exposed

sites in the Cumberland Mountains experience class 4 wind power, and in the Clinch Mountain area, class 2. The Tennessee and Sequatchie River valleys experience class 1 wind power, and the interior plateaus and plains, class 2.

7.2.3 Summer

Class 1 wind power is found over the entire state during summer, with the exception of the highest elevations of the Blue Ridge and Great Smoky Mountains, which are estimated to experience class 2 wind power. Upper-air wind speeds are low during summer, and surface pressure gradients are weak.

7.2.4 Autumn

Wind power over exposed ridge crests and mountain summits remains low, class 2 and 3, during autumn. This is because upper-air wind speeds are low due to the influence of the semipermanent Bermuda anticyclone over the southeastern part of the United States. River valleys and the inland plains and plateaus experience class 1 wind power during autumn.

7.3 FEATURES OF SELECTED STATIONS

Table 7.2 gives the location and annual average wind speed and power density for 11 stations in Tennessee for which digitized data are available from the NCC. Graphs of other features of the wind resource are shown in Figures 7.10 to 7.16. A brief description of each station including the representativeness and reliability of the data is presented here.

Bristol is located in the center of the northern portion of the Tennessee Valley and is shielded by mountains to the northwest and southeast. The wind power classification is not representative of any of the ridges and crests of the major mountains surrounding the area. The wind measurements are taken at the Tri-City Airport, equidistant from Bristol, Kingsport, and Johnson City, and the exposure of the instruments is excellent.

Chattanooga is located on the Tennessee River in the southern portion of the Tennessee Valley and is sheltered by mountainous ridges to the west and east. The ridges are oriented south-southwest to north-northeast. The wind power classification is representative of the valley floor but not of the ridges. Instrument exposure is excellent.

Dyersburg is located in middle western Tennessee on the alluvial plain of the Mississippi River. The land-form consists

of gently rolling hills, lower to the west and higher to the east. The wind power classification should be representative of the surrounding area, but the instrument exposure is uncertain due to the roof location.

Jackson is located on the eastern edge of the alluvial plain of the Mississippi River, and the gently rolling hills are slightly higher. The wind power classification should be representative of the surrounding area, but the instrument exposure is uncertain due to the roof location.

Knoxville is located in the center of the Tennessee River valley with ridges oriented southwest to northeast located to the east and west of the city. The wind power classification is representative of the valley, but not of the ridges. Wind data are from the McGhee-Tyson Airport located about 18 km (11 mi) south-southeast of the city, and the exposure of the instruments should be excellent.

Memphis, Naval Air Station, is located on the alluvial plain of the Mississippi River about 20 km (12.5 mi) north-northeast of the city of Memphis. There are no major topographic features to affect the exposure of the site, but the low anemometer height of 2.4 m (8 ft) makes the exposure of the wind instruments uncertain.

Memphis is located on an alluvial flood plain with no major topographical relief within 100 km (62 mi). The exposure of the wind measuring instruments is excellent, and the wind power classification should be representative of the surrounding area. The airport is located about 10 km (6 mi) south of the city.

Nashville is located on the Cumberland River in north central Tennessee. The exposure of the wind measuring instruments should be excellent, and the wind power classification should be representative of the basin area to the south and east of Nashville.

Smithville is located about 80 km (50 mi) east of Nashville, near the Caney Fork River. Site exposure is good, but the exposure of the wind instruments is uncertain because of the roof location.

Smyrna/Sewart AFB is located in the Nashville Basin about 24 km (15 mi) south-east of Nashville. The site exposure is representative of the basin area, but instrument exposure is uncertain because of the low anemometer height of 4.6 m (15 ft).

Tullahoma is located on a plateau in south central Tennessee. Site exposure is good, but wind power estimates must be used with caution because of the unknown anemometer height.

7.3.1 Interannual Wind Power and Speed

Interannual variations of wind power are small for most of the stations depicted in Figure 7.10. Memphis Naval Air Station shows the largest variations, with a maximum wind power of more than double the minimum value. This may be related to the low anemometer height of only 2.4 m (8 ft), which is an indication that wind measurements would be very sensitive to changes in surface roughness characteristics and the presence of any buildings in the vicinity of the instruments.

7.3.2 Monthly Average Wind Power and Speed

Most stations show maximum wind power and speed for March (Figure 7.11). The three stations with 1949-1954 periods of record, Dyersburg, Jackson, and Smithville, show January wind power to be equal to or greater than March levels. This appears to be related to the period of record, since all three stations reported January 1950 as having the highest monthly average wind power of the data period. All stations show minimum wind power for July and August.

7.3.3 Diurnal Wind Speed by Season

All of the stations show maximum wind speeds during the afternoon (Figure 7.12), between 1200 and 1500 local standard time (LST). Winter shows the smallest diurnal variation in wind speed. The other seasons show about equal levels of variation.

7.3.4 Directional Frequency and Average Speed

Stations located on the interior plains and plateaus show prevailing winds from the south. (Figure 7.13). The three stations located in the broad Tennessee Valley, Bristol, Knoxville, and Chattanooga, exhibit the channeling effect of the surrounding mountains in their directional frequency distributions. The preferred directions depend on the orientation of the mountains in the vicinity of the station, being north-south for Chattanooga, northeast-southwest for Knoxville, and east-west for Bristol. The highest wind speeds tend to be for directions from south through west to north. The weakest and least frequent winds tend to be from the east except where channeling occurs.

7.3.5 Annual Average Wind Speed Frequency

Observer biases are evident in actual distributions of wind speed for Dyersburg, Jackson, and Smithville (Figure 7.14). This bias is reflected in the peaks at 2, 5, and 8 m/s (5, 10, and 15 knots) and is not uncommon at stations with periods of record in the 1940s and 1950s. Tullahoma, with a data period in the 1960s, also shows some evidence of this bias, but it is less pronounced than for the three stations mentioned.

7.3.6 Annual Average Wind Speed and Power Duration

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

FIGURE 7.1. Geographic Map of Tennessee

FIGURE 7.2. Topographic Map of Tennessee

FIGURE 7.3. Land-Surface Form Map for Tennessee

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 Tennessee

FIGURE 7.5. Location of Stations Used in Tennessee Resource Assessment

FIGURE 7.6. Tennessee 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 ³	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 Tennessee

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	91,000	84.	110,000	100.
2	17,000	16.	17,000	16.
3	240	0.22	400	0.37
4	120	0.11	170	0.15
5	28	0.03	46	0.04
6	18	0.02	18	0.02
7	0	0.00	0	0.00

FIGURE 7.7. Certainty Rating of Tennessee 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>

Class 2

Class 3

FIGURE 7.8. Areal Distribution of Wind Resource in Tennessee (Classes 2 and 3)

Class 4

Class 5

FIGURE 7.8 (Continued). Areal Distribution of Wind Resource in Tennessee (Classes 4 and 5)

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

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

TABLE 7.2. Tennessee Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Annual Average Wind Speed, m/s				Annual Average Wind Power, watts/m ²		
						Anemometer Height, m	At Anemometer Height	At 10 m	At 50 m	At Anemometer Height	At 10 m	At 50 m
Bristol, Tennessee	Bristol Tri-City Airport	36.48	82.40	581	02/62-12/78	6.1	2.4	2.6	3.2	31	39	77
Chattanooga, Tennessee	Chattanooga Lovell Field	35.03	85.19	210	05/64-12/78	6.1	2.7	2.9	3.6	37	46	91
Dyersburg, Tennessee	Dyersburg AAF	36.02	89.40	103	01/49-12/54	11.3	3.7	3.6	4.6	72	68	136
Jackson, Tennessee	Jackson FSS	35.60	88.92	128	01/49-12/54	12.2	3.7	3.6	4.5	65	60	119
Knoxville, Tennessee	Knoxville McGhee- Tyson Airport	35.81	83.98	297	04/63-12/78	6.7	3.0	3.2	4.0	42	50	99
Memphis, Tennessee	Memphis Naval Air Station	35.34	89.86	90	01/69-12/78	2.4	2.9	3.6	4.5	47	87	173
Memphis, Tennessee	Memphis International Airport	35.05	89.98	86	01/65-12/78	6.7	4.0	4.2	5.3	76	90	180
Nashville, Tennessee	Nashville Berry Field	36.11	86.68	183	01/65-12/78	7.6	3.8	4.0	5.0	68	76	152
Smithville, Tennessee	Smithville CAA	35.96	85.78	329	10/49-04/54	7.9	3.2	3.3	4.2	47	52	104
Smyrna, Tennessee	Smyrna Sewart AFB	36.00	86.53	163	04/59-03/70	4.6	2.1	2.3	3.0	28	39	78
Tullahoma, Tennessee	Tullahoma Northern Field	35.38	86.23	329	01/63-07/69	Unk ^(b)	2.1	2.1	2.6	57	57	114

^(a)AAF - Army Air Field; FSS - Flight Service Station; CAA - Civil Aeronautics Administration; AFB - Air Force Base.

^(b)Unk - Anemometer height is unknown. Height of 10 m was assumed for estimating wind speed and power at 10 and 50 m.

FIGURE 7.10. Interannual Wind Power and Speed for Tennessee

FIGURE 7.11. Monthly Average Wind Power and Speed for Tennessee

FIGURE 7.12. Diurnal Wind Speed by Season for Tennessee

— PERCENT FREQUENCY LEFT ORDINATE — PERCENT
 - - - - - WIND SPEED RIGHT ORDINATE — M/S
 PNL-3195 WERA-5 ABSCISSA — WIND DIRECTION

FIGURE 7.13. Directional Frequency and Average Wind Speed for Tennessee

FIGURE 7.14. Annual Average Wind Speed Frequency for Tennessee

ORDINATE - PERCENT
ABSCISSA - M/S
PNL-3195 WERA-5

FIGURE 7.15. Annual Average Wind Speed Duration for Tennessee

ORDINATE - PERCENT
 ABSCISSA - WATTS/M²
 PNL-3195 WERA-5

FIGURE 7.16. Annual Average Wind Power Duration for Tennessee

VIRGINIA

CHAPTER 8: VIRGINIA

Virginia covers an area of 104,084 km² (40,817 mi²) and had a 1970 population of 4,651,448. The western mountainous areas are sparsely populated, while most of the population is in the lowlands with major concentrations in the areas of Washington, D.C., Richmond, and Norfolk. The topography of Virginia varies from coastal (Atlantic Ocean and Chesapeake Bay areas) to mountainous (Blue Ridge and Allegheny Mountains in the west), with the Piedmont Plateau traversing the central part of the state. The average elevation varies from 6 m (20 ft) above mean sea level (MSL) on the coast to 750 m (2,500 ft) MSL in the mountains. Most of the hilly Piedmont area averages approximately 120 m (400 ft) elevation.

Figure 8.1 shows the locations of the major geographic features of Virginia. Topographic relief is shown in Figure 8.2 and land-surface form in Figure 8.3.

National Climatic Center (NCC) data (Figure 8.4) are adequate around the major population centers in the eastern part of the state, but are very limited in the mountainous areas to the west. Data from the Piedmont area between the mountains and the coastal plains is scattered, with large areas without any NCC data. Data from numerous military and coast guard installations supplement National Weather Service and Federal Aviation Administration airport data in the coastal areas. Figure 8.5 shows the locations of data stations used in the assessment. Results from previous studies of coastal zone wind energy (Garstang, et al. 1978) were also incorporated into the assessment for coastal areas.

8.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in Virginia is shown in Figure 8.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Table 1.2). 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, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). In mountainous regions, the analyses also reflect major valleys.

In coastal areas, the estimates are representative of well-exposed land sites along the shoreline. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Table 1.2).

Annual average wind power for Virginia (Figure 8.6) ranges from class 5 for exposed ridge crests in the Allegheny Mountains of west central Virginia and class 3 and 4 over most of the Blue Ridge Mountains, to class 1 over the valleys and Mid-Atlantic Lowlands, and class 3 and 4 over exposed coastal sites on the Atlantic Ocean and Chesapeake Bay.

The mountainous areas of Virginia can be divided into distinct provinces based on their geomorphological characteristics. From east to west, beginning with the Blue Ridge Mountains, these provinces are known as the Blue Ridge, the Valley and Ridge, and the Appalachian Plateaus provinces (Fenneman 1938). Mountains in the Blue Ridge province are dissected by numerous valleys and gorges extending down from prominent summits. Elevation varies considerably along the ridge line. The Valley and Ridge province is characterized by a series of parallel ridges and valleys which are oriented in a general northeast-southwest direction. The ridges are less dissected than in the Blue Ridge province, with fewer prominent summits and less variation in elevation along the ridge lines. The Appalachian Plateaus province, which covers a small portion of southwestern Virginia north of the Clinch River, lacks the well-defined ridges of the Blue Ridge and the Valley and Ridge provinces, but is mountainous by virtue of mature erosion from many rivers and streams. These differences also have implications for the wind power characteristics which can be expected for the different regions, since terrain variations interact strongly with the surface windflow.

Because of their dissected structure, areas of the Blue Ridge Mountains may be expected to experience enhanced wind power potential due to the channelling of wind flow in the lateral valleys and gorges which broaden as they extend down from the major summits, and the venturi speed-up effect of wind flow through gaps between the mountain peaks.

Because the Allegheny Mountains are not dissected by lateral valleys and have fairly uniform ridge crest elevations, the wind flow over the mountains in the Valley and Ridge province will experience enhanced wind power on the windward slopes

and at ridge crests as a result of the venturi effect. Leeward slopes and valleys should experience low wind power. Gaps between ridge lines can also be expected to experience enhanced wind power. The lower elevation ridges may not experience any wind power enhancement and may even experience lower wind power due to sheltering by higher ridges, depending on the difference in elevation and proximity of the higher ridges.

The area of the Appalachian Plateaus province is not as favorable for wind power enhancement because of the absence of prominent terrain features such as mountain summits and well-defined ridge crests.

Much of Virginia's mountainous area is favorable for the kind of wind power enhancement described above, because of the orientation of the ridges perpendicular to the strong prevailing winds from the west through north. However, most of these features are of too small a scale to be represented on the wind power maps.

In coastal areas, wind power may vary substantially depending upon the exposure and orientation of a coastal site with respect to the over-water fetch of the prevailing winds, since the frictional drag on surface winds over water is much lower than over land surfaces. Thus, isolated islands and prominences on the coastline may experience wind power values one or possibly two classes higher than nearby sites on inlets or just inland.

8.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for Virginia are presented in Figure 8.7 for each one-third degree longitude by one-fourth degree latitude grid cell. Many of the grid cells in the mountainous areas received certainty ratings of 1 because of the complexity of the terrain, the high variability of the wind resource, and the absence of any representative surface data to supplement the estimates based on upper-air wind data. Certainty ratings of 2 were assigned to areas in the mountainous region where the variability of the resource was lower. Certainty ratings for the piedmont and coastal plains range from 2 for data-sparse areas, to 4 around the major population centers where data were generally adequate for characterizing the wind resource. Areas with only limited data received certainty ratings of 3. Certainty ratings of 3 were assigned to most of the exposed coastal areas of the Atlantic Ocean and Chesapeake Bay, even though data are available for several lo-

cations in the area. This is because much of the coastal data are of limited reliability, due to the short period of record and approximations used for unsummarized NCC data, the questionable quality of the early Coast Guard wind summaries which used very broad wind speed classes to report frequency distributions, and the questionable exposure of the wind measuring instruments at some of the naval facilities. In addition, the variability of the wind resource contributed to the lower certainty ratings for the coastal areas.

8.1.2 Areal Distribution

Table 8.1 summarizes the areal distribution of annual average wind power for Virginia. Figure 8.8 gives the percentage of land area for each grid cell which equals or exceeds a wind power of class 2, 3, 4, and 5. Nearly 1.0% of the land area experiences class 4 or higher wind power. The largest contribution to this 1.0% land area is from exposed ridge crests and mountain summits, with a smaller, but significant, contribution from exposed coastal sites on the Atlantic Ocean.

8.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 8.9. Winter is the season of maximum wind power over the ridge crests and mountain summits and over the exposed coastal areas. Spring is the season of maximum wind power over the lowlands between the mountains and the coast, and in the broad Shenandoah Valley. The maximum season of wind power for the Shenandoah Valley is based on data for Front Royal located in the northern portion of the valley. It is likely that most valleys in the mountainous areas of Virginia experience maximum wind power during spring (see Section 2.4). Summer is the season of lowest wind power potential for Virginia.

8.2.1 Winter

Exposed ridge crests and mountain summits experience at least class 6 wind power during winter, except for the lower ridges in the extreme north which are class 5, based on estimates from upper-air wind data. The Shenandoah Valley experiences class 2 wind power, but narrower valleys to the west are more sheltered from the prevailing winds and are expected to have class 1 wind power. The lowlands between the mountains and the coast experience class 1 wind power during winter, with the mountains acting as a partial barrier to the prevailing winds. The northern piedmont area is less sheltered from pre-

vailing winds and is estimated to have class 2 wind power. Exposed coastal sites on the Chesapeake Bay and Atlantic Ocean are estimated to have at least class 4 wind power during winter, with the eastern shore of the Bay assessed as class 5 due to its better exposure to the strong prevailing winds from the northwest and north. Class 2 or higher wind power extends about 20 km (12.5 mi) inland south of Norfolk and more than 50 km (30 mi) inland just south of the Potomac River. The location of the boundary between class 1 and class 2 wind power in the coastal area is based on the observed variation for existing data locations and a qualitative assessment of the effect of attenuation of wind power by the higher surface roughness. Because of the necessary qualitative assessment, the determination of this boundary is of limited reliability.

8.2.2 Spring

Exposed ridge crests and mountain summits experience at least class 4 wind power during spring, with the exception of the lower ridges in the extreme north which have class 3 wind power. The Shenandoah Valley and the upper piedmont to the south and east of Roanoke, experience class 2 wind power. The coastal and lowland areas show wind power levels about the same as winter levels, being somewhat higher than winter over the inland areas and somewhat lower than winter along the coast.

8.2.3 Summer

The maximum wind power during the summer is class 2, and is confined to the higher ridges of the Allegheny Mountains in west central Virginia and to well-exposed coastal sites along the Chesapeake Bay and the Atlantic Ocean. The remaining areas are estimated to experience class 1 wind power during summer.

8.2.4 Autumn

The maximum wind power during autumn is class 3. Classes 2 and 3 wind power are experienced over the exposed ridge crests and mountain summits. Exposed coastal sites also experience class 3 wind power during autumn. Valleys and the Mid-Atlantic Lowlands experience class 1 wind power. The summarized and unsummarized coastal and offshore data south of Cape Henry (east of Norfolk) show autumn wind power to be equal to or higher than spring levels in this area. This may be related to a shift in prevailing wind direction to northeast for autumn from southwest for spring and summer. However, it is difficult to determine the wind power along the coast for autumn since strong winds associated with hurricanes, which are most

common during autumn, may have biased the available summarized and unsummarized data.

8.3 FEATURES OF SELECTED STATIONS

Table 8.2 gives the location and annual average wind speed and power density for 21 stations in Virginia for which digitized data are available from the NCC. Graphs of other features of the wind resource are shown in Figures 8.10 to 8.16. A brief description of each station along with the representativeness and reliability of the data is presented here.

Blackstone is located on the Piedmont Plateau, just west of the fall line which separates the piedmont from the coastal plain, and about 65 km (40 mi) southwest of Richmond. The site has good exposure on the uplands, but the wind data may be unrepresentative because of the roof location of the anemometer.

Charlottesville is located in the foothills of the Blue Ridge Mountains in central Virginia. Wind measurements are taken at Albemarle Airport about 10 km (6 mi) north of the city. Instrument exposure should be excellent, but the site is sheltered by ridges 900 m (3,000 ft) high to the northwest and 300 m (1,000 ft) high to the southeast.

Chincoteague is located on the Chincoteague Bay which separates Assateague Island, forming the outer banks of the Atlantic Coast, and the mainland of the Delmarva Peninsula. It is a well-exposed coastal site, but instrument exposure may be poor due to the roof location. Measurements were taken at the Naval Air Station on Chincoteague Island.

Danville is located on the central piedmont in southern Virginia. Site and instrument exposure are uncertain.

Davison AAF is located on the coastal plain about 32 km (20 mi) southwest of Washington, D.C., with low to moderate relief west of the site. Wind power estimates may be unrepresentative (low) because of the low anemometer height of 4.6 m (15 ft).

Fort Eustis is located on the north bank of the James River about 50 km (30 mi) northwest of Norfolk. The wind power estimates may be unrepresentative because of the roof location of the anemometer.

Front Royal is located in the northern portion of the Shenandoah Valley. Data were collected at a Civil Aeronautics Administration facility located about 15 km (9 mi) north-northwest of the city, just

north of Massanutten Mountain in the center of the valley. The site should be representative of locations on the valley floor, but instrument exposure is unknown.

Gordonsville is located in the foothills of the Blue Ridge Mountains, about 30 km (20 mi) east of Charlottesville. The site is partially sheltered by a 400-m (1300 ft)-high ridge, 8 km (5 mi) to the northwest of the station.

Hampton (Langley Air Force Base) is located on the stretch of land between the James and York Rivers about 30 km (20 mi) northwest of Norfolk. It is a well-exposed coastal site, but wind power estimates may be unrepresentative (low) because of the low anemometer height of 4.0 m (13 ft).

Lynchburg is located adjacent to the foothills of the Blue Ridge Mountains on the piedmont uplands. The instrument exposure should be excellent, but the site is sheltered by mountains and hills to the northwest.

Norfolk is located on the south bank of the mouth of the James River in southern Virginia. Data are presented for Norfolk Naval Air Station (NAS) and Norfolk Regional Airport, about 12 km (7.5 mi) apart. Both sites are within a few kilometers of the southern end of the Chesapeake Bay. The instrument exposure is expected to be better for the airport than for the NAS due to the low anemometer height of 4.6 m (15 ft) for the latter.

Oceana NAS is located about 29 km (18 mi) southwest of Norfolk and within 10 km (6 mi) of the Atlantic coast. Site exposure is excellent, but wind power estimates may be unrepresentative (low) because of the low anemometer height of 4.0 m (13 ft).

Pulaski is located in southwestern Virginia near the transition between the Blue Ridge and Valley and Ridge provinces. Ridges about 300 m (1000 ft) higher than the elevation of the station are about 8 km (5 mi) to the northwest, with higher elevations farther west. Site and instrument exposure are unknown. (Data may be representative of broad valleys in the region).

Quantico is located on the west bank of the Potomac River about 50 km (30 mi) southwest of Washington, D.C., with hills rising to an elevation of about 120 m (400 ft) within a short distance west of the site. Wind power estimates may be unrepresentative of the plains and tablelands to the north and west of the site because of the sheltering effect of the nearby hills

and the low anemometer height of 4.3 m (14 ft).

Richmond is located in the central part of the state at the fall line which separates the Piedmont Plateau to the west from the Coastal Plain to the east. Byrd International Airport is located east of the city, on the Coastal Plain. Site exposure is representative of the Coastal Plain but may not be representative of the Piedmont areas to the west. Instrument exposure is excellent.

Roanoke is located in a major gap in the Blue Ridge Mountain Range at the southern end of the Shenandoah Valley. Site exposure is not representative of the uplands, and may not be representative of the lowlands to the south and east, but instrument exposure should be excellent.

Urbanna is located on the south bank of the Rappahannock River, about 25 km (15 mi) from the Chesapeake Bay. Site exposure is good, but wind power estimates may be unrepresentative because of the roof location of the anemometer, the short period of record, and the daytime-only observations.

Wallops Island is located on the Atlantic side of the Delmarva Peninsula, across the bay from Chincoteague. The site has good exposure, but instrument exposure is uncertain because of the roof location of the anemometer.

Dulles International Airport is located on the tablelands west of Washington, D.C. Site and instrument exposure are excellent.

Washington National Airport is located on the west bank of the Potomac River just south of Washington, D.C. Site and instrument exposure are excellent.

8.3.1 Interannual Wind Power and Speed

Interannual variations of wind power and speed are generally small for those stations with more reliable instrument exposures (Figure 8.10). Hampton (Langley Air Force Base) shows the largest interannual variations. These variations are not reflected in data for other nearby stations, suggesting that the instrument exposure may be unrepresentative for wind power calculations.

8.3.2 Monthly Average Wind Power and Speed

All of the stations show maximum wind power for December through April (Figure 8.11), with some showing pronounced monthly peaks, such as the March maximum for Front Royal, and others showing fairly uniform

wind power levels throughout winter and spring, such as Blackstone and the Norfolk Regional Airport.

8.3.3 Diurnal Wind Speed by Season

All of the stations show maximum wind power during the afternoon (Figure 8.12), between 1200 and 1500 local standard time (LST). Spring has the highest and winter the lowest diurnal variation for most stations; and coastal locations show smaller variations than inland stations. Data for Urbanna do not show the complete diurnal cycle, but the pattern is evident from the data available.

8.3.4 Directional Frequency and Average Speed

Peak frequencies are for winds out of the south through southwesterly directions for most stations (Figure 8.13). Data for Pulaski, Quantico and Roanoke show evidence of channelling by local terrain features. Most stations show maximum wind speeds for winds from the west through northwest, with coastal sites showing high wind speeds for directions with a long over-water fetch.

The absence of the wind speed maximum for winds from the northwest at Quantico is evidence of the possible influence of the hills to the west and north of the site on wind speed measurements.

8.3.5 Annual Average Wind Speed Frequency

Observer biases are evident in the actual distributions of wind speed for all stations with periods of record in the 1940s and 1950s (Figure 8.14). This bias is reflected in the peaks at 2, 5, and 8 m/s (5, 10, and 15 knots) and is not uncommon for data collected during that period.

8.3.6 Annual Average Wind Speed and Power Duration

The percentage of time 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 usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity. The higher wind speed and power duration curves for coastal sites can be related in part to the smaller diurnal variations of those sites.

0 50 100 105 200 Miles

0 50 100 150 200 Kilometers

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FIGURE 8.2. Topographic Map of Virginia

FIGURE 8.3. Land-Surface Form Map for Virginia

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 8.4. NCC Station Locations in Virginia

FIGURE 8.5. Location of Stations Used in Virginia Resource Assessment

FIGURE 8.6. Virginia 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 ³	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 Virginia

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	9,200	88.	100,000	100.
2	7,700	7.4	12,000	12.
3	3,700	3.6	4,800	4.6
4	980	0.94	1,000	0.98
5	48	0.05	48	0.05
6	0	0.00	0	0.00
7	0	0.00	0	0.00

FIGURE 8.7. Certainty Rating of Virginia 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>

Class 2

Class 3

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FIGURE 8.8. Areal Distribution of Wind Resource in Virginia (Classes 2 and 3)

Class 4

Class 5

FIGURE 8.8 (Continued). Areal Distribution of Wind Resource in Virginia (Classes 4 and 5)

WINTER

SUMMER

0 50 100 150 200 Miles

0 50 100 150 200 Kilometers

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

SPRING

AUTUMN

0 50 100 150 200 Miles

0 50 100 150 200 Kilometers

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

TABLE 8.2. Virginia Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s			Annual Average Wind Power, watts/m ²		
							At Anemometer Height	At 10 m	At 50 m	At Anemometer Height	At 10 m	At 50 m
Blackstone, Virginia	Blackstone CAA	37.08	77.94	134	10/50-12/58	7.9	3.4	3.5	4.4	50	55	110
Charlottesville, Virginia	Charlottesville Albemarle Airport	38.13	78.44	193	04/61-12/64	6.1	2.7	2.9	3.6	28	35	69
Chincoteague, Virginia	Chincoteague Naval Air Station	37.93	77.43	15	02/51-04/58	22.6	5.4	4.8	6.0	179	126	252
Danville, Virginia	Danville Municipal Airport	36.56	79.33	176	02/49-12/54	10.7	3.2	3.2	4.0	48	47	93
Davison, Virginia	Davison AAF	38.72	77.18	20	04/62-12/70	4.6	1.9	2.1	2.7	30	42	83
Fort Eustis, Virginia	Fort Eustis Felker AAF	37.13	76.59	7	11/60-04/67	18.3	3.5	3.2	4.0	65	50	100
Front Royal, Virginia	Front Royal CAA	39.00	78.23	208	09/49-02/56	7.6	3.5	3.6	4.6	79	89	177
Gordonsville, Virginia	Gordonsville CAA	38.06	78.14	135	09/50-12/58	8.5	2.8	2.9	3.6	46	49	98
Hampton, Virginia	Hampton Langley AFB	37.06	76.36	13	05/57-12/70	4.0	3.7	4.2	5.3	83	123	245
Lynchburg, Virginia	Lynchburg Municipal Airport	37.33	79.19	291	09/67-12/78	6.1	3.2	3.4	4.3	41	51	102
Norfolk, Virginia	Norfolk Naval Air Station	36.94	76.28	6	01/56-12/78	4.6	3.8	4.2	5.3	79	110	220
Norfolk, Virginia	Norfolk Regional Airport	36.89	76.19	13	08/73-12/78	6.1	4.6	4.9	6.2	111	138	275
Oceana, Virginia	Oceana Naval Air Station	36.83	76.03	8	02/60-12/78	4.0	3.1	3.5	4.4	52	77	153
Pulaski, Virginia	Pulaski New River Airport	37.08	80.78	668	01/49-12/54	16.5	4.3	4.0	5.0	108	87	174
Quantico, Virginia	Quantico Marine Corps Air Station	38.50	77.30	4	08/60-12/78	4.3	2.5	2.8	3.5	30	43	86
Richmond, Virginia	Richmond Byrd Field	37.50	77.33	50	11/61-12/78	6.1	3.3	3.5	4.5	43	53	106
Roanoke, Virginia	Roanoke Woodrum Field	37.31	79.96	364	03/66-12/78	9.1	3.8	3.9	4.8	75	78	156
Urbanna, Virginia	Urbanna Aviation Reports	37.63	76.58	27	04/49-03/51	14.3	3.7	3.5	4.4	57	49	97
Wallops Island, Virginia	Wallops Island WBO	37.84	75.48	4	10/66-12/78	10.7	5.0	5.0	6.2	160	155	310
Wash/Dulles, Virginia	Washington, D.C. Dulles Int. Airport	38.94	77.44	94	11/62-12/78	6.1	3.4	3.6	4.6	64	79	158
Wash/National, Virginia	Washington, D.C. National Airport	38.84	77.03	20	09/60-12/78	6.1	4.0	4.3	5.4	77	95	190

(a) CAA - Civil Aeronautics Administration Facility; AAF - Army Air Field; AFB - Air Force Base; WBO - Weather Bureau Office.

FIGURE 8.10. Interannual Wind Power and Speed for Virginia

FIGURE 8.10 (Continued). Interannual Wind Power and Speed for Virginia

FIGURE 8.11. Monthly Average Wind Power and Speed for Virginia

FIGURE 8.11 (Continued). Monthly Average Wind Power and Speed for Virginia

+---+ WINTER ◆---◆ SPRING
 ⊕---⊕ SUMMER ⊞---⊞ AUTUMN

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ORDINATE - M/S
 ABSCISSA - HOUR

FIGURE 8.12. Diurnal Wind Speed by Season for Virginia

FIGURE 8.12 (Continued). Diurnal Wind Speed by Season for Virginia

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-5
 ABSCISSA - WIND DIRECTION

FIGURE 8.13. Directional Frequency and Average Wind Speed for Virginia

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-5 ABSCISSA - WIND DIRECTION

FIGURE 8.13 (Continued). Directional Frequency and Average Wind Speed for Virginia

— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 - - - RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3195 WERA-5

FIGURE 8.14. Annual Average Wind Speed Frequency for Virginia

—— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 ----- RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3195 WERA-5

FIGURE 8.14 (Continued). Annual Average Wind Speed Frequency for Virginia

ORDINATE - PERCENT
 ABSCISSA - M/SEC
 PNL-3195 WEHA-b

FIGURE 8.15. Annual Average Wind Speed Duration for Virginia

ORDINATE -- PERCENT

ABSCISSA -- M/S

PNL-3195 WERA-5

FIGURE 8.15 (Continued). Annual Average Wind Speed Duration for Virginia

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WERA-5

FIGURE 8.16. Annual Average Wind Power Duration for Virginia

ORDINATE - PERCENT
 ABSCISSA - WATTS/M²
 PNL-3195 WERA-5

FIGURE 8.16 (Continued). Annual Average Wind Power Duration for Virginia

WEST VIRGINIA

CHAPTER 9: WEST VIRGINIA

West Virginia covers 549,666 km² (214,181 mi²) and its 1970 population was 1,744,237. Most of the population is located in the valleys of this mainly mountainous state. The major towns with their concentration of people are on the western edge of the state. The topography of West Virginia consists of a hilly area in the west and the Appalachian Mountains in the east. The average elevation in the west is about 230 m (750 ft) above mean sea level (MSL), increasing to over 1200 m (4000 ft) MSL in the Allegheny Mountains in the east. The extreme eastern part of the state, around Martinsburg, is a broad valley with elevations below 300 m (1000 ft) MSL. The highest point in West Virginia is Spruce Knob at 1482 m (4862 ft) MSL.

Figure 9.1 shows the locations of the major geographic features of West Virginia. Topographic relief is shown in Figure 9.2 and land-surface form in Figure 9.3.

National Climatic Center (NCC) data are limited to locations around the major cities of West Virginia, leaving large areas of the state, primarily in the central region, without any representative wind data (Figure 9.4). Moreover, most of the stations are located in the narrow valleys of the highly dissected plateaus in the west or in sheltered valleys in the mountainous region. Several fossil-fuel power plants with summarized wind data were identified for West Virginia. Only those located on uplands were used in the assessment, eliminating about one-half of the stations identified. Figure 9.5 shows the locations of data stations used in the assessment for West Virginia.

9.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density in West Virginia is shown in Figure 9.6. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Table 1.2). 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, the estimates are representative of large clearings with good exposure to the prevailing strong winds, such as airports, where runways are generally aligned parallel to the prevailing wind direction(s). In mountainous regions, the analyses also reflect major valleys. The percentage of

land area that is favorably exposed to the wind strongly depends on the land-surface form (Table 1.2).

The highest annual average wind power in West Virginia is class 5 (Figure 9.6), and extends over a large area of the higher elevations of the Allegheny Mountains, above about 1200 m (4000 ft) MSL, east of the Tygart Valley around Elkins. Wind power decreases to the west and to the east as elevations decrease. The boundary between class 1 and class 2 wind power in the west is estimated to run south from Parkersburg to just west of Charleston, and southwest from Charleston to the Kentucky border about 50 km (30 mi) south of Huntington. However, the sparsity of surface data for well-exposed sites in the plateau areas makes it very difficult to assess the location of this boundary. Valleys cut into the plateau and sheltered valleys and basins in the mountains are expected to experience class 1 wind power based on data for several valley locations.

Wind power estimates, based on upper-air wind data, for exposed ridge crests and mountain summits of the Allegheny Mountains were supplemented by summarized wind data from a two-level meteorological tower located near Mount Storm, approximately 70 km (45 mi) northeast of Elkins at an elevation of about 975 m (3200 ft) MSL. These data tended to support the reliability of the estimates based on upper-air wind data. However, it should be noted that significant areas in the Allegheny Mountains of West Virginia have an upland plateau structure, with more than 50% of the gently sloping area on the uplands (class c and d profile type in Hammond's land-surface form classification, see Section 1.8 and Figure 9.3). The increased surface drag due to friction on the windflow over the gently sloping uplands will tend to reduce wind power values below the levels estimated from upper-air wind speeds for some areas, since the upper-air estimates depend primarily on elevation of the ridges and summits. In these areas the map values will be representative of the exposed ridge crests and mountain summits which rise above the plateau level. Since enhanced wind power can be expected around certain topographic features (see Section 8.1), the map values are expected to be lower limits of wind power for well-exposed sites. The Allegheny Mountains, east of a line through Elkins and Bluefield, are in the Valley and Ridge province and are more favorable for wind power enhancement than the Appalachian Plateaus province (which includes the Allegheny Plateau).

A note should be made regarding the area of class 3 wind power located outside of the shaded area, to the west of the Tygart Valley, and why it has higher wind power than the class 2 shaded area to the southwest. The shaded area on the wind power maps indicates local relief of at least 300 m (1000 ft), or class 5 and 6 in Hammond's land-surface form classification for local relief (see Section 1.8 and Figure 9.3). Ridge crest and mountain summit elevations are similar in the two areas, but mean upper-air wind speeds increase to the north. The difference in upper-air wind speeds accounts for the difference in wind power between the areas.

9.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for West Virginia are presented in Figure 9.7 for each one-third degree longitude by one-fourth degree latitude grid cell. Most of the state received a certainty rating of 2 based on the use of upper-air wind data for estimates over ridge crests and mountain summits. A few grid cells in the northern part of the Allegheny Mountains received certainty ratings of 3 because the upper-air estimates were supplemented by surface data from exposed sites (one located in West Virginia and two located in western Maryland). The grid cell around Martinsburg in eastern West Virginia also received a certainty rating of 3. Certainty ratings of 1 were assigned to a few areas in the mountains where the variability of the wind resource is very high.

9.1.2 Areal Distribution

Table 9.1 summarizes the areal distribution of annual average wind power for West Virginia. Figure 9.8 gives the percent land area for each grid cell which experiences wind power greater than or equal to class 2, 3, 4, and 5. The effect of exposure partitioning on the distribution of wind power is very evident in the results for West Virginia, because most of the state is mountainous or hilly with a large percentage of the land area being sheltered from the strong prevailing winds. Whereas more than 90% of the grid cells were assigned wind power of class 2 or higher for exposed locations (Figure 9.8), only 6.2% of the land area of the state actually experiences class 2 or higher wind power. The effect of the large extent of the mountainous areas of West Virginia on areal distribution of the wind resource is also evident from a comparison with other states of the region (see Table 2.2). West Virginia has the highest percentage of land area which experiences

class 5 or higher wind power of all the states in the region, but has the second lowest percentage of land area with at least class 2 wind power (i.e., the second highest percentage land area with only class 1 wind power).

9.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 9.9. Winter is the season of maximum wind power over the entire state, except for sheltered valleys and basins in the mountainous areas where spring wind power is expected to be about equal to or higher than winter wind power. Data for three sheltered locations in the mountains support this assessment of seasonal maximum for valleys and basins. Summer is the season of lowest wind power over the entire state.

9.2.1 Winter

Class 7 wind power is estimated for most of the exposed ridge crest and mountain summit areas of the Allegheny Mountains. Uplands on the Appalachian Plateaus are estimated to vary from class 2 wind power in the far western portions around Huntington, to class 5 in the uplands west of Elkins where elevations exceed about 600 m (2000 ft). Lower ridges in eastern West Virginia are estimated to experience class 5 wind power. Sheltered valleys and basins are estimated to have class 1 wind power except for the broad valley around Martinsburg which experiences class 2 wind power.

9.2.2 Spring

Spring wind power ranges from class 1 in the basin along the Ohio River between Huntington and Parkersburg and in the sheltered valleys and basins, to class 5 over the Allegheny Mountains, with class 2 over the Appalachian Plateaus and in the broader valleys to the east. The lower ridges of eastern West Virginia experience class 3 wind power during spring.

9.2.3 Summer

The highest wind power during summer is class 2 and is confined to the higher elevations of the Allegheny Mountains east of Elkins. The remainder of the state experiences class 1 wind power during summer.

9.2.4 Autumn

The highest wind power during autumn is class 4 and occurs over the Allegheny Mountains east of Elkins, and in the northwestern portion of the mountains. The class 4 wind power in the north is attributed to the fact that outbreaks of polar air, with

associated strong surface pressure gradients, begin to penetrate into the area during autumn. These outbreaks do not affect the southern part of the state with much frequency until winter, and as a result, wind power is much lower to the south (classes 2 and 3). The valleys and basins and most of the Appalachian Plateaus experience class 1 wind power during autumn.

9.3 FEATURES OF SELECTED STATIONS

Table 9.2 gives the location and annual average wind speed and power density for 10 stations in West Virginia for which digitized data are available from the NCC. Graphs of other features of the wind resource are shown in Figures 9.10 to 9.16. A brief description of each station along with the representativeness and reliability of the data is presented here.

Beckley is located in the southcentral part of the state on the Appalachian Plateaus. The airport is located on a plateau about 150-250 m (500-800 ft) lower than surrounding plateau levels. The site exposure is considered moderate, but instrument exposure is uncertain because of the roof location.

Charleston is located in the eastcentral part of the state along the Kanawha River. Like Beckley, the airport is located on a plateau which is lower, about 150 m (500 ft), than surrounding plateaus. The site exposure is thus moderate, but the instrument exposure should be excellent.

Elkins is located in the Tygart River Valley in eastcentral West Virginia. The valley is oriented in a north-south direction. Ridges rise to about 400 m (1300 ft) above the valley floor within 6 km (4 mi) to the east and west of the airport, being somewhat more abrupt to the west. The wind measurements will be strongly influenced by the valley circulation. Instrument exposure should be excellent.

Huntington is located on the Ohio River in the most western part of the state. The Ohio River Valley is about 100 m (300 ft) deep and quite narrow at this point. Data are available for a Federal Aviation Administration (FAA) facility on the valley floor and for the Tri-State Airport located on a plateau south of the city. The former site is not well-exposed to the strong prevailing winds due to the valley location, and the latter location has moderate exposure with plateau elevations increasing steadily to the south and east. Instrument exposure for the FAA site is uncertain, but should be excellent for the Tri-State Airport.

Martinsburg is located in a broad valley in extreme eastern West Virginia. Data should be representative of the valley floor, but not of the ridges located to the northwest and southeast.

Morgantown is located in the northern part of the state, just west of the mountainous area. Instrument and site exposure are uncertain due to local topography and anemometer location.

Parkersburg is located on the Ohio River about midway between Huntington and Wheeling. The data presented are from a location in the river valley which is about 120 m (400 ft) deep at this point. Data are unrepresentative of exposed sites due to the sheltering effect of the valley walls.

Petersburg is located in a valley east of the highest ridges of the Allegheny Mountains. Data are representative of the valley floor, but not of surrounding ridges.

Wheeling is located on the Ohio River in the northern panhandle of the state. The airport is on a plateau above the river valley, about 16 km (10 mi) north of the city of Wheeling. Data are considered to be moderately representative of the plateau areas in the panhandle.

9.3.1 Interannual Wind Power and Speed

Interannual variations of wind power and speed are small for most of the stations presented in Figure 9.11. Martinsburg shows the largest variation for stations with periods of record of at least five years, with maximum wind power about twice the lowest values. These figures suggest that interannual variability of wind power is low for locations in the lowlands of the state, but no conclusions can reliably be drawn about the variability of the resource for exposed ridge crests and mountain summits. This is because of the lack of long-term data for exposed mountainous sites and the fact that since the lowlands are partially sheltered from prevailing winds over the region, they will be less influenced by the variability of these winds.

9.3.2 Monthly Average Wind Power and Speed

Most stations show maximum wind power for March (Figure 9.11), decreasing to a minimum for July and August. Elkins and Petersburg, both located in sheltered valleys in the Allegheny Mountains, show higher wind power levels maintained into April than for most other stations. This is indicative of the spring maximum expected for sheltered areas. The three

stations located farthest north, Morgantown, Parkersburg, and Wheeling, show wind power for November to be about equal to or higher than for December, a feature which is absent for stations located farther south. This may be taken as evidence of the influence of cold polar outbreaks on the northern portion of the state during late autumn referred to in Section 9.2.4.

9.3.3 Diurnal Wind Speed by Season

All of the stations show maximum wind speeds during the afternoon (Figure 9.12), between 1200 and 1500 local standard time (LST), but considerable differences are evident in some of the features of diurnal variation. Diurnal variation in wind speed is smallest for winter, but upland locations, Charleston, Huntington Tri-State, and Wheeling, show distinctively less variation than lowland locations. This is characteristic of the better exposed sites in mountainous or hilly terrain. Elkins shows the unique feature of a bimodal variation with wind speed increasing after the late-afternoon decline to a maximum around 2400 to 0100, and then declining again in early morning. This pattern is most pronounced in autumn. This is due to the drainage of cold air into the valley from the ridge tops to the west, which begins shortly after sunset and continues until the temperature difference between valley and ridge top has been minimized. The high level of wind speeds associated with the drainage flow, relative to daytime levels, is probably due to the steep slope of the ridge to the west of the airport. The low upper-air wind speeds and relatively dry atmosphere during autumn probably contribute to the pattern being more pronounced during that season.

9.3.4 Directional Frequency and Average Speed

Peak frequencies generally occur for winds from the south through southwest directions (Figure 9.13). Petersburg shows very evident channelling of wind flow in the valley with southeast and northwest maxima. The directional frequency for Elkins shows the influence of the drainage flow from the ridge to the west. Elkins exhibits drainage flows from the ridge to the west rather than from the ridges to the east because the prevailing westerlies at ridge crest elevation will force the cold air to drain down the east slope of the ridge. Maximum wind speeds at Elkins are for winds from the southwest through northwest.

9.3.5 Annual Average Wind Speed Frequency

Observer biases are evident in the actual distributions of wind speed for all stations with periods of record in the 1940s and 1950s (Figure 9.14). This bias is reflected in the peaks at 2, 5, and 8 m/s (5, 10, and 15 knots) and is not uncommon for data collected during that period.

9.3.6 Annual Average Wind Speed and Power Duration

The percentage of time a given wind speed or power is exceeded is shown in Figures 9.15 and 9.16. Abrupt changes in the slope of the duration curves usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 9.1. Geographic Map of West Virginia

FIGURE 9.2. Topographic Map of West Virginia

FIGURE 9.3. Land-Surface Form Map for West Virginia

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 9.4. NCC Station Locations in West Virginia

FIGURE 9.5. Location of Stations Used in West Virginia Resource Assessment

FIGURE 9.6. West Virginia 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 ³	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 9.1 Areal Distribution (km²) of Wind Power Classes in West Virginia

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	59,000	94.	63,000	100.
2	1,800	3.0	3,900	6.2
3	1,100	1.8	2,100	3.3
4	690	1.1	940	1.5
5	250	0.39	250	0.39
6	0	0.00	0	0.00
7	0	0.00	0	0.00

FIGURE 9.7. Certainty Rating of West Virginia 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 9.8. Areal Distribution of Wind Resource in West Virginia (Classes 2 and 3)

Class 4

Class 5

0 50 100 150 200 Miles

0 50 100 150 200 Kilometers

PNL-3195 WERA-5

FIGURE 9.8 (Continued). Areal Distribution of Wind Resource in West Virginia (Classes 4 and 5)

WINTER

SUMMER

FIGURE 9.9. Seasonal Average Wind Power in West Virginia (Winter, Summer)

SPRING

AUTUMN

FIGURE 9.9 (Continued). Seasonal Average Wind Power in West Virginia (Spring, Autumn)

TABLE 9.2. West Virginia Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Annual Average Wind Speed, m/s				Annual Average Wind Power, watts/m ²		
						Anemometer Height, m	At Anemometer Height	At 10 m	At 50 m	At Anemometer Height	At 10 m	At 50 m
Beckley, West Virginia	Beckley-Raleigh Memorial County Airport	37.78	81.11	874	05/63-12/78	15.2	4.2	4.0	5.0	90	75	150
Charleston, West Virginia	Charleston Kanawha Airport	38.37	81.60	290	01/65-12/78	9.8	2.8	2.8	3.5	38	38	76
Elkins, West Virginia	Elkins-Randolph County Airport	38.88	79.84	605	09/69-12/78	6.1	2.9	3.1	3.9	44	54	108
Huntington, West Virginia	Huntington Chesapeake Airport	38.41	82.50	173	04/48-01/61	8.5	1.4	1.4	1.8	16	17	34
Huntington/TS, West Virginia	Huntington Tri-State Airport	38.36	82.54	258	12/61-12/78	6.1	2.9	3.1	3.9	34	42	84
Martinsburg, West Virginia	Martinsburg Municipal Airport	39.39	77.98	166	06/49-12/64	7.9	2.8	2.9	3.6	63	70	139
Morgantown, West Virginia	Morgantown Municipal Airport	39.63	79.92	379	02/49-12/54	8.5	3.1	3.2	4.0	45	48	96
Parkersburg, West Virginia	Parkersburg WBO	39.26	81.56	202	01/48-12/54	25.6	3.3	2.9	3.6	67	45	89
Petersburg, West Virginia	Petersburg WBO	39.00	79.12	314	07/48-04/54	14.0	2.7	2.6	3.2	36	31	62
Wheeling, West Virginia	Wheeling Ohio County Airport	40.18	80.64	359	02/49-08/53	14.3	4.0	3.8	4.8	93	80	159

^(a)WBO - Weather Bureau Office.

FIGURE 9.10. Interannual Wind Power and Speed for West Virginia

FIGURE 9.11. Monthly Average Wind Power and Speed for West Virginia

FIGURE 9.12. Diurnal Wind Speed by Season for West Virginia

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - - - WIND SPEED RIGHT ORDINATE - M/SEC
 PNL-3195 WERA-5
 ABSCISSA - WIND DIRECTION

FIGURE 9.13. Directional Frequency and Average Wind Speed for West Virginia

— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 - - - RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3195 WERA-5

FIGURE 9.14. Annual Average Wind Speed Frequency for West Virginia

ORDINATE - PERCENT
ABSCISSA - M/S
PNL-3195 WERA-5

FIGURE 9.15. Annual Average Wind Speed Duration for West Virginia

ORDINATE - PERCENT
 ABSCISSA - WATTS/M²
 PNL-3195 WERA-5

FIGURE 9.16. Annual Average Wind Power Duration for West Virginia

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