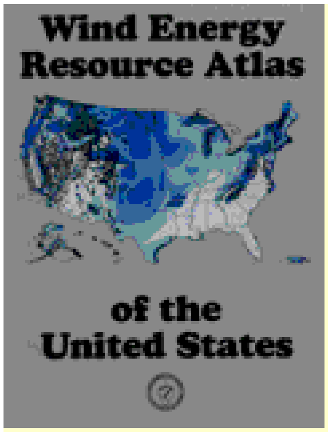

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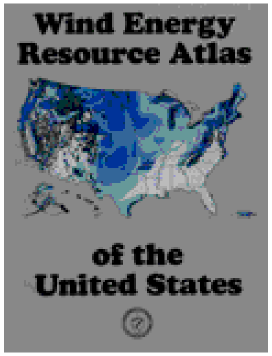

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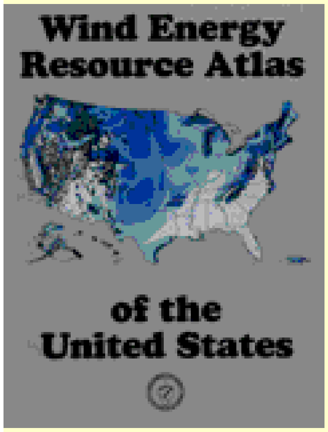

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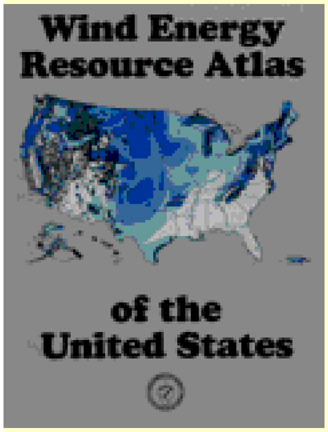

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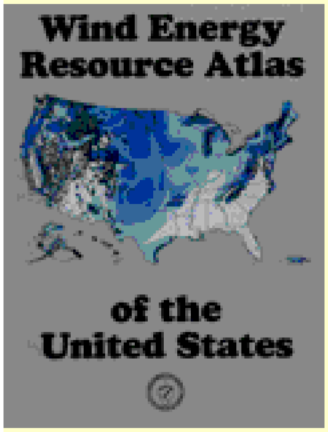

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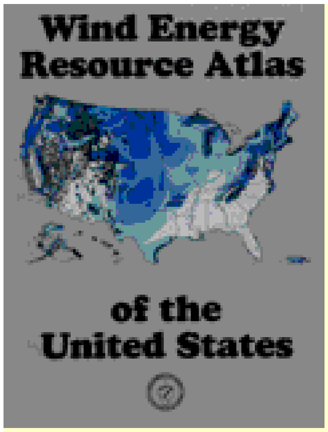

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Acknowledgements

This national wind energy atlas was made possible through the contributions and efforts of numerous groups from throughout the United States. We gratefully acknowledge the contractors who performed the regional wind energy assessments, which provided the backbone information upon which this national assessment is based. We also acknowledge the staff at the National Climatic Data Center (NCDC) for their valuable efforts in providing much of the information used for these assessments and for cooperating with us in establishing a national wind energy data base for public use. We extend our appreciation to the various federal, state, and private organizations and university groups for their cooperation in our search for new data.

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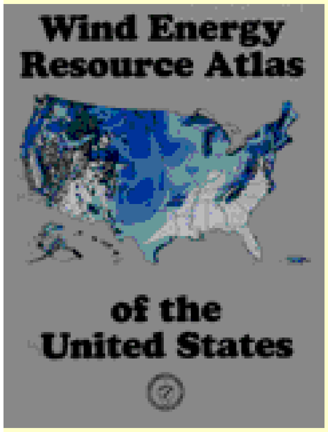

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Chapter 1: Introduction

This atlas estimates wind energy resource for the United States and its territories,[a1]. and indicates general areas where a high wind resource may exist. This information is valuable to wind energy developers and potential wind energy users because it allows them to choose a general area of estimated high wind resource for more detailed examination. A siting document, such as that written by Hiester and Pennell (1981), can assist a potential user in going from wind resource assessment to site selection.

Background

The national wind resource assessment was one of the initial goals of the Federal Wind Energy Program. Early research in wind characteristics included the development and application of techniques for estimating the magnitude and distribution of wind resource over a selected area. In 1979 and 1980, the Pacific Northwest Laboratory (PNL) used these resource assessment techniques in preparing twelve regional wind energy atlases covering the United States and its territories (Map A-l and Table A-l). The atlases depicted annual and seasonal average wind resource on a regional and state level. They also included the wind resource's certainty rating and the areal distribution (percentage land area suitable for wind energy development) based on variations in land-surface form. In addition, summary national wind resource maps were produced (Wind Energy Maps 1982) based on a synthesis of the 12 regional assessments (Elliott and Barchet 1981).

A wide variety of data types and analysis techniques were utilized in performing the regional wind energy assessments. Appendix A gives a complete description of the data sources and methodologies used in the regional assessments and their synthesis.

A wind energy data base containing detailed wind statistics for 975 stations in the United States was produced specifically for use in wind energy applications (Barchet 1981). This data base, which was used in producing regional wind energy assessments, was transferred to the National Climatic Data Center (Appendices B and C).

The twelve regional wind energy resource atlases were based on data collected before 1979. Most of the data used in the assessments were collected at anemometer heights and locations that were not chosen for wind energy assessment purposes. In many areas estimated to have a high wind resource, the certainty rating of this estimate is low because few or no data were available for exposed locations. However, since the later 1970s, hundreds of new sites have been instrumented specifically for wind energy assessment purposes, and many of these have been located in areas thought to have high wind resource but where data were previously not available or were very limited.

Updating the Assessment

In 1983, the U.S. Department of Energy (DOE) initiated a program administered by PNL to identify and assimilate new site data that could be useful in verifying or updating the wind resource estimates in many areas of the United States. The Pacific Northwest Laboratory contacted numerous federal, state, and private organizations throughout the country regarding existing or planned wind measurement studies to assess the wind energy resource or evaluate potential wind turbine sites. Hundreds of new sites were identified, many with records of sufficient duration to be useful in verifying or updating the previous wind resource estimates. For example, data were available from the DOE measurement program, at thirty-five potential wind turbine sites. The Bureau of Reclamation, Bonneville Power Administration, Western Area Power Administration, Alternative Energy Institute, and California Energy Commission, to name a few, have been involved with instrumenting numerous sites for wind energy assessment or siting purposes. Other organizations, such as the Tennessee Valley Authority (TVA), have performed updated wind energy assessments incorporating historical data from many sites that were not previously used in the regional atlases (e.g., historical data collected at TVA facilities).

New site data were identified and obtained for practically every region of the United States, and the majority of these new data were from areas estimated to have high wind resource in the regional atlases. Data were evaluated from approximately 270 new sites for use in verifying or updating the wind resource estimates. Approximately 200 of these new sites were instrumented specifically for wind energy assessment purposes.

The annual and seasonal average wind power maps were revised, based largely on the examination and analysis of these new site data. Certainty ratings credited to the wind resource were revised, and the areal distribution maps were updated to reflect changes in the wind resource estimates. The identification, screening, and evaluation of the new site data and the procedures used in verifying or updating the wind resource, certainty rating, and areal distribution maps are described in Appendix D. Appendix E summarizes data from the 35 DOE measurement sites, also called "candidate sites."

Map Descriptions

Chapter 2 presents the updated national maps of the annual and seasonal average wind resource, certainty rating, and areal distribution. The annual and seasonal average wind power maps appear in two forms: analyzed versions of the annual and seasonal average wind resource maps and gridded maps. Both are found in Chapter 2. To prepare the gridded maps (Maps 2-6 through 2-25), the analyzed wind resource maps (Maps 2-1 through 2-5) were divided into grid cells of 1/3° longitude by 1/4° latitude over the contiguous United States. The gridded maps were used to assess the certainty of the wind resource estimates and the areal distribution of the wind resources. Different-sized grid cells were used for Alaska, Hawaii, Puerto Rico, and the Virgin Islands.

The gridded maps of the wind resource given in Chapter 2 do not show some of the smaller scale features that are apparent on the analyzed maps. For this reason, the analyzed wind resource maps show greater detail than the gridded maps, especially in mountainous or coastal areas. However, the digitized maps of the wind resource allow the user to associate the wind power classes for specific grid cells with the certainty rating, land-surface form, or any other relevant quantity for those grid cells.

Chapter 3 presents regional summaries of the updated wind resource estimates (Maps 3-1 through 3-72). For each region, major wind resource areas are identified that have been estimated to have suitable wind energy potential for wind turbine applications. For those areas where little or no change was made from the resource estimate in the regional atlases, the descriptive text was extracted and reproduced here with very little revision. Maps of the annual average wind resource are presented individually for each state (or territory) in the region. Some of the larger states (i.e., Alaska, California, and Texas) are subdivided, whereas some of the smaller states are combined on one map. Each map has a latitude-longitude grid to facilitate locating specific places. In addition, each map shows the names of major cities, mountain ranges, geographical features, and prominent wind energy areas for reference purposes.

The wind resource maps estimate the resource in terms of wind power classes (Table 1-1), ranging from class 1 (the lowest) to class 7 (the highest). Each class represents a range of mean wind power density (in units of W/m^2) or equivalent mean wind speed at the specified height(s) above ground. Areas designated class 3 or greater are suitable for most wind turbine applications, whereas class 2 areas are marginal. Class 1 areas are generally not suitable, although a few locations (e.g., exposed hilltops not shown on the maps) with adequate wind resource for wind turbine applications may exist in some class I areas.

The wind power estimates apply to areas free of local obstructions to the wind and to terrain features that are well exposed to the wind, such as open plains, tablelands, and hilltops. Within the mountainous areas identified, wind resource estimates apply to exposed ridge crests and mountain summits.

Local terrain features can cause the mean wind energy to vary considerably over short distances, especially in areas of coastal, hilly, and mountainous terrain. Although the wind resource maps identify many areas estimated to have high wind resource, the maps do not depict variability caused by local terrain features.

This wind resource atlas was not intended to deal with variability on a local scale, but to indicate areas where high wind resource is possible. An example of a high wind resource area where considerable local variability occurs is Altamont Pass, California, an area where thousands of wind turbines have been installed. The national wind resource map depicts this area of high wind resource (which appears very small on the national scale map) but does not indicate the local variability which occurs within the area.

Siting handbooks that provide guidelines on siting small and large wind turbines (Wegley et al.1980, Hiester and Pennell 1981, Pennell 1982) address local terrain effects on the wind resource. For finer wind prospecting, consider the siting strategies described in these handbooks.

The wind resource analysis is based on data (where available) collected at heights of 20 to 60 m (65 to 200 ft) above ground at exposed sites. However, in most areas only near-surface data, 3 to 15 m (10 to 50 ft) above ground, were available for the assessment. Vertical extrapolation to 10 and 50 m (33 and 164 ft) is based primarily on the 1/7 power law (Appendix A) using data from exposed sites. Data available from many locations with measurements from more than one level indicate that, in spite of anomalies caused by terrain complexities and nocturnal jets at some locations, the 1/7 power law is generally appropriate (Appendix D). The 1/7 power law conveniently provides wind power densities at 50 m (164 ft) that are twice those at 10 m (33 ft).

The wind power density incorporates in a single number the combined effect of the frequency distribution of wind speeds and the dependence of the wind power on air density and on the cube of the wind speed. In (Table 1-1), the table of wind power classes (which is repeated on the national wind resource maps), the relationship between the mean wind power density and the mean wind speed assumes a Rayleigh distribution[a2] of wind speeds and sea-level air density. The decrease of air density with altitude requires a higher mean wind speed to achieve a given wind power density. To obtain the same wind power density, the mean wind speed must be about 1% higher than shown in the table for every 304 m (1,000 ft) of elevation above sea level.

(Table 1-2) shows why the annual average wind speed alone may not be a reliable indicator of the annual average wind power density. Data from the three locations listed indicate that the locations have identical mean wind speeds at 10 m (33 ft). However, the actual wind power density, which is based on the frequency distribution of the wind speeds, is substantially different for the three locations, such that each location has a different wind power class. The location in New York has a wind speed distribution which is approximated well by a Rayleigh wind speed distribution. The other two locations do not.

In extreme cases, the use of only the mean wind speed and the Rayleigh distribution to estimate the power density provides a much lower estimate than the actual power density. For example, a site near Ellensburg, Washington, has a mean annual wind speed of 5.2 m/s, which is class 3 wind power (160 W/ m^2) if the Rayleigh distribution is applicable. However, because the distribution of wind speeds at this site is much broader than that of a Rayleigh distribution, the actual wind power is class 6 (320 W/ m^2), or twice that estimated by the Rayleigh distribution.

The complexity of the topography and availability of reliable measurements in the vicinity determined the certainty rating credited to the wind resource estimates for exposed locations. These criteria determined the certainty of the wind resource estimate for each grid cell. The maps show the distribution of certainty ratings ranging from 1 for the lowest degree of certainty to 4 for the highest degree of certainty. These maps, depicting the degree of certainty of the wind resource estimates, should be used in combination with the wind resource maps.

Another factor of interest in interpreting wind power resource estimates is their areal distribution, that is, the percentage of land area represented by a specified wind power class. As the ruggedness of the terrain increases, the percentage of land area well exposed to the wind decreases dramatically. Maps in Chapter 2 show the areal distribution exceeding specified wind power classes. These maps indicate various areas of exposure, from mountainous terrain where only a small fraction of the land (<20%) is well exposed to flat terrain where most of the land (>80%) is well exposed.

[a1] U.S. Territories considered are Puerto Rico, three U.S. Virgin Islands (St. Thomas, St. Croix, and St. John), and several U.S. Pacific Islands, or island groups - Midway, Wake and Johnston Islands, Guam, and the Northern Marianas, Marshalls, and Carolines. References to Pacific Islands or Virgin Islands apply only to these U.S. territories.

[a2] The Rayleigh distribution is an analytical expression of a probability density function of wind speed. It seems to fit many observed wind speed distributions reasonably well, although there are exceptions. The advantage of using the Rayleigh distribution is that it is completely specified by one parameter, the long-term average wind speed.

Chapter 2: The National Wind Resource

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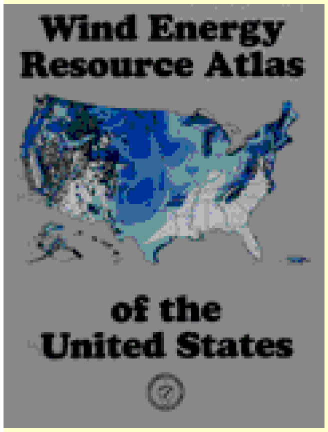

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Chapter 2: The National Wind Resource

This chapter describes the geographical distribution of the wind energy resource throughout the United States and its territories, the certainty credited to the wind resource estimates, and the areal distribution (percentage land area) of the wind resource. Two types of national wind resource maps are provided: analyzed (Maps 2-1 through 2-5) and gridded (Maps 2-6 through 2-25). Five fold out analyzed maps of the annual and seasonal average wind resource precede 20 gridded maps at the end of this chapter. Gridded maps are of the annual and seasonal average wind resource, the certainty rating of the resource estimates, and the areal distribution of the resource. They are shown for the contiguous United States, Alaska, Hawaii, Puerto Rico, and the Virgin Islands. Grid cells are 1/4° latitude by 1/3° longitude in the contiguous United States, 1/2° latitude by 1° longitude in Alaska, and 1/8° latitude by 1/8° longitude in Hawaii, Puerto Rico, and the Virgin Islands.

Because of the large areal extent of the Pacific Islands and the sparseness of the data for these islands, no wind resource information was digitized for inclusion in the gridded maps. Also, these islands are not shown on the analyzed maps (2-1 through 2-5), although a brief description of the estimated wind resource for these islands is included in the map description on analyzed Map 2-1. For information on the Pacific Islands, refer to Chapter 3 for maps and descriptions of these areas. Also, refer to the wind energy atlas (Volume 11) covering the Pacific Islands.

Chapter 1 provides information on how to interpret these maps. In the following discussions about the wind power maps, many references are made to specific geographic locations. Refer to the regional and state maps in Chapter 3 (Maps 3-1 through 3-72) to identify unfamiliar locations.

Annual Average Wind Resource

Areas that are potentially suitable for wind energy applications (wind power class 3 and above) are dispersed throughout much of the United States (Maps 2-6 and 2-16). Major areas of the United States that have a potentially suitable wind energy resource include: much of the Great Plains from northwestern Texas and eastern New Mexico northward to Montana, North Dakota, and western Minnesota; the Atlantic coast from North Carolina to Maine; the Pacific coast from Point Conception, California to Washington; the Texas Gulf coast; the Great Lakes; portions of Alaska, Hawaii, Puerto Rico, the Virgin Islands, and the Pacific Islands; exposed ridge crests and mountain summits throughout the Appalachians and the western United States; and specific wind corridors throughout the mountainous western states.

In the Great Plains, class 5 wind resource is found over elevated areas of North Dakota, such as the Pembina and Missouri escarpments and Turtle Mountains, and the hilltops and uplands of the Missouri Plateau in southwestern North Dakota and high plains in northwestern Montana near Cut Bank. Class 4 wind resource exists over hilltops and uplands of eastern Montana and high plains in northwestern Montana, much of North and South Dakota, the Sand Hills of Nebraska, western Minnesota, northwestern Iowa, the Texas Panhandle, northwestern Oklahoma, southcentral Kansas and the Flint Hills of eastern Kansas, uplands of eastern Colorado, and parts of northeastern New Mexico.

Exposed coastal areas in the Northeast from Maine to New Jersey and in the Northwest southward to northern California indicate class 4 or higher wind resource. Class 4 or higher wind resource also occurs over much of the Great Lakes and coastal areas where prevailing winds (from the strong southwest-to-northwest sector) have a long, open-water fetch. Class 3 wind resource can be found along exposed coastal areas from Delaware to North Carolina, much of the California coast north of Point Conception, and the Texas coastal areas from the Mexican border northward to Galveston. Along many coastal areas, the abrupt increase of surface roughness inland from the coastline because of vegetation and topography can rapidly attenuate the wind resource inland. Notable exceptions occur along the Texas coast and Cape Cod in Massachusetts where the coastal wind resource extends inland a considerable distance.

Many of the higher exposed ridge crests and mountain summits in the eastern and western United States experience high wind resource, because mean upper-air wind speeds are strong over most of the contiguous United States during much of the year. However extreme winds, icing, and inaccessibility caused by poor weather and snow depths during the winter severely restrict the suitability of many of these areas for wind energy development.

In basins, valleys, and lowland plains throughout the mountainous regions, mean annual wind power is generally low. During colder months, cold air often fills the basins and valleys, creating a vertical temperature profile that frequently remains stable throughout the day because of low insolation. Under these stable surface conditions, vertical mixing of the atmosphere is limited, and light surface winds usually persist in the lowland areas, even though winds may be strong on nearby higher terrain. In warmer months, although insolation and vertical mixing increase, mean wind speeds aloft are much lower than in colder months.

However, high wind resource at relatively low elevations in mountainous regions can occur where the air flow is channeled through constrictions or corridors that enhance the wind speeds. These wind corridors vary in width from just a few kilometers to over 50 km (31 mi). On the national maps, most of these wind corridors appear relatively small in geographical extent and many are hardly noticeable among the vast expanse of mountain ranges in the western United States. However, because many of these wind corridors serve as primary transportation corridors, they are easily accessible, in contrast to the higher mountain summits and ridge crests. Moreover, weather conditions are not nearly as severe in these corridors as they are on the higher mountain ranges. Thus, considerable activity in wind energy development is taking place in many of these wind corridors in the western United States. However, smaller scale terrain features within these corridors, combined with the larger scale channeling effects, can cause extreme local variability throughout many of these corridors and complicate the siting process.

Some notable corridors where class 4 or higher wind resource can be found are located in California, Oregon, Washington, Montana, and Wyoming. Isolated corridors with high resource may occur in some of the other states where mountainous terrain exists. In California, several corridors through the Coast Range occur from east of San Francisco southward to San Diego. Some of the notable corridors in California shown on the national annual average wind power map are in the areas of San Gorgonio, Tehachapi, Altamont and Pacheco Passes and the Carquinez Straits. In addition to these passes, high wind resource occurs over some of the lower ridges of the Coast Range in southern California. In Oregon and Washington, the two most notable corridors are the Columbia River corridor, which extends about 200 km (124 mi) eastward from Portland, Oregon, and the corridor in the vicinity of Ellensburg, Washington. In Montana, high wind corridors occur in the areas of Livingston, Whitehall and Harlowton-Judith Gap. In Wyoming, a broad gap over 100 km wide (62 mi) through the Rocky Mountains creates the vast wind corridor of high wind resource in southern Wyoming.

In Alaska, high wind resource (up to class 7) occurs over the Aleutian Islands, much of the coastal areas of northern and western Alaska, offshore islands in the Bering Sea and Gulf of Alaska, and over mountainous areas in northern, southern, and southeastern Alaska. Basins and valleys in interior Alaska generally have class 1 or 2 wind resource. A few corridors in interior Alaska are estimated to have high wind resource.

In Hawaii, interactions between prevailing trade winds and island topography determine the distribution of wind power. On all major islands, trades accelerate over coastal regions at the island corners. The best examples are regions of class 6 or higher wind power on Oahu, Kauai, Molokai, and Hawaii.

In Puerto Rico, class 3 or 4 wind resource is possible at sites along the northern and eastern coasts, which are well exposed to the prevailing trade winds, and at higher peaks and ridges in the interior.

The Virgin Islands are shown on the gridded map but not on the analyzed map. Wind resource of at least class 3 is possible at well-exposed sites on the central ridges, the northern, eastern, and southern coasts of St. Thomas, St. John, and St. Croix, as well as the windward sides of the smaller islands.

For the Pacific Islands, which are not shown on either the gridded or analyzed annual maps, please refer to Chapter 3 for maps and descriptions of these islands.

Seasonal Variations of the Wind Resource

Because there is considerable seasonal variation in the wind energy resource, with maxima in winter and spring and minima in summer and autumn throughout most of the contiguous United States, assessments of the wind energy resource have also been produced for each season. The geographical distribution of the wind resource throughout the nation is portrayed for each of the seasons in Maps 2-12 through 2-15 and 2-22 through 2-25. The Pacific Islands are not shown on the gridded or analyzed maps. However, a discussion of the seasonal variations of the wind resource for these islands based on wind power values estimated from ship wind data is included in this chapter. For further information on these islands, refer to Chapter 3 of this atlas and Volume 11 of the wind energy atlas covering the Pacific Islands. The season of maximum wind energy is winter in most of Alaska and many of the Pacific Islands, and summer in Hawaii, Puerto Rico, and many of the Virgin Islands. A substantial portion of the United States has class 3 or higher wind resource in spring and winter, whereas a considerably smaller portion has class 3 and above wind resource in summer. The distribution of wind resource throughout the United States in winter, spring, summer, and autumn is described more completely in the following four sections.

Winter Wind Resource (December, January, February)

In winter, mean upper-air wind speeds are stronger than in any other season over most of the contiguous United States. Class 3 and above wind resource can be found at exposed sites throughout most of the contiguous United States except for the southeastern United States (excluding ridge crests), much of southern Texas, the basins and valleys of the western United States, and heavily forested areas and sheltered valleys and basins of the northeastern United States. Over the northern Great Plains, class 5 wind resource is found in winter over portions of North and South Dakota. Class 5 and 6 resource occurs over portions of the high plains in northwestern Montana from Great Falls to the Canadian border. Class 4 wind resource covers a substantial part of the northern Great Plains, including much of the Dakotas, hilltops and uplands of eastern Montana, and the Sand Hills of Nebraska. The class 4 wind resource extends eastward into western and southern Minnesota and much of Iowa, hilltops and uplands in southwestern Wisconsin, and a portion of central Illinois.

Over the southern Great Plains, class 4 is prevalent over a portion of the Texas Panhandle, northwestern Oklahoma, and southcentral Kansas. Class 4 also occurs over the Flint Hills of eastern Kansas, portions of eastern Colorado, and extreme northwestern Kansas, and hilltops in northeastern New Mexico. A band of class 4 is estimated to exist along elevated areas of the Ozark Plateau in southern Missouri and over ridge crests and mountain summits of the Boston and Ouachita mountains in western Arkansas and eastern Oklahoma.

Exposed coastal areas in the Northeast and Northwest have class 5 or above wind resource in winter. Large portions of the Great Lakes shorelines and islands are estimated to have class 5 or 6 wind resource in winter. Class 3 or 4 wind resource can be found in winter along the coastal areas of much of central and northern California, North Carolina, Virginia, Texas, parts of Louisiana, and the Florida Keys.

In the East, from Tennessee and North Carolina northward to Maine, many exposed uplands, hilltops, and lower mountain summits are estimated to have class 4 wind resource in winter.

Many of the higher exposed ridge crests and mountain summits in the eastern and western United States experience as much as class 7 wind resource for a winter average. However, extreme winds, icing, and inaccessibility caused by poor weather and snow depths during winter severely restrict the suitability of many of these areas for wind energy development.

Although mean upper-air wind speeds are strongest in the winter, mean wind speeds are generally low in basins, valleys, and lowland plains throughout the mountainous regions. Cold air often fills the basins and valleys, creating a vertical temperature profile that frequently remains stable throughout the day because of low insolation. Under these stable surface conditions, vertical mixing of the atmosphere is limited, and light surface winds usually persist in the lowland areas, even though winds may be strong on nearby higher terrain. Thus, basins, valleys, and lowlands throughout the mountainous regions generally have only class 1 or 2 wind resource in the winter.

However, high wind resource in the winter can occur in areas where cold air drainage from higher elevations to lower elevations is channeled through constrictions or corridors that enhance the wind speeds. These wind corridors vary in width from just a few kilometers to over 50 km (31 mi). Highest wind speeds are usually near the corridor outlets. Wind corridors that have class 3 and above wind resource in the winter are located near Portland (the western part of Columbia River gorge) and La Grande, Oregon; Strevell, Idaho, near the Idaho-Utah border, about 120 km (75 mi) southeast of Twin Falls; Whitehall, Livingston, and Judith Gap, Montana; Cody, Wyoming; Santa Fe, New Mexico; and Milford, Utah. Several corridors are found in southern and central Wyoming, where prevalent high wind speeds are channeled and enhanced. An example of this is the area around Medicine Bow, Wyoming, where prevailing westerly winds are channeled between the Medicine Bow Mountains to the south and the Shirley Mountains to the north. This area has class 7 wind resource in the winter.

Throughout most of Alaska, winter is the season of maximum wind power. Areas with winter maxima include all of the southeast and southwest subregions, all mountain areas, and the west coast of southcentral Alaska. Very high wind resource (class 6 and 7) in winter occurs over the Aleutian Islands, much of the coastal areas of northern and western Alaska, offshore islands in the Bering Sea and Gulf of Alaska, and over some mountainous areas in southern and southeastern Alaska. Basins and valleys in interior Alaska generally have only class 1 or 2 wind resource. A few corridors in interior Alaska where the winds are channeled and enhanced have high wind resource in winter.

In Hawaii during winter, the trade winds are less frequent, though migratory anticyclones can produce strong trades for prolonged periods. Low pressure systems and intense cold fronts occasionally produce strong southwesterly and westerly winds. However, these systems do not occur often enough to alter the basic power density distributions. Wind power is greatest on coastal corners exposed to prevailing trade winds. Each island has some area of class 6 wind power. The Kohala and South Point areas on the island of Hawaii experience wind power of class 7 as does Ilio Point on northwestern Molokai.

For the Pacific Islands, winter is the season of maximum wind power over much of the region. Winter in American Samoa is June through August. Except for Guam (the largest Pacific Island), seasonal wind power values are presented for the surrounding ocean areas only. Cold air outbreaks from the Asian winter monsoon produce strong trade winds over the western North Pacific. Very high wind resource (class 6 and 7) is estimated for the Marshalls, the Northern Marianas and the ocean area around Guam. Class 4 wind resource is estimated for the southern mountains of Guam, while class 3 power is estimated for the rest of the island. Class 3 and 4 wind resource is estimated for the Carolines, which are located away from the major winter trade wind belts. Class 4 power is estimated for American Samoa, which is exposed to winter trade winds. Wake, Johnston, and Midway are estimated to have class 6 and 7 wind power.

Over Puerto Rico in winter, class 4 wind resource is estimated for the higher peaks and ridges in the interior. Class 3 wind resource is predominant at sites along the northern and eastern coasts, which are well exposed to the prevailing trade winds.

Over the Virgin Islands in winter, class 3 wind resource is estimated for exposed sites on the northern and eastern coasts. Class 4 is estimated for some of the higher ridge crests on St. Thomas and St. John.

Spring Wind Resource (March, April, May)

In spring, the mean upper-air flow is weaker than in winter but remains quite strong over most of the contiguous United States, although its strength decreases as spring progresses from March to May. Thus, in spring the wind resource is generally less than in winter on mountain summits and ridge crests (except in the extreme southern part of the Southwest) and exposed coastal areas of the Northwest, Northeast, and Great Lakes.

Because incoming insolation is greater in spring than in winter, temperature profiles are less stable, and more vertical mixing in the surface layer results than in winter. Therefore, near-surface mean wind speeds over the valleys, basins, and plains throughout most of the United States west of the Mississippi River are generally greater in spring than in winter. In the eastern third of the United States, mean wind speeds over the plains, basins, and valleys in spring are about the same magnitude as in winter or only slightly less, even though mean upper-air wind speeds are considerably greater in winter than in spring.

In spring, the coastal regions exhibit the greatest thermal contrasts between land and sea. The combined effects of weakened, but still significant, upper-air flow and regional, thermally induced flow in the coastal areas produce wind powers in the spring that exceed those in winter along much of the California coast and south Texas coast and are comparable to those in winter along much of the southern Atlantic coast, the Gulf coast, and the coastal areas of the western Great Lakes.

In spring, class 3 and above wind resource occurs at exposed areas throughout much of the United States, except the southeastern United States where class 3 and above is restricted to exposed mountain summits and ridge crests in the Appalachians and coastal areas from North Carolina northward.

Over much of the central United States from eastern Montana to Minnesota and south to Texas, wind power reaches a maximum in the spring. Areas of highest wind resource over this region, class 6, occur in the northern Great Plains over elevated escarpments and uplands throughout North Dakota, near Rapid City in South Dakota, and uplands near Circle, 110 km (70 mi) north of Miles City in eastern Montana. Class 5 occurs over the high plains of the Texas Panhandle, northwestern Oklahoma, and southcentral Kansas.

Areas of southern and central Wyoming and northwestern Montana that had class 6 and 7 in winter decrease by 1 to 2 power classes in spring.

Exposed coastal areas along the Pacific coast (north of Point Conception, California) have class 4 power in spring, and the wind power is accelerated to class 5 around more prominent capes such as Cape Blanco, Oregon, and Cape Mendocino, California. Exposed coastal areas of the Northeast (from North Carolina north to Maine) have class 4 and 5 power, increasing to class 6 over Cape Cod and Nantucket Island, Massachusetts. Class 4 and 5 resource occurs over much of the Great Lakes and their exposed coastal areas.

Along the south Texas coast, wind power in spring increases inland from class 3 over the outer coastal increased convection from greater solar heating. These factors reduce the wind power at exposed mountain locations from class 4 in winter to class 3 in spring.

Over the Virgin Islands, the trade winds weaken slightly in spring; thus, only class 2 wind power is typical of exposed coastal locations on the windward sides of the three main islands and the smaller islands. Class 3 wind power is estimated for some of the exposed ridge crests on the islands.

Summer Wind Resource (June, July, August)

In summer, wind speeds aloft diminish, and wind power is at its lowest over most of the United States. Although only class 1 or 2 wind power occurs over much of the contiguous United States, areas of class 3 or higher wind resource occur over much of the northern and southern Great Plains, the Great Lakes, the south Texas coast, the Pacific coast from southcentral California northward to Oregon, southern Wyoming, the wind corridors in specific areas of California, Oregon, Washington, Montana, and Utah, and exposed mountain summits and ridge crests throughout the West. In the Northeast, class 3 wind power in summer can be found over Cape Cod and Nantucket Island, Massachusetts, and exposed ridge crests in Vermont, New Hampshire, and Maine.

Summer is the season of maximum wind energy in Hawaii, Puerto Rico, the Virgin Islands, and parts of California, Oregon, and Washington. In these regions, specific areas have high wind energy resource in the summer.

Along the West Coast, class 3 or 4 wind resource occurs at exposed coastal areas from Point Conception, California, north through Oregon. Persistent, strong north-to-northwest winds, which occur during summer along much of the West Coast, are associated with the summer anticyclone (high-pressure system) over the eastern Pacific Ocean. The southern California coastline south of Point Conception has low wind power potential, because it is sheltered from the strong northwest winds by the Transverse Range. Major coastal capes that protrude into northerly flow experience the highest power, such as Cape Blanco and Cape Mendocino. Concave coastal areas, which are typically located between the protruding capes, typically have low-to-marginal wind resource (class 1 to 2) because they are sheltered from the strong northerly winds. The abrupt increase in surface roughness inland from the coastline, because of vegetation and topography, further slows the wind.

High wind resource in the Pacific coast states occurs inland where strong surface-pressure gradients created by the cold water and warm interior force marine air through the major gaps in the mountains into the interior. Strong, persistent winds occur during most of the summer in these wind corridors. Areas of class 6 or 7 wind resource exist in summer where the topography funnels or enhances the flow in these wind corridors. Several wind corridors of this nature occur in California, such as Carquinez Straits, and Altamont, Pacheco, Tehachapi, and San Gorgonio Passes. Two major wind corridors in the Northwest where areas of high wind resource occur in summer are the Columbia River corridor along the Oregon-Washington border and the Ellensburg corridor in Washington.

In Alaska, although summer is the season of minimum wind power, class 3 and higher wind power can be found along the Arctic coast, the western coast and islands offshore, over the Alaska Peninsula and Aleutian Islands, Kodiak Island, and at a few interior locations. Some of the Aleutians and well-exposed capes on the western coast of Alaska even have class 6 or 7 wind resource in summer, the season of lowest wind resource.

In Hawaii, summer is the season of maximum trade wind frequency and, in most regions, maximum wind power. Trade wind steadiness (defined as the ratio of resultant mean speed to mean wind speed) is typically 90%. In each county, some regions experience class 7 wind power and significant sections class 6. These summer trade winds are probably the steadiest wind power source in the United States.

For the Pacific Islands, summer is the season of minimum wind power over much of the region, with the exception of Johnston Island where strong summer trade winds indicate class 6 wind resource. Class 4 and 5 wind power is estimated for the central and northern Marshalls, while class 3 wind power is estimated for the Northern Marianas and the ocean area around Guam. Wind resource of only class 2 is estimated for the mountains of Guam with class 1 power estimated for the rest of the island. The near-equatorial trough dominates summer weather over the Carolines and the southern Marshalls where the wind resource is estimated to be only class 1. The monsoonal trough of northern Australia extends eastward over Samoa where class 2 wind power is estimated. Wind power at Wake and Midway is estimated to be class 4 and 3, respectively.

Over Puerto Rico, the summer trade winds are well developed throughout the lower atmosphere, making this the season of maximum wind power for most of Puerto Rico. Class 4 wind power can be found at exposed coastal sites on the northern and eastern coasts of Puerto Rico, on the windward sides of the outlying islands, at the highest mountain tops in Puerto Rico and on the exposed hilltops of Culebra and Vieques.

Over the Virgin Islands, summer is also the season of maximum wind power, as trade winds are well-developed throughout the lower atmosphere. Class 4 wind power is estimated for the ridgelines of St. Thomas and St. John, the highest hills on St. Croix, at well-exposed coastal locations, and on the eastern sides of the smaller islands.

Autumn Wind Resource (September, October, November)

In autumn, upper-air wind speeds increase as autumn progresses toward winter. Consequently, the mean wind power is considerably greater in November than in September over much of the country. Throughout most of the contiguous United States, the mean autumn wind resource is less than that of spring and winter but greater than that of summer.

In the contiguous United States, class 3 or greater wind resource in autumn occurs along the coastal areas of the Northeast (from Cape Hatteras northward), Northwest, Great Lakes, and a portion of the Texas coast; exposed mountain summits and ridge crests throughout the Appalachians and western! mountains; most of the Great Plains from northern Texas to North Dakota and Montana; and high plains and wind corridor areas in Montana and Wyoming. Some of the wind corridors in California continue to have high wind resource into the autumn.

In Alaska, autumn is the season of maximum wind power along much of the Arctic coast of northern Alaska, which experiences class 6 and 7 average wind power in the autumn. During this season there are more frequent migratory storms, and there is often open water early in the season. Some of the most severe storm surges on the Beaufort coast have occurred in September and October. By the middle of November, the sea ice generally has completely covered both the Chukchi and Beaufort seas, reducing the temperature contrast (and hence storm intensities) along the coasts. In other areas of Alaska, high wind resource in autumn occurs throughout the Aleutian Islands and most coastal areas of western and southern Alaska, although the wind resource in autumn is generally less than that in winter in these areas.

In Hawaii, autumn is a transition period marked by a gradual weakening of the North Pacific anticyclone and the first southward advances of cold fronts. Winds are weaker in autumn than in summer throughout the state. Nevertheless, the Kahuku region of Oahu and the Kohala mountains of Hawaii continue to experience class 7 wind power. The most dramatic wind power decrease is in northeastern Kanai, where Kilauea Point drops from a summer rating of class 7 to class 3 in autumn. Even in this relatively weak wind season, regions of class 6 wind power densities exist in each county.

Over the Pacific Islands, the weakened winds of summer persist into autumn except for the Northern Marianas, and Wake, Johnston, and Midway Islands where ship winds indicate that up to class 6 wind resource may be present. On Guam, class 3 wind power is estimated for the southern mountains with class 1 power estimated for the rest of the island. Class 3 wind power is estimated for the northern Marshalls, while only class 1 and 2 wind resource is estimated for the rest of the Pacific Islands.

Over Puerto Rico and the Virgin Islands, there is a marked decrease in the strength of the trade winds in the autumn. In addition, sea-land temperature differences are less, thus reducing the sea breeze. These factors combine to make autumn the season of minimum power. Only Cape San Juan, because of its excellent exposure, experiences class 3 wind power.

Certainty of the Resource Estimates

The degree of certainty with which the wind power class can be specified depends on three factors: the abundance and quality of data; the complexity of terrain; and the geographical variability of the resource (Appendix A has a more complete description of certainty rating). A certainty rating of the energy resource estimate from 1 (low) to 4 (high) has been made for each cell of a 1/4° latitude by 1/3° longitude grid in the contiguous United States, 1/2° latitude by 1° longitude in Alaska, and 1/8° latitude by 1/8° longitude in Hawaii, Puerto Rico, and the Virgin Islands.

Maps 2-7 and 2-17 show the certainty rating of the wind resource estimates for the United States. The largest area of certainty rating 4 in the contiguous United States occurs over the southeastern plains, from eastern North Carolina southward to Florida and westward to eastern Texas. A combination of factors (such as abundant surface wind data from exposed locations, tower wind data at levels of 50 m to 100 m (164 to 328 ft) above ground, small variability in the wind energy resource, and mostly flat to rolling terrain) indicate that this region of the country has low wind energy potential, with a high degree of confidence, for current wind turbine applications. Throughout this region, existing data indicate only class 1 wind power in the interior areas and only class 2 at exposed coastal areas from Louisiana to Florida and Georgia.

Another area of generally high certainty ratings occurs in the upper Midwest from Illinois eastward to western Ohio and southern Michigan. High certainty ratings have also been assigned to some of the major metropolitan areas in the Northeast. The wind resource estimates for much of the upper Midwest and Northeast are primarily based on abundant surface data from airfields and data from meteorological towers, ranging from 30 m to 200 m (98 to 656 ft) above ground, collected by utilities.

Areas of high certainty or high-intermediate certainty have been assigned to specific areas along the Great Lakes shorelines and the Northeast coast where the wind resource estimates are based on data collected near 50 m (164 ft) above ground and/or well exposed sites with data near 10 m (33 ft). For example, high certainties have been assigned to the grid cells in the vicinity of the DOE candidate sites at Montauk Point, New York, and Block Island, Rhode Island, because the wind resource values for these areas are based on approximately five years of wind measurements, 45.7 m (150 ft) above ground at well-exposed sites.

Over the Great Plains (from northern Texas and eastern New Mexico northward to the Dakotas), areas of highest certainty indicate specific areas where the wind resource estimates are based on wind data collected at or near the 50-m (164 ft) level at exposed sites. Usually, these are sites with two years or more wind data, where meteorological towers were instrumented specifically for wind energy assessment purposes. DOE instrumented many of these sites while others were established by the Alternative Energy Institute, Kansas State University, or other organizations. Areas over the Great Plains with high-intermediate certainty (rating 3) generally indicate areas where wind resource data exist at or near 10 m (e.g., 4 to 20 m above ground or 13 to 66 ft) at exposed sites and/or where limited wind data exist near 50 m (164 ft). Because of some uncertainty in the nature of the wind shear profile at specific sites, the wind resource at 50 m (164 ft) cannot be reliably estimated, with high confidence, from data collected near 10 m (33 ft). For example, in some areas of the Great Plains, the nocturnal wind shear is very strong such that these areas exhibit a strong nighttime maximum and daytime minimum in the wind resource at 50 m (164 ft). In other areas of the Great Plains, this is not the case, as the height of transition is considerably higher up. Existing data from meteorological towers in different areas of the Great Plains show considerable variation in the wind shear profiles.

In the West, high certainty areas are more sparse as a result of the overall greater complexity of the terrain and lack of data in many areas. Even in many areas of the West where considerable data exist, such as Los Angeles and San Francisco, California, and Denver, Colorado, the large spatial variability in the wind resource eliminates a high certainty rating. Two large areas in the West with a high certainty rating are the San Joaquin and Sacramento valleys in California and the Snake River valley in Idaho.

Most of the mountainous areas of the United States have certainty ratings of 1 or 2, as these areas generally had little representative surface data and estimates for summits and ridge crests were primarily derived from free-air measurements (e.g., weather balloons).

Over Alaska, certainty ratings are mostly low (1 and 2), primarily because of the complexity of the terrain over most of the state and sparsity of data in many areas. However, some areas with high wind resource and high certainty exist where representative surface data were available.

Over Hawaii, the distribution of certainty rating varies considerably from island to island. Certainty ratings are mostly 2 and 3 over Oahu and the island of Hawaii, with certainty 4 in the vicinity of Honolulu, Hilo, and Kona. Much of Maui and Molokai has complex terrain and/ or no historic data and, for these reasons, has mostly certainty ratings of 1 and 2. In Kauai, ratings vary from 1 over the central mountains and northwest coast to 4 at Lihue.

Over Puerto Rico, the wind power estimates for most of the coastline perimeter have a certainty rating of 3 because of the quantity of wind data and the predictable nature of the trade winds near the coastlines. Wind power in the entire mountainous interior of Puerto Rico has been assigned a certainty rating of 1, as there were no wind data from exposed sites in the mountainous areas.

Most of the Virgin Islands have been assigned a relatively low certainty of 2 as a result of the lack of data and the complex terrain of these islands.

For the Pacific Islands, refer to Volume 11 of the regional wind energy atlases, Hawaii and the Pacific Islands (Shroeder et al. 1981), for maps and discussion of the certainty ratings. Information for the Pacific Islands was not digitized, because the islands are dispersed throughout vast areas of the Pacific Ocean.

Maps 2-8, 2-9, 2-18, and 2-19 show the certainty of the wind resource estimates in the United States for those areas estimated to have an annual average wind resource of class 3 or greater and class 4 or greater, respectively. Only a small fraction of the areas estimated to have class 4 or greater wind resource can be assured, with high certainty, of having that resource. Except for the Great Plains, most of the high wind resource estimates are in mountainous, hilly, or coastal areas where there is considerable spatial variability in the wind resource. Especially in mountainous terrain, there was usually little surface data to verify the resource estimates based largely on upper-air wind data.

Areal Distribution of the Wind Resource

Because the wind power class values shown on the wind resource maps apply only to areas well exposed to the wind, the map area does not indicate the true land area experiencing this power. The fraction of the land area represented by the wind power class shown on the maps depends on the physical characteristics of the land-surface form. On a flat open plain, for example, close to 100% of the area will have a similar wind power class, while in hilly and mountainous areas the wind power class will only apply to a small proportion of the area that is well exposed.

The areal distribution of wind power is estimated by considering the percentage of land area that is well exposed, moderately exposed, and poorly exposed in each land-surface form, as described in Appendix A. The areal distributions have been determined for each cell of a 1/4° latitude by 1/3° longitude grid in the contiguous U.S., 1/2° latitude by 1° longitude in Alaska, and 1/8° latitude by 1° longitude in Hawaii, Puerto Rico, and the Virgin Islands.

The areal distribution is shown in Maps 2-10 and 2-20 for grid cells in which the annual average wind power is class 3 or greater and in Maps 2-11 and 2-21 for power class 4 or greater. Grid cells where 80% or more of the total land area has class 4 power are mostly located in the southern and northern Great Plains, coastal areas of Texas, and scattered areas along the Northeast coast and Great Lakes. Throughout the Appalachians and mountainous areas in the West, high wind resource only exists on a small fraction (1 to 20%) of the land area. In many mountainous areas, only 2 to 5% of land area is estimated to be well exposed. The isolated grid cells scattered throughout parts of California, Oregon, Washington, and Montana where class 4 power occurs over more than 20% of the land area in the cell represent windy coastal strips or islands in the coastal areas and wind corridors in the inland areas (such as San Gorgonio Pass in California, the Columbia River and Ellensburg corridors in Oregon and Washington, and the Whitehall and Livingston corridors in Montana). Over 50% of the land area in much of southern and central Wyoming and the plains in northwestern Montana has class 4 or greater annual average wind power.

Chapter 3 Regional Summaries

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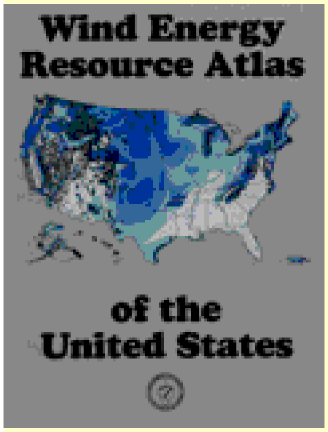

Wind Energy Resource Atlas of the United States

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[Chapter 2 The National Wind Resource]

Chapter 3: Regional Summaries

This chapter presents a summary of the United States wind energy resource on a region-by-region basis. The regions are identified on the map shown in Map 3-1; the numbers on the map indicate the order in which the regional information is presented. For each region, major wind resource areas are described that have been estimated to have suitable wind energy potential for wind turbine applications (class 3 or greater annual average wind power).

The regional summaries are accompanied by regional and state maps. The regional maps display major cities, mountain ranges, and geographic features. The state maps show the geographic distribution of annual average wind power and depict prominent wind energy areas and other geographic features. Chapter 1 gives information on interpreting the wind power maps.

A latitude-longitude grid is superimposed on each state map to facilitate locating specific places on the maps. The grid cells are 1/4° latitude by 1/3° longitude for states in the contiguous United States. This corresponds to grid cells that are approximately 25 by 25 km (15 by 15 mi). For Alaska, grid cells are 1/2° latitude by 1° longitude. For Hawaii, Puerto Rico, and the U.S. Virgin Islands, grid cells are 1/8°

latitude by 1/8° longitude.

Some of the larger states (i.e., Alaska, California, and Texas) are subdivided for the purpose of presenting the analyses more clearly. Some of the smaller states (i.e., Massachusetts, Connecticut, and Rhode Island; Vermont and New Hampshire; and Maryland and Delaware) are combined as a set of states on one map.

The Northwest Region

The Northwest region consists of Idaho, Montana, Oregon, Washington, and Wyoming. Almost half of the region's people live in western Washington and Oregon, where the region's two largest cities—Seattle and Portland—are located. The major cities, rivers, mountain ranges, and national parks are shown in Map 3-2.

The topography varies dramatically throughout the Northwest, which is dissected by the Cascade Range in the western part of the region and by the Rocky Mountains in the central and eastern parts of the region. Over one-third of the region's terrain is hilly and mountainous. Much of the mountainous terrain, and western Washington and Oregon, are heavily forested.

Areas of good wind energy potential are dispersed throughout the Northwest. Some notable areas where wind energy developments have occurred are the Columbia River corridor along the Oregon-Washington border between Portland and Boardman, Oregon, 275 km (170 mi) to the east of Portland; the Ellensburg corridor in central Washington; the Oregon coast; southern Wyoming (especially around Medicine Bow); and the Livingston corridor in southwestern Montana. Goodnoe Hills, located approximately 200 km (120 mi) east of Portland, is the site of three MOD-2 wind turbines currently being monitored by DOE. Medicine Bow, in southeastern Wyoming, has also served as a field test location for several large wind turbines. DOE sponsored measurement programs at seven sites in the Northwest region: Livingston, Montana; Boardman and Cape Blanco, Oregon; Augsburger Mountain, Diablo Dam, and Goodnoe Hills, Washington; and Bridger Butte, Wyoming. The Bonneville Power Administration has taken wind measurements at numerous sites throughout the western part of the Northwest region. The Bureau of Reclamation and Western Area Power Administration, among others, have also been active in selecting sites and measuring the wind resource for potential wind turbine applications.

Considerable amounts of new data have been collected throughout the Northwest region since the completion of the regional atlas (Elliott and Barchet 1980). Analyses of these new data have resulted in some significant changes in the wind energy analysis from the previous analysis.

Major areas in the Northwest region with class 3 or greater annual average wind power are described below. Maps of annual average wind power are presented as Maps 3-3 through 3-7 for Idaho, Montana, Oregon, Washington and Wyoming.

Oregon and Washington Coast

The estimated annual average wind power for exposed coastal areas of Oregon and Washington is class 4 at 50 m (164 ft). Specific sites that experience terrain-induced acceleration of the wind may have greater than class 4 power. The abrupt increase in surface roughness inland from the coastline, because of vegetation and topography, rapidly attenuates the wind resource landward. During winter, the season of maximum wind power at sites well-exposed to the prevailing south and southeasterly winds, high wind speeds are usually associated with storms and fronts moving in from the Pacific Ocean. However, during the summer, wind power is high along the central and southern Oregon coast at sites well-exposed to northerly winds and is associated with the strong surface pressure gradients created by the cold water and relatively warm interior.

Columbia River Corridor

The Columbia River wind corridor straddles the Oregon-Washington state border from just east of Portland, Oregon, to Boardman, Oregon (which is about 70 km or 40 mi west of Pendleton, Oregon). Goodnoe Hills, the site of three MOD-2 wind turbines, is located on a ridge in the eastern part of the Columbia River corridor.

The Columbia River gorge provides a low-elevation connection between continental air masses in the interior of the Columbia Basin east of the Cascade Range and the maritime air of the Pacific coast. Especially strong pressure gradients develop along the Cascades and force the air to flow rapidly eastward or westward through the gorge. Summer winds blow eastward from the cool, dense maritime air west of the Cascades to the hot, less dense air in the Columbia Basin. In winter, the comparatively cold air in the Columbia Basin frequently blows westward through the gorge.

Although the Columbia River corridor is generally an area of high wind resource, terrain variations cause considerable local variability in the wind resource. The wind resource has been measured at numerous sites throughout the Columbia River corridor, and the annual average wind resource at exposed areas ranges from class 3 to class 6. Spring and summer are the seasons of maximum wind power, except for the extreme west end where the maximum resource is in winter.

Central Washington Corridor

Near Ellensburg, Washington, another breach occurs in the Cascade Range, which separates maritime and continental air. Unlike the Columbia River gorge, the central Washington corridor consists of relatively low mountain passes leading into a broad valley corridor to the east. In winter, the cold, dense air to the east of the passes occasionally becomes deep enough to spill westward into the Puget Sound. However, in late spring and summer the cool, marine air over western Washington is often deep enough to flow eastward over the passes and through this valley corridor into the Columbia Basin.

Data from several sites throughout the central Washington corridor indicate that exposed areas have class 4 to 5 annual average wind resource, with class 6 resource during the spring and summer seasons. This high wind resource area extends eastward over the low ridges to Wanapum Dam on the Columbia River, about 50 km (30 mi) east of Ellensburg.

Northwestern Montana Plains

Areas of class 4 and 5 annual average wind power exist over the plains of northwestern Montana from near the Rocky Mountains eastward to Cut Bank and Great Falls. The highest wind energy occurs from October to April, when strong westerly to southwesterly winds frequently occur in association with intense surface pressure gradients. The seasonal average wind resource varies from a maximum of class 6 in winter to a minimum of class 2 and 3 in summer. New data collected at several sites throughout this region indicate that the highest wind resource exists in the northern part of the region, east of Glacier National Park in the vicinity of Browning and Cut Bank.

Southwestern Montana and Northwestern Wyoming Corridors

Areas with up to class 6 annual average wind resource, are found in several valley wind corridors in southwestern Montana. Three such areas that have been identified are located in the vicinities of Livingston, Whitehall, and Harlowton-Judith Gap. Another valley corridor of high wind resource (class 4) is located in northwestern Wyoming in the vicinity of Cody. Strong winds in these corridors are often associated with strong surface pressure gradients. The channeling effect of the valleys and the local terrain intensifies the winds set in motion by the pressure gradients. Prevailing strong winds at Livingston, Whitehall, and Cody are primarily from the southwest quadrant, in alignment with the orientation of the valley corridors. However, the Harlowton-Judith Gap area experiences frequently strong northerly winds caused by channeling of flow between the Little Belt and Big Snowy mountains.

All of these wind corridors have pronounced seasonal variations in wind power density, with a maximum power density in the winter. Neighboring valleys and basins lacking the appropriate orientation show a significantly reduced wind resource.

Wind data have been collected at several new sites throughout southwestern Montana and northwestern Wyoming since the late 1970s. These data indicate that considerable local variability exists in the wind resource in the vicinity of these wind corridors, although well-exposed sites can have up to class 6 to 7 annual wind power. The only known site where winds have been measured up to heights near 50 m (164 ft) above ground was the DOE candidate site at Livingston, where class 6 annual wind resource was measured.

Southern Wyoming Corridor

An area of high wind energy extends across southern Wyoming from the Utah border on the west to the Nebraska border on the east. This zone of high wind energy can be attributed to a major gap, about 150 km (90 mi) wide, in the north-south barrier of the Rocky Mountains. Prevailing westerly and southwesterly winds blow with little resistance through this gap across the relatively high plains and uplands of southern Wyoming. As a result, this is the largest region of non-mountainous terrain in the Northwest with a high wind energy resource.

Wind measurements taken throughout the extent of this high wind corridor in southern Wyoming indicate that exposed areas have class 4 to 6 annual average wind resource. Areas of highest wind resource occur where there is enhanced channeling by the terrain (e.g., between two mountain ranges) and/or where there is terrain-induced flow acceleration (e.g., over hilltops, uplands, or low ridges). One large area of exceptionally good wind energy potential occurs from near Rawlins eastward to Medicine Bow and the Laramie Mountains and southward along the Laramie Mountains divide to the Colorado border. Several large wind turbines have been installed in the Medicine Bow area.

Wind measurements from a DOE candidate site at Bridger Butte, in extreme southwestern Wyoming near Fort Bridger, showed class 6 annual average wind power at heights to 50 m (164 ft). Aircraft measurement (Dawson and Marwitz 1981) and surveys of eolian land forms (Marrs and Kopriva 1978) throughout southern Wyoming also indicate areas of very high wind energy potential. However, considerable variability in the wind resource exists in certain areas, especially where there are local terrain influences.

Winter is the season of maximum wind power, with class 7 power in the best areas. In summer, the season of minimum wind power, class 3 power can be expected in the best areas.

Plains and Uplands of Eastern Montana and Northeastern Wyoming

Class 3 and 4 annual average wind resource occurs over the open plains and upland areas throughout eastern Montana and northeastern Wyoming. There are relatively few wind measurement sites in this vast area, aside from airfield stations near the larger towns and cities. New data from the uplands area east of Circle, Montana, indicate class 4 wind energy potential.

Exposed Mountain Ridges and Summits

At least class 3 or higher wind power is estimated for most of the exposed mountain summits and ridge crests throughout the Northwest except for some of the lower, forested summits of Oregon and Washington. Average wind speeds may vary significantly 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 of other mountains and ridges. Winter is the season of highest wind power over most mountain summits and ridge crests in the Northwest because mean upper-air wind speeds are highest during this season. However, severe icing, access problems, and damaging storm winds severely restrict the suitability of wind energy development for many of the higher mountain summits and ridge crests in the Northwest.

The North Central Region

The North Central region, (Map 3-8), consists of Iowa, Minnesota, Nebraska, North Dakota, and South Dakota. Two-thirds of the residents live in Iowa and Minnesota. The region is largely rural.

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

Class 3 and higher wind energy potential exists at exposed areas throughout the North Central region except for portions of eastern Minnesota, southeastern Iowa and the Missouri River lowlands along the Nebraska-Iowa border. As a result of new measurement programs beginning in the late 1970s and early 1980s, several areas in the North Central region, notably in North Dakota, indicate significantly greater wind energy potential than previously estimated (although higher wind power was speculated) in the regional atlas (Freeman et al. 1981). These new measurements indicate that the annual average wind resource is class 5, and possibly class 6, in certain areas.

Very strong nocturnal shear is evident from data collected at a DOE-installed meteorological tower near Finley, North Dakota, such that the average annual wind shear increases at a rate much greater than that predicted by a 1/7 power law. Thus, data collected near 10 m (33 ft) may not provide a realistic indication of the wind power and diurnal variation at 50 m (164 ft). However, at other areas in the North Central region, such as Huron, South Dakota, the nocturnal wind speeds at 50 m (164 ft) are substantially less than those at Finley, North Dakota. Finley, located on an upland above an escarpment, is slightly elevated with respect to its regional terrain environment, whereas Huron, located in the James River plain, is slightly lower than the uplands to the east and west of the river plain.

Thus, minor variations in elevation appear to have a very significant influence on the wind energy resource in the northern Great Plains. Additional data are needed to evaluate the nature of the low-level nocturnal jet in this region and its effect on the spatial and temporal variation of the wind energy resource with respect to minor variations in elevation. Major areas with class 3 or greater annual average wind power are described below. Maps of annual average wind power are presented as Maps 3-9 through 3-13 for Iowa, Minnesota, Nebraska, and North and South Dakota.

Canadian Wind Corridor and the Red River Valley

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

Within this general area is the Red River valley. The Red River forms much of the boundary between North Dakota and northern Minnesota. This valley slopes downward to the north as the Red River flows northward into Lake Winnipeg. Data from stations near the Red River indicate some channeling effect, with prevailing winds being split between north and south directions. Data from Pembina and Grand Forks indicate annual wind power averages that are near the borderline between class 4 and class 5.

Missouri and Pembina Escarpments and Turtle Mountains

The Missouri Escarpment is an area of abrupt east-to-west rise of about 200 m (600 ft) in the otherwise flat terrain of eastern and central North Dakota and eastern South Dakota.

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

Wind measurements from new sites located on hilltops and uplands at the top of these escarpments indicate that these areas have class 5 annual average wind resource at 50 m (164 ft), with class 6 possible in some places. Almost 2 years of data from the DOE-installed site at Finley, North Dakota, located above the Pembina Escarpment, indicate class 6 at 50 m (164 ft) with maximum wind power at night. Class 4 power was measured at 10 m (33 ft), and the diurnal variation at 10 m (33 ft) was completely reversed from that at 50 m (164 ft). Data from another DOE-installed site located south of Minot, North Dakota, at the top of the Missouri Escarpment, indicate class 5 wind power. New site data collected near 10 m (33 ft) above ground by Bureau of Reclamation and Western Area Power Administration indicate class 4 and 5 power in the upland areas of the Missouri Coteau, located between the Missouri Escarpment and the Missouri River.

Maximum wind power occurs in spring, with class 6 to 7 power at 50 m (164 ft). The new data at Finley and Minot show very strong nocturnal wind shear during the summer and surprisingly high wind energy potential at 50 m (164 ft), class 6 and 4, respectively, for the summer season. Previous estimates of the summer wind resource in the regional atlas were only class 2 for these areas. However, longer-term data at 50 m (164 ft) are needed to verify the higher summer resource measured at Finley and Minot, which is based on only two summers' data.

Prairie Coteau and Lake Traverse Area

The Prairie Coteau is a basin-like plateau, rising about 200 to 250 m (656 to 820 ft) above the surrounding flat terrain, and containing numerous small moraine lakes. It is bounded on the east by an extension of the Missouri Escarpment and on the west by a similar though lower ridge. Sloping downward to the south, its north end appears on topographic maps as a wedge pointed north into the Canadian wind corridor.

To the east of the Prairie Coteau, near the Minnesota-South Dakota border formed by Lake Traverse, is an area that forms a divide between the Red River and Minnesota River drainages. New data collected near 10 m (33 ft) indicate class 4 power over these areas; however, class 5 is possible at 50 m (164 ft) if strong nocturnal shear occurs over these areas. No data at 50 m (164 ft) are available to verify this estimate.

Missouri Plateau and Sand Hills

New site data collected near 10 m (33 ft) from hilltops and uplands of the Missouri Plateau of the western Dakotas and the Sand Hills of northwestern Nebraska that are well exposed indicate class 4 to 5 wind power. Several instrumented sites near an upland divide in southwestern North Dakota measured class 5 wind power. Class 5 wind power was also measured over an elevated area in north-central South Dakota. Most other exposed sites of Missouri Plateau and Sand Hills measured class 4 power.

Many of the valleys and drainages in the Missouri Plateau are frequently sheltered from prevailing winds. These valleys have a lower wind power class, especially in winter and autumn when these valleys tend to fill with cold air. The resulting high stability restricts vertical mixing so that winds in these valleys are not as strong as on the uplands and better exposed areas. Examples of this are Bismarck and Williston, North Dakota, which are located in sheltered areas of the Missouri River valley.

Black Hills Ridge Crests

Exposed ridge crests and summits in the Black Hills are estimated to have at least class 4 annual average wind power. Average speed at any particular location depends on the elevation, orientation with respect to strong westerly winds, and proximity to other ridges and mountains. Wind power should be greatest at high elevations of the Black Hills that have wide-open exposure.

Open Hills and Plains of Southern Minnesota and Iowa

Exposed elevated sites in southern Minnesota and northwestern Iowa are estimated to have class 4 wind power, although no data from 30 to 50 m (98 to 164 ft) above ground were identified in these areas and surface data are very limited. Data from the Rochester Airport, located on an exposed ridge in southeastern Minnesota, indicate class 4 wind power. Limited data from northwestern Iowa and southwestern Minnesota also indicate class 4 power for exposed uplands. Class 3 wind power is estimated for exposed areas throughout the rest of Iowa, except for the extreme southeastern and southwestern parts of the state. Lower and more sheltered locations will have significantly less wind power, especially in winter and autumn when stable air in these lowlands restricts vertical mixing, causing wind speeds to be less than at higher locations.

Mesabi Range and Lake Superior Shore

In northeastern Minnesota, the Mesabi Range and Lake Superior shore are estimated to have class 3 annual average wind power. The Mesabi Range, which is oriented perpendicular to the strongest winds in the area, is estimated to have class 3 because of acceleration of winds blowing over this ridge. However, there were no data to verify this estimate.

The Lake Superior shore is exposed to the strong easterly winds from Lake Superior. Data from Duluth Airport indicate that strong easterly winds in this area may penetrate inland up to 25 km (15 mi). Thus, class 3 wind resource is estimated to extend inland up to 25 km (15 mi) from the shore.

The Great Lakes Region

The Great Lakes region consists of Illinois, Indiana, Michigan, Ohio, and Wisconsin. The major cities, lakes, rivers, and geographical features are shown in Map 3-14.

The topography of the region, relative to western sections of the United States, is not complex. The entire area is almost all glaciated; terrain ranges from flat in Indiana and Illinois to gently rolling in central and northern Wisconsin. The two exceptions are southeastern Ohio and extreme southwestern Wisconsin, where terrain is rugged and unglaciated. Areas near the Great Lakes have sandy bluffs and marshes. Glacial lakes are prevalent in Wisconsin and Michigan where the terrain is more hilly.

In the Great Lakes region, class 3 or higher wind energy potential is estimated for exposed coastal and offshore areas of Lakes Erie, Huron, Michigan, and Superior, hilltops and ridges in southwestern Wisconsin and in the upper part of Michigan's lower peninsula, and upland plains in west-central Illinois. Areas of highest wind energy potential in the region are the exposed coastal and offshore areas and islands of the Great Lakes. At least class 5 wind power can be expected over offshore areas of all the Great Lakes, with maximum wind power in the winter (class 6) and minimum wind power in the summer (class 3). Over offshore areas, prevailing strong winds are mostly from the northwest-to-southwest directions. Exposed coastal points along the eastern shore of Lake Michigan and along the northern and western part of Keweenaw Peninsula in Lake Superior are estimated to have class 5 wind power, because these areas are well exposed to the prevailing strong winds with a long fetch over the open waters.

Major wind resource areas in the Great Lakes region are described below in greater detail. Maps of annual average wind power are presented in Maps 3-15 through 3-19 for Illinois, Indiana, Michigan, Ohio and Wisconsin.

Lake Michigan

The annual average wind power for exposed coastal and offshore areas of Lake Michigan is estimated to range from class 3 to class 5. The abrupt increase in surface roughness inland from the coastline, because of vegetation and topography, rapidly attenuates the wind resource landward.

Areas of highest wind energy potential are the exposed offshore areas, islands and exposed capes, and points along the eastern shore of Lake Michigan. Class 5 wind power is estimated for these areas, with maximum wind power in the winter (class 6) and minimum wind power in the summer (class 3). Over the offshore areas, prevailing strong winds are mostly from the northwest-to-southwest directions. Exposed coastal points along the eastern shore of Lake Michigan are well exposed to these prevailing strong winds, which have a long fetch over the open water. The class 5 estimate for exposed coastal points along the eastern shore of Lake Michigan is verified by approximately two years of wind measurements at 30 and 46 m (98 to 151 ft) on a DOE-installed tower at Big Sable Point.

The western shore of Lake Michigan forms the eastern edge of Wisconsin and has an annual average wind power of class 3. This reduced wind power on the western shore reflects the prevailing westerly winds. Eastward-moving storm systems during the winter and late autumn are responsible for the easterly winds that flow off the lake. Thus, on the annual average, the wind power on the western shore is less than on the eastern shore but still reflects the influence of Lake Michigan. Lake breezes, which are maximized in the spring, also enhance the wind power potential along this shoreline.

Lake Huron

Like the Wisconsin shore of Lake Michigan, the Lake Huron shoreline was estimated to have class 3 annual average wind power with class 4 possible at some of the most prominent capes. Offshore, wind power increases to class 5.

The average prevailing winds are westerly. In addition to lake breeze effects in spring, during the storm season (late fall through early spring) northeasterly and easterly winds frequently blow off the water. Because the low surface friction of the lake surface does not reduce the wind velocity, the annual average wind power along the coast is higher than inland. The abrupt increase in surface roughness inland from the coastline, because of vegetation and topography, rapidly attenuates the wind resource landward.

Lake Erie

The coastal region of extreme northern Ohio has an estimated annual wind power of class 3, increasing to class 5 over offshore areas of Lake Erie. Prevailing northerly and westerly winds have a long, smooth fetch across Lake Erie, resulting in powerful winter and spring winds, especially along the coastal areas of northeastern Ohio. The shape of the coastline is such that exposed coastal sites can also experience strong onshore winds from the northeastern quadrant.

Lake Superior

The annual average wind power along Lake Superior shorelines is estimated to range from class 3 to class 5, with class 5 existing at exposed areas along the northern Keweenaw Peninsula, Isle Royale, and offshore areas of Lake Superior. In some areas, class 3 and 4 wind powers are estimated to occur at exposed sites 15 to 35 km (10 to 20 mi) inland from the shoreline. In the western part of Michigan's upper peninsula, the class 3 and 4 wind power areas represent exposed sites along the coast and in the Gogebic, Porcupine, and Huron mountains, where the wind power estimates are representative only of well-exposed sites on the higher elevations.

Hilltops and Uplands of Michigan's Lower Peninsula

In the northern part of Michigan's lower peninsula, exposed sites on elevated terrain features are estimated to have class 3 annual average wind power. These elevated terrain features comprise the higher mountains, hilltops, and uplands in this region.

Hilltops and Ridges in Southwestern Wisconsin

Exposed hilltops and ridges in southwestern Wisconsin are estimated to reach class 3 annual average wind power. Although representative data from well-exposed sites have not been identified in southwestern Wisconsin, long-term data are available from a well-exposed airport site (Rochester, Minnesota) located on a ridge in extreme southeastern Minnesota. Based on the data from this site, similarly well-exposed sites on hilltops and ridges in southwestern Wisconsin were estimated to have class 3 wind power.

West Central Illinois

Uplands of west-central Illinois from Quincy to Springfield are estimated to reach class 3 annual average wind power, slightly higher wind energy potential than other inland areas of Illinois. Long-term data from the Springfield Airport gave the highest annual average wind power of any airport site in Illinois. No 50-m (164 ft) data were identified in this area of Illinois (Paton et al. 1980).

The Northeast Region

The Northeast region consists of Connecticut, Massachusetts, Rhode Island, Maine, New Hampshire, Vermont, New Jersey, New York, and Pennsylvania. The region's total population in 1980 of 49,136,000 represents approximately one-fourth of the nation's population. A large percentage of the people in the Northeast live in the corridor between Boston and Philadelphia, while large areas of northern Maine and upstate New York are quite sparsely populated. The major cities, rivers, lakes, and mountain ranges are shown in Map 3-20.

The topography varies dramatically throughout the Northeast. The Appalachian Mountains extend in a bank from northern Maine beyond the southern border of Pennsylvania. To the east of the mountains lie piedmont and coastal plain regions. West of the mountains the land becomes flatter as one approaches the Great Lakes. A large portion of the land area of the Northeast is composed of either hills and mountains or open hills and mountains, while large areas of Massachusetts, Rhode Island, Maine, and New York are plains containing hills. The only area of tablelands in the Northeast extends in an arc from the Hudson River valley, across central New York, and into northwestern Pennsylvania. Central and southern New Jersey contain the only true plains in the region.

Areas of class 3 or higher wind energy potential occur throughout much of the Northeast region. The primary areas of good wind energy resource are the Atlantic coast, the Great Lakes, and exposed hilltops, ridge crests, and mountain summits from Pennsylvania to Maine. Areas of highest wind energy potential (class 5 and 6) are the outer coastal areas such as Cape Cod and Nantucket Island, offshore areas of Lake Ontario and Lake Erie, and the higher mountain summits of the Appalachians. Winter is the season of maximum wind power throughout the Northeast region. During this season, all except the most sheltered areas have class 3 or better wind resource, and exposed coastal areas and mountain summits can expect class 6 or 7 wind resource. In summer, the season of minimum wind power, class 3 wind resource can be found only on the outer coastal areas and highest mountain summits.

Major areas of wind resource in the Northeast region are described below. Maps of annual average wind power are presented in Maps 3-21 through 3-26 for Connecticut, Massachusetts and Rhode Island (displayed on one map), Maine, New Hampshire and Vermont (displayed on one map), New Jersey, New York, and Pennsylvania.

Atlantic Coastal Areas

The annual average wind power for exposed Atlantic coastal and offshore islands of the Northeast is primarily class 4, 5, and 6. Class 4 is found immediately along the coast, while class 6 exists along the outer capes and islands such as Cape Cod and Nantucket Island. Semi-enclosed bodies of water, such as Long Island Sound and Delaware Bay, have a lower wind resource (class 3).

When onshore flow occurs, the abrupt change in surface roughness inland from the coastline, because of vegetation and topography, rapidly attenuates the wind resource landward. The strongest onshore flow on the synoptic scale occurs most frequently in the winter and early spring and is associated with strong pressure gradients occurring with coastal storms.

Wind measurements up to 46 m (150 ft) above ground have been taken at four DOE-installed tower sites along the northeastern Atlantic coast—Nantucket Island and Provincetown, Massachusetts; Montauk Point, New York; and Block Island, Rhode Island. Long-term data (5 yr) from both Block Island and Montauk Point indicated class 4 annual average wind power at 50 m (164 ft) for those areas. Limited data (2 yr) from Nantucket Island and Provincetown indicated that these outer areas could have class 6 or better annual average wind power at 50 m (164 ft). At 10 m (33 ft), the annual average wind power varied considerably among these four sites and was only class 2 at Block Island and Provincetown. These data provide excellent examples of how local roughness features such as vegetation and buildings can reduce the wind power at levels near the ground and how near surface (10-m or 33 ft) data may not provide a realistic indication of the wind power at 50 m (164 ft).

Hills and Mountains of Vermont, New Hampshire, Maine, Massachusetts, and Connecticut

An extensive area, including most of Vermont and New Hampshire, as well as much of Maine, Massachusetts, and Connecticut, has annual average wind power of class 3 or higher on exposed locations. Highest powers (class 5 and 6) occur on the best-exposed mountain and ridge tops in Vermont's Green Mountains, New Hampshire's White Mountains, and Maine's Longfellow Mountains. The remainder of the hilltops and mountain tops in this area that are outside of these major ranges have class 3 or 4 wind power. At the highest elevations this wind power increases to class 6 and 7 in the winter. Average wind speeds may vary significantly from one ridge crest to another and are primarily influenced by the height and slope of the ridge, orientation to the prevailing winds, and the proximity of other mountains and ridges. For example, the White Mountains are indicated to have class 6 wind power, but Mount Washington, at 1,917 m (6,288 ft) elevation, is known to have considerably greater wind power as a result of terrain-induced acceleration as the air passes over the mountain.

Adirondack Mountains

Wind power of class 3 and higher is estimated for the high elevations of the Adirondack Mountains of northeastern New York. Two of the highest mountains, Mt. Marcy and Whiteface Mountain, have at least class 6 wind power. As in the case of Mount Washington, wind measurements on Whiteface Mountain indicate higher than class 6 power because of local acceleration effects. Mean upper-air wind speeds appear to be about the same over the Adirondack Mountains as they are over the mountains of northern New Hampshire and Vermont.

Hills and Mountains of Northern Pennsylvania, Southern New York, and Northwestern New Jersey

Class 3 and higher wind power is estimated for exposed hilltops, ridge crests, and mountain summits in Pennsylvania, southern New York, and northwestern New Jersey. The highest wind power, class 5, exists in southeastern New York on the higher summits of the Catskill Mountains. Other major mountains or mountain ranges included in this resource area are Bald Eagle Mountain, North Mountain, the Pocono Mountains, and the Allegheny Mountains. The wind power in much of this area increases to class 5 and 6 in the winter.

Lake Ontario and Lake Erie

Annual average wind power of class 3 or 4 is found along the coastal areas of both Lake Erie and Lake Ontario as the smooth, overwater fetch allows strong near-surface winds to develop. Class 5 is estimated to exist in the central part of both lakes. Existing data indicate that class 3 wind power may extend 30 to 40 km (20 to 25 mi) inland from the eastern shore of Lake Ontario (Pickering et al. 1980).

The East Central Region

The East Central region consists of Delaware, Kentucky, Maryland, North Carolina, Tennessee, Virginia, and West Virginia. North Carolina, Virginia, and Maryland account for nearly 60% of the region's population, of which most reside in the Mid-Atlantic Lowlands. The major cities, rivers, mountain ranges, and national parks are shown in Map 3-27.

The region's topography varies from rolling hills in the west to forested mountain ridges in the central portion to relatively flat coastal plains in the east. The mountain ridges are generally oriented in a northeast-southwest direction.

Areas of class 3 annual average wind power are found along exposed coastal areas from Delaware southward to Cape Lookout, North Carolina, including much of Delaware Bay, Chesapeake Bay, and Pamlico Sound. Seasonal average wind power along the coastal areas ranges from class 4 in the winter and spring to class 2 in the summer. Class 3 to 6 annual average wind resource is estimated for exposed mountain summits and ridge crests of the Appalachians. Over 4 years' data collected at a DOE wind turbine site on a 1,347 m (4419 ft) mountain summit near Boone, North Carolina, indicated class 4 annual average wind power at 50 m (164 ft). Seasonal average wind power ranged from a maximum of class 7 in winter to a minimum of class 2 in summer at this site.

Aside from the coastal areas and exposed mountains and ridges of the Appalachians, there is little wind energy potential in the remainder of the East Central region for current wind turbine applications (Brode et al. 1980).

Major areas of wind resource in the East Central region are described below. Maps of annual average wind power are presented in Maps 3-28 through 3-33 for Delaware and Maryland (displayed on one map), Kentucky, North Carolina, Tennessee, Virginia, and West Virginia.

Atlantic Coastal Areas

The annual average wind power for exposed coastal areas of Delaware, Maryland, Virginia, and North Carolina is estimated to be class 3. South of Cape Lookout, North Carolina, wind power decreases to class 2. There is a steep gradient in the estimated wind power within several kilometers of the coastline because of 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's coastline. While most 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.

Winter and spring are the seasons of maximum power for the coastal areas of the region, with class 4 wind power from Cape Hatteras northward. In summer, wind power decreases to a minimum of class 1 and 2 along the coastal areas.

Chesapeake and Delaware Bays

Much of the Chesapeake and Delaware bays are estimated to have class 3 wind power. Areas of highest wind resource are expected where there is a large fetch over open water for the prevailing strong winds, which come from the west through north directions. The complexity of the Chesapeake Bay shoreline, with its many islands and inlets, suggests a high variability of wind power in this area.

Exposed Mountain Ridges and Summits

Class 3 or higher wind power is estimated for exposed mountain summits and ridge crests in western North Carolina, eastern Tennessee, eastern West Virginia, western Maryland, and portions of Virginia. 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. Most of the ridges in Virginia, West Virginia, and western Maryland are oriented perpendicular to the prevailing westerly winds. As a result, the higher ridges may experience wind power that is considerably enhanced by a venturi speed-up effect - 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. In contrast to valley and plain locations, the daily maximum wind speed for mountain summits and ridge crests generally occurs at night; this situation occurs because the frictional boundary layer is more shallow as a result of the absence of solar heating and associated vertical mixing.

The Southeast Region

The Southeast region consists of Alabama, Florida, Georgia, Mississippi, and South Carolina. The region's total population in 1980 of 24,746,000 represents approximately one-tenth of the nation's population. Nearly three-quarters of the people in the Southeast live on the East Coast from South Carolina to Florida. The major cities, rivers, mountain ranges, and geographical features of the Southeast are shown in Map 3-34.

With the exception of the north-central portion of the Southeast region and a few scattered areas, the topography is relatively low and flat. Roughly 41% of the topography in the Southeast is irregular plains, 41% is flat and smooth plains, and only 18% is tableland, hills, and low mountains, which lie in the north-central part of the Southeast. The northern half of Alabama, the northern part of Georgia, and the far northwestern corner of South Carolina have the most complex terrain of the region, with tablelands, hills, and low mountains.

There is little wind energy potential in the Southeast region for existing wind turbine applications (Zabransky et al. 1981). Even along coastal areas, existing data from exposed sites indicate at best only class 2 at 50 m (164 ft) above ground. The only places in the Southeast region estimated to have class 3 or higher annual average wind resource are the exposed ridge crests and mountain summits confined to northeastern Georgia and extreme northwestern South Carolina, as described below. Maps of annual average wind power are presented in Maps 3-35 through 3-39 for Alabama, Florida, Georgia, Mississippi, and South Carolina.

Mountains of South Carolina and Georgia

The exposed ridge crests and mountaintops of the southern Appalachians in extreme northwestern South Carolina and northeastern Georgia have annual average wind power densities of class 3 to class 5. This area is highly confined and represents an extremely small percentage of exposed land in the Southeast region.

The South Central Region

The South Central region, consisting of Arkansas, Kansas, Louisiana, Missouri, Oklahoma, and Texas, is about the same size as Alaska and equal to one-fifth the area of the 48 contiguous states. Texas has 45% of the area and slightly more than 45% of the region's population. Over 40% of the people in the South Central region live in the six metropolitan areas that have over one million inhabitants each. In order of decreasing population, these are Dallas-Fort Worth, Texas; Houston, Texas; St. Louis, Missouri; Kansas City, Kansas; Kansas City, Missouri; New Orleans, Louisiana; and San Antonio, Texas. The major cities, rivers, mountains, and national parks of the South Central region are shown in Map 3-40.

The South Central region extends from the interior plains to the coastal plains with a few interior highlands in the east-central part. The Mississippi River makes up most of the eastern boundary of the region as it flows south to the Gulf of Mexico. The only major portions of the region that are mountainous are the western tip of Texas, and parts of Arkansas, Missouri, and extreme eastern Oklahoma.

A substantial portion of the South Central region has class 3 or higher annual average wind power. The most extensive area of wind resource includes most of Kansas, Oklahoma, and northwestern Texas, where a large fraction of the land area is well exposed to power-producing winds. Other areas of significant wind resource in the region include the Texas coast and exposed hilltops, ridge crests, and mountain summits in parts of southern Missouri, western Arkansas, eastern Oklahoma, and extreme western Texas.

Since the completion of the regional wind energy atlas (Edwards et al. 1981), many new sites have been instrumented to measure the wind resource throughout much of Kansas, western Oklahoma, and northwestern Texas. Wind measurements at levels up to 46 and 50 m (150 to 164 ft) above ground have been taken at 16 new sites in this area. Four of these were sites instrumented for the DOE candidate site program. These were located near Amarillo, Texas; Meade and Russell, Kansas; and Fort Sill, Oklahoma. Some other organizations involved in wind measurement activities in this area included the Alternative Energy Institute, Kansas State University, and Wichita State University. The composite analysis of the new wind data obtained for this area resulted in some significant revisions in analysis from the previous regional assessment.

For example, the class 5 area previously shown over the southern High Plains from north of Amarillo, Texas, to extreme southwestern Kansas, has been revised to class 4 and 3, based on the wind measurements taken at or near 50 m (164 ft) at five new sites in this area. In eastern Kansas, an area previously assigned class 3 has been up-graded to class 4, reflecting exposed areas in the Flint Hills where several new sites indicate class 4 (and possibly class 5) at 50 m (164 ft) above ground. In the Texas coastal area, the class 4 area was revised to class 3, based on new data at 30 to 60 m (98 to 164 ft) above ground from two sites and a re-analysis of the coastal data previously used in the regional assessment. The seasonal analyses in the Texas coastal area (presented on the national-scale maps) have been revised to show an on-shore maximum in the wind resource in the spring and summer. During these seasons, the wind resource is estimated to be greater along the inner coastal areas than along the offshore islands, such as Padre Island. Additional data are needed, especially at heights to 50 m (164 ft), to provide a more reliable estimate of the extent of this onshore maximum in the wind resource.

Major areas of wind resource in the South Central region are described below. Maps of annual average wind power are presented in Maps 3-41 through 3-47 for Arkansas, Kansas, Louisiana, Missouri, Oklahoma, and Texas. (Texas is displayed in two maps, one for West Texas and one for East Texas.)

The Great Plains

Exposed areas of the Great Plains encompassing a large area of northwestern Texas, Oklahoma, and Kansas have class 3 and 4 annual average wind power. The most extensive area of class 4 power extends from the Texas Panhandle to northwestern Oklahoma and south-central Kansas. In this area, the wind power is estimated to approach class 5 over some of the uplands and hills. However, over much of the Great Plains, local variations in terrain elevations and exposure cause variability in the wind resource, such that the wind resource may vary from class 2 over lowlands and river valleys to class 4 (and possibly class 5) over exposed uplands and hilltops.

Seasonal variations in the wind resource at 50 m (164 ft) over the area from the Texas Panhandle to south-central Kansas are not as large as indicated in the previous regional assessment. Spring is the season of maximum wind power, with class 5; however, an area of class 4 appears in each of the remaining three seasons. At the Amarillo DOE site, 5 years' data indicated that summer was the season of second highest wind power at 50 m or 164 ft (with a strong class 4), although summer was the season of lowest wind power at 10 m or 33 ft (with class 3). Strong nocturnal wind shear, especially prevalent during the summer, results in a higher wind power class at 50 m (164 ft) in the summer than would be indicated by 10-m (33 ft) data. Mean wind speeds at 50 m (164 ft) are greater at night than during the day.

Flint Hills of Eastern Kansas

The Flint Hills extend north to south through eastern Kansas. Wind measurements at heights to 50 m (164 ft) above ground at exposed sites in the Flint Hills indicate class 4 annual average wind power, and possibly class 5 over well-exposed areas of the southern Flint Hills. As it does over exposed uplands in the Great Plains, strong nocturnal shear occurs over elevated areas of the Flint Hills, such that mean wind speeds at 50 m (164 ft) are greater at night than during the day.

The wind resource at 50 m (164 ft) remains high throughout the four seasons; the seasonal average wind power is estimated to be a strong class 5 in the spring and class 4 in the other three seasons. Additional data are needed to verify the seasonal nature of the wind resource, because less than two years' data were available for this area at the time of this analysis.

Over most of the remainder of eastern Kansas, class 3 is estimated for the open plains and exposed uplands and hilltops.

Wichita Mountains of Southwestern Oklahoma

Limited data in the vicinity of the Wichita Mountains in southwestern Oklahoma indicate at least class 4 or higher wind power. Local, strong acceleration of the wind speeds is estimated to occur around the eastern and western ends of the Wichita Mountains, as a result of the prevailing strong northerly and southerly winds over this region. Limited data from a DOE-installed tower on the plains near the eastern end of the Wichita Mountains indicate very good wind energy potential (possibly class 6), although additional data are needed to verify the magnitude and nature of the wind resource in this area.

Texas Coastal Area

The Texas coastal area from Galveston south to the Mexican border is estimated to have class 3 annual average wind power. This wind resource extends up to 30 to 60 km (20 to 40 mi) inland. The wind resource along the inner coastal area (just onshore and to 30 km inland) may be slightly greater than that over the offshore islands, such as Padre Island. New site data from the offshore islands indicate class 2 to class 3 wind power at 50 m (164 ft), rather than the class 4 previously assigned in the regional atlas. Data at 60 m (197 ft) from the inner coastal area indicate class 3 annual average wind power. A reanalysis of the near-surface data from airfields in the inner coastal area also indicates that class 3, rather than class 4, is more appropriate to this area.

Seasonally, the inner coastal area is estimated to have greater wind power in spring and summer than the offshore islands. Existing data indicate a spring maximum of class 4 along the inner coastal area south of Matagorda and a winter maximum along the offshore islands and the coastal fringes northward to Galveston.

Ouachita Mountains and Boston Mountains

Upper-air wind data have been used to estimate class 3 and 4 wind power at exposed areas in the Ouachita and Boston mountains, which extend from Arkansas westward into Oklahoma. Although the wind power map implies that nearly one-fourth of Arkansas has class 3 and 4 wind power, the exposed mountain summits and ridge crests account for only 3% of Arkansas land area. No surface data from mountain summits or ridge crests in these areas were available to verify this wind resource.

Ozark Plateau

The Ozark Plateau is an area of forested hills and low mountains and ridges in southern Missouri and northwestern Arkansas. Exposed hilltops, ridge crests, and mountain summits of the Ozark Plateau are estimated to have class 3 annual average wind power, although no data were available from a well-exposed site to verify this wind resource. However, wind data from the Springfield, Missouri, airport, which is located on an upland near a crest in the Ozark Plateau but at an elevation approximately 60 m (197 ft) lower than the crest, indicates class 2 annual average wind resource. Thus, well-exposed sites at the highest elevations on the Ozark Plateau are expected to have at least class 3 wind power at 50 m (164 ft).

Seasonally, wind power over the Ozark Plateau is estimated to reach a maximum of class 4 in winter and spring, decreasing to a minimum of class 2 in the summer.

Rocky Mountain Extensions

The ridge crests and mountaintops of the Guadalupe and Davis mountains in the basin and range region of the Rocky Mountain extensions in southwestern Texas are estimated to have up to class 6 wind power. Surface data taken at Guadalupe Pass confirms this and suggests that there is some funneling in the passes and valleys.

The Southern Rocky Mountain Region

The Southern Rocky Mountain region consists of Arizona, Colorado, New Mexico and Utah. Over 60% of the region's people reside in the metropolitan areas of Denver, Colorado; Phoenix, Arizona; Salt Lake City, Utah; Tucson, Arizona; Albuquerque, New Mexico; and Colorado Springs, Colorado. The remainder of the region's people live in agricultural, industrial, and resort communities distributed throughout the area. The major cities, rivers, lakes, mountain ranges, and geographical features of the Southern Rocky Mountain region are shown in Map 3-48.

Topography varies dramatically throughout the Southern Rocky Mountain region. The region is dissected by the continental divide, which extends through central Colorado and western New Mexico, and is composed of five basic topographic areas: the high plains, the Rocky Mountains, the Colorado Plateau, the Great Basin, and the southwestern desert. The high plains area occupies roughly the eastern one-third of Colorado and New Mexico. The Rocky Mountains, which extend from north to south through Colorado and New Mexico, are composed of numerous ranges that attain elevations in excess of 4,250 m (13,944 ft). The Colorado Plateau occupies the area surrounding the Four Corners area. The Great Basin of western Utah is composed of desert basins, playas, and small mountain ranges. The southwestern desert includes the desert areas of southern New Mexico and southern Arizona.

Areas of class 3 or higher wind resource can be found throughout the Southern Rocky Mountain region. The most extensive area of wind resource is found over the high plains and uplands of eastern Colorado and eastern New Mexico. Over this area, the annual average wind resource is mostly class 3 and 4, but can be higher on well-exposed hilltops that are found over portions of the high plains region. Mountain summits and ridge crests estimated to have class 3 or higher wind resource exist throughout the Southern Rocky Mountain region. Higher mountain ranges are estimated to have at least class 6 wind power, but many of these may not be suitable because of the ruggedness of the terrain and the potential for extreme wind and icing conditions. Two valley wind corridors have been identified that are estimated to have at least class 3 wind resource. One of these wind corridors is in the vicinity of Milford, Utah, and the other is in the vicinity of Santa Fe, New Mexico.

These major areas of wind resource in the Southern Rocky Mountain region are described below. Maps of annual average wind power are presented in Maps 3-49 through 3-52 for Arizona, Colorado, New Mexico, and Utah.

Eastern Plains of Colorado and New Mexico

Class 3 and 4 annual average wind power is found on the high plains and uplands of eastern Colorado and eastern New Mexico. Strong northerly and southerly winds in this area are usually associated with the intense surface pressure gradients that are prevalent during the winter and spring. Plains areas farther west that are within the sheltering influence of the Rocky Mountains and river drainages generally have less wind power.

Buttes, hilltops, and other types of elevated summits are scattered throughout parts of the high plains, especially in northeastern New Mexico and southeastern Colorado. Well-exposed summits and hilltops, where there is terrain-induced acceleration of the wind, may have class 5 or higher wind resource. For example, a DOE site on a hilltop near Tucumcari in northeastern New Mexico indicated class 5 power at 50 m (164 ft) over a 2-year period. Another DOE site located on open plains near Clayton in northeastern New Mexico had class 3 wind power at 50 m (164 ft), based on 5 years' data. The class 5 power previously estimated for the plains area around Clayton in the regional atlas (Andersen et al. 1981) appears too high. These previous estimates were primarily based on near-surface, airfield data of unknown quality from the 1940s and early 1950s.

New site data throughout northeastern Colorado indicate an extensive area with class 4 annual average wind power. This is an upland region between the South Platte River to the north and the Arkansas River to the south. Wind power is considerably lower in the river plains and valleys than on the uplands.

Seasonal average wind power over the upland plains of eastern Colorado and New Mexico ranges from a maximum of class 4 and 5 in spring to a minimum of class 2 and 3 in summer.

Northern Colorado Plains

North of the South Platte River in northeastern Colorado, the elevation increases northward to the high plains of southeastern Wyoming and western Nebraska. The proximity of the sheltered South Platte River valley to the southern Wyoming wind corridor creates a steep gradient of annual average wind speed, and hence wind power, between these areas. The strong prevailing westerly winds, which blow uninterrupted through the large gap in the Continental Divide in southern Wyoming, appear to extend into northeastern Colorado and western Nebraska.

Class 4 to 6 annual average wind power is found in this part of Colorado south of the Wyoming and Nebraska borders. New site data indicate that class 4 wind power extends eastward to Peetz, Colorado. Class 6 wind power is found on the Laramie Mountains divide, a broad upland which extends southward just into Colorado.

Strongest winds in this area occur during the winter as a result of intense pressure gradients between the low-pressure systems moving east across the northern tier of states, and the semi-permanent high-pressure system that occupies the Great Basin. Prevailing wind directions during strongest winds are generally westerly and northwesterly.

Milford Corridor in Southwestern Utah

Class 3 annual average wind power is found in the valley corridor in the vicinity of Milford, Utah. Strong southwesterly winds frequently occur over this area, especially during the spring when the wind resource averages class 4. Higher wind resource may exist in areas where the terrain causes even stronger channeling of the winds. Data are scarce in this region of southwestern Utah, and the geographical extent of this wind resource area is not well known.

Santa Fe Corridor in Northern New Mexico

Class 3 annual average wind power is estimated for the Rio Grande Valley corridor in the vicinity of

Santa Fe, New Mexico. Wind speeds are enhanced as air flowing up or down the Rio Grande Valley is channeled and accelerated through a broad gap between two large mountain ranges. Wind resource reaches a maximum in the spring, when it averages class 4. Higher wind resource may exist in areas where the terrain causes even stronger channeling of the winds.

Exposed Mountain Ridges and Summits

Class 3 or higher annual average wind power is estimated for exposed mountain summits and ridge crests throughout the Southern Rocky Mountain region. Class 6 is estimated for the higher mountain ranges in parts of Colorado, New Mexico, and Utah. However, many of these higher mountain ranges may not be suitable for wind turbine applications because of extreme icing, damaging winds, and inaccessibility, especially during the winter.

Average wind speeds may vary significantly from one ridge crest site to another and are primarily influenced by the height and slope of the ridge, orientation to prevailing winds, and the proximity of other mountains and ridges. High wind resource may exist in mountain passes or saddles where prevailing strong winds are funneled. A DOE site at San Augustin Pass, located about 30 km (20 mi) northeast of Las Cruces in the San Andreas Mountains of southern New Mexico, indicated class 6 annual average wind power at 50 m (164 ft) with a strong class 7 in the winter and spring.

Winter is estimated to be the season of maximum wind power over mountain summits and ridge crests in Utah, Colorado, northern New Mexico, and northern Arizona, because mean upper-air wind speeds are highest over these areas during this season. However, on the exposed mountainous areas of southern Arizona and southern New Mexico, winter and spring power appear about equal and are the seasons of maximum wind power.

The Southwest Region

The Southwest region consists of California and Nevada. (To facilitate the presentation of the wind resource analysis, we have divided California along 37°N into northern and southern California). Nearly three-quarters of the inhabitants of the region live in coastal California, where the region's three large metropolitan areas—the San Francisco Bay area, Los Angeles Basin and San Diego—are located. Major cities, rivers, mountain ranges, and national parks are shown in Map 3-53.

There is a large variety of topography throughout the Southwest. California has many mountain ranges, several of which extend above 3,000 m (10,000 ft) in elevation. It also has some very large flat areas, notably the Central Valley, which is composed of both the Sacramento and San Joaquin valleys and is over 700 km (400 mi) long. The California desert is mostly composed of isolated peaks and ranges dotting an undulating basin. Nevada is composed almost exclusively of basin and range country; there is a series of parallel valleys alternating with steep mountain ranges. Some broad upland plains are found in northern Nevada near the Oregon and Idaho borders.

Considerable wind energy development has occurred in California; more wind turbines have been sited in California than in any other region of the United States. Extensive wind resource assessments have been conducted throughout California by the California Energy Commission (CEC) and various other organizations. The CEC has assimilated a wind resource data base on California that was utilized in verifying or updating this assessment. The DOE has sponsored wind measurement programs at three sites in California - Point Arena, San Gorgonio Pass, and Pacheco Pass - and one site in Nevada - Wells (located on a mountain ridge in northeastern Nevada about 65 km (40 mi) northeast of Elko).

Areas of class 3 and higher wind resource are dispersed throughout the Southwest region. The most notable areas where most of the wind energy development has been occurring are the coastal and inland passes through which cooler marine air is funneled to the warmer, drier valleys in the interior. At least six major passes, or wind corridors, with high wind resource occur throughout central and southern California. These are the Carquinez Straits, Altamont Pass, and Pacheco Pass in north central California and Tehachapi Pass, San Gorgonio Pass, and the Sierra Pelona in southern California. The annual average wind resource can reach class 6 or higher at well-exposed sites in these wind corridors. High wind resource is also found in some of the southeastern California desert corridors, such as the western part of the Antelope Valley and the Barstow-Daggett area.

Other areas of class 3 or greater wind resource in the region are the outer Channel Islands and exposed coastal areas north of Point Conception, and many of the exposed mountain summits and ridge crests that are located throughout the Southwest region.

Major areas of wind resource in the Southwest region are described below in greater detail. Maps of annual average wind power are presented in Maps 3-54 through 3-56 for California and Nevada. (California is displayed in two maps, one for northern California and one for southern California.)

Coastal Areas

The annual average wind power for exposed coastal areas of California north of Point Conception is estimated to be largely class 3, except for class 4 around Cape Mendocino. Because the prevailing wind direction is northwest during spring and summer and between the winter storms, and because much of the California coastline is oriented northwest to southeast, coastal areas that protrude into the flow experience the highest wind power. They also protrude into the southerly or southeasterly flow, which dominates during winter storms. However, because the rest of the shoreline is concave between these areas and thereby out of the strong flow, it experiences a markedly lower wind resource. The abrupt increase in surface roughness inland from the coastline, because of vegetation and topography, further slows the wind.

Almost 5 years of new site data from a DOE-installed tower at Point Arena indicated class 3 wind power at 50 m (164 ft). This site, which is well exposed to prevailing strong winds, is considered largely representative of exposed coastal areas of central California. Previous estimates of class 5 for much of this coastal area, which were based primarily on very limited surface data and offshore marine data (ship observations), appear too high (Simon et al. 1980). However, specific sites that experience local terrain-induced acceleration of the winds may exist that have class 5 or greater wind power. For example, limited data from a site on the exposed ridge crest at an elevation of about 450 m (1,476 ft) on Cape Mendocino indicate class 6 annual average wind power. In such areas of complex terrain, considerable spatial variability in the wind resource can be expected.

The southern California coastline south of Point Conception has very little wind power, because it is sheltered from the northwest winds by the Transverse Ranges. The outer Channel Islands (San Miguel, Santa Rosa, and San Nicolas) of southern California are far enough west to escape the sheltering that affects the rest of the southern California coastal area, and they are estimated to have class 3 to class 4 wind power.

Spring is the season of maximum wind power at exposed coastal areas from Point Arena south to Point Conception and the outer Channel Islands, where exposed areas average class 4 and 5 wind power. Over these areas, class 3 or greater wind resource is experienced in every season except autumn.

From Cape Mendocino northward, wind power is about equal in winter and spring, because strong winds associated with winter storms are more frequent along the northern California coast than the central and southern coast. Exposed areas on Cape Mendocino are estimated to have class 3 or greater wind power in every season.

Coastal Gaps

From spring through summer, the strong surface pressure gradients created by the cold water and warm interior force marine air through the gaps in the coastal mountains into the interior. This sea breeze is funneled in some cases by the topography. Where this happens, very strong and persistent winds are likely to occur. The Carquinez Straits, Altamont Pass, Pacheco Pass, San Gorgonio Pass, and the Sierra Pelona fall into this category. All have high annual average wind power and a spring or summer seasonal maximum. Although not a true gap, the Sierra Pelona region, which is located north of Los Angeles and south of Antelope Valley, is a long stretch of mountains that are lower than the mountain ranges on either side of it, and the marine air flows through this low area on its way to the Mojave Desert. The windiest areas are near the eastern end of each pass and the highest ridges of the Sierra Pelona.

Coastal Mountains

There are four areas of the Coast Range that have wind power of class 5 or better. Two areas, the higher mountains of northwestern California (2,000 to 3,000 m or 6,562 to 9,843 ft) and the San Gabriel Mountains east of Los Angeles (3,000 m or 9,843 ft), are strongly affected by the upper-air winds, and the wind resource therefore shows a strong winter maximum and summer minimum. They are 500 to 1,000 m (1,640 to 3,280 ft) higher than the surrounding mountains, so they are well-exposed to the free-air winds. The Vaca Mountains (about 900 m or 3,000 ft), west of Sacramento, and the Laguna

Mountains (about 2,000 m or 6,562 ft), east of San Diego, while higher than surrounding terrain and influenced by the upper-air flow, are also influenced by modified sea-breeze winds of spring and summer. Hence, their season of maximum wind power is winter, but the sea-breeze winds produce almost as much power in the spring, and the summer wind resource is not as low as in the other two areas. This sea-breeze circulation further complicates the wind regime of the Vaca Mountains. The prevailing strong winds of the other areas are generally westerly. This is true for the Vaca Mountains as well, except that they experience a definite wind shift from westerly during the day to northeasterly at night during the spring and summer.

Interior Mountains

The large mountain ranges of the Southwest have a high wind energy resource. The Cascades, Sierra Nevada, Tehachapis, and the ranges of Nevada are well exposed to the upper-air winds and therefore experience a winter maximum wind power. Where the mountain ranges and ridgelines are oriented perpendicular to the free-air flow, these winds may be further enhanced. Additionally, these ranges are large enough to separate adjacent air basins. The unequal heating of these basins during spring and summer produces air flow over some of these barriers. This flow results in wind speeds that are higher than those that would be found if only the upper-air winds produced the wind resource of the mountains.

Desert Wind Corridors of Southern California

East of the Coast Range in southern California, low-elevation wind corridors exist that have class 3 or greater wind resource. One notable wind corridor is Tehachapi Pass, near Mojave, where winds are funneled from the San Joaquin Valley into the Mojave Desert. Areas of class 6 annual average wind resource are indicated by new site data in the Tehachapi Pass vicinity. Spring and summer are the seasons of highest wind resource.

The western part of the Antelope Valley is another area of high resource potential. New site data in the extreme west end of the Antelope Valley indicate class 6 wind resource. Class 3 or higher wind resource is estimated to exist over much of the southern and western parts of the Antelope Valley. Spring and summer are seasons of maximum wind resource.

In the vicinity of Daggett (just east of Barstow), another wind corridor exists where desert winds are channeled between the Calico and Rodman Mountains. Over 20 years of data from the Daggett Airport show class 3 to 4 annual average wind power. New site data by the California Energy Commission also indicate class 3 to 4 wind power in this area. Maximum wind resource occurs in the spring and summer.

Desert Mountains of Southeastern California and Southern Nevada

Desert conditions are found in most of southeastern California and the valleys of southern Nevada. Intense heating will often generate strong afternoon winds that persist into the evening. The lack of vegetation and the preponderance of broad open valleys in California and narrower valleys in Nevada (which may funnel the winds) allow wind storms to sweep the desert with little abatement. In spite of these mechanisms, most desert floors have only class 1 or 2 power, as wind speeds decrease during the night and morning hours. The numerous mountain summits and ridgelines, which are less subject to stable layers that develop in the valley floors, may experience wind power of class 3 and higher. The lower mountains and ridges of southern California and southern Nevada, being more strongly affected by the thermal circulation, experience a spring maximum.

Alaska

Alaska covers an area of 1,518,776 km^2 (586,400 mi^2). Because of the state's large size, in the Alaska wind energy resource assessment (Wise et al. 1981) the state was divided into four subregions: northern, southeastern, south-central, and southwestern. The state population in 1980was 402,000. More than 40% of Alaska's population lives in the metropolitanarea of Anchorage, in the south-central subregion. The major cities, towns, villages, rivers, mountain ranges, and national parks are shown in Map 3-57.

The topography of Alaska varies from subregion to subregion. A large portion of the land is mountainous; the Brooks Range is in the northern subregion, the Alaska Range is in the south-central and southwestern subregions, and the Coast and St. Elias mountains are in the southeastern subregion. Flat coastal plains, such as those along the Arctic coast and Yukon-Kuskokwim Delta (in the northern and southcentral subregions, respectively) are also prominent features. Flat alluvial plains are found in the river valleys, such as the Yukon River valley in the southeast portion of the northern subregion. Upland plains are found throughout the state.

In Alaska, high wind resource occurs over the Aleutian Islands and the Alaska Peninsula, most coastal areas of northern and western Alaska, offshore islands of the Bering Sea and Gulf of Alaska, and over mountainous areas in northern, southern, and southeastern Alaska. The largest areas of class 7 wind power in the United States are located in Alaska—data from some of the Aleutian Islands indicate an annual average wind power over 1000 W/m^2 at 10 m, which corresponds to about 2000 W/m^2 at 50 m.

Major areas of wind resource in Alaska are described below. Maps of annual average wind power are presented for the four subregions in Maps 3-58 through 3-61.

Beaufort and Chukehi Sea Coast

The annual average wind power for exposed coastal and offshore areas is estimated to be at least class 5. Coastal areas near Barter Island, Point Lay, and Cape Lisburne show class 7. Even though much of the area north of the Brooks Range is of low relief, wind power drops off rapidly with distance from the coast as shown by data from Sagwon and Umiat. On the eastern Beaufort coast, an area with wind power of class 4 or higher appears to extend from the coast southward to the crests of the Brooks Range. Along the Chukchi Sea coast, wind power of class 5 to 7 is probably confined to near the coast, although there are no data available inland to corroborate this assumption.

Bering Sea Islands and Coast

Islands in the Bering Sea, such as the Pribilofs, St. Lawrence, St. Matthew, and Nunivak, all show annual wind powers of class 7 except in the vicinity of Savoonga on St. Lawrence Island, which has class 6. Along the coast from the Alaska Peninsula northward, wind power of class 5 or higher (with class 7 in exposed areas like the west end of the Seward Peninsula and the Cape Romanzof area) is shown. Wind power of class 5 or more extends eastward for 150 km (100 mi) in the Yukon-Kuskokwim Delta area, as shown by Bethel data.

Alaska Peninsula and the Aleutian Islands

The Alaska Peninsula west of 162°W shows annual wind power class 7 at all locations except those shielded somewhat by local terrain. The whole peninsula has class 5 or higher power. This area is along a major storm track from eastern Asia to North America. Storms generally move from west to east. Some storms also move northward through the Bering Sea, especially during the summer months. Amchitka and Asi Tanaga in the western Aleutians show mean annual wind power of over class 7 (1,000 W/m^2). Winter is the season of maximum wind power throughout the area.

Lower Cook Inlet

The area from Iliamna Lake to Kamishak Bay across Cook Inlet to the Barren Islands is a corridor for strong winds. This is reflected at Bruin Bay, which shows an average annual wind power of over 1,300 W/m^2. Subjective comments from mariners indicate that this lower Cook Inlet area can be very windy. Bruin Bay data and an examination of weather records from two drilling rigs operating in the area confirm this impression. There are no other permanent stations besides Bruin Bay that show this wind resource.

Gulf of Alaska Coast

Exposed areas of the entire Gulf of Alaska coast should experience mean annual wind power of class 3 or higher. Offshore data from Middleton Island indicate class 7 wind power. Shore data such as Cape Spencer, Cape Decision, Cape Hinchinbrook, and North Dutch Island reflect class 5 or higher power. Data from more sheltered locations, such as Cordova, Sitka, and Yakutat do not reflect these wind power classes. Most of this coastline is rugged and heavily wooded, so wind power estimates are very site-specific.

Exposed Mountain Ridges and Summits

At least class 3 or higher wind power is estimated for mountain summits and ridge crests in the Alaska Range, the Coast Mountains in southeastern Alaska, and portions of the Brooks Range. The map analyses represent the lower limits of the wind power resource for exposed areas. Wind speeds can vary significantly from one ridge crest to another as a result of the orientation to the prevailing slope of the ridge and its closeness to other ridgelines. Winter is the season for highest wind speed and power at mountain summits and ridge crests.

Hawaii and Pacific Islands Region

The Hawaii and Pacific Islands region differs significantly from the mainland regions. Though millions of square miles of ocean are included, land area is small. The state of Hawaii has 16,710 km^2 (6,450 mi^2), and more than 2,200 Pacific Islands affiliated with the United States have a total land area of 2,621 km^2 (1,012 mi^2). A map of the Hawaiian island chain is given in Map 3-62. The principal Pacific Islands and island groups described in this atlas are Guam, Wake, Johnston, and Midway Islands; and the northern Marianas, Carolines, Marshalls, and American Samoa. A map of the Pacific Islands is given in Map 3-63.

The major Hawaiian Islands (Kauai southeastward to Hawaii) are the peaks of submarine volcanoes. Local relief exceeds 900 m (3000 ft) on most of the major islands. Fifty percent of the land area lies above 600 m (2,000 ft) MSL elevation and nearly 50% lies within 8 km (5 miles) of the coastline.

The state of Hawaii had a population in 1980 of 965,000. The island of Hawaii comprises nearly two-thirds of the state's land area. Over 80% of the residents in the state live on the island of Oahu; this island consumes 90% of Hawaii's electric power.

The Pacific Islands are of two types: mountainous islands and atolls. The former, which are less than 1,000 m (3280 ft) elevation, include the Northern Marianas, Guam, American Samoa, and several of the Carolines. Most of the islands are atolls, which may not rise more than 5 m (17 ft) above the ocean.

The climate in the Pacific Islands is tropical. The Carolines mostly lie within the area of the near-equatorial convergence. Within this region, weather is dominated by light winds and humid, showery conditions. The eastern islands—Johnston, Midway, Wake, and the Marshalls—lie under the influence of brisk trade winds generated by the Pacific anticyclone. The trades weaken slightly in the western Pacific, though migratory anticyclones during winter provide brisk northeasterlies.

Samoa, in the southern hemisphere, experiences brisk trade winds during winter (June-August in the southern hemisphere). In summer, a monsoonal trough develops eastward from Australia, causing weak winds interrupted by tropical cyclones.

Tropical storms are major components of the climate of the Pacific Islands. Guam has been hit by some of the most devastating typhoons on record. Tropical storms are primarily late summer and early fall features, but have occurred in all months.

Local influences on climate vary with island type. Atolls exert little influence on the prevailing air streams. Diurnal variations on atolls match those observed for the open oceans. Mountainous islands, especially in areas of light synoptic winds such as at Ponape, produce significant local effects on cloudiness and precipitation.

Hawaiian Islands

Interactions between prevailing trade winds and island topography determine the distribution of wind power. On all major islands trades accelerate over coastal regions, especially at the corners. The best examples are regions of class 6 or higher wind power on Oahu, Kauai, Molokai, and Hawaii. The rampart-like mountain crests of Oahu enhance prevailing winds to class 6. On other islands, circular mountain shapes and extreme elevations prevent the type of wind acceleration observed on the Oahu ranges (Schroeder et al. 1981).

Annual average wind power in Kauai and Honolulu counties is presented in Map 3-64. The primary wind resources in Kauai County are on the southeastern and northeastern coasts of Kauai where trades accelerate around the island barrier. Broad areas of class 3 or higher wind power occur over the northern, southern, and eastern parts of Kanai, increasing to class 6 over the northeastern (Kilauea) and southeastern (Makahuena) points.

On Oahu (Honolulu County), the long Koolau mountain rampart and shorter Waianae Range enhance trades to class 6, although the rugged topography, watershed value, and turbulent air flows over these ranges may preclude practical application of wind power generation. The northeastern (Kahuku) and southeastern (Koko-head) tips of Oahu have areas of class 7 and broad areas of class 3 or higher. A class 3 and 4 area exists at Kaena Point on the island's northwestern tip, and class 3 areas exist along the southern coast west of Honolulu and southeastern coast north of Makapuu Point.

Maui County is made up of three principal islands: Molokai, Maui, and Lanai. A map of annual average wind power for Maui and Hawaii counties is given in Map 3-65.

Molokai is unique among the major Hawaiian Islands in that it lies almost parallel to the prevailing trades. Exposed areas on most of the island are estimated to have class 3 or above, and much of the northwestern quadrant is class 4 or above, becoming class 7 at Ilio Point. Eolian features are found in northwestern Molokai. A narrow belt of class 4 lies on the southeastern coast.

The primary wind resource on Maui lies in the central valley where trades accelerate between Haleakala and west Maui Volcano existing as class 5 and 6 near Maalaea Bay. Secondary power resources exist at the northern (class 3 and 4) and southeastern (class 3) tips.

Lanai lies partly in the wind shadow of western Maui. Nevertheless, deformed trees indicate that winds are slightly accelerated (class 4) over the northwestern third of Lanai. This area is exposed to winds funneling through the Pailolo Channel between Maui and Molokai. Exposed areas over the remainder of Lanai are estimated to have class 3 power.

Hawaii consists of five major mountains and the saddles between them. The tall volcanoes, Mauna Loa and Mauna Kea, provide a barrier to the trade winds, producing a stagnation which extends well upwind of Hilo. Trades diverted to the north of Mauna Kea accelerate through the Waimea saddle and over the Kohala Mountains, producing a significant area of class 7 wind power and a broad area of class 3 or higher wind power. A smaller area of high wind resource, up to class 7, exists at the south cape.

Pacific Islands

Wind power maps for the Pacific Islands are presented by island group - for Guam and the Marshalls (Map 3-66), the northern Marianas (Map 3-67), the Carolines and American Samoa (Map 3-68), and the isolated islands of Midway, Wake, and Johnston (Map 3-69). Except for Guam (the largest Pacific Island), wind power values are presented for the surrounding ocean areas; these estimates are based on ship wind data (Wyrtki and Meyers 1975) obtained over 6 years (1965 through 1970). The wind power estimates were calculated from mean wind speeds (averaged over 6 years) assuming a Rayleigh distribution of wind speeds.

Wind data from the Pacific Islands are sparse. Approximately half of the documented stations have questionable anemometer heights and exposures as a result of inadequate documentation. Wind power densities were available for some of the islands. Except for some of the small atolls, open-ocean wind power considerably exceeds island values. Apparently, well-exposed sites are rare in the Pacific Islands. Available site descriptions consistently mention adjacent stands of coconut palms.

Guam is the only Pacific island outside of the Hawaiian chain with more than one wind station. The island data indicate class 2 power, although ship wind data indicate class 5 to class 6 power in surrounding waters. Data from Andersen Air Force Base, on the plateau on what should be a windy island corner, indicate only class 2 power.

The Marshall Islands lie in a belt of strong ocean winds and possess the best wind power potential of the major Pacific Islands groups. Ship wind power densities reach class 7 in the northern Marshalls and class 4 in the south. With the exception of Enewetak and Kwajalein, island wind power densities differ drastically from the ship values.

The northern Marianas, which extend 700 km (435 mi) in a nearly north-south line, are volcanic peaks, some with considerable relief. Ship winds indicate power densities of class 5 to class 6 in surrounding waters, although available island data indicate class 2 and 3 power.

The Caroline group lies in a region of weaker ocean winds. The near-equatorial convergence migrating back and forth during the year accounts for weak winds, especially in the south. The islands lie well away from the major winter or summer trade wind belts. However, class 3 wind power potential appears to exist in the northern atolls such as Ulithi.

American Samoa consists of six mountainous islands. The main island, Tutuila, contains the only NCDC station, Pago Pago. Island data indicate little wind power potential, but ship winds indicate power densities of class 3 to class 4 in surrounding waters.

Midway, Wake, and Johnston Islands were grouped for convenience even though they are widely separated. Each is a low coral island with negligible relief and little vegetation. The data on Midway indicate only class 2 power. However, ship data show class 6 power for the ocean area. Thus, exposed sites on Midway may have higher power than that estimated from the island data. At Johnston Island, an atoll located 1,500 km (900 mi) south-southeast of Midway, brisk trade winds prevail throughout the year. Data from an apparently well-exposed station on Johnston Island indicate class 5 power, which is not significantly different from the class 6 power estimated for the ocean area. Wake Island is also an atoll, located north of the Marshall Islands. Like Johnston, data from an apparently well-exposed station on Wake Island indicate class 5 power, which is not significantly different from the class 6 power estimated for the ocean area.

Puerto Rico and Virgin Islands

The Puerto Rico/ Virgin Island region consists of the main island of Puerto Rico, its surrounding islands, the three main Virgin Islands (St. Thomas, St. Croix, and St. John), and several small islands in their immediate vicinity (see Map 3-70). This group of islands lies at the dividing point between the Greater and Lesser Antilles (which separate the Atlantic Ocean from the Caribbean Sea). The region totals slightly more than 9,100 km^2 (3,570 mi^2), which makes it a little smaller than the state of Connecticut, and has a population of approximately 3,000,000. Nearly 98% of the people in the region reside in Puerto Rico; about one-third of Puerto Rico's population lives in the metropolitan area of San Juan.

The topography throughout the region is generally hilly to mountainous. The main island of Puerto Rico is bounded on the north by a coastal plain averaging about 8 km (5 mi) in width. On the south coast the plain varies in width as mountains and hills intersect the coastline at several points. On the eastern end of the island a hilly valley extends inland to near Caguas. The coastal plain and valleys comprise 27% of Puerto Rico's total area. Hilly land surrounding the central mountain range occupies about 37% of the island's area. The interior of Puerto Rico consists of mountainous terrain of high local relief. This range of mountains, comprising 36% of the land area, runs east and west and is called the Cordillera Central. To the east of the main island are the hilly islands of Culebra and Vieques and to the west lies the island of Mona.

The three main Virgin Islands—St. Thomas, St. Croix, and St. John—are essentially mountains protruding from the sea. St. Croix, which has a valley sloping down from the center of the island to a broad coastal plain on the southern coast, is the only U.S. Virgin Island with a significant portion of flat land.

Puerto Rico - Windward Coastlines and Interior Mountains

Exposed points and capes along the entire northern coast, and most of the eastern coast, of Puerto Rico appear to have class 3 annual wind power as do the windward (northeastern) coasts of Culebra, Vieques, and Mona (Map 3-71). Perhaps the best wind resource in Puerto Rico can be found on Cape San Juan, which extends approximately 5 km (3 mi) seaward from the mainland on the extreme northeastern corner of Puerto Rico (Wegley et al. 1981). The mean wind speed at Cape San Juan slightly exceeds that of the mean trade wind flow because of acceleration of the trades as they round the windward corner of the island. The wind at this location appears to have a slight winter maximum, but remains strong during all seasons of the year.

The highest peaks and ridge crests of the Cordillera Central, Sierra de Cayey, and Sierra de Luquillo are estimated to have class 3 annual wind power. Considering the complexity of the terrain here, there may be individual ridges, gaps, or other wind-enhancing terrain features that have class 4 wind power.

St. Thomas - Windward Coast and Central Ridge

Several islands lie offshore near the northern coast of St. Thomas. The windward sides of these islands are estimated to have class 3 annual wind power. Exposed coastal sites on the northern coast as well as the exposed points at the southeast corner of St. Thomas also appear to have class 3 wind power (Map 3-72).

In central St. Thomas, the higher ridge and summits should have class 4 power. Some of the slightly lower peaks, particularly on the northeastern side of the island, are estimated to have class 3 annual wind power.

St. Croix - Central Ridge and Exposed Coastal Locations

The central St. Croix ridge runs east-west the entire length of the island. The orientation of the island and its ridgeline suggests that the areas of highest wind power include the higher peaks as well as their northern and southern shoulders, where acceleration of the prevailing easterlies occurs as they flow around these topographical barriers.

The eastern tip of St. Croix points into the trade winds. This tip, the exposed points on the northern and southern coast, and Buck Island (near the northeastern coast) are all estimated to have class 3 annual average wind power.

St. John - Ridge, East End Hills, and Windward Coast

A ridge of approximately 300 m (1,000 ft) MSL, paralleling the western shore of Coral Bay, appears to be the region of strongest winds (class 4 wind power) on St. John Island. The irregular coastline leaves many jutting points along the northeastern, eastern, and southeastern coasts. These points should have annual wind energy densities near class 3.

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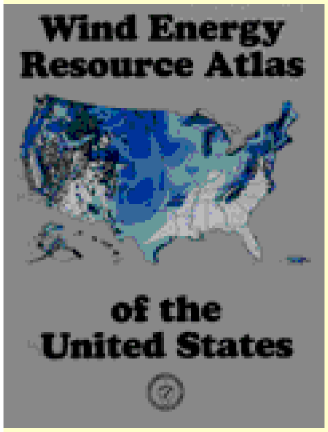

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Appendix A: Synthesis of Regional Assessments - Data Analysis and Assessment Methodologies

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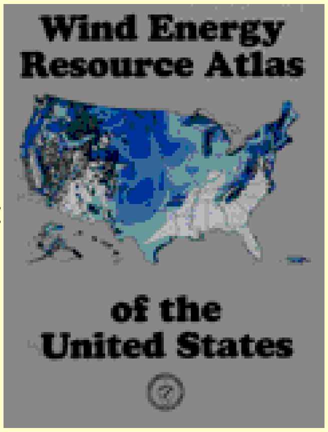
:

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Appendix A

Synthesis of Regional Assessments - Data Analysis and Assessment Methodologies

This national wind energy resource atlas is a synthesis and update of regional resource assessments that were performed in 1979 and 1980 by the Pacific Northwest Laboratory and other contractors. A list of the regional atlas titles is given in Table A-l; a map of the United States identifying the regional divisions is shown in Map A-l. This appendix summarizes the data sources and analysis techniques used in preparing the wind resource estimates.

A wide variety of data types and analysis techniques were utilized in performing the regional wind energy resource assessments and ultimately producing this wind energy atlas. The techniques developed by the Pacific Northwest Laboratory in the Northwest regional prototype provided the basis for the regional assessment con tractors to follow. However, the contractors were given some flexibility in refining or modifying the techniques where necessary or where a revised technique would improve the resource assessment.

The types of data utilized and the techniques employed varied somewhat from region to region. For example, the data and methods employed in mountainous regions were, by necessity, more varied than those in regions of mostly plains and little vertical relief. In mountainous areas, upper-air wind data were utilized in estimating the wind resource over exposed mountain summits and ridge crests where conventional surface data are scarce or not available. Moreover, more extensive use of qualitative indicators of the wind resource was made in mountainous areas than in nonmountainous areas, since greater variability of the wind resource usually occurs in mountainous areas.

These qualitative indicators included the identification of certain combinations of topographical and meteorological features, areas containing eolian landforms, and areas with flagged trees. Fairly intensive surveys of wind deformed vegetation were conducted in the Northeast and Southwest regions, the former using 30 newspaper surveys to solicit information from the public and the latter conducting aerial and ground surveillance over large areas to identify areas of wind-flagged trees.

Data types and techniques utilized in coastal areas varied from those utilized inland. Information on the coastal wind resource in many areas included data from ship observations within specified coastal marine areas. Techniques employed to estimate the variation of the wind resource inland from the shoreline considered the direction of the prevailing strong winds, alignment of the coastline, topography and vegetation conditions onshore, along with information on the wind resource at coastal and inland stations in the coastal region.

Techniques used in the low-latitude regions (e.g., Hawaii and the Pacific Islands and Puerto Rico and the Virgin Islands) varied from those used in the contiguous United States and Alaska. Revised methods were developed to estimate the wind resource over ridge crests and mountain summits in the regions, as it was recognized that the mean wind profile structure in the trade-wind regimes of Hawaii and Puerto Rico is considerably different than that of the contiguous United States.

Nationwide, the National Climatic Data Center (NCDC) accounted for about 70% of the approximately 3200 surface stations evaluated in the wind resource assessments. However, the types and sources of surface wind data used in the resource assessments varied considerably among the various regions. For example, some regions used considerable amounts of Forest Service data (e.g., the Northwest and Southwest regions), whereas other regions with large areas of forested terrain used little or no Forest Service data. Data from power plant sites made significant contributions to the data base in the Northeast, Southeast, and Great Lakes regions. Canadian data were useful in assessing the wind resource within the five regions bordering Canada. In the Southern Rocky Mountain region, an intensive effort was made to identify and utilize data from various other sources, which accounted for 50% of the data in this region, considerably more than in any other region.

This appendix provides a detailed description of the various data analysis and assessment methodologies employed in the regional wind resource assessments and, in essence, the synthesized national assessment. Tables have been prepared to summarize the various types of information, data, and techniques used in each of the regional assessments. Methods used to evaluate the certainty of the resource estimates and to assess the percentage land area with a given wind resource are also described in this chapter.

Identification of Wind Data Sources

The surface wind data on which the resource assessments were based were obtained from a variety of sources: the NCDC, the U.S. Forest Service, university research projects, existing and proposed power plant sites, and various other sources. Table A-2 describes the principal sources of data. Many other wind data sets available from university research projects, U.S. Department of Energy candidate wind turbine sites, wind energy field studies, and various other government and private organizations were also identified and used in the assessments where appropriate.

Table A-3 lists the number of stations with wind data from each source identified in the regional wind resource assessments. Table A-4 lists the number of stations identified in each of the 12 regions, from all sources.

The NCDC accounted for about 60% of all stations with wind data identified from all sources. In all regions except the Northwest and Southwest, the greatest percentage of the stations identified were from the NCDC. Forest Service stations accounted for about 26% of the total from all sources, although most of these data were generally of very limited value. The regions with the greatest number of stations from all sources were the Northwest and Southwest; however, Forest Service stations accounted for 54% (685) of the stations in the Northwest and 46% (443) of the stations in the Southwest. The three western regions, i.e., Northwest, Southwest, and Southern Rocky Mountain, accounted for 78% of the Forest Service stations in the United States.

A substantial number of wind data locations exist that are not reflected in Tables A-3 and A-4. Data from university research projects, private organizations, and government agencies other than the NCDC frequently exist in a format that 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. In most populated areas, adequate summarized data from the NCDC or other sources were usually available. In these areas, little or no effort was made to identify additional data.

Wind Data Screening

Review of Table A-4 indicates the large quantity of wind data identified in the assessments; however, not all of these data need to, or should, be used. Screening procedures were developed to select stations with the most useful data and to eliminate stations that would not significantly contribute information on the distribution of the wind resource.

In general, wind data in summarized or digitized format were chosen in preference to unsummarized data. For selected stations where both summarized and digitized data were available, the digitized data were used to prepare summaries that more fully characterized the wind resource than existing summaries. As previously described, PNL processed the NCDC-digitized data to produce extensive summaries of the wind characteristics. In contrast to many summarizations routinely available from NCDC, PNL's analyses examined the wind record only for periods of constant anemometer height, location, and observation frequency. Thus, the PNL summaries of the NCDC-digitized data were usually chosen in preference to the conventional summaries available from NCDC. However, there were still many stations with the conventional NCDC summaries for which only limited or no PNL summaries of digitized data were available.

Because many NCDC stations had several different types of summarized wind data covering various time periods, criteria were established to choose the best one or two summaries for those stations with several summaries. Using the NCDC *Index to Summarized Wind Data* (Changery et al. 1977) to identify the available summaries, the *Index - Original Surface Weather Records* to determine the frequency of observations, and the *National Wind Data Index* (Changery 1978) to determine anemometer height histories, summaries were selected that had:

- the most suitable format for wind-power assessment (see Table A-5 for rating of various formats)
- the longest recorded period
- the least changes in anemometer height and exposure
- the most daily observations.

In areas with a high density of stations (such as many of the large metropolitan areas) and a considerable amount of digitized or summarized data, only those stations appearing to have the best exposure and longest periods of unchanged anemometer height and location were usually selected. Conversely, many stations from smaller towns and in more remote locations had only one or two summaries, often in undesirable formats, to choose from. Frequently, anemometer heights were unknown for the summary period and wind observations were limited to daytime hours of operation at these stations.

For those stations with limited or no summarized or digitized wind data, unsummarized data were screened. Unsummarized data may take one of several forms, including WBANs (i.e., Weather Bureau, Air Force and Navy standard format reports), wind records, triple registers, and synoptic records. (Some of the forms, especially in the late 1930s and 1940s, occasionally included monthly average wind speeds.) Information on the type and frequency of observations, anemometer height and exposure, and station location were examined to determine the suitability of the unsummarized data for wind resource assessment. Some stations were eliminated from consideration. For many stations, at least one year of records was identified for evaluating the wind data.

Nationwide, the NCDC accounted for about 70% of the approximately 3200 stations evaluated in the wind resource assessments (see Table A-3). Most of the NCDC stations identified and screened with digitized or summarized data were eventually retained for potential use in the assessments. About 30%

of the NCDC stations with unsummarized data were selected for further evaluation.

Forest Service stations were screened largely on the basis of the number of observations, computed seasonal average wind speeds and powers, and location. Only 13% of these stations were ultimately retained to contribute information on the wind resource. Even most of those retained were of quite limited use, because of the once daily observation. Nevertheless, over 225 Forest Service stations provided much of the only quantitative surface wind data for many remote areas of the United States.

A high percentage of the data identified and screened from power plants and other sources were ultimately retained for evaluation.

Table A-4 showed considerable variation among the regions in the percent of stations retained for evaluation in the wind resource analyses. The regions with lowest percentage of stations retained were the Northwest, Southwest, and Southeast. The low percentages for the Northwest and Southwest are largely a result of the relatively large number of Forest Service stations in these two regions and the small percentage of these stations retained. In the Southeast, NCDC digitized data accounted for almost 70% of the stations ultimately retained for the analysis, considerably greater than the percentage for any other region. Because of the wide coverage of the digitized data and the predominantly low wind resource throughout most of this region, there was little need to retain and evaluate much of the additional data identified in order to further characterize the geographical distribution of the wind resource.

Because of the sparseness of wind data stations in the Puerto Rico/Virgin Island region, all wind data obtained were used in the analysis. Over 70% of the stations identified in the the Hawaii and Pacific Islands region were retained for the analysis.

Table A-6 lists the number of stations with wind data evaluated from each source from all 12 regions. Some notable differences among the regions in the types and sources of data utilized are apparent. Except for the Southern Rocky Mountain region, the NCDC was the primary source of most of the stations utilized. In three regions (the East Central, Southeast and South Central) the NCDC accounted for over 90% of the stations.

Forest Service stations accounted for about 30% of the stations utilized in the Southwest and 14% of the stations in the Northwest. These two regions accounted for over 70% of the Forest Service stations in the United States utilized in the analysis.

Wind data from power plant sites utilized in the analysis were most abundant in the Northeast and Great Lakes regions. However, these data accounted for less than 10% of the station data in these regions.

Data from numerous Canadian stations were utilized in the analysis in the five regions bordering Canada. Data from only three Mexican stations were useful in the three regions bordering Mexico.

Wind data from other sources accounted for 50% of the station data in the Southern Rocky Mountain region, 34% in the Hawaii and Pacific Islands region, and 25% in the Great Lakes region. Nationally, about 15% of the station data used in the analysis were obtained from other sources.

Two other types of wind data evaluated, in addition to the surface land-station data described above, were coastal marine area data and upper-air data. Table A-7 presents the extent to which these two types of data were applied in each of the regional atlases. An "X" means that the data were evaluated and applied extensively in estimating the wind resource. An "L" means that some data of this type were evaluated but applied only to a relatively small area or used only in a limited way. For example, coastal marine area data were used extensively in the wind resource assessments of three regions - the Northwest, Hawaii and Pacific Islands, and Puerto Rico and the Virgin Islands. For the Northwest, very few land-surface stations with good exposure were available for estimating the coastal wind resource. Therefore, estimates of the coastal wind resource were based primarily on the coastal marine area data, supplemented where possible by land stations. For Hawaii the coastal wind resource estimates were based primarily on land stations, whereas for the Pacific Islands (e.g., Midway, Wake, Johnston Islands, the Mariannas, the Marshalls, and Guam) open ocean wind power classes were presented along with wind power classes based on land stations for individual islands where available. For Puerto Rico and the Virgin Islands, there were few exposed coastal stations, so extensive use was made of the coastal marine data.

For six other regions, coastal marine data were evaluated but used primarily to supplement the existing station data. For these regions, the coastal wind resource estimates were based largely on the existing station data, although limited use was made of the coastal marine data. In some coastal areas of the United States, wind data were available from offshore "fixed" stations. These data were used instead of the coastal marine (ship observations) data.

Upper-air wind data were used in estimating the wind resource at mountain summit and ridge crest elevations, where existing surface station data are sparse. Extensive use of upper-air wind data was made in eight regions (see Table A- 7). In these regions, mountainous terrain covers a substantial part of the region. In three regions, mountainous terrain represents only a small fraction of the region's area. In one region, the Great Lakes, upper-air data were not needed as no areas of mountainous terrain (local relief >1000 ft) were identified.

Time Scales Used in the Analyses

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. These values were used only in the absence of other suitable wind data for an area.

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.

Calculation of Wind Power Density

For the purpose of mapping the geographical variation of the wind resource, wind power density was chosen in preference to wind speed because the power density value combines the effect of the distribution of wind speeds and the dependence of the power density on air density and on wind speed. Quantitative wind data in digitized, summarized, and unsummarized forms were evaluated for mean wind power density, which is calculated as described below for each type of data.

Digitized Data

For stations with l-hour and 3-hour digitized data, the average wind power density $\bar{P}$ (Watts/m^2) in a vertical plane perpendicular to the wind direction was calculated from

$$P = \frac{1}{2n}\sum_{i=1}^{n} \rho_i V^3{}_i$$

(1)

where

n = the number of observations in the averaging period
ρ_i = the air density (kg/m^3)

V_i = the wind speed (m/s) at the ith observation time.

The air density was computed from the measured temperature and station pressure or was estimated by correcting standard air density for station elevation. Air density (ρ) was calculated from measured temperature (T) and station pressure (P) by

$$\rho = {}^{P}/_{RT}$$

(2)

where R is a gas constant. If temperature or station pressure was not available, air density was estimated as a function only of station elevation (Z) by

$$\rho = 1.225 - \left(1.194 \times 10^{-4}\right)Z$$

(3)

which approximates the U.S. Standard Atmosphere profile for air density (NOAA 1976).

Summarized Data

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

$$\bar{P} = {}^{1}/_{2}\,\bar{\rho} \sum_{j=1}^{c} f_j V^3{}_j$$

(4)

where

$\bar{P}$ = the mean air density
c = the number of wind speed classes
f_j = frequency of occurrence of winds in the jth class
V_j = the median wind speed of the jth class.

The mean air density was usually calculated using Equation (3) above. A few of the regional atlases incorporated the seasonal variation of air density in the calculation of wind power.

Unsummarized Data

In those cases for which unsummarized wind data were assessed, the seasonal and annual average speeds, V, for most stations were estimated from a visual examination of one year's original weather records. Some station records, especially Form 1001A during the 1930s and 1940s, frequently reported 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, $\bar{P}$, was then estimated by assuming that the speed frequency distribution followed a Rayleigh distribution (Cliff 1977):

$$\bar{P} = 0.955\,\bar{\rho}\,\overline{V^3}$$

(5)

The visual examination of the data provided a crude but fast and inexpensive means of making a rough estimate of a station's seasonal and annual mean wind speeds. Generally, the best that could be achieved by this subjective technique was to estimate the mean wind speeds as light (<10 mph), moderate (10 to 12 mph), or strong (>12 mph). Wind speeds on record forms were usually in either mph or knots. Nevertheless, this subjective estimate of the mean wind speeds often provided the only information on the wind resource in many areas of the United States.

In certain cases, a more objective estimate of seasonal and annual average wind power was obtained for selected stations. To circumvent the laborious task of entering all the hourly (or 3-hourly) observations from a station's weather records, various techniques were employed. For example, for the East Central region, average seasonal wind speeds were computed based on every third observation over a one-month period from each season. This was done only for those stations that indicated high wind energy potential based on visual examination and that recorded at least eight observations per day during the diurnal cycle. Wind power was computed by Equation (5). For the North Central region, the average seasonal and annual cubed speed, $\overline{V^3}$,was estimated by manually averaging all V^3every third day for one year for selected stations with unsummarized data. Wind power density for these stations was then estimated by:

$$P = 1/2\,\bar{\rho}\,\overline{V^3}$$

(6)

For Hawaii and the Pacific Islands, the NCDC unsummarized original weather records were digitized and summarized for selected periods (periods were normally 12 months and ranged from a few months up to 2 years).

For Alaska and Puerto Rico and the Virgin Islands, the wind power density was estimated from the mean wind speeds by assuming Weibull speed frequency distributions other than the Rayleigh (see the respective regional atlases for details).

For the Northeast and Southeast regions, seasonal and annual wind speed frequency distributions were constructed manually from the original surface weather records of selected stations by scanning 1 year's data and entering every fourth hour into the distribution. The wind power density $\bar{P}$ was then computed by equation (4).

Table A-7 showed those regions of the United States where the standard methods developed by PNL to calculate or estimate wind power density were supplemented or refined by other methods. In practically all cases, these other methods were used only to calculate or estimate wind power density for stations with unsummarized data.

Vertical Adjustment

The anemometer height above the surface rarely was at either the 10-m (33-ft) or 50-m (164-ft) 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:

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

(7)

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 indicated an α ~ 1/7 to be widely applicable to low surface roughness and well exposed sites from which conventional NCDC data are available (Elliott 1979a). Thus, an α of 1/7 was used to adjust mean wind speed and wind power density to 10-m (33 ft) and 50-m (164 ft) reference levels at most stations with only one level of data. For a few stations for which the anemometer height was unknown, a height of 10 m (33 ft) was assumed.

A few sites had two (or more) levels of data appropriate for extrapolating to the 10-m (33 ft) and 50-m (164 ft) levels. At these sites, the α value calculated from the mean wind speed and/or power densities at the measurement heights was used to adjust the wind speed and power density to the 10-m (33 ft) and 50-m (164 ft) levels.

For the Northeast and Southeast regions, an adjustment factor based on appropriate roughness values was used for a few sites located in towns or surrounded by wooded areas having surface roughness greater than that at airport locations. The adjustment of wind data of stations having this characteristic, to the 10-m (33-ft) and 50-m (164-ft) reference levels, was accomplished using the following relationship:

$$\frac{\bar{V}_r}{\bar{V}_a} = \frac{B_r}{B_a} \quad or \quad \frac{\bar{P}_r}{\bar{P}_a} = \left(\frac{B_r}{B_a}\right)^3$$

(8)

where $\bar{V}_{a,r}$ and $\bar{P}_{a,r}$ are the same as in Equation (7) and the $B_{a,r}$ values are adjustment factors determined from a comparison of log-law wind speeds using appropriate roughness values for various surface environments (Wegley et al. 1980).

Wind Power Estimates for Mountainous Areas

Since existing surface data from mountain summits and ridge crests were very sparse, upper-air wind data were identified for potential use in estimating the free-air wind speeds at mountain summit and ridge crest elevations in mountainous areas. An earlier study by Wahl (1966) had shown a strong correlation between mountain-top and free-air wind speeds.

A method was developed to delineate mountainous areas in the United States and to determine representative elevations of mountain summits and ridge crests in the mountainous areas. Mountainous areas, consisting of prominent mountain summits and/or ridge crests where the local relief (over a unit square 6 mi across) exceeds 300 m (1000 ft), were delineated using maps of classes of land-surface form (Hammond 1964) and topographic maps.

Tablelands with canyons or valleys over 300 m (1000 ft) deep, hilly terrain areas with relief less than 300 m (1000 ft), and individual isolated mountains (e.g., an individual mountain located on a plain and less than 3 k (2 mi) in extent) were generally not designated as mountainous areas.

Sectional aeronautical charts were used in most of the regions to determine representative mean elevations of mountain summits and ridge crests in the mountainous areas. Other types of topographic contour maps were used in a few of the regions.

For the nine regions in the contiguous United States, a mean mountain-summit or ridge-crest elevation was determined for each 1/4° latitude by l/3° longitude cell over the mountainous areas. For Alaska, the cells were l/2° latitude by 1° longitude. For Hawaii and the Pacific Islands and Puerto Rico and the Virgin Islands, the cells were l/8° latitude by l/8° longitude.

The procedures used to estimate the mean free-air wind speed and wind power density at mountain-summit and ridge-crest elevations varied according to the sources of upper-air data and other climatological information used. A summary of upper-air data and procedures used in the regional wind energy assessments is provided below. For a more detailed and accurate description on a given region, refer to the wind energy resource atlas for that region. From the results in the regional assessments, one major revelation became apparent on estimating the mean wind speeds and wind power densities for mountain summits and ridge crests; that is, there is no universal procedure for reliably estimating the wind energy potential over mountainous areas. A procedure that appears to work well in one area of the country may give totally unrealistic estimates in another part of the country. Moreover, a procedure may not apply to all seasons of the year. For example, in the Southwest where the most abundant surface data existed from mountain summits and ridge crests, use of the conventional upper-air wind data to estimate ridge crest wind speeds gave fairly reliable estimates for winter but unrealistically low estimates for summer.

The procedure developed by PNL and applied in the Northwest prototype assessment made use of northern hemisphere upper-air climatologies for the 850-, 700-, and 500-mb levels (about 5,000, 10,000, and 18,000 ft elevation) by Crutcher (1959). The free-air wind speed at mountain-summit or ridge-crest elevation was interpolated from the mean scalar speeds on the constant-pressure surfaces. Estimates of the mountain-top wind speeds were made on a grid 1/4° latitude by 1/3° 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 were estimated. Linear extrapolation provided the mean free-air wind speed at the terrain elevation and the application of a Rayleigh speed distribution gave the mean free-air wind power. The mean wind power at the 10-m (33 ft) and 50-m (164 ft) 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 were considered lower limits for exposed ridge crests and mountain summits, since local terrain features in these mountainous areas can enhance the wind power considerably. Also, a major uncertainty in mountainous areas is the representativeness of some of the upper-air wind data from the rawinsonde stations upon which the free-air estimates are based. At some of the upper-air stations, the 850 mb level (about 5,000 ft elevation) is near or below the surface. Even the 700 mb level (about 10,000 ft elevation) at some stations (e.g., at Lander, Wyoming) is below the average mountain-summit elevations of nearby mountains.

Wherever possible, the estimates based on upper-air data 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.

Table A-7 shows the regions that used the "standard" (PNL-developed) procedure described above to arrive at the ridge-crest estimates and those regions that used other data and procedures or some refinements of the standard method developed in the Northwest prototype assessment. Five regions used the standard method and six regions used other methods or made refinements to the standard method. One region, the Great Lakes, did not have any mountainous areas. Below are the refinements made to the standard method.

Southwest. In the Southwest region, considerable surface wind data from mountain summits and ridge crests were available for verifying the estimates based on upper-air wind data. Particularly over some of the mountainous areas of the Southwest, applying the free-air winds often results in gross errors, especially during the warm season. Upper-air winds over the Southwest are extremely weak during the warm season, yet surface winds on many of the mountains are frequently strong due to the presence of thermally produced circulations of a mesoscale (monsoonal sea-breeze) and/or toposcale (surface slope heating) nature. Many unusual wind regimes unconnected to free-air flow have been documented in mountainous areas of California. The free-air technique would, for example, predict a mean power density of 15 to 25 W/m^2 over a mountain range with a true representative power density of 300+ W/m^2. The discrepancy is due to the presence of a modified sea-breeze flow into the desert. Mountain summit estimates were adjusted accordingly during the spring, summer, and fall when substantial fire weather data were available. Winter estimates closely followed the free-air technique, as thermal effects are greatly reduced in the cold season and synoptic effects are increased.

Northeast and Southeast. In the Northeast and Southeast regions, the estimation of wind power over mountains made use of *Winds Aloft Summaries* (NCDC 1970) for existing rawinsonde stations. Monthly and annual wind speed frequency distributions for 150 m (492 ft) and 300 m (1,000 ft) above the surface as well as for 500 m (1,640 ft) or 1,000 m (3,280 ft) above sea level were used to estimate wind power values for the mean ridge-crest or mountain- summit elevations. Wind power values were first computed for each level that was available for each station. The wind powers at 300 m (1,000 ft) above surface and the upper levels were then used to compute values of a power law exponent for each station for each month and on an annual basis. For the stations nearest each grid cell, the appropriate power law exponents were utilized to compute the wind power in the free atmosphere at the stations, using the cell's mean ridge crest or mountain summit elevation. Horizontal interpolation between stations to each grid cell was performed using an inverse distance squared weighting scheme. This procedure provided an estimate of the free-air wind power at the terrain elevation at the location of each grid cell. As in the standard method, the wind power at the 10-m (33 ft) and 50-m (164 ft) reference heights was taken to be one-third and two-thirds of the free-air value.

Alaska. Over Alaska, the estimation of wind power over mountains made use of *Meridional Cross*

Sections, Upper Winds Over the Northern Hemisphere (Crutcher 1961). The procedure used was very similar to the standard procedure, except that the free-air wind speed at mountain-summit or ridge-crest height was extrapolated (or interpolated) from the mean scalar speeds on the meridional cross sections, and estimates of the mountaintop wind speeds were made on a grid 1/2° latitude by 1° longitude.

Hawaii and Pacific Islands. Over Hawaii and the Pacific Islands, the estimation of wind power over mountains made use of tropical upper-air wind climatologies (Wiederanders 1961), satellite-derived winds, and NCDC upper-air summaries. Major differences from previous atlases occur in Hawaii. The dominant weather system is the trade wind. Peak trade wind speeds occur at 600 m (2,000 ft) and a strong temperature inversion overlies the trades at about 2,200 m (7,000 ft). For mountains above 1,500 m (5,000 ft), the trades are diverted around the mountain barrier. However, elongated low ranges such as Oahu's Koolau Range (900 m or 3,000 ft) allow significant enhancement of open ocean winds as they pass the crest. For the Oahu ranges, estimates from representative wind stations were applied to the mountain crests. For taller Hawaiian mountains and for those in the Pacific Islands (where the trade inversion is not as significant a factor), the procedures developed by PNL were used.

Puerto Rico and the Virgin Islands. Over Puerto Rico and the Virgin Islands, the estimation of wind power over mountains made use of the northern hemisphere upper-air wind climatology for the 850-mb constant-pressure level by Crutcher (1959) and the 1,500-m (7,000 ft) winds-aloft summaries (NCDC 1970). The free-air wind speeds at mountain-peak or ridge-crest heights were estimated using seasonal mean scalar speeds on the 850-mb pressure surfaces, San Juan pibal summaries (Stone 1942), and the San Juan and St. Croix 1,500 m winds-aloft summaries. Extrapolation down to mountain-peak or ridge-crest height was done using a mean trade-wind profile observed by Riehl (1954) and modified by seasonal variations noted by Stone (1942). Estimates of average wind speeds were made for the mean mountain-top/ridge-crest elevations within each 1/8° latitude-longitude cell. The Rayleigh distribution was first used to convert mean free-air wind speeds to free-air wind power. However, the Rayleigh distribution was found to significantly overestimate free-air wind power in the region due to the steadiness of the trade winds. Consequently, the annual and seasonal Rayleigh free-air wind power estimates were corrected by fitting a Weibull distribution to the data (using a least-squares fit) and applying only a percentage of the Rayleigh wind power based upon the value of the Weibull shape parameter. The mean wind power at the 10-m (33 ft) and 50-m (164 ft) reference heights was assumed to be one-third and two-thirds of the free-air values, respectively.

Qualitative Indicators of the Wind Resource

Although approximately 3,000 stations provided the wind resource assessment of the United States with quantitative data, these stations were not uniformly distributed. Most of the stations are located in populated areas and along transportation corridors. Large areas in the United States are devoid of any form of quantitative wind data suitable for this assessment. Furthermore, in areas of complex terrain (including the various mountainous areas), most observation sites (except for some Forest Service fire lookout sites) are confined to valley locations. To evaluate the distribution of the wind resource in data-sparse areas, three qualitative indicators of the wind speed or power were developed and employed, where applicable, in various regions of the United States.

Topographic/ Meteorological Indicators

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
  - strong upper-air winds or
  - 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 pressure patterns and air flow.

Table A-7 showed the extent to which topographic/meteorological indicators of the wind resource were used in each of the 12 regions of the United States. Except in the Southeast region, considerable use was made of topographic/meteorological indicators to subjectively estimate the wind resource potential in data-sparse areas. The most extensive use of these indicators was in the assessments of the mountainous areas of the United States, where these indicators were often applied to infer considerable variability in the spatial distribution of the wind resource.

Wind-Deformed Vegetation

Evidence of strong persistent winds can also be found in wind-deformed vegetation, as first described by Putnam (1948). Mean wind speeds can be deduced from the extent of such deformation on trees and shrubs, as discussed by Hewson et al. (1979) and Wade and Hewson (1980). However, there are a number of practical limitations to the use of trees as indicators of mean wind speed. Although wind-flagged trees may indicate that the mean wind speeds are stronger than 4 m/s, trees that are unflagged do not indicate that the winds are light. There may be locations where strong winds come from several directions, and persistence from any one direction is insufficient to cause wind flagging. Nevertheless, in spite of the possible errors that are inherent in use of trees as an indicator of mean annual wind speed, they are useful in identifying potential areas with moderate-to-high wind resource.

Areas of wind-deformed vegetation were identified and evaluated to deduce estimates of the wind resource in four of the regional wind energy assessments: the Northeast, Northwest, Southwest, and Alaska. Methods employed to identify areas of wind-deformed vegetation included aerial, ground, and newspaper surveys.

In the Northeast region, a public survey was conducted through 30 newspapers in the Northeast to solicit information from the public concerning areas of wind-deformed trees as well as other qualitative information on particularly windy areas. As a result of the newspaper surveys, wind resource estimates for 61 sites with wind-deformed trees were included in the Northeast assessment.

In the Southwest region, an aerial survey of Nevada mountains and a ground survey of the California coastal mountains were made to identify areas of wind-deformed vegetation.

In the Northwest region, results of aerial and ground surveys reported by Hewson et al. (1978) provided information on areas of wind-deformed trees and estimates of the wind resource in western Washington and Oregon.

In Alaska, wind-deformed vegetation in the Portage Pass area was evaluated to deduce mean wind speeds and estimates of the wind resource.

Eolian Landforms

The removal and deposition of surface materials by the wind to form playas, sand dunes, and other types of eolian landforms indicate strong winds from a nearly constant direction. Correlating characteristics of eolian features to long-term mean wind speeds has proven difficult (Marrs and Gaylord 1979). However, the distribution of eolian features was used to delineate locations with strong winds and potentially high wind resource in some data-sparse areas in three of the regional assessments: Northwest, Southwest, and Hawaii and the Pacific Islands.

Areas in the Northwest containing eolian landforms were identified by Marrs and Kopriva (1978). The most extensive areas of eolian landforms identified in the Northwest were in central and southern Wyoming.

In Hawaii, eolian features aided in delineating the high wind energy area of northwestern Molokai.

Analysis of the Wind Resource

The production of mean wind power density maps 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 that are well exposed to the wind. 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. 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 is not representative of poorly exposed locations. Estimates for areas of ridge crests and summits depicted on the maps are lower limits to the wind power expected at well-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.

To represent the wind resource at well-exposed sites, it was necessary to evaluate the general land-surface form and topography in the vicinity of every data site. Maps were prepared showing the location of stations, the mean wind power density, the character of anemometer exposure (if known), and the topography and land-surface form.

Preliminary analyses of the wind power density were drawn, noting peculiar anomalies in the site values and the analyzed patterns. The wind characteristics at the anomalous sites (e.g., sites with wind power density significantly different from nearby sites in the area) and topography in the vicinity of the sites were then evaluated in greater detail to determine the possible causes of the anomalous values.

For example, if a site's wind power appeared anomalously high, the evaluator might take a closer look at the site exposure to determine if the site is located on a hilltop, ridge crest, or other elevated feature. In some areas, combinations of topographical and meteorological features that could be indicative of the high resource were considered, where appropriate. If no feasible explanation for the anomalously high value could be found, then the evaluator might consider the value to be unrepresentative and choose to ignore it or adjust it accordingly. If a site's value appeared anomalously low, the evaluator might look for indicators of poor anemometer exposure, poor site exposure, or where appropriate, meteorological and topographical features typically associated with low wind resource. Estimates of the wind power over mountain summits and ridge crests based on upper-air data were evaluated and compared with surface data from ridge crests and summits, where available. In some areas, this comparison resulted in an adjustment of the ridge-crest estimates (e.g., in southern California). Qualitative indicators of the wind resource contributed information in some data-sparse areas.

Only after all these data and information were completely evaluated were the final analyses constructed. The maps for each state were merged into a regional mosaic. The regional mosaics were eventually synthesized into a national assessment.

Wind Power 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 A-8 gives the power density limits for the wind power classes used in the regional atlas for the 10-m (33-ft) and 50-m (164-ft) reference levels.

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/ m3), a mean wind speed can be determined for each wind power class limit. The decrease of air density with elevation requires the mean Rayleigh speed to increase by about 3%/1,000 m elevation (1%/1,000 ft) to maintain the same wind 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 A-8. Conversely, a broader distribution of wind speeds will slightly reduce the equivalent mean speed.

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. However, 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 United States.

For each class of 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 specified by Hammond. Table A-9 gives the average percentage of land area that is designated as exposed terrain for the different classes of land-surface form found in the Northwest region. There are slight variations in these average percentages from region to region.

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 terrains, 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 grid cell of a 1/4° latitude by l/3° longitude grid over the contiguous U.S. by considering the influence of the above three factors on the certainty of the estimate of the wind power class. Different sized grid cells were used for the other regions. The certainty ratings have been digitized for each grid cell in the United States.

The definitions for the certainty ratings are adopted from those used by Voelker et al. (1979) in a resource assessment of U.S. Forest service tracts. The certainty ratings for the wind resource assessment are defined as follows:

Rating 1. The lowest degree of certainty. A combination of the following conditions exists:

- No data exist in the vicinity of the cell.
- The terrain is highly complex.
- Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.

Rating 2. A low-intermediate degree of certainty. One of the following conditions exists:

- Few 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.
- Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale

variability of the resource is large.

Rating 3. A high-intermediate degree of certainty. One of the following conditions exists:

- 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.
- Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.

Rating 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.

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. Table A-9 shows the averages for 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: better exposure than typical for the terrain, exposure typical for that land-surface form, partially sheltered exposure, and very sheltered exposure. The partitioning of the land-surface forms into the four categories was based primarily on the parameters used to classify the land-surface forms.

In order to adjust the wind power density from the map value to the various exposure categories, the power density was scaled to be greater than, equal to, slightly less than, and 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 in Hammond's maps of the land-surface form. 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.

For each grid cell, 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. In the regional atlases, areal distribution maps on a state-by-state basis are shown for threshold values of wind power classes 2, 3, 4, and 5. In this atlas, national areal distribution maps are shown for threshold values of wind power class 3 and 4.

In each of the 12 regional atlases, a summary table of the areal distribution that combines the contributions by each cell is provided for the region and for each state in the region. For each wind power class, the sum of the area contributed by each exposure category was also determined for each state and the region. Summing the area associated with each wind 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 (km^2) 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 estimate 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 these assessments. 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.

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Appendix B Synthesis of Regional Assessments - Data Analysis and Assessment Methodologies

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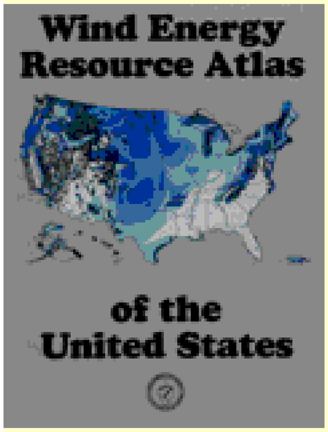

Wind Energy Resource Atlas of the United States

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Appendix A Synthesis of Regional Assessments - Data Analysis and Assessment Methodologies

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Appendix B

Wind Energy Resource Information System (WERIS)

The National Climatic Data Center (NCDC) in Asheville, North Carolina makes available a wind data base designed specifically for use in wind energy applications. The data base includes approximately 975 station locations in the United States, Puerto Rico, and the Pactfic Islands. Wind speed and direction data from specific locations were analyzed with various techniques to estimate wind power at exposed sites. The data base includes wind power statistics and several other wind summaries, such as direction vs. speed and speed vs. hour-of-day frequency distributions. The major source of wind data that went into the wind resource assessments was the NCDC Airways Surface Observations data set (TD-1440) that had been coded onto magnetic tape, either as hourly or 3-hourly observations (Appendix C). The Pactfic Northwest Laboratory, as part of its activity in wind resource assessment for the Department of Energy, analyzed the data in the tape set through the end of 1978 for pertinent wind energy statistics.

Analyses were performed on each period of record during which the anemometer height, anemometer location, and frequency of observation were found among the 975 locations. Considerable use was made of the National Wind Data Index (Changery 1978) to identify these periods. The data base is archived on microfiche and magnetic tape.

Microfiche Tables

Nineteen different kinds of tables for 975 stations were produced in this analysis. Standard information given with each table includes the table number, station name, station WBAN number, period of record, number of valid observations, and anemometer height and reference location.

Table B-1 outlines 19 tables of statistics on one microfiche per city per period of constant anemometer location. A user may order a copy of the fiche or select specific tables to be produced on paper (see this page for ordering information).

Digital File

The wind digital file was originally designed as an interactive system. Unfortunately, because of a shortage of communication ports on the National Climatic Data Center (NCDC) computers, users cannot currently access the data base directly. Magnetic tapes containing operational programs and data files must be transferred from tape to disk in order to use this system. The NCDC, acting in place of the user, will query the data base to produce a user-tailored subset of the data base. For information on the types of possible outputs, request a copy of the WERIS user's manual TD-9793.

The data base that can be produced for the user will be some subset of the information contained in the microfiche tables. The NCDC will execute any combination of the four primary data selections and display programs: Annual, Frequency, Climate, and Persistence. The type of data each of these programs access is described below.

1. *Annual*- means and standard deviations of wind speed and wind energy flux, pattern factor, and Weibull distribution parameters by month and year for the period of record.
2. *Frequency*-mean wind speed and speed frequency distribution by hour of the day and by direction for each month of the period including an annual summary.
3. *Climate*-means of air temperature, pressure, and density plus occurrences of thirteen weather events by month for the period of record.
4. *Persistence*-the number of runs of various durations in which the wind speed exceeded a threshold speed or the direction remained constant for the period of record.

Summary

The NCDC can provide microfiche copies of the table data or hard copy prints from the microfiche. The NCDC can also provide digital selections of specific subsets of the data. For more information on the National Wind Data Base, write or call:

National Climatic Data Center
Information Services Division
Federal Building
Asheville, NC 28801-2696
(704) 259-0682
FTS 8-672-0682

Reference

Changery, M. J. 1978. *National Wind Data Index.*
HCO/T1041-01, DOE/NOAA, E(49-26)-1041, National Climatic Data Center, Asheville, North Carolina.

Appendix C Annual and Seasonal Mean Wind Speed and Power Summaries For Selected Stations in the United States and Its Territories

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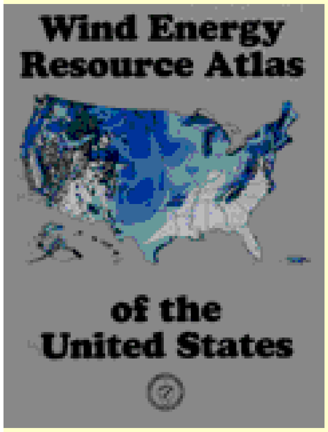

Wind Energy Resource Atlas of the United States

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Appendix B Wind Energy Resource Information System (WERIS)

Appendix C

Annual and Seasonal Mean Wind Speed and Power Summaries For Selected Stations in the United States and Its Territories

Wind data from 975 stations in the National Climatic Data Center (NCDC) tape set TD-1440 were analyzed to provide much of the data used to create the National Wind Energy Assessment. For these 975 stations, 1,889 separate periods of record were identified, during which anemometer location, observation, frequency, and data coding frequency were constant. In this appendix, summary information on station identification, location, and annual and seasonal mean wind speeds and wind power densities are presented for these stations and periods.(see Table C-1)

Stations are grouped alphabetically by state with postal abbreviation information on each period of record following chronologically. The NCDC station number code (WBAN) is used to uniquely identify stations with the same city name. The agency responsible for station operation is identified by the TYP code:

TYP	Type of Station Making Observations
A	Air Force
N	Navy
W	Service Weather
F	FAA

Station location is given by its latitude and longitude coordinates in degrees (DD) and minutes (MM). Positive latitude is north of the equator. West longitudes are less than zero. Station elevation is given in meters above mean sea level. Station location information was largely obtained from the NCDC publication *WBAN Station Numbers* (NCDC 1978).

Period of record information was extracted from the *National Wind Data Index* (Changery 1978). Starting and ending dates, coded YY=Year, MM=Month, and DD=Day, were selected to maximize the length of record. The change in coding frequency from hourly to 3-hourly by the NCDC at the end of 1964 results in many periods ending near 641231 and starting near 650101; many periods of record for Air Force stations end at 701231 at which time the NCDC stopped digitizing Air Force data. The NCDC stopped digitizing navy data on an hourly basis after February 1972. A break in the period of record also occurs if the observation frequency at the stations changed. The OBS code indicates the number of hours per day that observations were taken at the station:

OBS	Hours of Observation Per Day
A	24
B	19-23
C	12-18
D	5-11
E	4
F	Less than 3
Blank	Unknown

Periods of record were most often interrupted by changes in anemometer height or location. Changery's index documents these changes and gives an anemometer height and location history for each station. Anemometer height is reported here in meters above the ground. The LOC code describes the type of structure on which the anemometer was located:

LOC	Anemometer Location
R	Roof-Top

G	Ground Mast
B	Beacon Tower
U	Unknown Location
E	Estimated Wind, No Anemometer

A roof-top location means the anemometer was located on a mast on the roof of a building with the height of the anemometer above ground as given. There is no information on the height of the mast above the roof. A ground mast signifies that the mast, with its base on the ground, is used primarily to support the anemometer. Beacon tower locations mean that the tower is not primarily used to support the anemometer but has other functions. A few early periods of record were coded from estimated wind speeds; no anemometer was available at the site. Anemometers with unknown locations usually also are at unknown heights, which are coded as -99.9.

Annual mean wind speed, in m/s, and annual mean wind power density, in W/m^2, are calculated from all available data for the period of record. Seasonal mean values are based on the following months:

Season	Months Included
Winter	December, January, February
Spring	March, April, May
Summer	June, July, August
Autumn	September, October, November

FLAGS USED IN THE TABLE:

Seasonal means were calculated by weighting monthly mean values by the number of observations in the month normalized by the total number of observations in the season over the period of record. Two data quality checks were calculated for the annual and seasonal mean values. The first is the ratio of the number of valid wind speed observations to the maximum possible number of observations that could have been coded during the period of record. The second is the ratio of the number of wind power density calculations that were made using estimated values of air pressure and temperature to the total number of wind power density calculations made for the period. A code symbol, after the wind power value, indicates the status of the two data quality checks:

Code	Ratio: Total Number/Maximum Possible Number	Ratio: Estimated Number/Total Number
Blank	≥0.75	≤0.50

#	≥0.75	≥0.50
*	<0.75	≤0.50
%	<0.75	>0.50

Annual or seasonal mean speed and power values with the * (or %) symbol may not be very representative of the period of record because of significant data gaps. Annual or seasonal mean wind power with the # (or %) symbol may be as much as 20% in error because climatic mean air temperature were used to calculate the hourly (or 3-hourly) wind power values that went into the calculation of the mean value. Missing values, coded -99.9 for the wind speed and -999 for wind power, indicate no data were available to calculate the mean for that season. For a very small number of stations, errors in wind speed reporting or coding errors on the TD-1440 tapes resulted in anomalously high wind power densities for the month in which the error occurred. Negative wind power values, other than -999, are used to indicate that these high values have been replaced by the mean of the preceding and following months in the calculation of the annual and seasonal mean power.

References

Changery, M. J. 1978. National Wind Data Index. HCO/T1041-01, DOE/NOAA, E(49-26) 1041, National Climatic Data Center, Asheville, North Carolina.

NCDC. 1978. WBAN Station Numbers. National Climatic Data Center, Asheville, North Carolina.

Appendix D Evaluation of New Site Data for Verifying or Updating The Wind Resource Estimates

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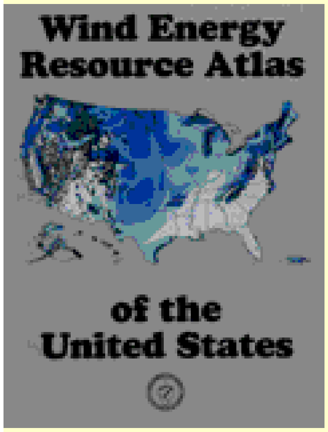

Wind Energy Resource Atlas of the United States

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Appendix D

Evaluation of New Site Data for Verifying or Updating The Wind Resource Estimates

The twelve regional wind energy resource atlases were based on data collected before 1979. Most of the data used in the assessments were collected at anemometer heights and locations that were not chosen for wind energy assessment purposes. In many areas estimated to have a high wind resource, the certainty rating of this estimate is low because few or no data were available for exposed locations. Since 1978 many locations have been instrumented specifically for wind energy assessment purposes. Many of these new locations have been places thought to have high wind resource but where previous historical data were not available or were very limited.

Since the late 1970s, numerous organizations around the country have been involved in wind measurement studies to assess wind energy potential or evaluate potential wind turbine sites. Many locations selected as potential wind turbine sites were instrumented by the U.S. Department of Energy

(DOE). The Bureau of Reclamation (BuRec), Bonneville Power Administration (BPA), Western Area Power Administration (WAPA), Alternative Energy Institute (AEI), and California Energy Commission (CEC), to name a few, have also been involved with instrumenting numerous sites for wind energy assessment or siting purposes. Other organizations, such as the Tennessee Valley Authority (TVA), have performed wind energy assessments incorporating historical data from many sites that were not previously used in the regional atlases (e.g., historical data collected at TVA facilities).

Data records of sufficient length are now available to evaluate the wind resource at hundreds of new sites throughout the country. In this study, data have been evaluated from approximately 270 new sites for use in verifying or updating of the wind resource estimates in the regional atlases. Approximately 200 of the new sites were instrumented specifically for wind energy assessment purposes.

The measured wind resource at the new sites has been compared with the estimated wind resource from the regional atlases, which were based to a large extent on conventional data from airport and military installations. At sites where the measured wind resource was significantly different from the estimated resource, the site's characteristics and wind data were examined in greater detail, where possible. In many cases, data used in the regional atlases were also evaluated in greater detail to determine possible causes for differences between the wind resource indicated by the new site data and that used in the regional atlas. In cases where the evaluation of the new site data indicated that the annual average wind resource estimate(s) for an area(s) should be updated, further analysis was carried out to determine the extent of the area(s) over which these revisions were applicable. This procedure was repeated on a seasonal basis, using seasonal data where available or applicable. In areas where seasonal data were not available or were very limited (for two seasons or less), the change in the seasonal average wind resource was scaled to the change in the annual average wind resource. However, in some areas, new site data indicated that the seasonal trends were substantially different from those presented in the regional atlases. In these areas, further evaluations of the new site data versus the data used in the regional atlases were carried out to determine possible causes for the differences in the seasonal trends. Where the new site data were determined to be more valid and representative than the data or method used in the regional atlases, the seasonal maps were revised as necessary.

In addition to updating the annual and seasonal average wind power maps, maps of the certainty ratings credited to the wind resource estimates and areal distribution (percentage land area) exceeding specified wind power class were also updated. Certainty ratings were upgraded where new site data from exposed sites, especially at heights to 50 m (164 ft) above ground, provided increased confidence in the wind resource estimates. In a few areas, certainty ratings were lowered where new site data of unknown exposure and/or quality indicated a higher or lower wind power class than previously analyzed. In many areas of the Great Plains and Midwest, where a certainty rating of 4 was previously assigned, the certainty rating was lowered if no data were available at heights of 30 to 50 m (164 ft) above ground to verify the wind resource estimate. New site data show that wind power class at 10 m (33 ft) is not always a reliable indicator of the wind power class at 50 m (164 ft), even at apparently well-exposed sites. Thus, estimates for an area that are based solely on data collected at or near 10 m (33 ft) above ground are not credited with the highest certainty rating in the updated assessment. Certainty ratings over inland areas of the Southeastern plains, from eastern North Carolina southward to Florida and westward to eastern Texas, were upgraded to certainty rating 4 everywhere because of factors (e.g., abundant surface data, tower data, small variability in the wind resource, mostly flat to rolling terrain, high roughness) indicating that this region of the country has low wind energy potential with a high degree of confidence for current wind turbine applications.

Areal distribution (percentage land area) maps were not only updated to reflect the revisions in the updated annual average wind power map, but improved to more realistically reflect coastal areas of high wind resource that were omitted in the areal distribution maps in the regional atlases because of the computational scheme used. Areas where these problems occurred have been identified and corrected to provide a more representative analysis in the updated areal distribution maps. In addition, land areas previously omitted in the regional atlases, such as islands in the Great Lakes and islands off the Northeast coast, have been identified and included on the updated areal distribution maps.

In the remainder of this appendix, we describe the sources of the new site data obtained, the procedures used in the screening and evaluation of these data, and the results of the evaluation. The updated wind power analyses, which are based largely on the evaluation and analysis of these new site data, are presented in Chapters 2 and 3 of this atlas, not in this appendix. Site-specific data, such as site location and average wind speed and power, are not presented for the new sites used in this study, except for the DOE candidate wind turbine sites listed in Appendix E. However, references to where the new site data were obtained are included for most of data sources identified in this study.

Comparisons of the estimated versus the measured wind resource at the new sites are described on a region-by-region basis, not on a site-by-site basis except where reference is made to specific DOE candidate wind turbine sites within a region. Some other aspects of the new site data presented here are tables of the distribution of new sites as a function of the measured and estimated wind resources and their difference, comparisons of the actual wind resource versus that computed using a Rayleigh wind speed distribution, and comparisons of the actual wind resource at 50 m (164 ft) versus that based on an extrapolation from 10 m (33 ft).

Sources of New Wind Data

An effort was made to identify new wind data from various regions of the United States. Organizations contacted in each region were asked about other possible sources of data in their region. This procedure reduced the chance of omitting a major source of new data. However, it was not the intent of this study to identify all sources of new data. Priority was given to identifying summarized wind data, as opposed to raw data, in regions where high wind energy resource was estimated and where new data were collected specifically for wind energy assessment purposes.

Data from a variety of sources were identified and new data were identified in practically every region of the country. A few organizations contacted had proprietary data. Some organizations had just recently installed wind measurement sites or indicated plans to install sites. Several organizations had performed wind energy resource assessments for specific areas incorporating historical wind data used in the regional wind energy atlases and other historical or new data.

The largest amount of data available was from an ongoing project by the California Energy Commission to establish a wind data base of all information acquired within and near the state of California (Waco and Wurst 1983). The data base consists of mean wind speed data acquired by utilities, Federal agencies, and private wind turbine developers. Other major sources of wind data were information acquired from recently completed or ongoing Federal measurement programs (Mah1983; Harrison and Hightower 1983; Bureau of Reclamation 1982, 1983; Baker et al. 1981; Baker, Wade and Persson 1982; Baker and Hewson 1980; Sandusky et al. 1983), and analysis of data available within the Tennessee Valley Authority service region (McGrew, Nielsen and Wiesner 1981). Other data sources were anemometer loan programs (Gipe 1982; Reynolds 1981; Theisen 1983), measurement and data analysis programs sponsored by state energy offices (Sforza, Bailey and Smorto 1980; Otawa, Shoen and Justham 1982; Takle, Brown and Davis 1978), measurement and data analysis programs conducted by universities (Johnson 1982; Myers and Thomann 1982; Lockwood et al. 1981; Martner 1981; Meyers 1979; Huxoll and Wagner 1981; Wagner and Meyers 1981; Ramage, Oshiro and Yokogawa 1979; Wentink 1981; Griscom, Collins and Seavy 1982), and measurement programs conducted by utilities (Kuffel 1982; Colyn and Thero 1982). In total, data from approximately 1100 locations were identified, but after screening only slightly more than 25%, or data from 272 locations, were used in this study.

The format of the obtained data varied markedly. For many locations only mean wind speed data were available, while for others mean wind speed and wind power density were available. The estimates of wind power density reported were usually based on the average of the hourly data or computed from the frequency distribution of the hourly wind speeds. However, the reported values of wind power density from a few sources were computed using an assumed frequency distribution of wind speeds, such as the Rayleigh distribution.

Anemometer heights varied considerably among the sources and frequently among the sites from a given source. At some sites, data were available at two or more levels above ground level. For both the single and multilevel sites, the lowest sensor level was typically at 9 to 15 m (50 ft) above ground level but ranged from 4 to 30 m (98 ft) above ground. Most sources provided summarized data for the heights at which the data were collected; however, a few sources only reported information adjusted to a common height(s) above ground.

The sites for which data were provided were usually assumed to be well exposed to the local wind flow regime. Only a few data sources provided a detailed description of the exposure at each site. Most sites were located in areas estimated to have class 3 or greater wind energy potential in the regional wind energy atlases. One exception was the resource assessment of the Tennessee Valley Authority service area (McGrew, Nielsen and Wiesner 1981), where the majority of sites were located in areas estimated to have only class 1 or 2 wind power.

Data Screening and Analysis

Once the data were obtained, but before the analysis was begun, data was screened to eliminate redundancy or data with an insufficient period of record. In addition, because of the varied formats of the data sets, preliminary data evaluation and analysis were required. Results of this screening were used to determine which data would be used for comparison with the results from the regional atlases. For example, intercomparison of data from two sites within the same grid cell have resulted in additional data being eliminated from further comparative studies. Aspects of these tasks are described below.

Screening of the Data

As a result of the screening process about 75% of the data made available were eliminated for use in the study. Most of the data eliminated fell into one or more of the following categories:

- same data as used in the regional wind energy atlases
- period of record was less than 10 months
- too much missing data to be considered representative
- evidence of poor exposure (e.g., anomalously low wind speeds)
- site location was not provided (e.g., no latitude, longitude coordinates or locator maps)
- proprietary data.

Most data that were eliminated fell into the first two categories. For example, data provided in the wind resource assessment of the BPA service area (Baker, Wade and Persson 1982), the TVA service area (McGrew, Nielsen and Wiesner 1981), California (CEC), New York (Sforza, Bailey and Smorto 1980), and Hawaii (Ramage, Oshiro and Yokogawa 1979) contained a large amount of data previously used in the regional wind energy atlases. Huxoll and Wagner (1981) reanalyzed wind data from the coastal region of Texas but used an extrapolation technique dependent on atmospheric stability. The measurement program being conducted by the Western Area Power Administration (Mah 1983) had only recently begun and only about half of the sites had an adequate amount of data. Less than 10 months of data were available for the sites in New Hampshire (Lockwood et al. 1981), Rhode Island (Griscom, Collins and Seavey 1982), and the anemometer loan program sites in Pennsylvania (Gipe 1982).

Some data were eliminated because the data or site information showed strong evidence of poor exposure. For example, sites with considerably lower wind speeds, in comparison with other data in the vicinity, were eliminated. Surprisingly, data from some of the anemometer loan program sites showed considerably lower wind speeds than existing data from nearby airports and were, thus, eliminated for use in this study.

Analysis and Evaluation of Data

After the initial screening, the data were coded into a standard format. Information coded included: source identification, site number, site name, state, site location by latitude and longitude, site elevation above sea level, height(s) of the anemometer(s) above ground, period of record, mean wind speed, mean wind power density (if available) and the height(s) at which the wind speed and wind power density apply.

Since the data sets existed in various formats, the coded data were first processed so all data were of the same units, and data were adjusted to a common height above ground. Obtaining mean wind speed and available power at the 10- (33 ft) and 50-m (164 ft) levels above the site elevation generally required the use of a suitable extrapolation technique. Mean wind speeds and powers were extrapolated from the anemometer height level to 10 (33 ft) and 50 m (164 ft) above ground by use of the 1/7 power law. For those sites with only mean wind speed data, the available power was estimated by assuming a Rayleigh distribution of wind speeds.

Once the analysis was performed, the wind power classes were determined. These are the same power class ratings used in the regional atlases and this national assessment. Locations of the sites were evaluated to determine if more than one site was within a grid cell (the grid cell dimensions were 1/4° latitude by 1/3° longitude.) If so, the site with the highest power class rating in the grid cell was usually retained unless the data from another site in the cell was considered more representative of mean conditions for an exposed location in the cell (e.g., longer period of record).

After the final screening to eliminate sites within the same grid cell, 270 sites were retained for further evaluation and comparison with the estimates of the wind energy resource in the regional atlases. Table D-l lists the major sources of new data from which at least 10 sites were retained for this study. These sources accounted for about 90% of the new data used in this evaluation. Various other sources accounted for the remaining 10% of the new data used. The site data were dispersed over large geographical areas and primarily located in areas estimated (predicted) to have class 3 or greater wind energy potential, except for the data in the TVA service area and parts of California and New York.

Most of the new sites in the Great Plains from Texas northward to North Dakota were in areas estimated to have class 3 to class 5 wind resource in the regional atlases. New sites in Wyoming and western Montana were also located mostly in areas estimated to have high wind energy potential. In Washington and Oregon, the highest concentration of new sites was in the Columbia River corridor along the Oregon-Washington border, where estimates of the wind resource ranged from class 3 to class 6. In California, new sites were dispersed throughout the state over areas of high and low wind resource. Many new sites were located in or near the Coastal Range wind corridors (e.g., San Gorgonio, Altamont, and Pacheco passes and Carquinez Straits) estimated to have high wind energy potential. Several sites located on mountain summits or ridge crests in Nevada and northeastern California were estimated to have class 5 to 7 wind energy potential. In the East, new sites along the Northeast coast from Long Island to Cape Cod were located in areas estimated to have class 4 and 5 wind resource. Also, several new sites were located along Lake Ontario and Lake Michigan where class 3 and 4 power were predicted. Along the south Texas coast, where a band of class 4 power was estimated, one new site was located on an offshore island and one new site several kilometers inland from the inner coastline.

A comparison of the geographical distribution of the estimated versus measured wind energy resource, adjusted to 10 m (33 ft) at the 270 locations indicated considerably greater spatial variability in the measured resource than in the estimated resource, except over the TVA service area, where uniformly low wind resource was prevalent. Although numerous sites in the Great Plains measured class 4 or greater wind power, quite a few sites in the Great Plains measured only class 1or 2 power. Throughout the West there was considerable intersite variability in the measured wind resource.

Many of these new sites were not installed specifically for wind energy purposes but were installed by or for utilities or other organizations to collect data for other purposes. A few sites were airports or Federal facilities with historical data that were not identified or used in the regional wind energy assessments. Of the 270 sites, 196 sites were determined to have been installed specifically for wind energy assessment purposes in mind. (There was some uncertainty as to the purpose of a few sites.) Approximately two-thirds of the 196 special sites measured class 3 or greater wind resource, whereas roughly one-third measured only class 1 or 2 wind resource. Of the 74 sites that were not installed for wind energy purposes, 80% showed low wind energy potential (class 1 or 2).

Table D-2 gives the number of new sites at which the measured wind resource and at which the estimated wind resource was in each of the seven wind power classes for all new sites and special new sites installed specifically for wind energy assessment purposes. In both cases, the number of sites at which the measured resource is either low (class 1 or 2) or very high (class 6 or 7) is substantially greater than the number of sites predicted. Consequently, the number of sites that had class 3 to 5 power is considerably less than that predicted by the national assessment. In conclusion, there is much more variability in the distribution of the measured resources than in the estimated (predicted) resources.

Considering all 270 new sites, 70% were located in grid cells estimated (predicted) to have class 3 or greater wind power. The measured wind resource was class 3 or greater at 52% of the sites. However, 21% of the sites measured class 5 or greater power, whereas only 13% of the sites were predicted to have this much power.

Considering the 196 special new sites, 86% were located in grid cells estimated to have class 3 or greater power, while 64% measured class 3 or greater power. In areas estimated to have class 5 or greater power, 27% of the sites measured this much power whereas only 16% were predicted to have this power.

Comparisons of Estimated and Measured Resource

The wind resource measured at the new sites was compared with the resource estimates from the regional atlases to determine the difference between the measured and estimated resource at each of the 270 sites. The results of this comparison are not shown here on a site-by-site basis, as it is not the intent of this evaluation to present the site-specific data. Moreover, data from a specific site may not be representative of the general area and could be misleading, without the appropriate information on its location and exposure. Instead, the results of this comparison are described on a region-by-region basis, with some reference to specific sites where examples are used. A summary of the results based on all the new site data in the United States is given at the end of this section.

Over the Great Plains from Texas north to North Dakota and Montana, there were considerably more sites where the estimated resource exceeded the measured resource than vice versa. At some of these sites where the measured resource is less than estimated, we suspect that the site exposure may not be optimum (e.g., local obstructions such as trees and buildings may exist in the vicinity). It appears that some of the sites had lower wind resource than estimated because they are located in areas of relatively lower elevation than nearby terrain. A few of the sites that were located near airports had considerably lower wind speeds than the nearby airport during the same period, indicating that the site's anemometer was not well exposed.

However, a large fraction of the new sites throughout the Great Plains had the same wind power class as estimated or only slightly greater or less than that estimated. This indicates that, for the most part, the estimates in the regional atlases are fairly representative of the typical exposed locations in the Great Plains.

Ten sites in the Great Plains had considerably greater wind resource than estimated. Most of these sites were located on elevated terrain features, which were higher than much of the surrounding terrain. The regional atlases depict the prominent ridge crests and mountain ranges in the United States but do not depict less prominent terrain features such as the relatively low ridges and hills scattered throughout portions of the Great Plains. However, many of these elevated terrain features in the Great Plains can be expected to have greater wind energy potential than that estimated for the open plains and rolling country, as was indicated in the assessment of the North Central region (Freeman et al. 1981).

The review of all the new wind data for the Great Plains from Texas to the Dakotas indicates several areas where the representative, new site data indicate higher or lower wind resource than was estimated in the regional atlases. One such area was the class 5 area in the southern Great Plains over the Texas-Oklahoma Panhandle. Eight new sites were located in this region, including four sites that also had data at approximately 50 m (164 ft) above ground. None of these new sites indicated the class 5 wind power at either the 10-m (33 ft) or 50-m (164 ft) level that was estimated in the regional atlases, but instead measured class 3 and 4 power. In the regional atlases, the data used in this area were older airport data from the 1930s to the early 1950s as no recent data were summarized or digitized. The authors now believe that these older data are biased on the high side. For example, at Clayton, New Mexico, the airport data from 1948 to 1951 show wind power class 5 (280 W/m^2 at 10 m or 33 ft), whereas the nearby new site data from 1977 to 1982 at Clayton give wind power class 3 (170 W/m^2 at 10 m or 33 ft). Both site locations appear almost equally well exposed to the wind. An interesting note is that there is only a 1 m/s difference in the mean annual wind speeds at 10 m (33 ft) between these two locations, but this results in a significant difference in the wind power density (over 100 W/m^2 difference at 10 m or 33 ft).

New site data indicate that the estimates may be on the low side in parts of North Dakota. Two years of new data were collected at 9 m (30 ft) and 45 m (148 ft) near Finley in eastern North Dakota. The low-level data indicated class 4 power, which agrees well with the estimates in the regional atlases. However, at the upper level the wind power was class 6 (740 W/m^2 at 45 m or 148 ft) at this site. A more detailed analysis of this site's data reveals very strong nocturnal shear, which results in considerably greater power at 50 m (164 ft) than at 10 m (33 ft). If this site's wind regime is characteristic of that over the larger areas of eastern North Dakota and western Minnesota, then the wind power estimates in the regional atlas may be one to two power classes too low (for the 50 m [164 ft level]). Additional data are needed to more reliably estimate the extent of the wind resource over these areas.

In western North Dakota, new site data at five different exposed locations indicate class 4 to 5 wind power potential at 10m (33 ft), in comparison to the class 3 to 4 estimates in the regional atlases. A site near Minot indicates class 5 potential at 50 m (164 ft) for exposed areas in western North Dakota, in comparison to the class 4 power estimated for 50 m (164 ft) in the regional atlases.

In southern Wyoming, 16 new sites indicate considerable variability in the wind resource, ranging from class 1 to class 7. A few of these new sites with low wind resource are suspected of having poor site exposure. Data from exposed sites in southeastern and southwestern Wyoming indicate class 6 wind power at 10 m (33 ft) and 50 m (164 ft), in comparison to the class 4 and 5 estimates in the regional atlases.

In the TVA service area in the Southeast, additional site data confirm, to a higher certainty, that the resource is low throughout this region, except for exposed mountain summits in the Appalachians. In the Northeast, many sites had lower wind resource than estimated; however, many of these were sites that were not installed for wind energy purposes. Thus, the exposure of these sites is questionable. Exposed sites along the Atlantic coast from Long Island to Cape Cod and along the coasts of Lake Ontario and eastern Lake Erie mostly had comparable or slightly less wind resource than indicated by the estimates in the regional atlases.

In mountainous regions (as in much of the western U.S.), comparisons of the measured and estimated wind power classes at specific sites can be misleading if the types of terrain features represented by the grid cell estimate and site location are not the same. For example, the grid cell estimate may be representative of a ridge crest or mountain summit, whereas the site location may be in a valley. Likewise, the opposite situation may occur where the site is on an exposed ridge crest, but the estimate is representative of a plain or valley.

However, in most cases the grid cell estimate and new site data are for locations of the same terrain type (i.e., ridge crest, broad valley, open plain, tableland, etc.). In complex terrain, many of the large differences between the estimated and measured resource may be attributed to local variations in the resource over the same terrain feature(s) within the same grid cell. For example, the wind resource at 10 m (33 ft) along a ridge can vary by several wind power classes from one part of the ridge to another part. This has been documented in numerous studies of the resource in complex terrain areas.

Table D-3 gives the number of sites in the United States for which the difference in wind power class (measured minus estimated) was a given amount. At 65% of all new sites, the measured wind power was within one power class of the estimated power, and at 30% of these there was no difference in the power class. The measured wind power at 35% of all new sites differed by 2 or more classes from the estimated power; approximately half of these were greater and half less than the estimated power class. For special new sites (those sites installed specifically for wind energy purposes), 26% of the sites had the same class as the estimated power and 57% of the sites were within ± 1 power class. Thus, 43% of the sites differed by 2 or more power classes from the estimated power class.

Table D-4 shows the distribution of the number of new sites by measured wind power class and the difference between the measured minus the estimated wind power class. For new sites that have low wind resource (power class 1 or 2), the measured resource is less than the estimated resource at 67% of the sites and greater than the estimated resource at only 5% of the sites. However, for new sites with class 4 or greater wind resource, over 60% had higher wind resource than estimated whereas only 9% had less resource than estimated. Approximately 65% of the sites with class 5 or greater resource had considerably more wind resource (two or more classes greater) than estimated. Thus, the information in Table D-4 indicates that a significant percentage of the sites with high wind resource were in areas estimated to have much lower wind resource, and vice versa.

Comparison of Rayleigh and Actual Wind Power

At 109 of the 270 new sites, only mean wind speed data were provided. At these sites, the wind power was computed assuming a Rayleigh distribution of wind speeds.

At the other 161 sites, the wind power was based on the actual distribution of wind speeds. For these sites, the wind power based on a Rayleigh speed distribution was also computed and compared with the actual wind power. The results of this comparison are shown in Table D-5. These results indicate that use of the Rayleigh distribution would underestimate the power class at 37% of the sites and overestimate the power class at only 4% of the sites.

If we consider only those sites where moderate-to-high wind power (class 3 or greater) was measured, then the results are quite different. The wind power was class 3 or greater at 75 sites. Use of the Rayleigh distribution would underestimate the wind power class at 52% of these sites, and at 15% of the sites the power would be underestimated by two or more power classes. The power would be overestimated by one class at only 7% of the sites. At none of the sites would the power be overestimated by two or more classes.

Thus, the data available for this study indicate that in areas of high wind energy potential, use of the Rayleigh distribution frequently underestimates the power but rarely overestimates the power. These results apply to 10 m (33 ft) and represent an average over a wide geographical distribution of sites throughout the contiguous United States. They may not apply to certain specific regions or be entirely representative of any given region.

Comparison of Actual and Extrapolated Power at 50 m (164 ft)

For the majority of the 270 new sites, only one level of wind data was available and it was usually nearer the 10-m (33 ft) level than the 50-m (164 ft) level. The wind power at 50 m (164 ft) at these sites was estimated using the 1/7 power law equation.

However, at 63 new sites wind data were available for two or more heights above ground, usually near the 10-m (33 ft) and 50-m (164 ft) levels. At these sites, a more accurate estimate of wind power at the 50-m height could be obtained than at sites with only one level of data near 10 m (33 ft). A comparison was made between the actual wind power at 50 m (164 ft), based on data collected at or near the 50-m (164 ft) level, and the estimated wind power at 50 m (164 ft) based on data collected at or near 10 m (33 ft) and extrapolated to 50-m (164 ft) using the 1/7 power law. The results of this comparison are shown in Table D-6 for sites with class 1 or 2 wind power and for sites with class 3 or greater wind power.

At 38 sites where class 3 or greater wind power was measured at or near the 50-m level, only 16 sites (42%) would have the same wind power class at 50 m (164 ft) if 10 m (33 ft) data and the 1/7 power law were used to estimate the 50-m (164 ft) power. The actual wind power class at 50 m (164 ft) was greater than the estimated power class at 37% of the sites, and at half of these the actual exceeded the estimated by two or more power classes. Most of the sites with the largest difference between the actual and estimated power classes at 50 m (164 ft) are located in areas where trees are prevalent in the surrounding environment. For example, at many of the sites in the eastern United States (e.g., Northeast and Great Lakes regions), the actual wind power at 50 m (164 ft) is considerably greater than the estimated power.

Over most of the Great Plains, there was little difference in the actual and estimated power at 50 m (164 ft), so the 1/7 power law appears appropriate to most exposed locations throughout the southern and central Great Plains. An exception to this is eastern North Dakota, where the actual wind power at 50 m (164 ft) was two power classes greater than the estimated power. Very strong nocturnal shear primarily accounts for this large difference between the actual and estimated power at 50 m (164 ft) in this area.

The actual power at 50 m (164 ft) was less than the estimated power at 21% of the 38 sites with moderate-to-high wind power at 50 m (164 ft). Most of these sites are located on ridge crests, hilltops, and other elevated terrain features where a local acceleration of the wind is caused by the terrain feature. For example, the actual wind power at 50 m (164 ft) was considerably less than the estimated power extrapolated up from 10 m (33 ft) at Wells, Nevada (a ridge crest site), San Augustin Pass, New Mexico (a mountain pass), and Point Conception, California (a coastal head).

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Appendix E

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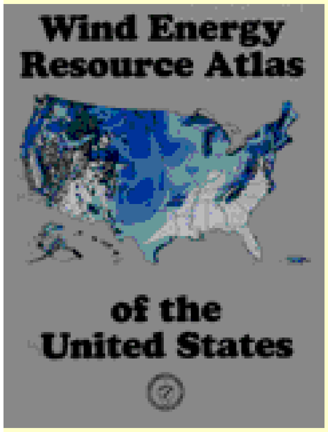

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Appendix D Evaluation of New Site Data for Verifying or Updating The Wind Resource Estimates

Appendix E

Annual and Seasonal Mean Wind Speed and Power Summaries For 35 Candidate Wind Turbine Sites

The U.S. Department of Energy (DOE) has sponsored meteorological measurement programs at a number of locations around the United States for the purpose of site evaluation for wind energy utilization. The locations are identified in Map E-1. Seventeen candidate sites were originally selected from proposals submitted by electric utility organizations in 1976. Data measurement programs began at most of these sites in late 1976 or 1977. At most sites, the sensors were installed at 9.1 m (30 ft) and 45.7 m (150 ft) levels. At some sites, the lower level was installed at 18.2 m (60 ft) to avoid effects on the measurements by nearby obstructions. At Cold Bay, Alaska, the top level sensor was mounted at 21.8 m (72 ft) on a Federal Aviation Administration tower. Two sites, Kacna Point, Hawaii, and Boardman, Oregon, had data acquisition programs in progress, and, thus, installation of government equipment was not required. Data at most of the sites were initially recorded on strip-chart recorders. In late 1978 and early 1979, all strip-chart recorders were replaced with digital cassette data loggers.

In 1980, an additional 20 sites were added to the candidate site measurement program. Ultimately, towers were installed at 18 of these 20 sites. Configuration of the measurement system at these sites differed somewhat from those at the 17 original sites. The data were collected from sensors at three levels on a meteorological tower. At most of the sites, the sensor heights were at 9.1 m (30 ft), 30.0 m (100 ft), and 45.7 m (150 ft). The data were recorded digitally at each site on a data cassette recording system with an instantaneous sample of data recorded every two minutes.

In 1981, after installation of large wind turbines at six sites (including the MOD-2 cluster at Goodnoe Hills, Washington), the emphasis of the DOE program was shifted from systems development to technology research. Because of this, the candidate site program, which had also served to develop and apply techniques for analyzing wind resources and for prospecting for good sites, was curtailed. Measurements at most of the original 17 sites (with the exception of those having large wind turbines for field testing) were terminated. The candidate site meteorological data acquisition program was completed at all remaining sites as of September 30, 1982. Most of the equipment that was in the field at that time was turned over to participating utilities for their own use. A history of the candidate site program was published by Renne et al. (1982).

Summarized data for the seventeen original sites are available in a series of annual data reports (Sandusky and Renne 1981a, 1981b; and Sandusky et al. 1982a) and a cumulative data report through December 1981 (Sandusky et al. 1982b). Summarized data for the new sites selected and for those original sites with data collection programs continuing into 1982 are also available (Sandusky et al. 1983). These reports contain information for each site on data recovery rates, available power, maximum values observed, annual mean wind speed values, diurnal mean wind speed and direction values, frequency distribution of wind speed, wind speed persistence, and power law exponent as a function of wind direction.

In this appendix, summaries of the annual and seasonal average wind speed and wind power density are presented for 35 of the DOE candidate sites. The site name, location, elevation, period of record, and anemometer heights corresponding to the speed and power summaries are provided for each site. In the listing of the mean speed and power summaries, an asterisk (*) denotes that the mean wind speed and power are based on less than 75% data recovery for the period. A pound symbol (#) indicates that the annual wind speed and power are based on less than four full seasons' data. The recovery rates for all sensor levels for the sites in Hawaii and Vermont were lower than what is normally considered acceptable. These sites were located in remote areas and were affected by an extremely hostile environment of salt spray and moisture (Hawaii) or severe icing (Vermont) that affected the operation of sensors and data loggers.

These candidate site data summaries were evaluated and used in verifying or updating the wind energy estimates presented in this atlas for the United States. The evaluation and use of the wind data from some of the sites in updating the wind resource assessment are described in Appendix D of this atlas and throughout Chapter 3 (the regional summaries).

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Table E-1. U.S. Department of Energy candidate wind turbine sites

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Table E-1. U.S. Department of Energy candidate wind turbine sites

					Period		Anem	Mean Wind Speed (M/S) and Wind Power Density (Watt/m^2)									
ST	Station Name	Lat	Long	Elev	Start	End	HT	Annual		Winter		Spring		Summer		Autumn	
		DD.MM	DDD.MM	(M)	YYMMDD	YYMMDD	(M)	Spd	Pow	Spd	Pow	Spd	Pow	Spd	Pow	Spd	Pow
AK	COLD BAY	55.12	-162.43	29	770801	810930	21.8	7.3	496*	7.9	604*	6.9	449	7.1	425*	7.2	511*
							9.1	6.5	352*	7.2	446*	6.1	300	6.2	297*	6.8	389*
CA	POINT ARENA	38.56	-123.43	21	770101	810930	45.7	6.5	322	6.1	347	7.2	385	6.8	304*	5.9	250
							9.1	4.7	130	4.3	137	5.3	164	5.0	127	4.0	90
CA	ROMERO OVERLOOK	37.04	-121.13	458	801001	820930	45.7	6.4	266	4.9	119	6.8	344	8.2	446	5.4	140*
							30.0	5.3	165	3.7	62	5.9	213	7.2	278	4.5	99*
							9.1	4.8	126	3.2	43	5.4	173	6.5	214	4.1	73*
CA	SAN GORGONIO PASS	33.57	-116.35	344	761201	820907	45.7	7.7	712	4.9	280	9.7	1074	9.9	1009*	6.4	481*
							9.1	6.2	351	4.2	153	7.7	526	7.8	489	5.2	230*
HI	ILIO POINT, MOLOKAI	21.13	-157.15	61	810101	820531	45.7	10.9	1032#	9.3	752*	10.5	878*	13.8	1746*	-99.9	-999
							30.0	8.1	488#	5.2	211*	7.9	445*	10.5	766*	-99.9	-999
							9.1	7.3	369#	5.3	240#	7.8	415*	8.2	402#	-99.9	-999
HI	KAHUA RANCH, HAWAII	29.07	-155.47	1030	810201	820228	45.7	11.3	1528*	-99.9	-999	12.1	1571*	13.9	2214*	10.0	1303*
							30.0	9.2	974*	8.5	750*	10.6	1290*	10.6	1465*	7.8	548*
							9.1	8.6	732*	6.6	515*	8.8	817*	9.0	801*	9.6	780*
HI	KAHUKU POINT, OAHU	21.42	-157.60	108	800901	820531	45.7	8.1	567#	6.5	381*	9.5	747*	-99.9	-999	9.2	699*
							30.0	8.0	538#	6.4	380*	9.3	690*	-99.9	-999	8.9	618*
							9.1	7.6	465#	5.9	314*	8.9	617*	-99.9	-999	8.5	537*
KS	MEADE	37.18	-100.18	756	800701	820930	45.7	8.3	484*	7.7	377*	8.8	609*	8.4	457*	8.2	469
							30.0	7.1	362*	7.1	389*	7.0	373*	7.1	321*	7.1	379
							9.1	5.7	214	5.6	192*	6.3	289*	5.8	196	5.4	190
KS	RUSSELL	38.51	-98.51	564	761201	810831	45.7	7.3	373	7.2	362	7.4	411	7.2	357	7.3	356
							9.1	5.3	173	5.1	163	5.6	207	5.2	157	5.2	159
MA	HOLYOKE	42.18	-72.35	372	761201	810930	45.7	6.9	390	8.3	616*	7.1	434	5.5	194	6.7	337
							18.2	4.7	118	5.6	183*	5.0	153	3.7	52*	4.5	92
MA	NANTUCKET ISLAND	41.14	-70.00	12	801101	811231	45.7	9.1	697*	10.5	1148*	9.1	620	7.9	404	9.5	756*
							30.0	8.1	631#	9.6	957*	7.3	436*	6.9	433*	-99.9	-999
							9.1	6.2	359*	9.7	1082*	5.5	225	3.8	88*	6.9	326*
MA	PROVINCETOWN	42.03	-70.12	10	810101	820831	45.7	9.8	768*	10.2	895*	11.3	1206*	9.6	665*	8.8	554
							30.0	7.5	441*	8.3	626*	8.3	573*	5.8	185*	7.2	361
							9.1	4.5	109*	4.5	101*	5.6	204*	4.0	64*	3.8	57*
MI	BIG SABLE POINT	44.03	-86.31	179	810101	820914	45.7	8.6	592*	9.8	822*	8.8	607*	6.9	308	9.5	737
							30.0	7.0	382	8.9	660*	7.4	398*	5.4	171	7.2	408
							9.1	5.7	210*	7.2	358*	6.2	247*	4.7	109	6.0	260*
MI	LUDINGTON	43.53	-86.26	213	770401	791031	45.7	7.5	466	8.5	635	7.4	437	6.4	292	8.2	590
							18.2	5.2	181	5.8	245	5.6	209	4.2	100	5.2	194*
MT	LIVINGSTON	45.40	-110.30	1420	800901	820930	45.7	8.4	794*	11.6	1868*	7.9	580*	6.5	288	8.2	627
							30.0	7.8	671	10.7	1429	7.2	472*	5.7	226	7.7	569
							9.1	6.8	457	9.6	1010	5.8	242*	5.0	153	6.7	383

NE	KINGSLEY DAM	41.12	-101.40	1024	761201	810831	45.7	6.5	286	6.5	277	6.9	345	6.0	216	6.7	297
							9.1	5.3	160	5.2	152	5.7	211	4.9	117	5.3	154
NV	WELLS	41.03	-114.35	2268	801001	820131	45.7	7.8	408	7.3	348	8.8	491	8.5	563	7.3	318
							30.0	7.2	337	7.1	345*	7.6	354	7.6	360	6.9	305
							9.1	6.8	304*	6.4	301*	7.9	409*	6.6	226*	6.5	278
NM	CLAYTON	36.27	-103.10	1536	770501	820928	45.7	7.3	334	7.2	324*	8.1	451	6.9	260	7.0	308
							9.1	5.4	162	5.1	141*	6.2	234	5.2	132	5.0	136
NM	SAN AUGUSTIN PASS	32.26	-106.33	1859	801101	820930	45.7	9.3	758*	12.8	1637*	11.2	1275	7.7	330	8.0	453
							30.0	8.1	569*	10.2	1165*	10.1	991*	6.9	268	7.2	380
							9.1	7.6	508*	7.8	581*	9.8	964*	6.5	253	7.2	416
NM	TUCUMCARI	35.08	-103.45	1354	801101	820831	45.7	8.6	518*	8.4	490*	9.0	597	8.6	490*	7.9	376*
							30.0	7.6	403*	7.3	366*	8.0	467	8.0	413*	6.8	267*
							9.1	6.4	254*	6.0	209*	6.5	262	7.0	312	5.5	147*
NY	MONTAUK POINT	41.03	-71.57	2	770101	820531	45.7	7.2	436	8.4	641	7.1	406	5.6	188*	7.2	418*
							18.2	6.2	309	7.6	500	6.1	275	4.7	116*	6.3	302*
NC	BOONE	36.14	-81.41	1347	761201	810531	76.2	8.0	562	9.9	1014*	8.3	568	6.4	264	7.5	437*
							18.2	6.1	314*	8.2	652*	6.2	301	4.6	114	5.3	194*
ND	FINLEY	47.31	-97.52	472	801001	820930	45.7	9.1	737	8.7	647	9.9	935*	8.9	678	9.2	752
							30.0	7.7	450*	7.7	423	8.1	570*	7.0	316*	8.4	547*
							9.1	6.1	234	6.0	217	6.8	317*	5.6	197	6.2	227
ND	MINOT	48.00	-101.18	675	801001	820930	45.7	8.4	533	8.3	529	8.9	633	7.5	398	9.0	596*
							30.0	7.8	439	7.5	413	8.5	549	7.1	325	8.2	487*
							9.1	6.5	271	6.1	244	7.2	359	6.3	238	6.5	251*
OK	FORT SILL	34.39	-98.27	366	800901	811231	45.7	9.3	706#	8.8	582*	10.6	973*	-99.9	-999	8.8	641*
							30.0	6.6	316*	6.0	244*	6.9	359	5.7	229*	7.2	375*
							9.1	5.6	212#	4.7	148*	7.0	393*	-99.9	-999	5.9	210*
OR	BOARDMAN	47.41	-119.50	212	781001	810930	70.1	5.5	278	3.9	167	6.6	383	7.0	400	4.6	181
							39.6	5.0	206	3.4	112	6.0	275	6.3	296	4.1	134
							9.1	3.8	102	2.6	56	4.8	165	4.7	136	3.1	55
PR	CULEBRA	18.20	-65.19	80	770301	820531	45.7	7.0	291*	7.0	298*	7.1	311	7.7	343*	6.3	203*
							9.1	6.2	208	6.1	207*	6.1	215	6.8	244	5.6	158
RI	BLOCK ISLAND	41.11	-71.34	14	761201	820623	45.7	7.4	407	8.4	586	7.5	399*	6.2	224	7.4	388
							9.1	5.0	133	5.7	203	5.0	128*	4.0	65	4.9	122
SD	HURON	44.24	-98.09	396	761201	820930	45.7	6.8	332	6.8	358	7.2	387	6.2	234	6.9	352
							9.1	4.7	131	4.7	141	5.2	161	4.3	91	4.7	128
TX	AMARILLO	35.17	-101.45	1091	770301	810930	45.7	8.1	464	7.7	398	8.6	532	8.3	475	7.8	428
							9.1	6.3	228	6.1	221	6.8	274	6.1	190	6.0	225
VT	STRATTON MT.	43.05	-73.56	1183	810101	811231	45.7	11.4	1305#	-99.9	-999	-99.9	-999	-99.9	-999	9.9	944*
							30.0	9.4	855#	-99.9	-999	-99.9	-999	-99.9	-999	-99.9	-999
							9.1	6.2	215#	-99.9	-999	-99.9	-999	5.6	150*	6.9	277*
WA	AUGPURGER MT.	45.44	-121.41	853	761201	780131	45.7	8.7	631*	7.8	543*	9.0	654*	10.1	867	7.8	426
							9.1	6.9	322*	6.3	289*	7.1	339*	9.1	597*	6.5	241
WA	DIABLO DAM	48.43	-121.07	500	801201	820630	45.7	5.1	159	4.4	101	5.1	153	6.6	278	4.9	134

							30.0	3.7	78*	3.4	55*	3.9	84*	4.4	109	3.2	54
							9.1	1.7	5*	2.1	10*	1.6	3	1.7	4	1.3	1
WA	GOODNOE HILLS	45.47	-120.33	805	800701	820430	105.1	7.1	403*	7.5	509*	7.3	366*	7.8	480*	6.4	320
							60.9	6.7	340*	6.9	408*	7.3	350*	7.8	444*	5.9	254
							15.2	5.4	173*	5.4	196*	5.7	164*	6.4	229*	5.0	142
WY	BRIDGER BUTTE	41.17	-110.29	2290	800901	820930	45.7	8.4	589	9.4	821*	8.5	570	7.4	396	8.4	629
							30.0	8.2	542	9.1	737*	8.3	525	7.4	392	8.2	575
							9.1	7.0	371	7.7	467*	7.3	376	6.4	272	7.0	398

* Mean wind speed and power are based on less than 75% data recovery for the period.

Annual wind speed and power are based on less than four full seasons data.

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