**Wind Energy Resource Atlas:
Volume 12 -
Puerto Rico and U.S. Virgin Islands**

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WIND ENERGY RESOURCE ATLAS:

VOLUME 12 - Puerto Rico and U.S. Virgin Islands

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PREFACE

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

This atlas of the wind energy resource is composed of introductory and background information, a regional summary of the wind resource, and assessments of the wind resource in two subregions (Puerto Rico and the U.S. Virgin Islands). Chapter 1 provides background on how the wind resource is assessed and on how the results of the assessment should be interpreted. A description of the wind resource on a regional scale is then given in Chapter 2. The results of the wind energy assessments for both subregions are assembled in this chapter into an overview and summary of the various features of the regional wind energy resource. Chapter 3 provides an introduction and outline to the descriptions of the wind resource for the subregions that are presented in Chapters 4 and 5. The subregional wind energy resource is described in greater detail than is the regional wind energy resource, and features of selected stations are discussed. This preface outlines the use and interpretation of the information found in the subregional chapters.

Much of the information in Chapters 4 and 5 is given in graphic or tabular form. As is discussed in Section 3.1, the sequence of maps, tables, and graphs is the same in both chapters. References to these figures and tables are made here with an asterisk (*) in place of the chapter number (e.g., Figure *.1, Table *.2). Similar maps and tables are found in Chapter 2 on the regional wind resource. References to the regional maps and tables are made in brackets, [].

Figure *.1 shows the major geographical (mountains, rivers) and cultural (cities, towns) features in both subregions. [Figure 2.1 identifies the islands in the region.] Figure *.2 portrays their topography in shaded relief. The shaded relief allows the reader to visualize the character of the terrain surrounding locations of special interest. Superimposed on these subregional maps (but not the regional maps) is a grid of dashed lines one-eighth degree (74') longitude by one-eighth degree (74') latitude. This grid is repeated on nearly all subsequent maps to give the reader an adequate frame of reference for locating the same feature on different maps.

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

Figure *.4 identifies and locates wind data sites relevant to the assessment. All locations in the subregions for which the National Climatic Center (NCC) has wind data in its archives are shown and named in Figure *.4. However, this assessment is based on NCC data augmented by data from other sources (see Sections 1.1 and 1.2). Therefore data from

other sources are also identified and located on Figure *.4. Sections 1.3 through 1.5 briefly describe the methods used to analyze the wind data and evaluate the wind power. One of these methods is extrapolation of free-air speeds to exposed mountain tops. Figure *.5 shows the free-air profiles used to perform this extrapolation.

The wind energy resource for Puerto Rico and the U.S. Virgin Islands is illustrated using several maps. The wind power maps represent a careful synthesis of quantitative wind data guided by state-of-the-art concepts on air flow near the earth's surface. Section 1.6 describes how the analysis of the wind data is transformed into the map of annual average wind power density found in Figure *.6 [Figure 2.21]. This map gives the annual average wind power density at typically exposed sites. A discussion of the classes of wind power density in Section 1.7 gives the relationship between mean wind power density (watts/m^2) and mean wind speed (m/s or mph).

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

The terrain feature with typical good exposure to the wind in a particular land-surface form provides a convenient and essential reference point on which to base the analyses of the wind resource shown in Figure *.6. However, a substantial portion of the terrain may have poorer than typical exposure to the wind and will have a lower wind resource than shown on the wind power maps. The maps of Figures *.8 through *.11 provide an estimate of the percentage of area in each grid cell that may experience at least each of four different wind power classes. Section 1.10 discusses the assumptions underlying the evaluation of the areal distribution of the wind resource. The area of Puerto Rico and the U.S. Virgin Islands estimated to experience a particular wind power class is given in Table *.1 [Table 2.2]. This table summarizes the contribution made by each grid cell to the areal distribution of wind power for both subregions.

The annual average wind power density compresses into a single statistic time-varying trends on several time scales, e.g., annual, seasonal, monthly, and daily. In this atlas, the seasonal evolution of the geographical distribution of wind power is shown at the sub-regional level. The maps of Figures *.12 through *.15 give the average wind power density for winter, spring, summer, and autumn. The interpretation of the seasonal average wind power maps is identical to that for the annual average wind power map. [For the entire region, Figure 2.3 shows only the season of maximum power.]

Additional information on the time variation and other characteristics of the wind resource in both subregions is presented for selected locations for which the National Climatic Center placed 1-hourly or 3-hourly time-series data on magnetic tape. Descriptions of the characteristics of the wind resource presented for these stations are given in Section 3.2. The urge to consider information pertaining to one of these sites as representative of some other location must be tempered with the realization that wind characteristics are extremely

site-dependent. The degree of correspondence between the wind characteristics at one site and those at another site depends on the similarity between the topographical setting of the sites, the weather patterns that affect the sites and the obstructions to the wind in the vicinity of the sites.

Table *.2 identifies the stations, and gives their location (see also Figure *.4) and annual average wind speed and power density. Figure *.16 shows how the yearly mean speed and power varied during the period of record. The monthly mean wind speed and power over the course of a year are shown in Figure *.17. The hourly mean wind speed over the course of a day is shown in Figure *.18 with a separate curve for each season. Figures *.17 and *.18 indicate the time of year and time of day, respectively, when the wind resource is available. Figure *.16, on the other hand, indicates the year-to-year variability that might be expected in the yearly mean resource.

The frequency of occurrence of winds from a particular direction and of winds with a particular speed is shown in Figures *.19 and *.20, respectively. The information on wind direction may be important in assessing the availability of the wind resource relative to surrounding terrain or nearby obstructions. However, it is also important to realize that the wind direction statistics are highly dependent on the location of the instrument site relative to obstructions and major terrain features, e.g., valleys, ridges, and mountain ranges.

Figures *.21 and *.22 portray speed and power frequency statistics in the form of speed and power exceedance curves, respectively. The fraction of the total period of record that the speed equals or exceeds a given value is shown in Figure *.21. The power exceedance curve in Figure *.22 gives the fraction of the period of record for which the power exceeds a given value.

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

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CHAPTER 1: REGIONAL WIND ENERGY RESOURCE ASSESSMENT

Rapid development of wind as a source of commercial electric power is the principal goal of the Federal Wind Energy Program. Utility planning, wind turbine manufacturing and marketing of wind energy conversion systems all depend on detailed wind resource assessments. This atlas of the Puerto Rico/U.S. Virgin Island wind resource, a product of the Wind Characteristics Program Element of the Federal Wind Energy Program, is a portion of the information for meeting these various needs.

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

The Puerto Rico/U.S. Virgin Island atlas assimilates three collections of wind resource data: one for the region as a whole and one each for both the Commonwealth of Puerto Rico and the U.S. Virgin Islands. For the two subregions, features of the climate, topography and wind resource are discussed in greater detail than is provided in the regional discussion, and the data locations on which the assessment is based are mapped. Variations, over several time scales, in the wind resource at selected stations in both subregions are shown on graphs of monthly average and interannual wind speed and power, and hourly average wind speed for each season. Other graphs present speed, direction and duration frequencies of the wind at these locations.

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

FIGURE 1-1. Geographic Divisions for Regional Wind Energy Assessments

1.1 IDENTIFICATION OF WIND DATA SOURCES

The surface wind data on which this assessment has been based were obtained from several sources: the National Climatic Center (NCC), a DOE wind turbine site, and governmental and private organizations. The National Climatic Center offers the largest collection of wind data. Surveys and indices of wind data archived at the NCC (Changery 1975, 1978; Changery et al. 1977) are extremely helpful in locating available wind data. The Index of Original Surface Weather Records, published by the NCC for each individual state and for U.S. possessions, provides additional information about stations at which wind data have been taken.

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

TABLE 1.1 - Stations With Wind Data in the Puerto Rico/U.S. Virgin Island Region Used in the Assessment

Source and Type	Number
National Climatic Center	
• Digitized	6
• Summarized	1
• Unsummarized	8
Power Plants/ Industrial Sites	3
DOE Wind Turbine Sites	1
Upper Air Stations	2
Other	1

Conventional NCC surface weather data were supplemented by surface wind analyses for two areas of the Caribbean (Naval Weather Service Detachment 1974), monthly mean 1500 m wind summaries for two sites in the region (Winds Aloft Summaries, NCC 1970), and upper-air wind climatology compiled by Crutcher (1959) for the northern hemisphere.

1.2 WIND DATA SCREENING

Due to the paucity and sparseness of wind data stations in the Puerto Rico/U.S. Virgin Island region, all wind data obtained (see Table 1.1) were used in the analysis. When stations had both summarized and digitized data, the digitized data were used for selected stations to prepare a more extensive characterization of the wind resource. When more than one type of summary (see Changery et al. 1977) was available for a given station, the summary covering the longest period of record with constant anemometer height and location, with the greatest number of wind speed and direction classes, and with the highest frequency of daily observations was generally chosen.

1.3 TIME SCALES IN REGIONAL ASSESSMENTS

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

The four seasons are defined as:

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

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

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

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

1.4 EVALUATION OF WIND DATA

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

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

where

n = the number of observations in the averaging period

ρ_i = the density (in kg/m³) computed from the station pressure and temperature

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

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

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

where

$\bar{\rho}$ = the mean air density

c = the number of wind speed classes

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

v_j = the median wind speed of the j th class.

In those cases for which unsummarized wind data were assessed, the seasonal and annual average speeds, $\bar{V}$, were calculated using at least one year's original weather records. The wind power density, $\bar{P}$, was then roughly estimated by assuming that the speed frequency distribution was a Rayleigh distribution (Cliff 1977):

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

The Rayleigh wind power density estimate was then adjusted using Equation (5) and estimating Weibull shape factors (k).

1.4.1 Vertical Adjustment

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

$$\frac{\bar{v}_r}{\bar{v}_a} = \left(\frac{z_r}{z_a} \right)^\alpha \quad \text{or} \quad \frac{\bar{P}_r}{\bar{P}_a} = \left(\frac{z_r}{z_a} \right)^{3\alpha} \quad (4)$$

where

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

α = the power law exponent.

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

1.4.2 Estimates for Mountainous Areas

The 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 winds aloft summaries (NCC 1970). Since earlier studies had shown a strong correlation between mountain-top and free-air wind speeds (Wahl 1966), 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 (see Figures 4.5 and 5.5). Estimates of average wind speeds were made for the mean mountain-top/ridge-crest elevations within each one-eighth degree 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.

Cherry (1980) showed that the ratio of wind power computed from a Rayleigh distribution to that from a Weibull distribution having the same mean is given by

$$R = (k-1)^{-0.494} \quad (5)$$

where

R = the ratio of Weibull power to Rayleigh power

k = the Weibull shape factor.

At typical "k" values observed in the trade-wind regimes, this technique results in a 10 to 30% reduction in available wind power estimates.

After making the above correction, the mean wind power at the 10 m and 50 m reference heights was assumed to be one-third and two-thirds of the free-air values respectively, to account for frictional slowing of the wind near the surface.

Though these estimates are considered to be lower limits for exposed ridges and mountain tops, local terrain features may enhance the wind power. However, there is much uncertainty in these estimates of wind power because no surface data from ridge crests were used in this analysis and because of the possible disruptive effects on airflow of orographic convection (Malkus 1955).

1.5 QUALITATIVE WIND INDICATORS

Nearly all of the stations used in the Puerto Rico/U.S. Virgin Island wind resource assessment are at coastal locations. The main island of Puerto Rico is ringed with data; the Virgin Islands' wind data are from airports on the leeward sides of two islands. Several islands had no data at all. Since no data were located and used for the mountainous interior of the larger islands, it was necessary to use a combination of topographical and meteorological indicators (Elliott 1979a) in these data-sparse areas. The features in the region indicative of high mean wind speeds are:

- coastal locations exposed to the prevailing easterlies

- exposed ridges and mountain summits
- gaps and passes parallel to the wind flow.

Other topographical indicators of strong winds discussed by Elliott (1979a) do not occur in the region.

Features that indicate low mean wind speeds are:

- sheltered valleys or basins
- short/narrow valleys perpendicular to the tradewinds
- areas of high surface roughness (sub-urban areas, forested hilly terrain).

Other techniques for identifying areas of high average winds, such as eolian land forms (Marrs and Gaylord 1979) and wind-deformed vegetation (Hewson et al. 1978, 1979) were not used. Very few eolian landforms indicative of strong winds exist, and these are near areas for which quantitative wind data are available. Wind-deformed vegetation exists at some locations, but it was neither possible to make a complete survey of the region, nor to relate quantitatively the deformation to mean wind speed.

1.6 WIND POWER MAPS

The production of mean wind power density maps, such as those presented for both subregions, depended on the coherent synthesis of several pieces of information. The goal of the synthesis process was to present wind power density values representative of sites well exposed to the prevailing strong winds. Hilltops, ridge crests, mountain summits, large clearings, exposed coastal locations and other locations free of local obstructions to the wind are expected to have good exposure to the wind (see Table 1.2). In contrast, locations in narrow valleys and canyons, downwind of hills and obstructions, or in forested or urban areas are likely to have poor exposure. The wind power density shown on the maps in this atlas will not be representative of poorly exposed locations. Estimates for ridge crests and summits (the shaded areas on the maps) are lower limits to the wind power expected at exposed sites. In such areas, local terrain features can enhance the wind power considerably (Wegley et al. 1980). By specifying the type of wind exposure to which the map values of wind power pertain, we avoid the ambiguity that typical-location or average-for-the-terrain values might introduce. In this atlas, the terms-wind energy, wind power and wind power density are used synonymously.

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

1.7 WIND POWER DENSITY CLASSES

The analysis of wind power maps departs from conventional isopleth analyses by showing the boundaries of wind power density classes. Each wind power class represents the range of wind power densities likely to be encountered at exposed sites within an area designated as having that wind power class. Table 1.3 gives the power density limits for the wind power classes used in the atlas for the 10-m (33-ft) and 50-m (164-ft) reference levels. As a convenience for the reader, the definitions of the wind power density classes are repeated with the annual wind power map for the region and for both Puerto Rico and the U.S. Virgin Islands.

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

1.8 CLASSES OF LAND-SURFACE FORM

The physical characteristics of the land-surface form affect the number of wind turbines that can be sited in exposed

places. For example, over 90% of the land area in a flat plain may be favorably exposed to the wind, whereas in mountainous terrain only the ridge crests and passes, which may be only a small percentage (<5%) of the land area, may represent exposed sites. The map of classes of land-surface form by Hammond (1964) provided information used to classify land-surface form in the Puerto Rico/U.S. Virgin Island region.^(a) Several characteristics coded by Hammond are:

- percentage of land area occupied by surfaces of gentle inclination (less than 8% slope)
- local relief, the maximum difference in elevation within a unit square 6 miles across
- percentage of gently inclined surfaces that lie in the lower half of the local relief
- land area covered by sand, ice, and standing water
- pattern of major crests, peaks, and escarpments.

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

For each land-surface form, the percentage of land area that is representative of well exposed, moderately exposed, and poorly exposed sites has been estimated using the average for the land-surface forms in the Northwest region (Elliott and Barchet 1980b). These percentages were determined subjectively as a function of the slope, local relief, and profile type. Table 1.2 gives the average percentage of land area that is designated as exposed terrain for the different classes of land-surface form. For simplicity, the percentages shown for each class of land-surface form have been

(a) The land-surface form maps shown for Puerto Rico and the U.S. Virgin Islands were developed by the author using detailed topographic maps and the criteria described in this section.

averaged over the range of categories in local relief and profile type found in the region. For example, the 27% for open hills is an average for C2 through C4. The average percentage of land area that is designated as exposed terrain ranges from 93% in smooth plains to 3% in mountainous areas where the exposed areas are usually the ridge crests and mountain summits.

1.9 CERTAINTY RATING

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

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

A certainty rating from 1 (low) to 4 (high) of the wind energy resource estimate has been made for each cell of a one-eighth degree latitude by one-eighth degree longitude by considering the influence of the above three factors on the certainty of the estimate of the wind power class for each cell. The definitions for the certainty ratings are adopted from those used by Voelker et al. (1979) in a resource assessment of U.S. Forest Service tracts. The certainty ratings for the wind resource assessment are defined as follows:

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: <ol style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	A low-intermediate degree of certainty. One of the following conditions exists:

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

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

1.10 AREAL DISTRIBUTION OF THE WIND RESOURCE

As noted above, the wind power density class values shown on the maps apply only to sites well exposed to the wind. Therefore, the map area designated as having a particular wind power class does not indicate the true land area experiencing this wind power. Instead, there is a complicated and difficult-to-quantify relationship among the class of land-surface form, the land surface area and the map value of wind power density. For each land-surface form, the fraction of land area that would be favorably exposed to the winds, i.e., have the wind power density indicated on the map, was estimated (see Table 1.2 for averages in various land-surface forms).

Furthermore, to be able to establish a wind power density for the remaining area, it was also necessary to specify a factor by which the wind power shown on the map is reduced in the less-exposed areas. As an additional complication, some land-surface forms, isolated hills and ridges that rise above a nearly flat landscape may even experience a higher power density than the map indicates.

To accommodate these various situations, the land area represented by a given land-surface form was divided into four exposure categories: 1) better exposure than typical for the terrain, 2) exposure typical for that land-surface form, 3) partially sheltered exposure, and 4) very sheltered exposure. The partitioning of the land-surface forms into the four categories was based on the work of Elliott and Barchet (1980b).

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

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

and by scaling the wind power class to each category, the contribution of that cell to the areal distribution was determined.

A cell-by-cell representation of the areal distribution is given in a map that indicates the percentage land area in a cell over which the wind power class equals or exceeds a threshold value. Four areal distribution maps are shown in Chapters 4 and 5 for threshold values of classes 2, 3, 4 and 5.

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

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

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

Land-Surface Form	Exposed Feature (Map Value)	Percentage Area ^(a)
Plains: A1; B1,2	Plains	93
Plains With Hills: A, B3a,b	Open Plains	79
Plains With Mountains: B4-6a,b	Plains (not shaded) ^(b)	67
	Ridge Crests and Mountain Summits (shaded)	10
Tablelands: B3-6c,d	Tablelands, Uplands ^(c)	80
Open Hills: C2-4	Hilltops and Uplands ^(c)	27
Open Mountains: C5-6	Broad Valleys (not shaded)	80
	Ridge Crests and Mountain Summits (shaded) ^(c)	12
Hills: D3-4	Hilltops and Uplands	9
Mountains: D5-6	Ridge Crests and Mountain Summits (shaded)	3

^(a)Percentage represents an average over the land-surface forms found in the Northwest region (Elliott and Barchet 1980b).

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

^(c)Due to the small size of the islands and their rugged terrain, tablelands and open mountains are not found in the Puerto Rico/U.S. Virgin Island region.

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

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

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

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

TABLE 1.4. Scheme of Classification

Slope (1st item)

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

Local Relief (2nd item)

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

Profile Type (3rd item)

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

CHAPTER 2: REGIONAL FEATURES

In this chapter, the geography, climate, annual average wind power and seasonal variations in the wind power are described for the Puerto Rico/U.S. Virgin Island region. Assessments of the wind resource for both subregions were performed using the methods described in Chapter 1. These assessments were then combined to depict the wind energy potential for the entire region. Areas in the region that are estimated to have the greatest wind resource are also described in this chapter.

2.1 GEOGRAPHY AND TOPOGRAPHY

The Puerto Rico/U.S. 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 Figure 2.1). 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 islands are located at about 18° north latitude and extend from 64½° to 68° west longitude (slightly farther east than the state of Maine). This region totals slightly more than 9,100 km² (3,570 mi²), which makes it a little smaller than the state of Connecticut. The region had a population of approximately 2,775,000 in 1970 (see Table 2.1). Nearly 98% of the population of the region resides in Puerto Rico; about 20% of Puerto Rico's population lives in the city of San Juan, located on the island's northern coast. The second largest population center is the city of Ponce (pop. 160,000) on the southern coast. The region's major cities, rivers, mountain ranges and parks are shown in Figures 4.1 and 5.1.

TABLE 2.1. Land Area and Population of the Puerto Rico/U.S. Virgin Island Region

Island	Area		Population (1970)	Population Density	
	km ²	mi ²		Per km ²	Per mi ²
Puerto Rico	8,554	3,353	2,758,000	322	823
Vieques	133	52	8,000	60	160
Mona	51	20	(a)	(a)	(a)
Culebra	26	10	900	35	90
St. Thomas	82	32	31,867	389	996
St. Croix	214	84	29,246	137	348
St. John	48	19	1,689	35	89

(a) Not permanently inhabited.

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 ringing the central mountain range occupies about 37% of the island's area. In the north-central region of Puerto Rico, a wind and water-eroded limestone plateau has produced an area stippled with conical hills called mogotes. The interior of Puerto Rico consists of mountainous terrain of high local relief (see Figures 4.2 and 4.3). This range of mountains, comprising 36% of the land area, runs east and west and is called the Cordillera Central. The highest peak is Cerro de Punta, 1,338 m (4,389 ft). To the east of the main island are the hilly islands of Culebra and Vieques. Sixty-five km (40 mi) to the west lies the plateau-like island of Mona.

The three main U.S. 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 (see Figures 5.2 and 5.3).

2.2 CLIMATE

The climate of Puerto Rico and the U.S. Virgin Islands is produced by the interaction of the trade winds with the topography combined with periodic disturbances to the mean easterly flow. Such disturbances include easterly waves, tropical storms and frontal passages (the remnants of mid-latitude cold fronts). The interruption of the trades by the mountains produces a variety of micro-climates, especially on the main island of Puerto Rico. Here the upslope flow on the east end of the island produces the El Yunque rain forest, where 450 cm (180 in.) of rain fall annually. Annual precipitation ranges from 229 cm (90 in.) in the central mountains to less than 76 cm (30 in.) on the semi-arid west and southwest coasts (Wagenheim 1970). Rainfall in the U.S. Virgin Islands, while averaging about 127 cm (50 in.), varies with topography. It is generally greatest on the windward (east and northeast) slopes of the larger islands. Precipitation shows some seasonal variation with a maximum in late summer and a minimum in late winter.

At sea-level locations mean annual temperature is nearly uniform at 26°C (79°F) throughout the entire region. However, different diurnal temperature patterns are caused by the topography. For example, the average daily temperature range in the mountains and along the west coast of Puerto Rico is about 13°C (24°F), while along the north coast (which is more exposed to the trades) the daily range is only 6°C (10°F).

The contrast between the north coast and the west coast can be explained by land-sea breeze effects. The sea breeze at the west end of the island (which is the leeward end), must overcome the trade winds before it can move inland. This delays formation of the sea breeze until late afternoon, allowing the land to warm for most of the day. On the windward east end of the island, the sea breeze reinforces the trades, permitting onshore flow to develop earlier in the day and thus moderating temperatures.

The temperature range varies little from season to season at a particular location, but the warmest temperatures generally occur in September and the coolest in February (Riehl 1954). Both extremes lag about 60 days behind the maximum and minimum sun angles and are coincidental with the maximum and minimum sea-surface temperatures. The temperature extremes for the region are 39°C (103°F) recorded on the south coast of Puerto Rico and 4°C (39°F) observed in the Puerto Rican mountains during winter.

Average maximum temperatures at San Juan, Puerto Rico, are 30°C (86°F) in the summer and 27°C (80°F) in the winter. Minima average 24°C (75°F) in summer and 21°C (69°F) in winter. The San Juan temperatures are typical of the windward portions of Puerto Rico and of the coasts of the smaller islands. In the mountains maximum temperatures average 32°C (89°F) in summer and 28°C (83°F) in winter, while minima average 19°C (66°F) in summer and 15°C (59°F) in winter (Riehl 1954).

2.3 WIND POWER IN THE PUERTO RICO/U.S VIRGIN ISLAND REGION

The annual average wind power density for Puerto Rico and the U.S. Virgin Islands is shown in Figure 2.2. The analyses of average wind power density apply only to terrain features that are favorably exposed to the prevailing wind. Exposed features include mountain tops, ridge crests, hill-tops, and exposed coastal locations such as points and capes (see Section 1.6). However nearby terrain features or meteorological phenomena (such as convection) may interact with the prevailing winds to vary the wind power at some exposed sites as

much as + 50% from the analyzed value. [See Wegley et al. (1980) for more information on the effects of terrain features upon the wind flow]. In forested areas the assessment values are representative of large clearings or of sites on towers located 30 ft or more above the vegetation. The percentage of land area favorably exposed to the wind depends strongly upon the land-surface forms, which are depicted in Figures 4.3 and 5.3.

High wind resource areas (class 4 and above) can be found on the main island of Puerto Rico and all three main U.S. Virgin Islands. In general, these areas are confined to exposed ridge crests, the shoulders of such ridges, and to the exposed coastal locations on the windward sides of the islands. Further description of these areas follows in Section 2.5. For more complete discussions of the wind power in Puerto Rico and the U.S. Virgin Islands refer to Chapters 4 and 5, respectively.

2.3.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power resource were assigned to each grid cell as described in Section 1.9. Maps of certainty rating for the two subregions accompany descriptions of that subregion's resource (Chapters 4 and 5). Though possible certainty ratings range from a high of 4 to a low of 1, no areas in the region were assigned a certainty of 4. This is because of the sparseness of the data, the scarcity of high quality data at exposed locations and the complexity of the terrain. The structure of the trade winds themselves is fairly well understood. This fact coupled with the concentration of wind data along the coasts led to the assignment of a high-intermediate certainty rating (3) along portions of the coasts of Puerto Rico and other islands having wind data. The general understanding of the trades permitted the assignment of a certainty rating of 2 on the smaller islands even where little or no quantitative wind data exist.

Though much research has been directed toward gaining an understanding of the trade winds, much less is known about the interaction between the trades and small mountainous islands. Meteorological phenomena such as the orographic convection cells over Puerto Rico observed by Malkus (1955) cause much uncertainty as to what wind speeds actually occur near the surface of exposed mountains and ridges. Consequently, the mountainous interior, which has very little quantitative wind data, has been assigned the lowest certainty rating.

2.3.2 Areal Distribution

Through the superposition of a grid one-eighth degree longitude by one-eighth degree latitude over the region, the areal distribution of wind power can be computed as described in Section 1.10. Of the 224 grid cells into which the region was divided, only two cells have class 4 annual wind power. These are both located on the main island of Puerto Rico, one on a mountain peak, the other on a well-exposed cape. During the season of maximum power (generally summer) considerably more land area falls in the class 4 or greater wind power class (see Figures 4.8 and 5.8).

Though 38 of the grid cells are depicted as having class 3 wind power, most of these are either in rugged terrain or in coastal areas having mostly water within the grid cell. Therefore, only about 4% of the total land area actually has class 3 wind power (see Figures 4.8 and 5.8 for more detail).

The land area estimated to have low, class 1, wind power density is about 75%, which is considerably more than is suggested by Figure 4.2. This leaves about 21% of the total land area of the region in power class 2.

Table 2.2 summarizes the results of the computation of the areal distribution for the Puerto Rico/U.S. Virgin Island region. The subjectivity underlying the assignment of exposure partitioning and power scaling warrants reporting the areas and percentages to no more than one decimal place (see Section 1.10). Thus, due to rounding off, individual areas and percentages may not sum to their stated totals.

2.4 SEASONAL VARIATIONS IN THE WIND RESOURCE

The southwest Atlantic trade winds are best developed during the summer months, June through August. This is indicated by a pronounced summer maximum in raw and gale wind speeds at San Juan and on St. Croix (NCC 1970 and Stone 1942), and by summer maxima at most coastal stations in Puerto Rico and the Virgin Islands. However, there is a secondary maximum during the winter (December through February) both at the surface and aloft. As indicated in Figure 2.3, the central mountains and northern coastal plains of Puerto Rico, all of the U.S. Virgin Islands, and all the smaller islands appear to have wind power maxima in the summer.

The interaction of topography and solar heating with the trade winds produces some exceptions to the summer wind maxima. Exposed sites on the northeast and southeast

corners of Puerto Rico appear to have slightly stronger winds in winter. This is due partly to weaker land breezes opposing the trades during winter nights. In addition the trades shift more northeasterly, thus more perpendicular to the coast, and they continue to blow at speeds only slightly less than during the summer.

On the west end of Puerto Rico the summer onshore flow is often well developed by mid to late afternoon. Since this flow directly opposes the trades, daytime easterly winds are reduced in speed, or they are overcome for a short while as the onshore flow develops. But during the winter, the sea breeze is not as strong, and is usually overridden by the prevailing easterlies. Consequently, the summer wind power is less on the west end of the island, resulting in a winter wind power maximum.

The spring maximum shown on the south coast of Puerto Rico, though based only on limited data, does appear to exist. The sea breeze here provides most of the wind power. The trades make a smaller contribution to the wind power due to the sheltering effects of the mountains to the north and the southerly acceleration produced by the land-sea thermal gradient during the day. The springtime maximum in wind power is produced by stronger and longer lasting sea breezes. In the spring, land-sea temperature differences are at a maximum. The temperature differential produces stronger sea breezes along the southern coast as far east as Guayama. The strength and regularity of the sea breeze may enhance the value of wind power on the south coast far above what would normally be expected at a low annual wind power (class 1) site.

2.5 MAJOR WIND RESOURCE AREAS

The major areas of the Puerto Rico/U.S. Virgin Island region having annual average wind power of class 3 or higher are briefly described in this section. More details are provided in Chapters 4 and 5. For locations of place names, refer to the geographical maps (Figures 4.1 and 5.1).

2.5.1 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 (northeast) coasts of Culebra, Vieques and Mona. 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. Here, the mean wind speed slightly exceeds that of the mean

trade wind flow due to acceleration of the flow during the day as it approaches the heated island (Malkus 1955) and possible acceleration of the trades as they round the windward corner of the island. This type of acceleration has been observed in the Pacific trades on the Hawaiian Islands (Ramage 1979). The wind here 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. This analysis for the Puerto Rican mountains agrees fairly well with that of Poland and Krawitz (1979).

2.5.2 St. Thomas - Windward Coast and Central Ridge

Several islands lie offshore near the northern coast of St. Thomas, such as Hans Lollik Island. 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.

The central St. Thomas ridge extends from just north of Harry S. Truman Airport southeastward to the east end of the island. Several isolated peaks exceeding 300 m MSL (1000 ft) line the ridge. The ridge is oriented at about a 45-degree angle to the mean trade wind flow, thus ridge-type accelerations of the flow are reduced. It is estimated from upper-air data and meteorological reasoning that the north and south shoulders of the higher peaks as well as their summits have an annual average wind power density of class 4. Some of the slightly lower peaks, particularly on the northeastern side of the island, are estimated to have class 3 annual wind power.

2.5.3 St. Croix - Central Ridge and Exposed Coastal Locations

The central St. Croix ridge runs east-west the entire length of the island. Several saddles and valleys transect the ridge. The result is that class 3 wind power areas are located on several high hills (over 210 m or 700 ft MSL) along the ridgeline. 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, like an arrow, into the trade winds. This tip, the exposed points on the north and south coast, as well as Buck Island (near the northeast coast) are all estimated to have class 3 annual average wind power.

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

A ridgeline of approximately 300 m (1000 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. Since the ridge is nearly normal to the trade wind flow, terrain enhancement of the wind appears likely both over the ridge and at the north and south ends. The hills at the extreme east end of the island are a second area of high wind power (class 3) due to their exposure to the easterly flow and their elevation. There are a few high peaks of about 300 m (1000 ft) elevation near the west end of the island. However, the sheltering effects of the ridge upwind appear to reduce their wind power somewhat. The irregular coastline leaves many jutting points along the northeast, east, and southeast coasts. These should have annual wind energy densities near that of the mean surface flow (class 3).

FIGURE 2.1. Geographic Map of Puerto Rico and the U.S. Virgin Islands

FIGURE 2.2. Annual Average Wind Power in Puerto Rico and the U.S. Virgin Islands

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

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

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

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

TABLE 2.2. Areal Distribution of Wind Power Classes in Puerto Rico and the U.S. Virgin Islands

Power Class	Land Area (km ²) Equal or Exceeding Power Class		
	Entire Region	Puerto Rico	Virgin Islands
1	9,108	8,764	344
2	2,307	2,193	115
3	398	373	25
4	11	11	0(a)
5	5	5	0

Power Class	Percentage Land Area Equal or Exceeding Power Class		
	Entire Region	Puerto Rico	Virgin Islands
1	100.0	100.0	100.0
2	25.3	25.1	33.4
3	4.4	4.3	7.3
4	0.1	0.1	0.0(a)
5	0.1	0.1	0.0

(a) Comparison of these values with the annual wind power map for the U.S. Virgin Islands (Figure 2.2) seems to be contradictory because there are small areas of class 4 wind in the figure. The reader should interpret the zeros as very small areas (less than 1 km²) that are below the resolution of the areal distribution algorithm.

FIGURE 2.3. Seasonal Average Wind Power in Puerto Rico and the U.S. Virgin Islands

CHAPTER 3: SUBREGIONAL FEATURES

The wind resource for each subregion is described in Chapters 4 and 5. The text of each description is followed by maps, graphs and tables that identify features of the geography and the wind energy resource and summarize the data collected from the observation stations. The sequence of maps, tables and graphs used to depict these features is presented in Table 3.1. In Chapters 4 and 5, these illustrations are presented so that related information is on facing pages and can be viewed simultaneously.

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

3.1 MAPS OF SUBREGIONAL FEATURES

The maps of cultural geography show the locations of major cities, rivers and terrain features for both territories. The shaded topographic relief map of Puerto Rico is a reproduction of the 1:240,000 scale U.S. Geological Survey map. The shaded topographic relief map of the U.S. Virgin Islands was drawn from topographic

maps. Since land-surface form maps of an adequate scale were not available for Puerto Rico or the U.S. Virgin Islands, these maps were constructed, using Hammond's classification scheme (Hammond 1964). The use of the land-surface form map was described in Section 1.8.

In addition to the map showing the location of surface wind data stations used in the assessment, a figure is shown to present the upper-air wind profiles used for extrapolating free-air wind power to exposed mountain peaks and ridge summits. The method of extrapolation is described in Section 1.4.2.

The map of annual average wind power is accompanied by maps of the certainty rating of the estimated annual average wind power by grid cell, and of the areal distribution of the wind resource by grid cell. The certainty rating, which ranges from 1 (low) to 4 (high), indicates the level of confidence in the estimates of the wind resource in each cell of the grid. The certainty rating is based on the availability of wind data, the complexity of the terrain, and the inherent geographical variability of the wind resource (see Section 1.9). The

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

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

maps of areal distribution give the percentage of land area in each cell estimated to experience an annual average wind power class equal to or exceeding power classes 2, 3, 4, and 5 (see Section 1.10).

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

3.2 FEATURES OF SELECTED STATIONS

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

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

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

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

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

R - indicates the anemometer was located on the roof of a control tower, operations building, hangar or other similar structure. Normal mast heights were 2 to 4 m (6 to 12 ft) above roof line; however, many inner-city locations used considerably taller masts. The listed heights are elevation above ground level, not roof level; the "R" indicates an exposure type.

G - indicates the anemometer was located on a mast attached directly to the ground. Most anemometers at airport locations changed from a roof to ground exposure by the early 1960s.

B - indicates a beacon tower exposure. For these locations, neither R nor G was considered satisfactory.

UNK - indicates that documentation on instrument heights was not available.

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

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

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

3.2.1 Interannual Wind Power and Speed

The plots of interannual wind speed and power portray the variations of the yearly average over all periods of record. The beginning and ending of each period of record with constant anemometer height and location are designated by a "plus" symbol on the wind power curve and by a "diamond" symbol on the wind speed curve. If the anemometer height was unknown, a height of

10 m was assumed. Only yearly mean wind speeds based on 12 months' data (January through December) were plotted.

3.2.2 Monthly Average Wind Power and Speed

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

3.2.3 Diurnal Wind Speed by Season

The diurnal variation in wind speed according to season is plotted on graphs containing four curves, one for each season. Local standard time (LST) is used with hour 24 as midnight and hour 1 as the beginning hour. For National Weather Service and Federal Aviation Administration stations, the diurnal curves are based on 24 observations daily for periods ending before 1965, and on 8 observations daily for periods ending after 1964. For Air Force stations the diurnal curves are usually based on 24 observations daily regardless of the period. The diurnal curves for Navy stations are based on 24 observations daily for periods ending before March 1972 and on 8 observations for periods ending after February 1972.

3.2.4 Directional Frequency and Average Speed

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

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

3.2.5 Annual Average Wind Speed Frequency

Graphs of the annual average frequency of wind speeds are shown in 1 m/s intervals about each whole m/s wind speed. Along with the observed distribution, a Rayleigh wind speed distribution based on the annual mean speed is shown. Stations well exposed to the trades generally have a peaked distribution, with the peak occurring at, or near, the mean wind speed. However, other pronounced peaks in the distribution may reflect observer bias toward certain wind speeds, such as 2, 5, and 8 m/s (5, 10, and 15 knots). This bias occurs more frequently in records prior to 1960. Because many of the wind instruments used had a threshold velocity of about 1.5 m/s (3 knots), the frequency of observations in the 1 m/s class is often lower than the frequency of the calm and 2 m/s classes.

3.2.6 Annual Average Wind Speed and Power Duration

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

PUERTO RICO

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CHAPTER 4: PUERTO RICO

The Commonwealth of Puerto Rico includes the main island of Puerto Rico, the islands of Vieques, Mona, and Culebra, and several very small islands adjacent to the four larger islands (see Figure 4.1). The total land area is approximately 8,764 km² (3,435 mi²) and the commonwealth had a total population of 2,776,900 in 1970. Over 99% of the population resides on the main island of Puerto Rico, where the major population center is San Juan, on the northern coast. Other major cities are shown in Figure 4.1.

The interior of the island of Puerto Rico is mountainous. Here the local relief exceeds 300 m (1,000 ft) (see Figures 4.2 and 4.3). The central mountain range, Cordillera Central, has mountain peaks exceeding 1,000 m (3,200 ft) above sea level. The El Yunque rain forest in the northeast also has peaks exceeding 1,000 m. The coastal plain along the northern coast gives way to a karst region (an area dotted with conical hills) about 8 km (5 mi) inland. The narrow coastal plain on the south is of varying width and is bounded abruptly on the north by mountains. The islands of Vieques and Culebra are hilly, having a local relief of less than 300 m (1,000 ft). However, the island of Mona is more of a plateau; there is a 60 m (200 ft) cliff on the northern coast that tapers gradually down to near sea level on the southeastern coast.

Most of the wind data used in this analysis come from sites in the coastal plains ringing the perimeter of the main island of Puerto Rico (see Figure 4.4). However, few of these sites are well exposed to the prevailing trade winds. The interior of Puerto Rico has no wind stations at well-exposed mountain locations, and is nearly void of any wind data. Culebra is the only one of the outlying islands for which wind data were located and used in this assessment.

As described in Section 1.4.2, wind power over the mountains was estimated by extrapolating free-air wind speeds to exposed mountain tops. Figure 4.5 shows the profiles of wind speed and power density for Puerto Rico.

4.1 ANNUAL AVERAGE WIND POWER

The annual average wind power densities shown for Puerto Rico (Figure 4.6) tend to mask important variations of the wind on a seasonal/diurnal basis (see Section 4.3.3 for further discussion). However, most of the promising areas for wind energy are

indicated by a class 3 or greater wind power on the annual power map. The exposed coastal locations near Cape San Juan, on the northeastern corner of Puerto Rico, are the primary locations estimated to have class 4 annual average wind power. Here the good exposure to the prevailing easterlies, plus their enhancement by the sea breeze, produce persistent moderate winds. There may be a few other locations on the northern and eastern coasts of Puerto Rico where good exposure and terrain enhancement of the wind combine to produce class 4 wind power. Class 3 annual wind power appears to occur at exposed coastal locations on the northern, eastern and southeastern coasts of Puerto Rico, at exposed windward coastal locations and hilltops on all of the outlying islands, and at exposed mountain peaks and ridge summits in the interior of Puerto Rico.

The mean flow of the trade winds provides class 3 power in the vicinity of Puerto Rico; however, frictional slowing of the wind as it moves onshore produces mid to high class 2 wind power on the northern coast of Puerto Rico, on the less-exposed interior mountain tops, and in the interior of the smaller islands. The blocking effects of the island reduce the power to class 2 on the southern coast of Puerto Rico. Here much of the wind energy comes from the daytime sea breeze. The southern coastal plain and the western coast of Puerto Rico are sufficiently sheltered by mountains to reduce the annual wind power to class 1. Class 1 wind power also occurs in the lee (southwest coast) of all of the outlying islands due to blockage of the trade winds.

4.1.1 Certainty Rating of the Wind Resource

The wind power estimates for most of the perimeter of Puerto Rico have a certainty rating of 3 (see Figure 4.7) due to the quantity of wind data and the predictable nature of the trade winds near the coastlines. Exceptions are the southwestern coast, a portion of the southeastern coastline (near Guayama), and the eastern coast (near Roosevelt Roads). These three areas have been assigned ratings of 2 for the following reasons: the southwestern coast, though it has no wind data, has relatively simple terrain (a coastal plain); the southeastern coast has wind data in the vicinity (from Yabucoa^(a) and Point Tuna), but the terrain is complex; and the eastern coast has limited data (from Roosevelt Roads Naval Station) that may not represent exposed locations in that area.

(a) Yabucoa wind data were extracted from a report by Engineering-Science de Puerto Rico (1971).

Wind power in the entire mountainous interior of Puerto Rico has been assigned a certainty rating of 1. In this region, no wind data from exposed sites were used in the analysis. This fact, complicated by the interaction of the trades with the rugged terrain, frequent convection, and seasonal changes in the vertical profile of the trade wind, made the extrapolation of estimated free-air wind speeds to mountain tops and ridge summits tentative.

The outlying islands were assigned a certainty rating of 2 due to the lack of wind data used in the analysis. However, the island of Culebra was an exception. Here the U.S. Department of Energy (DOE) has a wind turbine site from which high quality data have been collected from a well-exposed tower for nearly 4 years. However, due to the hilly terrain, Culebra was assigned a certainty rating of 3.

4.1.2 Areal Distribution

The areal distribution of wind power in Puerto Rico is illustrated in Figure 4.8. The numbers identify the percentage area in each grid cell having wind power equaling or exceeding the given threshold value. Annual average wind power of class 5 or higher does not appear to occur in Puerto Rico, while class 4 or higher is shown to occur in only two grid cells. One of these is on the northeastern coast of Puerto Rico. This cell contains the well-exposed Cape San Juan. The other cell contains an exposed mountain peak in north-central Puerto Rico. The total land area within these two grid cells estimated to have class 4 or higher wind power is small. However, as is mentioned in Section 4.1, there may be additional specific sites having class 4 wind power. But, these are below the level of resolution of the areal distribution algorithm used in this analysis.

The section of Figure 4.8 depicting areas of Puerto Rico having at least class 3 wind power appears to lack continuity along the coastlines. Here the large variation of values between adjacent grid cells is due to the algorithm used to convert land-surface form into exposure categories (see Section 1.8).

In the northeastern and northwestern coastal regions of Puerto Rico, the 100% values for class 3 or greater wind power estimates are realistic. Here the small amount of land area in the grid cells, which are all on a well-exposed coastal plain, justifies the high percentages assigned. In the interior mountains of Puerto Rico, the percent land area per grid cell having at least class 3 wind power ranges only from 3 to 5% due to the rugged terrain. The hilly island of Culebra is

estimated to have 5 to 7% of its land area in class 3 wind power. Because only a narrow strip of well-exposed coastal area lies in the grid cell, the northeastern coast of Vieques appears to have 88% of the area in class 3 wind power. Once again, this is only a very small land area, about 20 km² (8 mi²).

Class 2 wind power seems to occur in 88 to 100% of the land area of the northern coastal plain of Puerto Rico, the northern coast of Vieques, and Mona. Over half of the land area in the hilly plains of the north-central interior of Puerto Rico shows annual average wind power of at least class 2. The mountainous interiors of Puerto Rico and Culebra show only 5 to 7% of the land having class 2 wind power. Sheltering from the prevailing winds, by either mountains or the island wake, produces class 1 wind power on the leeward sides of Puerto Rico (even in the westernmost mountains, see Figure 4.6) and the outlying islands.

4.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 4.9. The season of maximum wind power is generally summer throughout Puerto Rico. Exceptions are portions of the eastern and western coasts of the main island, which exhibit a slight winter maximum and the southern coast, which has a slight spring maximum. Autumn is the season of minimum wind power throughout this region.

4.2.1 Winter

The winter wind power patterns observed in Puerto Rico are governed by four primary factors. First, the trade wind profile changes so that the mean wind in the lower 1,500 m (5,000 ft) decreases, but the level of maximum wind drops to about 700 m (2,300 ft) as depicted in Figure 4.5, thereby reaching many of the higher mountain peaks and ridge summits. Second, the steadiness of the trades decreases; however, increased occurrences of strong winds result in an overall increase in available power. Third, the land-sea breeze cycles are less pronounced than in the warmer months because there is less solar heating. Also, the decrease in solar heating appears to suppress convection, and thereby increase the wind flow in the mountainous regions. Finally, the trade winds shift to a more northeasterly direction in response to the southward movement of the Atlantic subtropical high.

As a result of the factors mentioned above, class 4 wind power occurs on the higher peaks and ridges in the interior (see Figure 4.9). An apparent acceleration of the flow around the northeastern and

southeastern corners of Puerto Rico and sea breeze enhancement produce class 4 wind power at exposed coastal sites near Cape San Juan and Point Tuna (see Figure 4.4 for location of these wind stations).

Class 3 wind power is found on the lower mountains and ridges surrounding the Cordillera Central, Sierra Cayey, and Sierra de Luquillo. Class 3 wind power is also predominant at exposed sites along the entire northern coast of Puerto Rico, along the eastern coast (from Fajardo to Yabucoa) and on the north and east sides of the outlying islands.

As the air moves inland from the coastline, rapid frictional slowing occurs in the first kilometer, producing class 2 wind power along the northern coastal plain of the main island. The slightly sheltered mountains on the western and southwestern parts of Puerto Rico also appear to have class 2 wind power, as do the interior portions of the outlying islands.

Class 1 wind power occurs along the sheltered western coast, the southern and southwestern coastal plains, and in the hilly lowlands near Humacao and Caguas.

4.2.2 Spring

In the spring, the highest wind power in Puerto Rico is class 3 (see Figure 4.9). Class 3 wind power appears to occur at all exposed coastal sites on the northern, northeastern, and southeastern coasts of Puerto Rico. Class 3 wind power can also be expected on the windward (northeastern) cliffs of Mona.

Wind power at the higher elevations is influenced by the decreased upper air flow occurring in the spring (see Figure 4.5) and increased convection from greater solar heating. These factors reduce the wind power at exposed mountain locations from class 4 in winter to a low class 3 in spring.

Class 2 wind power can be found on all the outlying islands, except on their leeward sides, where only class 1 power is found. Class 2 power also appears to occur on the following coastal locations of Puerto Rico: the extreme northwestern coast, the central portion of the eastern coast and the entire southern coast.

Class 2 wind power can also be found at most exposed locations in the northern interior and the southeastern interior of Puerto Rico. Exceptions are the class 1 wind power areas along the western coast, the western and southwestern interior, and

the hilly lowlands extending inland from Humacao on the eastern coast.

Every wind station on the southern coast used in this assessment has a springtime maximum wind power. The strength and regularity of the sea breeze is the primary contributing factor. This regularity could enhance the economic value of wind power along the southern coast not only in the spring, but also in summer and early autumn, because a daytime power demand would be matched very well by the observed diurnal land-sea breeze pattern.

4.2.3 Summer

In the summer the trade winds are well developed throughout the lower atmosphere (see Figure 4.5), 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. Class 3 wind power is found at some exposed locations on the southern and southeastern coasts of Puerto Rico and in much of the mountainous interior. Class 2 wind power appears to exist along most of the southern coast and in the hilly lowlands near Humacao and Caguas.

Class 1 wind power occurs mainly along the western coast, near Mayaguez. Here the sea breeze directly opposes the trade winds during most of the day. Class 1 power also occurs in the southern interior of Puerto Rico where poor exposure to the trades and blocking by the mountains to the northeast reduce the winds.

4.2.4 Autumn

In the autumn there is a noticeable decrease in the strength of the trade winds throughout the lower atmosphere (see Figure 4.5). In addition, sea-land temperature differences are less, thus reducing the sea breeze on the main island. These factors combine to make autumn the season of minimum power throughout the commonwealth. Only Cape San Juan, due to its excellent exposure, experiences class 3 wind power. Well-exposed locations on the four corners of Puerto Rico and the windward sides of the outlying islands appear to have class 2 wind power. The decrease in the winds aloft reduces the wind power to class 2 at exposed mountain locations in the Puerto Rican interior and on the hills of Culebra and Vieques. All other parts of Puerto Rico offer only class 1 wind power during autumn.

4.3 FEATURES OF SELECTED STATIONS

Table 4.2 gives the location and annual wind speed and power of four stations in Puerto Rico for which digitized wind data are available. Because these data are digitized, they are summarized graphically to show various features of the wind resource at the stations (see Figures 4.10 to 4.16). The four stations, all on the main island of Puerto Rico, are near the northwestern, north-central, eastern and south-central coasts.

Information from other wind stations at strategic locations was used for describing the wind resource of Puerto Rico (see the summarized data locations in Figure 4.4). Though detailed graphs could not be produced for these stations, their wind characteristics will be included in the discussion, when applicable, in order to present a better overall picture of the wind resource.

Aguadilla wind data are actually taken at Ramey Air Force Base. The wind station is located on the extreme northwestern corner of Puerto Rico, approximately 1 km (0.6 mi) inland on a plateau 70 m (227 ft) above sea level. The site appears to be typical of locations on the coastal plain of northwestern Puerto Rico.

Ponce is an airport site approximately 3 km (2 mi) east of the city of Ponce on the southern coastal plain of Puerto Rico. The station site is approximately 5 km (3 mi) inland at about 8 m (25 ft) above sea level. It is typical of inland sites along the southern coastal plain of Puerto Rico from Aguirre to Guayanilla.

Roosevelt Roads Naval Air Station is located at the eastern end of Puerto Rico near the foothills of the Sierra de Luquillo. Though the site is on the narrow coastal plain, swamp lands and islands near the shore extend approximately 5 km (3 mi) to the east and thus reduce the strength of the trade winds at the station.

San Juan International Airport is located on the northern coastal plain of Puerto Rico, immediately east of the city of San Juan. The airport is less than 1 km (0.5 mi) from the coast, but is partially blocked from the trade winds by Point Maldonado. This point extends about 2 km (1.25 mi) seaward just east of the airport. Thus, San Juan airport should be considered typical of partially sheltered sites (category 3 exposure, see Section 1.10) in the northern coastal plain of Puerto Rico.

4.3.1 Interannual Wind Power and Speed

Only three stations in Puerto Rico have lengthy periods of record in which the

anemometer was not moved: Aguadilla (1958 to 1970), Roosevelt Roads (1965 to 1978) and San Juan (1962 to 1970 and 1971 to 1978). The periods of overlap indicate a high positive correlation in the interannual variation of wind (see Figure 4.10). For example, consider the 6-year period, 1965 to 1970. At all three stations the wind was at a relative maximum in 1965, dropped to a minimum in 1968 and 1969, then increased. The highest interannual variations in wind speed and power occur at San Juan. The highest percentage variations occur at Roosevelt Roads; however, this is due to the low mean wind speed there.

4.3.2 Monthly Average Wind Power and Speed

As indicated by Figures 4.11 and 2.3, most of Puerto Rico has a midsummer wind energy maximum. A secondary maximum in late winter to early spring is also exhibited by many locations. These two maxima are to be expected considering the seasonal variations in the trade winds (Figure 4.5). However, the interaction of the trades with the topography and the differential solar heating, in combination with seasonal changes in the sea-surface temperature, produce local areas of either winter or spring maximum wind energy. For example, consider the southern coast of Puerto Rico. All five stations used in the analysis of the southern coast, from Guayanilla to Aguirre (see Figure 4.4), show at least a slight spring maximum in wind energy. This is due primarily to the strength of the sea breeze. On the southern coast, the sea breeze provides most of the usable wind energy.

The sea breeze is strong and frequent during the spring because of the maximum annual temperature differential between the land and the sea surface. Furthermore, considering locations from west to east along the southern coast, average wind speeds, and thus wind energy, increase with distance eastward. This occurs because the basic trade-wind flow enhances the sea breeze more at the southeastern corner of the island than in the south-central or southwestern portions. Consequently, the monthly average wind power for Ponce shown in Figure 4.10 is typical of the seasonal wind pattern along the south coast, but since Ponce lies in the central southern coast, it is neither typical of strength of the winds nor of the amount of wind energy available at all locations. For example, the spring 10-m (33-ft) winds increase eastward from Ponce (3.7 m/s, class 1 wind power) to Aguirre (4.6 m/s, class 2 wind power) and eventually reach over 6 m/s (class 4 wind power) at Point Tuna on the extreme southeastern corner of Puerto Rico.

Winter wind energy maxima are observed at Cape San Juan on the northeastern coast, Point Tuna and Yabucoa on the southeastern coast and at Mayaguez on the western coast of Puerto Rico. The winter maxima at the eastern corners of the island occur for similar reasons, suggesting that each of these sites is probably typical of other locations in its vicinity. On the north-eastern and southeastern corners of the island the land-sea breeze effects appear to be reduced in the winter. Though less enhancement of the trade winds by the sea breeze occurs during the day, there is also less opposition by the land breeze during the night. The turning of the trades to a more northeasterly direction in the winter may accelerate the flow around the entire east end of Puerto Rico. This shift of direction also causes the trades to flow more perpendicularly to the coast near Cape San Juan, producing stronger winds at exposed coastal sites. Another factor to be considered in the winter is the significant drop in the height of maximum winds from 1,000 m (3,200 ft) in summer to near 700 m (2,200 ft) in winter. This could conceivably produce a winter maximum in wind energy at mountain tops farther inland than depicted in Figure 2.3 and possibly at other mountain peaks and ridge summits in the interior of the island.

The winter wind energy maximum at the west end of the island is more easily explained. Mayaguez, typical of most sites along the west central coast, experiences much weaker sea breezes in winter than in summer. Since the sea breeze coming from the west opposes the easterly trades, the weaker sea breeze allows stronger mean winds in the winter than in summer. However, as one moves from Mayaguez toward Aguadilla (on the northwestern corner of the island) there is less blocking of the wind by the island and more direct exposure to the trade winds, and therefore a distinct summer maximum of wind energy occurs (note the peak for Aguadilla in July in Figure 4.11).

4.3.3 Diurnal Wind Speed by Season

Stations in Puerto Rico generally experience their strongest winds during the late morning and early afternoon and their weakest winds in the early morning hours, regardless of season. This is supported by the diurnal wind plots in Figure 4.12. Other wind data stations used in the Puerto Rican analysis support this generalization for the northern and southern coasts of the main island and the outlying islands, but there are exceptions along the eastern and western coasts of Puerto Rico.

Two exposed coastal sites at the east end of the island, Cape San Juan and Point

Tuna, show daily wind maxima at 1300 to 1500 LST in the winter, but have strongest winds between 0700 and 0900 LST in the summer. At the west end of Puerto Rico, Mayaguez has a late afternoon wind maximum (1400 to 1700 LST) in summer due to the delay in the formation of a westerly sea breeze caused by the opposition of the prevailing easterlies. During the late winter and spring dry season, increased insolation causes an earlier onset of the sea breeze. Furthermore, Mayaguez may have a secondary wind maximum at night because drainage winds from the mountains to the east reinforce the trade winds (Riehl 1954).

The largest diurnal variations occur in spring or summer and the least diurnal variations occur in autumn. On the southern coast, spring is the season of maximum diurnal variation followed closely by the summer (see Ponce, Figure 4.18). This is due to the strong, recurrent sea breeze in the spring, which is the primary source of usable wind energy along the southern coast. On the northern coast, summer shows the largest diurnal variation in wind speed because of the opposition to the trades by the land breeze at night and reinforcement of the trades by the sea breeze during the day.

The small diurnal variation shown at Roosevelt Roads also occurs at other sites on the east coast of Puerto Rico. Point Tuna and Cape San Juan, both well-exposed coastal sites, show only slight diurnal variations in the wind.

4.3.4 Directional Frequency and Average Speed

San Juan and Aguadilla (Figure 4.13) are fairly typical of northern coastal sites in that they show a distinct prevailing direction of east and a maximum wind speed direction of east-northeast. The slight shift from east to east-northeast between prevailing direction and direction of strongest wind speed is caused by sea-breeze modification of the prevailing easterlies during the day. The minimum wind speed direction is southeast, caused by land breeze modification of the trade winds during the night. On the southern coast the pattern is reversed, as indicated by Ponce. During the night a weak northerly land breeze often develops and increased atmospheric stability reduces the influence of the trade winds. However, during the day, sea breezes add a southerly component to the trade winds, thereby producing a primary wind speed maximum (and secondary wind direction maximum) of southeast.

On the east end of Puerto Rico, Roosevelt Roads appears to have a pronounced, singular prevailing wind direction of east and maximum wind speed direction of east-northeast. The swamplands and islands east of the station cause the maximum speed direction of east-northeast (i.e., the strongest winds are those that bypass these terrain obstacles). However, the single directional peak at east is somewhat deceiving. Scanning the observations at Roosevelt Roads reveals an extremely high frequency of calm winds (i.e., winds below the threshold of the anemometer). The mountains southwest of the station produce frequent, light drainage winds from the southwest. The stronger of these winds show up as a secondary maximum in wind speed at south-southwest. The light drainage winds are reported as calms and thus are not included in the directional frequency plot. However, it appears that a well-defined secondary wind direction maximum occurs from the south-southwest, having a much lower mean wind speed than is shown in Figure 4.13.

Though very few data are available from the west end of Puerto Rico, limited data analysis from Mayaguez suggests bimodal wind direction maxima from both the east-northeast and west-northwest, and light (4 m/s) mean wind speed maxima from those same directions.

4.3.5 Annual Average Wind Speed Frequency Distribution

All of the observed wind speed frequency distributions are heavily biased toward 2,

5, and 8 m/s (5, 10 and 15 knots). This is very apparent in Figure 4.14 for Ponce and San Juan, where spikes in the observed speed distribution occur at precisely these speeds. Furthermore, all speeds less than or equal to the anemometer threshold (about 1 m/s) are classified as calm, thus producing a peak at 0 m/s and a valley at 1 m/s as shown in the San Juan speed frequency distribution. If one were to remove the biases by flattening the spikes and producing a smoother distribution, San Juan would very nearly follow the Rayleigh distribution. Thus it appears that the Rayleigh distribution may be a reasonable approximation for some inland sites and partially sheltered coastal sites in Puerto Rico. However, well-exposed locations exhibit the persistence of the trade winds, which cause a very peaked speed distribution with a small variation about the mean speed. Such peaked distributions can be expected at exposed coastal locations, mountain peaks, and the windward side of the outlying islands.

4.3.6 Annual Average Wind Speed and Power Duration

The percentage time that a specified wind speed or power is exceeded is shown in Figures 4.15 and 4.16 respectively. Abrupt changes in the slope of the curves reflect the observer biases and instrument threshold speeds mentioned in the previous section. San Juan is a prime example; the slope of the wind speed duration curve changes abruptly at 2 m/s and the wind power duration at about 50 watts/m².

FIGURE 4.1. Geographic Map of Puerto Rico

FIGURE 4.2. Topographic Map of Puerto Rico

FIGURE 4.3. Classes of Land-Surface Form in Puerto Rico

LAND-SURFACE FORM LEGEND

PLAINS

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

PLAINS WITH HILLS OR MOUNTAINS

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

OPEN HILLS AND MOUNTAINS

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

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

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

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

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

LOCAL RELIEF (2nd LETTER)

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

PROFILE TYPE (3rd LETTER)

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

DATA SOURCE	DIGITIZED DATA	SUMMARIZED DATA	UNSUMMARIZED DATA	UPPER AIR DATA
NCC	□	○	△	×
OTHER	■	●	▲	

FIGURE 4.4. Locations of Data Stations in Puerto Rico

FIGURE 4.5. Seasonal Free-Air Wind Speed and Wind Power Density Profiles for Puerto Rico

- (a) Speed profiles are based upon winds aloft summaries (NCC 1970), the mean trade wind profile (Riehl 1954) modified by seasonal profile variations (Stone 1942).
 (b) Mean air densities for 15° north latitude are used (ESSA 1966).
 (c) Power is computed by multiplying the Rayleigh power (Equation 3, Section 1.4) by a fraction, "R", that is based upon the Weibull shape factor, "k" (Equation 5, Section 1.4.2).

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

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

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

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

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

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	6,570	74.9	8,764	100.0
2	1,820	20.8	2,193	25.1
3	363	4.1	373	4.3
4	5	0.06	11	0.12
5	5	0.06	5	0.06
6	0	0.00	0

FIGURE 4.7. Certainty Rating of the Puerto

Resource

CERTAINTY RATING LEGEND

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

Class 5

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

Summer

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

Autumn

FIGURE 4.9 (Continued). Seasonal Average Wind Power in Puerto Rico (Spring, Autumn)

TABLE 4.2. Puerto Rico Stations with Graphs of the Wind Characteristics

Stations	Stations Name ^(a)	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s			Annual Average Wind Power watts/m ²		
							At Anemometer Height, m	At 10 m	At 50 m	At Anemometer Height, m	At 10 m	At 50 m
Aguadilla	Rarney AFB	18.50	67.13	75	04/57-12/70	4.0	3.6	4.1	5.2	75	112	222
Ponce	Ponce AAB	18.02	66.50	9	07/41-10/45	9.8	3.3	3.3	4.2	59	59	118
Roosevelt Roads	Roosevelt Roads NAS	18.25	65.63	11	07/57-12/63	26.8	4.5	3.9	4.9	93	61	121
San Juan	San Juan International Airport	18.43	66.00	22	04/61-12/78	6.1	4.0	4.3	5.4	80	99	197

^(a) AFB-Air Force Base; AAB-Army Air Base; NAS-Naval Air Station

FIGURE 4.10. Interannual Wind Power and Speed for Puerto Rico

FIGURE 4.11. Monthly Average Wind Power and Speed for Puerto Rico

FIGURE 4.12. Diurnal Wind Speed by Season for Puerto Rico

FIGURE 4.13. Directional Frequency and Average Speed for Puerto Rico

— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3195 WERA-12

FIGURE 4.14. Annual Average Wind Speed Frequency for Puerto Rico

FIGURE 4.15. Annual Average Wind Speed Duration for Puerto Rico

ORDINATE - PERCENT
 ABSCISSA - WATTS/M²
 PNL-3195 WERA 12

AGUADILLA PR 04/57-12/70
 11603 Z= 40 G, V= 3.6, P= 75E

PONCE PR 07/41-10/45
 11607 Z= 9.8 V= 3.3, P= 59E

ROOSEVELT ROA. PR 07/57-12/63
 11630 Z=26.8 R, V= 4.5, P= 93

SAN JUAN PR 04/61-12/78
 11641 Z= 6.1 G, V= 4.0, P= 80

FIGURE 4.16. Annual Average Wind Power Duration for Puerto Rico

U.S. VIRGIN ISLANDS

U.S. VIRGIN ISLANDS

CHAPTER 5: THE U.S. VIRGIN ISLANDS

The U.S. Virgin Island Territory lies approximately 80 km (50 mi) east of the island of Puerto Rico (see Figure 2.1). The territory is composed of three main islands (St. Thomas, St. Croix, and St. John) as well as fifty or more small islands, and cays (only a few of which are inhabited). A map of the territory is shown in Figure 5.1.

St. Thomas, with a land area of 82 km² (32 mi²), has very rugged topography (Figures 5.2 and 5.3). Steep slopes lead from the 470 m (1,550 ft) summit of Crown Mountain to the coasts. Several other peaks exceed 300 m (1,000 ft). The coastline is very irregular, with many exposed points and sheltered bays. St. Thomas has the largest population of the islands (nearly 32,000). Most of St. Thomas' population lives in the city of Charlotte Amalie, the capital of the U.S. Virgin Islands. The single source of surface wind data for the island used in this analysis was Harry S. Truman Airport, on the southwestern (leeward) coast.

St. John, which lies immediately to the east of St. Thomas, is the smallest of the three major islands with 48 km² (19 mi²), most of which is national parkland. St. John has much the same topography as St. Thomas (see Figure 5.2). However, the highest peak, Bordeaux Mountain, (400 m, 1,300 ft) as well as the other hilltops, are slightly lower than those on St. Thomas. The coastline is very irregular with many exposed points and sheltered bays. The permanent population is low (1,689) and is centered in the town of Cruz Bay. No wind data were obtained from St. John for the wind resource assessment.

St. Croix lies approximately 55 km (35 mi) south of St. John. With a land area of 214 km² (84 mi²), it is the only one of the three islands having a large portion of flat land (see Figures 5.2 and 5.3). This has led to some industrial growth and a growing population of near 30,000. The two primary towns are Frederiksted, on the west coast, and Christiansted, on the north coast (see Figure 5.1). The only wind data obtained from St. Croix were from Alexander Hamilton Airport (previously named Benedict Field) on the south coast. Both digitized surface data and 1,500 m (5,000 ft) pibal summaries were used in the analysis (see Figure 5.4).

As described in Section 1.4.2, wind power over the mountains was estimated by extrapolating free-air wind speeds to exposed mountain tops. Figure 4.5 shows the profiles of wind speed and power density for the U.S. Virgin Islands.

5.1 ANNUAL AVERAGE WIND POWER

The mean trade wind flow appears to be slightly stronger in the U.S. Virgin Islands than it is in Puerto Rico, as is reflected in Figure 5.6. However, near the surface the strength of the trades still is estimated to produce only class 3 wind power. Consequently, only sites at exposed coastal locations, or at higher elevations, should experience class 3 or greater annual wind power (see Figure 5.6). Such locations include 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.

As in the case of Puerto Rico, the U.S. Virgin Island annual average wind power analysis masks some important wind variations. These seasonal/diurnal wind variations could impact the economic viability of wind energy in the U.S. Virgin Islands.

5.1.1 Certainty Rating of the Wind Resource

St. Thomas, St. John and their surrounding islands have been assigned a relatively low certainty rating of 2 (see Figure 5.7). This is due to the lack of data and to the complex terrain of these islands. The single wind data location, Harry S. Truman Airport, is in a very sheltered location, and thus cannot be considered typical of well-exposed sites. The analysis relied primarily on the basic understanding of the trade winds and limited information on their interaction with the topography.

The terrain of St. Croix Island is much more uniform than that of either St. Thomas or St. John. The single wind data source used, Alexander Hamilton Airport/Benedict Field, lies in the southern coastal plain. Though partially sheltered by topography and buildings, this site provides sufficient insight into the local winds to warrant a certainty rating of 3 within the grid cell containing the airport. The remainder of St. Croix is either of hilly terrain and/or sufficiently far from the wind data location as to introduce uncertainty into the analysis, so a certainty rating of 2 was assigned.

5.1.2 Areal Distribution

The areal distribution of wind power in the Virgin Islands is estimated in Figure 5.8 and Table 5.1. The numbers in each grid cell are an attempt to quantify the percentage area in the cell in which a specified wind power threshold is met or exceeded.

Section 1.10 explains the relationships assumed between land-surface form, land-surface area, exposure category and the resultant map and tabular values of the areal distribution of wind power density. For the sake of uniformity in the wind resource atlases, these relationships were used for the U.S. Virgin Islands. Unfortunately, they do not always apply well here due to the size of the grid cells used and the complex terrain. The small grid cells (thus enlarged maps) mean that the detail of the topographic analysis far exceeds the resolution used in developing the exposure category algorithm. Since only one land-surface form (the predominant one) can be assigned to a grid cell, other land surfaces within the grid cell are not considered. This leads to a problem that is illustrated by the map for power class 4. This figure shows an absence of class 4 annual wind power areas in the U.S. Virgin Islands, which contradicts the presence of the class 4 areas shown in Figure 5.6 (annual average wind power). As more data are gathered and the wind power analysis is verified and updated where necessary, such problems can be resolved. But for the present, the areal distribution maps and the areal distribution table should be viewed as being very tentative. Furthermore, the lack of land area having class 4 or higher power should be interpreted to mean that only a very small amount of land area may have class 4 wind power and that the attempt to identify individual, small-scale terrain features giving rise to class 4 wind power (and to sum their areas) is beyond the scope of the present wind resource assessment.

The problems discussed above are evident even for class 2 wind power areal distribution (Figure 5.8). The values assigned to the islands north of St. Thomas (90%) in reality would be highly dependent upon the individual topography of each island. For example, a hill-shaped island would have about 50% of its area exposed to the wind and 50% would be in the sheltered lee of the island. The 10% assigned to St. Thomas and St. John is a reasonable estimate for class 2 or greater wind power because of the rugged terrain.

The octagonal analysis of St. Croix, caused by the unfortunate position of the grid lines, produces highly biased areal distribution analyses. Class 2 or greater wind power is shown as covering 88% of the grid cells designated as coastal plain (i.e., B1 or B2 areas in Figure 5.3). This is probably too high a percentage because significant portions of land area in these grid cells are mountainous and thus contain sheltered land. An opposite situation occurs for the portions of St. Croix assigned

5 to 7% class 2 wind power; here the relatively smooth coastal plains, particularly on the southern coast, should increase these percentages.

Class 3 or greater wind power is shown to occur over 10% of St. John and St. Thomas islands. On St. Croix, the lack of any class 3 wind power in the western and central hills of the island is caused by the areal distribution scheme.

5.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 5.9. In the U.S. Virgin Islands, summer is the season of maximum wind power. At the exposed locations winter appears to rank second, followed by spring. There is significantly less wind power in autumn than the other three seasons.

5.2.1 Winter

The winter wind power patterns observed in the U.S. Virgin Islands appear to be governed by three primary factors. First, the level of maximum wind speed drops to near 700 m (2,300 ft). Second, the trade winds, though very steady, are not as strong as in late spring or summer. Third, the trades shift to a more northeasterly direction in winter.

The lowering of the level of maximum winds (see Figure 5.5), combined with a slight increase in atmospheric stability, increases the wind power at the higher hilltops and ridge crests to values near the summer maximum wind power. The increased steadiness of the trades (reflected by the decrease in the standard deviation of the upper air wind speed), combined with the shift to a northeasterly direction, produces a secondary wind power maximum during winter at exposed sites on the windward sides of the islands.

The factors mentioned above should produce class 4 wind power along the central ridgeline of St. Thomas, which lies perpendicular to the prevailing wind direction. A similar pattern occurs along the high ridgeline paralleling Coral Bay on St. John.

Class 3 wind power can be expected on St. Thomas at exposed coastal locations (excluding the sheltered western portion) and on the interior hilltops below 300 m (1,000 ft) MSL. The same pattern appears to occur on St. John. Class 3 is the highest wind power on St. Croix during winter. It is limited to the higher hilltops on the central ridgeline and to exposed sites on the northern and eastern coasts. The smaller islands should also experience class 3 wind power during winter on their windward (northeastern and eastern) sides.

Class 2 wind power on St. Thomas is limited to the partially sheltered north-western end of the island. St. John, because of its irregular coastline, has partially sheltered areas around the perimeter of the island (except for the windward coast) and in the lower interior hills. Most of the coastal plain and southern coast of St. Croix experiences class 2 wind power during winter as do the partially sheltered hills on the western end and the south-central portion of the island.

Class 1 wind power can be expected on the sheltered south coast of St. Thomas, the extreme west coasts of St. John and St. Croix, as well as in the lowlands transecting the central ridge of St. Croix.

5.2.2 Spring

In the spring the trade winds weaken slightly, the level of maximum winds begins to rise and the winds shift to a more easterly direction. Consequently, class 3 is the highest wind power class expected in spring. Class 3 wind power is limited to the St. Thomas and St. John ridgelines, the higher hills at the western end of St. John, and to a few hilltops in the northwestern portion of St. Croix.

Class 2 wind power is typical of exposed coastal locations on the windward sides of the three main islands and the smaller islands. Class 2 wind power should also occur on the lower hilltops, along the windward sides and in the interior of St. Thomas and St. John, as well as on the lower hilltops of the St. Croix ridgeline.

Class 1 wind power is predominant along the leeward (southern and western) side of St. Thomas, rings most of the perimeter of St. John, and encompasses the entire coastal plain and interior lowlands of St. Croix.

5.2.3 Summer

During summer the trade winds are well developed throughout the lower atmosphere (see Figure 5.5) and shift to the east-southeast. The wind speed in the free atmosphere below 1,500 m (5,000 ft) varies little about its mean. This fact, combined with the method of extrapolation to mountain tops (see Section 1.4.2), produces estimates of class 4 wind power for the ridgelines of St. Thomas and St. John, the highest hills on St. Croix, at well-exposed coastal locations (primarily the fingerlike points) and on the eastern sides of the smaller islands.

Class 3 wind power is confined to the lower (or slightly less exposed) hills of St. Thomas, St. John and St. Croix, the

northern, eastern and southern coastlines of St. John, and at some slightly sheltered coastal locations on these islands.

Class 2 wind power is limited to the slightly sheltered interior parts of the three major islands, while class 1 wind power occurs in the sheltered depressions and valleys of all three islands and lowlands of St. Croix. Furthermore, St. Croix is large enough to produce distinguishable sea-breeze effects, which may reduce the wind power to class 1 at the sheltered west end of the island.

5.2.4 Autumn

In autumn there is a marked decrease in the strength of the trade winds (see Figure 5.5), especially in October and November. This results in low wind power throughout the U.S. Virgin Islands. Only the exposed hills, exposed coastal locations and windward (eastern) sides of the well-exposed, smaller islands appear to have class 2 wind power. The remainder of the subregion has only class 1 wind power in autumn.

5.3 FEATURES OF SELECTED STATIONS

Table 5.2 gives the location and annual wind speed and power of the two stations in the U.S. Virgin Islands for which digitized wind data are available. These data are graphically summarized in Figures 5.10 through 5.16 to show various features of the wind resource.

St. Croix wind data were collected at Alexander Hamilton Airport (see Figure 5.4), formerly Benedict Field. The airport is located in the relatively flat southern coastal plain of St. Croix, approximately 1 km (0.75 mi) inland at 17 m (56 ft) above sea level. It appears that the wind data were affected slightly by buildings and that the anemometer was partially sheltered from northerly winds by a 61 m (200 ft) hill less than 0.5 km (500 yards) to the north. The airport site, therefore, appears typical of partially sheltered sites in the southern coastal plain of St. Croix. Well-exposed sites, particularly those within 400 m (0.25 mi) of the coast, should have wind energy densities approximately one class higher than that found at the airport.

St. Thomas wind data are taken at Harry S. Truman Airport on the south side of the island (see Figure 5.4). The airport is about 3 m (10 ft) above sea level and is within 400 m (0.25 mi) of the shore, but is blocked by the terrain from all but westerly winds.^(a) consequently, these data must be

(a) These winds occur less than 1% of the time and are very light unless associated with tropical storms.

considered typical of very sheltered coastal locations on the island.

5.3.1 Interannual Wind Power and Speed

The two U.S. Virgin Island wind sites have an 8-year period of overlapping records, from 1953 to 1960, when the anemometers were not moved. Comparison of the inter-annual variations in wind speed and power of Figure 5.10 shows very little correlation. St. Croix exhibits a much larger standard deviation of both wind speed and power for each month, each year, and for the period of record than does St. Thomas.

5.3.2 Monthly Average Wind Power and Speed

As indicated by Figure 5.11, summer is the season of maximum wind speed and wind energy for both St. Croix and St. Thomas. There appears to be a slight secondary maximum in February and March (as was noted at several locations in Puerto Rico, Section 4.3.2). These variations coincide well with the annual variations in the strength of the trade winds as depicted in Figure 5.5.

5.3.3 Diurnal Wind Speed by Season

Very regular diurnal wind patterns are shown at both St. Croix and St. Thomas (Figure 5.12). The period of maximum wind power occurs at about 1300 LST at both locations regardless of season. Minimum wind power occurs at St. Croix at 0400 LST year-round, with a slight secondary minimum at about 1200 LST. On St. Thomas the minimum occurs a little later, at 0600 LST during all seasons.

The size of St. Croix coupled with the size of its southern coastal plain causes more pronounced sea-breeze effects than are found on St. Thomas. This results in a larger diurnal variation in the wind speed. The magnitude and regularity of the diurnal wind speed variations in the Virgin Islands are such that wind power may be feasible for some applications even though the annual average wind power is low. For example, consider the very sheltered location of St. Thomas as a "worst case". In spite of its poor exposure, summer wind speeds average 5.5 to 6.5 m/s (12 to 15 mph) from 1000 to 1500 LST during summer (which is equivalent to class 3 or 4 wind power) and even reach class 2 wind power levels during autumn afternoons. On St. Croix the summer afternoon winds average about 7 m/s (16 mph), which is equivalent to class 5 or 6 wind power. However, the wind speeds are equivalent to only class 2 wind power during autumn afternoons. The availability of usable wind power during the afternoons of most of the year may make wind power much

more attractive than is indicated by the low numbers in the annual and seasonal wind power analyses.

5.3.4 Directional Frequency and Average Speed

St. Croix (Alexander Hamilton Airport) is fairly typical of the coastal plain of the island. Here the primary wind direction maximum is east-northeast, but, the secondary direction maximum and primary wind speed maximum direction is east-southeast. This is apparently due to a combination of the annual directional shift of the trade winds and a slight modification by the sea breeze during the day and land breeze at night. For example, during winter the trades are primarily east-northeast; this produces east-northeast to northeast winds over 50% of the time at the St. Croix site, but the overland fetch reduces the speeds to an average of 4.4 m/s (10 mph) from the north-east while east-southeast winds occur only 14% of the time with an average speed of about 5.9 m/s (13 mph). From April to June the land-sea breeze effects are at a maximum on St. Croix. In June there is a maximum of east-southeast winds (30%) with a mean speed of 6.6 m/s (15 mph) while the night winds tend to turn more northeast and average only about 4.4 m/s (10 mph).

Other factors affecting the direction and speed of the wind at the St. Croix site are the 61 m (200 ft) hill directly north of the airfield. The hill practically eliminates any occurrences of north winds. It appears that buildings may have reduced the recorded wind speeds slightly and had an indeterminate effect on wind direction.

St. Thomas has a single predominant wind direction of east, as shown in Figure 5.13. This is due to the prevailing direction of the trades and the topography surrounding the airport. Low-level easterly winds appear to be channeled between the islands south of Charlotte Amalie and through a gap between the coastal hills to the south of the airport and the higher interior hills to the north. The gap is approximately 42 m (140 ft) deep, and consequently its effects on the wind flow are less during the warmest part of the day when a slight sea breeze enhances the trade winds. This gap produces a wind speed maximum at the airport from the east-southeast at about 5.8 m/s (13 mph). The secondary maximum of wind speed from the southwest shown in the figure represents less than 1% of all observations. This maximum is produced by occasional very high wind speeds caused by tropical storms and moderate winds associated with occasional cold frontal passages in winter.

During the winter the direction of maximum wind speed becomes north-northeast at the St. Thomas site; the speed averages 5.4 m/s (12 mph). This shift in direction is caused by the shift in the trades to a more northeasterly direction and an apparent channeling over a saddle in the central St. Thomas ridgeline, which lies north-northeast of Harry S. Truman Airport.

Due to the complex terrain of the island, the interaction of the trade winds and topography will produce site-specific combinations of prevailing wind direction and direction of maximum wind power. Though it is beyond the scope of this assessment to analyze the entire U.S. Virgin Islands at this level of detail, it is hoped that this discussion of wind speeds and direction will alert the reader to some of the factors important in determining the winds at a specific site in this region of sparse wind data and thus enable him to interpret the wind power analyses more intelligently.

5.3.5 Annual Average Wind Speed Frequency Distribution

As illustrated in Figure 5.14, the wind speed distributions exhibit a heavy observer

bias toward 2, 5 and 8 m/s (5, 10, and 15 kts). The high frequency of calms (6% at St. Croix and 11% at St. Thomas) is caused primarily by the anemometer threshold. If these biases were removed, both the St. Croix and St. Thomas locations would follow the Rayleigh distribution very closely. However, this should not be construed to be the case for all sites in the U.S. Virgin Islands. Both sites shown are at least partially sheltered from the trade winds. This tends to reduce the mean speed and produce a larger deviation about the mean. Consequently, well-exposed sites would be expected to have a very peaked distribution with much less variation about the mean speed.

5.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a specified wind speed or power is exceeded is shown in Figures 5.15 and 5.16. Sharp changes in the slope of the curves, such as observed at about 2 m/s in Figure 5.15, are caused by the observer bias mentioned in the previous section.

FIGURE 5.1. Geographic Map of the U.S. Virgin Islands

FIGURE 5.2. Topographic Map of the U.S. Virgin Islands

FIGURE 5.3. Classes of Land-Surface Form in the U.S. Virgin Islands

LAND-SURFACE FORM LEGEND

PLAINS

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

TABLELANDS

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

PLAINS WITH HILLS OR MOUNTAINS

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

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

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

OPEN HILLS AND MOUNTAINS

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

LOCAL RELIEF (2nd LETTER)

- 1** **0 TO 30m (1 TO 100 ft)**
- 2** **30 TO 90m (100 TO 300 ft)**
- 3** **90 TO 150m (300 TO 500 ft)**
- 4** **150 TO 300m (500 TO 1000 ft)**
- 5** **300 TO 900m 11000 TO 3000 ft)**
- 6** **900 TO 1500m 13000 TO 5000 ft)**

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

PROFILE TYPE (3rd LETTER)

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

FIGURE 5.4. Wind Data Sites in the U.S. Virgin Islands

FIGURE 5.5. Seasonal Free-Air Wind Speed and Wind Power Density Profiles for the U.S. Virgin Islands

- (a) Speed profiles are based upon winds aloft summaries (NCC 1970), the mean trade wind profile (Riehl 1954) modified by seasonal profile variations (Stone 1942).
- (b) Mean air densities for 15° north latitude are used ESSA (1966).
- (c) Power is computed by multiplying the Rayleigh power (Equation 3, Section 1.4) by fraction, "R", that is based upon the Weibull shape factor, "k" (Equation 5, Section 1.4.2).

FIGURE 5.6. Annual Average Wind Power in the U.S. Virgin Islands

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

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

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

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

TABLE 5.1. Areal Distribution (km²) of Wind Power Classes in the U.S. Virgin Islands

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	229	66.6	344	100.0
2	90	26.1	115	33.4
3	25	7.3	25	7.3
4	0	0.0	0	0.0

CERTAINTY RATING LEGEND

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

Class 2

FIGURE 5.8. Areal Distribution of Wind Resource in the U.S. Virgin Islands (Power Class 2); Percent of Land Area With or Exceeding Power Class Shown

Class 3

FIGURE 5.8 (Continued). Areal Distribution of Wind Resource in the U.S. Virgin Islands (Power Class 3); Percent of Land Area With or Exceeding Power Class Shown

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