Cuba Wind Energy Resource Mapping Activity

Introduction

This document describes the development of detailed high-resolution (1 km^2) wind energy resource maps for the country of Cuba. These maps were created at the United States Department of Energy's National Renewable Energy Laboratory (NREL) as part of the Solar and Wind Energy Resource Assessment (SWERA) project for the United Nations Environment Programme. The wind mapping activity covered approximately 110,000 km^2 of land area and, including offshore areas, more than 150,000 km^2. The maps can be found in a separate part of the SWERA archive.

NREL's Wind Resource Assessment and Mapping System (WRAMS) is a combination of analytical, numerical, and empirical methods using Geographic Information System (GIS) mapping tools and data sets. In the sections below, we discuss the data sets, analysis methods, and mapping system used by NREL to perform the Cuba wind mapping activity. We also present the results of the wind resource assessment, highlighting the major wind resource areas identified and providing confirmation of the resource estimates with available measurement data. Finally, we present estimates of the wind electric potential for Cuba.

Meteorological Data

Introduction

An accurate wind resource assessment depends on the quantity and quality of the available meteorological data. NREL reviews many sources of wind data and previous wind assessments as part of its overall evaluation. Several global data sets maintained at NREL, including surface and upper-air observations spanning many years of record, were used in this assessment. These data were supplemented with information from sources in Cuba that included summaries of wind data from meteorological stations and some wind measurement towers.

Because the quality of data in any particular data set can vary, and high-quality data can be quite sparse in many regions, multiple data sets are used. Each data set plays an integral role in the overall assessment.

Surface Data

High quality surface wind data from well-exposed locations can provide the best indication of the magnitude and distribution of the wind resource in the region. Studies by NREL and others in many different regions of the world have found that the quality of surface wind data from meteorological stations varies and is often unreliable for wind resource assessment purposes.

The following sections present a summary of the surface data sets obtained and examined in the assessment.

DATSAV2 Data

The DATSAV2 global climatic database obtained from the U.S. National Climatic Data Center (NCDC) contains the surface weather observations, transmitted via the Global Telecommunications System (GTS), from first-order meteorological stations throughout the world. Meteorological parameters such as wind speed, wind direction, temperature, pressure and altimeter setting are used to create statistical summaries of wind characteristics. A unique six-digit number based on the World Meteorological Organization (WMO) numbering system identifies each station in the DATSAV2 data set.

Sixty-one stations in Cuba are included in the DATSAV2 data set. NREL processed these data for initial examination and potential use in its meteorological evaluation and validation of the numerical model data for Cuba. The number of observations at the individual stations for each year and from year to year is highly variable. The stations in Cuba typically recorded hourly data, though many stations recorded observations only during daylight hours.

The processed data records from the DATSAV2 data contained monthly and annual averages of wind speed and wind power. These data are useful for evaluating the interannual and monthly variability, and the diurnal distribution of wind speed and wind power, plus the joint frequency of wind speed and direction.

Historical Data from the Cuba Institute of Meteorology

NREL received from the Cuban Institute of Meteorology (CIM) several summaries of surface wind data. First, CIM sent us a list of 70 stations where they have observation data. The list included the station name, location, and elevation, the anemometer height, and the anemometer equipment. Most of the anemometer heights were 10 m above ground. CIM also sent summarized wind data from 22 stations. Twenty of the 22 stations were in the DATSAV2 database but, the CIM data covered a different period-of-record and in some cases had more data than the DATSAV2 data set. Finally, CIM sent us a preliminary wind resource map produced in 1995 for our review.

Upper-air Data

NREL's upper-air data sets include both observational and computer model-derived upper-air information. The following upper-air data sets were used for this mapping project.

Automated Data Processing (ADP) Data

The ADP upper-air database consists of information obtained from surface-launched meteorological instrument packages. These packages are launched via balloon once or twice daily and are managed under WMO guidance and procedures. ADP data was available for three locations in Cuba (Havana, Camaguay, and Guantanamo). These data were supplemented by ADP data from stations in the surrounding countries in the Caribbean. The ADP data was used to create profiles of monthly and annual average wind speeds and frequency distributions of wind speed and wind direction for a number of pressure levels and height levels from the surface up to 3000 m above the surface.

CIM Data

The CIM sent NREL a report detailing the upper-air characteristics at the Casablanca (Havana) upper-air station for the years 1993 and 1994. The information had more detail from the ground to 1 km above ground than the ADP data for the same site. The data provided in the report proved to be useful in confirming the wind characteristics apparent in the ADP data.

Reanalysis Data

The U.S. National Centers for Environmental Prediction, in collaboration with U.S. National Center for Atmospheric Research, produced a reanalysis data set. This is a 45-year record of global analyses of atmospheric parameters. This project used a global weather prediction computer model to create worldwide data sets of wind, temperature, and other variables on a global 208-km resolution grid. Reanalysis incorporates all available rawinsonde and pilot balloon data, as well as observations from surface, ship, aircraft, satellites, and other data sources. Reanalysis data for the Cuba region were produced for four times a day.

Satellite Ocean Wind Data

Measurements and estimates of ocean winds can greatly aid the assessment of the wind resource for the extensive coastal areas and offshore islands of Cuba. NREL examines several types of satellite-based scatterometer estimates of wind data over ocean areas including QuikSCAT, SSM/I, and TMI data sets. These data give estimates of wind speeds 10 m above the ocean surface and provide an excellent overview of the ambient wind conditions in the ocean areas off the coast of Cuba. However, due to inherent uncertainties with the satellite-based estimates, they should be compared with available measurement data wherever possible.

Numerical Model Data

AWS Truewind (AWST), of Albany, New York, provided NREL with wind speed and wind power data for Cuba on a 1 km by 1 km grid with data at levels from 30 m to 500 m above ground. Surface roughness and elevation data from its MesoMap system were also provided to NREL. This data set was used as an initial estimate for the distribution of the wind speed and power in Cuba. The section on the wind resource mapping system describes how the numerical model data were generated.

Data Analysis Methodology

Introduction

The following sections describe the WRAMS including the methodology used to analyze and evaluate the meteorological data used for this resource assessment and the mapping system used to generate the resource maps. Both components are crucial for the production of wind resource maps that are accurate enough to stimulate the development of wind energy in the study regions. The goal of WRAMS is to have the final wind resource data accurate to within 10% of annual average wind speed and 20% of annual average wind power for a large majority (80%) of the grid points.

Data Evaluation and Analysis

Initial Approach

The quality of the meteorological input used to generate the final maps depends on understanding the important wind characteristics in the study region such as the interannual, seasonal, and diurnal variability of the wind and the prevailing wind direction. NREL used innovative assessment methods on existing meteorological data sets to develop a conceptual understanding of these key wind characteristics. These data sets, discussed earlier, are maintained at NREL as part of its global archive and are supplemented with data sets obtained from Cuba. NREL's approach depends on the critical analysis of all the available surface and upper-air data for the Cuba mapping region and the surrounding areas. NREL used a comprehensive data-processing package to convert the data to statistical summaries of the wind characteristics for more than 60 surface stations and numerous upper-air locations. The summaries were used to highlight regional wind characteristics.

Surface Data Evaluation

Years of resource assessment experience at NREL have revealed many problems with the available land-based surface wind data collected at meteorological stations in much of the world. Problems associated with observations taken at the meteorological stations include a lack of information on anemometer height, exposure, hardware, maintenance history, and observational procedures. These problems can cause the quality of observations to be extremely variable. In addition, many areas of the world with good or excellent potential wind resource areas have very little or no meteorological station data to help assess the level of the available wind resource.

NREL takes specific steps in its evaluation and analysis to overcome these problems. Site-specific products were screened for consistency and reasonableness. For example, the interannual wind speeds were evaluated to identify obvious trends in the data or periods of questionable data. Only representative data periods were selected for the assessment. The summarized products were also cross-referenced to select the sites that appeared to have the best exposure to the prevailing wind. These data, in combination with summaries of data obtained from sources in Cuba, were used to develop an understanding of the wind characteristics of the study region.

Upper-Air Data Evaluation

Upper-air data can be useful in assessing the regional wind resource in several ways. First, upper-air data can be used to estimate the resource at low levels just above the surface. The low-level resource estimation is quite important in areas where surface data is either sparse or not available. Second, upper-air data can be used to approximate vertical profiles of wind speed and power. The vertical profiles are used to extrapolate the level wind resource to elevated terrain features and to identify low-level wind speed maximums that can enhance the wind resource at turbine hub-height.

NREL generated summaries of wind speed and wind power at specific height levels above the surface, as well as monthly and annual average vertical profiles of wind speed and power. One problem that occurs in the evaluation of upper-air data for complex terrain areas is that some locations where the balloons are launched are blocked from the ambient wind flow by high terrain. Using vertical profiles from reanalysis grid points heavily influenced by the "blocked" locations can be misleading because the profiles only represent conditions at the upper-air station and will not apply throughout the region of interest.

Therefore, NREL's analysis of the upper-air data uses vertical profiles that we judge to be representative of the ambient wind flow in a particular region.

Goals of Data Evaluation

The goal of a critical analysis and evaluation of surface and upper-air data is to develop a conceptual model of the physical mechanisms on a regional and local scale that influence the wind flow. When there is conflicting wind characteristic data in an analysis region, the preponderance of meteorological evidence from the region serves as the basis for the conceptual model.

The critical data analysis and the conceptual model are particularly important because a key component of NREL's wind mapping system requires that empirical adjustments be made to wind power values before the final maps are produced. The conceptual understanding developed by the critical analysis of the available data guides the development of empirical relationships that are the basis of algorithms used to adjust the wind power. This empirical approach depends on an accurate ambient wind profile of the few hundred meters closest to the surface and being able to adjust it down to the surface layer. A prime advantage of this method is that NREL can produce reliable wind resource maps without having high quality surface wind data for the study region.

Wind Resource Mapping System

General Description

NREL's mapping system uses GIS mapping software. The main GIS software, ArcInfo®, is a powerful and complex package that features a large number of routines for scientific analysis.

The mapping system is divided into three main components: the input data, the wind power adjustments, and the output section that produces the final wind resource maps. These components are described below.

Input Data

The two primary model inputs are digital terrain data and meteorological data. The elevation information consists of Digital Elevation Model (DEM) terrain data that divide the analysis region into individual grid cells, each having its own unique elevation value. The U.S. Geological Survey's Earth Resource Observing Satellite Data Center produced updated DEMs for most of the world from previously classified U.S. Department of Defense data and other sources. The data sets have a resolution of 1 km^2 and are available for large parts of the world.

The meteorological inputs to the mapping system come in two phases. The first phase provides wind power data for each grid cell obtained via output from a mesoscale numerical model. The second phase, following the data screening process, consists of empirical adjustments to the original wind power value based on NREL's meteorological analysis and a comparison of the numerical model data to wind measurement data throughout the study region.

AWST provided to NREL the initial wind power density values for each grid cell in the Cuba mapping region. AWST used its MesoMap system to calculate the wind power density values. The MesoMap system consists of the MASS (a mesoscale numerical model) and WindMap (a mass conserving wind flow model).

The MASS model simulated weather conditions over the Cuba region and the surrounding areas for 366 days randomly selected from a 15-year period. The random sampling was stratified so that each month and season was represented equally. Each simulation generates wind and other meteorological variables throughout the model domain for a particular day and stores the information at hourly intervals. The simulations use a variety of meteorological and geophysical data. MASS uses climatic data to establish the initial conditions for each simulation as well as lateral boundary conditions for the model. The model determines the evolution of atmospheric conditions within the study region during each simulation.

The main geophysical inputs into MASS are elevation, land cover, greenness of vegetation, and soil moisture. The MASS translates both land cover and vegetation greenness into important surface parameters such as surface roughness.

The MASS was run with a horizontal resolution of 2.5 km. After all the simulations were completed, the results were processed into summary data files that were input into the WindMap model. WindMap then calculated the wind power density down to the final 1 km by 1 km grid cell resolution.

The empirical wind power adjustment modules in NREL's wind mapping system use different routines depending on the results of NREL's data evaluation and validation. Power adjustment factors can be initialized to account for terrain features that accelerate or block the flow; the relative elevation of particular terrain features; proximity to lakes, oceans, or other large water bodies; or any combination of the above.

Mapping Products

Wind Power Maps and Classifications

The primary output of the mapping system is a color-coded wind power map in units of W/m^2 (wind power density) and equivalent mean wind speed for each individual grid cell. Wind power density is a better indicator of the available resource because it incorporates the combined effects of the wind speed frequency distribution, the dependence of the wind power on air density, and the cube of the wind speed. The final wind power values for Cuba are estimates that account for NREL's empirical adjustments (where necessary) and the surface roughness of each grid cell derived from the MASS model output.

Seven wind power classifications, based on ranges of wind power density, were used for the Cuba map. Each of the classifications was qualitatively defined for utility-scale applications (poor to excellent). In general, locations with an annual average wind resource greater than 400 W/m^2 (or about 7.0 m/s) at 50 m above ground are the most suitable for utility-scale applications.

Additional Mapping Products

The mapping system output uses software to produce the proper map projection for the study region, and to label the map with useful information such as a legend, latitude and longitude lines, locations of meteorological and other wind measurement stations, important cities, and a distance scale. The DEM data can also be used to create a color-coded elevation map, a hill-shaded relief map, and a map of the elevation contours. When combined with the wind power maps, these products provide the user with a three-dimensional image of the distribution of the wind power in the analysis region.

Limitations of Mapping Technique

There are several limitations to the mapping technique, the first of which is the resolution of the DEM terrain data. Significant terrain variations can occur within the DEM's 1 km^2 area; thus, the wind resource estimate for a particular grid cell may not apply to all areas within the cell. A second potential problem lies with the extrapolation of the conceptual model of the wind flow to the analysis region. Many complexities in the wind flow exist that make this an inexact methodology. The complexities include the structure of low-level jets and their interaction with the boundary layer; localized circulations, such as land-sea breezes, and mountain-valley flows; and channeling effects in areas of steeply sloping terrain. Finally, the power estimates in Cuba are based on each grid cell's surface roughness based on the MASS output. Because the geophysical input to MASS is not 100% accurate, there can be errors in the surface roughness estimate and consequently the level of wind resource for particular locations in Cuba.

Analysis and Mapping Results

This section describes the results of the evaluation of data from wind measurement locations, the validation and adjustment of the numerical model estimates, and the final wind resource estimates including their confirmation with available measurement data.

Evaluation of Wind Measurement Data

Unfortunately, no wind measurement data were available from towers at heights of 30 m and above for use in the wind mapping and validation of the 50-m wind resource estimates.

NREL processed the observation data for 61 meteorological stations included in the DATSAV2 data set and also obtained summaries of wind data for selected meteorological stations from CMI. Major limitations of the meteorological station data in the validation process include lack of information on the exposure of the wind measurement equipment and the variation of the wind resource with height (wind shear) to extrapolate the 10-m measurements up to the 50-m height. A major advantage of the meteorological station data was the long period of selected data (several years or more) at many of the stations used in the validation. Meteorological stations in Cuba may be located at an airport or in the city. Our analysis of wind data from airports and city meteorological stations located nearby indicated that average wind speeds measured at airports in Cuba are often more than 1.5 to 2 times those measured at the city stations. Therefore, the estimated wind power densities for the airports are several times more than those for the city stations. Wind data from airports are usually more reliable than data collected at city stations where wind measurements are likely to be reduced by buildings and other obstructions. This explains why we prefer the data from airport anemometers (rather than city stations) where available. A small reduction of just 1 m/s in the measured wind speed can result in a large reduction (such as 30% to 50%) in the wind power density. NREL has documented comparisons of airport and city station wind measurements in other wind resource assessment studies including one for Mexico.

For most inland regions of Cuba, the best wind measurement data for the wind assessment and validation efforts were largely the data from airports, for reasons described above. For elevated terrain features, such as hilltops and mountain summits, no data were available from measurement stations except for one high-elevation mountain summit in southeastern Cuba. Therefore, the upper-air data provided the primary basis for the validation of numerical model estimates for elevated terrain features. The upper-air data shows a strong low-level maximum of wind resource, especially in central and eastern Cuba, which provided useful validation data for exposed terrain features located at elevations within or near the low-level wind maximum.

For coastal areas, data were available from some exposed coastal stations in different regions of Cuba. The ocean satellite data were also used in the wind resource assessment of coastal and offshore areas.

Validation and Adjustment of Numerical Model Data

NREL compared the numerical model data for Cuba to its estimates of the wind resource based on the intensive analysis of other data sets described above (surface data, upper-air data, and satellite ocean data). These validation results were then used by NREL to identify regions where its analytical and empirical methods would be applied in revising the estimates from the numerical model data. These revisions resulted in substantial increases in the wind resource over areas of eastern Cuba, hills and ridges in central and western Cuba, Isla de la Juventud in southwestern Cuba, specific coastal and offshore areas, and a few other specific places. The upper-air data shows that the strongest winds aloft are at elevations of only 300 m to 600 m above sea level, where the low-level wind speed maximum occurs. The numerical model data underestimated the strength of this low-level wind maximum, thus exposed terrain features located at or near the these elevations had some of the largest increases. In eastern Cuba, these areas included the hills and elevated terrain features from Camaguey to Holguin to Cabo Lucrecia. Other specific areas of eastern Cuba with increases included many coastal areas, hills of the eastern tip, and a wind corridor region north of Santiago de Cuba. The leeward plains and coasts, such as the region from Bayamo to southwest of Camaguey, had modest increases. The higher ridges and mountain summits located generally south and east of Bayamo, including those in the Sierra Maestra, were unchanged or had slight decreases.

Summary of Cuba's Wind Resource and Confirmation of Final Estimates

Much of the northern coast and southeastern coast of Cuba is estimated to have Class 3 resource, with some Class 4 areas in southeastern coastal and offshore areas. The Class 3 coastal resource is confirmed by data from stations at Moa and Punta Lucrecia. Other coastal stations confirm the Class 2 coastal resource (Baracoa, Casablanca, Varadero, Cabo San Antonio, Cabo Cruz, Punta Maisi), although the resource could be Class 3 in more exposed areas that may exist near of some of these stations. The station at Cayo Largo del Sur confirms the Class 2 resource estimate for offshore areas of southwestern Cuba.

The Class 2 resource estimates in many areas of central and eastern Cuba are confirmed by the airport measurement data, including Camaguey, Victoria de las Tunas, Holguin, Bayamo, and Manzanillo. These airports are located at elevations of approximately 100 m or lower. Many of the exposed terrain areas at higher elevations, such as 200 m to 500 m above sea level, are estimated to have from Class 3 to 5, based on analysis of the upper-air wind data.

The windiest airport in Cuba is Nueva Gerona on Isla de la Juventud, where the data indicated at least Class 3 potential. This is reflected by the Class 3 estimates for much of the northern part of Isla de la Juventud.

The only mountain summit station with wind data was Gran Piedra at 1226 m elevation, located near Santiago de Cuba in southeastern Cuba. These data confirm the Class 3 estimates for some of these high ridges and mountain summits. Upper-air data indicate that the wind resource decreases substantially at elevations above 800 m, so the higher ridge crests and mountain summits of southeastern Cuba are generally estimated to have only Class 2-3 resources. The wind resource map shows some lower elevation wind corridors (such as one north of Santiago de Cuba) and other areas of good-to-excellent resource in southeastern Cuba, but no measurement data were available from these areas.

Gross Wind Electric Potential

The wind resource classifications in the following tables match those shown on the wind resource maps. The installed capacity in the table represents gross wind electric potential not reduced by factors such as land-use exclusions, the existing transmission grid, and accessibility. The methods for converting the wind resource to wind electric potential are those used regularly by NREL. The assumptions used for the wind potential calculations are listed at the bottom of Table 1.

Each color-coded square kilometer on the map has an assigned annual wind power density at the 50-m height expressed in units of W/m^2. NREL uses a simple formula to compute the potential installed capacity in MW for grid cells with an annual wind power density of 300 W/m^2 and greater (moderate-to-excellent wind resource for utility-scale wind applications). The potential installed capacity of a grid cell was set equal to zero, if its wind power density was less than 300 W/m^2. Another scenario presented in this section included only those grid cells with an annual average power density of 400 W/m^2 and greater (good-to-excellent wind resource for utility-scale wind applications).

The estimates of windy area and potential wind capacity are listed in Table 1 for Cuba, and by province in Table 2. These areas include all land on the main land mass and offshore islands. Water bodies that are entirely or part inside the main land mass of the mapped region are also included. Offshore water areas are not included.

Table 1. Cuba – Wind Electric Potential

Good-to-Excellent Wind Resource at 50 m

Wind Resource Utility Scale	Wind Class	Wind Power at 50 m W/m^2	Wind Speed at 50 m m/s*	Total Area km^2	Percent Windy Land	Total Capacity Installed MW
Good	4	400 – 500	7.0 – 7.5	448	0.4	2,240
Excellent	5	500 – 600	7.5 – 8.0	63	<0.1	315
Total				511	0.5	2,555

Moderate-to-Excellent Wind Resource at 50 m

Wind Resource Utility Scale	Wind Class	Wind Power at 50 m W/m^2	Wind Speed at 50 m m/s*	Total Area km^2	Percent Windy Land	Total Capacity Installed MW
Moderate	3	300 – 400	6.4 – 7.0	3,770	3.4	18,850
Good	4	400 – 500	7.0 – 7.5	448	0.4	2,240
Excellent	5	500 – 600	7.5 – 8.0	63	<0.1	315
Total				4,281	3.9	21,405

*** Wind speeds are based on a Weibull k value of 2.0**

<u>Assumptions</u>
Installed capacity per km^2 = 5 MW
Total land area of Cuba = 110,860 km^2

Table 2. Wind Electric Potential by Province

Moderate to Excellent Wind Resource by Province

Province	Class 3 (km^2)	Class 4 (km^2)	Class 5 (km^2)	Good to Excellent Potential (MW)	Moderate to Excellent Potential (MW))
Camaguey	396	0	0	0	1,980
Ciego de Avila	57	11	0	55	340
Cienfuegos	43	9	1	50	265
Ciudad de la Habana	0	0	0	0	0
Granma	2	0	0	0	10
Guantanamo	277	81	4	425	1,810
Holguin	930	195	56	1,255	5,905
Isla de la Juventud (special municipality)	949	0	0	0	4,745
La Habana	120	0	0	0	600
Las Tunas	158	0	0	0	790
Matanzas	93	0	0	0	465
Pinar del Rio	17	0	0	0	85
Sancti Spiritus	154	38	0	190	960
Santiago de Cuba	278	114	2	580	1,970
Villa Clara	296	0	0	0	1,480
Total	3,770	448	63	2,555	21,405

Assumptions
Installed capacity per km^2 = 5 MW

We estimate that there are 511 km^2 of areas with good-to-excellent wind resource potential in Cuba, and these windy areas represent 0.5% of Cuba's total land area of 110,860 km^2. Using a conservative assumption of 5 MW per km^2, this windy area could support more than 2,500 MW of potential installed capacity.

If additional areas with moderate wind resource potential are considered, the estimated total windy area (as shown in Table 1) increases to 4,281 km^2. This amount of windy area represents 3.9% of Cuba's total area and could support more than 21,000 MW of installed capacity.

Additional studies are required to accurately assess the wind electric potential, considering factors such as land-use exclusions and the existing transmission grid and accessibility.