Ghana 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 Ghana. 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 Ghana 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 Ghana.

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 Ghana that included summaries of wind data from meteorological stations and wind measurement towers installed for assessing the wind resource.

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.

Twenty-one stations in Ghana are included in the DATSAV2 data set. NREL processed these data (plus a few stations in other countries located near the borders of Ghana) for initial examination and potential use in its meteorological evaluation and validation of the numerical model data for the Ghana region. The major drawback of the DATSAV2 Ghana data is that the anemometers were only 2 m above the ground except for two airport locations (Accra and Takoradi) where the anemometer height was 10 m. Because of obstructions and surface roughness near the ground, 2 m data are not generally very useful for assessing the wind resource at 50 m. The number of observations at the individual sites for each year and from year to year is highly variable. The stations in Ghana typically recorded data every 3 hours, though the Accra airport recorded hourly data.

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 Ghana Meteorological Service Department

NREL received summaries of wind measurements taken at the 22 synoptic stations operated by the Meteorological Service Department (MSD) of Ghana. The list of stations included the 21 stations in the DATSAV2 data set plus one additional synoptic station. The MSD information consisted of monthly mean wind speeds adjusted to 12 m and 50 m above ground for the period 1995-2002.

Energy Commission Data

The Energy Commission (EC) of Ghana initiated a wind measurement program in 1999 at 5 sites near and along the coast of Ghana near Accra. The anemometer height at these measurement stations was 12 m. The EC established another five sites in 2001 to cover the coastal areas from the Cote D'Ivoire to Togo. Anemometers again were established at 12 m. NREL received data summaries from its Ghana partners for these 10 sites. The periods-of-record were between one and two years.

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 two locations in Ghana, Accra and Tamale. These data were supplemented by ADP data from stations in the surrounding countries. Because collection of these data in this region was not as consistent as in other parts of the world, information on the vertical profile of wind speed and power was not readily extracted from the ADP data. Therefore, NREL largely depended on the reanalysis data set, described below, for its analysis of the upper-air 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 Ghana 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 Ghana wind resource along the southern coast. 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 Ghana. However, due to inherent uncertainties with the satellite-based estimates, they should be compared with available measurement data wherever possible. The QuikSCAT satellite estimates were used most prominently in the Ghana assessment because the pattern of its wind estimates agreed most closely with the data measured at the coastal stations.

Numerical Model Data

AWS Truewind (AWST), of Albany, New York, provided NREL with wind speed and wind power data for Ghana 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 Ghana. 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 Ghana. NREL's approach depends on the critical analysis of all the available surface and upper-air data for the Ghana 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 the surface stations and 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 wind data from coastal wind measurement towers obtained from sources in Ghana, 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 Ghana 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 Ghana 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 Ghana 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 Ghana 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 Ghana 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 Ghana.

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 and analyzed the observation data for 21 meteorological stations included in the DATSAV2 data set and analyzed summaries of wind data for 10 wind measurement towers established by the Energy Commission of Ghana. The major drawback of the meteorological station data in Ghana is that anemometers were only 2 m above ground except for two airport locations (Accra and Takoradi) where the anemometer height was 10 m. Because of obstructions and surface roughness near the ground, 2 m average wind speeds were generally very low (less than 2-3 m/s) and these data were considered not reliable for assessing the wind resource at 50 m.

The best surface wind measurement data for the Ghana wind assessment and validation efforts were all from coastal areas, because the two airport stations and the 10 EC measurement stations (12-m anemometer heights) were located in coastal areas. The ocean satellite wind data were also used in the assessment and validation of coastal and offshore areas.

For inland regions of Ghana, all the measurement stations had anemometer heights of only 2m and were not considered reliable for use in the assessment for reasons previously described. Therefore, the upper-air data provided the primary basis for the assessment and validation of numerical model estimates, especially for elevated terrain features, as discussed below.

Validation and Adjustment of Numerical Model Data

NREL compared the numerical model data for Ghana 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 many of the elevated terrain features throughout much of Ghana, coastal and offshore areas, and a few other specific places. The upper-air data shows a strong low-level jet especially in central regions of Ghana, which justified increasing the wind resource values for many of the elevated and exposed terrain features. The jet speeds are strongest at heights of 600 m to 1000 m above sea level and from April to October when the southwest monsoon winds are most intense.

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

Areas estimated to Class 3 and higher wind resource primarily occur on exposed elevated terrain features, such as hilltops and ridge crests, at elevations generally above about 450 m. Unfortunately, no data from wind measurement towers were available from these areas. The strongest winds aloft are in central and northern Ghana at heights of 600 m to 1000 m above sea level. Some of the most promising areas estimated to have good-to-excellent (Class 4-6) wind resource are the highest ridges near the border with Togo and the highest ridges northwest of Accra from about 6 degrees to 8 degrees latitude.

Along coastal areas, wind data from the Energy Commission of Ghana measurement program at 12-m height generally confirmed the Class 2 coastal resource in southeast Ghana and Class 1-2 coastal resource in southwest Ghana. The QuikSCAT ocean satellite wind data confirmed the Class 2 offshore estimates for southeast Ghana and Class 1 estimates for southwest Ghana. The windiest areas, according to the ocean satellite data and available wind measurement data, are located east of 0 degree longitude.

Class 1 wind resource is estimated for most inland areas of Ghana, expect for elevated terrain areas and near the southwest arm of Lake Volta. All the inland meteorological stations in Ghana were located in areas estimated to have only Class 1 resource. The anemometer heights at all the inland meteorological stations were just 2 meters above ground and the measured wind speeds were very low, with annual average values less than 2 m/s. Although these data were unreliable for use in the confirmation of the 50-m resource estimates, the assessment results based on other data and methods indicate that these stations were indeed located in low wind resource areas which could help to explain why the measured 2-m speeds were very low. In coastal areas where Class 2 resource is estimated, the average wind speeds measured by the 2-m meteorological stations were generally in the range of 2-3 m/s, which is somewhat higher than those measured at the inland stations.

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 Ghana, and by province in Table 2. These areas include all land on the main land mass, and water bodies that are entirely or part inside the main land mass. Offshore water areas are not included.

We estimate that there are 413 km^2 of areas with good-to-excellent wind resource potential in Ghana, and these windy areas represent 0.2% of Ghana's total land area of 230,940 km^2. Using a conservative assumption of 5 MW per km^2, this windy area could support more than 2,000 MW of potential installed wind capacity.

If additional areas with moderate wind resource potential are considered, the estimated total windy area (as shown in Table 1) increases to 1,128 km^2. This amount of windy area represents 0.5% of Ghana's total area and could support more than 5,600 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.

Table 1. Ghana – 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	268	0.1	1,340
Excellent	5	500 – 600	7.5 – 8.0	82	<0.1	410
Excellent	6	600 – 800	8.0 – 8.8	63	<0.1	315
Total				413	0.2	2,065

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	715	0.3	3,575
Good	4	400 – 500	7.0 – 7.5	268	0.1	1,340
Excellent	5	500 – 600	7.5 – 8.0	82	<0.1	410
Excellent	6	600 – 800	8.0 – 8.8	63	<0.1	315
Total				1,128	0.5	5,640

* **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 Ghana = 230,940 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)	Class 6 (km^2)	Good to Excellent Potential (MW)	Moderate to Excellent Potential (MW))
Ashanti	93	11	0	0	55	520
Brong-Ahafo	83	17	16	2	175	590
Central	0	0	0	0	0	0
Eastern	285	26	0	0	130	1,555
Greater Accra	0	0	0	0	0	0
Northern	73	53	0	0	265	630
Upper East	0	0	0	0	0	0
Upper West	0	0	0	0	0	0
Volta	181	161	66	61	1,440	2,345
Western	0	0	0	0	0	0
Total	715	268	82	63	2,065	5,640

Assumptions
Installed capacity per km^2 = 5 MW