Central America Wind Energy Resource Mapping Activity

Introduction

This document describes the development of detailed high-resolution (1 km^2) wind energy resource maps for the region of Central America that includes the countries of Belize, El Salvador, Guatemala, Honduras, and Nicaragua. 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 regional wind mapping activity covered vast areas totaling about 400,000 km^2 of land area and, including offshore areas, almost 500,000 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 Central America 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 the mapped region of Central America and each country.

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 Central America that included data from 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.

NREL processed 50 stations from the DATSAV2 data set for initial examination and potential use in its meteorological evaluation and validation of the numerical model data. These stations were largely from the five Central American countries but also included a few stations from other countries that were located near the borders of the mapping region. The number of observations at the individual stations for each year and from year to year is highly variable. The stations in Central America typically recorded data every 3 hours, though some of the larger airports recorded hourly observations.

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 Kenetech Measurement Data

NREL has measurement data from Kenetech Wind Power (now defunct) as part of its global meteorological data set. Data from 14 Kenetech towers in Central America were used in the mapping project. Anemometer heights varied from tower to tower but 30 m measurements were available at most of the towers.

National Rural Electric Cooperative Association (NRECA) Data

NRECA sent to NREL data from 19 measurement stations in Central America established during the 1990s. The measurement towers varied in size with 30 m or 40 m usually the highest anemometer level on the tower.

Supplemental Meteorological Stations

NREL received data summaries for 55 additional meteorological stations from NRECA and the Central American partners. Some of the organizations that provided data were the University of Central America (El Salvador), the National Energy Commission (Nicaragua), and the Department of Energy (Honduras).

Proprietary Data from Wind Developers

NREL was able to obtain proprietary data from various wind developers taken at locations in Belize, Guatemala, Honduras, and Nicaragua. Data from 22 developer locations were used in the mapping project. The measurement towers varied in size with 30 m or 40 m usually the highest anemometer level on the tower.

Upper-air Data

NREL's in-house 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 seven locations in the Central America mapping region and border areas. 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.

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 Central America 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 Central America. 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 coasts of Central America. 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 the Central America mapping region 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 Central America. 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 Central America. NREL's approach depends on the critical analysis of all the available surface and upper-air data for the Central America 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 100 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 high-quality data from available wind measurement towers, 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 Central America 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 Central America 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 the Central America region 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 maps of the Central America region. 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 Central America 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 Central America.

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

The considerable high-quality wind data from more than 50 wind measurement towers obtained from NRECA, Kenetech, and wind developers were quite valuable in developing more accurate wind resource maps than would have been possible otherwise. Many of the measurement towers were located in areas of good-to-excellent wind resource and had anemometers at heights up to 30 m and 40 m above ground, which are much better for validation purposes than data from heights near 10 m such as those from the meteorological stations. However, limitations with the data from the wind measurement towers and the resulting uncertainties need to be recognized to appropriately apply these data in the validation process. Uncertainties result from short periods of data collection, and possible effects of tower structures and mounting booms on measurement accuracy. Only about one year of data was available for many of the measurement sites. Yearly wind speeds can vary up to 10% or more from the long-term means, and yearly wind power densities can vary up to 30% or more from the long-term means. We did not attempt to evaluate if an individual year (or period of measurement) may be a typical, low, or high wind year. Tower shadow effects and mounting booms can cause reductions in the measured wind speeds, but these reductions are not easily quantified.

NREL processed the observation data from 50 meteorological stations and obtained summaries of the wind data for 55 additional stations. 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 wind resource 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. Most of the meteorological stations are located in low wind resource areas, which limited their use except for verifying the low wind resource usually indicated by the numerical model data for these areas. Moreover, meteorological stations located in good wind resource areas sometimes indicated low wind resource because of obstructions that severely reduced the wind speed measurements. The Rivas meteorological station, which is located in a windy region of southern Nicaragua, is example of a station where the 10-m measurements are severely reduced by obstructions and consequently the measured wind speeds are quite low. Meteorological stations in Central America may be located at an airport or in the city. In some places such as Guatemala City, the anemometers from the airport (La Aurora) and meteorological service (Insivumeh) are nearby, but there are dramatic differences in the annual average measured wind speeds and wind power densities at 10 m. The averages for the airport anemometer are 5.3 m/s and 137 W/m^2, whereas they are only 1.8 m/s and 18 W/m^2 for the meteorological service anemometer which is severely obstructed to the prevailing winds from the north. This explains why we usually preferred the data from airport anemometers, rather than urban locations, where available.

Validation and Adjustment of Numerical Model Data

NREL compared the numerical model data for Central America 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 southern Nicaragua (especially Rivas Province and Lake Nicaragua), coastal and offshore areas of the Caribbean Sea (especially the coastal and offshore areas of eastern Honduras and northern Nicaragua), many of the ridge crests and elevated terrain features in Central America, Huite region of Guatemala, and other specific places. The numerical model data remained unchanged in many areas of Central America, including the good-to-excellent resource areas shown for elevated terrain features and wind corridors throughout much of the mountainous region extending from southwestern Nicaragua through southern Honduras and El Salvador to southeastern Guatemala.

We believe that the high wind resource shown for some of the leeward downslope areas of the mountainous terrain could be overestimated by the model, but without sufficient data from these areas we generally left these estimates unchanged. However, there was data to validate the estimates in specific places in these mountainous regions as described below. In other regions such as southern Nicaragua (particularly Rivas Province and Lake Nicaragua), Huite region of Guatemala, some and coastal and offshore areas of Caribbean Sea, the available data showed considerably higher wind resource than indicated by the model data which justified revising these areas. Upper-air data and some wind measurement data from elevated terrain areas in Belize and northern areas of Honduras and eastern areas of Nicaragua indicated higher resource than the model data, so these areas were revised accordingly.

Country Summaries of Wind Resource and Confirmation of Final Estimates

Nicaragua

Data from NRECA, Kenetech, and wind developers confirm the areas of good-to-excellent wind resource (Class 4-7) in southern Nicaragua including the inland areas of Rivas province, Lake Nicaragua shores and islands, and elevated terrain areas in the regions near Managua and Juigalpa. There are numerous other areas of good-to-excellent wind resource in western Nicaragua, as indicated by the wind map. Ocean satellite data show the areas of good-to-excellent resource of the Pacific Ocean coastal and offshore areas of southern Nicaragua, particularly the coastal areas of Rivas Province where the data indicate excellent potential. However, along the northwestern coastal and offshore areas of Nicaragua, the ocean satellite data indicate low-to-marginal wind resource (Class 1-2). Along the Caribbean Sea, the ocean satellite data indicate the areas of moderate-to-good wind resource (Class 3-4) for exposed coastal areas and offshore islands. No wind measurement data were available for these exposed coastal and offshore areas of the Caribbean Sea; however, data from Puerto Cabezas airport located a few kilometers inland of the coast indicates Class 2 wind resource. In these coastal areas of eastern Nicaragua, the wind resource can decrease rapidly inland of the coast (as shown on the wind map) because of tree cover and atmospheric stability effects.

Honduras

Data from Kenetech and wind developers confirm the areas of good-to-excellent wind resource (Class 4-7) on the ridge crests and elevated terrain areas in the region near Tegucigalpa, particularly at several sites near Santa Ana along the divide south of Tegucigalpa. Moreover, upper-air data from Tegucigalpa confirm the very strong winds aloft that occur in this region. There are numerous other areas of good-to-excellent wind resource in southern Honduras, as indicated by the wind map. Some of the prominent ridge crests in northern Honduras are expected to have good wind resource, based on upper-air data and as indicated on the wind map, but no measurement data were available from these areas. Ocean satellite data show the areas of moderate-to-good wind resource (Class 3-4) for exposed coastal areas and offshore islands of the Caribbean Sea, except for the western coast of Honduras where the resource decreases to only Class 1-2. Unfortunately, no wind measurement data were available to confirm the Class 3-4 resource estimated for the exposed coastal areas. Data from NRECA (Roatan) and meteorological stations (Guanaja) confirm the Class 3-4 resource on the offshore islands.

El Salvador

The map of El Salvador shows many areas of good-to-excellent wind resource, particularly on elevated terrain areas of southwest and northwest El Salvador and along the border with Honduras. The only confirmation of good wind resource in El Salvador is from the Cerro Verde meteorological station located on elevated terrain. According to a report by NRECA, the annual average 10-m wind speed measured at this station was 6.4 m/s. NRECA installed three wind measurement towers in El Salvador, but unfortunately insufficient data were available from these locations for validation purposes. For coastal and offshore areas, ocean satellite data and meteorological station data confirm the low-to-marginal resource estimated for most areas; however, the wind maps indicates some promising coastal areas near the border with Guatemala and eastern places near the Gulf of Fonseca.

Guatemala

Data from NRECA, Kenetech, and wind developers confirm areas of good wind resource in southeastern Guatemala. Data were available from several different regions including passes and exposed terrain areas located south of Guatemala City and Antigua, ridges near Comapa and the border with El Salvador, and ridges in the Huite region near Zacapa. The wind map shows many other areas in southern and eastern Guatemala with good-to-excellent wind resources. The map indicates that the wind resource is generally less at very high elevations, such as those above 2500-3000 m, than exposed terrain features at elevations of 800-2000 m. This reduced wind resource at very high elevations is confirmed by upper-air data and by measurement towers, including data from a site at 3300 m elevation in southwestern Guatemala where measured wind resource was only low-to-marginal (Class 1-2). Data from the coastal areas of Guatemala, from both the Pacific Ocean coast and the Gulf of Honduras (Caribbean Sea) confirm the low resource estimates generally shown by the wind map for these areas, and ocean satellite data also indicated low wind resource for the offshore areas. No data were available to confirm the Class 3-4 resource estimated for the Pacific coastal area near the border with El Salvador.

Belize

Data from NRECA and wind developers confirm the moderate-to-good wind resource (Class 3-4) in well exposed areas of elevated terrain in Belize. Upper-air data from Belize also show the strong winds aloft at elevations of 600 m and above, which would support the good wind resource in elevated terrain areas. The wind map shows low-to-marginal wind resource (Class 1-2) along most of the coastal area of Belize, except for moderate (Class 3) resource in northern areas. The Class 1-2 resource for coastal areas from Belize southward is confirmed by data from wind developers and from the Belize airport. The Class 3 estimates for the extreme northern areas including the offshore islands is confirmed by an NREL wind measurement tower installed in Xcalac, Mexico, about 5 km north of the Belize border on Ambergris Cay. Several years of data from the Xcalac tower indicated high Class 3 to low Class 4 resource, so based on these data some of the offshore islands and cays of Belize could have up to Class 4 resource. The Class 3 estimates for the coastal areas of Chetumal Bay in northern Belize are confirmed by data from Chetumal, Mexico, airport which is located about 2 km north of the Belize border.

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 the Central America region, and by country 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, most significantly Lake Nicaragua, are also included. Offshore water areas are not included.

We estimate that there are 12,969 km^2 of areas with good-to-excellent wind resource potential in the mapped region of Central America, and these windy areas represent 3.3% the mapped region. Using a conservative assumption of 5 MW per km^2, this windy area could support almost 65,000 MW of potential installed capacity. There are 5713 km^2 (1.5% of the mapped region) considered to have excellent wind resource potential, and this windy area could support more than 28,500 MW of capacity.

If additional areas with moderate wind resource potential are considered, the estimated total windy area (as shown in Table 1) increases to more than 26,000 km^2. This amount of windy area represents 6.7% of the mapped region and could support more than 130,000 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.

Table 1. Central America – Gross 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	7,256	1.8	36,280
Excellent	5	500 – 600	7.5 – 8.0	2,983	0.8	14,915
Excellent	6	600 – 800	8.0 – 8.8	2,293	0.6	11,465
Excellent	7	> 800	> 8.8	437	0.1	2,185
Total				12,969	3.3	64,845

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	13,270	3.4	66,350
Good	4	400 – 500	7.0 – 7.5	7,256	1.8	36,280
Excellent	5	500 – 600	7.5 – 8.0	2,983	0.8	14,915
Excellent	6	600 – 800	8.0 – 8.8	2,293	0.6	11,465
Excellent	7	> 800	> 8.8	437	0.1	2,185
Total				26,239	6.7	131,195

*** Wind speeds assume a Weibull k value of 2.0 and sea level air density**

<u>Assumptions</u>
Installed capacity per km^2 = 5 MW
Total land area of mapped countries in Central America = 394,280 km^2

Table 2. Gross Wind Electric Potential by Country

Country	Class 3 (km^2)	Class 4 (km^2)	Class 5 (km^2)	Class 6 (km^2)	Class 7 (km^2)	Good to Excellent Potential (MW)	Moderate to Excellent Potential (MW)	Good to Excellent Percent Windy Land	Mod. to Excellent Percent Windy Land
Belize	497	234	6	0	0	1,200	3,685	1.1%	3.3%
El Salvador	1,195	750	313	269	44	6,880	12,855	6.6%	12.4%
Guatemala	1,877	1,003	320	200	45	7,840	17,225	1.4%	3.1%
Honduras	2,880	1,211	485	355	121	10,860	25,260	1.9%	4.5%
Nicaragua	6,821	4,058	1,859	1,469	227	38,065	72,170	5.9%	11.2%
Total	13,270	7,256	2,983	2,293	437	64,845	131,195	3.3%	6.7%

<u>Assumptions</u>
Installed capacity per km^2 = 5 MW