Bhutan Wind Resource Mapping

Introduction

This document describes the development of a detailed high-resolution (1-km^2) wind energy resource map for the country of Bhutan. The map was created by the United States Department of Energy's National Renewable Energy Laboratory (NREL) in support of a project sponsored by the United States Agency for International Development's (USAID) South Asia Regional Initiative for Energy Cooperation and Development (SARI/Energy).

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 Bhutan wind-mapping activity. We also present the results of the wind resource assessment, highlighting the major wind resource areas identified.

Meteorological Data

An accurate wind resource assessment depends on the quantity and quality of the available meteorological data. As part of its overall evaluation, NREL reviews many sources of wind data and previous wind assessments. Analysts reviewed several NREL-maintained global data sets for this assessment, including surface and upper-air observations spanning many years of record. These data were supplemented with information from sources in Bhutan that included wind data from meteorological stations.

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 summarize the surface data sets obtained and examined in the assessment.

<u>ISH Data</u>

The Integrated Surface Hourly (ISH) 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 ISH data set.

Unfortunately, the ISH data set did not include any stations in Bhutan, but it included a few stations in other countries near the borders of Bhutan. NREL processed these data for initial examination of the wind resource characteristics in areas near Bhutan. The processed data records from the ISH data contained monthly and annual averages of wind speed and wind power. These data are useful for evaluating the interannual and monthly variability, the diurnal distribution of wind speed and wind power, and the joint frequency of wind speed and direction.

Meteorological Station Data from Bhutan

The Department of Energy, Ministry of Economic Affairs, Royal Government of Bhutan provided NREL with hourly wind measurement data collected at the 12 meteorological stations in Bhutan listed in the table below. Periods of data collection at the stations ranged from about one to three years except for four years at the capital city of Thimphu. The reported anemometer heights above ground were 5 meters at eight stations and 20 meters at four stations.

Information on the Bhutan Meteorological Stations

Station and Anem Hgt	Lat (dd mm)	Lon (dd mm)	Elev (m)	From	To
Bhur 20m	26 54.233	90 26.033	380	2006-03-26	2008-05-19
Bumthang 5m	27 32.417	90 45.300	2569	2005-01-01	2007-11-04
Dagana 5m	27 04.267	89 52.267	1472	2006-03-06	2008-05-30
Deothang 5m	26 51.350	91 28.000	305	2006-09-09	2008-05-03
Gasa 5m	27 54.000	89 42.983	2780	2006-06-16	2007-11-03
Kanglung 20m	27 16.950	91 31.333	1945	2005-07-07	2007-11-06
Punakha 5m	27 34.900	89 51.983	1247	2006-06-14	2008-05-17
Thimphu 5m	27 28.267	89 38.233	2303	2004-03-19	2008-05-22
Trongsa 5m	27 30.117	90 30.300	2136	2006-05-01	2008-05-04
Tsirang 20m	27 00.000	90 07.300	1532	2006-05-09	2007-09-30
Tyangtse 5m	27 36.000	91 30.000	1841	2006-05-01	2008-05-03
Wangdi 20m	27 29.200	89 54.050	1190	2006-09-29	2008-04-20

NREL processed these data to analyze the wind resource characteristics at each station including the monthly and annual averages of wind speed and wind power, the diurnal distribution of wind speeds, and the joint frequency of wind speed and direction.

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. Although ADP upper-air data were not available for locations in Bhutan, ADP data from stations in the surrounding countries were useful in examining the general characteristics of the winds in the region.

Numerical Model Data

AWS Truewind (AWST), of Albany, New York, provided NREL with wind speed and wind power data for Bhutan on a 1 km-by-1 km grid with data at levels from 30 m to 200 m above ground. This data set was used as an initial estimate for the distribution of the wind speed and power in Bhutan. 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 Bhutan. NREL's approach depends on the critical analysis of all of the available surface and upper-air data for the mapping region and the surrounding area. 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 vary greatly. 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 various data summaries and time-series of data were evaluated to identify suspicious or questionable data. The goal was to select the most representative data for the assessment.

Upper-Air Data Evaluation

Upper-air data can be useful in assessing the regional wind resource in several ways. Bhutan is largely a very mountainous country. The upper-air data can be used to approximate vertical profiles of wind speed and power, and to extrapolate the wind resource to elevated terrain features such as ridge crests and mountain summits.

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.

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: input data, wind power adjustments, and an 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 or finer 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. This is based on NREL's meteorological analysis and a comparison of the numerical model data to wind measurement data available for the study region.

AWST provided NREL with the initial wind power density values for each grid cell in the Bhutan mapping region and 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 Bhutan and the surrounding area for 366 days randomly selected from the 1989-2003 15-year historical record. The random sampling was stratified so that each month and season was represented equally in the sample; only the year is randomized. 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 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 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 Bhutan 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 Bhutan map. Each of the classifications was qualitatively defined (poor to excellent) generally appropriate for large wind power applications. In general, locations with an annual average wind resource greater than 300 W/m^2 at 50 m above ground are suitable for large wind energy applications. Small wind energy applications may be feasible with lower levels of wind resource.

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 localized circulations, such as mountain-valley flows and channeling effects in areas of steeply sloping terrain. Finally, the power estimates in Bhutan 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 Bhutan.

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 above 20 m for use in the wind mapping and validation of the 50-m wind resource estimates.

NREL processed and analyzed the observation data for the 12 meteorological stations in Bhutan provided by the Bhutan Department of Energy. The major drawback of the meteorological station data in Bhutan is that anemometers were only 5 m above ground at eight of the 12 stations. Because of obstructions and surface roughness near the ground, there is considerable uncertainty in the wind speeds and wind power densities particularly for the data collected at only 5 m above ground. Nevertheless, data from three of the eight stations with measurements at 5-m height indicated significant wind resource. These stations were Bumthang, Punakha, and Tyangtse. Data from two of the four stations with measurements at 20-m height indicated significant wind resource. These stations were Tsirang and Wangdi. The five stations with significant wind resource indicate at least one or more seasons with “good to excellent” wind potential (Class 4-7 wind resource) and “moderate to excellent” wind potential on an annual basis. In general, the strongest winds at these stations were observed from late morning to afternoon. The winds are frequently very strong at these stations around midday to early afternoon, and typically light or calm from during night to early morning hours.

In the Bhutan valley areas that have strong daytime winds, an annual or monthly average wind speed alone is not a reliable indicator of the wind resource because calm and light winds are often prevalent during most of the evening, night, and early morning hours. For example, Tyangtse (located in a valley area of northeast Bhutan) has an annual wind speed of 4.6 m/s at 5-m height, which could infer only marginal wind resource. However, Tyangtse has an annual wind power density of 318 W/m^2 at 5-m height, which indicates “excellent” wind energy potential. The high wind energy potential at Tyangtse is due to the wind power available from the very strong wind speeds (> 10 m/s) that occur from about 10 a.m. to 4 p.m. throughout most of the year.

The 12 meteorological stations in Bhutan are in valley regions. There are no measurement stations on elevated mountain summits and ridge crests in Bhutan. Therefore, the upper-air data provided the primary basis for the assessment and validation of numerical model estimates for the elevated terrain features.

Validation and Adjustment of Numerical Model Data

NREL compared the numerical model data for Bhutan to its estimates of the wind resource based on the intensive analysis of other data sets described above. NREL then used these validation results 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 for many valley areas throughout much of Bhutan. As noted above, the measurement data from the meteorological stations indicated valley areas with "moderate to excellent" wind energy potential. The numerical model data indicated only low wind resource potential in the valley areas of Bhutan. Evidently, the numerical model methods could not resolve the strong mountain-valley circulations that are apparent in many of the valley areas of Bhutan. In addition to the wind resource areas identified by the measurement data, NREL has identified many other valley areas estimated to have significant wind resources.

HOMER Wind Resource Data

The wind data for the HOMER (NREL's Micropower Optimization Model) wind resource inputs were created using a combination of the validated NREL wind maps, supplemental wind characteristics from the AWST mesoscale wind models, the surface wind measurements supplied by the Bhutan Department of Energy, and modeled data from the 46-year National Center for Atmospheric Research (NCAR)/National Centers for Environmental Prediction (NCEP) Reanalysis database.

For the HOMER wind supplied by the Geospatial Toolkit, we are using the model's wind synthesizer to produce hourly wind speed for a representative year of data. The wind synthesizer interface requires the following inputs:

1. Average wind speed for each month.
2. Annual average Weibull K shape parameter.
3. Annual average autocorrelation coefficient.
4. Annual diurnal pattern, peak hour, and pattern strength.

For high-elevation locations with useful amounts of wind power, as shown by the AWST model runs, NREL used the AWST monthly wind power patterns as HOMER inputs. These generally show large amounts of wind power in the winter months, very little in the summer. For Weibull K, we use a number calculated from the annual average wind speed and power from AWST data. Because NREL had no measured wind data from any location representative of this wind regime, we chose to use typical wind parameters of the midlatitudes - autocorrelation = 0.9, diurnal pattern strength = 0.15, peak hour =16 (4 PM local time). The average monthly wind speed is calculated from the average wind power (from the AWST map database) using the annual average Weibull K.

For valley locations, NREL developed wind power estimates using available measurement data the methods described in the previous sections. At these locations, the AWST monthly patterns were not used, because the AWST model data did not resolve the strong mountain-valley circulations apparent in many valley areas of Bhutan. NREL chose to use the three highest-quality surface measurement stations – Tyangtse, Tsirang, and Punakha – as standard profiles.

All valley wind power locations were assigned one of these three profiles (see Figure 1, and summary wind discussion above.) The average wind power at each valley location is multiplied by the ratio factor in Figure 1 to get the monthly wind power. We then assign each wind power location a Weibull K of 2.0, and use this plus the wind power and the local elevation to create a characteristic monthly average wind speed.

The measured wind data show a very strong diurnal pattern peaking at midday with very low wind speeds at night. This pattern creates a challenge in providing realistic wind patterns in the HOMER synthesized wind speeds. NREL conducted tests of the wind power output from the HOMER wind synthesizer, relative to the inputs. The following values provided realistic outputs while preserving the wind power class of the chosen site. The parameters for the three profiles are:

Profile	Weibull K	Pattern Strength	AutoCorrelation	Peak Hour
1	2	0.75	0.9	13
2	2	0.75	0.9	13
3	2	0.75	0.9	14

Note: This technique creates an average wind speed, which preserves the wind power class of the location. This average wind speed may be different than the average measured at the site. However, this technique has been tested and shown to be more realistic than using the observed wind speeds.

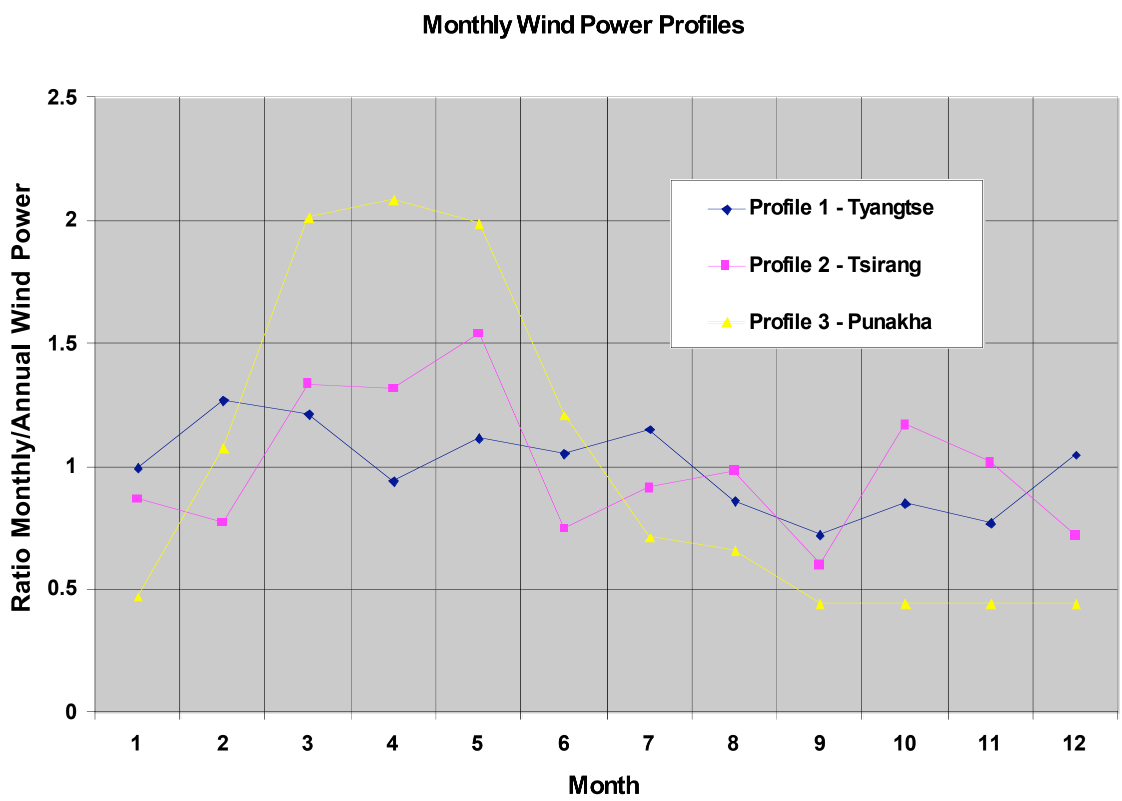

Figure 1. Wind power profiles for the Bhutan valley locations, derived from surface measurements at three sites.

Summary of Bhutan's Wind Resource

Areas estimated with a wind resource of Class 3 and higher wind occur throughout many valley areas as indicated on the wind map, particularly areas where the strong daytime valley winds are channeled and accelerated by the terrain features. Some prominent windy valley areas include those near Wangdi and Punakha in central Bhutan, and Tyangtse and Dungkar in eastern Bhutan. In some of the windiest valley areas, average wind speeds during midday to early afternoon hours are 8 to 10 m/s or greater. Although there are many valley areas where we estimate significant wind resources, there are many other valley areas that are estimated to have generally low wind resource. Of the 12 measurement stations, the data from seven stations indicated low wind resource, which is also shown on the wind map for these valley areas.

Based on the limited measurement data available from some of the windy valley areas of Bhutan, it appears that the seasonal variation of the wind resource is very complex and varies among the different regions. At Punakha and Wangdi in west-central Bhutan, winds are strongest during the spring (from late winter to early summer) and weakest during the autumn to early winter period. The strong daytime winds are generally up valley, from south to north, most of the year. At Tsirang in south-central Bhutan, the strong daytime winds are generally down valley (north to south) from late winter to early summer and up valley from mid-summer through autumn. Seasonal variations at Tsirang are less extreme than those at Punakha. For example, Punakha has much greater wind power in spring than in autumn, but Tsirang has only slightly greater wind power in spring than in autumn. At Tyangtse in northeastern Bhutan, the seasonal variations are minor and the wind resource is generally "good to excellent" throughout the year. The windiest months are from December to July, but daytime winds are still quite strong from August through November. Wind direction data were not available for Tyangtse.

At high elevations such as ridge crests and mountain summits, the numerical model data and upper-air measurements from weather balloon data in the region indicate that the wind resource is generally low, except for the highest elevations in some northern and eastern areas of Bhutan. Unfortunately, no data from wind-measurement towers were available from high-elevation mountain summits and ridge-crest areas to verify these estimates.