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Wind Resource Estimation and Mapping at the National Renewable Energy Laboratory

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WIND RESOURCE ESTIMATION AND MAPPING AT THE NATIONAL RENEWABLE ENERGY LABORATORY

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ABSTRACT

The National Renewable Energy Laboratory (NREL) has developed an automated technique for wind resource mapping to aid in the acceleration of wind energy deployment. The new automated mapping system was developed with the following two primary goals: 1) to produce a more consistent and detailed analysis of the wind resource for a variety of physiographic settings, particularly in areas of complex terrain; and 2) to generate high quality map products on a timely basis. Using computer mapping techniques reduces the time it takes to produce a wind map that reflects a consistent analysis of the distribution of the wind resource throughout the region of interest. NREL's mapping system uses commercially available geographic information system software packages. Regional wind resource maps using this new system have been produced for areas of the United States, Mexico, Chile, Indonesia (1), and China. Countrywide wind resource assessments are under way for the Philippines, the Dominican Republic, and Mongolia. Regional assessments in Argentina and Russia are scheduled to begin soon.

1. APPROACH

The mapping system is designed to display regional (greater than 50,000 km^2) distributions of the wind resource. The maps are intended to denote areas where wind energy projects could be feasible. Figure 1 shows regions of the world where the National Renewable Energy Laboratory (NREL) has performed recent wind resource assessments. The wind power density, rather than wind speed, is presented on the wind resource maps because it provides a truer indication of the wind resource potential. The primary output of the mapping system is a gridded, color-coded wind power map in units of W/m^2 and equivalent mean wind speed for each individual cell. Most of the final wind resource maps have a 1-km^2 grid cell resolution. Despite this high resolution, the maps are not intended to be used for micrositing purposes because of terrain induced variability of the wind resource that can occur within a grid cell.

The computer mapping system uses an empirical and analytical approach to determine the level of the wind resource for a particular location. At this time, the wind mapping system does not use any explicit boundary layer equations or geostrophic adjustment equations, as some other wind flow models do.

The major meteorological assumption that underlies NREL's mapping technique is that there are empirical relationships in many parts of the world between the free-air (higher than 100 - 200 m above ground level) speed, the wind speed over the ocean (where applicable), and the distribution of the wind resource over the land areas. Empirical relationships have been noticed in previous NREL wind resource assessment work for well exposed locations with low surface roughness in diverse areas of the world. Accordingly, the wind resource values presented on the maps are the estimates for a non-sheltered location with low surface roughness (short grasslands, for example). NREL's mapping system takes a "top-down" method in the adjustment of much of the available wind data. That is to say, the NREL approach takes the free-air wind profile in the lowest few hundred meters above the surface and adjusts it down to the surface. NREL decided to use the "top-down" method because of many problems with the available land-based surface wind data in most of the world. A lack of information about observation procedures, and anemometer

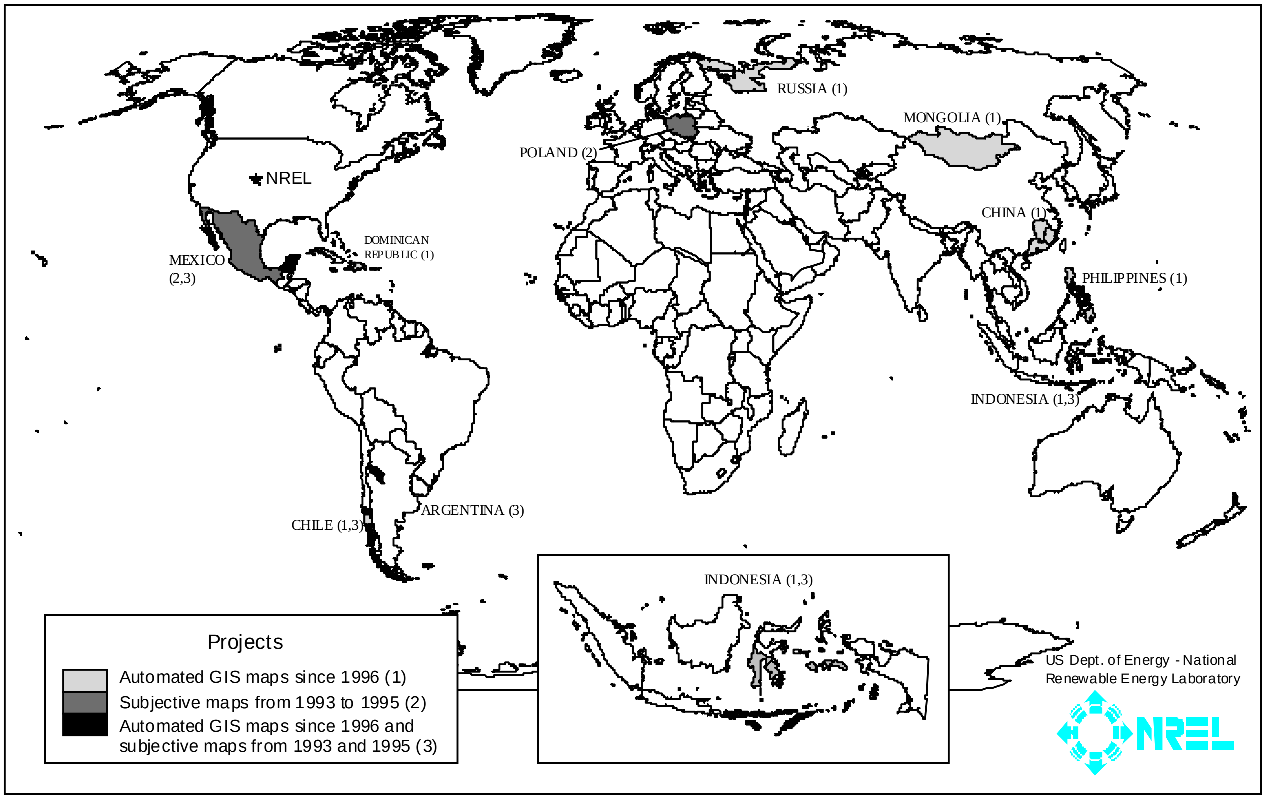

Fig. 1: National Renewable Energy Laboratory international wind resource mapping projects.

hardware, height, exposure, and maintenance history are just a few of the problems. In addition, many areas of the world with the potential to have good-to-excellent wind resource sites have very few or no meteorological stations present. The result is that, overall, the available surface wind data from meteorological stations are not reliable enough to use directly as input in the wind mapping system. However, these data are critically analyzed to assess the wind characteristics (e.g., seasonal, diurnal, and directional) in a study region.

2. DATA SETS AND ANALYSIS METHODS

The major data sets used in NREL's wind resource assessment methodology are described below.

2.1 Surface Data

DATSAV2 - This global climatic database, which was obtained from the U.S. National Climatic Data Center (NCDC), contains digital hourly surface weather observations from first-order meteorological stations throughout the world. This data set is the primary source of surface wind information used in our assessments. NREL currently has more than 25 years of DATSAV2 data in its archive, spanning the period from 1973 to mid-1998. Meteorological parameters such as wind speed, wind direction, temperature, pressure and altimeter setting are extracted from the hourly observations and used to create statistical summaries of wind characteristics.

Marine Climatic Atlas of the World - This data set, compiled from historical ship observations, presents summarized wind statistics for a 1^{o} latitude by 1^{o} longitude grid. Measurements are concentrated along the major shipping routes. Included are summaries of the monthly means and standard deviations of wind speed, pressure, temperature, and wind direction frequency and speed.

Special Sensor Microwave Imager (SSMI) - The SSMI, which is part of the Defense Meteorological Satellite Program, provides 10-m ocean wind speed measurements. This data set provides much more uniform and detailed coverage of oceanic wind speeds than the Marine Climatic Atlas of the World. NREL currently has 10 years of SSMI data covering the period from 1988 to 1997.

2.2 Upper-Air Data

Upper-air data can provide an estimate of the wind resource at low levels in the atmosphere and contribute to the understanding of the vertical distribution of the wind resource. This is useful in estimating the winds on elevated terrain features and for estimating the wind resource at other exposed locations in a particular region.

Automated Data Processing (ADP) Reports - This data set contains upper-air observations from rawinsonde instruments and pilot balloons for approximately 1800 stations worldwide. Observation times include 00, 06, 12, and 18 Greenwich Mean Time (GMT). Wind information is available from the surface, the mandatory pressure levels (1000 mb, 850 mb, 700 mb, and 500 mb), the significant pressure levels and, for some stations, specified geopotential heights above the surface. NREL currently has more than 25 years of observations from 1973 through mid-1998.

Global Gridded Upper-Air Statistics - This data set contains monthly means and standard deviations of climatic elements for the mandatory pressure levels on a 2.5 degree global grid. The data were obtained from the NCDC and cover the period from 1980 to 1991. This data set is used to supplement the ADP information in areas where upper-air data are scarce.

Reanalysis Data - This data set, created by the U.S. National Centers for Environmental Prediction and the National Center for Atmospheric Research, contains worldwide information on wind, temperature, and other variables on a terrain-following, 208-km resolution grid with more than 18,000 points. The output is available four times a day at 00, 06, 12, and 18 GMT. This data set has better vertical resolution in the boundary layer than the ADP data. NREL has obtained 40 years (1958-1997) of the raw data and is currently investigating the optimum way of integrating the reanalysis data into its wind resource assessment methodology.

2.3 Data Analysis

An accurate wind resource assessment is highly dependent on the quantity and quality of the meteorological data input into the automated system. NREL reviews the data sets mentioned above, and previous wind energy assessments, as part of its overall evaluation. The use of multiple data sets is necessary because the quality of data in any particular dataset can vary, and because high quality data can be quite sparse in many regions of the world.

A critical analysis of the climatic data is performed to ensure that the meteorological input is as precise as possible. Wind characteristic summaries are generated for surface and upper-air observations. The generated summaries are cross-referenced against each other to aid in understanding the prevalent wind characteristics in the study area. For example, the interannual surface wind speeds are evaluated to identify obvious trends in the data or periods of questionable data. Data periods determined to be most representative are selected from the entire record for use in assessments. The goal of the data analysis and screening process is to develop a conceptual model of the physical mechanisms, both regional and local, that influence the wind flow. The ultimate goal of the analysis is to enable the meteorological analyst to attain a conceptual model of the physical mechanism(s), whether produced by large and/or local scale factors that cause the wind to blow in a particular region. The conceptual model guides the development of the empirical relationships that serve as the basis of the algorithms that calculate wind power. The analyst is ultimately responsible for preparing the meteorological data input into the mapping system.

3. MAPPING SYSTEM

The mapping system is divided into three main components: the input data, the wind power calculations, and the mapping products. These components are described below.

3.1 Input Data

The two primary model inputs are digital terrain data and formatted meteorological data. The elevation information consists of Digital Elevation Model (DEM) terrain data that divide the analysis region into individual grid cells, each with its own elevation value. The United States Geological Survey Earth Resource Observing Satellite Data Center recently produced new DEMs for most of the world. The new data sets have a resolution of 1 km^2.

The meteorological inputs to the mapping system are vertical profiles of free-air wind power density, wind power roses (which specify the percentage of total power from the wind by direction sector), and the open ocean wind power density, where appropriate. The vertical profiles are broken down into 100-m intervals centered every 100 m above sea level (asl), except for the lowest layer, which is at 50 m asl. The wind power rose is used to determine the degree of exposure of a particular grid cell to the power producing winds. The open ocean wind power density is derived from the SSMI and ship wind speed observations, converted to wind power density and extrapolated to 30 m for use by the mapping system.

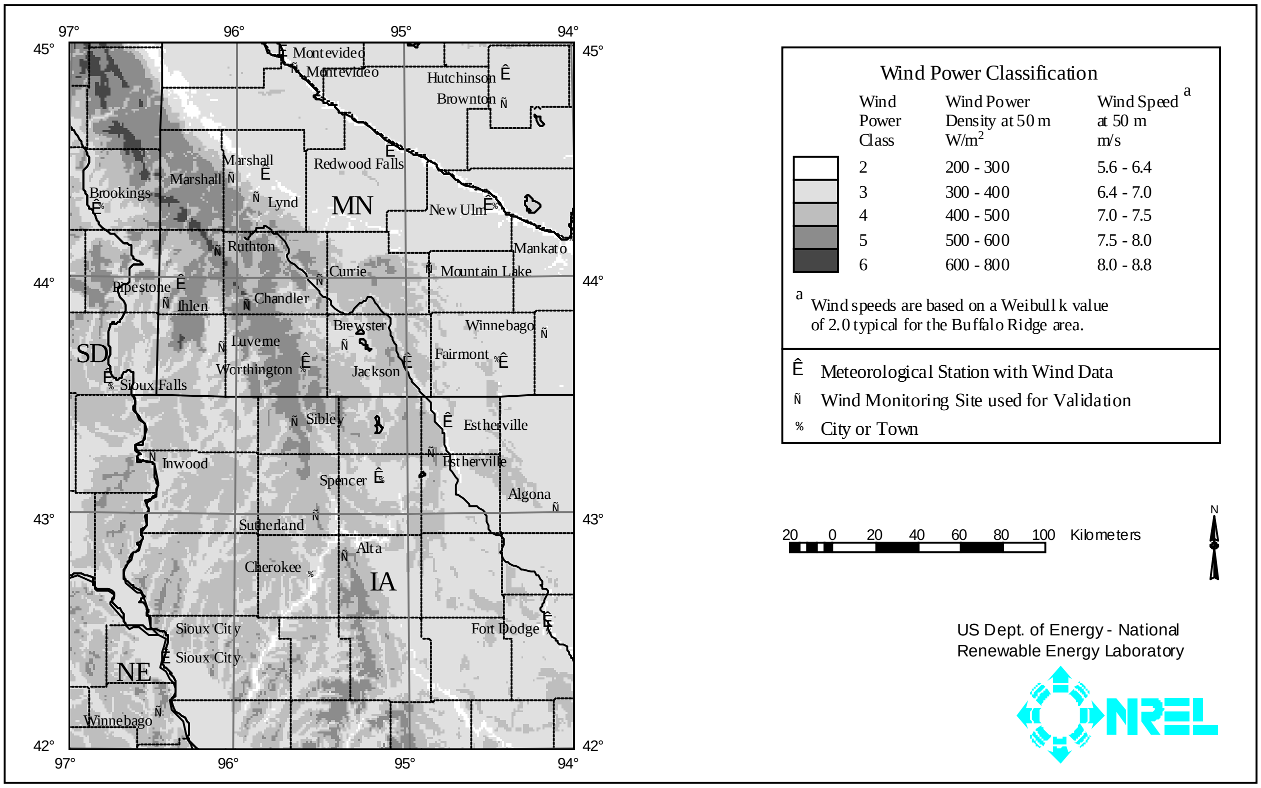

Fig. 2: Wind resource map for the Buffalo Ridge area.

3.2 Wind Power Calculations

The mapping system is designed to calculate the wind power for those grid cells that meet certain exposure and slope requirements. Therefore, the mapping system identifies the most favorable wind resource areas. The vertical profiles of free-air wind power density serve as the input for a base wind power density value for a particular grid cell. The wind power calculations in the wind mapping system are adjustments to the base free-air wind power density values of each grid cell. The factors that either decrease or increase the base wind power value for a particular grid cell are terrain considerations, relative and absolute elevation, the aspect of the terrain, distance from ocean or lake shoreline, and the influence of thermal or other types of small-scale wind flow patterns. When a coastal area or an area with large water bodies (e.g., lakes, estuaries, and fjords) is being mapped, the distance between a grid cell and the body of water also becomes an important component of the wind power calculation. For areas not located near a large water body, the wind power is derived from the vertical profile of wind power density. However, for areas within a few kilometers of an ocean, lake, or other large water body, the mapping system calculates the power based on the ambient wind flow near the surface and the amount of fetch the prevailing winds have across the water body. The final wind power estimates for these coastal or lakeshore cells are based on the maximum value calculated from either of these methods.

3.3 Mapping Products

The primary product of the mapping system is a wind power density map of favorable wind resource areas. The wind resource values presented are estimates for non-sheltered locations with low surface roughness (e.g., short grasslands). The DEM data can 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 enable the user to obtain an understanding for the three-dimensional distribution of the wind power for the study region.

Two examples of NREL's wind resource map are shown. The first, (Figure 2) is a wind resource map of the Buffalo Ridge area of the northern Great Plains. Several wind energy plants are either being installed, or have recently been installed, in this region. The map, which covers a 3^{o}

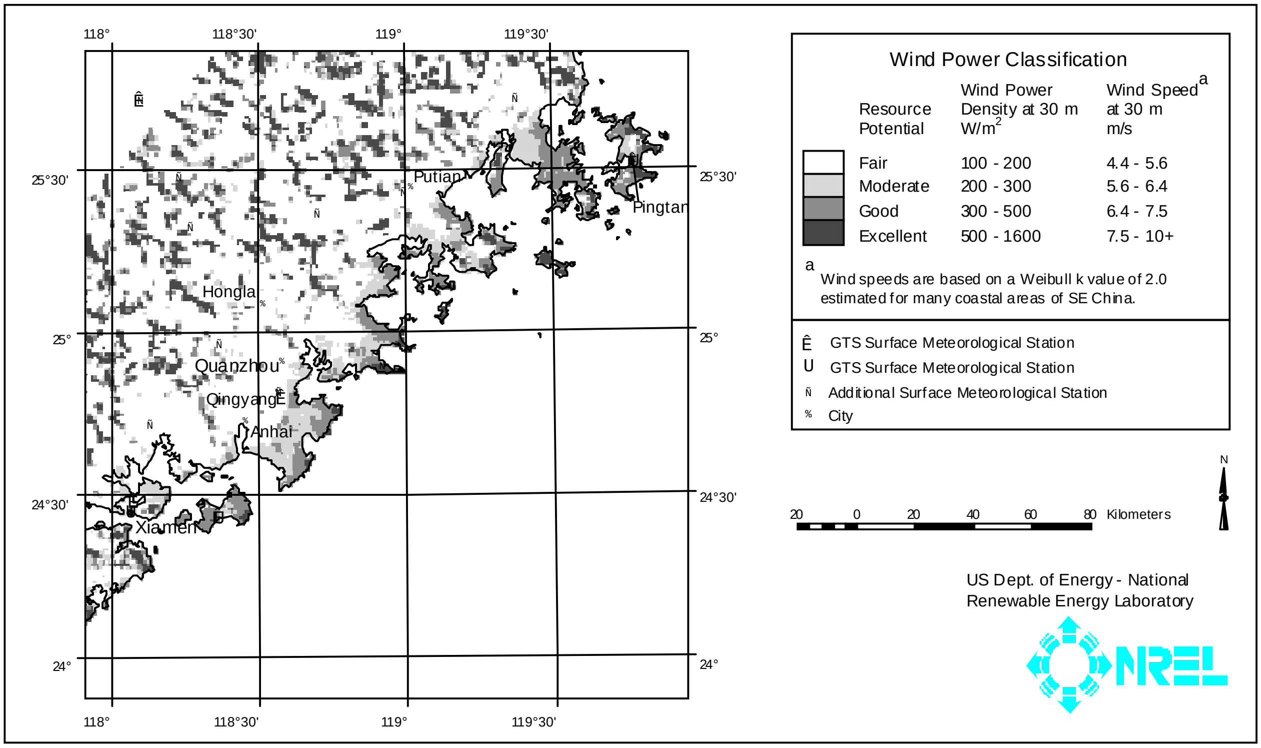

Fig. 3: Wind resource map for the central coast of Fujian Province.

latitude by 3^{o} longitude area centered on the western section of the Minnesota-Iowa border, shows significant variation of the wind resource in what is generally perceived as a flat area (slopes less than 3%). Nevertheless, based on the upper-air meteorological input, elevation changes in the area have a notable impact on the estimated resource level. This area has numerous stations designed specifically for wind energy measurement, enabling a validation study (2) to be performed on the mapping results. Nineteen stations were used as validation sites. The wind power estimate from the mapping system was within 20% of the measured power at 15 of the 19 sites.

Figure 3 is a wind resource map for the central coast of Fujian Province in southeastern China. The map was produced for a project jointly funded by the U.S. Department of Energy and the U.S. Environmental Protection Agency. The region's geographical features include an indented shoreline with hills along the Pacific Ocean (South China Sea) coast, a narrow coastal plain in some areas, and mountainous terrain within 50 km of the coast. The Pacific coast of Fujian has been an area of interest to U.S. wind energy developers; this map is designed to help concentrate their efforts on the areas with the greatest resource. The best resource is found on the South China Sea coast and the higher inland ridges. We hope to obtain future wind energy measurements in this region in order undertake a validation study similar to the one done for the Great Plains.

3.4 Limitations of the Mapping Technique

There are several limitations to the mapping technique, the first of which is the resolution of the DEM 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 is the development of the conceptual model of the wind flow and its extrapolation to the region. There are many complex factors in the wind flow that make this an inexact process, including the structure of low-level jets and their interaction with the boundary layer, and localized circulations, such as land-sea breezes, mountain-valley flows, and channeling effects in mountainous areas. These factors affect the amount of momentum that is transported to the surface from free-air levels; such processes can only be approximated in the mapping system. Finally, the power estimates are valid for areas with low surface roughness. Estimates for areas with a higher surface roughness need to be adjusted down by as much as 25% to 60%, depending on the amount of obstructions to the wind flow.

4. CONCLUSIONS

During the course of NREL's wind mapping studies, we encountered many different types of wind climates and boundary layer interactions for a wide variety of regions. This factor causes the general structure of the individual algorithms used in the mapping system to be continually evolving in order to continue to produce the most useful wind maps. We have started to validate some of the system results, recognizing that this is not currently feasible in some regions because of the lack of quality wind measurements. Validation results will be used to help improve the mapping system.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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