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Development and Validation of High-Resolution State Wind Resource Maps for the United States

D. Elliott and M. Schwartz

Technical Report
NREL/TP-500-38127
July 2005

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Background

The National Renewable Energy Laboratory (NREL) has coordinated the development and validation of high-resolution state wind resource maps for much of the United States. The majority of these maps were produced for NREL by TrueWind Solutions (now AWS Truewind [AWST]) based in Albany, New York, using its proprietary MesoMap system. AWST's system uses a version of a numerical mesoscale weather prediction model as the basis for calculating the wind resource and important wind flow characteristics. The independent validation project was a cooperative activity among NREL, AWST, and private meteorological consultants.

The validation concept originated at a May 2001 technical workshop held at NREL to discuss updating the *Wind Energy Resource Atlas of the United States* (Elliott et al., 1987). Part of the workshop, which included more than 20 attendees from the wind resource mapping and consulting community, was dedicated to reviewing the latest techniques for wind resource assessment and mapping. It became evident that using a numerical modeling approach was soon to be the preferred technique for wind resource mapping for several reasons. The numerical modeling technique is faster compared to older mapping methods and, in theory, should be quite accurate because it directly estimates the magnitude of boundary-layer processes that affect the wind resource at a particular location. Numerical modeling output combined with high-resolution terrain data can produce useful wind resource information at a horizontal resolution of 1 km or finer. At the time of the workshop, the numerical modeling approach was new and relatively unproven, and experienced meteorological consultants questioned the accuracy of the approach. It was clear that high-resolution state or regional wind maps produced by this method would have to undergo independent validation (i.e., a comparison between model estimates and measured data at specific locations) before the results would be accepted by the wind energy community and developers.

Concurrent with the workshop, the Wind Powering America initiative (Flowers and Dougherty, 2001) was actively supporting the acceleration of wind energy development in the Northwest region of the United States with the production of high-resolution wind resource maps. Thus, the high-resolution wind resource maps for the states of Washington, Oregon, Idaho, Montana, and Wyoming became the pilot validation effort. The lessons and experience gained from the ultimately successful Northwest validation effort (Elliott and Schwartz, 2002) led to similar validation projects for the Southwest and Mid-Atlantic regions as well as California, Hawaii, and several states in the Midwest. The purpose of the validation effort is to produce the best map possible within fairly stringent time constraints. Technical issues that arose during the process had to be resolved quickly and research on these issues, though important, would not be a significant part of the validation process.

Mapping and Validation Approach and Results

The approach for developing the final wind resource maps consisted of three steps: 1) modeling and production of the preliminary maps by AWST; 2) review and validation of the preliminary maps by NREL and meteorological consultants; and 3) revisions required to create the final maps.

MesoMap, the modeling and mapping system employed by AWST, consists of three components: models, databases, and computer and storage systems (Brower et al., 2001). At the core of the MesoMap system is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model used in commercial and research applications. MASS can be coupled to WindMap, a mass-consistent wind-flow model, to increase the spatial resolution of the MASS simulations. The main meteorological inputs for MASS are model-derived gridded historical weather data (the reanalysis database), weather balloon data, and land surface measurements. The main geophysical inputs are elevation, land cover, vegetation cover, soil moisture, and, where applicable, sea-surface temperatures. The MesoMap system creates a wind resource map by simulating weather conditions from a large number of days (typically 365 days) selected from a historical period (typically 15 years). For each day in the sample, the wind speed and direction and other weather variables (including temperature, pressure, moisture, etc.) are simulated and stored at hourly intervals over the model domain. When the simulations are finished, the data are compiled and summarized to produce maps of mean wind speed, power density, and other statistics at various heights above ground. The final MASS simulation output for the maps ranged from 2.0 to 2.6 km resolution. These data were then used in WindMap to improve the final resolution to less than 1 km.

The validations were done on AWST's preliminary maps of mean annual wind speed at heights of 30 meters and 50 meters above ground level(agl) and mean annual wind power density at 50 meters agl. NREL and the meteorological consultants worked independently to identify and obtain available wind measurement data for use in the validation. The bulk of the wind data used in the validation were collected by the weather service, agricultural, transportation, and environmental agencies. Most of these data were collected at heights at or near 10 meters agl. The estimation of the wind shears (change of wind speed and power density with height) was a major issue in extrapolating data measured at lower heights to the 30- and 50-meter estimates. NREL generally used the standard 1/7 power law equation for the vertical adjustment, though for special circumstances (e.g., coastal locations and acceleration zones) other power law values were used. Decisions about the wind shear adjustments for the data provided by the meteorological consultants were left to their discretion. For some regions, there were substantial wind measurement data from heights near 30 to 50 meters, particularly in areas where wind projects have been developed or are being considered. Measurement data from these heights were the most valuable, because these data are at or near the map heights for which the wind resource estimates were generated. Many of the taller tower wind measurement data sets are proprietary, but as a result of the efforts of the private consultants, summaries of the proprietary data were used in the validation.

Using the available wind data, NREL and the consultants validated the wind speed maps. NREL also validated the wind power density maps, except for a few locations where hourly or adequate time series data were not available to estimate the wind power density. NREL developed spreadsheets to score the validations for each state. Each spreadsheet contained entries for wind monitoring station locations and elevation, anemometer measuring heights, period of record, measured wind speed and power density, wind speed and power adjusted to map height, the map estimates of speed and power, and any qualitative comments the validators wished to make. Qualitative comments included any special circumstances about a particular monitoring station or special wind resource knowledge about a certain area. NREL asked its consultants to fill out the spreadsheet as completely as possible, including essential monitoring station metadata and the adjusted measured and mapped wind speeds. The consultants also had the option to include a general geographic description of the station location rather than a specific latitude and longitude for proprietary data. Upon completion, the consultants sent the spreadsheets to NREL and AWST for review. The results formed the basis for adjusting the preliminary wind maps. Comprehensive discussions between NREL and AWST resolved outstanding technical issues and defined the adjustments to be made to the preliminary maps in order to produce the final wind resource maps.

As shown in Figure 1, final validated wind maps have been produced for more than 30 states, many under the Wind Powering America initiative and cost-shared by states. Recent maps produced in 2004 and 2005 include the states of Indiana, Ohio, Hawaii, Michigan, Missouri, and Nebraska. Validation is in progress for Alaska (specific areas) and Arkansas. Figures 2 and 3 show the final wind power density and wind speed maps (50 m) for the states of Nebraska and Michigan. These maps also show major transmission lines, county boundaries, and Indian Reservations. It should be noted that the maps are not intended for micrositing because the numerical model resolution does not capture all of the smaller terrain features.

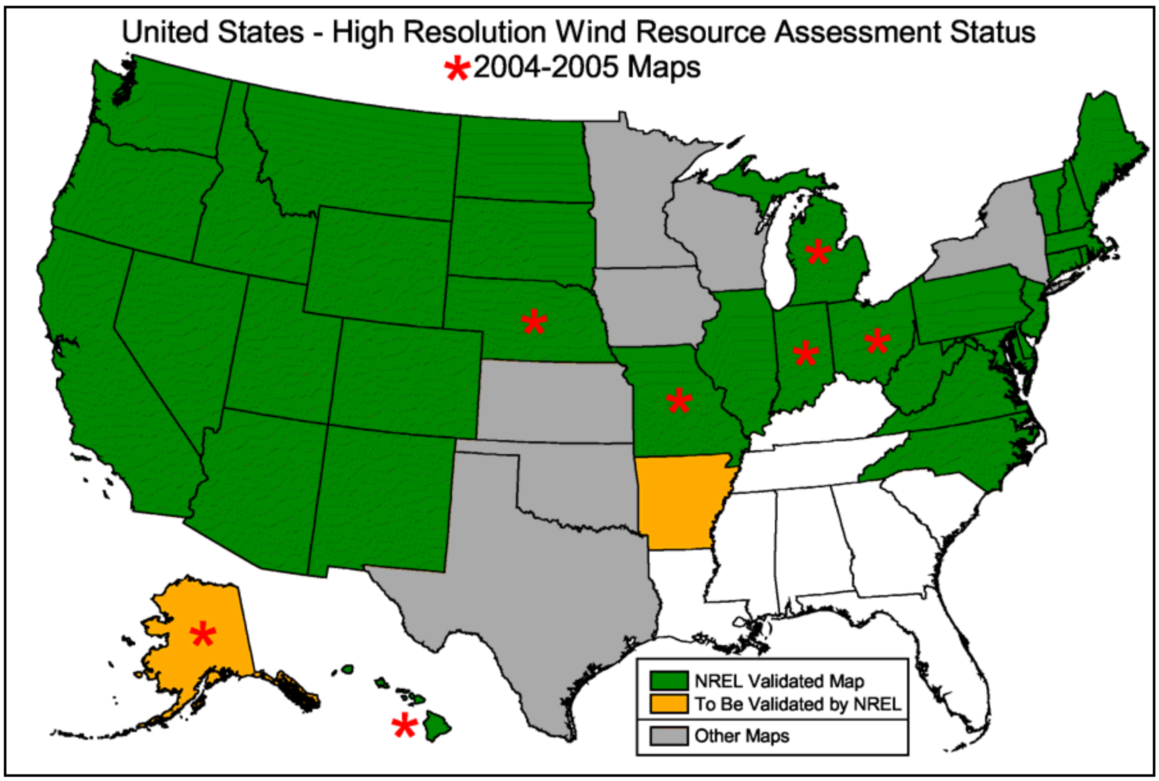


Figure 1. Status of high-resolution wind resource maps.

The wind power classifications on the high-resolution wind power maps correspond to the seven power classes used for the 1987 U.S. wind atlas. Areas with Class 4 and higher wind resource are generally considered to have good potential for utility-scale wind energy applications. Given the advances in wind energy technology, a number of locations in Class 3 resource areas may be suitable for utility-scale development particularly at heights of 80 m and above and in areas of high wind shear. Tall-tower wind measurements (at heights up to 100m and above) have recently been conducted in some states (such as Indiana, Minnesota, and Kansas) and are underway or planned in additional states to better assess the wind shear and detailed wind resource characteristics at increased heights.

In Figure 2, the wind power map shows that major areas of good wind resource are found throughout much of Nebraska except the eastern fringe. Transmission lines either traverse or are located in close proximity to many of the good wind resource areas. Some of the good wind resource areas contain significant areas of excellent wind resource. The best wind resource areas are typically located on elevated terrain features, whereas the lowest wind resources are generally located in valleys and basins with relatively low elevations.

In Figure 3, the wind power map shows that the best wind resource areas in Michigan are concentrated along the immediate shores of the Great Lakes and offshore islands. The Great Lakes' offshore resources are good-to-outstanding. A large area of Class 3 resource is located northeast of Saginaw on the "thumb" of the state. As noted above, specific locations in Class 3 areas may be suitable for utility-scale development, particularly at increased heights and in locations with high wind shear.

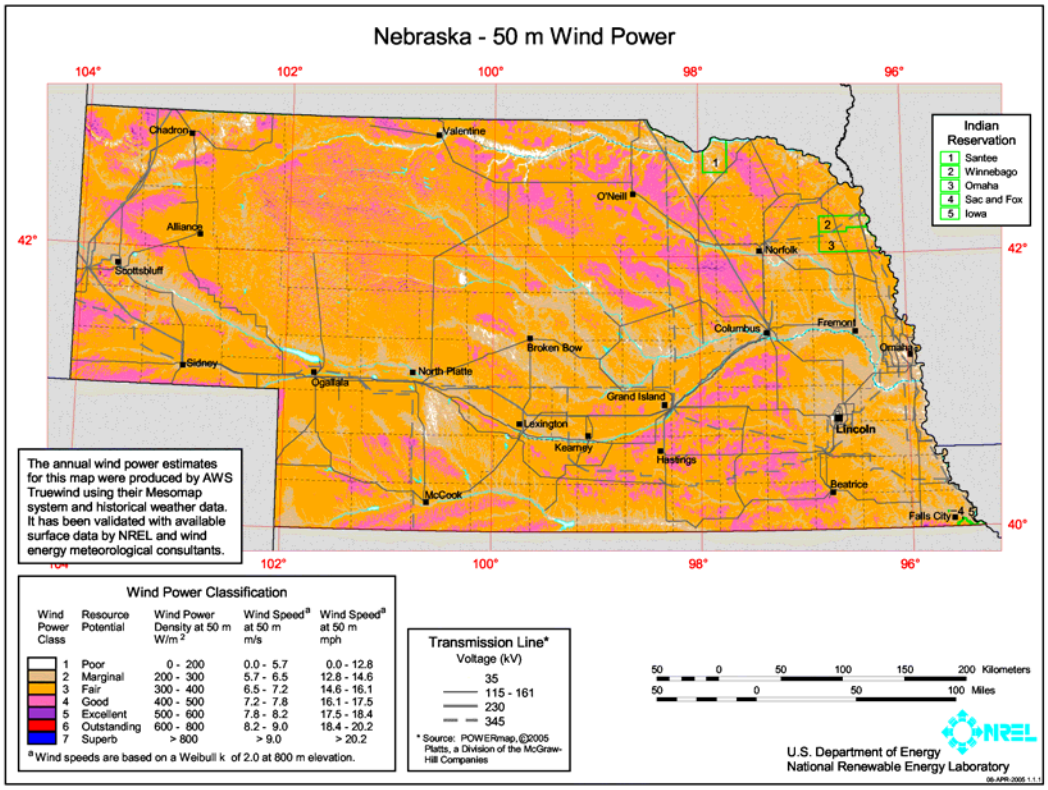
The links to all of the high-resolution state wind resource maps can be found at http://www.eere.energy.gov/windpoweringamerica/wind_resources.html.

Technical Modeling Issues

The intensive validation effort has identified several technical sources of model error (Brower, et al., 2004). Two of the most important are surface roughness parameterization, and atmospheric stability in the lower boundary layer. Though it was beyond the scope of the mapping and validation projects to study these in detail, identification of the sources of error has enabled AWST to make improvements to the MesoMap system.

Land cover data (directly related to surface roughness parameterization) obtained via remote sensing techniques must be properly interpreted to obtain realistic roughness values. Public global data sets contain errors because of their relatively coarse resolution and do not explicitly present information on vegetation height and density. Using higher-quality data sets such as the 1 km or better resolution Moderate Resolution Imaging Spectroradiometer data in the model is mitigating these problems.

The thermal stability of the atmosphere has an important effect on the vertical wind profile and on estimates of the wind resource at a particular height. The model accounts for different stability conditions by changing the mixing parameterization. Although these equations work well most of



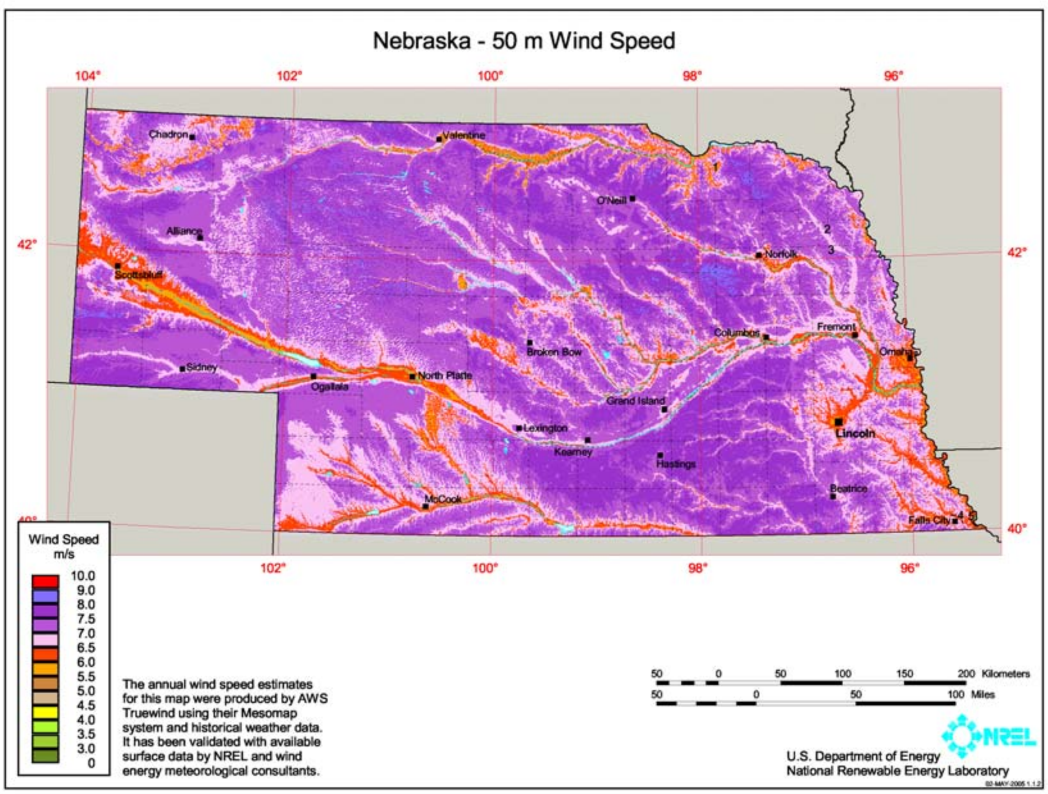
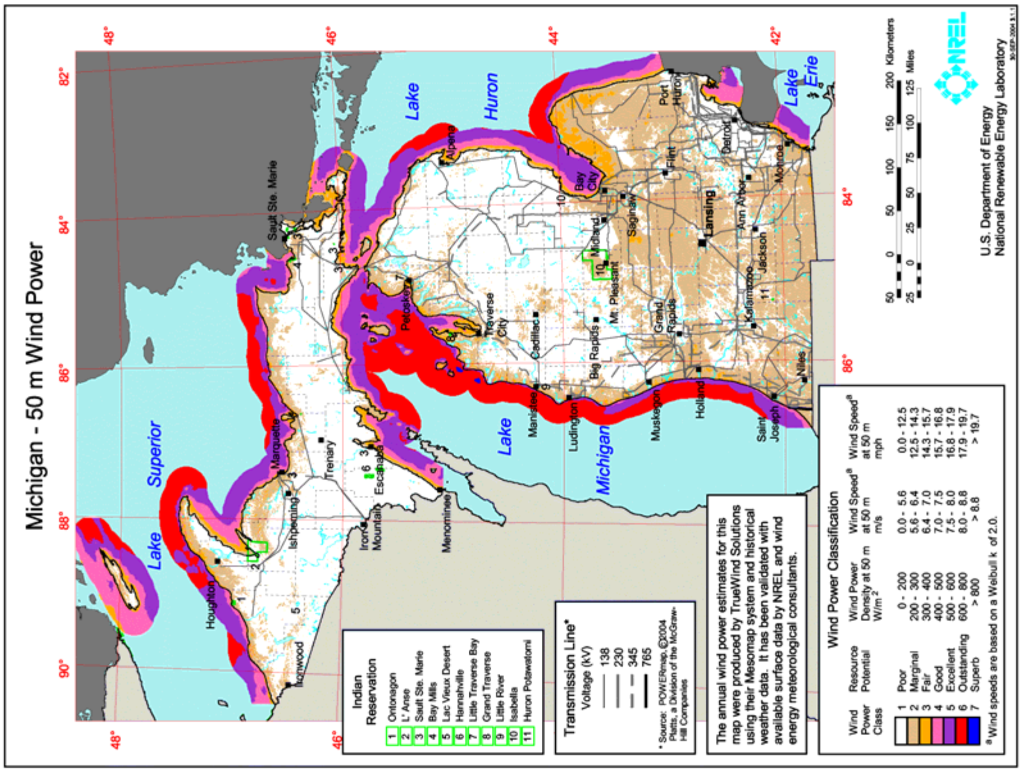


Figure 2. Final 50-m wind power (top) and wind speed (bottom) for Nebraska.



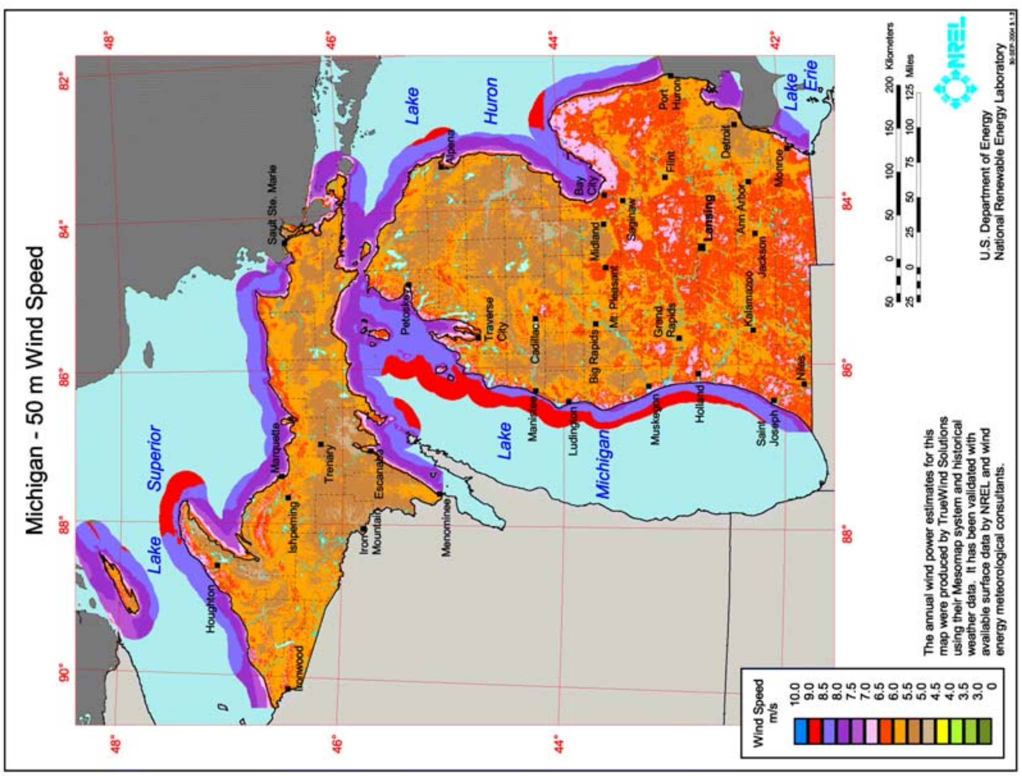


Figure 3. Final 50-m wind power (top) and wind speed (bottom) for Michigan

the time, highly stable and unstable atmospheric conditions pose particular challenges. AWST has recently adapted a method to determine the depth of the stable boundary layer based on turbulent kinetic energy to improve this aspect of model performance.

Conclusion

The validation process produced high-resolution wind resource maps that have proven to be quite useful for developers, state planners, and others. The validation was successful because of the iterative process facilitated by the cooperative efforts of NREL, AWST, and the consultant team. Success can be attributed in part to the availability of high-quality data from many areas and the validators' knowledge of the wind resource in the mapped regions. Lessons learned from previous efforts continue to be applied to validations of new regions being mapped, including the maps in progress for Alaska.

Important technical modeling and mapping issues have become better defined because of the validation project, and AWST is incorporating changes into the MesoMap system to produce improved model results.

NREL has also produced and validated new high-resolution wind resource maps and atlases for several countries around the world. These efforts are financially supported by the United States Agency for International Development, United Nations Environment Programme, and other organizations. The links to these maps and atlases can be found at http://www.rsvp.nrel.gov/wind_resources.html.

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The National Renewable Energy Laboratory (NREL) has coordinated the development and validation of high-resolution state wind resource maps for much of the United States. The majority of these maps were produced for NREL by TrueWind Solutions (now AWS Truewind [AWST]) based in Albany, New York, using its proprietary MesoMap system. AWST's system uses a version of a numerical mesoscale weather prediction model as the basis for calculating the wind resource and important wind flow characteristics. The independent validation project was a cooperative activity among NREL, AWST, and private meteorological consultants. This paper describes the mapping and validation approach and results and discusses the technical modeling issues encountered during the project.

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