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Remapping of the Wind Energy Resource in the Midwestern United States

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5.2 REMAPPING OF THE WIND ENERGY RESOURCE IN THE MIDWESTERN UNITED STATES

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1. INTRODUCTION

A recent increase in interest and development of wind energy in the Midwestern United States has focused the need for updating wind resource maps of this area. The wind resource assessment group at the National Renewable Energy Laboratory (NREL), a U.S. Department of Energy (DOE) laboratory, has produced updated high-resolution (1-km) wind resource maps for several states in this region. NREL used computerized wind resource mapping tools, including a comprehensive meteorological database and Geographic Information System (GIS) software, both developed over the past 5 years, to create updated wind resource maps of North Dakota, South Dakota, and Illinois. These states were chosen because DOE believed that creating updated wind resource maps to supersede those generated in the 1980s could accelerate wind energy development in these states. The previous state wind resource maps appear in the *Wind Energy Resource Atlas of the United States* (Elliott et al., 1987; we refer to it in this paper as the 1987 Atlas). The older maps have a 25-km resolution and were based primarily on wind data measured by airport anemometers (usually 6–10 m high) supplemented in a few areas by wind measurements taken at taller (40–50 m) towers.

2. BACKGROUND

Both the 1987 Atlas maps and the updated state maps show average annual wind power density values, rather than average wind speed, as the basis for defining the wind resource level in a particular area. Wind power density is used because this value considers not only the average wind speed at a location but also the wind speed distribution. The distribution of wind speed is important because the available wind energy is proportional to the cube of the wind speed. Thus, different locations with the same average wind speed can have much different (greater than 50%) wind power density values because of variations in the wind speed distribution. The wind power density values are broken down into seven power classes. Class 1 locations have the least amount of available wind energy and Class 7 locations have the most. In general, locations with a Class 5 and higher wind resource are suitable for large, utility-scale wind farm applications. Class 4 areas are likely to be suitable for utility-scale applications in the near future with the expected advances in wind turbine technology. Areas with a Class 3 and higher wind resource are generally suitable for smaller stand-alone wind turbine applications and for distributed generation applications because these applications need less wind resource to make them economically viable. It is important to note that in the 1987 Atlas the wind power classes assigned to a particular 25×25 km grid cell indicated the predominant power class for exposed areas in that grid cell. The 1987 Atlas contains a general discussion of wind power density and the wind power class issues.

In addition, the 1987 Atlas pointed out some interesting contrasts for the estimated wind resource in the states of North Dakota, South Dakota, and Illinois. North and South Dakota had large areas of the Class 4 resource (approximately 7.0–7.5 m/s annual wind speed at 50 m height), along with significant regions of Class 5 (7.5–8.0 m/s), especially in North Dakota. No exposed areas in these states had less than the Class 3 (6.4–7.0 m/s) wind resource. The 1987 maps indicated that North and South Dakota had good potential for large wind farm development and that virtually all areas of both states were suitable for small wind turbine applications. In contrast, Illinois was shown to have only a Class 2 (5.6–6.4 m/s) resource over most of the state (some Class 1 in southern Illinois) with only small areas of Class 3 in the west-central part of the state and along the Lake Michigan shoreline. The 1987 Atlas illustrated that wind energy development in Illinois, except for small wind turbine applications in limited areas, would not likely be economically feasible.

We did not use the 1987 Atlas maps as a direct basis for the updated maps. Instead, we approached each state wind-mapping project as if no previous wind maps were available. However, we did integrate the meteorological data used for the 1987 Atlas into the database used for these projects.

The following sections of the paper discuss the computer mapping system, the data sets, and the methodology employed in these projects in more detail. Next, we describe the mapping results for the individual states. Finally, we compare the updated maps to those contained in the 1987 Atlas.

3. NREL'S COMPUTER MAPPING SYSTEM

The computer mapping system at NREL uses an empirical and analytical approach to determine the level of the wind resource for a particular location. The wind mapping system does not use any explicit atmospheric boundary layer equations or geostrophic adjustment equations as do some other wind flow models. The mapping system is designed to display regional (greater

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than 50,000 km^2) distributions of the wind resource and to denote areas where wind energy projects are likely to be feasible.

Underlying the NREL technique is the major meteorological assumption that there are empirical relationships in many parts of the world among the free-air (higher than 100–200 m above the 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 NREL wind maps are estimates for non-sheltered locations with low roughness (short grasslands, for example). NREL also uses a “top-down” method for adjusting much of the available wind data. The NREL approach takes the free-air wind speed and power profile in the lowest few hundred meters above the surface and adjusts these down to wind turbine hub-height. In this way, NREL can produce a wind resource map with valuable information even if high-quality surface wind data are not available.

The final wind resource maps were produced using commercially available GIS software packages produced by Environmental Systems Research Institute Inc., of Redlands, California and custom GIS-based tools developed at NREL. These powerful and complex packages feature a large number of routines for scientific analysis, along with tools used to display spatial information. Elliott and Schwartz (1998) offer a more complete description of the mapping system.

4. NREL DATA SETS

NREL uses a variety of climatic data sets for its wind resource mapping projects. For the three states studied in these projects, we used three types of climatic data—surface station observation data, upper-air observation data, and model-derived upper-air data. A complete description of the data sets used in NREL’s projects can be found in Schwartz (1999).

4.1 Surface Data

DATSAV2—We obtained this data set, which contains digital hourly surface observations from first-order meteorological stations, from the U.S. National Climatic Data Center (NCDC). In the United States these data are predominantly collected from airport anemometers, along with a few observations from Coast Guard stations and radar installations. This data set contains airport data that were not available for the 1987 Atlas and data from many automated stations installed at small airports since the early 1990s.

4.2 Upper-Air Data

Automated Data Processing (ADP) Reports—This data set contains upper-air observations from rawinsonde instruments and pilot balloons recorded up to 4 times per day. Wind information is available from the surface, the mandatory pressure levels, the significant pressure levels, and specified geopotential heights above the surface. Wind data estimated at 300-m intervals are especially useful for deriving vertical profiles of both wind speed and wind power at an upper-air measurement location.

Global Gridded Upper-Air Statistics (GUACA)—This This model-derived data set, also obtained from NCDC, contains monthly means of climatic elements for the mandatory pressure levels on a 2.5-degree grid. We use these data to supplement the ADP information where upper-air observations are scarce and to discern geographical patterns of the upper-air wind speed.

Reanalysis Data—NREL has obtained 40 years (1958–1997) of the Reanalysis data created by the U.S. National Centers for Environmental Prediction and the National Center for Atmospheric Research. This data set contains wind, temperature, and other variables on a 208-km grid. NREL uses Sigma (terrain-following) level data in its analyses because the data have good vertical resolution in the boundary layer. Reanalysis data are quite useful for defining geographic patterns of the wind speed and power in the lowest few hundred meters above the ground; this is especially true in noncomplex terrain.

5. METHODOLOGY

The quality of the final wind resource map depends on the quality of the meteorological data input into the wind mapping system. NREL reviews the climatic data sets and performs a critical analysis of those data. We generate summaries of wind characteristics for the surface and upper-air data and cross-reference the summaries to aid us in determining the prevalent wind characteristics in the study area. For example, we evaluate interannual surface wind speeds to identify obvious trends in the data or periods of questionable data. Data periods determined to be the most representative are selected from the entire period of record for use in assessments. The data analysis and screening process is designed to allow the analyst to develop a conceptual model of the physical mechanisms that influence the wind flow in the study region. The conceptual model guides the development of the empirical relationships that serve as the basis of the algorithms that calculate the wind power values seen on the maps.

NREL’s mapping system combines the meteorological input, the wind power calculation modules, and digital terrain data to produce a variety of maps. In addition to the wind resource map a color-coded elevation map, a hill-shaded relief map, and a map of elevation contours can be produced.

6. ANALYSIS OF WIND CHARACTERISTICS IN THE MIDWEST

The key data sets used in the analysis of North Dakota, South Dakota, and Illinois were the DATSAV2, the ADP upper-air observations, and the Reanalysis and GUACA upper-air climatic statistics. These data were supplemented by some surface observations taken at taller (40–50 m) towers specifically for wind energy measurement. The GUACA and Reanalysis data were analyzed and combined to derive the geographic pattern of the low-level (surface to 500 m above the ground) analysis from eastern Montana across to western Michigan and from southern Canada down to Missouri and Illinois. We cross-checked the low-level analysis against ADP observation data to ensure consistency between the observed data and the low-level analysis, and found no major inconsistencies. The analysis indicated that although the 1987 Atlas maps were basically accurate at a large scale, there were some areas both in the Dakotas and in Illinois where an updated map would identify a higher wind resource than previously shown. Conversely, a few areas were shown to have a lower resource than can be seen on the 1987 maps.

We also characterized the seasonal wind resource patterns and the prevailing wind direction data as part of building the conceptual wind flow model for this region. The seasonal wind and prevailing wind direction patterns at turbine hub-height are similar in the Dakotas and Illinois despite the large distance separating these states. The peak seasonal wind resource is found during the spring (March–May), with winter (December–February) also having relatively high resource. The lowest wind resource is found during summer. The two prevailing wind directions are west-northwest and south. The westerly winds prevail in winter and early spring and southerly winds prevail from mid-late spring through the remainder of the warm season.

There are some variations to this general pattern, most notably in western North and South Dakota. Western and central areas of these states (west of about 98 degrees longitude) have more westerly winds and higher relative seasonal resources in winter and summer compared to places in the eastern portions of the states. Also, although the data show that the upper-air winds are weaker over the western Dakotas than over the eastern sections of the states, the surface observations from the DATSAV2 data set do not indicate a notable west-to-east gradient in the level of the surface wind resource. This indicates that more turbulent mixing of momentum toward the surface occurs in the western regions of North and South Dakota compared to the eastern regions. A look at the Reanalysis temperature profiles for the western sections evidences a more unstable atmosphere (higher mean lapse rates) in these parts of the states. This factor supports the conclusion that more turbulent mixing of momentum occurs in the western Dakotas compared to the eastern Dakotas.

6.1 North and South Dakota Wind Mapping Results

Figure 1 shows the comparison between the 1987 Atlas wind resource maps of North and South Dakota and the updated maps. The most striking difference between the two maps is the precision of the wind resource pattern on the newer map. The updated map clearly depicts the variation of the wind resource that results from significant terrain features. In fact, the considerable variation of the wind resource across the “flat” plains of the Midwest was one of the primary results of these mapping projects.

A notable feature of the wind resource pattern on the updated map is the increase of the Class 5 (with some Class 6 areas) resource seen in central, western, and northeastern South Dakota. The GUACA and Reanalysis-based analysis indicated a regional low-level wind maximum centered in central South Dakota and extending toward the northwestern part of the state and into southwest North Dakota. The area of the strongest low-level winds in central and western South Dakota also has topographical features such as divides of relatively high terrain between river valleys. The combination of the strong low-level wind and relatively high terrain produces an area that possesses a significant Class 5 wind resource. The higher wind areas of northeastern South Dakota are located on Buffalo Ridge, a prominent glacial divide between the James and Minnesota River valleys. The topography of the Black Hills region of southwestern South Dakota is a complex, with exposed mountain peaks and sheltered valleys. Exposed Black Hills peaks have Class 6 and Class 7 resource (greater than 8.0 m/s annual wind speed).

The updated map shows pockets of Class 6 resource on the plains of North and South Dakota, features that did not appear on the 1987 map. The more notable areas of Class 6 resource are near the Missouri River in South Dakota and along an upland that extends from southern North Dakota into northern South Dakota near 99 degrees longitude.

The areas having the Class 5 resource in North Dakota are not quite as extensive on the updated maps compared to the 1987 maps. This results from the finer resolution of the updated map as well as from the analysis of the climatic data. The data evidenced a gradient of the low-level wind from the maximum in southern North Dakota toward weaker low-level winds in extreme northeastern North Dakota. This gradient, along with the absence of much relatively high terrain in northern sections of the state, has resulted in mapping only Class 3 and lower resource in much of eastern and northern North Dakota compared to the Class 4 and Class 5 areas on the 1987 map.

We validated the new North Dakota map using seven measurement sites. We were able to perform this

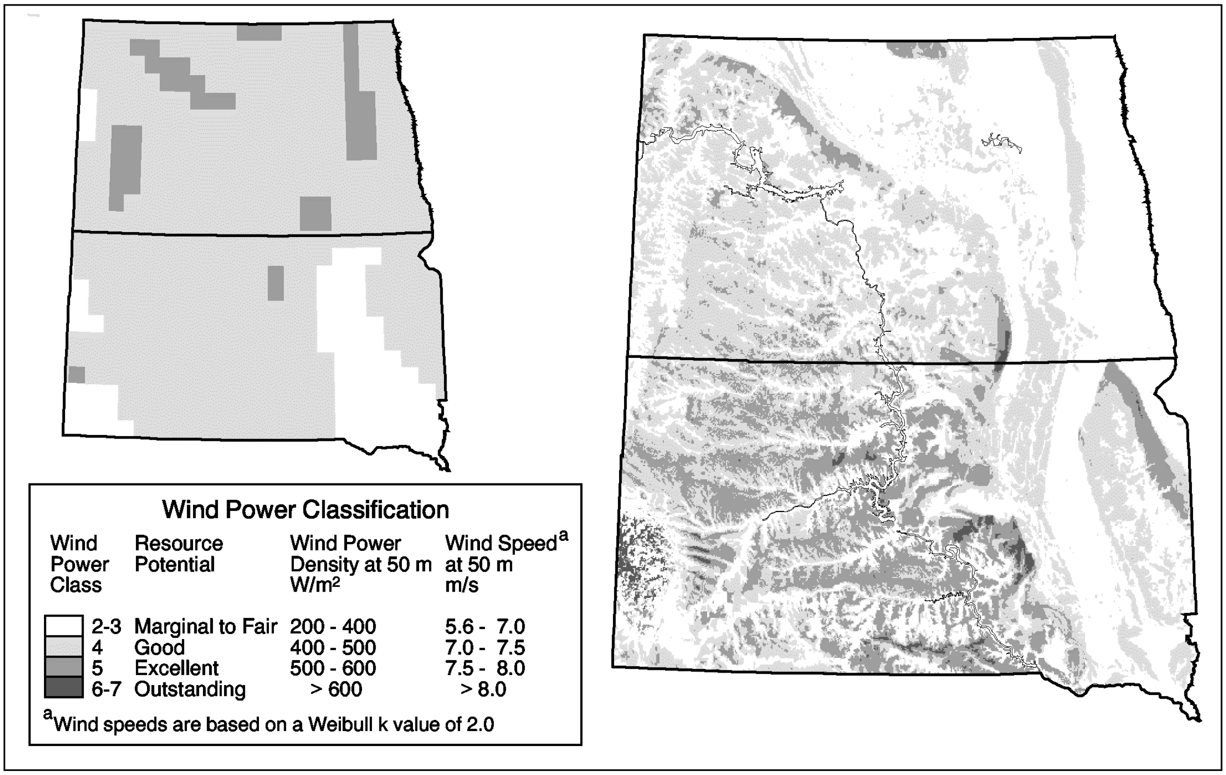

Figure 1. North and South Dakota wind resource maps from the 1987 Atlas (left) and the 2000 assessment (right)

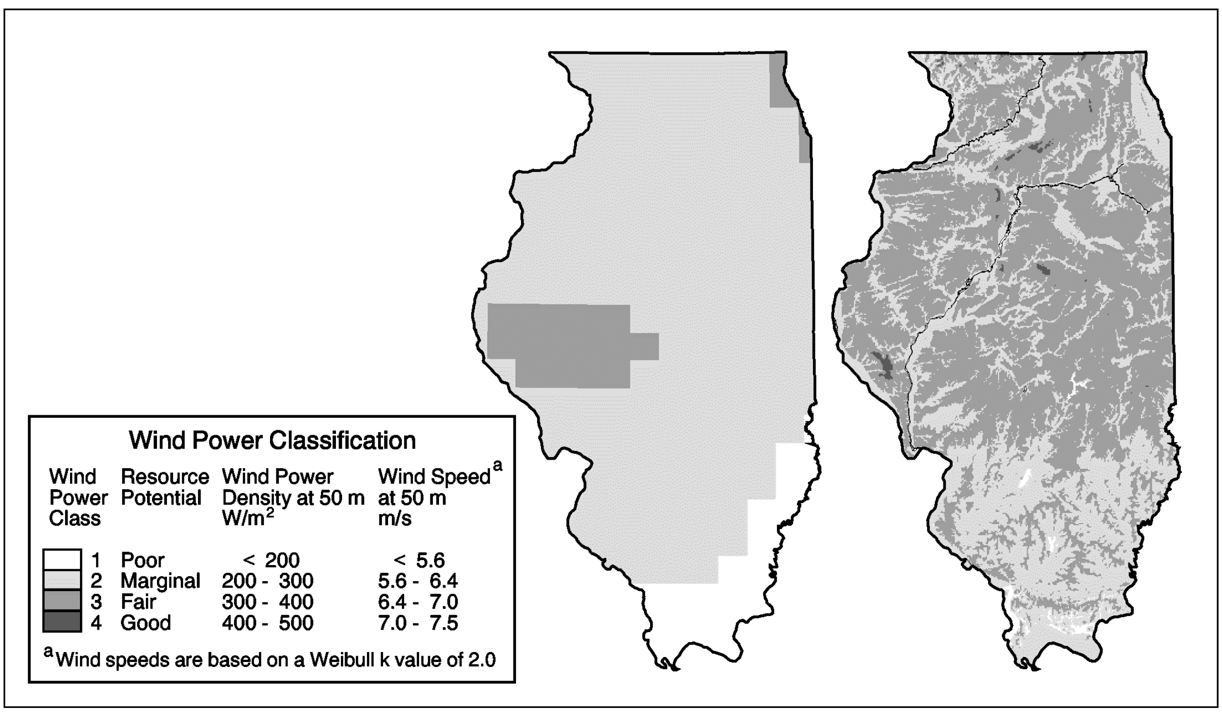

Figure 2. Illinois wind resource maps from the 1987 Atlas (left) and the 2001 assessment (right)

validation because data from 40-m towers, originally collected by utilities for wind energy measurement purposes, were publicly released by the state of North Dakota. At six of the seven sites, our annual average wind power estimates were within 20% of measured values. This level of accuracy (80+% of validation sites within 20% of measured power) is typical of the updated maps that NREL has produced. As a whole the NREL map tended to be conservative in its wind resource estimates. At five of the seven sites, the mapped resource was lower than the measured resource. Unfortunately no publicly available measurement data were available for validating the map in South Dakota, but given the similarities in the terrain and climate, we believe that the map has the same degree of accuracy in South Dakota as in North Dakota.

The expanses of "windy" (Class 4 resource and higher) lands in the Dakotas are large. Even with the reduced areas of Class 4 and higher on the updated map, more than 70,000 km^2 of land possess at least Class 4 resource in North Dakota. South Dakota has more than 120,000 km^2 of Class 4 and higher wind resource. The nearly 200,000 km^2 of windy land in these states can potentially support the production of hundreds of thousands of megawatts of electricity from wind energy.

6.2 Illinois Wind Mapping Results

Figure 2 shows the 1987 Atlas and the updated 2001 wind maps for Illinois. The most interesting feature on the 2001 map is the general increase in the wind resource throughout the state compared to the 1987 map. The 2001 map shows large areas of the Class 3 resource with pockets of Class 4; the 1987 map shows only Class 2 and a bit of Class 3. The Class 4 resource areas on the 2001 map are found on the higher terrain in central and northern sections of Illinois. We observed some subtle differences in the wind climate between central and northern Illinois. Although both regions have a maximum wind resource in the spring, southerly winds prevail in central Illinois during this season. The prevailing direction in northern Illinois was from the west.

The analysis of the low-level wind pattern depicted by the GUACA and Reanalysis data indicated that the 1987 Atlas underestimated the wind resource in central and northern Illinois. This was reinforced when we analyzed the DATSAV2 data from the airports near Bloomington (low Class 4 wind), and Champaign (high Class 3 resource). Data from these airports were not part of the 1987 data set. The data furnished important indications of the true level of the resource in the central part of the state. We believe that the wind resource was underestimated in the northern part of the state because the surface data available in 1987 were from airports located in relatively low terrain, meaning that they did not accurately represent the wind resource across a larger region. As in the maps of North and South Dakota, the large variation of the wind resource in "flat" areas across Illinois is a significant finding of these mapping studies.

More than 600 km^2 of windy lands in Illinois are seen on the updated map compared to virtually no windy land on the 1987 map. A few hundred kilometers of windy land could potentially support thousands of megawatts of wind generation in the state. The new map allows policy makers to plan for the possible contribution of wind contributing to the energy load centers of Chicago and St. Louis. In addition, the increase in the Class 3 resource boosts the likelihood that small wind turbine applications can be used throughout much of the state. Although we have not yet performed a comprehensive validation of the updated map, some proprietary data indicate that the accuracy of the Illinois map is similar to that of the Dakota maps. No public data are available for a comprehensive validation, but we hope to obtain proprietary data to complete this task.

7. CONCLUSION

In the past 2 years, NREL has produced updated wind resource maps of Illinois, North Dakota, and South Dakota at a horizontal resolution of 1 km. This is an improvement over the maps in the 1987 that had a 25-km resolution. As part of developing an understanding of the wind climate in the Midwestern United States, NREL analyzed its available in-house climate data sets including DATSAV2, GUACA, and Reanalysis. We combined the information from the analysis with the terrain data in the computerized wind mapping system to produce these updated maps.

The updated maps show more precise patterns of the wind resource and significant variation of the resource across the seemingly flat terrain of the three states. The new, higher resolution maps reveal many pockets of higher wind resource in the three states than those seen on the older maps. The information on the updated maps can be quite helpful in determining where wind farms can be located. The success and popularity of NREL's updated state wind maps have spurred interest in wind energy, leading to increased demand for higher resolution wind resource maps in other areas of the country.

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A recent increase in interest and development of wind energy in the Midwestern United States has focused the need for updating wind resource maps of this area. The wind resource assessment group at the National Renewable Energy Laboratory (NREL), a U.S. Department of Energy (DOE) laboratory, has produced updated high-resolution (1-km) wind resource maps for several states in this region. This abstract describes the computerized tools and methodology used by NREL to create the higher resolution maps.

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