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Validation of Regional Wind Resource Predictions in the Northern Great Plains

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VALIDATION OF REGIONAL WIND RESOURCE PREDICTIONS IN THE NORTHERN GREAT PLAINS

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INTRODUCTION and APPROACH

The development and validation of computerized wind mapping tools for regional assessment purposes is an important step in accelerating wind energy deployment. This paper summarizes the results of a validation study of the automated wind resource mapping technique developed at the National Renewable Energy Laboratory (NREL). This technique uses Geographic Information System (GIS) software and produces high horizontal resolution (1 km) wind resource maps. The automated wind maps have been used to help plan wind measurement programs and to define potential areas for wind energy projects in countries such as Mexico, Chile, Indonesia, and China.

We chose a U.S. location for this project to test the accuracy of the automated mapping technique in a region where the wind resource distribution was already fairly well known. The Buffalo Ridge region of the Northern Great Plains served as the subject area. The study area covered northwestern Iowa, southwestern Minnesota, and adjacent parts of South Dakota and Nebraska. This area had several advantages for use in a validation study. First, this area has active wind energy development and the results would be of interest to the wind energy community. Second, a validation data set would be fairly easy to derive because recent wind measurements were taken in that region specifically for wind energy purposes. These data were publicly available and easily obtained. Finally, the relatively simple terrain in that region enabled this study to be completed in a timely manner.

Our approach in this study was to map the Buffalo Ridge region as if it were part of a foreign country with limited surface meteorological data. This approach would ensure that analysis and mapping preparation employed at NREL for this project would be comparable to other wind mapping projects. A map of the wind power density distribution for Buffalo Ridge would be produced, and the measured data from the validation data set would be used to evaluate the accuracy of the map. This approach made a detailed analysis of the validation data set a necessity. Any discrepancies in the quality and reliability of the validation data set had to be resolved before the data could be used to judge the accuracy of the mapping system. In summary, the components of the approach to this validation study included meteorological analysis to prepare model input data; production of the computerized wind resource map; analysis of the validation data set; comparison of computerized wind resource distribution and the validation data; and conclusions reached as a result of this project.

NREL COMPUTER MAPPING SYSTEM

NREL developed the automated technique for wind resource mapping for several reasons. The primary reason is that the computerized technique greatly reduces the human effort needed to create a wind resource map as compared to the old style manual analysis that characterized wind mapping in the 1980s and early 1990s. This is especially true for areas of complex terrain. Under the old style of manual analysis, the distribution of the wind resource had to be physically drawn on topographic maps to highlight features such as ridge crests and elevated plateaus. Naturally, this process was time consuming, subjective, and prone to inconsistencies in the analysis. Using computer mapping techniques reduces the time it takes to produce a wind map that reflects a consistent analysis of the wind resource distribution throughout the region of interest. This factor is quite important when clients need a quality wind resource map in a relatively short period of time. The mapping technique uses commercially available GIS software packages produced by Environmental Systems Research Institute Inc., of Redlands, California. The main GIS software is ARC/INFO, a powerful and complex package featuring a large number of routines for scientific analysis. None of the ARC/INFO analysis routines is specifically designed for wind resource assessment work; therefore, NREL's mapping technique requires extensive programming in ARC/INFO in order to create combinations of scientific routines that mimic direct wind resource assessment methods.

The computer mapping system uses an empirical and analytical approach to determine the level of the wind resource for a particular location. This approach was taken because of the necessity of developing a quick method of producing useful wind maps for specific projects. Thus, the wind mapping system does not use any explicit atmospheric boundary layer equations or geostrophic adjustment equations as some other wind flow models do. The mapping system is designed to display regional (greater than 50,000 sq. km) distributions of the wind resource. The maps are intended to denote the areas where wind energy projects are likely to be feasible. The maps are not intended to be used for micrositing purposes.

The major meteorological assumption that underlies the NREL technique is that there are empirical relationships in many parts of the world among the free-air (higher than 100-200 meters 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 in the world. Accordingly, the wind resource values presented on the maps are the estimates for a non-sheltered location with low roughness (short grasslands, for example). Another important difference between the NREL approach and approaches used by other wind mapping systems is that NREL 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 speed profile in the lowest few hundred meters above the surface and adjusts these data to produce a wind power profile from the surface to as high as 3000 meters above the surface. In contrast, other wind mapping tools depend on the availability of high quality surface wind data and adjust these data up to a turbine hub-height. NREL uses 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 hardware, height, exposure and maintenance history are just a few of the problems. In addition, very little surface data exist for many areas of the world that may have good to excellent wind resource. Overall, the available surface wind data in much of the world is not reliable or abundant enough to use directly as input in the wind mapping system.

The wind mapping system is organized into three main components. The input data, the wind power density calculation, and the output section that produces the final wind resource map. The meteorological and geographical information from NREL's comprehensive global data bases give input to the mapping system. A description of the meteorological data sets and details on the digital elevation data used by the mapping system can be found in previous publications (Elliott and Schwartz 1996, 1997). The precision of the meteorological input data is the most important factor in determining wind map accuracy. To ensure that the input is as precise as possible, a critical analysis of the available climatic data in the NREL data sets is performed. Products generated from the raw data for the analysis are cross-referenced against each other to understand the prevalent wind characteristics in the study area. The ultimate goal of the analysis is to enable investigators to gain a conceptual model of the physical mechanism(s), whether produced by large and/or local scale features 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 the wind power. It is in this step that any high quality surface wind data is integrated into the mapping system. The meteorological input for the system can be broken down into three major formats. The first format is a wind power rose. The power rose expresses the percent of the total potential power of the wind in a region by direction. The directional input is divided into twelve 30° sectors starting at 360° (0°) with the sum of total energy always equal to 100 percent. The wind power rose is used to determine the degree of exposure of a particular grid cell to the power producing winds in complex (non-flat) terrain and along coastlines and shorelines. The second format is a vertical profile of free-air wind power density. These profiles are divided into 100 meter intervals. The free-air wind power density values are then used as a base value by the power calculation algorithms. The third major format is the open ocean wind power density. This value is calculated from the marine wind data when ocean coastlines are present in the mapped region. Ocean wind power values are applied to areas within 5 km of the coast.

For this Buffalo Ridge project, a mapping system process defined the terrain as "flat" throughout the area of interest. As a result, the wind power rose was not used in the mapping activity. In this study, the base wind power density values were adjusted by empirical absolute and relative elevation factors to calculate the wind power density distribution on the final map. These values are for non-sheltered locations in areas of low surface roughness. The output section of the mapping system produces the final wind resource map with a proper map projection for the region, plus a map legend showing the level of resource for the different wind power classes.

There are limitations to the NREL mapping system. There are two types of limitations that bear the most on this particular study. NREL uses 1 km resolution digital elevation data for its wind mapping, because this is the highest resolution currently available for most of the world. However, the terrain can vary significantly within a 1 km area even in "flat" terrain so the estimate for a particular grid cell may not apply to all areas within the grid cell. The other limitation is that surface roughness, which can greatly affect the wind power at a specific location, is not explicitly used in the wind power calculations. The reason for this is that surface roughness data for most of the world is not available in digital form and is very expensive to gather. As already stated, the power estimates are valid for areas with low surface roughness. If the maps are to be applied for regions with higher degrees of surface roughness, then the estimates on the wind resource maps would have to be reduced by 25% to 60%. The exact level of reduction would depend on the degree of surface roughness in a particular area.

MAPPING RESULTS

The wind resource mapping system was run on a 3° latitude by 3° longitude area centered on the western section of the Minnesota-Iowa border. In general, the terrain gradually slopes up from east to west, with the average slope over the region less than one percent. The regional elevation ranges from around 250 m above sea level in the Minnesota River Valley to over 600 m above sea level in eastern South Dakota. The primary cities in the study region are Sioux Falls, South Dakota, and Sioux City, Iowa. The major terrain feature is the Buffalo Ridge, which runs northwest to southeast extending from eastern South Dakota to north-central Iowa. This feature gradually becomes less distinguishable as it extends further south. Figure 1 is the annual average wind resource map for the Buffalo Ridge area as calculated by the automated system. The map uses the wind power classes defined in the "Wind Energy Resource Atlas of the United States" (U.S. Atlas) (Elliott et al. 1987). The pattern on the map reflects the power density calculated for each 1 square km grid cell.

Strong free-air winds over the region are the basis for the high level of wind resource shown on this map. Information from three stations (Omaha, Nebraska, Huron, South Dakota, and St. Cloud, Minnesota) were used to determine the free-air wind power profiles over the region. A salient feature of the annual average free-air data at all of these stations was the high wind speed (9 to 10 m/s) and wind power density (800 to 900 W/m^2) found at 0600 Local Standard Time just a couple of hundred meters above the surface. These profiles, when adjusted, by absolute and relative elevation factors resulted in the level of wind resource indicated on the map. Moderate (class 3) wind energy levels were estimated for the lower elevation plains with some class 2 resource in some river valleys and along the northeastern edge of Buffalo Ridge. The terrain features which had higher

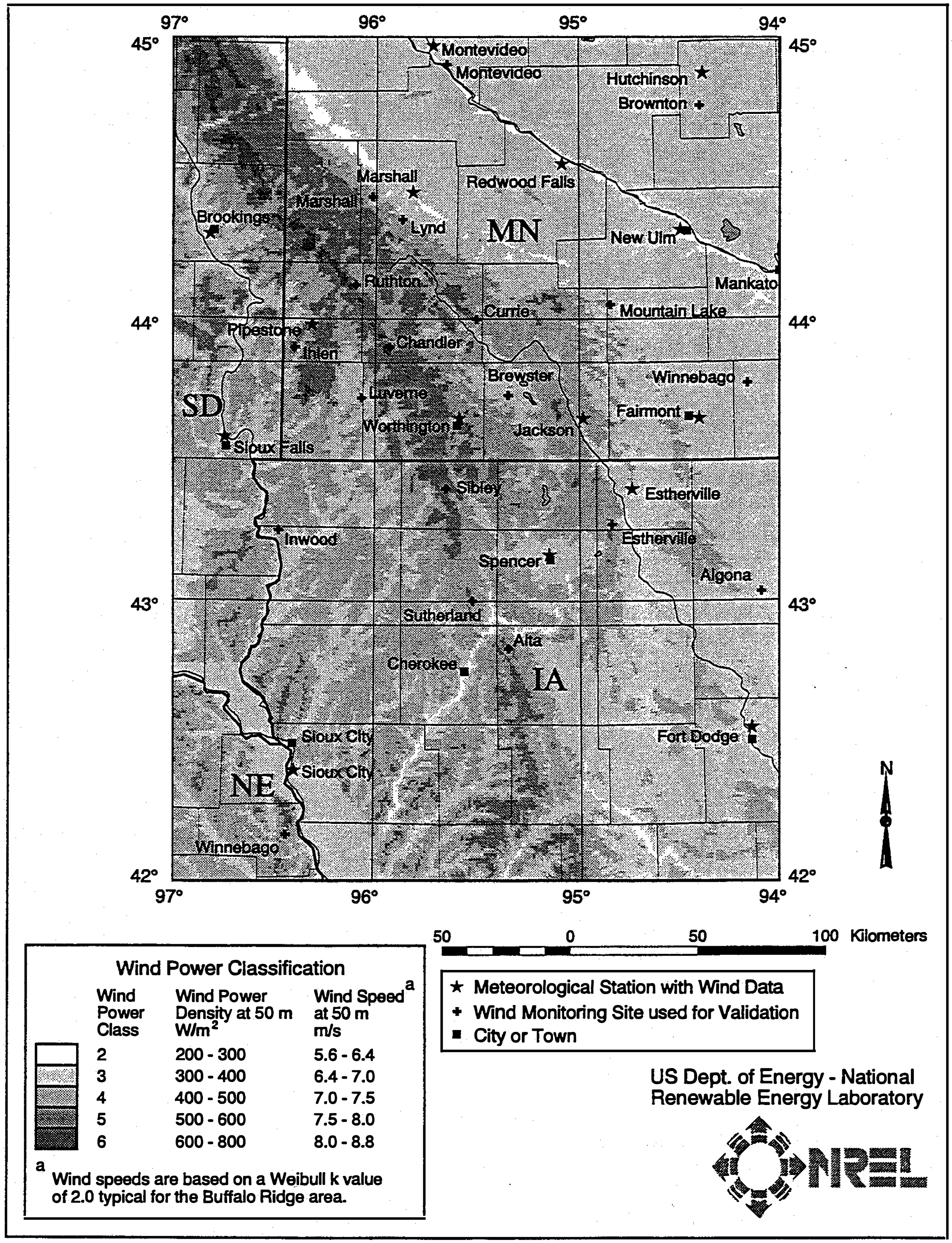

FIGURE 1. WIND RESOURCE MAP FOR BUFFALO RIDGE AREA

relative elevations than the surrounding 100 km region in general were mapped with a higher (class 4 and class 5) wind resource. The highest wind resource estimated by the automated technique were areas of class 6 located on the highest elevations of Buffalo Ridge. The wind speeds associated with the various power classes were not directly computed, but estimated using a Weibull k value of 2.0, which is estimated to be typical for many locations in the region based on upper-air and high quality surface data. The wind resource levels and distribution patterns compare favorably to those found in the U.S. Atlas.

VALIDATION PROCEDURES

The Buffalo Ridge area has an abundance of National Weather Service (NWS) meteorological stations and publicly available wind energy measurement data compared to other regions of the United States. A map of the locations of the NWS airport stations and the stations used for validation is presented in Figure 2. Wind measurements from a total of nineteen locations were used for validation. Six stations were located in Iowa, twelve were in Minnesota, and one was located in Nebraska. All of the validation data were publicly available. The sources of validation wind data in Iowa and Minnesota were the Iowa Wind Energy Institute (IWEI) and the Minnesota Department of Public Service, respectively. These organizations operate and maintain wind measurement stations as part of wind energy assessment programs financed by their respective states. The Nebraska station used for validation was located in Winnebago, Nebraska. The data from this station was collected as part of the Utility Wind Resource Assessment Program (U*WRAP) (Elliott and Schwartz, 1996). The utilities in Nebraska have made these data available to the public through the High Plains Climate Center in Lincoln, Nebraska. The validation measurements used in this study were all taken from 1993 to 1997. The periods of record at the individual stations varied from one year to three years. Data at the stations were collected at various levels ranging from 10 meters to 70 meters above the ground. If available, wind power data collected at the 50 meter level were used in this study. Otherwise, power data collected at 30 meters and 40 meters were adjusted to 50 meters using the one-seventh power law. In all, 15 out of the 19 validation stations had sufficient power data at 50 meters. Thirty meter data were adjusted to 50 meter values at two stations and 40 meter data were adjusted at two stations. In these cases, the power density was adjusted using a 3/7 shear exponent, a value that was supported by preliminary analyses of the 10 meter and 50 meter data at several stations.

An important part of NREL's validation procedures was to perform its own quality control on the validation data sets. Therefore, NREL obtained the actual hourly digital data sets of the wind observations, not just the existing summaries from the Iowa, Minnesota, and Nebraska data sources. A preliminary screening of the raw hourly data established that considerable quality control work was required to produce a "clean" data set for use in validation. First, there were bad data in the hourly data sets caused by factors such as non-functioning anemometers and wind vanes and malfunctioning data loggers. The causes of these equipment failures are varied with icing and lightning strikes the most prevalent causes. There was some guidance from IWEI about known problem periods at the Iowa stations, but for the most part, NREL had to develop computer software to detect and eliminate bad data records. Another consideration in the process of creating a "clean" data set is the effect of tower shadowing. This potential problem was quite noticeable in data from lattice tower locations but was also evident from locations with tilt-up towers. Fortunately, both the state-run and the U*WRAP wind measurement programs used redundant anemometers at the higher measurement levels. Both of the anemometers were used to adjust the data for the tower shadow effect. Based on a review of wind speed plots from the prime and redundant anemometers, we decided, if the two anemometer wind speeds were within 2 m/s of each other, the average wind speed was used to produce the "clean" data set. If the anemometer wind speeds were more than 2 m/s apart, the higher value was used.

The measured wind power values from the "clean" data set were further adjusted before comparisons were made to the mapped values. There were three types of adjustments made. The first type of adjustment was the most difficult to estimate, but it may have been the most important. This was the adjustment made to the

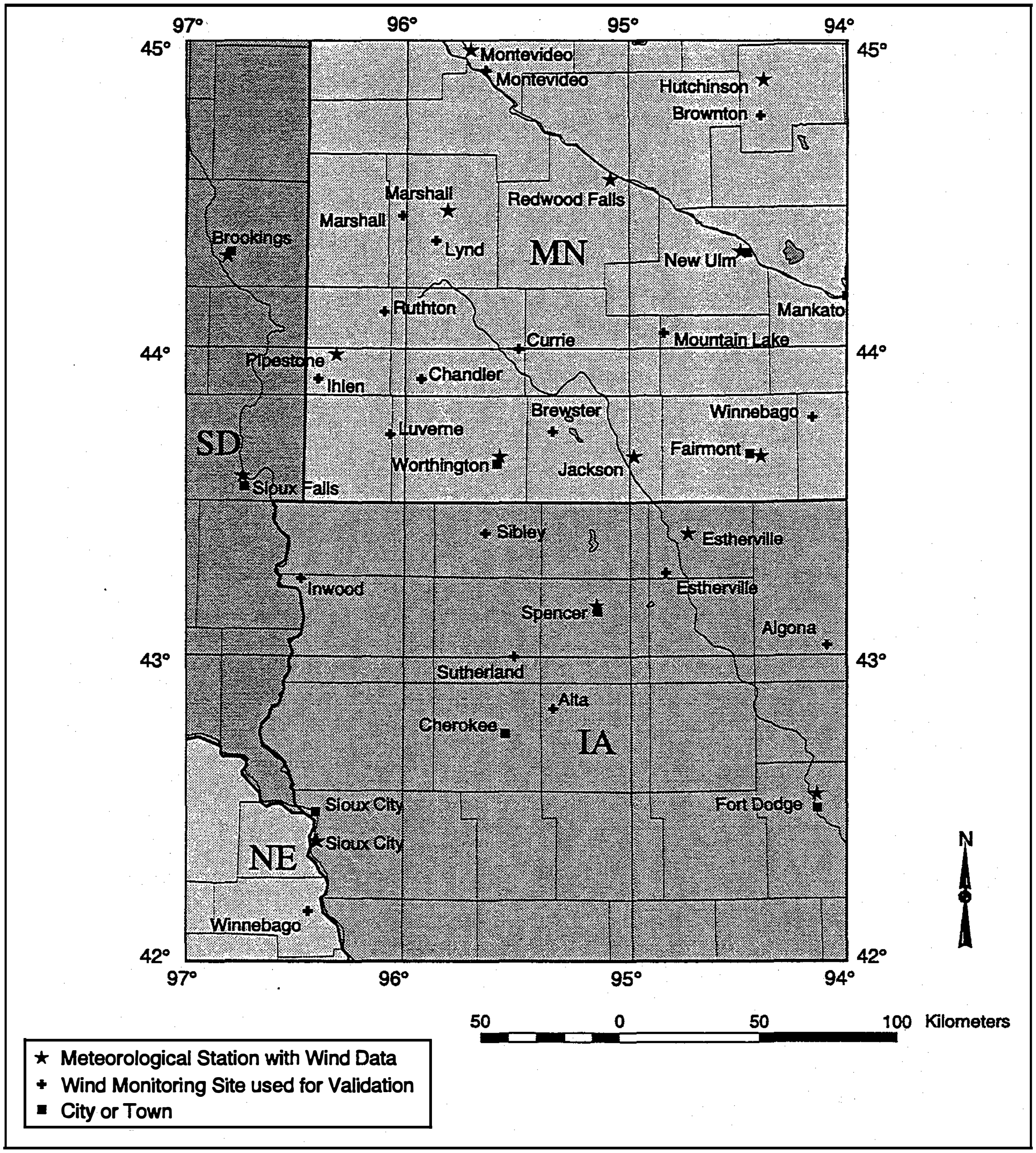

FIGURE 2. LOCATIONS OF METEOROLOGICAL STATIONS AND VALIDATION STATIONS

wind power density at a station when large gaps in the data occurred because of equipment failure. The short period of record (1 to 3 years) of the validation data exacerbated this problem. At several stations, some of the monthly wind speed and power values were unrepresentative and totally different from those at other nearby stations due to data gaps. The unrepresentative values were adjusted through comparisons with other regional stations where data gaps for the same general time frame were either much smaller or non-existent. A consistent month to month pattern of wind power values at the validation stations emerged after these adjustments were made. Climatological adjustment of the data was the second adjustment type. This was done by comparing the wind observations at major airports such as Sioux Falls and Sioux City during the time frame of the validation data with the long-term (more than 20 years) measurements. In this case, the climatological adjustment to the wind power values ranged from 0% to an increase of 6%, depending on the period of record at an individual station. The third type of adjustment was an across-the-board increase of 10% to the wind power values at the validation stations. This was done to account for the difference in wind power values between using hourly average data and the one or two minute average that constitute the airport observations, the basis of the distribution of the wind power classes in the U.S. Atlas. This made the power values compatible at the validation and the NWS wind measurement locations. We judge the final adjusted validation wind power values to be accurate within 5% to 10%.

VALIDATION RESULTS AND POTENTIAL SOURCES OF ERROR

The accuracy of the wind power predictions produced by the mapping system was tested by comparing the adjusted annual average wind power values from the validation data set to the mapped values. The limited (1 km) resolution of the elevation data combined with a degree of uncertainty of the exact location of the measurement towers within a grid cell, convinced us that an area averaged wind power value would provide a fairer test of accuracy than a single grid cell power value. Therefore, the predicted power values were the average for grid cells in a 3 km by 3 km square centered on the grid cell location of the validation station. Table 1 presents the results for the 19 stations. A simple ratio of the measured annual average power to the predicted power provides a straightforward indicator of map accuracy. When this ratio is below (above) 1.0, the mapping system overpredicted (underpredicted) the level of wind resource at the measurement location.

The predicted values were within 10% of the measured values at 9 of the 19 validation sites, and within 5% at five locations. These five sites were located either on the northeastern side of Buffalo Ridge or in relatively low elevation regions within the ridge area. The predicted values differed from the measured value by more than 20% at four sites with three of these sites at higher elevations in Iowa. In all of these cases, the mapping system overpredicted the wind resource. Overall, the mapping system tended to overpredict the wind power for locations on top of Buffalo Ridge and at higher elevations in Iowa and Nebraska. The computerized map predicted individual grid cells in these areas to have class 5 and class 6 wind resource. Six validation sites were predicted to have class 5 (500-600 W/m^2) wind resource. Of these six sites, the predicted values were greater than the measured values by more than 5% at five sites. The geographic area where mapping system tended to underestimate the wind resource was along the northeastern side of Buffalo Ridge. The three locations where the mapping system underpredicted the resource by more than 5% (ratio greater than 1.05) were located in this region. There are several potential sources of the differences noted between the mapped and measured values. The most probable source are the adjustments made to the free-air data. There is always a question of how much of the free-air momentum is transported towards the surface. The amount of the momentum evident on the vertical profiles that is transported down to turbine hub-height will depend on factors such as solar angle, frequency of large-scale weather systems, and the degree of moist and dry mixing processes. The horizontal interpolation of the free-air data from the three upper-air stations used in the analysis can also introduce uncertainty into the mapping results. Often, there is a difference between the distribution of wind speeds in the free-air and that at turbine hub-height, and the magnitude of this difference can affect the accuracy of the adjustment of the free-air power towards the surface. Finally, the upper-air data are taken only once or twice a day. Thus, the upper-air data set is only a "snapshot" of the wind characteristics. Atmospheric conditions can vary significantly between observation times but not all of the variability is captured in the available upper-air data.

The process of creating a "clean" validation data set can be a source of error. Although automated computer routines can eliminate much of the guesswork in identifying periods of invalid data, there is still some subjectivity involved in analyzing the quality of a validation data set. Estimating the wind resource at a station

TABLE 1. VALIDATION RESULTS FOR BUFFALO RIDGE AREA

State	Station	Long. (deg)	Lat. (deg)	Elev. (m)	Period of Record	Measured Power (W/m^2)	Predicted Power	M/P Ratio
IA	Algona	94.13	43.03	384	94-97	410	382.4	1.07
IA	Alta	95.35	42.83	469	94-97	410	533.8	0.77
IA	Estherville*	94.85	43.27	475	94-97	500	510.3	0.98
IA	Inwood	96.47	43.25	451	94-97	355	468.0	0.76
IA	Sibley	95.65	43.40	490	94-97	410	511.5	0.80
IA	Sutherland	95.52	43.00	460	94-97	395	499.2	0.79
MN	Brewster	95.35	43.73	436	95-97	365	357.5	1.02
MN	Brownton	94.40	44.75	316	95-97	250	343.7	0.73
MN	Chandler	95.93	43.90	556	96-97	510	567.2	0.90
MN	Currie	95.50	44.00	465	95-97	430	448.9	0.96
MN	Ihlen*	96.40	43.90	488	96-97	420	511.8	0.82
MN	Luverne	96.07	43.72	466	95-97	350	357.5	0.98
MN	Lynd	95.87	44.35	442	93-95	470	422.8	1.11
MN	Marshall	96.02	44.43	451	96-97	460	442.4	1.04
MN	Montevideo	95.65	44.90	454	95-97	220	318.4	0.69
MN	Mountain Lake	94.85	44.05	357	95-97	365	406.3	0.90
MN	Ruthton*	96.10	44.12	579	93-95	490	536.1	0.91
MN	Winnebago	94.18	43.77	345	95-97	360	317.8	1.13
NE	Winnebago*	96.42	42.17	457	95-97	410	474.8	0.86

* Stations where data were interpolated to 50 meter level from measurements at 30 or 40 meters above ground

when there are significant gaps in the data also introduces uncertainty into the measured data values and affects validation results. A final concern is the problem of validating a regional wind mapping pattern with data from specific locations. Local exposure, terrain variations, and changes in surface roughness, which influence the wind resource at a particular location, often occur on too small of a scale to be resolved by the 1 km elevation data set used in this study. This problem is not easily resolved since higher resolution elevation data, though available for the United States, are not generally available for the rest of the world and obtaining detailed surface roughness data is quite time consuming and expensive. Lastly, assessing the accuracy of the regional patterns generated by the mapping system by using point measurements is inherently inexact.

CONCLUSIONS

The evidence indicates that NREL's mapping system produced a realistic distribution of the wind resource for the Buffalo Ridge region of the Northern Great Plains. The wind resource map was validated using wind energy measurement data from 19 locations in Minnesota, Iowa, and Nebraska. The difference between the wind power class estimated by the wind mapping system for a particular validation site and the wind class measured at that site was never greater than one power class. In addition, the estimated wind power density was within 20% of the measured values for a large majority of the validation sites (15 out of 19). The resulting wind resource pattern also compares favorably with that found in the U.S. Atlas. The main imperfection of the wind resource map is that it indicates more variation of the wind resource from the top of Buffalo Ridge to the lower plains on the northeast side of the ridge in Minnesota and Iowa than is present based on the validation data. Absolute and relative elevation were the determining factors of the wind resource for each grid cell in the NREL mapping system. Thus, there are other processes that effect the distribution of the wind resource in this region.

The resource on top of the ridge was overpredicted by the mapping system in general, by about 10% to 20%. Therefore, the class 6 areas shown on the map are likely to be class 5. Also, the total area of class 5 resource in the region is less than what is shown on the map. We believe the main causes of the overprediction of the resource are boundary-layer mixing and stability processes that effect the amount of momentum that is transported to the surface from free-air levels. These processes are only simply approximated in the mapping system. Seasonal evaluations of the mapping system may be able to further define the extent of error associated with inexact approximations of these processes. The resource along the northeastern edge of Buffalo Ridge was, in some instances, underpredicted by about 5% to 20%. Class 4 resource is probably a bit more widespread just on the eastern edge of Buffalo Ridge than is shown on the map and the mapped class 2 resource along the edge of this feature is likely to have been a class 3 resource. The reasons for the mapping system underprediction are not clear, but there is one hypothesis that appears to be especially intriguing. An evaluation of a large-scale relative elevation map of the region revealed that the areas of underprediction were located along the sides of a relative elevation terrain feature or in gaps between two relative elevation terrain features. This implies that there could be low-level acceleration zones and wind corridors located in "flat" terrain. Available wind measurement data is limited but, if these acceleration zones and wind corridors are real, then the number of potential wind farm locations in the Great Plains may be increased in certain regions.

Overall, the results of this validation study were encouraging. There are plans for subsequent validation of the NREL mapping system. Seasonal validation of the Buffalo Ridge area is an upcoming activity as is validating the mapping system for an area with more complex terrain. Future improvements to the mapping system could include incorporating new climatic data sets for analysis purposes, directly using land-use data for wind power calculations, and developing more sophisticated atmospheric mixing algorithms. In addition, NREL will explore the use of new tools, such as mesoscale (about 50 km horizontal resolution) numerical weather and climate models for advanced versions of the mapping system.

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