January 2001 • NREL/CP-500-29164

Conference Paper

Geographic Information Systems in Support of Wind Energy Activities at NREL

Preprint

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To be presented at the
39th AIAA Aerospace Sciences Meeting
Reno, Nevada
January 8–11, 2001

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GEOGRAPHIC INFORMATION SYSTEMS IN SUPPORT OF WIND ENERGY ACTIVITIES AT NREL

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ABSTRACT

The National Renewable Energy Laboratory (NREL) uses Geographic Information Systems (GIS) to further the development of wind energy resources in support of the U.S. Department of Energy (DOE) Wind Energy Program and its Wind Powering America Initiative. A GIS consists of computer hardware and software that inputs, stores, maintains, manipulates, analyzes, and outputs geographically referenced data. Some of the elements of NREL's GIS data used in wind energy activities include wind measurement sites, transmission lines, federal facility information, and modeled wind resources. A relatively simple GIS analysis technique involves combining data layers to summarize spatial information. This type of analysis is used to identify areas with strong potential for wind resource development using potential wind resource availability, electricity rate, and federal electricity load information. More complex GIS analyses can define relationships among the mapped wind energy resources, potential energy load characterization, and utility integration problems. A GIS is an outstanding tool for wind energy activities because data can be readily updated and the results of the GIS analyses can be expressed as charts, tables, and maps. These outputs are in digital formats that allow the results of GIS analyses to be quickly and efficiently distributed to the wind energy industry.

BACKGROUND

A Geographic Information System (GIS) is a valuable tool for wind resource assessment and development because it utilizes the significant spatial components found in both. Wind resource potential is strongly influenced by the exposure and the orientation of the terrain relative to the prevailing wind direction. The development of wind resources is significantly influenced by proximity to existing transmission lines, current land use, and potential energy demand. These relationships can be readily quantified with the spatial capabilities that are inherent in a GIS.

Before 1995, manual spatial analysis techniques were used to support the U.S. Department of Energy's (DOE) Wind Energy Program. This included the development of the *Wind Energy Resource Atlas of the United States*[1] by the Pacific Northwest Laboratory (PNL). Analysts at PNL used sectional aeronautical charts with topography information. Topography influences the wind resource by boosting or reducing it, particularly in areas of complex terrain. In a later project, analysts compared maps of federally administered environmental areas and landform to roughly estimate the percentage of windy land area that would not be developed for environmental reasons (e.g. wilderness areas, national parks). [2]

In 1995, the wind resource assessment group at the National Renewable Energy Laboratory (NREL) began developing an automated GIS Wind Resource Assessment Model (WRAM). This model allows for a more consistent application of analysis techniques in a regional assessment, a more detailed analysis of the wind resource, and it produces high-quality maps that can be easily distributed to clients.[3] NREL has used the WRAM to conduct both domestic and international wind resource assessments. Domestic wind resource assessments have been completed for the states of North Dakota, South Dakota and Vermont and the Buffalo Ridge area of Minnesota, South Dakota, Iowa, and Nebraska. International wind resource assessments have been completed for the Dominican Republic, Mongolia, the Philippines, and regions of Chile, China, Indonesia, and Mexico. The resulting wind resource maps have been used to help plan wind measurement programs and to identify potential areas for wind energy projects.

The role of GIS at NREL has expanded to include many other tasks that directly or indirectly affect the development of wind resources. These activities include: distributing data and maps to interested members of the wind energy industry; generating maps of topography, measurement locations, and other data to determine the spatial distribution and relationships of the information; and spatial analyses to describe the potential generating capacity of an area or potential electricity demand. Specifically, GIS has been a valuable tool in furthering the objectives of the U.S. Department of Energy's (DOE's) Wind Powering America initiative.

WHAT IS A GIS?

A GIS can be defined as the computer hardware, software, and technical expertise that inputs, stores, maintains, manipulates, analyzes, and outputs geographically referenced data.[4] A GIS combines the power of spatial database management with high resolution graphic display to effectively present information.

The essential components of a GIS can be divided into five broad categories: data acquisition; pre-processing; data management; manipulation and analysis; and product generation.[5]

Data Acquisition
NREL gathers data from many sources including the U.S. Geological Survey, the National Climatic Data Center, foreign countries, and commercial sources. The reliability of a new data source must be assessed before it can be confidently used. If necessary data is not available in digital format, information contained in paper format can be brought into a digital format with manual data entry or map digitizing. Datasets used by NREL include a global 1-square-kilometer (km^2) resolution digital elevation model, detailed hydrography layers, federal land ownership, federal facility locations, and political features.

Preprocessing
Data from outside sources must be preprocessed to ensure it will match other data formats at NREL. In particular, the units of measurement and the coordinate system must be consistent to ensure all data can be used together appropriately.

Data Management
The databases are defined with specific, common fields in consistent formats. The data is generally organized by geographic extent, original source, and planned use.

Manipulation and Analysis
The data can be manipulated using spatial overlays, extractions, or complex combinations of spatial functions that allow exploration of the spatial relationships in the data. Detailed examples of some of the GIS analyses conducted at NREL will be presented later in this paper.

Output Generation
The outputs of a GIS can include statistical reports, tables, charts, on-screen displays, and high-quality maps. The outputs are produced in digital formats that can be quickly and easily distributed to the wind energy industry.

WIND RESOURCE ASSESSMENT MODEL (WRAM)

The WRAM is used to produce a wind resource map of gridded wind power density values with a 1-km^2 resolution. The WRAM was developed with ArcInfo , a powerful GIS software package developed by Environmental Systems Research Institute Inc. ArcInfo contains a large number of routines for scientific analysis. Because these routines were not specifically designed for wind resource assessment work, they had to be combined into specific ArcInfo programs. Each program performs a different part of the wind resource assessment methodology. After five years of development, the WRAM now consists of 34 separate ArcInfo programs. The WRAM was designed for regional (areas greater than 50,000 km^2) wind resource assessments.

The WRAM is designed to work in different geographic and terrain categories. The geographic categories are inland areas and ocean and lake coastal areas. The terrain categories are complex, flat, and mixed. Complex is characterized by hilly and mountainous terrain. Flat describes flat to slightly inclined and gently rolling terrain. Mixed is a combination of complex and flat terrain. The combination of programs used for the wind resource assessment depends on the combination of geographic and terrain settings in the study area. Some programs are general in scope and may be applied to multiple settings, while other programs are specific to only one setting. For example, a coastal exposure program would not be used for an inland area with no lakes large enough to significantly influence the wind resource.

The WRAM requires terrain input in the form of a Digital Elevation Model (DEM) with a spatial resolution of 1-km^2. The DEM represents the elevation data as a grid, dividing the analysis area into individual cells. The value of each cell represents the average elevation within that cell.

The WRAM uses three types of meteorological inputs: wind power roses; vertical profiles of wind power; and, where appropriate, open ocean wind power. A wind power rose represents the total potential wind power in a region by wind direction. The directional input is divided into twelve 30° or thirty-six 10° sectors, depending on the complexity of the terrain. Each sector is assigned a percentage of the total wind power so that the sum of all sectors is 100%. The wind rose is used to determine the exposure a grid cell has to the power-producing wind in complex terrain and ocean and lake coastal areas. The vertical profile represents the free-air wind power density by elevation in a region. These profiles are determined for 100-meter intervals, each of which is assigned a free-air wind power density value. These values are used to assign each grid cell a base wind power value determined by the cell elevation. Open ocean wind power density is only used in a coastal or island setting and is applied to onshore areas within 5 kilometers of the coast.[6]

The WRAM calculates the final wind power density by adjusting the base wind power density. The factors that decrease or increase the base wind power density value for a particular grid cell are terrain blocking, relative and absolute elevation, aspect (slope of terrain relative to the prevailing wind direction), distance from ocean or lake coastlines, and small-scale wind-flow patterns, such as local sea breezes. The WRAM applies these calculations over short-range (less than 10 km), medium-range (10–50 km), and long-range (greater than 50 km) distances.

The calculations that produce these factors range from very complex manipulations between the wind power rose and DEM (terrain blocking) to simple manipulations of the DEM (short-range relative elevation). For example, the following steps are required to produce the short-range relative elevation factor grid. First, the average elevation of a selected area around each grid cell is calculated and then assigned to each cell. Second, the difference between the cell's absolute elevation value and average elevation value is calculated and then assigned to each cell. Third, a factor based on this difference is assigned to each grid cell. The equations that produce these grids are as follows:

Average elevation = AVERAGE (DEM, Selected area)
Relative elevation = DEM - Average elevation
Relative elevation factor = CLASSIFY (Relative elevation, factor table)

The wind power grid is then produced as follows:

Wind power = Base wind power density * Terrain blocking factors * Aspect factors* Distance from coastline factors * Relative elevation factors * Small-scale wind-flow pattern factors

The wind power grid produced by the WRAM can then be classified by ranges of wind power density expressed in W/m^2 and displayed as a color-coded map. The values on the map apply to areas of low surface roughness (e.g. grasslands). Data conversion routines permit the wind power grid to be exported to other standard file formats that facilitate use by our clients.

WIND POWERING AMERICA

The Wind Powering America is a regionally-based DOE initiative with the following goals[7]:

- Increase the use of wind energy in the United States to 5% of the nation's total electricity needs by 2020
- Increase the use of wind energy by the federal government to 5% of its total electricity needs by 2010
- Increase wind capacity to 5,000 megawatts (MW) by 2005 and 10,000 MW by 2010

It is hoped that much of the new installed capacity will benefit American farmers, Native Americans and other rural landowners by providing them with new sources of income.

State Wind Resource Development Potential

One of the initial tasks assigned in support of Wind Powering America was to identify states with qualities favorable to wind energy development based on wind resource availability, potential federal load, and electricity rates.

The following data layers were used for a spatial overlay analysis:

1. Wind resource data for the United States were available from the *Wind Energy Resource Atlas of the United States*[1] at a much coarser resolution (1/3° of longitude by 1/4° of latitude) than that currently produced by the WRAM (1-km^2). The total land area in the atlas with a power class rating of 3 and above was summarized by state and county. The summarized area does not represent the actual amount of windy land available for wind energy development; one power class was assigned to each 1/3° by 1/4° region, but there can be large variations in actual resource because it is being applied to such a large area. For this reason, the summarized area should only be used to rank the relative abundance of available windy land when comparing states and counties.

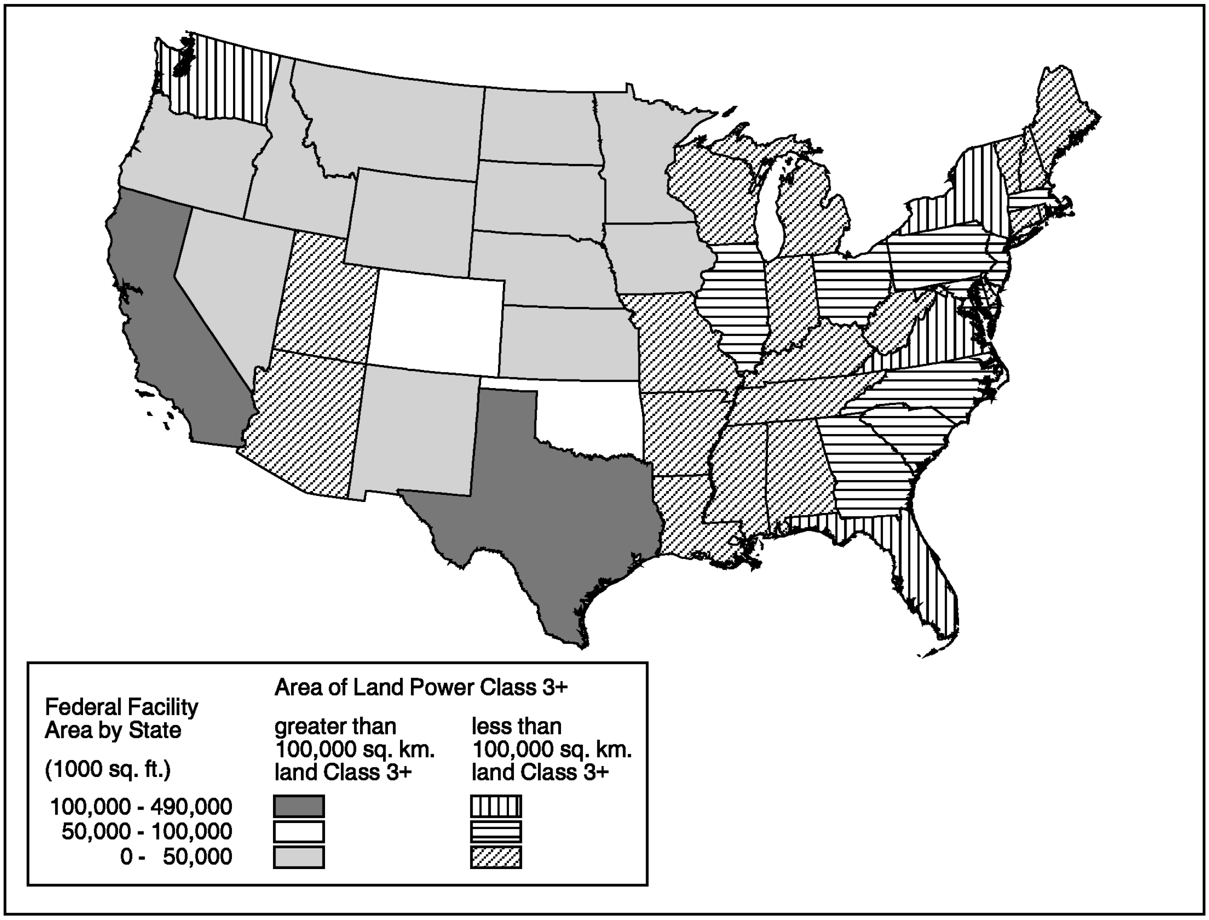


Figure 1. Identification of areas with abundant wind resource and potential federal electricity demand.

2. Data on the location and size of many federal facilities were available through a database maintained by the Federal Energy Management Program (FEMP). A substantial portion of a federal facility's electricity usage is due to heating and cooling, therefore, building area was deemed a suitable interim substitute to describe a facility's total electricity usage and potential load. The total federal facility building area was summarized by state and county. A future task includes updating the analysis to reflect information about actual facility electricity usage instead of building area as a guide.

3. National federal electricity rate data were not available; however, information on 1993 residential electric rates was available from a previous project. The rates were assumed to be representative of the relative electricity rates in place nationally. These data were only available at the county level, and did not include Alaska or Hawaii.

The three data layers were combined to create a new data layer encoded with a matrix of values

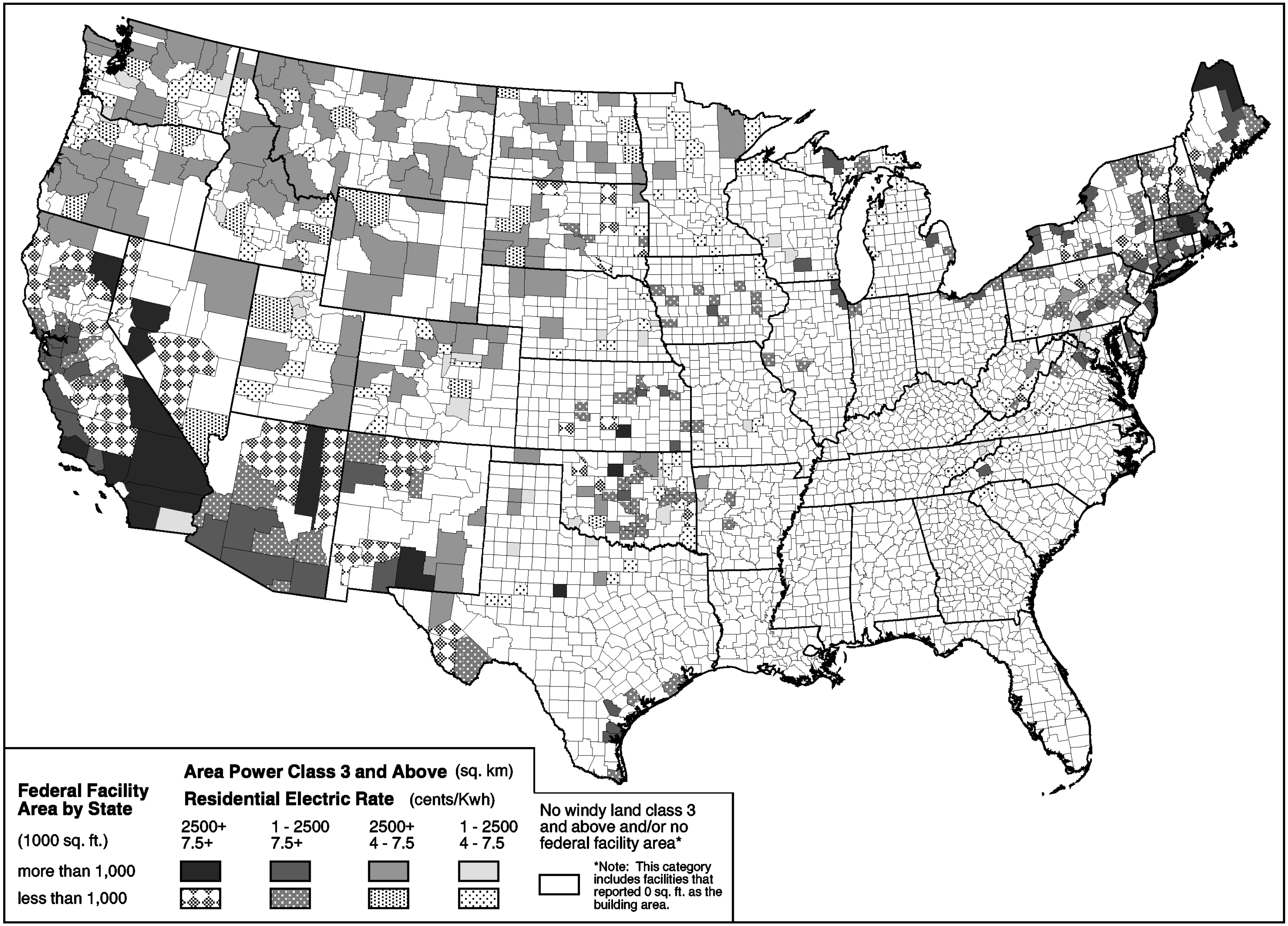


Figure 2. Wind development potential based on 1) potential federal load as measured by building area; 2) abundance of windy land; and 3) electricity rate.

that describe the criteria used to combine them. For example, the features selected in response to the following query represent the areas with the most potential for wind resource development at the county level.

Query: ([Windy Land > 2500] and [Electric Rate > 7.5] and [Facility Area > 1000])

The selected features would receive a value of "1" to represent the elements of this query. The selection and assignment process continues until each category of the matrix is represented by a unique value. The map is then classified using the matrix, and the information can be presented with a complex but informative legend. Maps of individual data layers can also be generated when necessary.

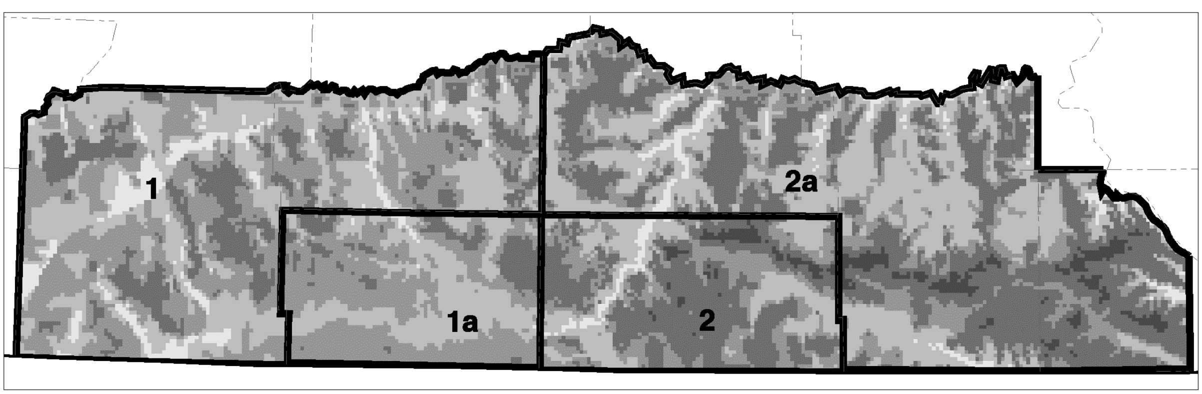
The wind resource and building area data layers were combined to highlight states with excellent wind resource potential and high potential federal load (Figure 1). However, electric rates could vary widely within a state. Rather than calculate an average electricity rate for the state, a second analysis was completed at the county level that combined all three data layers (Figure 2). This preliminary spatial analysis was completed very quickly using data already available at NREL.

<u>Wind Electric Potential of Native American Lands</u>

Another Wind Powering America task was to assess the wind resource development potential on Native American lands. Figure 3 shows a subset of the 1-km^2 wind resource assessment of South Dakota, depicting the wind resource potential on the Pine Ridge and Rosebud reservations. Similar calculations were made for each of the reservations in North and South Dakota; the only states with significant Native American lands that have been mapped using the WRAM.

The wind resource was summarized for each reservation to determine the area of land in each power class. The land area was aggregated into two categories: power classes 4–6, representing areas suitable to development for utility-scale applications; and power classes 2–6, representing areas suitable for development for rural or off-grid applications. A broad capacity range of 5–10 MW/km^2 was applied to the aggregated area to determine each reservation's wind electric potential. The output of this analysis is a table, which has been incorporated into the map.

Each cell represents 1-km^2 and may contain areas of varying suitability for wind development. However, development of only 10% of the land area designated with the best resource (power classes 4-6) using a conservative capacity number of 5 MW/km^2 yields a potential production capacity of almost 2600 MW on the Pine Ridge reservation. To put this number into perspective, as of June 2000, the total installed U.S. wind capacity was 2471 MW. The development of the wind resource available on these two reservations alone would dramatically increase the total wind resource capacity of the United States and meet the Wind



Indian Reservation	Wind Electric Potential (MW) Class 4 - 6	Class 2 - 6
1 Pine Ridge	25,780 - 51,560	45,050 - 90,100
1a - Additional area of interest	9,995 - 19,990	15,230 - 30,460
2 Rosebud	17,400 - 34,800	25,750 - 51,500
2a - Additional area of interest	30,260 - 60,560	48,975 - 97,950

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7

[a]Wind speeds are based on a Weibull k value of 2.0

Figure 3. Wind resource and potential wind generation capacity of the Pine Ridge and Rosebud reservations.

Powering America goal of 5000 MW of capacity by 2005.

Development of wind resource on Native American lands will provide the tribes with revenue and capital development funds from outside interests. Native American tribes also control land outside the recognized reservation boundaries and can use wind resource assessments to guide future land purchases for wind resource development. The calculated resource potential can be readily updated as the reservation tribal boundaries change.

SUMMARY

In the last five years, the role of GIS in DOE's Wind Energy Program at NREL has increased dramatically. It has evolved from a tool that provided professional graphic output with limited automated GIS capabilities, to a model for wind resource assessment, to a versatile tool researchers can use to examine and analyze data relationships to extract useful information. GIS has proven its value at NREL by presenting information that aids wind energy development decisions and will continue to play a vital and ever-expanding role at NREL based on its utility in the assessment and development of wind energy.

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB NO. 0704-0188*
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE January 2001	3. REPORT TYPE AND DATES COVERED Conference paper	
4. TITLE AND SUBTITLE Geographic Information Systems in Support of Wind Energy Activities at NREL			5. FUNDING NUMBERS WER11050 WER13510
6. AUTHOR(S) D. M. Heimiller, S. R. Haymes			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393			8. PERFORMING ORGANIZATION REPORT NUMBER NREL/CP-500-29164
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161			12b. DISTRIBUTION CODE
13. ABSTRACT *(Maximum 200 words)* The National Renewable Energy Laboratory (NREL) uses Geographic Information Systems (GIS) to further the development of wind energy resources in support of the U.S. Department of Energy (DOE) Wind Energy Program and its Wind Powering America Initiative. Some of the elements of NREL's GIS data used in wind energy activities include wind measurement sites, transmission lines, federal facility information, and modeled wind resources. More complex GIS analyses can define relationships among the mapped wind energy resources, potential energy load characterization, and utility integration problems. A GIS is an outstanding tool for wind energy activities because data can be readily updated and the results of the GIS analyses can be expressed as charts, tables, and maps. These outputs are in digital formats that allow the results of GIS analyses to be quickly and efficiently distributed to the wind energy industry.			
14. SUBJECT TERMS Wind energy resources, Geographic Information Systems, wind energy resource maps			15. NUMBER OF PAGES
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL