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WIND RESOURCE MAPPING OF THE STATE OF VERMONT

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INTRODUCTION AND APPROACH

This paper summarizes the results of a wind mapping project and a validation study for the state of Vermont. The computerized wind resource mapping technique used for this project was developed at the National Renewable Energy Laboratory (NREL). The technique uses Geographic Information System (GIS) software and produces high resolution ($1 km^2$) wind resource maps.

This technique was previously applied to the Buffalo Ridge region of the northern Great Plains (Elliott and Schwartz, 1998); an area of active wind energy measurements and development with relatively simple terrain. The state of Vermont was chosen as a follow-on project to Buffalo Ridge for several reasons. First, the state has complex terrain, so it is a suitable candidate to test the accuracy of the NREL mapping system in a mountainous region. Second, many Vermont officials are generally sympathetic to the use of renewable energy, and third, the state is home to both wind turbine and wind measurement equipment manufacturers. Furthermore, Vermont is the home to the first wind farm in New England; the 6.1 MW power plant in Searsburg, located in the southwestern part of the state.

NREL's approach for mapping Vermont was similar to that taken for the Buffalo Ridge region of the northern Great Plains. The approach did not require use of high quality surface wind data, although these data were integrated into the assessment methodology where available. In many regions of the world, reliable surface wind data are sparse and sometimes not available for areas of interest. Therefore, NREL designed its wind mapping technique to develop detailed wind maps for vast areas without reliance on high quality data from surface wind measurement stations. This approach turned out to be especially appropriate for Vermont, because public wind data within the state were quite limited and available for only a few airport stations located in valleys with poor-to-marginal wind resources.

For the Vermont project, a wind power density map was produced, and measured data from the validation data set was used to evaluate the accuracy of the mapping system. However, the quality of the validation data set had to be determined before the data could be used to judge the accuracy of the map. This task was complicated by the sparse nature of publicly available validation data for wind measurement sites in Vermont, which necessitated the use of proprietary wind measurement data for much of the validation. In summary, the activities in this mapping project included meteorological analysis, production of the computerized wind map of Vermont, validation of the map, and conclusions reached as a result of the project.

NREL'S COMPUTERIZED MAPPING SYSTEM

NREL has been developing its computerized, GIS-based mapping technique since 1996. The primary reasons for its development were to reduce the human effort needed to create a wind resource map and to produce a wind map that reflects a consistent analysis of the wind resource distribution throughout a region of interest. The mapping technique uses commercially available GIS software featuring a large number of routines designed for scientific analysis. However, none of the routines are specifically designed for wind resource assessment work. The many routines had to be combined to mimic direct wind resource assessment methods.

At present, the computerized wind mapping system takes a strictly empirical, analytical approach to determine the level of the wind resource at a particular location. 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 (rather than local or micrositing) distributions of the wind resource to a spatial resolution of 1 km^2. The detailed maps facilitate the rapid identification of the most favorable wind resource areas within a region.

The meteorological assumption that there are empirical relationships in many parts of the world among the free-air (higher than 100-200 meters above the ground) speed, the wind speed over the ocean (where applicable), and the distribution of the wind resource over the land areas, is the basis of NREL's technique. NREL uses a "top down" method to adjust much of the available wind data. That is to say, NREL takes the free-air wind speed profile for heights up to 3000 meters above the surface and adjusts these data to produce a wind power profile in the lowest few hundred meters above the surface. The prime advantage to this method is that NREL can produce a useful wind resource map without having high quality surface wind data for the study region.

There are many problems with the available land-based surface wind data collected at meteorological stations around the world. Problems include a lack of information about observation procedures and anemometer hardware, height, exposure, and maintenance history. In general, available surface wind data in much of the world are not reliable or abundant enough to use directly as input in the wind mapping system.

NREL's "top down" approach requires a critical analysis of the available climatic data sets in the study region. Graphical and tabular wind characteristic products generated from the raw data need to be cross-referenced to understand the prevalent wind characteristics in the study area. The ultimate goal of the analysis is to create a conceptual model of the physical mechanism(s) that cause the wind to blow in a particular region. The conceptual model guides the development of the empirical relationships that are the basis of the wind power calculation algorithms and enables meteorological input into the model to be as precise as possible. The accuracy of the final wind map is highly dependent on the precision of the input data. A description of the meteorological data sets, details on the digital elevation data used by the mapping system, and the formats of the meteorological input can be found in previous publications (Elliott and Schwartz, 1996, 1997, 1998; Schwartz and Elliott, 1997).

As with all modeling techniques, there are limitations to the NREL mapping system. There are two important limitations on the Vermont study. First, NREL uses 1 km 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, especially in complex terrain. The wind power estimate for a particular grid cell may not apply to all areas within a grid cell. Therefore, the maps are not intended for micrositing purposes. The other important 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. Although roughness/land-use data for most of the world is available in digital form, questions need to be resolved about the resolution and accuracy of this data set and its fitness for use in 1 km resolution wind resource maps. In general, the power estimates on the map are valid for areas with low surface roughness such as grasslands. Reductions of 25% to 60% need to be made to the power estimates for areas with high surface roughness. 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 approximately a 3° latitude by 3° longitude area centered on the state of Vermont. The topography of Vermont can be roughly divided into two major sections. Lake Champlain and its basin/valley system extend north-south and cover the extreme western part of the state from central Vermont northwards to the Quebec border. The Adirondack Mountains in New York form the western boundary and the north-south oriented Green Mountains form the eastern border of the Champlain Valley. The elevation in the Champlain Valley is less than 100 m above sea level. The Green Mountain chain covers most of the remaining state and the narrow Connecticut River Valley forms the eastern border between Vermont and New Hampshire. The terrain in the Green Mountains is complex. The highest peaks are above 1200 m in elevation, and many ridges have elevations between 800 m and 1000 m. In contrast, the lower elevations of the river gorges that cut through this region are only 100 m to 200 m above sea level.

The salient feature of Vermont's wind climate in the higher elevations is the strong, persistent free-air winds from the west and northwest. High free-air wind speeds (9.5 m/s and greater) occur at fairly low levels (900 m above sea level and higher). Information from several upper-air stations in New York and New England (Albany, New York; New York City, New York; Caribou, Maine; Portland, Maine; and Chatham, Massachusetts) was used to analyze the extent of the strong free-air wind regime. Analysis showed that all of Vermont is subject to these strong free-air winds, with the highest wind speeds found in the northeastern part of the state and the lowest in the extreme northwestern part of the state. The evidence indicated that there was little gradient in the free-air wind speeds over the central and southern part of Vermont. The free-air wind power density at the ridge and mountain peak elevations in Vermont was estimated to be between 1000 and 1200 W/m^2. The wind climate in the Champlain Valley is different from that of the mountainous areas. The near-surface winds have a bimodal (southerly and westerly) wind direction due to channeling along the valley because of the barriers created by the Adirondacks to the west and the Green Mountains to the east of the valley. The upper-air winds below 900 m at Albany, New York, in the Hudson River Valley, another channeled valley in the region, reflect the bimodal wind direction. Wind speeds are lower over this valley than the free-air wind speeds at other regional upper-air stations not located in a channeled valley. Above 900 m the upper-air winds are quite similar in speed and direction throughout this region. This indicates that exposed ridges below 900 m in elevation that lie within the influence of channeled valleys such as Lake Champlain and the Connecticut River would have lower resource than exposed ridges in the Green Mountains.

Figure 1 is the annual average wind resource map for Vermont as calculated by the automated system. A color version of this map can be found through the NREL Center for Renewable Energy Resources Web page at www.nrel.gov/energy_resources. The map uses the wind power classes defined in the *Wind Energy Resource Atlas of the United States* (Elliott et al., 1987). The legend shows estimated wind speeds for power classes 2 through 7 based on a Weibull k value of 2.0. Grid cells with class 1 resource or grid cells that did not meet exposure or slope criteria are blank. The most prominent feature of the resource map is the areas of class 6 and class 7 resources evidenced on exposed ridges in the Green Mountains. This is not surprising considering the high free-air wind power density values at ridgetop level. The southwestern and northeastern parts of the state have the broadest areas of high level of resource. The high resource areas in central Vermont are generally confined to the five narrow ridgelines that comprise the Green Mountains in this area. Most of the higher exposed elevations located in the Champlain and Connecticut Valleys have class 4 and class 5 resources and a few grid cells have class 6 or class 7 resources. The Champlain Valley plain has class 1 or class 2 resources. This map is somewhat different from the Vermont resource map shown in the *Wind Resource Atlas*. The resource on the Green Mountain ridge crests on this map is about 1 to 2 power classes higher than the estimates in the *Wind Resource Atlas*. We believe that the newer estimates are realistic based on the available upper-air data and data from locations used for validation. The Champlain Valley estimates in both *the Wind Resource Atlas* and on this map were class 1 and class 2, though the distributions of the resource were different.

VALIDATION

Vermont and its surrounding region, unlike the Buffalo Ridge region (Elliott and Schwartz, 1998), does not have many meteorological stations and publicly available wind energy measurement data available to use as map validation. The stations are located in sheltered river valleys or near Lake Champlain. Measurements taken specifically for wind energy purposes, while generally at exposed high elevation locations, are proprietary and were difficult to obtain for this study. Fortunately, through the efforts of Dave Blittersdorf of NRG Systems Inc., who provided NREL with data from NRG Systems measurement sites, and one of the authors, who had access to measurement sites operated for Green Mountain Power (GMP), enough measurement data were obtained to conduct a validation study of the mapping results. The NRG sites were distributed throughout the central and northern parts of the state, and the GMP sites were concentrated in the extreme southern part of Vermont.

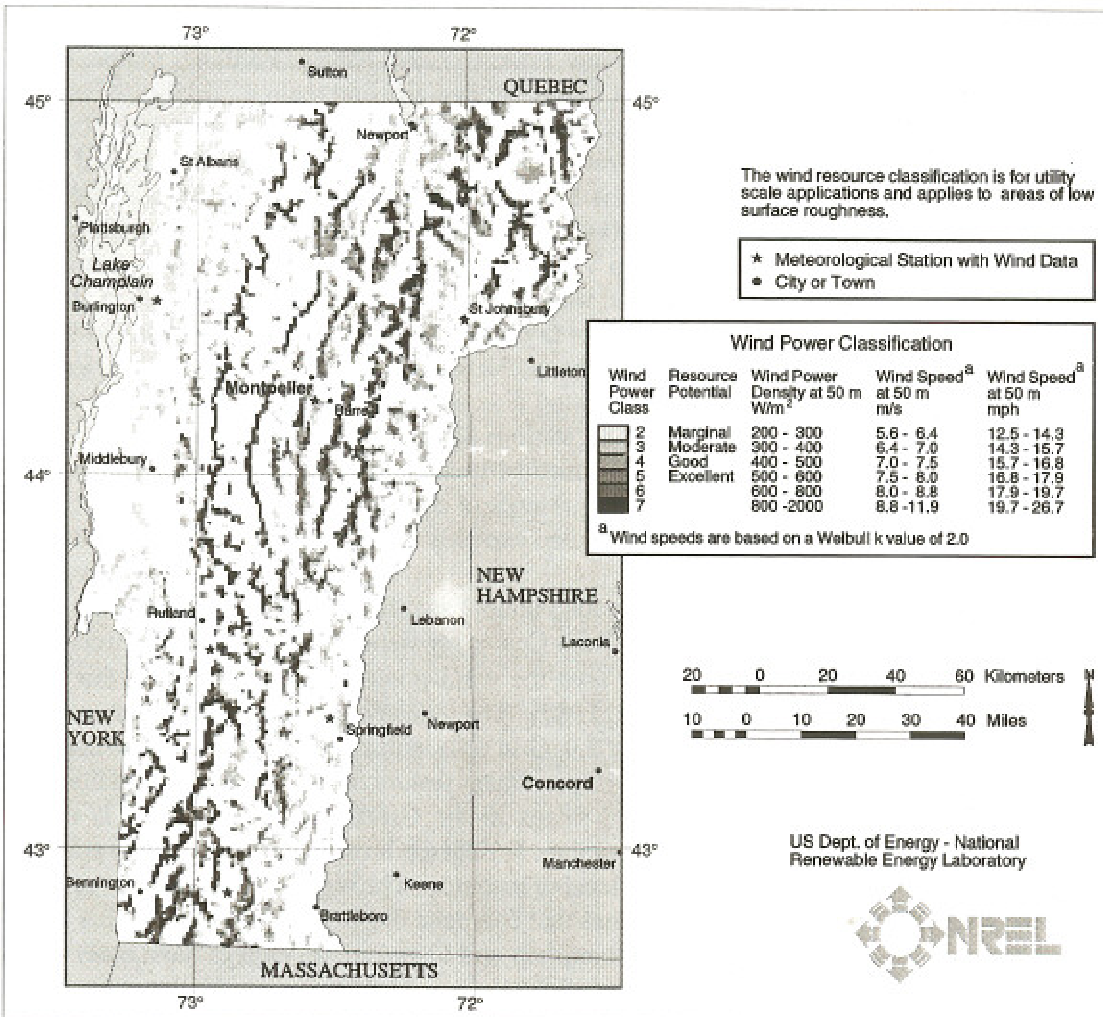

Figure 1. Annual average wind resource map of Vermont.

Data from several dozen sites were available for the validation study. However, not all sites were suitable for inclusion in the study. The primary criterion for choosing a particular site was the number of hours of usable data. Sites had to have around a full year (8760 hours) or more of valid data to be chosen for the study. The second criterion was elevation of the site. A number of sites at low elevation with poor wind resource were not included in the study. Most of the validation sites had elevations above 600 m. The sites with the longest period of record were used as local "long-term" references. A few of the GMP locations had data for over 3 years, and one site had over 5 years of data. Wind data from other sites with shorter periods of record were correlated to these references, and speed ratios were calculated between the reference and short-term sites. The speed ratio was multiplied by the long-term observed mean speed at the reference site to estimate long-term mean speeds at the short-term sites.

A significant problem faced in the validation study was the estimation of vertical wind shear at all the sites because none of the sites had data at 50 m; the wind power classification height of the map. About half of the sites had data near 30 m, and some towers had multiple measurement levels. Vertical shear estimates were made for each site based on the observed shear at the multilevel towers, the site elevation, amount of forest cover, and previous knowledge of shear in Vermont. Speed shear exponent values at the well exposed ridgeline sites were generally assumed to be 0.15. The shear exponent values over all 10 sites ranged from 0.05 to 0.30. The speed shear at each site was used to normalize the estimates to the 50 m level.

Validation for the ridge crest estimates presented a more complicated problem than validation for relatively flat areas, such as Buffalo Ridge. The potential variation of wind power along ridge crests makes comparisons between specific site measurements and mapped 1 km grid cell values quite difficult to interpret. This situation was further compounded by time constraints on completing the map and validation study. Because of these factors, we decided to use comparisons of measured and predicted wind speeds instead of wind power density as the basis of the validation statistics. Ten sites were chosen for the final validation study. The estimated 50 m wind speeds at the validation sites were compared to an estimated wind speed based on the mapped wind power densities of the 1 km grid cells. If the validation site was located well within a particular grid cell, the estimated 50 m wind speed would be the midpoint of speed range of that power class as noted on the map legend. If the site was located near the boundary of two or more wind power cells, the estimated speed would be the value at the boundary between the cells. Table 1 shows the results of the comparisons. For 9 out of the 10 sites, NREL's estimate was within one-half a power class of the estimate based on the measurements. This roughly translates into accuracy within 10% to 15% in regards to wind power estimates. The one site that differed by more than one class was a well-exposed ridgeline with higher elevations (100 m to 150 m) in three directions. It is unknown as to whether local effects at that measurement site, longer- range effects that our mapping method did not integrate, or a combination of these and other factors (such as assumed wind shear) caused the difference between the map's estimates and estimated speed at this site.

Table 1. Validation of NREL's Wind Resource Predictions for the Vermont Map

Site Name	NREL's Predicted Wind Power Class[1]		NREL Midpoint 50m Speed Prediction (m/s)	Nierenberg 50m Speed Estimate[2] Based on Observed (m/s)	Estimated[3] Shear Exponent	Power Class Difference (Observed - Predicted)[4]
Mt. Mansfield	7	Excellent	10.3	12.0	0.05	0
Burke Mtn.	6-7	Excellent	8.8	9.5	0.10	0.5
SN	6-7	Excellent	8.8	9.0	0.15	0
3054	6-7	Excellent	8.8	8.5	0.15	- 0.5
Ho	6-7	Excellent	8.8	8.0	0.15	- 0.5
Du	6-7	Excellent	8.8	7.0	0.25	- 2.5
EQ	6	Excellent	8.4	8.5	0.07	0
Grandpa's Knob	4-5	Good/Excellent	7.5	7.5	0.15	0
Charlotte	2	Marginal	6.0	5.5	0.30	-0.5
Barre East	1	Low	3.5	3.4	0.25	0

Notes:

1. Some validation sites straddle cells with two different wind classes. Resolution of wind class cells on the map is 1 km^2. Predicted values are based on long-term meteorological data.
2. Most of the sites only had about 1 year of data. These were correlated to other reference sites with 3-5 years of data. No attempt has been made to correct 3-5 year observed mean speeds to longer-term climatological averages.
3. Wind data collected at heights ranging from 11m to 36m AGL, and shear is estimated.
4. Mean absolute difference: 0.45.

There are several potential sources of error in the validation study. The quality and quantity of the validation data set are two probable error sources. No 50 m wind data were collected at the validation sites. Therefore, no direct comparisons with the map estimates could be made. All of the validation data had to be estimated assuming a particular wind shear. Many of the validation sites had a short (about 1 year) period of record. These sites were correlated to reference sites with about 5 years of data. Errors could have occurred both in the correlation process and also because a climatological adjustment of the 5-year data to longer-term means was not attempted in this study.

As in the Buffalo Ridge study, the question of how much of the free-air momentum is transported down to turbine hub-height is always a concern. Factors such as solar-angle, frequency of large-scale weather systems, and moist and dry boundary layer processes affect the momentum that is transferred towards the surface. In addition, local stability effects caused by the rolling terrain in some parts of the Green Mountains and larger scale stability effects caused by the arrangement and aspect of ridgetops can also have a significant influence on the wind power at a particular location and can be a source of error. A final concern is the problem of validating a regional wind mapping pattern with point data. The 1 km elevation data set used in this study is often too large scale to resolve changes in surface roughness and terrain variations that influence the wind resource at specific sites. This problem is not easily resolved because using higher resolution elevation data that are available for this area would have greatly increased the cost and time needed to complete this study.

CONCLUSIONS

NREL's mapping system has produced a reasonable distribution of the wind resource in the state of Vermont. The wind resource map was validated using wind energy measurement data from 10 locations in Vermont, eight of which are located on ridgetops. At nine of the sites, the difference between the wind power class estimated by the wind mapping system and the wind class measured at the site was less than one power class. The estimated wind power density was within 10% to 15% of the measured values for these nine sites. The wind resource pattern was similar to that found in the *Wind Resource Atlas*, though the level of resource on exposed ridgetop locations is one to two power classes higher on the new map compared to the atlas. In our opinion, the greatest uncertainty with the map results occurs on ridgetops at slightly lower elevations than those ridgetops 10 to 20 km upwind. It is probable that the mapping model overestimated the wind resource on many of the lower ridgetops by about one power class because of blocking or stability effects not explicitly accounted for by the automated system.

The validation study for Vermont and its complex terrain was encouraging and will be helpful in future planning for an automated wind mapping tool. The idea that a positive relationship exists between the strength of the upper-air winds and winds at the surface in Vermont was reinforced by the results of the validation study, particularly at ridgetop locations where 90% of the validation stations were within 10% to 15% in power of the measured value. The study also demonstrated that integrating sophisticated lower boundary layer mixing and stability algorithms into the automated tool would enhance the accuracy of the model. In all, the automated mapping tool worked well for this complex topographic region in the northeastern United States.

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