EFFECT OF LOCAL SCALE TOPOGRAPHY ON WIND ENERGY POTENTIAL

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ABSTRACT

Wind energy potential at a site can be crudely estimated using climatological wind data from the nearest observing site maintained by the National Weather Service or other public organization. A more refined extrapolation from the long-term observing site to the site of interest can be done based on elevation differences. We report here comparison between measurements made at a hilltop site identified as a likely site for installation of electric power generating wind turbines, and routine wind observations made at a National Weather Service observing site at the Rapid City Regional Airport, 4 km away. Despite the proximity of the two sites, there are significant differences between them in energy generation potential due to local-scale topographic variations. A simple commonly-used relationship can be used to extrapolate from mean wind speeds observed at the airport to those observed at the nearby hilltop site.

INTRODUCTION

The identification of optimum sites for installing wind-powered equipment, such as wind-powered electrical generation equipment, is a complex process. There are technical considerations, such as measuring or estimating the important characteristics of the wind. These characteristics include its mean speed, speed frequency distribution, and steadiness. There are economic and political considerations, such as the costs to develop the site, the limitations on structures and siting set by local zoning ordinances, and the proximity to transmission capacity when electricity is to be sold to distant customers. In this presentation we focus on technical issues related to the meteorology of the site.

Very often a quantitative record of wind characteristics is not available for sites that appear subjectively to be good sites for wind power installations. Such subjectively identified characteristics might be elevation above local terrain, inferences from the leaning or shaping of trees (i.e. "flag" trees with most of their upwind branches stunted or lost), or anecdotal experiences of people living at or visiting the site. In this situation, it is often possible to locate a wind record at a nearby monitoring site, such as an airport, National Weather Service office, highway weather monitoring site or public utility installation. If the local surface characteristics of the monitoring site are similar to those of the site of interest, similar wind characteristics might be inferred.

At National Weather Service offices in the United States, and at most installations sponsored by national meteorological agencies around the world, wind direction and speed are monitored at a height of 10 m (33ft) above ground level (AGL). Wind monitoring conducted by other federal, state, and local agencies may be at different heights, typically lower. Occasionally as in the Wind Resource Assessment Network in South Dakota (http://www.engineering.sdstate.edu/~wran/) monitoring is conducted at higher heights. While wind characteristics may vary slowly with horizontal separation over uniform terrain, wind speed typically increases dramatically with height AGL. When the atmosphere near the ground is well-mixed in typical daytime conditions, and terrain is relatively flat with no nearby obstructions, the variation of wind speed with height, near the ground, can be approximated as

$$\frac{V}{V_o} = \left(\frac{Z}{Z_0}\right)^{\frac{1}{7}} \tag{1}$$

where Z is the height above ground of interest, Z_0 is the height above ground where the observation is made, and V and V_0 are the wind speeds at the corresponding heights. (See, for example, the ***Wind Resource Atlas of the United States***, at http://rredc.nrel.gov/wind/pubs/atlas/). Equation (1) represents an attempt to define average variation when the wind blowing along the earth's surface has blown over a considerable fetch of uniform terrain. Instantaneously at any site, and certainly often over complex terrains, wind speed may increase more or less rapidly with height AGL.

While it is generally observed that average wind speeds are higher at higher elevations in mountainous areas, the 1/7 power law defined in equation (1) refers to wind speed variation with height AGL in the free atmosphere, not wind speed variations near the ground at two horizontally-separated sites with differing geographic elevations. Because air blowing upward or downward along a mountain surface experiences drag, the wind speed at a mountain peak will typically be much less than what would be estimated using equation (1), the wind speed at the base of the mountain, and the distance from base to peak.

We will test equation (1) with observations acquired recently in the Rapid City area to verify the conditions within which it is valid.

OBSERVATIONS

Rapid City is on the eastern flank of the Black Hills. Several streams flow generally eastward through the Rapid City area and have over the eons carved valleys. One of these streams is Box Elder Creek. Figure 1 shows a 3-dimensional perspective rendering of a section of terrain east of Rapid City derived from a digital elevation model. The view is eastward along the Interstate 90 highway, with Box Elder Creek to the right (south) of the highway. Rapid City Regional Airport (RAP) is to the south (right), and Ellsworth Air Force Base (RCA) is to the north (left). Figure 2 shows a perspective view of the same area from the

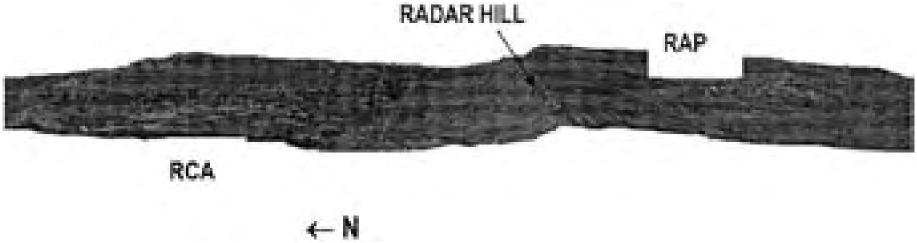

Figure 1. Topography of the region to the east of Rapid City where Ellsworth Air Force Base (RCA) and Rapid City Regional Airport (RAP) are located. Radar Hill is denoted by the red square in the center of the figure. The distance from Radar Hill to the southeast end of the runway at RCA is 4 km. It is also 4 km from Radar Hill to the northwest end of the RAP runway.

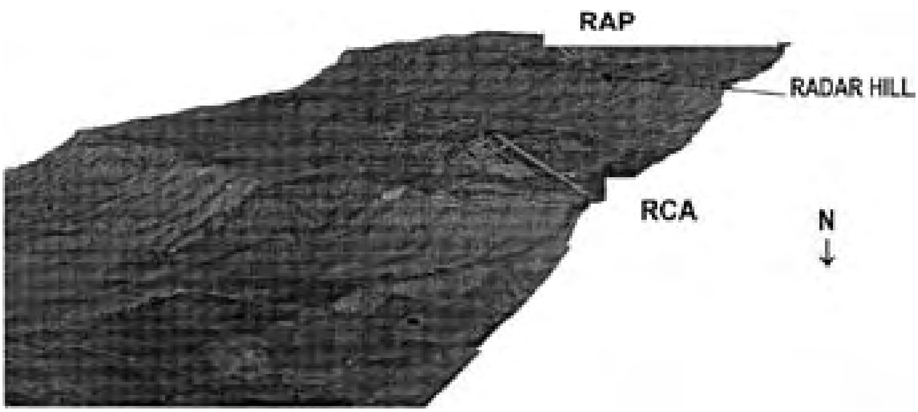

Figure 2. As in Figure 1, but view is southeastward.

northwest looking southeastward. Radar Hill is 4 km due south of RCA, and 4 km northeast of RAP.

On the ridge on the south side of the valley is a site where a Nike anti-missile defense system was established in the late 1950's. This system was removed shortly after it was built in order to comply with an arms reduction treaty signed at that time between the US and the USSR. In the latter portion of the 1960's, the Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology operated a radar at the site in support of various weather research activities. The site became known locally as Radar Hill. There have been no field research activities at this site since the early 1970's but the ~15 m (50 ft) tall radar tower and dish still stands.

In May, 2002, a rotating cup anemometer and a wind vane were mounted on a 10 m (33 ft) mast that was originally part of a lightning protection system, just south of the radar dish. The top of the mast protruded well above the one-story buildings in the vicinity. Winds impinging on the mast from the prevailing northwesterly and southeasterly directions were unobstructed by buildings or the radar. Wind speed and direction were recorded on a battery-powered data logger at hourly intervals over the following 16 months, ending in September, 2003.

ANALYSIS

The data from the Radar Hill site were processed and analyzed using the Winsite software package (Second Wind, Inc.). In addition, the archived hourly data from the National Weather Service Automated Surface Observing System (ASOS) installation at RAP for this 16 month period were obtained from the National Climatic Data Center (NCDC). The U.S. Air Force Air Weather Service maintains two anemometers, one at each end of the runway at RCA. Air Weather Service personnel manually record observations hourly including the winds from whichever is the downwind end of the runway. Data for 2002 were obtained from the office of the State Climatologist at South Dakota State University. Data from RCA for 2003 are not available for this study. Winds are monitored by the ASOS and by the RCA anemometers at the same height, 10 m AGL, as the winds at Radar Hill.

Figure 3 illustrates the frequency distribution of the wind speeds observed at Radar Hill during the fall of 2002. The distribution is monomodal with a long tail extending towards higher speeds. The mode speed is just below 10 mph. Figure 4 shows frequency distributions for each of 16 bands of wind direction, as well as a wind rose illustrating the overall frequency with which wind blows from each direction. The wind roses for RAP and RCA are qualitatively quite similar (not shown). The most common wind direction on Radar Hill during this period was northwest, from which the wind blew 24% of the time. The next most common direction was south southeast, with a frequency of 15%. The strongest

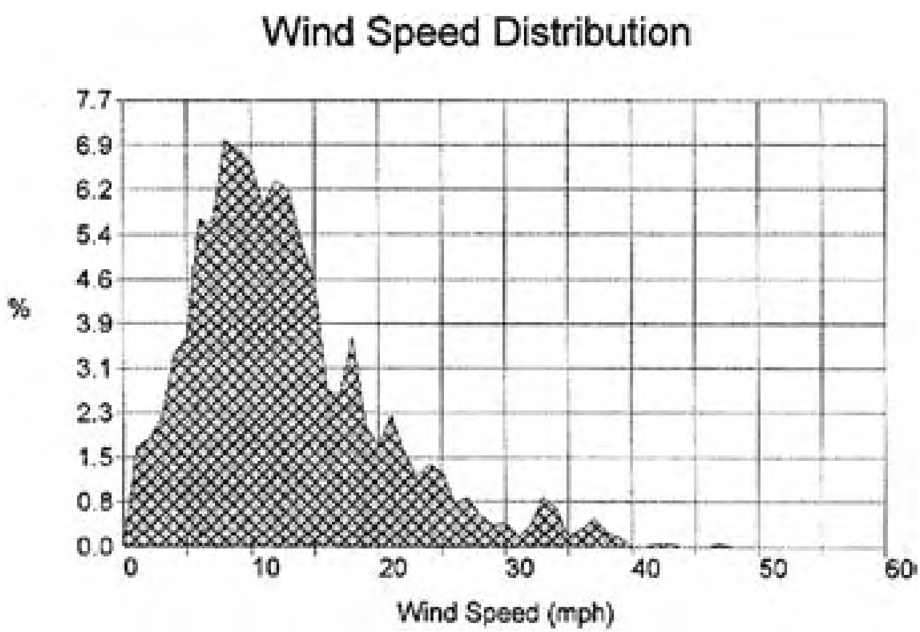

Figure 3. Hourly wind speed frequency distribution for the Radar Hill site from 7 September to 14 November, 2002.

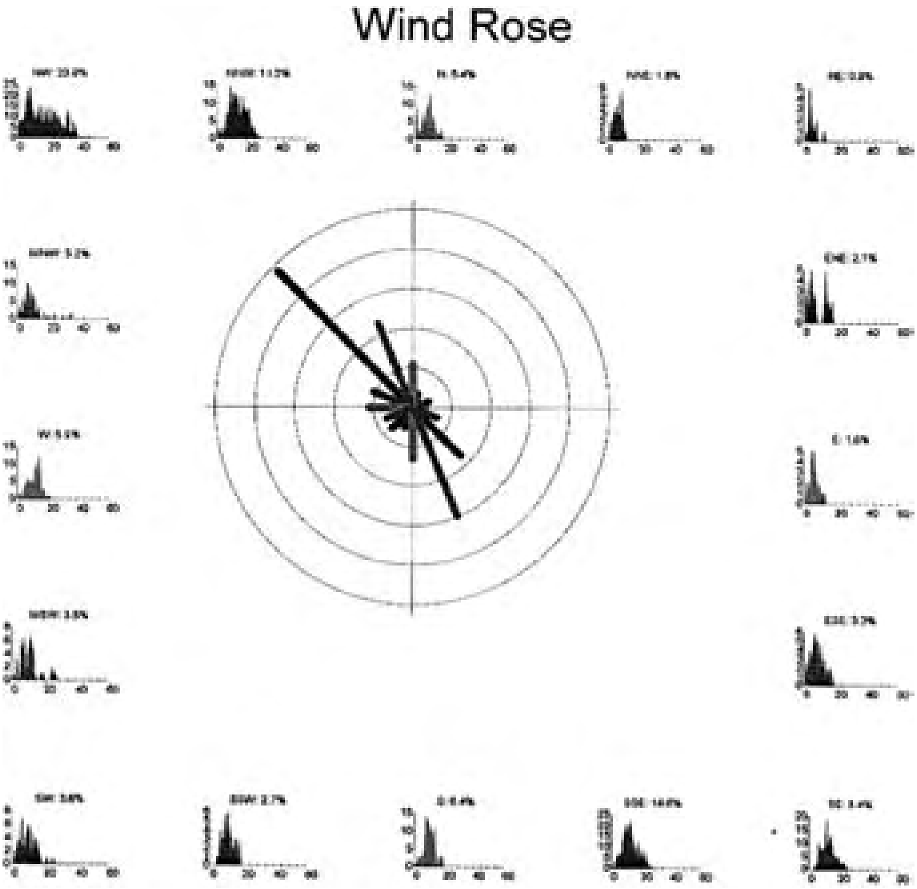

Figure 4. Wind rose for Radar Hill, with wind speed frequency diagrams for each of 16 compass directions, covering the same period of time as Figure 3.

speeds and highest average speed occur with northwest winds. The wind roses for each other season (winter, spring and summer) are qualitatively very similar, except that there is a relatively higher frequency of winds from the southeast in summer.

A comparison between monthly average wind speeds for RAP, RCA, and Radar Hill during the 16 month study is shown in Figure 5. Radar Hill wind speeds are consistently highest of the three sites, and RAP consistently has the lowest winds. The relative variations from month-to-month at a given site are similar for all sites. During the period of these observations, this variation did not follow the usual pattern of lower speeds in the summer and higher speeds in the winter previously found at sites in the Black Hills region (Pokkunuri et al. 2002). The highest monthly averages were found in the summer of 2002, late fall of 2002, and spring of 2003, while the lowest occurred in the winter months. The overall average wind speed over this period is 12.7 mph (5.7 m s^{-1}) at Radar Hill, and 9.9 mph (4.4 m s^{-1}) at RAP.

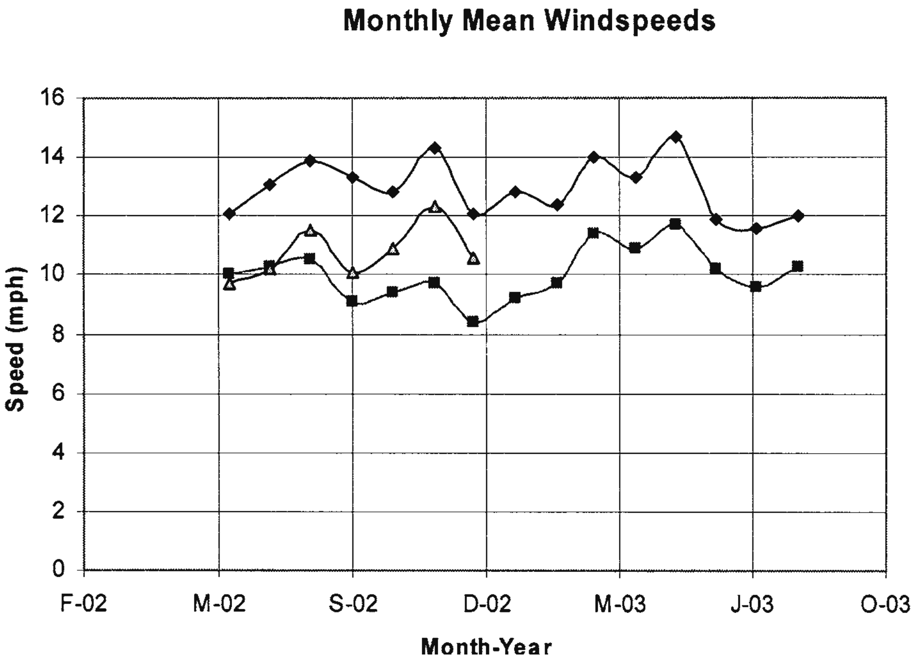

Figure 5. Monthly mean wind speeds at RAP (boxes), RCA (triangles), and Radar Hill (diamonds).

DISCUSSION

If one were to try to estimate the winds at Radar Hill without installing any wind measuring equipment at the site, but instead using the easily accessible NCDC archived data from RAP, one would use the elevation difference between the two sites and equation (1) to extrapolate to the elevation of the anemometer on Radar Hill. The relatively steep slope of the northwest flank of the hill, up which the wind blows almost one-fourth of the time, makes the site resemble a free-standing tower. The wind speed decrease between the free atmosphere above and the ground below does not reach equilibrium with the local terrain over the short upslope distance between the valley floor and the hill top. The wind at anemometer height on the ridge top might be expected to be almost the same as the wind speed at the same elevation above sea level out over the upstream valley.

The elevation of the surface at the Radar Hill site is 3410 ft (1040 m) above mean sea level (MSL) while RAP is at 3150 ft (960 m) MSL. Using the actual height of the RAP and Radar Hill observations, 10 m AGL, we find

$$V = V_0\left(\frac{1050-970}{10}\right)^{\frac{1}{7}} \tag{2}$$

For an average wind speed of 9.9 mph at RAP, the prediction for Radar Hill is 13.3 mph, just 5% higher than the actually observed average wind of 12.7 mph.

These results show that equation (1) does a reasonable job of estimating average wind speeds at sites on top of steep terrain features based on winds observed near the ground at nearby locations.

Ellsworth (RCA) is at an elevation of 3277 ft (999 m) MSL, about 40 m higher than RAP. Its average wind speed is indeed higher than at RAP, but the RCA wind observations are made in flat areas adjacent to the runway where the vertical wind profile is expected to be equilibrated with local terrain, just as at RAP. Therefore, the wind speed difference between RAP and RCA should not be predicted using equation (1) and the elevation difference between the two sites. Using just the period for which data are available from all three sites (May – December, 2002) the average wind speed at RAP is 9.4 mph (4.2 m s^{-1})while at RCA it is 10.4 mph (4.6 m s^{-1}). Based on equation (1) and an elevation difference of 40 m, one would expect the average wind speed 40 m above the RAP anemometer to be 11.8 mph (5.3 m s^{-1}), more than 13% higher than observed. It is clear that equation (1) is not applicable to this kind of extrapolation. The RCA anemometers are less protected than the one at RAP from the prevailing northwest wind direction, and this may be a factor in the higher average wind speeds there.

In an earlier study, wind data were analyzed from three sites in the higher elevations of the central Black Hills, and a hilltop site within rolling terrain 25 km north of the Black Hills (Pokkunuri et al. 2002). The observations were made at 100 ft (30 m) AGL in open fields. Average wind speeds ranged from 11.8 to 14.5 mph (5.3 to 6.5 m s^{-1}), with the northern site having the highest average. If the Radar Hill average is extrapolated from 10 to 30 m height using equation (1), then an average wind speed of 14.8 mph results, very close to that of the best of those sites investigated earlier.

The U.S. Department of Energy classifies sites for wind energy installations with a 7-class scale based on mean wind speed. (See, again, the ***Wind Resource Atlas of the United States***, at http://rredc.nrel.gov/wind/pubs/atlas/). Based on this scale, the Radar Hill site is a Class 4 site. Class 4 sites currently are considered marginal for large-scale commercial development. Such development involves erecting very large turbines, generating over 1 MW of power in moderate winds, with hub heights approaching 50 m and blade lengths exceeding 30 m, costing well over $1 M. The Department of Energy is currently promoting development of smaller-scale turbines for residential or local applications that will be economical at Class 3 and 4 wind energy sites.

It is possible that wind speed increases more rapidly than indicated by equation (1) with increasing height AGL at the Radar Hill site, due to its steep relief. Further investigation with winds measured using a taller tower is required to test this conjecture. If it is true, then for larger turbines the site might rank as Class 5 or 6 and be viable for commercial development.

Interestingly, recent estimates by the Department of Energy of wind energy potential for the State of South Dakota show estimates of Class 5 and 6 on the ridges to the east of Rapid City. See http://www.eere.energy.gov/windandhydro/windpoweringamerica/pdfs/wind_maps/sd_50m.pdf . Unlike the earlier wind energy study sponsored by the Department of Energy (***Wind Resource Atlas of the United States***, http://rredc.nrel.gov/wind/pubs/atlas/), almost no information is available describing how these more recent estimates were made. It is known that sophisticated mesoscale atmospheric models were employed, as well as a variety of observed wind records, but the quantitative details are apparently not available to the general public. These studies were aimed at predicting winds at higher height (50 m AGL) than studied in the present work. It is possible that over ridges winds actually are higher than is expected using 10 m AGL winds and equation (1). Perhaps in the future it will be possible to obtain more information and additional observations, and thus to reconcile the apparent disagreement between the recent statewide resource assessment and the observations obtained in the present study.

CONCLUSION

Winds were measured from May, 2002, into September, 2003, at the Radar Hill site east of Rapid City. Mean windspeed measured at 10 AGL was 12.7 mph (5.7 m s^{-1}). Extrapolation from climatological wind measurements made at RAP, 4 km southwest of Radar Hill, based on the elevation difference, yield an estimate of 13.3 mph, 5% higher than the observed value. Extrapolation from climatological measurements at official observing sites to wind speeds at nearby hilltop sites using equation (1) yields a reasonable estimate of average wind speed.

ACKNOWLEDGEMENTS

Radar Hill wind observations were conducted by Duane Steichen and Lance Gilmore, then electrical engineering students at the South Dakota School of Mines and Technology (SDSMT). Bill Capehart (SDSMT) prepared Figures 1 and 2. Dennis Todey and Chirag Shukla (South Dakota State University) assisted with obtaining the climatological data from RCA. The equipment used was funded by Black Hills Power Corporation and the South Dakota Community Foundation. The author thanks the State of South Dakota for support to perform the analyses and prepare this presentation.

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