ANALYSIS OF WIND OBSERVATIONS IN THE BLACK HILLS REGION

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ABSTRACT

The potential for wind energy production was assessed for 4 specially instrumented sites in the region of the Black Hills of South Dakota. More than 3 years of observations were obtained at 75 and 100 ft AGL at these sites, from 1995-1998. A site to the north of the main body of the Black Hills, north of Sturgis and southwest of Bear Butte, has significantly higher mean winds than the other sites, although it is also the site at the lowest terrain elevation. Monthly mean winds at 100ft AGL at this site were more than 14 mph while mean winds were near 12 mph at 3 other sites in the higher elevations of the Black Hills region. The frequency distribution of wind speeds has a broader multi-modal form at the most windy site compared to the other sites, with significantly more frequent occurrence of winds greater than 30 mph compared to the other sites. The strongest winds at all sites were typically northwesterly, although strong winds also occur from the southwest, south, and southeast in fall, winter, and spring, at most sites. At all sites, summer was typically the season with the lightest winds. There was weak correlation between monthly mean wind speeds at the Rapid City Regional Airport and at the three sites around the northern and central Black Hills. There was no correlation between monthly mean wind speeds at Rapid City Regional Airport and the site at Four Corners, Wyoming on the western border of the Black Hills, about 100 km west of the airport. These results suggest that examination of the 100+ year record of winds at the official observing sites in and around Rapid City may yield a valid estimate of the variability of winds at sites like those involved in this study as long as they are in the central or eastern portion of the Black Hills. Rapid City winds will not be as good a predictor of winds on the western side of the Black Hills.

Keywords

Wind, meteorology, renewable energy

INTRODUCTION

Hasan and Hughes (1995) discuss almost one year of wind observations at four sites in the Black Hills region of western South Dakota. These investigators installed instrumentation at these sites with support from the Black Hills Power and Light Company (now called Black Hills Power) to evaluate the potential for commercial generation of electric power using wind turbines at these sites and other sites with similar exposure in the Black Hills region. All sites were chosen based on their exposure, proximity to transmission lines, and the permission and support of landowners. The locations of the sites are indicated on a regional map in Figure 1. Three of the four sites, one near Four Corners, Wyoming, another on the Clinton Ranch, and a third on the Sanders ranch, are all located on relatively high terrain in a roughly west-east line extending across the central Black Hills. The fourth site is located on grazing land then owned by the Homestake Mining Company 14 miles north of the Sturgis, on lower terrain to the north of the Black Hills. Bear Butte rises about 4 miles east northeast of this Homestake site.

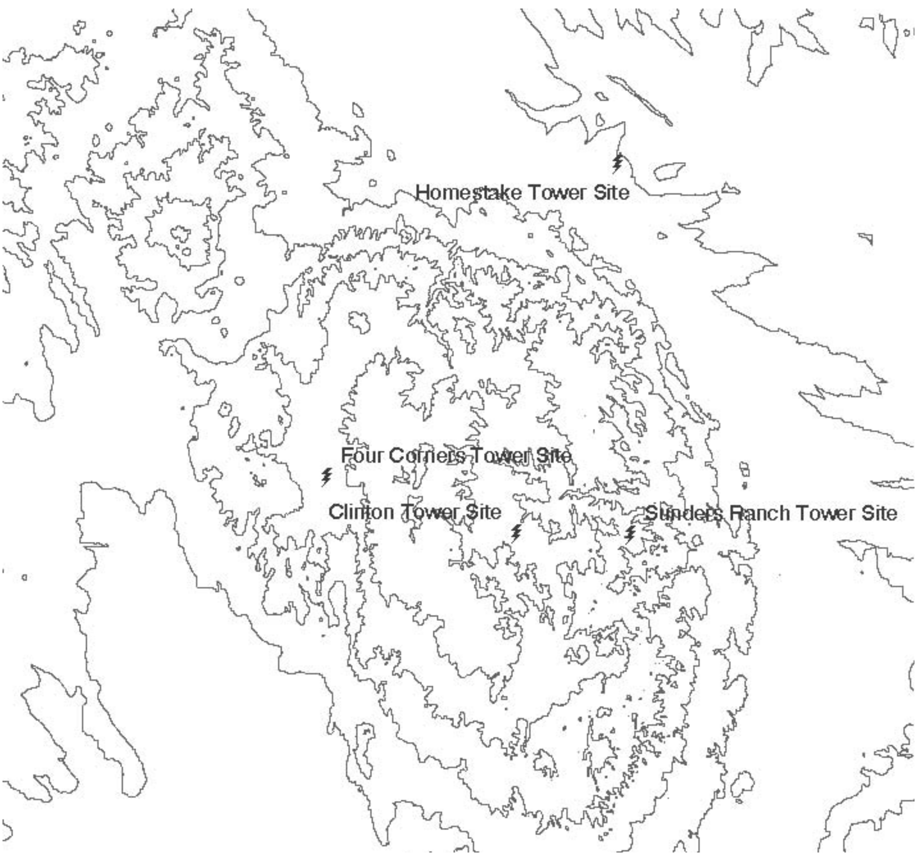

Figure 1. Contour map of the Black Hills region of South Dakota with Black Hills Power and Light Company wind survey sites indicated. Contour interval is 200 m, and spatial resolution is 50 m.

Wind speed observations were obtained at 2 levels at each site, 100ft (30 m) and 70 ft (21 m) above ground level (AGL). Wind direction was observed only at the 100ft (30 m) level. Data obtained beginning in September 1994, and continuing through July 1995, were discussed in the initial report by Hasan and Hughes. Although all 4 sites were located in open areas where high mean wind speeds were expected, based on low-spatial-resolution national wind energy surveys, only one site, the Homestake site on the northern flank of the Black Hills, actually turned out to have high enough and steady enough winds for economical wind turbine power generation.

We examine here several years of additional data to see whether or not the climatological characteristics of wind at these sites, estimated based on the first year of observations, remained similar over a several year period. Equipment failures occurred over these subsequent years, and the last good quality data from the last functioning site were obtained in the spring of 1999. Wind vanes were more prone to failure than anemometers. Hail from thunderstorms is known to have been responsible for some of the instrument losses. Other weather hazards (lightning, winter icing, etc.) may have been responsible for other losses.

In this discussion we will focus mainly on the meteorological analysis of the wind observations, with some emphasis on those characteristics of wind that contribute to a more useable wind-driven turbine electric power-generating site.

REVIEW OF FIRST YEAR'S DATA

Towers and instrumentation were installed in the summer and fall seasons, 1994. Data were recorded on-site using battery-powered data loggers. Magnetic data cards were exchanged and batteries replaced during roughly bi-monthly site visits by project personnel. An analysis of the first year of data was performed during fall, 1995.

(Hasan and Hughes, 1995) reported mean wind speeds at 100 ft (30 m) AGL, based on the 11 to 12 months of data available at that time from each site, are shown in Table 1.

Table 1.

Site	Mean Wind speed (mph)
Clinton	12.3
Sanders	11.9
Four Corners	11.9
Homestake	14.3

Monthly mean wind speeds varied from 10 to 18 mph. Variation from month-to-month was greatest at the Homestake site and least at the Four Corners site. At most sites, for this period, the maximum monthly means occurred in the fall (October or November) and spring (March and April), within lower means in early winter (December) and late summer (July and August). For comparison, the annual mean wind speed at the official wind observing height of 33 ft (10 m) AGL at the

Rapid City Regional Airport is 11 mph, based on observations from 1930-1996 (National Climatic Data Center, 1998). Monthly means at the airport vary from 10 to 13 mph, with highest monthly means in March and April, and lowest means in July and August.

The (non-zero) wind speed frequency distribution was monomodal at 3 of the sites, with most frequent wind speeds at these sites between 9 to 12 mph, and a peak frequency for the mode wind speed of 6 to 7% of all 15 min observing periods. At these 3 sites, the wind speed was < 1 mph for 5 to 8% of the time, and wind speeds greater than 20 mph were observed no more than 2% of the time.

At the 4th site, the Homestake site, the peak in the wind speed frequency distribution was much broader and extending to greater speeds. There was a broad peak in the distribution, with each integer wind speed value between 7 and 22 mph being observed more than 3% of the time.

At all 4 sites, the dominant winds were from the SW and NW quadrants. Winds were most frequently from the NW at all sites except Clinton, where the most frequent wind direction was SW. The Four Corners wind vane data show an unrealistically narrow peak from the NW in the direction distribution. This wind vane apparently was not functioning properly as early as this first season of data.

All sites are on cleared land that is elevated above the surroundings in most directions. There is a small knob of land located about 300 m south of the Clinton site that might account for the dearth of strong winds from the south at that site. The Sanders site sits on a prominent knob just east of a south-north valley through which runs US Route 385. Channeling of winds by this valley may account for the relatively more frequent southerly winds observed at this site compared to the others. The strongest winds at all sites were most frequently from the north and west quadrants. The weakest winds were from the east.

We next compare these published analyses based on the nearly complete first year of data from each site, to an analysis of the entire record, extending to 4 years for some parameters at some sites.

ANALYSIS OF COMPLETE DATA SET

An analysis of the complete data set was performed using the Winsite software package (Second Wind, Inc., Somerville, MA. URL: http://www.secondwind.com). In the present analysis data were broken down seasonally, and wind roses and wind speed frequency spectra were computed for each site for the 'seasons' January-March ('winter'), April-June ('spring'), July-September ('summer'), and October-December ('fall'). Although seasonality of the wind regime over the Black Hills may not correspond exactly to these calendar periods each year, the aim is to capture at least some of the seasonal variability. Hasan and Hughes (1995) note that overall, for the period fall, 1994, through summer, 1995, fall and spring were windier than summer. In the following analysis we look in more detail at how much variation there is from 'season' to 'season', and from one year to the next in a given 'season'.

WIND DIRECTION DISTRIBUTION BY SEASON

The Four Corners wind direction data appear to be unreliable, even during the first year, indicating an unrealistically narrow peak frequency from the northwest. From April 1996, onward, the wind direction is indicated as always exactly from the northwest. This appears to be due to a failure in the recording of the wind vane position, although as even as late as the spring, 1999, the wind vane appeared to be working properly mechanically.

The Homestake wind direction data also developed problems early in the study, becoming unrealistic during summer, 1995. During the period of reliable data, there is a prominent peak in frequency and magnitude of northwesterly winds, from December 1994, through March 1995. In spring, 1995, there were some frequent and strong winds from the southeast, as well as from the northwest, associated with several strong low-pressure systems that passed near or over the Black Hills region during April of that year.

At the Sanders site, good data are available from winter, 1995, through summer, 1996. The most frequent and strongest winds were from the northwest, although spring and summer in both 1995 and 1996 also show frequent winds from the south and southeast that generally are not quite as strong as the northwest winds. It is probable that these spring and summer south and southeasterly winds result from synoptic-scale low pressure areas moving through or around the region in the this time period.

At the Clinton site good direction data are available from fall, 1994, through summer 1997. Westerly winds dominate during this period from fall, through winter, and spring. Summers generally are dominated by winds from the southeast through west quadrants, although summer, 1997, also shows a prominent northwesterly wind peak. Winds from the southeast are not as strong at this site as they are at the Sanders and Homestake sites. The Clinton site is more centrally located in the Black Hills and often does not see winds as strong as those at the Sanders and Homestake sites (Sanders near the eastern edge, Homestake somewhat north of the northern edge of the Black Hills) when springtime low-pressure areas migrate by the region.

WIND SPEED FREQUENCY DISTRIBUTIONS BY SEASON

Wind speed data were generally more reliable than wind direction data. The 3 higher elevation sites had similar mean wind speeds, while the Homestake site on lower elevation land to the north of the Black Hills (see Figure 1), had a significantly higher mean wind speed. Data generally are available from fall, 1994, or winter, 1995, through winter, 1998. The wind speed at 100 ft (33 m) AGL will be the basis for the following discussion.

At Four Corners the seasonal frequency distributions typically were monomodal. An example from winter, 1995, is shown in Figure 2. In this season, the peak value of 12 mph was observed 6.7% of the time. Over the entire period of record the peak seasonal median wind speeds varied between 10 and 13 mph and this peak value was observed from 6 to 8% of the time. Winds

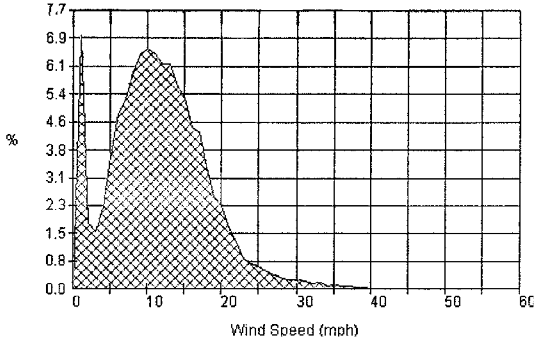

Figure 2. Frequency distribution of mean wind over 15 minute intervals at the Four Corners site for Winter, 1995. Data are from the 100 ft. (30m.) AGL level.

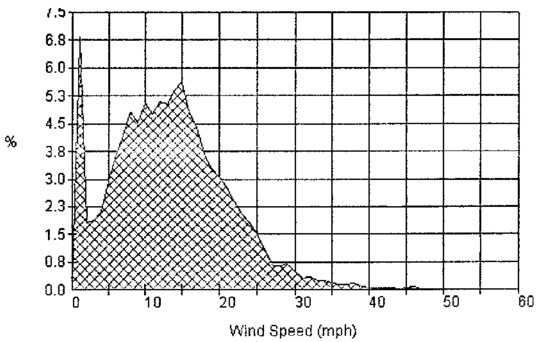

Figure 3. Frequency distribution of mean wind over 15 minute intervals at the Clinton Ranch site for Fall, 1995. Data are from the 100 ft. (30m.) AGL level.

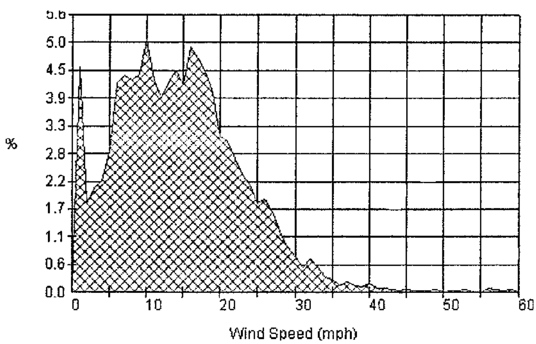

Figure 4. Frequency distribution of mean wind over 15 minute intervals at the Homestake site for Spring, 1996. Data are from the 100 ft. (30m.) AGL level.

greater than 20 mph were least frequent during summer. Near-zero winds were generally least frequent in the spring, but there was much year-to-year variability in the frequency of very light winds in a given season. Outside of the tendency for winds to be generally lighter in the summer, we found in all seasons, at this site, that there was about as much variability from year-to-year in a given season, as there was within a year from season-to-season. Of course, the seasons do not necessarily change at precise 3-month intervals at the same times each year, and some of the 'seasonal' variability is probably due to variation in the timing and length of the true meteorological seasons, fall, winter, spring, and summer.

Seasonal trends similar to those at the Four Corners site were observed at the Sanders Ranch and Clinton Ranch sites. At these latter two sites, the months with higher median winds speeds tended to have broader maxima in their speed frequency distribution, and a longer tail towards high wind speeds, compared to the Four Corners data. An example from the Clinton Ranch from the Fall, 1995, is shown in Figure 3. The winds at the Sanders Ranch and Clinton Ranch sites were more variable from season-to-season than at Four Corners, with seasonal median wind speeds ranging from 7-16 mph at the Sanders site and 8-17 mph at the Clinton site.

The Homestake site was the windiest site, with much broader maxima in the seasonal speed frequency distributions compared to the other sites. These speed frequency distributions almost always exhibited multiple modes along with much fatter tails extending towards higher speeds. An example from Spring, 1996, is shown in Figure 4. The lowest mode typically was in the 7-10 mph range, and an upper mode typically was between 13 and 21 mph. As at the other sites, winds were lightest in the summer, and speed frequency distributions tended to be more monomodal in summer than during the other 3 seasons. Higher winds were almost always observed at the Homestake site in the fall through spring seasons, compared to the other sites. The frequency distributions, though broader at the Homestake site, were somewhat less variable in shape than at the other sites during fall through spring.

SEASONAL MEAN WINDS

Monthly mean winds at 100 ft (30 m) AGL at the four wind survey sites were computed and compared to those at 33 ft (10 m) AGL Rapid City Regional Airport. The monthly mean winds at the airport are almost always lower than at any of the four sites. The primary reason is the fact that the wind speed measurement is made at a lower height AGL at the airport at the other sites, but geographic location differences may also play some role. The Homestake site generally has the highest monthly mean winds among the 5 sites, consistent with Table 1 in which it also had the highest mean winds over the entire first year of the study, and Table 2, in which it had the highest mean wind over the entire period of study.

Although the wind speeds at the study sites cannot be directly compared to those at the airport due to the different heights at which observations were made, it is possible to compare deviations from the long-term mean at each study site to the corresponding deviation at the airport. Correlation coefficients for each series, correlating monthly mean wind speed at each study site with monthly mean wind speed at the airport, for the period January, 1995, through February, 1998, are listed in Table 2. Correlation coefficients range from 0.01 to 0.39, with the best correlation between airport and Homestake site wind speeds, and the worst correlation between airport and Four Corners site wind speeds. All sites except Four Corners show larger amplitude of variability from month-to-month and season-to-season compared to the airport.

Table 2.

Site	Airport	Clinton	Four Corners	Sanders	Homestake
Mean Wind (mph)	10.4	12.2	11.8	12.3	14.5
Correlation Coefficient	1	0.31	0.01	0.32	0.39

The Four Corners site is on the western edge of the Black Hills, while the other sites are along the eastern and northern periphery (Sanders, Rapid City Airport, and Homestake) or in the east central (Clinton) Black Hills. Geographic distance as well as location on opposite sides of a significant terrain feature, the Black Hills, probably account for the independence of wind variability between the Four Corners site and the airport.

Table 2, based on more than three years of data, shows essentially the same relative ranking between mean wind speeds at the four Black Hills Power study sites as was found by Hasan and Hughes (1995) from an analysis of just the first year of data. Mean wind speed over the whole period at the Homestake site is more than 2 mph faster than mean winds at the other 3 sites, which are similar in magnitude to each other. This small difference translates to a significant difference in wind energy class as defined in Hasan and Hughes (1995). The Clinton, Four Corners and Sanders sites are Class 2, while the Homestake site is Class 4. Based on the mean wind speed of 10.4 mph at 33 ft (10 m) AGL at the Rapid City Airport, the class definitions given by Hasan and Hughes (1995), suggest that the Rapid City Airport site also would be a Class 2 wind energy site.

DISCUSSION AND CONCLUSIONS

This analysis confirms the relative rankings for wind energy production between the four Black Hills Power sites deduced in a study of wind energy potentials by Hasan and Hughes (1995). The earlier study looked at the first year of observations, while the present study examined more than 3 years of observations (including the same first year). The Homestake site, north of Sturgis and southwest of Bear Butte, has significantly higher mean winds than the other sites. Mean winds at 100ft (30 m) AGL are more than 14 mph at the Homestake site while they are near 12 mph at the other sites. The frequency distribution of wind speeds has a broader multi-modal form at the Homestake site compare to the other sites, with a significantly more frequent occurrence of winds greater than 30 mph compared to the other sites.

Wind direction data from the Four Corners site were found to be unreliable for the entire period, while at the other sites the direction data became unreliable after about the first year. The strongest winds at all sites with valid wind direction observations are most frequently northwesterly, although strong winds also are common from the southwest, south, and southeast in fall, winter, and spring, at most sites. At all sites, summer was typically the season with the lightest winds.

There was weak correlation between monthly mean wind speeds at the Rapid City Regional Airport and at the three sites around the northern and eastern fringe of, and in the east central, Black Hills. There was no correlation between monthly mean wind speeds at Rapid City Regional Airport and the Four Corners, Wyoming, site on the western border of the Black Hills. The variability in monthly and seasonal mean winds at the 100 ft (30 m) level at the northern and eastern sites was greater than the variability at 33 ft (10 m) at the airport. The wind speed at 100 ft (30 m) AGL at Four Corners was less variable than at all other sites, including the airport.

These results suggest that examination of the 100+ year record of winds at the various official observing sites in and around Rapid City used since the late 1800's may yield a rough estimate of the variability on century time scales of winds at sites like those involved in this study as long as they are on the same side of the Black Hills as Rapid City. Rapid City winds will not be a good predictor of winds on the western side of the Black Hills.

When estimating wind energy potential over broad areas, it often is assumed that winds will be generally higher over higher terrain. This study shows that this in not true in the Black Hills region. Other factors, including interaction between the northern flank of the Black Hills and strong northwest winds from cold season storms, and possibly some channeling of these winds between the northern flank of the Black Hills and the neighboring Bear Butte, can lead to higher mean winds at lower elevations. The higher mean speed results from the appearance of a second mode in the wind speed frequency distribution at higher speeds, while at the other sites the frequency distribution is monomodal with a much lower frequency of higher wind speeds.

One of the problems with generation of electric power using wind-driven turbines is the variability of the winds, and the frequent lack of sufficient wind at any one site to generate useable power. This study suggests that a power distribution grid covering an area equivalent to or larger in size compared to the Black Hills region, with wind generation sites distributed over the entire grid area, may be able to depend on having some wind-generated power from at least some of the sites much of the time. In comparison, a distribution system with most of its wind-generation capacity located at one or a few sites will have more intermittent power contributions from wind-driven turbines.

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