REGIONAL WIND ENERGY ANALYSIS FOR THE CENTRAL UNITED STATES

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Abstract

In situ measurements of wind speed from 28 wind-monitoring sites across North Dakota, Minnesota, Iowa, and Kansas were used in conjunction with a turbine manufacturer's power curve to produce multiple time series of energy production. In this study, a regional wind farm was designed with equal capacity at all 28 sites. Although some sites have better wind resources than others, the purpose of this study was not to optimize the geographic distribution of wind turbines, but to investigate the variability of wind energy generation across the region.

The production from this hypothetical regional wind farm was compared to production from a single location. For this study, the location of the single site is rotated among the 28 various monitoring locations. The comparison of energy production from the individual sites versus production from a regional wind farm showed the variability in energy production was reduced by a factor of 1.75–3.4.

Executive Summary

As part of the U.S. Department of Energy (DOE) program entitled Plains Organization for Wind Energy Resources℠ (POWER℠), the Energy & Environmental Research Center (EERC) is investigating the advantages of regional-scale wind farms. The benefits of geographically dispersed energy production have been previously investigated by the U.S. National Renewable Energy Laboratory (NREL) and others. Unlike previous research (refer to Literature Review section), in situ data at or near 50 meters were used to investigate the variability of wind energy generation across a multistate region in the central United States.

The analyses involved using in situ measurements from 28 wind-monitoring sites to estimate the energy production for two scenarios. The first scenario involved a single Vestas V-47 turbine placed at each location for a total of 28 turbines (regional scenario).The second scenario involved placing all 28 turbines at the same location. Furthermore, the location was rotated among the 28 various sites, thus creating 28 distinct solutions.

The two scenarios were compared to each other with time series overlays of hourly energy production and annual average diurnal patterns. Additionally, the maximum, minimum, and standard deviation of changes in energy production from hour to hour were compared between the two scenarios. Results indeed indicate a significant reduction in overall variability in energy production with geographically dispersed wind turbines. Reduction in variability ranged from a factor of 1.75–3.4, depending on the location of the single site in the second scenario.

The correlation in wind energy production between station pairs was calculated for station pairs in two orientations: north to south and west to east. The purpose of this analysis was to determine whether energy production from stations in the north complemented the production from southern sites better than stations in the west complemented production from sites in the east. Results suggest that a west-to-east dispersion of wind farms is more beneficial than a north-to-south configuration.

Introduction

As the use of wind power generation increases, more attention is being given to finding methods to improve regulation and reliability of energy generation from wind farms. The problem lies mainly with the variability of the wind. Several options are being looked at, including energy storage systems and wind–hybrid generation systems. In addition to these options, the EERC is looking into the benefits of geographically spread generation to improve regulation and reliability of wind energy.

NREL and the Utility Wind Interest Group have done extensive work in researching the impacts of wind energy on utilities. Several utilities have deemed it necessary to have excessive reserve requirements for wind (i.e., one-to-one ratio). For example, a 200-MW nameplate (rated) wind farm with an annual average production capacity of 30% would require 60 MW of fossil fuel backup generation. Recent studies have shown this to be unnecessary. Milligan (2003) showed that reserve requirements decrease for wind generation in Iowa if the generation is spread across the state versus being located at one primary location. In the situation that wind generation is spread across Iowa, 200-MW rated capacity equals 11.36% of Iowa's peak demand and requires 4.23% of rated capacity or 8.5 MW in extra load following reserves for a 99% confidence interval. 8.5 MW versus 60 MW is a significant difference in reserve requirements.

This paper will not directly address regulation and system reliability. Instead, this paper presents a simple analysis of wind data collected from various sites across the central United States. The purpose of this study is to determine the variability of wind resource data over a broad geographic area and the impact this would have on wind power production if turbines were operated as a single system over this broad area versus a single site.

Literature Review

The idea of using a geographically dispersed system of wind turbines to minimize the effects of an intermittent wind resource is not a novel idea. In the late 1970s, Edward Kahn used California wind and utility data to evaluate the reliability of wind generators in a utility system. Kahn (1979) concluded that the reliability increases as a function of geographic dispersal of wind turbines.

During the late 1990s and early 2000s, several studies came out of NREL that addressed wind variability issues. Milligan and Artig (1998) investigated the effects of geographical distribution on the electrical reliability of wind power plants. The potential reliability of wind farms at several wind-monitoring sites in Minnesota was analyzed with 1 year's worth of wind and utility data and production cost–reliability models. In their report, they concluded that electrical reliability of wind plants is optimized with a geographical diverse mix of sites. The following year, Milligan and Artig extended their analyses to include wind data from multiple years (Milligan and Artig, 1999). The use of more wind data changed the best mix and location of wind capacity in Minnesota; however, the reliability remained optimized with geographically dispersed wind power plant development. In addition, Milligan and Artig (1999) showed some of the hour-to-hour smoothing benefits of geographical dispersion of wind sites.

Benefits to system regulation, that is, the grid management of electric fluctuations with a timescale of minutes, have also been investigated by NREL. Ernst (1999) analyzed individual wind turbine and aggregate power output data from a 250-MW German wind data project. The study found a significant decrease in the system regulation burden with increasing numbers of wind turbines and that the number of turbines had more influence on the regulation burden than the physical separation of wind plants. Additionally, Ernst discovered that wind turbines only a couple of kilometers apart are almost totally independent during a short average time such as 5 minutes.

Another study on system regulation was presented at the American Wind Energy Association's (AWEA's) 2001 WindPower Conference in Washington, D.C. Hudson et al (2001) quantified the magnitude of regulation services typically be required to support a wind-generation facility on a grid system. As in Ernst (1999), the study found the relative amount of regulation support required for a wind plant decreases as the number of wind turbines in the system increases.

In addition to being beneficial to regulation, geographic distribution also benefits load following, that is, the variability of the demand on the utility system. Timescales of load following vary from 10 minutes to a few hours. In an effort to understand the load requirements for wind power plants, Milligan (2003) performed an analysis on hourly load data for Iowa and the impacts wind plants would have in this time domain. Again, a significant difference was identified between geographically dispersed cases and non-geographically dispersed cases. Results showed load-following requirements to be substantially reduced with geographically dispersed wind plants versus the non-geographically dispersed case. Maximum up- and down-ramp requirements on the grid system are reduced as well.

An evaluation of a Renewable Portfolio Standard (RPS) by the state of Iowa during the late 1990s led to the investigation of wind energy potential in Iowa and its potential effects to the electric grid. Milligan and Factor (2000) discuss various methods for choosing locations and wind plant capacities across Iowa. The goal of the research was to determine the geographic distribution that maximized economic benefit and system reliability. The study concludes that the maximum and minimum hourly power swings are significantly reduced by spreading the wind capacity over several geographically dispersed sites. However, geographic distribution provides the greatest economic benefit when all wind plants are developed in high wind resource areas (>7.2 m/s) versus simply developing the widest geographic distribution regardless of wind resource.

Other evidence of the benefit of geographically dispersed wind farms comes from a recent wind resource assessment study by Stanford University. Archer and Jacobson (2003) performed a study to quantify U.S. wind power at 80 meters using a new methodology for estimating wind speeds at 80 meters. The method utilizes both surface data (i.e., 10-meter wind speeds) and radiosonde observation (RAOB) data in a least-squares-fitting approach to estimate 80-meter wind speeds. The study found that the number of days with no wind power and the standard deviation of wind speed are substantially reduced if multiple sites are considered versus a single site. From this finding, Archer and Jacobson speculate that extra reserve requirements may decrease with increasing spatial distribution of wind farms.

Data

Wind speed data were obtained from POWER's wind resource database. The study analyzed hourly averaged wind speed data collected at heights between 25 and 60 meters. Wind direction and air temperature data were not utilized by the study. Wind direction data from the monitoring sites are typically used to determine tower shadowing. Unfortunately, the orientations of the sensors for several of the sites were not known. Where multiple sensors existed at the same height, the faster of the two average hourly wind speeds was used by the study.

Computations of energy production do not require wind directional information; however, air temperature is significant. Three reasons existed for not incorporating air temperature in the energy calculations. First, some of the monitoring sites used in this study did not have temperature sensors. Second, manufacturer's power curves for wind turbines are generally standardized to sea-level pressure and 15°C. Lastly, the assumption is made that the diurnal variability in air temperature will not be a significant contributor to the variability of energy production.

A wind turbine power curve is another piece of information necessary for calculating energy production. The 660-kW nameplate capacity Vestas V-47 turbine was chosen for this study. The choice was based on the popularity of the Vestas machine in the central United States during the late 1990s. The manufacturer's published power curve for the V-47 was obtained in a spreadsheet format with power output based on discrete 1-m/s bins. Three equations were developed and used to model the shape of the distribution. The equations provided a continuous estimate of power production based on wind speed.

Wind data from tall towers across the region were obtained from the POWER database. The database is publicly accessible and available at www.undeerc.org/wind . POWER did not fund or operate the monitoring sites used in this study. Data from Minnesota were collected by the Minnesota Department of Commerce; North Dakota and Kansas data were collected as part of utility programs with multiple contributors; and Iowa's data set was collected by the Iowa Wind Energy Institute.

Methodology

The study focuses on the characteristics of the wind at a height of 50 meters. Although hub heights of utility-scale wind turbines are closer to heights of 100 meters, the data available for the central United States are primarily at or around 50 meters. Additionally, an objective was to minimize wind speed errors due to interpolation or extrapolation of the data.

During the first phase of the study, the group had to determine a 1-year period within the POWER database that has the most geographically dispersed and largest number of active stations. The 1-year period chosen was from July 1, 1996, to June 30, 1997. Data for a total of 48 sites were available. Eight sites were located in North Dakota, 12 in Iowa, 22 in Minnesota, and six in Kansas.

Wind speed data for 50 meters or the two closest heights to 50 meters were imported into spreadsheets for the 48 wind-monitoring sites. Holes or gaps in the time series were identified in the data sets. Bad and suspect data were also identified and flagged in the data sets. Quality control procedures used to identify those data that are bad or suspicious include the following:

- Range tests for wind speed
- Wind-speed standard deviation tests
- Time series visually inspected via graphs for anomalies
- Weather reports from nearby airports or weather surface stations

A time series column of hourly averaged wind speeds at 50 meters was created for each of the remaining stations. Time series were generated based on the results of the quality assurance. For example, if a site had a single sensor at 50 meters and the average hourly wind speed was flagged for a particular hour, then no value was recorded in the column for that hour. Wind speeds were calculated for a height of 50 meters if a site lacked a 50-meter sensor. If a station did not have an anemometer at 50 meters, the shear exponent between two measuring heights was calculated for each hourly record and used to estimate the wind speed at 50 meters. On the other hand, if stations had duplicate 50-meter sensors, the larger of the two wind speeds was selected to represent the hourly average wind speed.

The next step was to determine the sites to be used in the analyses. Two criteria were established for the selection process.

1. If nonflagged and existing data records numbered less than 85% of the total 8760 possible records, those sites were removed from consideration.
2. If an area had a large number of sites compared to the rest of the region, the number of selected sites within the area was reduced in order to prevent effects of data clustering on the statistics. Selection of sites within the station clusters was based on the following three criteria:
   a. The final station spacing within the cluster had to be representative of station density across the region.
   b. Sites with 50-meter sensors were favored over sites that did not have sensors at that height.
   c. Correlation coefficients were computed between Stations A and B based on their wind speeds. The coefficients provide an idea of the linear association of changes in wind speed between two stations. Station pairs with smaller coefficients were given preference in the selection process.

Using these criteria, the original 48 sites were narrowed down to a field of 28. Figure 1 illustrates the sites that made the final selection.

Energy production is dependent upon the type of wind turbine. The Vestas V-47 turbine power curve was selected for this study (Figure 2). Three equations were developed to model the manufacturer’s published power production distribution. The three equations represent a different portion of the power curve (e.g., lower, middle, and upper). Logical statements were developed to determine which equation applied to each hourly averaged wind speed value. These statements were applied to the data in spreadsheets and hourly average energy production estimated from the wind speeds.

Two cases or scenarios were developed for the purposes of the study. Case 1 represents energy production for 28 wind turbines spread across 28 sites. Case 2

FIGURE 1. LOCATIONS OF THE 28 SELECTED WIND-MONITORING SITES ARE SHOWN ON THE MAP OF THE CENTRAL UNITED STATES.

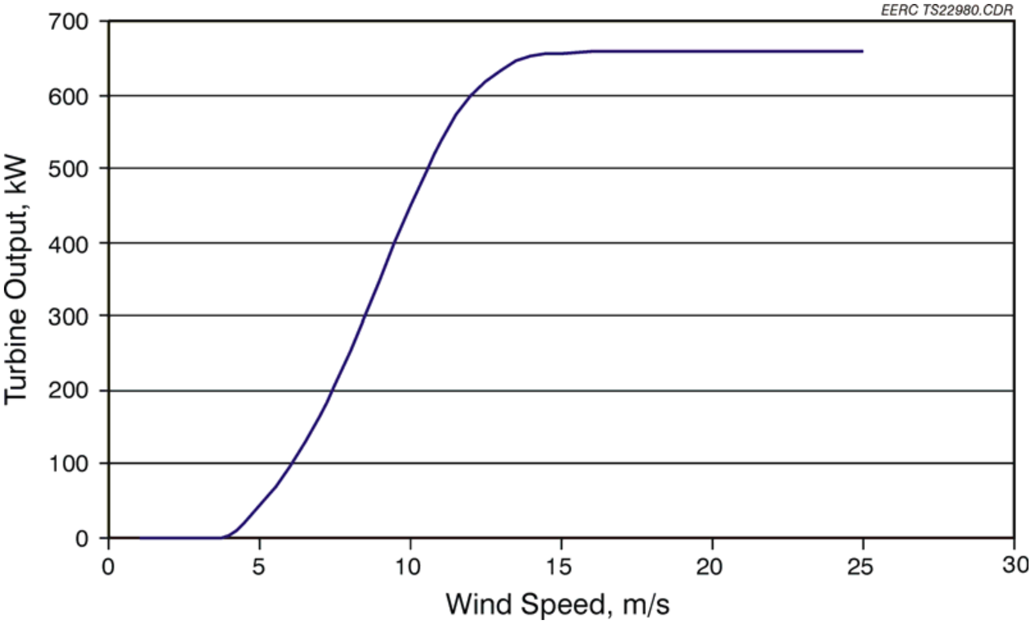

FIGURE 2. MANUFACTURER'S POWER PRODUCTION CURVE FOR THE 660-KW-RATED V-47 TURBINE.

corresponds to 28 turbines at a single location. The single location was rotated among the 28 wind-monitoring sites so that the choice of location was taken into account. In short, Case 1 represents a geographically dispersed set of wind turbines while Case 2 represents a single wind farm.

The study was not able to factor in the variability of energy production across a wind farm. Consequently, the estimates of energy production for Case 2 required taking the calculated energy production from one wind turbine located at the site of the monitoring tower and multiplying the value by 28. Although this estimate is not representative of energy production from a wind farm, it does provide a worst-case scenario of hourly variability in production.

Another caveat is that energy production values are not available for all 28 monitoring sites at all times. For example, Arlington, Iowa, had bad or missing wind speed data for November 27, 1996, at 07:00 LST, so energy production was not estimated for that hour. As a result, the energy production total for Case 1 at that time would be short by one turbine. To remedy this problem, the total energy production for each hour was normalized by the number of values that went into the total and multiplied by 28.

When comparing Case 1 to Case 2, Case 1 statistics were based on data from the same times for which data were available in Case 2. For example, Case 2 lacked an energy production value for November 27, 1996, at 07:00 LST for the wind farm located at Arlington, Iowa. Although Case 1 has an estimate of energy production for this hour, the estimate was not used in the statistics between the two cases. In summary, the study went to great lengths to make sure analyses of energy production between the two cases were based on the same hours.

Results

Reduction of variability in hourly energy production is evident in the time series between the two cases. Figure 3 shows hourly energy production between Cases 1 and 2 (Chandler, Minnesota) during July 1996. Note, the minimum production in Case 2 is 0 kWh while for Case 1 it is 330 kWh. The visible differences in volatility of energy production held true for all months. Figure 4 provides an example of energy production during December 1996.

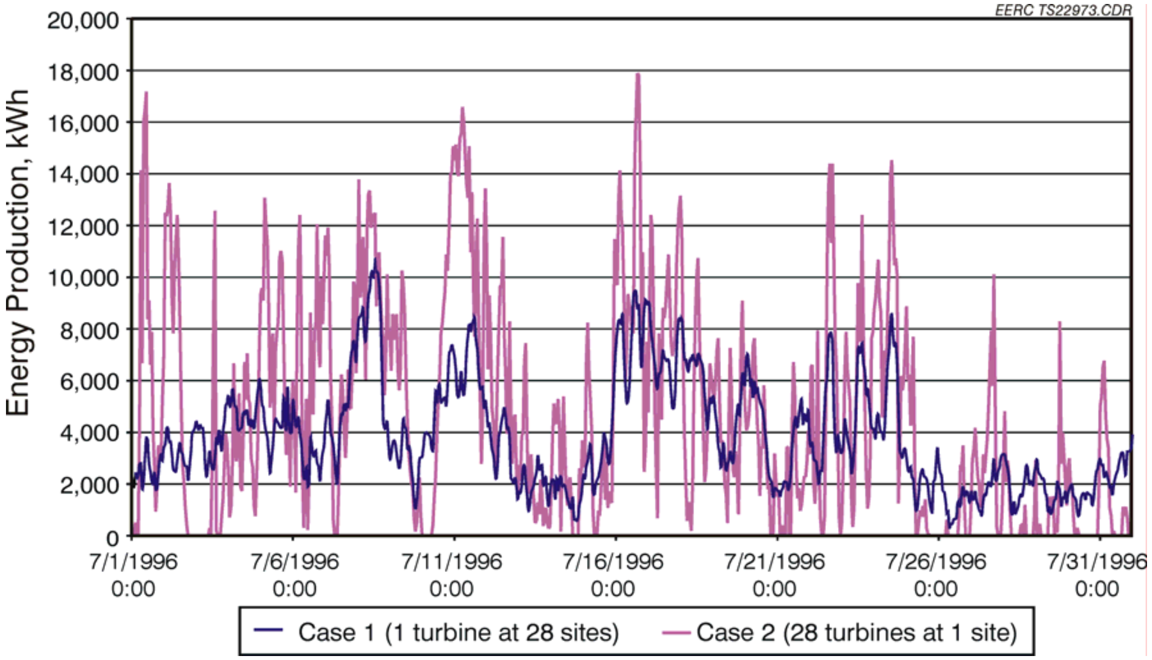

FIGURE 3. JULY 1996 TIME SERIES OF ENERGY PRODUCTION FOR THE TWO CASES. CASE 1 (DARKER LINE) REPRESENTS PRODUCTION FROM 28 TURBINES SPREAD ACROSS 28 SITES. CASE 2 (LIGHTER LINE) REPRESENTS PRODUCTION FROM 28 TURBINES AT THE CHANDLER, MINNESOTA, SITE.

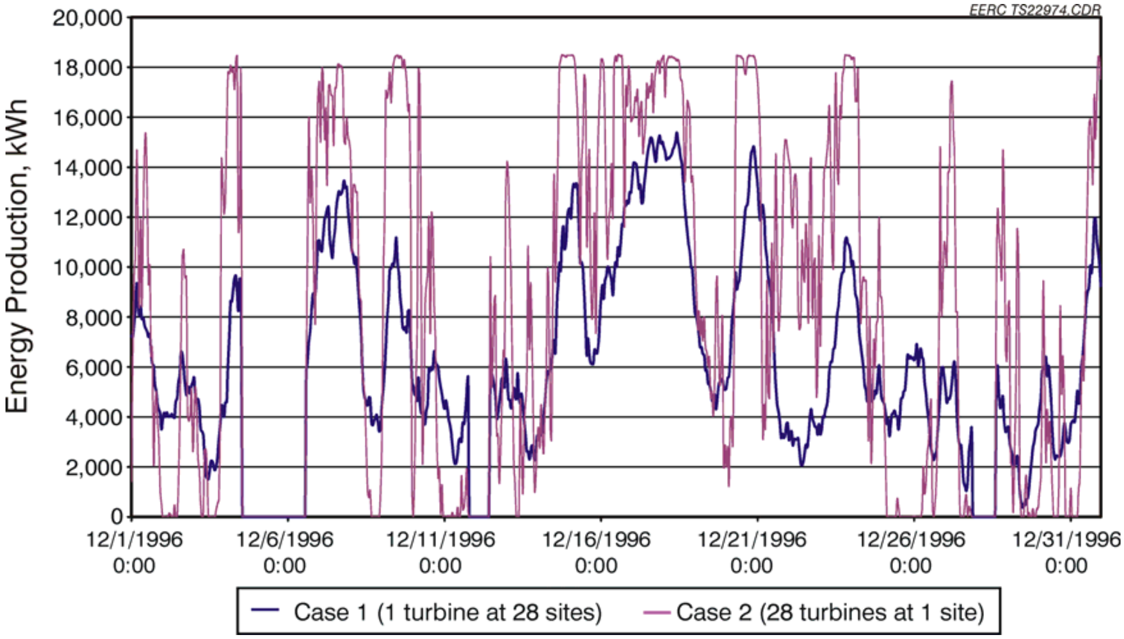

FIGURE 4. DECEMBER 1996 TIME SERIES OF ENERGY PRODUCTION FOR THE TWO CASES. CASE 1 (DARKER LINE) REPRESENTS PRODUCTION FROM 28 TURBINES SPREAD ACROSS 28 SITES. CASE 2 (LIGHTER LINE) REPRESENTS PRODUCTION FROM 28 TURBINES AT THE CHANDLER, MINNESOTA, SITE.

An annual ratio between hourly energy production for Cases 1 and 2 were calculated for each site (Table 1). The ratio represents the annual variance in energy production for Case 2 divided by the annual variance in energy production for Case 1. For example, a 28-turbine wind farm in Chandler, Minnesota, was estimated to have an annual energy production variance of 3786 $(MWh)^2$, while a 28-turbine wind farm spread across the 28 monitoring sites would have an estimated annual energy production variance of 1239 $(MWh)^2$. The ratio between these two estimates would be approximately 3.06. In other words, the variability of energy production for Case 2 at Chandler, Minnesota, is 3 times that of Case 1.

TABLE 1. RATIO VALUES PROVIDE A MEASURE TO JUDGE THE IMPROVEMENT OF VARIABILITY BETWEEN CASE 1 AND THE INDIVIDUAL SITES USED IN CASE 2.

	Brownton	**Cedar**	**Arlington**	**Muscatine**	**Nerstrand**	**Crookston**	**Turin**	**Forest City**	**Sabin**	**Red Oak**	**Alberta**
Variability Ratio	1.76	1.82	1.93	1.94	2.21	2.25	2.26	2.32	2.34	2.40	2.53

	Inwood	**Lakin**	**Wabasso**	**Olga**	**Green River**	**Radcliffe**	**Gun Barrel**	**Deerhead**	**Estherville**	**Petersburg**	**Beaumont**
Variability Ratio	2.54	2.68	2.69	2.72	2.74	2.76	2.78	2.85	2.96	2.97	3.00

	Chandler	**Bear Creek**	**Ray**	**Wilton**	**Benedict**	**Alfred**					
Variability Ratio	3.05	3.10	3.11	3.23	3.36	3.43					

From the calculated ratios, a pattern was recognized between the ratio and the average annual wind speeds for all sites. Figure 5 illustrates the pattern. A strong linear signal exists between the variability of energy production and the average annual wind speed. From the figure, it is evident that sites with larger average wind speeds also have more variable winds and energy production. The economics between the value of stronger winds versus the value of less variable winds is a topic for future research.

The variability in energy production was also examined from a diurnal perspective. Figure 6 illustrates the diurnal pattern in energy production for the region. The values provided on the graph were calculated by averaging all values of energy production for a particular hour. For example, the value at 00:00 LST is the average of energy production values at 00:00 LST for the entire year. From the figure it is evident that a

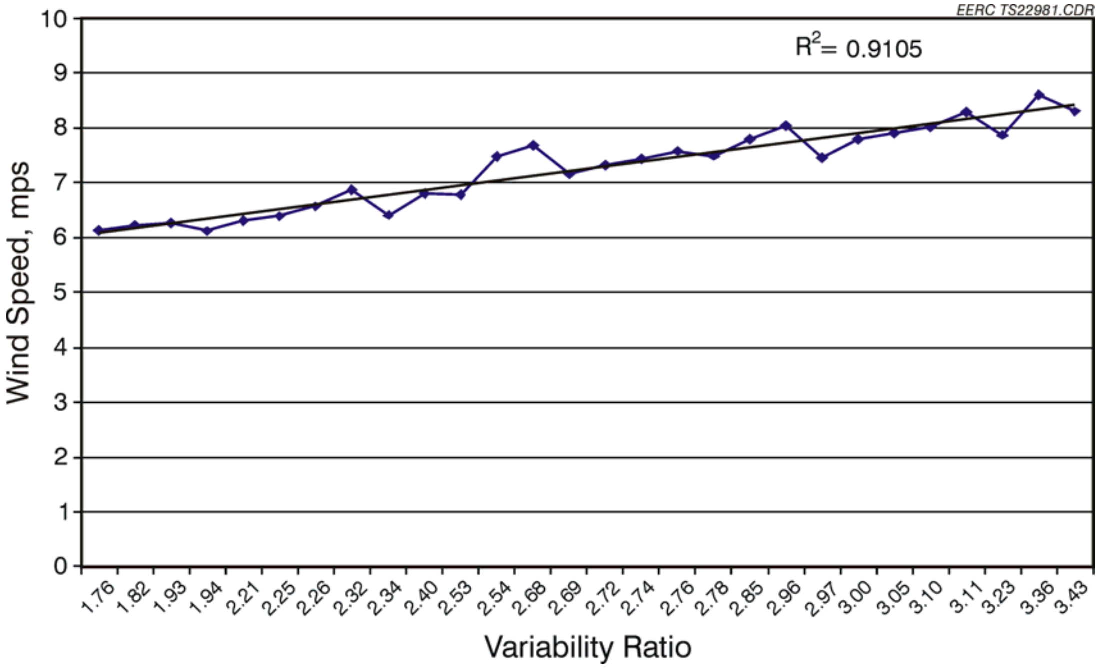

FIGURE 5. THE REDUCTION IN WIND ENERGY VARIABILITY BETWEEN GEOGRAPHICALLY DISPERSED SITES AND 28 INDIVIDUAL SITES PLOTTED AGAINST THE MEAN ANNUAL WIND SPEED FOR EACH STATION.

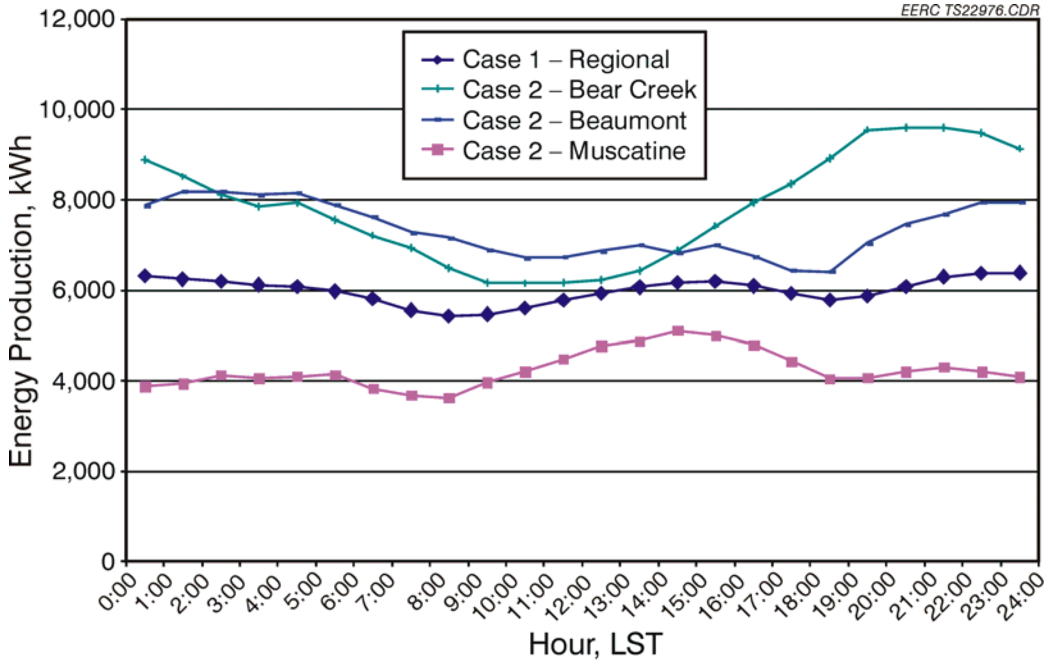

FIGURE 6. ANNUAL AVERAGE DIURNAL PLOTS OF WIND ENERGY PRODUCTION FOR FOUR SCENARIOS. THE THICK DARK BLUE LINE REPRESENTS THE MEAN DIURNAL PATTERN FOR THE REGION. THE OTHER THREE TIME SERIES ARE FOR VARIOUS SITES ACROSS THE REGION.

regional system of wind farms would smooth diurnal patterns in wind energy production. Additionally, energy output would reach a relative maximum during the afternoon.

Of the various methods for illustrating wind energy variability, the most comprehensive graph is shown in Figure 7. The I-beam graph contains two sets of symbols: vertical lines and bars. The vertical lines illustrate the maximum and minimum changes in energy output between consecutive hours. The red bars indicate one standard deviation about the mean change in hourly output. The results clearly show that a regional system of wind farms (labeled “region”) significantly decreases the variability of hour-to-hour energy production.

Wind farms with uncorrelated or negatively correlated time series of energy production will have some synergy if operated as a group. In other words, a lull in energy production at one site may be offset by a boost in energy production at another site. The correlation of energy production between station pairs is dependent on the distance between wind turbines and wind farms. For example, over simple terrain, wind farms within a few kilometers of each other will have similar time series of energy production because sites experience similar atmospheric conditions most of the time. However, if these sites were hundreds of kilometers apart, atmospheric conditions as well as topography will likely be significantly different for each site.

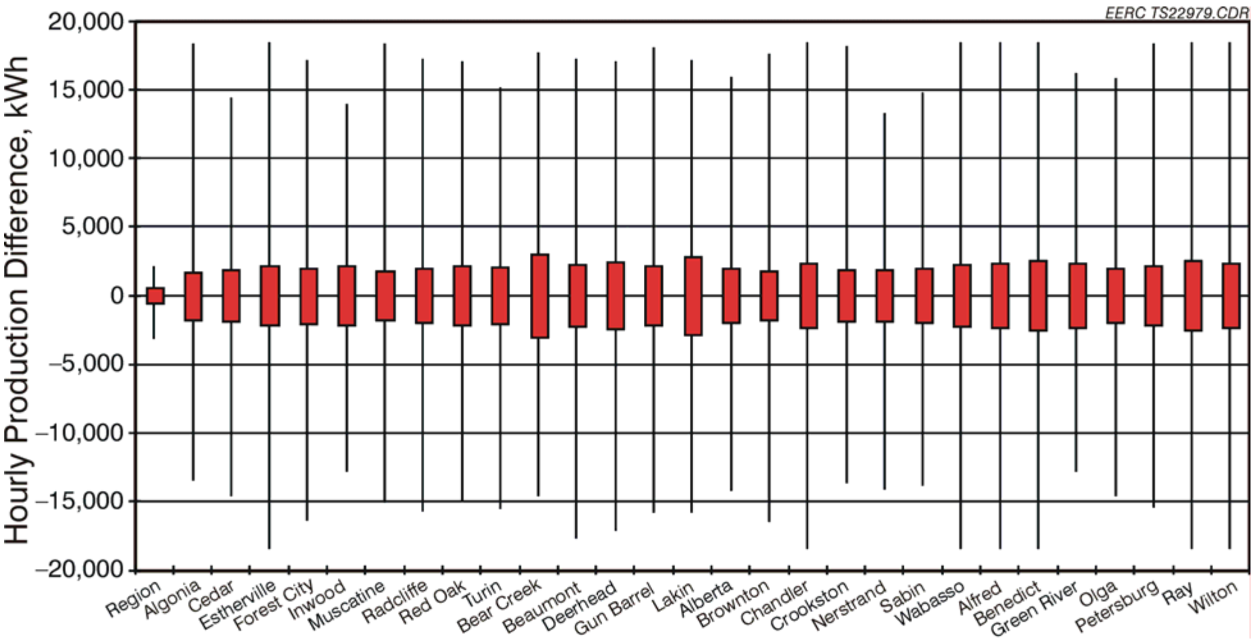

FIGURE 7. VERTICAL LINES INDICATE THE MINIMUM AND MAXIMUM CHANGES IN ENERGY OUTPUT FROM CONSECUTIVE HOURS. THE RED BARS REPRESENT ONE STANDARD DEVIATION ABOUT THE MEAN CHANGE IN HOURLY ENERGY OUTPUT.

The spread of stations from North Dakota to Minnesota and from Minnesota to Iowa and Kansas presented an opportunity to investigate synergies between station pairs along a north–south (N–S) line versus station pairs along a west–east (W–E) line. The objective of such comparison was to determine the orientation of wind farms most beneficial to energy production. In order to be classified as a N–S station pair, the stations had to have an east or west offset of less than 30 km (Figure 8). Alternatively, station pairs were classified into the W–E category if the stations were within 30 km north or south of each other.

Correlations of wind speeds between station pairs were calculated and plotted versus distance (Figure 9). Data points in the figure come from 19 N–S station pairs and 13 W–E station pairs. The results indicate that W–E sites become uncorrelated with distance at a slightly faster rate than N–S sites. An outcome that is likely the result of fronts oriented predominantly north to south versus east to west as they cross the Great Plains.

Conclusions

Wind energy production from geographically dispersed locations reduces the overall variability in energy production. Results from this study suggest that variability can be reduced by a factor of 1.75–3.4. Additionally, a regional system of wind farms would smooth diurnal patterns in wind energy production, and energy output would reach a maximum during the afternoon to match typical peak demand. Finally, results

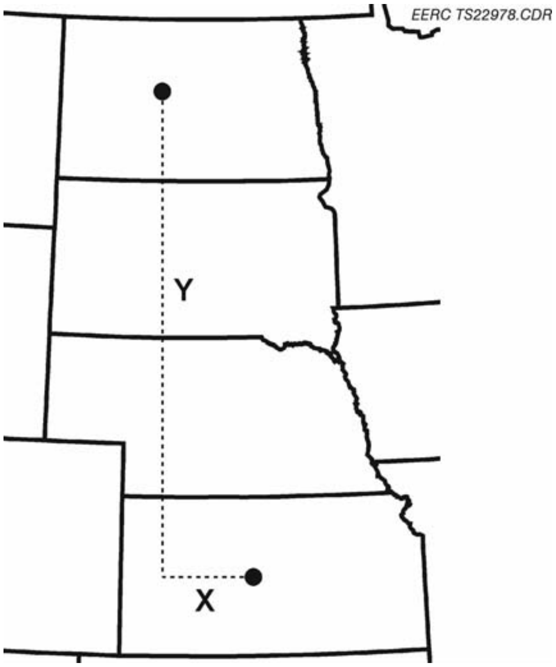

FIGURE 8. DOTTED LINES INDICATE N–S AND W–E DISTANCES. X MUST BE LESS THAN 30 KM TO CLASSIFY ANY TWO STATIONS AS N–S STATION PAIR.

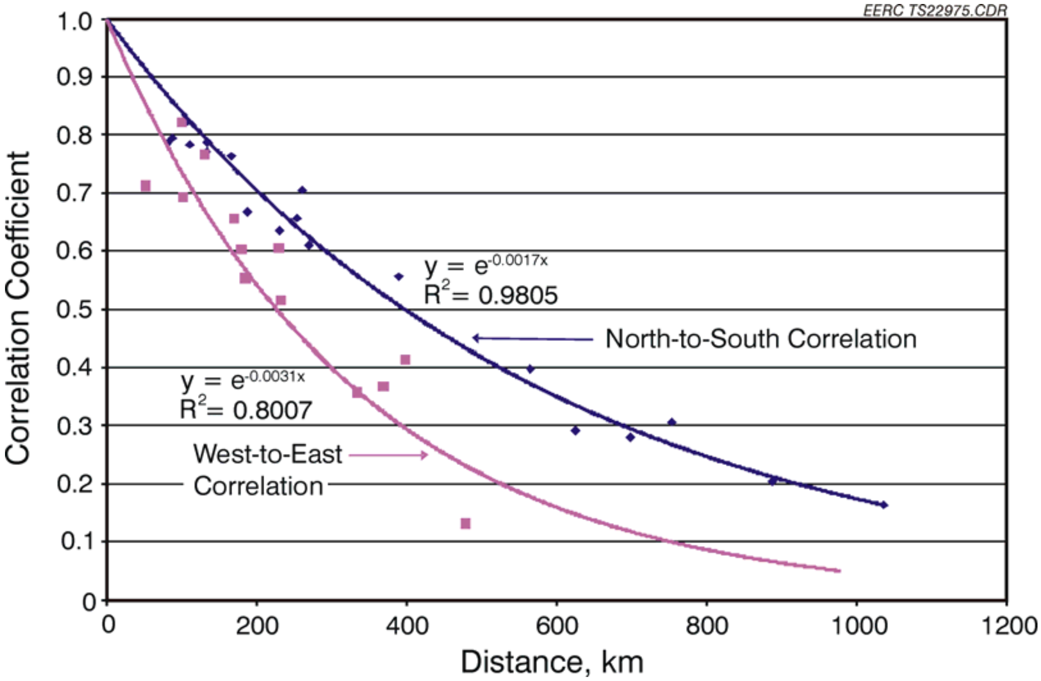

FIGURE 9. NAVY BLUE DIAMONDS AND TREND LINE REPRESENT POWER PRODUCTION CORRELATION BETWEEN STATION PAIRS THAT LIE ON A N–S LINE. THE PINK SQUARES AND TREND LINE REPRESENT POWER PRODUCTION CORRELATION BETWEEN STATION PAIRS THAT LIE ON A W–E LINE.

suggest that a west-to-east dispersion of wind farms will be more effective at reducing variability in wind energy production than a north-to-south configuration.

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