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Variability of Wind Power Near Oklahoma City and Implications for Siting of Wind Turbines

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September 1987

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VARIABILITY OF WIND POWER NEAR OKLAHOMA CITY
AND IMPLICATIONS FOR SITING OF WIND TURBINES

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PREFACE

This report documents the work conducted under DOE Interagency Agreement DE-A106-81RL 10336 by Edwin Kessler, the Director of the National Severe Storms Laboratory when the project began. Dr. Kessler has since retired from NSSL and is now employed by the Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, and as Adjunct Professor, Departments of Geography and Meteorology, in Norman, Oklahoma. Dr. Kessler was assisted in the study by Ritchie Eyster, of the Cooperative Institute for Mesoscale Meteorological Studies; Mr. Eyster is now a meteorologist with the Pest Control Engineering Research Unit, Agricultural Research Service, College Station, Texas.

ACKNOWLEDGMENTS

Thanks to Deborah Hill for her compilation of data during early stages of this study, and to able secretaries Barbara Franklin and Joy Walton. Staff of the Rural Electric Cooperative, Lindsay, Oklahoma, have been helpful on several occasions, and we particularly thank Johnny Waters and Wayne Loafman, REC Manager. Many thanks to Profs. Bergey and Chartock for meter readings that provided the basis for estimating average winds at their sites and some important underpinnings for our principal conclusions. And we surely appreciate the sharing attitude and assistance with calibration and its interpretation provided by staff of Bergey Windpower Company. National Severe Storms Laboratory (NSSL) engineer John Carter designed and fabricated the Hall Effect current probe, and gave critical help with calibrations; NSSL technicians Jerry Wardius and Robert Goldsmith calibrated anemometers and installed them on the GPA tower, maintained the NSSL mesonetwork station at GPA with 20-ft tower, and facilitated access to magnetic tape recordings from the surface station through software adaptations. Staff of the Oklahoma City Weather Service Forecast Office have been very helpful and we particularly thank Chief Technician Warren Walker for valuable counsel. And there were many enlightening conversations about boundary layer meteorology with NSSL scientist Robert Rabin. Many thanks to Joan Kimpel for preparing fine illustrations from sketches, to Peggy Baker for preparing the tables, and to the first author's wife, Lottie, whose support was indispensable to completion of the project. Finally, we thank project monitor Alan Miller of the Pacific Northwest Laboratory for having administered financial support that made student participation possible. We also appreciate his confidence in us while he waited a rather long time for this report.

EXECUTIVE SUMMARY

Data from five sites near Oklahoma City were examined to assess wind power availability. Wind turbines of identical manufacture were operated at three of the sites, one of which was also equipped with anemometers on a 100-ft tower. Comprehensive anemometric data were available from the other two sites. The study indicates that the average wind speed varies substantially over Oklahoma's rolling plains, which have often been nominally regarded as flat for purposes of wind power generation. Average wind differences may be as much as 5 mph at 20 ft above ground level, and 7 mph at 100 ft above ground level for elevation differences of about 200 ft above mean sea level, even in the absence of substantial features of local terrain. Local altitude above mean sea level seems to be as influential as the shape of local terrain in determining the average wind speed.

The wind turbine used at a meteorologically instrumented site in the study produced the power expected from it for the wind regime in which it was situated. The observed variations of local wind imply variations in annual kWh of as much as a factor of four between identical turbines located at similar heights above ground level in shallow valleys and on hilltops or elevated extended flat areas.

Studies should be conducted to test these findings with independent data.

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INTRODUCTION

The use of wind for sailing began in prehistoric times, and wind has been used as a source of energy for grinding grain and pumping water for about 1,000 years. The first windmills for electrical power generation were developed around 1900, but their use in the United States diminished as cheap electrical power was carried by wire to practically every human abode and industry from central generating plants. Indeed, cheap power became a ubiquitous and indispensable component of all technologically advanced societies (Torrey 1976).

Depletion of fuels and irregularly increasing cost of fuels in the late twentieth century have stimulated reexamination of renewable energy sources for generation of electricity. Design of modern windmills reflects decades of learning and experience in aerodynamics, materials fabrication, and development of control equipment (Park 1981).

Since 1975, thousands of wind power generators, also known as Wind Energy Conversion Systems or WECS, have been manufactured and installed, but it is not yet clear that they can be cost effective in a large sense with the 1980s' relationship between the cost of their manufacture and installation on one hand and utility rates on the other. The distribution of wind power generator installations in the United States has been closely related to tax credits, both state and federal, as well as to winds that are a relatively reliable source of abundant power, i.e., comparatively steady and strong and reasonably widespread.

This study is intended to be a contribution to selection of sites where wind energy conversion systems can operate effectively. We compare meteorological data and wind power data from several sites. At three sites, wind power data were collected from identical machines over approximately 2 years. At one of the sites, there is also a recording meteorological station, whose data are compared with data collected at Will Rogers World Airport, Oklahoma City, 28 miles to the north. We also consider wind data of importance that were gathered during 1966 and 1967 at the tower of WKY-TV (now KTVY) in the northern part of Oklahoma City, 14 miles north-northeast of Will Rogers. Statistical properties of the wind and of the wind power data are presented,

and the power generating capability of the wind converter is evaluated as a function of wind speed and in relation to the sites. Evidence is presented for a strong dependence of wind power on variations of only a few hundred feet in local elevation above mean sea level. This dependence seems to rival local terrain features in importance.

THE STUDY SITES

Table 1 lists site coordinates and some other site data. All three wind power generator sites are equipped with the BWC 1000-S wind power generator^(a). Complete meteorological data are available for the entire period from the National Weather Service (NWS) Forecast Office at Oklahoma City, and for selected periods at Great Plains Apiaries and at the instrumented tall transmitter tower of KTVY.

Here is a general discussion of each site.

GREAT PLAINS APIARIES (GPA)

This site is at the farm residence of the first author. The wind power generator tower and meteorological sensors and recorders are in a rectangular area approximately 75 ft north to south and 115 ft east to west (approximately one-fifth acre), enclosed by a barbed wire fence, as shown in Figure 1. From the first metered installation on January 10, 1981, until February 23, 1982, the generator was on top of a 60-ft tower; anemometers were installed on the same tower at levels of 32 and 53 ft on April 3, 1981. During February 23 through 28, 1982, the height of the tower was increased to 100 ft, and the anemometer at 53 ft was moved to 93 ft, about 3 ft below the lowest sweep of the rotor propeller. This history is also indicated in Table 2.

As shown in Figure 1c, there are one-story dwellings approximately 150 ft south and 175 ft northeast of the generator tower. A garage is adjacent to the south fence of the enclosure, immediately south of the generator tower, and there are trees (mostly black locust) in the area, mostly less than 20 ft tall, but a few 25 to 30 ft tall in the southwest quadrant at a distance of 150 ft and at about 10 ft lower elevation. The trees have thin foliage, but the anemometric record on the 20-ft tower is affected by the trees and by the house and garage to the south, when the wind blows from the southwest quadrant. The wind records at 32 ft and higher appear to be essentially unaffected by obstructions in any direction.

(a) Manufactured by the Bergey Windpower Company, 2001 Priestly Drive, Norman, Oklahoma 73069.

TABLE 1. Site Summary

Site	Coordinates(a) N by W	Distance from WKY (statute miles)	Wind Energy Converter?	Meteorology	Altitude Tower Base (ft, MSL)	Topography	Quadrangle Chart 7.5 Minute Series
WKY-TV	35°34'06" 97°29'20"	0	No	Wind data from 23-ft tower and 1600-ft tower during selected periods	1165, 1148	Gently rolling plain, incised occasionally by streams	Spencer Britton
Will Rogers World Airport	35°23'24"(b) 97°36'03"	13.8	No	Wind data from 20-ft tower and earlier from 55 and 70 ft	1285	Plain	Okla City Okla City SW Okla City SE Mustang
Bergey	35°10'45" 97°30'58"	26.9	Yes 60-ft tower	No	1175	Hillside on rolling plain	Newcastle
Chartock	35°09'48" 97°31'44"	28.1	Yes 40-ft tower	No	1280	Hillside on rolling plain	Newcastle
Great Plains Apiaries	34°58'47" 97°31'16"	40.7	Yes 60- and 100- ft tower(c)	Wind data for selected periods(c)	1085	Shallow valley on rolling plain incised occa- sionally by streams	Criner

(a) The last digit in coordinate positions is not precise.

(b) Coordinates for wind data 1981 through 1985; other data are collected approximately 1 mile north.

(c) More detail in Table 2.

(a)

FIGURE 1. Three Views of the GPA Site. (a) View from the south of BWC 1000-S shortly after its installation at Great Plains Apiaries in January 1981. Photo courtesy of Rural Electric Cooperative, Lindsay, Oklahoma; (b) View of the GPA site from the southeast before the surface station had been fitted with solar cells; (c) View of the GPA site from the northwest during winter 1985-1986. The top of the 20-ft tower of the NSSL mesonetwork station, with a cup anemometer and wind vane, is visible to the left of the wind generator tower, now 100 ft tall. The cottage to the left is approximately 125 ft northeast of the 20-ft tower.

(b)

(c)

FIGURE 1. (contd)

TABLE 2. Wind Energy Conversion and Wind Measurement
at Great Plains Apiaries

<u>Anemometry</u>	<u>Dates</u>
20-ft tower ^(a)	Spring seasons and some other periods since 1981
32 and 53 ft ^(b)	Selected intervals during Apr. 3, 1981 to Feb. 23, 1982
32 and 93 ft ^(b)	Selected intervals since Feb. 28, 1982
<u>Wind Power Generation</u>	
60-ft tower	Almost continuous with favorable wind during Jan. 10, 1981 - Feb. 23, 1982
100-ft tower	Almost continuous with favorable wind since Feb. 28, 1982

- (a) The 20-ft tower is part of a closely spaced network of surface stations operated by NSSL. It is 57 ft east of the wind generator tower.
- (b) Measurements at these heights are made with anemometers on the wind generator tower.

As shown in Figure 2, the GPA site is on the north side of the bottom of the valley of Finn Creek, a tributary of the Washita River. The elevation of 1085 ft MSL at tower base is approximately 20 ft above the base of Finn Creek's flood plain, which is incised an additional 15 to 20 ft in a narrow channel. The creek is bordered by deciduous trees whose average height is about 30 ft. The boundary of the dense cover along Finn Creek lies 400 to 600 ft south of the instrument enclosure and at lower elevation.

RESIDENCE OF PROF. AND MRS. MICHAEL CHARTOCK

This site, at approximately 1280 ft MSL, is on the northeast slope (5%) of a hill whose summit at 1310 ft MSL lies about 0.2 mile south of the wind power generator. This summit is the easternmost of four that trend toward azimuth 240 degrees for a distance of 1.5 miles and that collectively form a ridge at an elevation of about 1300 ft MSL. The area is essentially treeless,

FIGURE 2. Section of the Criner Quadrangle Illustrating Topography Around the Wind Generator Site at GPA. Contours in this and other quadrangles are at intervals of 10 ft.

and the few trees near the wind power generator (which is mounted on a 40-ft tower) are only about 15 ft tall, as shown in Figure 3. This site is the highest of the wind power generator sites studied here. Approximately 1000 ft northeast of the Chartock site, the slope becomes much reduced. About one mile to the northeast, there is an escarpment and an abrupt drop of about 90 ft to the 2- to 3-mile-wide flood plain of the South Canadian River. Along azimuths east through south to north, the terrain is similar to that surrounding Great Plains Apiaries, but the average elevation is about 100 ft higher.

(a)

(b)

FIGURE 3. Photographs of Chartock Site. (a) View toward ENE and toward the Chartock wind energy converter;
(b) Same machine viewed from the north-northwest.

RESIDENCE OF PROF. AND MRS. KARL H. BERGEY

This site, approximately 1180 ft MSL, is about 1.3 miles north-northeast of the Chartock site, and is 100 ft lower on the same hillside, as shown in Figure 4. The Bergey site is just 0.2 miles southwest of the edge of the South Canadian River flood plain and 70 ft above it. The 60-ft generator tower stands well above the scattered trees, as shown in Figure 5.

OKLAHOMA CITY NATIONAL WEATHER SERVICE FORECAST OFFICE

For purposes of commerce, the principal airport complex at Oklahoma City is called Will Rogers World Airport. As shown in Figure 6, this area is essentially flat. The nearest significant building from the anemometer site is the airport terminal, which lies toward the north-northeast at a distance of 0.4 mile. To the west, just beyond the edge of the quadrangle chart shown as Figure 7, the terrain rises irregularly. The altitude of the airport anemometer site is only 5 ft higher than the Chartock site, but the average elevation in the 1-mile radius of the Oklahoma City site is about 40 ft higher.

INSTRUMENTED TALL TOWER OF WKY-TV

The 1600-ft tower of WKY-TV (now KTVY) is about 7 miles north of downtown Oklahoma City and 14 miles north-northeast of the airport anemometer installation. Figure 8 is a photograph of the site, and Figure 9a gives details of the topography surrounding the tall tower and a surface station 250 ft to the west-northwest. The surface station is located on ground 17 ft higher than the base of the tall tower to avoid or reduce effects on wind measurements of the nearby gully and transmitter building. The base of the tall tower is at elevation 1148 ft MSL. Wind at the surface station is measured atop a 23-ft tower whose base is at elevation 1165 ft MSL; this elevation is 120 ft lower with respect to MSL than the base of the tower at Will Rogers World Airport from which the official Oklahoma City Weather Service Forecast Office (WSFO) wind measurements are made.

Topography in the general area is shown in Figure 9b. Slopes are about half as steep as in the neighborhood of Great Plains Apiaries; the average altitude is about the same.

FIGURE 4. Section of Newcastle Quadrangle Illustrating Topography Surrounding Chartock and Bergey Wind Generator Sites

FIGURE 5. Bergey Wind Generator on a 60-ft Tower Viewed from SSW

FIGURE 6. View of Anemometer Installation Operated by the National Weather Service at Will Rogers World Airport, Oklahoma City. The direction of view is toward the northeast.

FIGURE 7. Topography in the Vicinity of the Oklahoma City Site of Facilities of the National Weather Service Forecast Office

Conduit bridge & elevator landing.
(S) (Looking SE.) Highest terrain 1/2 mi.
NW. Transmitter bldg. to left.

FIGURE 8. Base of the Meteorologically Instrumented Tower of WKY-TV (now KTVY), and Local Terrain, as Seen From the Southwest

(a)

(b)

FIGURE 9. Topographic Maps of the WKY Tower Site and Surrounding Area. (a) Topography near the WKY tower. Note locations of the main tower, surface station tower, transmitter building, and gulley, all discussed in the text. The sloping line west of the arrow labelled "WKY TV Tower" is a catwalk, pictured in part in Figure 8. Contours are at intervals of 5 ft. (b) Portions of quadrangle charts showing topography within a few miles of the WKY transmitter tower.

WIND CLIMATOLOGY OF OKLAHOMA CITY

MEASUREMENTS OF WIND AT WILL ROGERS WORLD AIRPORT

Meteorological observations and climatological records were begun at downtown Oklahoma City in 1890, but early data were influenced by buildings in the downtown area, forcing relocations of the station. A weather station was established in 1932 at Will Rogers Field, now Will Rogers World Airport, and there were dual observations of some parameters until offices were consolidated at the Airport in 1954.

The airport anemometer was at first 70 ft above ground, on the Airport Administration Building. In 1954 it was relocated to a height of 55 ft above ground on top of Page Hangar #3, and in 1965 it was relocated to its present site atop a 20-ft tower on the ground about 1 mile south of the Page Hangar. The present location and the location of Page Hangar #3 are shown in Figure 7.

Some of the early Oklahoma City data appear to have been lost, but monthly and annual climatological summaries are available^(a) that indicate the average wind speed at the airport locations by months beginning with 1949. Thus, monthly climatological data provide mean monthly wind speeds at a height 70 ft above ground at Will Rogers World Airport for the 5-year period 1949 through 1953, and subsequent annual summaries provide monthly averages for the other anemometer locations at Will Rogers World Airport. Average monthly and annual data for the 5-year periods 1949 through 1953, 1960 through 1964, and 1981 through 1985 are presented in Table 3 and Figure 10.

We note that recent issues of annual climatological data for Oklahoma City (and other locations) present annual averages based on 30-year periods. Thus, for example, recent issues present the wind climatology as averages for the period 1941 through 1970 (most recently, 1951 through 1980). But, as noted above, the anemometer at Oklahoma City was at three different altitudes above ground during these periods, and as Table 3 and Figure 10 show, the wind is substantially stronger at the higher altitudes. A significant error

(a) From the National Oceanic and Atmospheric Administration (NOAA), Environmental Data and Information Service, National Climatic Data Center, Asheville, North Carolina 28801.

TABLE 3. Wind Observations at Will Rogers World Airport, Oklahoma City

	Averages in Miles Per Hour												
	<u>J</u>	<u>F</u>	<u>M</u>	<u>A</u>	<u>M</u>	<u>J</u>	<u>J</u>	<u>A</u>	<u>S</u>	<u>O</u>	<u>N</u>	<u>D</u>	<u>Annual</u>
<u>1949 Through 1953, 70 ft Above Ground on Airport Administration Building</u>													
Avg. Wind	16.4	15.4	17.5	17.0	15.5	15.8	12.5	11.4	12.7	13.7	14.3	15.1	14.8
St. Dev. of Average	0.5	0.7	0.6	1.3	0.4	0.7	0.6	0.9	0.7	0.6	0.4	0.8	0.3
Max. for any month:	20.2, April 1951												
Min. for any month:	8.8, August 1950												
<u>1960 Through 1964, 55 ft Above Ground on Page Hanger #3</u>													
Avg. Wind	13.2	13.9	15.2	15.3	14.6	12.3	11.8	11.6	11.0	12.0	12.6	12.4	13.0
St. Dev. of Average	0.5	0.3	0.5	0.6	0.6	0.4	0.3	0.5	0.6	0.4	0.3	0.3	0.1
Max. for any month:	16.4, May 1962 and April 1963												
Min. for any month:	9.9, September 1963												
<u>1981 Through 1985, 20 ft Above Ground on Tower 1 Mile South of Page Hanger #3</u>													
Avg. Wind	11.6	12.2	12.5	13.0	11.2	10.6	9.5	9.7	11.3	11.2	11.9	11.4	11.4
St. Dev. of Average	0.6	0.4	0.2	0.4	0.3	0.5	0.2	0.5	0.5	0.5	0.4	0.4	0.1
Max. for any month:	13.7, January 1982												
Min. for any month:	8.2, August 1983

FIGURE 10. Average Wind Speeds by Month at Will Rogers World Airport, for Selected 5-Year Periods When the Anemometer was at Different Heights

would be made if the presented wind averages were taken as representative of the 20-ft current anemometer altitude and then extrapolated to a greater height for purposes of estimating the generating potential of a wind machine at the greater altitude. Thus, some annual summaries for Oklahoma City show the average annual wind speed to be 12.7 mph, while Table 3 shows that the average for the 1981 through 1985 period when the anemometer was uniformly at the altitude 20 ft above ground was 11.4 mph. It seems that Table 3 and Figure 10 offer a better basis than the annual climatological summary for estimating the wind at Oklahoma City near the altitudes shown.

Because the power of the wind is proportional to the cube of the speed, most of the potential for wind power conversion resides in speeds faster than the average speed, and the shape of the wind speed distribution figures importantly in the design of devices for wind power conversion. The distribution of wind speed derived from 2920 3-hourly observations made during 1983 from the 20-ft tower at Will Rogers World Airport is illustrated in Figure 11. The figure shows the raw distribution of speeds reported at intervals of 3 hours. The observations are of 1-minute average speeds, as presented in units of knots in NOAA's monthly summary of local climatological data. The scale in statute miles per hour has been supplied by multiplying the values in knots by 1.1516.

FIGURE 11. Distribution of 2920 3-hourly Observations of Wind Speed Made at Will Rogers World Airport During 1983. The pattern factor $\bar{V^3} / \bar{V}^3$ is 1.775. The average wind speed is 9.524 knots or 10.968 mph. The root mean cube wind speed is 11.53 knots or 13.277 mph. The units of the raw data are knots.

Notice in Figure 11 that there seems to be a slight bias toward reports at multiples of 5 knots. Notice also that although Oklahoma City is actually a comparatively windy place among U.S. cities, only 8 out of the 2920 observations from 20 ft above the ground are reported as 30 knots or higher. Since these averages are associated with peaks and lulls^(a), we have sought more direct information by developing the distribution of "fastest mile" shown in

(a) The width of the wind speed distribution near the ground is typically 0.2 to 0.4 of the short period average speed. See Crawford and Hudson (1970) and Barclay and Wilk (1970).

Figure 12. The fastest mile values are presented in NOAA's local climatological data for each day of the year. Only 7 of 365 reports exceed 30 mph.

Finally, in Figure 13, we present the cumulative distribution of wind power, as derived from the same data presented in Figure 11. Notice that 85% of the power resides in speeds faster than the average speed. About 80% of the wind power is represented in speeds from 10 to 25 mph, 70% between 11 and 21 mph. The median power wind speed is 14.7 knots, 16.9 mph. Only about 3% reside in speeds faster than 30 mph.

WIND DATA FROM THE TALL TRANSMITTER TOWER

Observations of wind speed at six levels on the tall tower of WKY-TV and at the adjacent surface station were recorded by NSSL staff during more than 99% of the hours from June 1, 1966, through May 31, 1967 (Crawford and Hudson 1970). The average speed by months at the surface station is shown in Figure 14. The annual average speed at the WKY 23-ft tower was 8.1 knots (9.3 mph). Since, as shown further in the section immediately following this one, the Will Rogers average during that observational year was about 0.5 mph less than the long period (5-year) average shown in Table 3, we estimate the long period average 23-ft wind at the WKY tower to be about 9.8 mph.

COMPARISON OF DATA FROM WILL ROGERS WORLD AIRPORT AND THE WKY SITE

The WKY wind of 9.3 mph was significantly less than the average 10.9 mph recorded on the 20-ft tower at Will Rogers World Airport during the same period. The Will Rogers data are also shown by months in Figure 14. Furthermore, the average wind at the 146-ft level on the tall tower during this same period was 11.3 knots, or 13.0 mph, only about 0.5 mph faster than we expect the 55-ft wind to have been reported from Will Rogers, had measurements at that altitude been continued there (cf. 5-year average for 55-ft altitude at Oklahoma City in Table 3). Thus, the average wind speed at the well-exposed 146-ft level at WKY seems nearly the same as the average wind speed at an altitude of only 55 ft at Will Rogers World Airport. Why isn't the WKY wind appreciably stronger?

FIGURE 12. Distribution of 365 Daily Magnitudes of "Fastest Mile" Reported from Will Rogers World Airport During 1983. The absence of reports at 19 mph is a result of conversion of units, as discussed by Lockhart (1979).

FIGURE 13. Cumulative Distribution of Power in the Wind, i.e., the Cumulative Product of the Number of Observations at Each Speed with the Cube of the Speed, Based on the Data Presented in Figure 11. The median power wind speed is 14.7 kts or 16.9 mph.

FIGURE 14. Average Wind Speeds by Month on the 23-ft Tower of the Surface Station at WKY-TV, and on the 20-ft Tower at Will Rogers World Airport, Both During June 1, 1966, Through May 31, 1967 (after Crawford and Hudson 1970). Lines are labeled with annual averages.

Crawford and Hudson propose that the difference between Will Rogers and WKY speeds may arise from effects of local terrain or from effects of the built-up part of Oklahoma City, which considerably lies between the two sites, approximately 6 miles south of the WKY tower. We tend to discount these possibilities, for three reasons. First, the wind speed difference has the same sign and similar magnitude in all months--in nearly half the months, south winds predominated, but during the other half, northerly components were prominent. If the city were influencing the wind speed at WKY, one would expect to see a stronger effect during the warm season when the winds almost always have a southerly component. Secondly, the terrain has rather small slopes except in very limited gullies, is nearly treeless, and meets the criteria for flatness quoted by Wegley et al. (1980, p. 71). Third, we observe Geiger's (1957) indication that an effect of windbreaks extends downwind to a distance 25 to 35 times the height of the windbreak. While it is hardly clear that this relationship would scale to the height of tall buildings, we note that the height of the tallest building in downtown Oklahoma City today is about

500 ft^(a), and 35 times this distance is just 3.3 miles. It seems unlikely that a significant effect would be observed twice this far, although further information on this point should be sought.

Another explanation for the difference between wind speeds at WKY/KTVY and at Will Rogers World Airport is suggested by their difference in MSL altitudes. The top of the 23-ft tower at WKY is 117 ft lower with respect to MSL than the top of the 20-ft tower at Will Rogers, and altitude of 146 ft on the WKY tower is actually 46 ft lower with respect to MSL than an altitude of 55 ft above ground on Page Hangar #3, where the 55-ft data base was acquired.^(b) Weaker winds at WKY may reflect a positive correlation between boundary layer winds and terrain altitude. Such a conclusion is supported by additional data presented in following sections of this report.

-
- (a) The Liberty National Bank Building, completed in August 1971, is approximately 500 ft high (36 stories). During 1966 and 1967, the tallest buildings in Oklahoma City were 400 to 450 ft high.
 - (b) This altitude difference between Will Rogers World Airport and KTVY is not at all apparent to the driver or passengers in a car passing through Oklahoma City, nor to passengers on aircraft approaching or flying by the Airport, but it is plainly indicated on topographic maps.

WINDS AT GREAT PLAINS APIARIES
AND WILL ROGERS WORLD AIRPORT COMPARED

DATA AND ANALYSIS

Anemometers were calibrated and installed at 32 ft and 93 ft on the wind power generator tower at GPA on April 3, 1981. When a section was added to the tower during the last week of February 1982, to increase its height, the anemometer at 53 ft was moved to 93 ft. The numerical uncertainty of calibrated anemometers is about 1 mph plus 5% of the speed (Mazzarella 1986). Below 4 mph, there is an inaccuracy related to an immobility of the anemometer--the starting speed is nominally 2 mph, but sometimes it must be as much as 3 or even 4 mph, because during several months of 1983, no entries of 1, 2, or 3 knots were recorded in NOAA's local climatological data. The anemometers at GPA are the same type used by NWS and in the NSSL mesonetwork generally; they are designated F420C wind transmitters.

During selected periods, the anemometric data were transmitted to the digital processor and tape recorder at the adjacent NSSL surface station, where wind data from 20, 32, and 93 ft were then recorded on the same magnetic tape^(a), and later printed to show average values for each hour. For certain dates during May, September, and December 1982, and January 1983, winds at the different tower heights at GPA were tabulated at the eight 3-hour intervals starting at 00 CST. Wind data for the same 3-hour intervals were extracted from NOAA's monthly summary of local climatological data for Oklahoma City. The data were then averaged for those days that were judged to have been uninfluenced by thunderstorms or other significant disturbances on a scale apt to produce systematic differences between the winds at Will Rogers World Airport and Great Plains Apiaries, which are 28 miles apart. The results of this work are indicated in Figures 15, 16, and 17, and in Table 4.

(a) This procedure produced considerable difficulty. The surface station is powered by solar cells and is thereby normally isolated from external sources of interference. It is, therefore, rarely damaged by electrical surges, even during severe thunderstorms. This situation was altered substantially for the worse when the station was connected to conductors from the 100-ft tower.

FIGURE 15. Diurnal Variation of Average Winds at 20, 32, and 93 ft AGL at Great Plains Apiaries and at 20 ft AGL at Will Rogers World Airport, Oklahoma City, During Three Indicated Periods. At GPA, the lines representing stronger wind speeds correspond to higher altitudes. The average wind is stronger at 20 ft AGL at Will Rogers World Airport than it is at 93 ft AGL at Great Plains Apiaries.

FIGURE 16. The Average Wind Speeds at Will Rogers World Airport and at Great Plains Apiaries During the Same Three Periods Shown in Figure 15. Three additional days during December 1982 were judged to be characterized by nonuniform weather in central Oklahoma.

FIGURE 17. The Ordinate Represents the Difference in Average Winds on a 20-ft Tower at Will Rogers World Airport and at 93 ft on a 100-ft Tower at GPA. The abscissa shows the average wind speed at Will Rogers. The Will Rogers wind is almost always the stronger, but the magnitude of the difference is not shown to be related to speed.

TABLE 4. Comparison of Average Wind Speeds at Great Plains Apiaries and Will Rogers World Airport

	<u>Average Wind Speeds (statute miles per hour)</u>			
	<u>10 Days in May 1982</u>	<u>2 Days in Sept 1982</u>	<u>14 Days in Dec 1982 and Jan 1983</u>	<u>Grand Average</u>
OKC - 20 ft AGL	10.6	9.2	11.0	10.3
GPA - 100 ft AGL (extrapolated)	9.4	7.0	8.7	8.36
GPA - 93 ft	9.1	6.7	8.5	8.1
GPA - 32 ft	7.1	4.9	6.8	6.3
GPA - 20 ft	6.6	4.3	6.6	5.8

With respect to the diurnal variations shown in Figure 15, note that all the curves have practically the same shape. During nighttime hours, 2100 to 0600, the speeds are relatively low, and they are substantially higher during 0900 to 1800. The stronger winds during the winter period were confined to 0900 to 1500, relatable to the shorter period of daylight. Of course, the diurnal shapes are as expected, and the similarities within groups and the regular increase of speed with altitude are a basis for some confidence in the integrity of the data. What is, perhaps, surprising is the magnitude of the difference between the average wind at Great Plains Apiaries and Will Rogers World Airport. This is further illustrated in Table 4, which includes estimated average winds at 100-ft altitude at Great Plains Apiaries, produced by extrapolation with the gradient between 32 ft and 93 ft AGL. It appears that the wind at the height 20 ft AGL at Will Rogers is about 2 mph stronger, on the average, than the wind at height 100 ft AGL at Great Plains Apiaries.

The data from Will Rogers and from the 93-ft level at GPA used in Figure 15, plus data from three other days, have been averaged by 24-hour periods starting at 00CST and are illustrated in Figure 16. It appears that the difference in speed is independent of the speed. During only 2 of 39 days was the average wind at 93 ft at Great Plains Apiaries indicated as faster (very slightly) than the wind at 20 ft AGL at Will Rogers.

In order to try to be sure that the average difference in wind speed between Will Rogers and GPA is unrelated to the magnitude of the speed, Figure 17 was prepared. This figure shows the average difference and the average speed on each day represented in Figure 15 and Table 4. The variations do not exhibit a systematic trend or pattern. Similarly, to determine if the speed differences are related to local time, Figure 18 was prepared. We see that if there is a relationship to time of day, our data are inadequate to establish its nature with any clarity. Finally, we looked for a possible relationship between wind direction and speed differences, but found only apparent random variability. Most of the winds during May and September were southeasterly, and during December and January, the wind was from the northwest on most dates.

The most important result of this analysis is that the average wind speed at a height of 100 ft at Great Plains Apiaries is about 2 mph less than the average wind speed on a 20-ft tower at Will Rogers World Airport. The data gathered may be too limited and crude to establish whether the magnitude of the wind difference at any moment is systematically related to the magnitude of the wind itself, to wind direction, or to time of day.

During the periods examined in detail, the average 100-ft wind at GPA was 8.3 mph, while it was 10.3 mph on the 20-ft tower at Will Rogers World Airport. Since the long-term average on the Will Rogers tower is 11.4 mph, we estimate the long-term average at 100 ft at GPA to be near 9.4 mph. The difference between GPA and Will Rogers is very significant for generation of electrical power from the wind--an increase of 2 mph near 10 mph represents an 80% increase of wind power. Furthermore, given the statistics of Table 3, we might conclude that a wind power converter at a height of 70 ft at Will Rogers could generate nearly four times more power than the same machine would generate on the 100-ft GPA tower!^(a)

(a) This assumes that at both sites the average wind power, proportional to $\bar{V}^3$, is the same multiple of the power of the average wind $\bar{V}$, and that the power inherent in the different wind speeds is converted with the same efficiency. Of course, neither assumption is quite correct, but the relationship serves to underscore the importance of selecting a windy site for a wind machine. A more detailed evaluation is presented in the section immediately following this one.

FIGURE 18. The Magnitude of the Average Difference Between Will Rogers Winds and GPA 93-ft Winds, in Relation to Time of Day. No trend is apparent.

DISCUSSION OF RESULTS AND SEARCH FOR EXPLANATION

Wind directions during the periods of test were predominantly from the southeast (May and September) or from the northwest (December and January). In both directions from the Great Plains Apiaries tower, the terrain rises approximately 100 ft in a distance of 1 mile (see Figure 2). The average slope in these directions is thus near 2%. The steepest slope is toward the north, 80 ft in 0.5 mile, or just 3%; slopes as great as 5% are very localized. The maximum and minimum elevation in Figure 2 are 1210 and 1020 ft, and the maximum and minimum elevations within 10 miles are 1310 and 950 ft. The Great Plains Apiaries site thus comfortably meets criteria for flat terrain quoted from Wegley et al. (1980, p. 71):

Terrain can be considered flat if it meets the following conditions; however, these conditions are very conservative...

1. the elevation difference between the site and the surrounding terrain is less than 200 ft for 2 to 3 miles in any direction;
2. the ratio h/l in Figure 4 [Figure 19 in the present document] is less than 0.03 (that is, a 3% grade).....

h = largest difference of terrain

l = length over which largest difference of terrain occurs

FIGURE 19. Determination of Flat Terrain [after Frost and Nowak (1977), Presented by Wegley et al. (1980)]

Clearly, however, the wind speeds at Great Plains Apiaries are substantially less than indicated by climatological data based on observations at Will Rogers Airport, just 28 miles to the north, with no notable topographic feature between the two sites. Both sites are on a rolling, gently tilted plain. What is going on here?

We propose that in addition to local effects of topography, obstructions, and surface roughness treated by Wegley et al. (1980), and by others in the abundant literature on wind power, there is a generalized Bernoulli effect, in central Oklahoma at least, resulting from changes in altitude. Thus, the boundary layer is squeezed or expanded vertically as it moves horizontally over sloping terrain--we propose that the effect is strongest near earth's surface and diminishes with height. In order to illustrate the process, which is analogous in effects to a hill or variation in diameter of a pipe, or variations in the depth or width of a stream, we present Figure 20. Here are plotted the normalized average data from Great Plains Apiaries, the WKY site, and Will Rogers World Airport along a line sloping to represent terrain altitude. Isopleths show observed average wind speed, normalized with respect to the long-term averages at Oklahoma City. Thus the GPA data are presented as the observations at GPA summed with 1.1 mph, which is the difference between the Will Rogers wind at 20 ft during the observational period at GPA and the

FIGURE 20. The Average Wind Speed on Various Towers in the Oklahoma City Area have been Calculated and Inferred from Measurements and are here Plotted at Their Respective Altitudes MSL. Wind variations are consistent with the hypothesis that the thickness of the boundary layer is inversely related to terrain height. The heavy sloping lines represent the ground plane and an upper substantial surface marking the boundary of an hypothesized layer in which the horizontal flux of mass is conserved.

long period (5-year) 20-ft average at Will Rogers airport. Similarly, the WKY averages during the 1966-67 period of continuous observations there have been raised by 0.4 mph as discussed in the section on wind data from the tall transmitter tower.

The average speed multiplied by the unit depth at various points on the diagram is proportional to the mean flux of air through the depth. Since there is no significant accumulation of air at any point along the model trajectories, the total flux must be equal at all points along the path. The data indicate that the air in a depth of 100 ft at the 1150-ft elevation of the WKY tower occupies a layer approximately 130 ft deep at the 1085-ft

elevation of GPA, and an 83-ft depth at the 1285-ft altitude of the Will Rogers Airport site. In other words, a layer 130 ft deep is modeled to contract 47 ft as it moves over terrain that rises 200 ft MSL. Apart from hydrostatic pressure variations associated with the various elevations, the horizontal pressure changes would be about 0.05 mb with a 2 mph speed change when the average wind speed is about 10 mph.

Of course, in our attempt to illustrate a plausible mechanism for the systematic wind variations, we have omitted many known influencing factors--rather than iterate possibilities here, we leave this to a future study, and perhaps to others better practiced in boundary layer theory. It is important to note, however, that the inviscid theory invoked here implies a decrement of wind speed at lower elevations (MSL) that is larger in proportion to the wind speed. In other words, lower elevation implies a larger channel for the flow, which would slow down in proportion to its speed. Although such an effect is not detected in our data, we cannot dismiss the possibility that the theory has merit, because our data display much random variability and are narrowly based. If further study of the proposed mechanism is undertaken, early objectives must include identification of sources of variance in the wind speed differences between sites and melding of analysis of a more detailed and precise data base with sound theory.

Finally, we emphasize that we are proposing an important effect on wind of a factor distinct from local obstructions, surface roughness or friction, local topographic features, and thermal wind. Thus, we would expect wind speeds at GPA to be influenced toward significantly lower values than those at Will Rogers World Airport even if the GPA site were on either a perfectly level or uniformly tilted grassy plain at an elevation of 1085 MSL. Indeed, the WKY tower site is a very nearly level grassy plain, with nearest buildings (except for the transmitter building) only one story in height and scattered about a mile away, and the wind speed there is significantly less than at Will Rogers World Airport.

SPECIFICATIONS AND OPERATING CHARACTERISTICS OF THE WIND POWER CONVERTER

The BWC 1000-S wind energy converter was used at all three wind power sites considered here, as listed in Table 1. According to the manufacturer, this machine starts generating electricity at 9.0 mph, produces 1 kW of electrical power at 24.5 mph, and turns out of the wind (furls) at 30 mph. During normal operation, its three blades point into the wind; the rotor diameter is 9.2 ft, and the machine weighs 134 lb. Direct current is obtained by rectification of the output of a permanent magnet alternator driven directly by the rotor; it is converted and matched to 115-V alternating current, 60 Hz, by a synchronous inverter denoted Powersync®. The rotor blades bear off-axis forward-projecting weights (Powerflex® System) that twist the fiberglass blades toward smaller pitch angle at higher rotation rates in order to combine aerodynamic efficiency in strong wind with large starting torque.

Engineer John Carter of the National Severe Storms Laboratory designed and built a sensor^(a) which causes the pen of an Esterline Angus recorder to register in relation to the power generated by the BWC 1000-S. Figure 21 shows this relationship as reported by Mr. Carter, in cooperation with the Bergey Windpower Company.

In order to measure the power of the BWC 1000-S in relation to wind speed, and also to measure the winds and their fluctuations with some precision, three Esterline-Angus strip chart recorders were installed near the inverter in a garage at Great Plains Apiaries (Figure 22a). One of the recorders measured the output of the BWC 1000-S, and the other two recorded the wind speed at two levels on the wind power generator tower. These recorders are adjacent to the inverter and to the meter installed by the Rural Electric Cooperative (REC) to monitor power production from the wind machine. The REC also installed a ratcheted meter where the utility lines first enter GPA, in order to monitor power flows into and out of the premises (Figure 22b). The

(a) The sensor is a probe for electrical current that operates on the basis of the Hall Effect.

® Trademark of the Bergey Windpower Company, Norman, Oklahoma.

FIGURE 21. Esterline-Angus Pen Deflection on Charts Shown in Figures 23 and 27 ff. vs. Wind Generator Power Before the Inverter

FIGURE 22. Equipment Recording the Power Generated by the BWC Machines at GPA. (a) Esterline-Angus recorders in a garage at Great Plains Apiaries. The Powersync inverter is at upper left, and the Hall Effect current probe designed by John Carter hangs from the lower surface of the inverter box. Below the inverter is a switch box to control the machine's connection to the utility line, and an electric meter which indicates net power out of the inverter. (b) Ratcheted and unratcheted meters where lines of the Rural Electric Cooperative enter GPA. The difference between the readings of these meters measures the flow of power off the premises, i.e., into the REC network.

servicing utility provided similar watt-hour meter installations at the other WECS sites.

Figure 23 shows a portion of strip chart data collected on November 11, 1982, when there was a substantial wind. In order to track variations of wind and generator output on the temporal scale of seconds, the recorders connected with the wind power generator and with the anemometer at 93 ft on the tower were both placed in the fast drive mode, wherein successive vertical arcs on the chart represent increments of approximately 4 s. The charts are not electrically or mechanically synchronized with each other, and they run at slightly different speeds, but it was practical to synchronize them manually while giving close attention to both during their travel. The maximum asynchronism is estimated to be about one-half of the space between successive vertical arcs. Figure 23 depicts a period of about 3 min from high-speed recordings made during 15 min.

Note the area marked "A" in Figure 23. This shows that larger amounts of power were produced with faster winds when the speed was less than 26 knots (30 mph). The region marked "B" is one of those that illustrates furling and marked power reduction with wind speed above 26 knots.

Significant points at corresponding times on both curves were marked and the matching values tabulated. Similar records were acquired and analyzed on five other days, as noted in Figure 24, which presents a plot of power from the converter in relation to wind speed. Part of the scatter in Figure 24 is attributable to errors of 1 mph or so in defining the wind at the same moment that the power is read, but a substantial part of the scatter corresponds to the fact that the power generated at any moment depends on the wind velocity history during the preceding few seconds, as well as on the current magnitude of the speed.

In Figure 24, the heavy curve is based on data supplied by Mr. Jim Frazier of Bergey Windpower Company, on July 20, 1984. According to Table 4, we should add 0.3 mph to our winds to account for the probable average difference in speed between 93 ft and the 100-ft height of the rotor, but even with this adjustment, the BWC estimates appear to be conservative ratings for the BWC 1000-S.

FIGURE 23. Simultaneous Records of Wind Speed at 93 ft (above) and Electrical Power Before the Inverter (below) Produced by a BWC 1000-S Machine at 100 ft on the Same Tower, November 11, 1982. The interval between vertical arcs is very nearly 4 s. In the area marked "A", where the maximum speed is indicated as 26 knots (30 mph), power production is larger with stronger winds. During the period marked "B", furling occurred as the wind speed exceeded 26 knots. The area marked "C" shows an oscillatory furling of the machine, with a period of about 15 s, which may occur while the wind speed is rather steady between 26 and 30 knots (30 and 35 mph). Both the power generated and the wind speed are closely proportional to the deflections on the respective charts. The ratio of the maximum to the average power is substantially larger than the ratio of maximum to average wind speed because wind power is proportional to the cube of the wind speed.

FIGURE 24. Power vs. Wind Speed Based on Simultaneous Measurements on 6 Days. The vertical array of dots centered about 30 mph represents various degrees of furling. The heavy line represents calibration data developed by the Bergey Windpower Company.

Note in Figure 24 that some power is generated at wind speeds less than the 9-mph startup speed. This reflects the fact that the rotor, once started, continues to turn at speeds somewhat less than 9 mph.

The data given provide a basis for calculating the efficiency with which the BWC 1000-S converts wind power to electrical power. Since the rotor diameter is 9.2 ft (2.8 m), its cross-sectional area in m^2 is 6.16, and the wind power in watts in this area is $0.5 \times \rho \times 6.16$ with ρ in kg/m^3 and V in m s^{-1} (see also Appendix B). In the calculations presented in Table 5 and graphed in Figure 25, we have taken $\rho = 1.15 \text{ kg}/\text{m}^3$, which corresponds closely to usual values in central Oklahoma, and we have adjusted the center of gravity of dots in Figure 23 by about 0.3 mph. The values may then be compared with 0.593, the conversion efficiency of an ideal rotor. The measured electrical power values before the inverter are reduced about 8% by conversion of direct to alternating current in the inverter.

TABLE 5. Conversion Efficiency of the BWC 1000-S

Wind Speed at the 93-ft Anemometer	Wind Speed at the Generator		Wind Power in Watts ₂ in 6.16 m ²	BWC 1000-S Output (watts) (Figure 24)	Conversion Efficiency (%)
	(mph)	(m s ⁻¹)			
9.7	10	4.46	314	60	19
14.7	15	6.70	1065	340	32
17.2	17.5	7.82	1694	520	31
19.7	20	8.92	2513	750	30
24.7	25	11.16	4923	1060	22
29.7	30	13.39	8503	500	6
34.7	35	15.63	13525	250	2
39.7	40	17.86	20179	350	2

FIGURE 25. Efficiency with which Wind Energy is Converted to Electrical Energy by the BWC 1000-S, Drawn from the Data in Table 5

ESTIMATION OF THE ANNUAL OUTPUT OF THE BWC 1000-S

We can apply Figure 25 with a distribution of annual wind speed to estimate the annual energy production of the wind energy converter.

As illustrated in Figure 11, the wind speed distribution at Will Rogers World Airport during 1983 had a pattern factor ($\bar{V}^3/\bar{V}^3$) of 1.775. As shown in Appendix C, the Will Rogers distribution is closely approximated by a Weibull distribution with the same pattern factor. As discussed by Justus (1986), it has been common practice to use the Weibull distribution with pattern factor 1.91 (Rayleigh distribution) to estimate wind power availability, and we have only modified this to the extent of applying the Weibull distribution with pattern factor 1.775.

The results of our calculations over a range of average wind speeds from zero to 10 m s^{-1} are shown in Figure 26, which illustrates a remarkable range of expected electrical energy. Thus, we estimate that the machine at GPA at 100-ft altitude would produce only about 1000 kWh per year (perhaps only 920 after adjustment for losses in the inverter), while a machine on a 70-ft tower at Will Rogers World Airport would produce three times as much energy. The estimate for GPA receives excellent confirmation in data summarized in the section on annual wind energy conversion at GPA in this report.

The estimated overall efficiency of the BWC 1000-S machine is also illustrated in Figure 26. The machine is a relatively efficient converter in the range of annual average wind speed from $3 \text{ to } 7 \text{ m s}^{-1}$ (7 to 16 mph). At faster average speeds, it seems that a modification in machine design would be appropriate, in order to take better advantage of the considerable power then resident in speeds up to $15 \text{ or } 20 \text{ m s}^{-1}$ (35 to 45 mph).

FIGURE 26. Expected Annual Output of the BWC 1000-S in Relation to Average Annual Wind Speed, with Reference to Some Locations in and Near Oklahoma City. The overall efficiency is the ratio of the expected energy output to the total annual energy in a Weibull distribution with the same average speed, a pattern factor of 1.775, and an air density of 1.15 kg m^{-3} . The Chartock and Will Rogers 100-ft estimates involve data in Table 9. WRWA in the figure denotes Will Rogers World Airport.

SOME FEATURES OF WIND POWER PRODUCTION AT THREE WIND POWER GENERATOR SITES

SHORT PERIOD CHARACTERISTICS

Power Output at GPA in Relation to Wind at the Site

We here illustrate various wind regimes and characteristics of wind turbine performance. Although such data are presented elsewhere in a considerable literature (Pacific Northwest Laboratory 1986), the following discussion serves to document the data base of the present study and characteristics of the BWC 1000-S.

The output of the wind machine is a strong function of the wind speed at moderate speeds, especially between 10 and 20 mph, and is significantly modified by furling characteristics of the machine in winds stronger than 25 mph. The machine starts from rest in a wind of about 9 mph, but once started, it continues to turn and to generate power down to wind speeds of about 6 mph. Thus, except for a damping of wind fluctuations faster than about 5 s by rotor inertia, the output of the wind machine is somewhat more variable and episodic than the wind itself.

Figures 27 through 31 illustrate power generation in a variety of wind conditions. Successive vertical trending arcs on the strip chart mark 5-min increments.

In Figure 27, the rotor was stationary and the wind speed was below the machine's starting threshold of about 9 mph (8 knots) on October 15, 1984, until it crossed that threshold at 0155 CST. Then the machine started, the power rose abruptly, and subsequently the power fluctuated with the wind.

In Figure 28, the machine is shown to continue generating power as the wind diminished below the starting threshold on October 19, 1984. The rotor finally became stationary when the indicated wind speed declined below 6 knots.

In Figure 29, we illustrate power generation during irregular, light-to-moderate winds. The rotor started at 0443 when the wind speed is indicated to have attained 10 knots, somewhat faster than the nominal starting speed. At 0615, it stopped when the wind speed declined to 6 knots. It started a

FIGURE 27. Esterline-Angus Strip Chart Records of Wind Speed and of Power from the BWC 1000-S at GPA. The rotor at 100 ft AGL started turning when the wind speed at 32 ft increased above 8 knots at 0155 CST. Add approximately 2.5 min (one-half division) to the wind chart to have it synchronous with the generator chart.

FIGURE 28. Power Generation Continued on October 19, 1984, Until the Wind Speed Declined Below 6 Knots at 0235. Add about 7 min (1.5 divisions) to the wind chart to have it synchronous with the generator chart.

FIGURE 29. Illustration of Slight Irregularities in Rotor Starting and Stopping, and Temporal Variability of the Wind Speed, Discussed in the Text

FIGURE 30. Illustration of the Nature of the Generator Output in Strong Winds, and of the Reduction of Power Output With Furling in Rare Winds of Gale Force. Further discussion is in the text.

FIGURE 31. Illustration of Some Irregularities in the Anemometers, Large Relatively Stable Electrical Output When Winds are Relatively Steady and Optimally Strong, and Safety Features of the Wind Power Converter. See text for further discussion.

second time as the wind increased past 7 knots, and thereafter continued to rotate, albeit slowly, through several indicated wind declines below 7 knots.

Note in Figure 29 the rather prominent wind power variations on scales from a few minutes to 10 or 20. The time scale of the fluctuations and the average wind speed of about 10 knots suggest that the fluctuations are distributed on Earth at distances of a few miles. Thus, the output of generators spaced several miles apart would show little correlation, and the short period fluctuating component of the array output would be a substantially smaller proportion of the whole than is the fluctuating component from a single machine.

Figure 30 illustrates the nature of the output of the BWC 1000-S in unusually strong winds. From 1200 to 1530 on October 16, 1984, wind speeds averaged above 25 knots (near 30 mph), and there were occasional periods up to 10 minutes long when the wind averaged well above 30 knots. The peak gust indicated is 45 knots (52 mph). During such winds, the wind energy converter is furled more than half the time, and power production is reduced accordingly. We crudely estimate the average deflection of the generator chart to be 25 units during this period--this corresponds to an average power output of 420 W, according to Figure 20. After 1530, the average wind speed declined to about 19 knots, but the average deflection increased to about 32 units, or 600 W according to Figure 20. During the latter period, owing to substantial excursions of the instantaneous wind, the power output was still reduced by furling. Note that the largest mean deflection, about 45 units, more than 800 W, occurred around 1530, when the average speed declined to about 18 knots (21 mph) for about 5 min.

Finally, in Figure 31, we illustrate a variety of features associated with intense weather systems during the evening of April 21, 1985.^(a) The two wind charts agree in time, and the generator record must be retarded approximately 1 min (one-fifth division) to have it synchronous with the others. Notice first that the lower anemometer records greater speeds than the upper anemometer around 2000 CST, when the magnitudes are quite small, but this behavior is not repeated near midnight with similarly low values. Since it seems very unlikely that the wind speed at 93 ft AGL would be smaller than that at 32 ft for as long as the 15-min period indicated, we assume that the exercise administered to the anemometers by strong winds between 2100 and 2200 changed the characteristics of one or both. The wind increased sharply from 15 knots at the upper level at 2112, and a peak gust of 45 knots is recorded at 93 ft at 2122. The strong winds appear more turbulent at 32 ft than at 93 ft, as measured by the width of their envelope, but the range of their short period fluctuations is markedly smaller than in the case illustrated in Figure 29. We suppose that this smaller range associates with a

(a) Records at Great Plains Apiaries show that only 0.10" of precipitation fell that night, but the wind record indicates that there were strong local disturbances and perhaps thunderstorms in the vicinity.

markedly stable nocturnal boundary layer, perhaps originating in cool thunderstorm downdrafts.

We deduce further from the wind record in Figure 31 that the strong wind fluctuated at a faster pace than the wind on October 16, 1984, though the former fluctuated in a narrower range. It is interesting also, though perhaps not very consequential, that the wind machine apparently furled and unfurled with considerable frequency during several minutes when the wind speed was continuously well above the level at which furling is induced. Another interesting feature in the generator record appears around 2130 CST, when the power output fluctuated only between the large values 660 and 1280 W for several minutes. Thus, furling did not occur during this period, and we see that when the wind is relatively steady at an optimally large value, relatively steady large outputs are obtained. Thus, the data indicate that more power is produced when strong winds are less turbulent.

Finally, note outages at 2136 and 2153, lasting approximately 2 and 7 min, respectively. The BWC wind energy converter has safety features that produce disconnection when power generation exceeds the rate that can be properly handled by the inverter, and, more importantly, when line power is lost. It seems likely that these two outages were related to the latter condition, which might have been caused by strong winds blowing power lines into contact with each other or by effects of lightning strikes to ground. Once the wind energy system disconnects from the utility line, reconnection is not made until line power is present and the rotor has slowed sufficiently to avoid the placement of a large transient on the line.

We note that situations such as those presented above could be somewhat assessed statistically with data of the types presented by Crawford and Hudson (1970) and Elliott (1984).

Average Power Output at GPA in Relation to Three-Hourly Wind Data at Will Rogers World Airport

Beginning on Sunday, October 3, 1982, a diligent effort was made to read frequently the watt-hour meter that registers the cumulative energy provided by the wind machine after the inverter. Frequent readings, sometimes several in a day during periods of strong and variable winds, continued through March

1983. Average rates of power production were calculated by dividing the difference between successive meter readings by the difference in time between them. Three-hourly wind readings at Will Rogers, tabulated in NOAA's local climatological data, were then averaged in groups corresponding to the intervals between meter readings. For example, 3-hourly readings at 1200 and 1500 CST would be averaged for comparison with power produced between 0930 and 1545 CST. Three-hourly winds at 0900 and 1800 would be linked with meter readings prior to and subsequent to, respectively, the readings at 0930 and 1545. Of course, considerable scatter is expected to associate with data so imperfectly matched.

Figure 32 presents our tabulations as a scatter diagram. The two calibrations shown are taken from Figure 24 and Table 5. The data show strongly an extension of the difference between the BWC calibration and the centroid of data in Figure 24--in other words, the wind power generator appears to produce substantially more power at slow wind speeds than is predicted by either the Bergey Windpower Company or Carter-Frazier calibrations, and substantially less power at the higher wind speeds. A little reflection suggests an explanation, though perhaps only a partial one. The average winds are defined by discrete measurements numbering from two to eight. The individual values typically vary over a range of a factor of two. Thus, the average wind power is significantly larger than the power of the average wind. The difference is amplified a little more by the envelope of the short-period average. This might explain the tendency for points to lie above the calibration curves in the low speed area of the scatter diagram. In the area of strong wind speeds, it may be that the furling process associated with strong wind gusts reduces the average power delivered by the machine. It seems that further study of this, in order to be definitive, must be based in analysis of the fluctuating wind and wind machine behavior down to the short periods illustrated in Figure 23.

FIGURE 32. Average Rate of Power Production by the BWC 1000-S at Great Plains Apiaries and Average Wind at Oklahoma City. Points represent time periods from a few hours to 24 hours in length, and from two to eight 3-hourly wind observations. Heavy lines represent calibrations shown in Figure 24.

DIURNAL CHARACTERISTICS OF WIND POWER PRODUCTION

When wind machines were installed at the Bergey and Chartock sites and at Great Plains Apiaries (see Table 1), the associated watt-hour meters were usually read daily at about 0800 by Prof. Bergey, twice daily at 0800 and 1800 by Prof. Chartock, and somewhat more frequently though irregularly at GPA. The resulting data allow several comparisons.

Prof. Chartock's readings at about 0800 and 1800 CST with the frequent readings at GPA provide for day to night comparisons of power production at both sites, as shown in Table 6. The table shows that the Chartock machine produced 72% more power 40 ft above a hillside than the GPA machine produced

TABLE 6. Generation of Energy During February 6 Through 28, 1981

<u>Site</u>	<u>Total Energy Produced (kWh)</u>	<u>Avg. Generation During 10 Daytime Hours (kWh)</u>	<u>Avg. Generation During 14 Nighttime Hours (kWh)</u>	<u>Ratio of Daytime to Nighttime Rates</u>
Chartock	88	2.17	1.65	1.83
GPA (60-ft tower)	51	1.48	0.74	2.79

during the same period on a 60-ft tower in a shallow valley. Also, the relative decline of power from day to night is much larger at the GPA valley site. The GPA data may be compared with the indications of Figures 16 and 24.

SIMILARITY OF DAILY ENERGY PRODUCTION AT THE THREE WIND POWER GENERATOR SITES AND CORRELATIONS WITH DAILY AVERAGE WIND

Figure 33 shows daily energy production at the three sites and the average 24-hr wind speed on the 20-ft tower at Will Rogers World Airport. The average winds are centered at 1200 CST, and the daily energy productions are centered at 2000, since the meters were read by all parties at 0800 each day, but not at 2400. The plotted data show strong correlation of wind energy conversion among the three wind power generator sites, and close association of energy production with daily average wind speed at Will Rogers, during February 1981. During the period illustrated, the GPA machine was on a 60-ft tower. Quantitatively, both the Chartock with Bergey and Chartock with GPA outputs are linearly correlated with a coefficient of 0.95. In Figure 34, the average output of the three sites is plotted against the average 20-ft wind speed at Will Rogers World Airport. Figures 33 and 34 indicate that daily energy production from an individual wind power generator or from an array can be fairly predictable in terms of the daily average wind. Note also that the statistical relationship suggested by Figure 32, in agreement with Figure 34, is more nearly linear than the calibration curves shown in the former illustration.

FIGURE 33. Daily Wind Converter Output at Three Locations and Daily Average Wind Speed at Oklahoma City During February 1981

FIGURE 34. The Average Daily Outputs Shown in Figure 33 are Plotted Against the Average Wind Speed at Will Rogers World Airport, Oklahoma City

ESTIMATED OUTPUT OF A MACHINE ARRAY

As shown in Figures 27 through 31, the power generated by a single BWC 1000-S is highly variable over short periods in response to gustiness of the wind. We expect that the greater inertia of larger machines would tend more to damp fluctuations at the shortest periods, but there would remain the substantial fluctuations associated with periods of minutes and more, also evident in the figures. Over any period substantially longer than the period of strong fluctuations, the generator output can be characterized by a constant average component plus a variable noisy component defined by the standard deviation $K\bar{P}$, where K is about 0.5 (for example). Imagine a number N of wind machines whose instantaneous output is uncorrelated. Then their total average output is $N\bar{P}$ and the standard deviation of the total instantaneous output is $\sqrt{N}K\bar{P}$. Thus the effect of adding additional machines is to reduce the ratio of the ripple to the steady component. If there is one machine, then the short-period excursions span a range about as large as the average power. But if there were 100 machines, the excursions would span only 5% of the 100 times larger average power. If there were 2500 machines, the ripple would be only 1% of the 2500 times larger power.

As noted, the analysis above assumes that the outputs of individual machines are uncorrelated. The truth of this assumption depends on the temporal and spatial scale of wind variations. These quantities can be evaluated from the records. For example, the diurnal variation of wind at the heights of the turbines used in this study is similar at all the sites studied here, with the wind minimum occurring at night.^(a) No matter how many ordinary wind power generators are in an array in central Oklahoma with individual components varying diurnally in the same way as those studied here, the array output will reflect the diurnal variation of wind. On the other hand, the gustiness of a turbulent boundary layer may be decorrelated within a few hundred feet. The pattern of cloud streets decorrelates on a scale of several miles, and of thunderstorms on a scale of several tens of miles.

(a) Above a height of about 200 ft at the WKY tower, the maximum average wind occurs during nighttime hours, as shown by Crawford and Hudson (1970). The height at which the phase of the diurnal wave reverses varies somewhat with location.

Suppose that favorable sites for wind energy converters were identified at intervals of 5 miles in a 15 x 15 mile area and that four wind machines were installed at the corners of a 500-ft square at each site. In typical winds, each local array would have an output whose fluctuation, as a fraction of the whole over periods of a half minute or so, is about half of that of an individual machine. The minute-by-minute fluctuations of a typical array would be further reduced by a factor of four, through effects of combination with 16 other widely spaced local arrays. Further, the fluctuation of the output of the total array over periods as long as an hour in many situations would be a factor of four less than the variation of a single four-machine local array.

With a network more extended, the short-period variations of array output would become less and less significant, but daily, weekly, and seasonal variations would remain. Even if the network were extended over the whole United States, it seems that there would be large output variations, corresponding to variable periods of extensive storminess and calm. Such variations might be reduced a little by identifying sites where winds are negatively correlated with each other.

Other approaches to the problem discussed above have, for examples, been presented by Pape (1981), Park et al. (1982), and Schlueter et al. (1983). Our simple conclusion is that fluctuations in wind power generator output on small scales need not inhibit the widespread use of wind machines to save nonrenewable fuels, but important fluctuations on large scales mean that wind power by itself cannot be substituted for base generating capacity. The latter conclusion is founded further in the observation that strong winds do not necessarily accompany periods of peak demand for electricity.^(a)

(a) Largest demand at this writing in much of the United States relates to air conditioning in summer, when winds tend to be light in most temperate regions.

HISTORY OF MONTHLY ENERGY PRODUCTION AT THE THREE SITES, AND ANALYSIS

Profs. Bergey and Chartock cooperated in this study by reading the watt-hour meters at their wind machines daily or twice daily for extended periods. A summary which shows the output of the machines by months is given as Table 7. We note that all three machines were among the earliest installed (the one at GPA was the eighth) and, as with any new technology, there were some irregularities in operation that took time to correct. Since not all irregularities were immediately known or documented, and only a few were measured, there is a contribution to uncertainty from this source, especially during the early years.

Effects of Changes of Tower Height and Propeller on Energy Production

The GPA installation was originally made with a 60-ft tower, but after a few months it was hoped that by extending the tower, there would be a more meaningful contribution to the power utilized at this site. That our hopes were realized is shown in Figure 35, where are plotted the ratios of the monthly energy production at the Chartock and GPA sites. There are 10 months when the GPA machine was 60 ft AGL, and 4 months after the GPA machine was raised to 100 ft. Notice that with the GPA tower at 60 ft, the ratio of Chartock to GPA outputs tended to be higher with smaller energies. This is consistent with our other data. The energy generated is not far from a linear function of the wind speed at speeds greater than the startup speed, but the ratio between two small numbers is larger than the ratio between two larger numbers when the difference within pairs is the same. This difference of ratios practically disappeared after the GPA tower was raised, because the performance of the two machines became very similar.

The salutary effect of increasing tower height is also clearly shown in Figure 36, where monthly energy production at GPA is plotted against monthly average speed of the wind a height of 20 ft at Will Rogers World Airport. There were three full months of observation at the greater height before a fiberglass propeller of improved configuration was provided and installed by the manufacturer in place of the original aluminum propeller. Although more data points would be nice to have, the information is convincing with respect to remarkable increases in energy production from both increased tower height and improved propeller.

TABLE 7. Energy Generated by the Wind at Three Sites, by Months, and Average Wind Speed at Will Rogers World Airport

Month	Bergey	Chartock	GPA	Okla City Average Wind (mph)
Feb. 1981	74 ^(a)	-- ^(c)	63 ^(a)	13.0
Mar.	76	113 ^(c)	76	12.4
Apr.	107	128	72	13.6
May	64	102	69	12.0
June	--	94	--	11.3
July	--	48	14	9.7
Aug.	15	25	7	9.8
Sept.	46	49	20	10.6
Oct.	64	88	42	12.4
Nov.	58	80	43	10.6
Dec.	65	89	44	10.9
Jan. 1982	--	136	72	13.7
Feb.	--	91	-- ^(d)	12.4
Mar.	--	--	99 ^(e)	13.2
Apr.	--	--	-- ^(e)	13.3
May	84	--	79	11.1
June	35 ^(b)	-- ^(b)	35 ^(b)	10.1
July	63 ^(b)	-- ^(b)	43 ^(b)	10.0
Aug.	64	--	39 ^(f)	10.4
Sept.	69	--	56	9.8
Oct.	93	--	87	9.7
Nov.	142	129	105	11.8
Dec.	116	--	96	10.7
Jan. 1983	81	93	77	10.5
Feb.	Larger Machine Installed	68	64	10.6
Mar.		134	135	12.2
Apr.		Regular Reading Discontinued	155	13.5
May			101	10.3
June			71	9.1
July			56	9.7
Aug.			30	8.2
Sept.			75	12.0
Oct.			70	10.4
Nov.			117	12.3
Dec.			80	12.6
Jan. 1984			78	11.0
Feb.		Cumulative Power at Chartock Site	107	12.8
Mar.			126	12.4
Apr.			155 ^(g)	12.9
May		Jan. 12, 1983	88 ^(g)	11.4
June		1927 kwh	19	10.9
July			28	8.7
Aug.		May 9, 1984	26	9.1
Sept.		3513 kwh	84	11.8
Oct.			62	12.1
Nov.			110	13.2
Dec.			75	12.2
Jan. 1985			63 ^(h)	12.4
Feb.			67 ^(h)	12.5
Mar.			127	12.5
Apr.			106	11.5
May			78	11.0
June			79.	11.8
July			24	9.6
Aug.			34	11.0
Sept.			78	12.5
Oct.			92	11.4
Nov.			84	11.4
Dec.			74	10.9
Jan. 1986			103	11.5
Feb.			91	13.5
Mar.			136	14.0
Apr.			110	13.6

(a) 60-ft tower, started operation Jan. 1981.

(b) Improved propellers installed at GPA July 15.

(c) 40-ft tower, started operation Feb. 5, 1981.

(d) Tower height increased to 100 ft.

(e) Machine down for calibration.

(f) Furling cable inadvertently too tight.

(g) Control box faulty May 27 through June 16, 1984.

(h) Furling cable broke at base of generator, about Fe.

FIGURE 35. Ratios Between Monthly Energy Produced at the Chartock and GPA Sites Before and After the GPA Tower was Extended

FIGURE 36. Monthly Energy Production at GPA vs. Monthly Average Wind Speed at Will Rogers Before and After the GPA Tower was Extended and an Improved Propeller Installed

Estimation of Average Wind at the Bergey and Chartock Sites From Energy Data

By combining some information in Table 7 with the indications of Figure 26, we can try to estimate the difference in average wind speed at our three wind sites. There are 10 months with totals at both the Bergey and Chartock sites. The energy accumulated during these 10 months are 718 and 896 kWh, respectively. Without November 1982, the totals are 576 and 767 kWh. The ratios are 1.25 and 1.33.

We can also compare Chartock and GPA. On January 12, 1983, the cumulative energy production at the Chartock site totalled 1927 kWh, and a spot reading on May 9, 1984 showed it to be 3513 kWh. The energy produced during the 16 months intervening was thus 1586 kWh. The energy generated from the 100-ft GPA tower during the same period was 1502 kWh, and the ratio of Chartock to GPA is 1.056. The generators are believed to have operated substantially continuously and reliably at both sites during this 16-month period.

Finally, we compare Bergey and GPA during four months after new propellers were installed at all sites and the GPA machine was working well atop a 100-ft tower (we omit November 1982). The result is $359/316 = 1.136$.

These results, tabulated in Table 8, are not sufficiently consistent to allow a firm conclusion. However, we tend to discount the earliest data and accept the 1982 through 1984 data. Thus, Table 9 shows in its third column our conclusions regarding relative energy production at the GPA, Chartock,

TABLE 8. Ratios of Energy Produced at Three WECS Sites During Selected Periods

<u>Sites</u>	<u>Period and Number of Months</u>	<u>Numerical Value</u>
<u>Chartock</u> <u>Bergey</u>	Feb. 1981 - Jan. 1983; 10 or 9 ^(a)	1.25 or 1.33
<u>Chartock</u> <u>GPA</u>	1983 and 1984, 16	1.056
<u>Bergey</u> <u>GPA</u>	Sept. 1982 - Jan. 1983, except Nov. 1982, 4 mo	1.136

(a) November 1982 excluded.

TABLE 9. Estimated Winds at 20 and 100 ft AGL and Estimated Potential Power at the Will Rogers World Airport Site

Site	Altitude of Tower Base (feet MSL)	Relative Power Produced	Avg. Annual Wind Speed at Tower Top (mph)	Estimated Average Annual Wind Speed (mph)			
				Will Rogers Extrapolation		GPA Extrapolation	
				20 ft	100 ft	20 ft	100 ft
GPA, 20-ft wind and 100-ft wind and generator tower	1085	1.0	9.40(a)	6.9(a)	9.4(a)	6.9(a)	9.40(a)
Chartock, 40-ft generator tower	1280	1.05	9.53	8.19	13.55	8.81	11.69
Bergey, 60-ft generator tower	1175	1.1	9.65	7.07	12.33	8.21	11.09
Will Rogers, 20-ft tower	1285	1.8(b)	11.35(a)	11.35(a)	16.71	11.35(a)	15.88

(a) Measured directly.

(b) Estimated from wind data and comparisons with WECS sites.

and Bergey sites on 100-, 40-, and 60-ft towers, respectively. Numbers are rounded to reflect uncertainty. Figure 26 provides estimates of the annual average wind speeds listed in the second and third rows of the fourth column. With respect to the fourth row, a reverse procedure is employed. Thus, the last entry in Column 4, 11.35, is the average annual wind actually measured on the 20-ft tower at Will Rogers World Airport. Reference to Figure 26 shows that the expected annual energy production for this annual average wind speed is 1809 kWh, or approximately 1.8 times the calculated value for GPA. Thus, 1.8 is the last entry in the second column.

The last four columns in Table 9 present results of different extrapolations of the wind to heights of 20 and 100 ft at the four locations. Boundary values are actual measurements at 20 and 93 ft at GPA and at 20 and 70 ft at Will Rogers World Airport. Thus, the second and third rows of columns 5 and 6 show estimates of the 20- and 100-ft winds at the Chartock and Bergey sites, based on the estimates in column 4 extended linearly according to the measured gradient of winds between 20 and 70 ft at Will Rogers World Airport (0.067 mph/ft, see Figure 10). In columns 7 and 8, the same data in column 4 are extended linearly according to the difference of average wind between 20 and 93 ft at GPA. Implications of these extrapolations for wind energy production by the BWC 1000-S are indicated in Figure 26 by the Chartock and Will Rogers 100-ft marks on the line labeled "Estimated annual output".^(a)

We have considerable confidence in the rank order of numbers in the third and fourth columns of Table 9, if only because we are convinced that the wind speed is a strong function of altitude MSL, but we do not take the absolute magnitudes, even the units' digits, with much confidence. But what we have done does indicate again that differences between nearby sites can be quite large, and of very large significance for wind power generation, even where terrain is gently rolling. Confirmatory experiments are indicated.

Further discussion of the indicated wind speed at the Chartock site is offered. Although the Chartock site is at practically the same altitude MSL

(a) It is possible that the 70-ft winds at Oklahoma City were influenced by the building on which the mast was placed. Geometry of installations on the Administration Building and on Page Hanger #3 are not known to the authors.

as the Will Rogers NWS site, the average wind at the Chartock site is estimated to be about 2.5 mph less at the same altitude AGL. Three possible explanations come to mind. We would like to believe that the Chartock wind is less because of local topography. Since the wind in Oklahoma is from the southerly quadrant more than half the time, and strong winds particularly so (Crawford and Hudson 1970), the ridge 0.2 miles south of the Chartock site is usually upwind. Wegley et al. (1980, pp. 23-25) show this situation to be marked by turbulence or even a reverse rotor in the region corresponding to the Chartock site. Thus, the average speed there may be less and the turbulence greater than usually corresponds to the Chartock altitude MSL. This argument can be applied to the Bergey site as well. On the other hand, we recall that both of these sites meet the criteria for flat terrain, as quoted by Wegley et al. (1980). A second possibility is that the average speed is as great at the Chartock site as at Will Rogers, but that the BWC 1000-S does not produce power at this speed as indicated in Figure 26 because of the (incompletely investigated) furling properties at the higher speeds, and perhaps because of turbulence at the Chartock site. A third possibility is that our principal findings regarding the variability of the wind are erroneous in a significant way.

Monthly Energy Production at Great Plains Apiaries in Relation to Average Monthly Wind Speeds at Will Rogers World Airport

Data in the first, fourth, and fifth columns of Table 7 are indicated in the scatter diagrams, Figures 37 and 38. A linear fit to the data seems appropriate, and the correlation coefficients are 0.82 during 20 months from September 1982 to April 1984 and 0.78 during 22 months from July 1984 to April 1986. A few months in which there were known planned or inadvertent irregularities in wind power generator performance have been omitted in the scatter diagrams.

We observe that the later data are somewhat more widely scattered--the coefficient of determination (i.e., r^2 , the explained variance) declines from 0.66 to 0.60. Also the lines of best fit, while having closely similar slopes, decrease during the later period by about 25 kWh in the predicted monthly production at a given wind speed.

FIGURE 37. Monthly Energy Production at Great Plains Apiaries vs. Monthly Average Wind Speed at Will Rogers World Airport, for 20 Months During September 1982 Through April 1984

FIGURE 38. As in Figure 37, Except for 22 Months During July 1984 Through April 1986

Of course, we are pressed to learn why the change occurred and have two suggestions beyond the obvious sense that some variation is to be expected. First, an uncertainty had developed with regard to the furling mechanism of the generator at GPA some time before February 1985. The condition culminated about February 20, when the furling cable broke off near the base of the generator housing and fell to the ground inside the tower envelope. Thereafter, no furling cable was used, and such does not appear to be necessary, though the cable occasionally represents a convenience. One can wait for the wind to stop on rare occasions when the machine needs servicing, and the machine can be disconnected from the utility line without furling it.

The weight of the furling cable is a force that tends to induce furling. A little tension on the winch at the base of the tower is added to the weight of the cable at the base of the generator. If the winch tension plus the weight are considerable, the machine furls in wind substantially lighter than the specifications call for, and there is corresponding loss of power production. The effect could be avoided by having a strain reliever connected to the cable near the base of the generator, or by having no cable at all. As noted above, the latter has been the case at GPA since the cable break in February 1985.

Now, examination of the distribution of points in Figure 38 in relation to the line of best fit reveals an interesting pattern. We have classified the points according to their location above the line, very close to or on the line, or below the line. Table 10 presents a list of categories in chronological order. Table 10 supports the thought that the condition corrected near the end of February 1985 had prevailed for several months and had resulted in a significant loss of power conversion capacity.

Our second observation has to do with the wind data from Will Rogers. Notice that the average wind for March 1986, 14.0 mph, is the highest for the entire period since the generator was installed in February 1981. Nevertheless, the GPA wind power generator produced substantially less energy than previously produced with reportedly weaker winds, although the generator appeared to be working properly and well during all the period after the furling cable broke.

TABLE 10. Classification of Points in Figure 3B in Relation to the Line of Best Fit: O, on or near the line; B, below; A, above

July	1984	O	June	1985	O
August	1984	O	July	1985	B
September	1984	O	August	1985	B
October	1984	B	September	1985	B
November	1984	O	October	1985	A
December	1984	B	November	1985	A
January	1985	B	December	1985	A
February	1985	B	January	1986	A
March	1985	A	February	1986	B
April	1985	A	March	1986	A
May	1985	A	April	1986	O

FIGURE 39. Monthly Average Wind Data at Will Rogers World Airport, January 1981 Through April 1986

Figure 39 presents monthly average wind data for the entire period in Table 7. Figure 39 shows that 5 of the 11 months from June 1985 through April 1986 are represented by peaks in average wind for months of the same name, extending back to February 1981. This seems particularly significant in view of the fact that the Will Rogers anemometer was calibrated in May 1985. Perhaps there is a difference of 1-2 to 1 mph in the data before and after the calibration, in relation to the true wind. Relatively faster reports move points to the right in Figure 38, and thus would produce a difference between Figures 37 and 38 in the direction observed.

This is not a criticism of operation of the Weather Service equipment. We are writing of details, and while the differences described are significant for wind power generation, they lie within assigned limits of uncertainty for the anemometers in operational use. We are near the limits of our equipment, but other strategies may prove productive.

Annual Wind Energy Conversion at GPA

Table 11 lists annual energy output of the BWC 1000-S at GPA for years 1981 through 1985. Note that the values agree very well with an indication of Figure 26, viz., the GPA site should produce about 1000 kWh/yr. Several matters come to mind as we consider variations in output from year to year. Low values during 1981 are principally a result of the machine having been on a 60-ft tower with the original propeller. During 1982, the machine was on the 60-ft tower in January and 5 days of production were lost in February as the tower was extended. In April 1982, 10 days of production were lost as various equipment was calibrated. The original propeller was replaced by an improved version on July 15. The larger output in 1982 than in 1981 is thus attributable to extension of the tower and installation of an improved propeller, as also shown in Figure 36. The permanent improvements more than compensated for brief out-of-service periods.

During all of 1983, the wind machine worked uninterruptedly on the 100-ft tower with improved propeller; such operation is consistent with the relatively large amount of energy produced that year, with slightly reduced annual wind speed.

TABLE 11. Cumulative Energy Production Totals During Successive Years and Annual Energy Production at GPA

<u>Date</u>	<u>Cumulative Energy Production at GPA (kWh)</u>	<u>Year</u>	<u>Annual Energy Production (kWh)</u>	<u>Avg. Annual Wind Speed; Will Rogers Airport (mph)</u>
Jan. 10, 1981	0	1981	491	11.40
Jan. 1, 1982	491.2	1982	802	11.35
Jan. 1, 1983	1293.4	1983	1032	10.94
Jan. 1, 1984	2325	1984	952	11.54
Jan. 1, 1985	3277	1985	901	11.54
Jan. 1, 1986	4187			

During 1984, energy appeared to be reduced during May, and especially during June because of damage to the inverter, apparently inflicted during a thunderstorm on May 27. Toward the end of that year, there may have been some reduction of output owing to the furling cable problem, which culminated in a broken furling cable about February 20, 1985. The 1985 total is low in relation to the reported average annual wind speed, but in the preceding section we show reason to believe that after May 1985 the reported winds were faster relative to the true winds than those reported prior to May 1985.

Overall, it appears that we have an uncertainty of 10 to 15% in expected annual energy production in relation to the reported average annual wind. The data are nevertheless reasonably consistent with our estimates based on calibrations, as discussed in the section on estimation of the annual output of the BWC 1000-S, and the variations are not large enough to mask our principal conclusions.

SUMMARY AND CONCLUDING REMARKS

We have examined data on wind and wind energy conversion at five locations in and near Oklahoma City. One location had both anemometers and wind turbine, two had wind turbines only, and two had anemometers only.

The wind data show a marked dependence of average wind speed on station elevation above mean sea level. Thus, the average wind speed near the top of a 100-ft tower in a valley with gently sloping sides is 2 mph less than on the top of a 20-ft tower operated by the National Weather Service at Will Rogers World Airport, Oklahoma City. The base of the 20-ft tower is 200 ft higher MSL than is the base of the tower in the valley. The 200-ft difference in terrain elevation MSL is representative of variations in central Oklahoma over distances of several miles; most slopes are 2 to 3%. Although such slopes have often been treated as flat for purposes of wind energy conversion, this study indicates that such treatment is probably a too-drastic simplification of natural conditions.

Further support for this finding is presented by the average wind on a 23-ft tower at the KTVY television transmitter, about 15 miles northeast of Will Rogers World Airport. The average wind on the 23-ft KTVY tower is 1.6 mph less than on the 20-ft airport tower. Although differences of elevation between these sites are not evident to the casual observer, topographic charts show that the base of the tower at KTVY is 120 ft lower than is the tower at the airport.

No relationship of wind differences between sites to wind speed or direction or time of day was identified, although large variability in the data precludes firm conclusions concerning these particulars.

The observations suggest that differences up to about 5 mph at 20 ft AGL and 7 mph at 100 ft AGL may be representative of average winds at points in the neighborhood of Oklahoma City whose elevations differ by about 200 ft. We propose that the Bernoulli effect has an important function in determining the observed dependence of wind speed on station elevation, but we do not present a formal mathematical theory. A mathematical model that incorporates just this effect has been presented by Endlich et al. (1982) and significantly, though not totally, confirmed with real data.

Wind turbines of identical manufacture were operated at three sites. At the turbine site equipped with anemometers, it was determined that the turbine output corresponded closely to the manufacturer's calibration, which was confirmed with independent data. Turbine performance at the other sites provided bases for estimation of the average wind speed at those sites.

One conclusion of our study is that different sites near Oklahoma City probably associate with wind energy generating capacities that differ from each other by up to a factor of three or even four, even in the absence of locally prominent features of terrain. A second conclusion is that the Oklahoma City site of National Weather Service observations is probably among the windiest sites in the surrounding area; hence estimates of wind turbine performance based on Oklahoma City climatological data are apt to err on the high side when applied to nearby sites, which are usually at somewhat lower elevations. A third conclusion pertains to the realm of meteorological observations, where systematic contributions to estimates of divergence at low altitudes probably attend measurements of near-surface parameters by network stations at various altitudes above mean sea level.

This study also presents various records and comparisons, not all novel, but nevertheless interesting, and with pedagogical value for the uninitiated. There are illustrations of records of wind energy under operational conditions, which show characteristics of both wind and turbine and of the interaction between them. A large correlation is shown between daily and monthly average wind at sites about 20 miles apart. The diurnal variation of wind is shown to be larger in a valley than on a hilltop.

Calibrations are presented and there is discussion of various uncertainties, some of which remain unresolved. For example, one of the wind power sites is within a few feet of the altitude at Will Rogers World Airport, yet the wind power record indicates that the wind speed is significantly less there than at the airport. We cannot be certain of this; however, we tentatively attribute lower wind speed to the presence of a hilltop upstream of the wind energy site with respect to the prevailing wind.

We propose that data available from extensive networks of stations deployed in Oklahoma and Kansas during various periods for meteorological studies be examined for independent evidence in support of a strong dependence of wind speed on station elevation.

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APPENDIX A

VARIETY OF UNITS IN WIND DATA

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VARIETY OF UNITS IN WIND DATA

The data used in this study are, in their original form, presented in three different systems of measurement. We have tended to use statute miles per hour (mph), and have converted units in many cases.

The National Weather Service three-hourly wind data, listed in Local Climatological Data, are given in knots (nautical miles per hour). The daily and monthly averages on the same form are in statute miles per hour.

The data of WKY-TV are presented in knots in the report by Crawford and Hudson (1970).

At Great Plains Apiaries, the Esterline-Angus strip charts are delineated in knots, and the digital records at the NSSL surface station are in meters per second (m s^{-1}).

The process of converting the various data to common measures can give rise to errors, and can be frustrating. For the record, we here list the constants we used for converting units.

1 knot	= 1.1516 mph	1 mph = 0.86836 knot
1 m s^{-1}	= 2.23694 mph	1 mph = 0.44704 m s^{-1}
1 km hr^{-1}	= 0.6214 mph	1 mph = 1.6093 km hr^{-1}

APPENDIX B

POWER OF THE WIND

APPENDIX B

POWER OF THE WIND

The power of the instantaneous wind in watts per square meter is given by $P = 0.5 \rho V^3$, where the units of V are m s^{-1} and the units of air density, ρ , are kg m^{-3} . In constructing Figure B-1, we have taken $\rho = 1 \text{ kg m}^{-3}$. The outer ordinate labels denote W m^{-2} of the instantaneous wind, while the inner labels are larger by the factor 8.76, and denote $\text{kWh m}^{-2} \text{ yr}^{-1}$ for an annual steady wind of magnitude given on the abscissa. This graph can be used to estimate the annual energy in the average wind if the pattern factor of the wind distribution is approximately known. The factor 1.91 is commonly used, while 1.775 was identified in 1983 data from Will Rogers World Airport. Thus, if the wind is 10 mph with air density 1 g m^{-3} , its instantaneous power is almost 45 W m^{-2} and annual energy in steady wind of that speed is 390 kWh m^{-2} .

If the average real fluctuating wind is 10 mph, then with a Weibull pattern factor of 1.9, the annual energy in the wind is $390 \times 1.9 = 741 \text{ kWh m}^{-2}$. A further upward adjustment for air density by a factor 1.1 to 1.2 is indicated for locations between sea level and 3000 ft MSL.

FIGURE B.1. Instantaneous Power (Outer Ordinate Scales) and Cumulative Annual Energy (Inner Ordinate Scales) in Relation to Steady Wind. An air density of 1 kg m^{-3} is assumed. To estimate cumulative annual energy in real (variable) winds, multiply the inner scale by the Weibull pattern factor, usually about 1.8 to 1.9.

APPENDIX C

MORE ON THE WEIBULL DISTRIBUTION

APPENDIX C

MORE ON THE WEIBULL DISTRIBUTION

Figure 11 shows the distribution of wind speed in 3-hourly reports from Will Rogers World Airport in 1983. The pattern factor, $(\overline{V^3})/(\overline{V})^3$, of this distribution is 1.775. In Figure C-1 we present a Weibull distribution with this same pattern factor and with the same average value of speed (9.524 knots) overlain with the distribution of Figure 11. The Weibull distribution is defined by

$$p(V) = (k/c)(V/c)^{k-1} \exp[-(V/c)^k],$$

and is discussed by Justus (1986), for example. The constant c is the scale factor and has units of speed. In the special case where the dimensionless shape factor $k = 2$, the energy pattern factor is 1.91, and the function is the better known Rayleigh distribution.

The fit of the Weibull distribution to the observations seems remarkably close, especially in the fast wind tail of the distribution. Differences at low speeds are substantially instrumental in origin, because the anemometers in operational use are typically stationary up to speeds of 2 to 3 knots. The only other notable differences between the real and model distributions occur around the average wind, where the real distribution is slightly more peaked (leptokurtic; see, for example, Chapter 10 in Croxton and Cowden 1939).

It is convenient to have a mathematical model that fits the distribution of real wind speed so closely, because a variety of parameters can be calculated with confidence, and various tendencies readily estimated.

In Figure C-2, we present Weibull distributions with pattern factor 1.775, for average wind speeds at increments of 5 units. The total power in these distributions scales as $(\overline{V})^3$, because the energy pattern factor is constant.

In Figure C-3, we present Weibull distributions with different shape parameters k , which associate with different energy pattern factors as shown. The scale on the left applies to the wind, and the scale to the right applies

to the energy available annually in a cross section of 1 m^2 , with $\rho = 1 \text{ kg m}^{-3}$. Notice that the total power in the distribution increases, i.e., the pattern factor increases, as the shape parameter k decreases. If the energy pattern factor or shape parameter of the wind are not representative of real conditions, there would be a contribution to error in estimates of total energy available, and a more significant error in the distribution of power at the higher wind speeds. The Bergey Wind Power Company used the usual value of k , 2.0, (Rayleigh distribution) and a corresponding pattern factor of 1.91 in their evaluations, while we used a pattern factor of 1.775 with corresponding $k = 2.16$, based on analysis of only 1 year of data from Will Rogers World Airport. It would be interesting to examine other wind data, particularly from greater heights at Will Rogers, to learn more about applicability of Weibull distribution parameters. A considerable amount of such material is archived in reports sponsored by the Pacific Northwest Laboratory (1986).

FIGURE C.1. Weibull Distribution With Pattern Factor 1.775 Overlain on Distribution (With the Same Pattern Factor) of Wind Speed at Will Rogers World Airport During 1983

FIGURE C.2. Weibull Distributions With Different Values of Average Speed, and the Same Values of Form Factor $k = 2.16$ and Associated Pattern Factor 1.775. Because the pattern factor is constant, the total power in the distributions is proportional to $\bar{V}^3$.

FIGURE C.3. Weibull Distributions With the Same Value of Average Speed, 5 m s^{-1} , and Different Values of the Form Factor k and Associated Pattern Factors. The distribution of power in the wind is also shown, with annual energy totals in 1 m^2 .

FIGURE 2.1. Weight Distributions with Different Values of Average Speed and Same Values of Energy Factor $k = 2$. The Associated Energy Factor is 1.77. Since the energy factor is constant, the distribution of the wind is proportional to V .

FIGURE 2.2. Weight Distributions with the Same Value of Average Speed and Different Values of the Energy Factor $k = 2$. The Associated Energy Factor is 1.77. Since the energy factor is constant, the distribution of the wind is proportional to V .

APPENDIX D

MORE ON CALIBRATIONS

APPENDIX D

MORE ON CALIBRATIONS

The calibration procedure described in the section on specifications and operating characteristics of the wind power converter, in the main text of this report, was applied with the Esterline-Angus recorders at GPA when the wind energy converter was mounted at 60 ft AGL, and later at 100 ft AGL. Figure D-1 shows E-A strip chart deflections indicative of the magnitude of power from the wind energy converter vs. wind speed at the anemometer mounted about 7 ft below the hub in both cases. There are some differences between the figures that suggest sources and magnitudes of some uncertainties. The later calibration indicates a little larger average power at all wind speeds, most notably at speeds near the limit where furling begins. The general difference probably associates with the more efficient propeller in place at the later time. Further, it seems that furling occurred at slightly lower wind speeds than specified by the manufacturer while the machine was mounted at 60 ft. This may have subtracted noticeably from the power that would have been available otherwise at the higher wind speeds. Other sources of variation probably lie in the E-A recorder itself, whose zero adjustment has some importance, and in human frailty. The 60-ft calibrations have not been used in developing the evaluations that culminate in Figure 26 of this report.

FIGURE D.1. Wind Energy Converter-caused E-A Deflection vs. Wind Speed. (a) During two periods while the generator was atop a tower 60 ft high; (b) Same during five periods after the tower was extended to 100 ft.

APPENDIX E

POWER FLOWS TO THE UTILITY - PRESENTATION TO THE
OKLAHOMA CORPORATION COMMISSION ON CAUSE 27208:
"COGENERATION AND SMALL POWER PRODUCTION RULES,
REGULATIONS AND STANDARD TARIFFS UNDER PURPA"

APPENDIX E

POWER FLOWS TO THE UTILITY - PRESENTATION TO THE OKLAHOMA CORPORATION COMMISSION ON CAUSE 27208: "COGENERATION AND SMALL POWER PRODUCTION RULES, REGULATIONS AND STANDARD TARIFFS UNDER PURPA"

Cause 27208 was discussed by advocates of various viewpoints at a hearing on May 18, 1984, and printed materials were also presented to the Oklahoma Corporation Commission. A written statement reflecting some of the data of our study was submitted and summarized orally at the hearing. The principal conclusion of this statement is that the amount of energy exported from the GPA wind energy converter to the utility was no more than a few kWh per month, an amount too small to be metered accurately. It is suggested therefore, that the installation of two meters to monitor power flows probably represents a wasteful expense at residences where the WECS produces only 20% or less of the total energy consumed.

Because the statement prepared for the Corporation Commission contains some data and analyses not included elsewhere in this report, we have appended it to complete the record.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES
National Severe Storms Laboratory
1313 Halley Circle
Norman, Oklahoma 73069

May 11, 1984

ev

Secretary
Oklahoma Corporation Commission
Jim Thorpe Building
2101 North Lincoln Blvd.
Oklahoma City, Oklahoma 73105

Dear Secretary,

This refers to Cause No. 27208.

Department of Energy Interagency Agreement No. DE-A 106-81RL 10336, provided funds to the National Severe Storms Laboratory in support of a study of power generation by the wind. Principal aspects of the study have utilized records made at three sites with identical wind generators (BWC 1000, manufactured by Bergey Windpower Company, Norman, Okla.). Meteorological data recorded at one of the sites and at the National Weather Service Forecast Office at Oklahoma City has also been utilized.

Some results of the study that relate to Cause 27208 are described in the attached papers.

Sincerely yours,

Edwin Kessler
Director

Enc: Comments on Cause 27208
with five tables and
seven figures (Nos. 1a,b
through 6)

Comments on Cause 27208

Background: The source of data discussed here has been a study conducted under Department of Energy Interagency Agreement No. DE-A 106-81RL 10336. Power meter readings and other records were collected at the sites indicated in Table 1 and in Figures 1a and 1b equipped with BWC 1000 wind generators, manufactured by Bergey Wind Power Company, Norman, Oklahoma. These machines produce about 1 Kw at 20 knots (23 mph) as indicated in Figure 2. Meteorological data was acquired from the National Weather Service Forecast Office at Oklahoma City, and from various publications.

Section II.D.4. of the Cause

Data of the project lend support to net energy billing in the situations investigated. The ratcheted meter at the Kessler site measures the flow of power into the site from REC lines. The unratcheted meter at the Kessler site measures the net flow from the REC into the site. The difference between the readings of these two meters indicates the power which flows onto the REC lines during periods when wind power generation is large and local consumption is small.

These flows are tabulated in Table 2, and plotted in Figure 3. Examination of Figure 3 shows a trend that is expected, but fails to show another. Thus when local monthly power production is large and purchases of power small, we expect to have a relatively large flow of power to the utility. Such is indeed indicated by the relatively large numbers at the lower right of

Figure 3. However, with local monthly production constant, we expect smaller flows to the utility as monthly purchases increase, i.e., the numbers within Figure 3 should become smaller from the bottom to the top of the diagram. This is not a prominent feature of the data, especially with small local monthly production. Further, since the amount of electricity exported from the Kessler site cannot be less than zero, the appearance of negative numbers is proof that there are meter errors. Of course, all meters are more or less erroneous--the point to be made here is that the meter errors seem comparable in magnitude to the small monthly accumulations due to flows offsite from the Kessler residence.

This point is reinforced by Table 3 and Figure 4, which shows no correlation between quantities which must be highly correlated. In other words, a larger fraction of local power production must be exported when local production is a larger fraction of local consumption.* The lack of measured correlation appears to stem from metering errors most manifested when flows offsite are very small.

In view of the existence of errors of about the same order as the quantity measured, the small size of the quantities involved, and the considerable cost of electric meters, it would seem appropriate to dispense with the extra meter needed to identify all components of the power flow. It should not be required to keep a meter to monitor a power flow that affects the billing

*This should apply at a particular site with stable statistical properties of supply and demand. It should not necessarily be applicable in a comparison of different sites.

by an amount not significantly larger than the annualized cost of the meter. Net energy billing would also reduce the administrative work required to assign costs and credits at different rates to the different kinds of power flows.

Section III E of the Cause - Safety and Reliability

1. Safety

Data was collected at the three generator sites during the period February 1981-May 1984 as indicated in Tables 2, 3, 4, and 5. During all of this period, no situation became known to the investigators in which any of the generators failed to connect or disconnect properly to lines of the public utilities.

The generators studied were among the first in the series of the same type produced by the manufacturer. During the investigative period, various improvements were made at the wind generator installations, in order to increase the amount of power generated at the sites. None of these changes produced or was associated with any malconnection. It is believed that there have been several lightning strikes to the tower at the Kessler site. None of these have been associated with damage in the control unit, although there was damage from lightning to solid state circuitry used for recording meteorological variables sensed on the generator tower.

2. Reliability

While this study has not had examination of reliability of the instruments as a major objective, data on such is available for the Kessler site. There were two electrical outages soon after installation, attributable to

manufacturing defects in this early model, and they were repaired by the manufacturer under the warranty. Since June 1981, the machine at the Kessler site has not experienced any electrical malfunction.

We discovered that the valley topography at the Kessler site was seriously inhibiting wind power generation there, and the decision was made to raise the tower height at this site from 60 to 100 feet. Results of the study indicate that the windspeed is a remarkable function of the altitude at the base of the tower, and of the neighboring topography, as well as of tower altitude. Figure 5 shows that the average windspeed on a 21 foot tower at the Oklahoma City airport weather station, 1285 MSL, is greater than that on taller towers at all of the wind generator sites studied.

Figure 6 shows that with the parameters of operation well established, a high correlation exists between the mean monthly wind speed and the monthly power output. The variance depicted in this figure is believed to relate in part to poorly documented variations of the furling cable of the Kessler machine site. Furling behavior is affected by the weight of the furling cable and its tension, and there were changes in these parameters when their relationship to power output was not fully appreciated. This situation has now been remedied and data collected in the future should be indicative of a less variable relationship between monthly power generation and average windspeed.

Figure Captions

- 1a,b Portions of USGS Quadrangle charts showing locations of sites used in this study.
- 2 Output power of the BWC 1000 under actual wind conditions on the 100 ft tower at the Kessler site.
- 3 Meter indications of power transferred to REC lines in relation to purchases and local production.
- 4 The indicated lack of correlation seems explicable in terms of meter errors at low power flows.
- 5 The wind on a 21 foot tower at Oklahoma City (1285' MSL) is stronger on the average than at any of the generator sites studied. Closed lines indicate distribution of data points on different days. Points at the right are outliers indicative of problems in analyses of this kind. Chartock and Bergey loci are based on extrapolation of wind-generator output relationship developed at the Kessler site.
- 6 Monthly production on 100 ft tower at the Kessler site, in relation to monthly average wind speed in Oklahoma City as measured from a 21 ft tower. The OKC 21 ft average wind is stronger than the wind 100 ft above ground at the Kessler site, a valley location.

Bergey and Chartock sites

Figure 1a

Kessler site (Great Plains Apiaries)

Figure 1b

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

E. Kessler to Corporation Commission
May 11, 1984

Table 1. General Site Data

Site	Location*	Height of tower	Altitude of tower base (MSL)	Topography
Bergey	35°10'45"N x 97°30'58"W	60 ft	1175'	Hillside
Chartock	35°09'48"N x 97°31'44"W	40 ft	1280'	Hillside, near summit
Kessler	34°58'47"N x 97°31'16"W	60 and 100 ft**	1085'	Valley

*The last digit in coordinate positions is not precise.

**The tower height was increased from 60 to 100 feet during 23-28 Feb, 1982.
This site includes extensive meteorological instrumentation.

Table 2. Power Production and Consumption (Kwh)
E. Kessler residence, McClain County, Okla.

Month	(1) Purchased from REC	(2) Local Production	(3) Transferred to REC	(4) Total local Consumption (1)+(2)-(3)
Feb. 1981	487	63	15	535
Mar.	461	77	21	517
Apr.	377	71	18	430
May	407	68	14	461
June	625	--	9	--
July	742	17	13	746
Aug.	681	8	3	686
Sept.	478	20	8	490
Oct.	478	42	11	509
Nov.	490	43	14	519
Dec.	492	44	10	526
Jan. 1982	571	73	12	632
Feb.	555	--	3	--
Mar.	465	99	27	537
Apr.	439	66	19	486
May	373	79	14	438
June	410	35	11	434
July	608	43	8	643
Aug.	643	--	10	--
Sept.	462	58	11	509
Oct.	407	88	20	475
Nov.	319	102	19	402
Dec.	455	94	28	521
Jan. 1983	463	77	17	523
Feb.	446	64	13	497
Mar.	346	135	40	441
Apr.	383	156	44	495
May	350	101	27	424
June	489	71	9	551
July	728	56	1	783
Aug.	887	31	7	911
Sept.	731	74	18	787
Oct.	575	70	-2	647
Nov.	543	117	24	636
Dec.	1159	80	5	1234
Jan. 1984	1085	78	-1	1164
Feb.	678	107	19	766
Mar.	553	126	19	660
Apr.	440	151	31	560
Subtotals	19458*	2684*	567*	21575*
	1823**	83**	22**	
Totals	21281	2767	589	23459

*Does not include June 1981 nor Feb & Aug 1982

**Sum of June 1981 and Feb & Aug 1982

Check data	21723 ^o	2789 ^o	21723 ^o (ratcheted meter)
	-434 [☆]	-22 [☆]	21133 ^o (unratcheted meter)
	21289	2767	590

^oMeter readings on May 2, 1984
[☆]Meter readings on Jan 31, 1981

Data are omitted in column 2 where
the wind generator operated less
than the full month.

Table 3. Monthly ratios of electrical energy flow
E. Kessler residence

	<u>Kwh locally produced</u> <u>Total Kwh consumed</u>	<u>Kwh to REC</u> <u>Kwh produced locally</u>
Feb. 1981	.118	.238
Mar.	.149	.272
Apr.	.165	.254
May	.148	.206
June	--	--
July	.023	.764
Aug.	.012	.375
Sept.	.041	.400
Oct.	.083	.262
Nov.	.082	.326
Dec.	.083	.227
Jan. 1982	.116	.164
Feb.	--	--
Mar.	.184	.273
Apr.	.136	.288
May	.180	.177
June	.081	.314
July	.067	.186
Aug.	--	--
Sept.	.114	.190
Oct.	.185	.227
Nov.	.253	.186
Dec.	.180	.298
Jan. 1983	.147	.221
Feb.	.129	.203
Mar.	.306	.296
Apr.	.215	.282
May	.238	.267
June	.129	.127
July	.072	.018
Aug.	.034	.226
Sept.	.094	.243
Oct.	.108	-.029
Nov.	.184	.205
Dec.	.065	.063
Jan. 1984	.067	-.013
Feb.	.140	.178
Mar.	.191	.151
Apr.	.270	.205

Table 4. Power generated by the wind at indicated sites, by months (kwh).

Month	Bergey	Chartock	Kessler	Okla.City average wind (mph)
Feb. 1981	74 ¹	--	63 ¹	13.0
Mar.	76	113 ³	76	12.4
Apr.	107	128	72	13.6
May	64	102	69	12.0
June	--	94	--	11.3
July	--	48	14	9.7
Aug.	15	25	7	9.8
Sept.	46	49	20	10.6
Oct.	64	88	42	12.4
Nov.	58	80	43	10.6
Dec.	65	89	44	10.9
Jan. 1982	--	136	72	13.7
Feb.	--	91	-- ⁴	12.4
Mar.	--	--	99	13.2
Apr.	--	--	-- ⁵	13.3
May	84	--	79	11.1
June	35	--	35	10.1
July	63 ²	-- ²	43 ²	10.0
Aug.	64	--	39 ⁶	10.4
Sept.	69	--	56	9.8
Oct.	93	--	87	9.7
Nov.	142	--	105	11.8
Dec.	116	--	96	10.7
Jan. 1983	81	93	77	10.5
Feb.	Larger	68	64	10.5
Mar.	Machine	134	135	12.2
Apr.	Installed	No daily or	155	13.5
May		monthly records	101	10.3
June			71	9.1
July			56	9.7
Aug.			30	8.2
Sept.			75	12.0
Oct.			70	10.4
Nov.			117	12.3
Dec.			80	12.6
Jan. 1984			78	11.0
Feb.			107	12.8
Mar.			126	12.4
Apr.			151	12.9

- Notes: 1. 60 ft. tower
2. Improved propellers installed
3. 40 ft tower
4. Tower height increased to 100 ft
5. Machine down for calibration
6. Furling cable inadvertently too tight

Table 5. Cumulative Kwh

<u>Date</u>	<u>Kessler</u>	<u>Chartock</u>
12 Jan 1983	1310	1927
9 May 1984	2812	3513
<hr/>	<hr/>	<hr/>
Difference	1502	1586

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