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INTRODUCTION

At the present time there exists a capability to manufacture wind turbines for generating electric power to be fed into the utility grid. These turbines would not be large by conventional power plant standards; individual wind machines might generate between 100 kW to 1 MW under rated wind conditions. Larger amounts of power could be provided by interconnecting a number of such wind generators. One such system has already been built by several industries under contract to NASA (Thomas, 1975). This machine, rated at 100 kW and located at Plum Brook, Ohio, has undergone a limited amount of testing. It is presently experiencing some problems with its rotor, but it is expected that improvements in the propellor will soon allow testing to continue. NASA presently plans to build several systems similar to this one and place them around the country for demonstration purposes. NASA is also investigating wind generators up to 1500 kW with certain of these units to also be used to demonstrate the feasibility of generating power from the wind. Wind generators for commercially producing electric power are not currently being mass produced because it is not yet clear that the production of power from the wind is yet economically feasible, even at the low prices attributed to mass production. As the cost of energy from other sources continues to increase, wind power may have a much stronger competitive position.

Wind generators for commercial use would be designed to minimize the cost of the energy produced. Such an optimization requires that the wind turbine be matched to the wind regime in which it is to operate. Data from the National Weather Service (NWS) for the years 1968 to 1973 is used here to estimate the wind characteristics for Wichita, Kansas. The performance of the NASA 100 kW prototype is then analyzed in the Wichita wind climate.

The power available in the wind is proportional to the wind velocity cubed (V^3). Therefore, to determine the power in the wind it is necessary to calculate the average value of the velocity cubed. However, even this average will allow only a determination of the total power in the wind. Practical wind generation systems operate over only a limited range of wind speeds and, to match the generator to the wind regime properly, it is usually necessary to know the number of hours the wind blows at any given speed. To allow this matching to be done relatively easily, wind speed information is usually displayed on a velocity frequency curve which displays the number of hours the wind blows at each velocity, or a wind duration curve which shows the number of hours the wind is at or above a particular wind speed. An example of a velocity duration curve for Plum Brook, Ohio, which was estimated from data taken in 1972, is shown in Fig. 1 (Thomas, 1975).

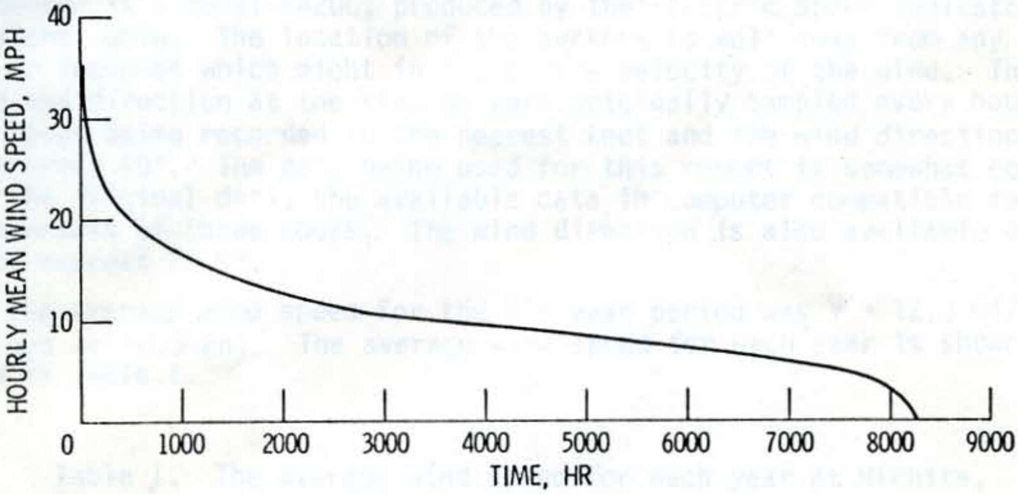

Fig. 1. Velocity duration curve for Plum Brook, Ohio, produced from data for the year 1972.

The energy contained in any range of wind speeds can then be obtained from either of these graphs. The estimation of the velocity frequency curve, or any of the graphs, requires data taken over a period of time long enough to include instances of each wind condition.

In many instances there exist marked hourly and monthly variations in the wind speed. This will be shown to be true for the Wichita data. These variations can be estimated if sufficient samples are obtained, which usually requires data over a period of several years. How much variation there is for periods of a year or longer is not quite as clear. There is some indication that for weather stations in the United States there is not too much variation from year to year (Golding, 1955), thus samples obtained over a few years might provide a good estimate of the velocity duration curve. However, relatively rare conditions, such as high winds, might not be adequately protrayed by a few years data.

The direction from which the wind blows can also be important for power generation. Direction is probably more important for generator siting than it is for the design of the generator itself. Several studies (Simmons, 1975) have shown that there is an increase in wind velocity over certain topographic features such as hills and ridges. The effectiveness of these features in modifying the wind flow depends to some extent upon their orientation with the wind velocity. Wind direction statistics then help in picking sites for the wind generators.

WICHITA WIND DATA

The data presented here was taken by the National Weather Service for the period 1968 to 1973 at the Wichita, Kansas, municipal airport. The weather station coordinates are 37°29'N, 97°25'W. The anemometer is located between the runways at the airport. The ground elevation at the airport is 1321 feet, the height of the sensors is 25 feet above the ground. The anemometer is a model F420C, produced by the Electric Speed Indicator Co., Cleveland, Ohio. The location of the sensors is well away from any buildings or features which might influence the velocity of the wind. The wind speed and direction at the station were originally sampled every hour, with wind speed being recorded to the nearest knot and the wind direction to the nearest 10°. The data being used for this report is somewhat coarser than the original data; the available data in computer compatible form is at intervals of three hours. The wind direction is also available only to the nearest 22.5°.

The average wind speed for the six year period was $\overline{V}$ = 12.0 mi/hr (5.4 m/s or 10.5 kn). The average wind speed for each year is shown below in Table I.

Table I. The average wind speed for each year at Wichita, Kansas, for the years 1968 through 1973.

Year	$\overline{V}$(mi/hr)	$\overline{V}$(knots)	$\overline{V}$(m/s)
1968	12.8	11.1	5.7
1969	11.6	10.1	5.2
1970	12.4	10.8	5.6
1971	12.3	10.7	5.5
1972	10.7	9.3	4.8
1973	12.2	10.6	5.5

It can be seen from the table that there is, in this case, quite a variation in average wind speed from year to year. The sample standard deviation about the mean of 12 mi/hr is .75 mi/hr. 1972 was the calmest year, with an average wind speed more than one mile per hour below the mean for the six years. Since the energy in the wind varies with V^3, it does not necessarily follow that there was less energy in the wind in 1972 than in any other year, and it turns out that 1972 was not the year with the least energy, as will be shown later.

From 1968 to 1973 there were hourly and monthly variations of wind speed in Wichita. The National Weather Service states that in Wichita the windiest month is March and the calmest month is July (National Climatic Center, 1975). The monthly average wind speed for each month for the period 1968 to 1973 is shown in Table II.

Table II. Monthly average wind speeds in Wichita calculated from 1968 to 1973 data.

Month	$\overline{V}$,mi/hr	$\overline{V}$,kn	$\overline{V}$,m/s
Jan	12.0	10.4	5.4
Feb	11.9	10.3	5.3
Mar	13.7	11.9	6.1
Apr	13.8	12.0	6.2
May	12.1	10.5	5.4
June	12.2	10.6	5.5
July	11.2	9.7	5.0
Aug	10.9	9.5	4.9
Sept	11.7	10.2	5.2
Oct	11.8	10.2	5.3
Nov	11.6	10.1	5.2
Dec	11.5	10.0	5.1

From the table it is seen that for these six years the spring is the windiest and the summer is the calmest time of the year, with March and April having an average wind speed more than 2.5 mi/hr higher than July and August. Since the power in the wind varies as V^3, there is much more power available in the spring months than during the rest of the year. The difference is listed later in the report in Table VII. The windiest month for this time period was actually April and the calmest was August. These months are different than the long term maximum and minimum months specified by NWS, but the difference in wind speed between the months March and April and between July and August is not large, and the data for these six years seem to support pretty well the conclusions drawn by NWS. The diurnal variation in wind speed is discussed later and is shown in Fig. 6.

The wind direction for the six years for all wind speeds is shown in Fig. 2. The direction interval is 22.5°. There is some doubt as to how a direction was assigned to a zero wind speed. The wind was calm for 1920 hours during the six year period and 1161 hours were assigned the direction 0° (north), and 219 hours were assigned a south direction. The rest of the hours seemed to be parceled out to the other directions. This distribution of direction assignment for the calm periods will have a minor effect upon the direction distribution shown in Fig. 2.

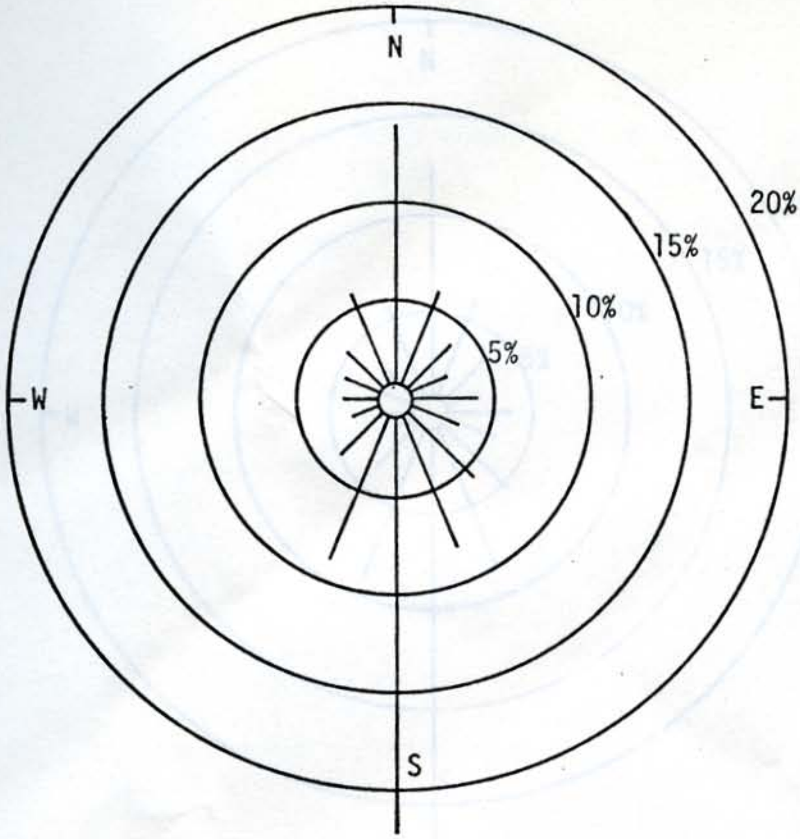

Fig. 2. The distribution of the direction of the wind in Wichita for the period 1968 to 1973 for all wind speeds. Wind direction samples are grouped in intervals of 22.5°.

The higher wind speeds are usually of more interest for power generation by a wind turbine. With this fact in mind, the direction distribution for wind speeds greater than or equal to five knots is shown in Fig. 3. It can be seen that the distribution for speeds greater than or equal to five knots is not significantly different than that for all wind speeds. The wind blows from the southern section (the 22.5° segment centered around south) more than from any other section and is from the northern section the next largest percentage of the time. From this data it would appear that siting of a wind generator should be to enhance primarily the winds from the southerly directions and secondarily the winds from the north. East and west winds would receive the least consideration. For reference, the percentage of time the wind blows from each direction is reproduced in Table III.

Another statistic which could be of interest for the siting of wind generators would be the correlation of wind speed and direction. If a generator were to run for a particular range of wind speeds and be shut down for all other wind speeds, the direction distribution of the wind speeds for which the generator would be operating would be of most interest. The direction distribution for each individual wind speed is not listed here. Instead, the average velocity of the wind from each 22.5° segment is listed in Table IV.

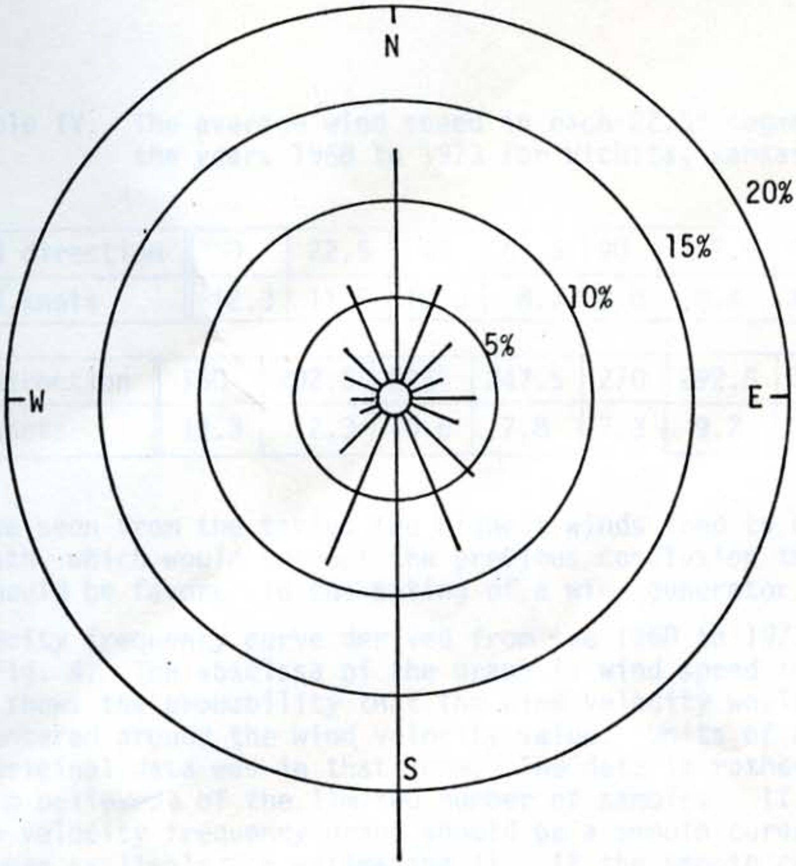

Fig. 3. The wind direction distribution for Wichita for the years 1968 to 1973 for wind speeds greater than or equal to five knots. Wind direction samples are grouped in intervals of 22.5°.

Table III. The percentage of time the wind comes from various directions for Wichita for the years 1968 to 1973 for all winds and for winds greater than or equal to five knots. Grouping is done in intervals of 22.5°. Direction is clockwise from north.

Degrees from north	0	22.5	45	67.5	90	112.5	135	157.5
All wind speeds	13.9	5.9	4.1	2.7	4.2	3.5	5.4	8.1
$V \geq$ five knots	12.5	6.2	4.0	2.6	4.1	3.5	5.4	8.4

Degrees from north	180	202.5	225	247.5	270	292.5	315	337.5
All wind speeds	22.1	8.7	4.0	2.3	2.7	2.9	3.6	5.9
$V \geq$ five knots	23.5	9.1	4.0	2.0	2.2	2.8	3.6	6.1

Table IV. The average wind speed in each 22.5° segment for the years 1968 to 1973 for Wichita, Kansas.

Wind direction	0	22.5	45	67.5	90	112.5	135	157.5
$\overline{V}$,knots	12.3	11.5	10.0	8.7	8.0	8.4	8.6	9.9

Wind direction	180	202.5	225	247.5	270	292.5	315	337.5
$\overline{V}$,knots	12.3	12.3	10.6	7.8	7.3	9.2	10.6	11.8

As can be seen from the table, the highest winds tend to be from the north and south, which would support the previous conclusion that these directions should be favored in the siting of a wind generator.

The velocity frequency curve derived from the 1968 to 1973 Wichita data is shown in Fig. 4. The abscissa of the graph is wind speed in knots and the ordinate shows the probability that the wind velocity would be in a one knot range centered around the wind velocity value. Units of knots are used because the original data was in that form. The data is rather widespread because, it is believed, of the limited number of samples. It seems reasonable that the velocity frequency graph should be a smooth curve if enough data points were available for estimating it. If the smooth curve could be described by an analytical function calculations using the wind speed distribution can often be done much more easily. Justus (1975) has reported success fitting the velocity frequency curve with the function in Eq. 1.

$$p(V)dV = \frac{\beta}{\alpha}\left[\frac{V}{\alpha}\right]^{\beta-1} e^{-\left[\frac{V}{\alpha}\right]^{\beta}} dV \tag{1}$$

In this equation V is wind velocity and β and α are parameters which are adjusted to fit the curve to the data. p(V) is the wind speed probability density function and p(V)dV is the probability the wind is between V and V + dV. Zero wind velocities are excluded for fitting the curve.

The wind duration curve shows the time the wind is at or above a particular velocity. The informaton in the curve is essentially the same as that in the velocity frequency curve. The duration curve for the 1968 to 1973 data is shown in Fig. 5. The curve fitted to the data is also shown.

Another wind speed statistic which is of interest in connecting wind generators into the utility grid system is the occurrence of calm periods when generation is not possible. Six years data is not nearly sufficient to estimate a general distribution of calm periods, but it is possible to list the number of hours the wind velocity was under a particular value and the longest period of time the wind was continuously under that value. This is done in Table V for wind speeds up to 9 knots.

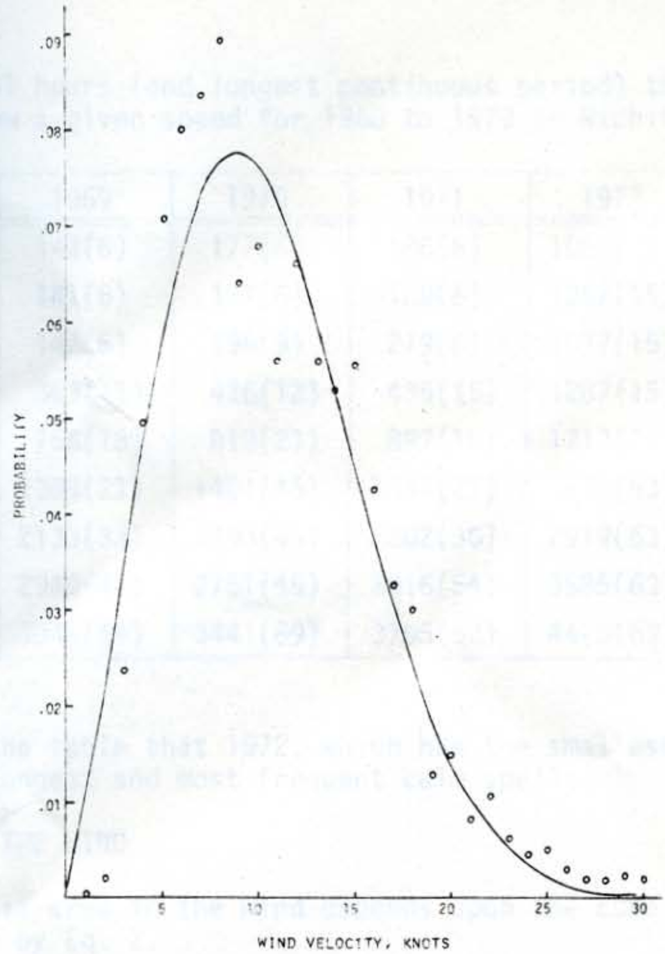

Fig. 4. The velocity frequency distribution of the wind for the years 1968 to 1973, and a least squares fit of Eq. 1 to the data with α = 11.8 knots, β = 2.2.

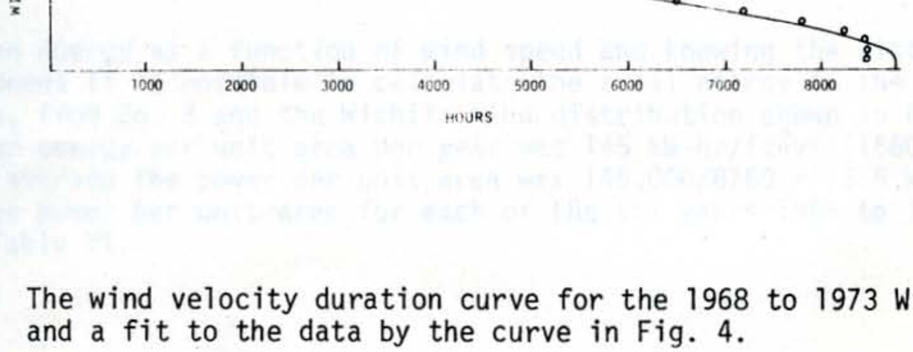

Fig. 5. The wind velocity duration curve for the 1968 to 1973 Wichita data and a fit to the data by the curve in Fig. 4.

Table V. Total hours (and longest continuous period) the wind is below a given speed for 1968 to 1973 in Wichita, Kansas.

V	1968	1969	1970	1971	1972	1973
1 kn	114(6)	141(6)	177(6)	186(6)	1062(15)	340(12)
2	114(6)	141(6)	177(6)	189(6)	1062(15)	243(12)
3	120(6)	147(6)	195(9)	219(6)	1077(15)	258(12)
4	288(9)	363(15)	426(12)	435(15)	1287(15)	429(15)
5	690(18)	756(18)	813(21)	897(18)	1713(24)	882(24)
6	1221(27)	1388(21)	1401(45)	1551(27)	2235(63)	1527(33)
7	1848(42)	2133(33)	2103(45)	2202(36)	2919(63)	2172(39)
8	2574(57)	2940(42)	2751(45)	2916(54)	3585(63)	2847(69)
9	3186(84)	3846(54)	3441(69)	3705(60)	4428(69)	3549(69)

It can be seen from the table that 1972, which has the smallest average wind speed, also has the longest and most frequent calm spells.

ENERGY ESTIMATION IN THE WIND

The power per unit area in the wind depends upon the cube of the wind velocity and is given by Eq. 2.

$$P = \rho V^3/2 \tag{2}$$

V - Wind velocity

ρ - Air density

Using an air density of .00227 slugs/ft^3 (1.17 Kg/m^3), for an altitude of 1300 ft and a temperature of 69°F, the power in the wind per unit area can be expressed by Eq. 3a-c.

$$P = .00485V^3 \text{ W/ft}^2 \quad \text{V in mi/hr} \tag{3a}$$

$$P = .584V^3 \text{ W/m}^2 \quad \text{V in m/s} \tag{3b}$$

$$P = .00738V^3 \text{ W/ft}^2 \quad \text{V in knots} \tag{3c}$$

Knowing the energy as a function of wind speed and knowing the distribution of wind speeds it is possible to calculate the total energy in the wind. As an example, from Eq. 3 and the Wichita wind distribution shown in Fig. 4, the average energy per unit area per year was 145 kW-hr/ft^{2}yr (1560 kW-hr/m^{2}yr), or on the average the power per unit area was 145,000/8760 = 16.5 W/ft^2. The average power per unit area for each of the six years 1968 to 1973 is shown in Table VI.

Table VI. The average power per unit area in the wind for the years 1968 to 1973 in Wichita.

Year	Power
1968	18.4 W/ft^2
1969	14.0
1970	17.4
1971	18.0
1972	14.1
1973	17.0

It can be seen from the table that there was a considerable variation in energy content in the wind per year during this six year period. Table I lists the average wind speed for each year; the calmest year from an average wind speed criteria was 1972. There was, however, slightly more energy in the wind in 1972 than there was in 1969, even though the average wind speed was nearly one mile per hour lower in 1972. There must have been some high wind in 1972 which contributed a large amount of energy to the energy average; the effect of the cubing of the wind velocity could thus raise the average energy considerably while having a smaller effect on the mean wind speed. The difference in the average wind speed on a monthly basis was listed in Table II. The difference in the energy in the wind from month to month can be considerable, since energy is proportional to the wind velocity cubed. The average energy in W/ft^2 for each month is shown in Table VII.

Table VII. The average power in W/ft^2 for each month calculated over the years 1968 to 1973 for Wichita.

Month	Power, W/ft^2
Jan	16.3
Feb	17.4
Mar	24.4
Apr	24.0
May	15.7
June	16.6
July	11.7
Aug	10.9
Sept	14.3
Oct	15.7
Nov	15.4
Dec	15.7

March and April winds have the most energy, with a rather sharp drop off in the amount of energy available in May. June actually has more energy in its winds than May does for this sample period, but that difference might not hold over a longer time period. July and August are the least energetic months, having, in this case, less than half the energy available in March and April. Outside of the two windy months and the two calm months, the energy available is fairly constant at about 16 W/ft^2.

As was mentioned before, there is a considerable diurnal variation in the amount of energy in the wind as well as the monthly variation. Fig. 6 shows the hourly variation in power per unit area in the wind for each month for the six year period. During most months there appears to be a minimum early in the morning and a peak about three in the afternoon. The peak might not be right at 3 o'clock, however; the data used here was at three hour intervals, so the peaks might be occurring at some other time in the afternoon and the peaks in power are probably not as sharp as they are drawn in this figure.

It is not possible, of course, for a wind power generating system to remove all the energy from the wind. Betz (1928) has shown that a rotor could remove at a maximum .593 of the energy from a moving airstream. A practical rotor extracts somewhat less than the theoretical maximum. Some of the power delivered by the rotor is also wasted in mechanical and electrical losses. As a result, the overall system might convert to electrical power 30%, or even less, on up to perhaps 50% of the primary energy in the wind when the wind turbine is running. In addition, most wind generators run over only a particular range of wind speeds, and energy in the wind at velocities outside the operating range is lost.

WIND GENERATOR PERFORMANCE

From the distribution of the energy in the wind, which can be obtained from Fig. 4, and knowing the rating of the wind generator to be installed, e.g. 100 kW, the propellor size (in the case of the horizontal axis machine) and the rotational speed of the propellor (assuming it is to run at a constant speed) can be determined. The calculation is not always straightforward, however. Optimization is usually done either to minimize the cost of the generator per kilowatt rating or to minimize the cost of the energy produced per year. The latter criteria would probably be used in most cases. If a large rotor is used, the wind generator will intercept a large amount of energy, and the turbine will run at rated power for a greater percentage of time than with the use of a smaller rotor. However, the cost of the rotor (and probably other parts of the system), will increase with rotor size. The cost of the rotor is a significant percentage of the cost of the wind generator, hence rotor cost will have to be balanced against energy generated.

The performance of the rotor is normally a function of the ratio between its rotational speed and the speed of the wind. Its efficiency is designated by the power coefficient C_p, the ratio between the power extracted by the rotor and the power in the wind. A curve of rotor C_p is usually derived as a function of tip speed ratio, the ratio of the speed at the tip of the propellor to the undisturbed wind speed. Knowing the C_p curve for the rotor, and for the entire generating system if necessary, various combinations of rotor size and operating points can be combined with the wind speed statistics to determine what design will be optimum for a particular site.

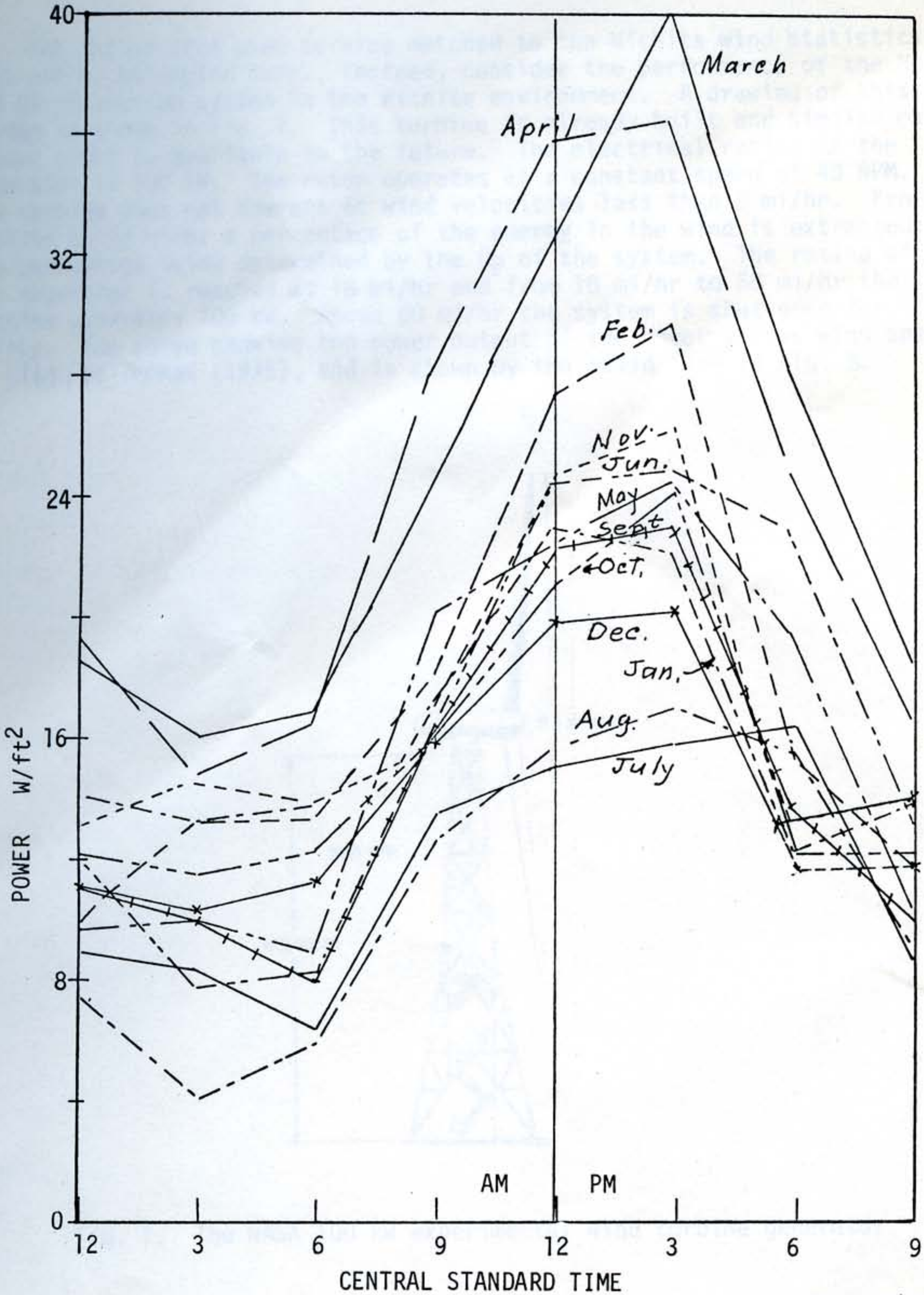

Fig. 6. The diurnal variation in wind power for each month of the year derived from 1968 to 1973 Wichita data.

The design of a wind turbine matched to the Wichita wind statistics will not be attempted here. Instead, consider the performance of the NASA 100 kW generating system in the Wichita environment. A drawing of this system is shown in Fig. 7. This turbine is already built and similar machines might be available in the future. The electrical rating of the generator is 100 kW. The rotor operates at a constant speed of 40 RPM. The machine does not operate at wind velocities less than 8 mi/hr. From 8 mi/hr to 18 mi/hr a percentage of the energy in the wind is extracted; the percentage being determined by the C_p of the system. The rating of the generator is reached at 18 mi/hr and from 18 mi/hr to 60 mi/hr the machine generates 100 kW. Above 60 mi/hr the system is shut down for safety. The curve showing the power output of the rotor versus wind speed is given by Thomas (1975), and is shown by the solid line in Fig. 8.

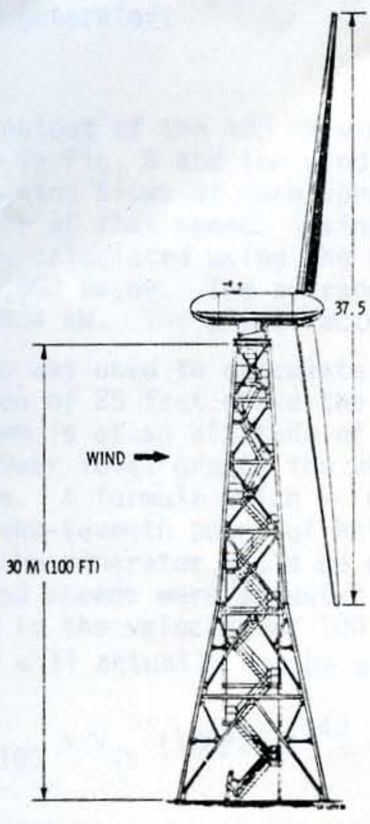

Fig. 7. The NASA 100 kW experimental wind turbine generator.

Instead of using the curve shown it appears that a straight line approximation as shown by the dashed line in Fig. 8 would not badly mis-estimate the power delivered by the generator. Using this straight line the power output of the wind generator will be over estimated somewhat, but hopefully not by a significant amount. At wind speeds of 18 mi/hr and above the rotor delivers 133 kW to the generating system. The actual output of the generator is 100 kW. For calculations here it will be assumed that the power coefficient of the system excluding the rotor (from the output of the rotor to the electrical output terminals) is 100/133 = .75 for all wind speeds when the system is running.

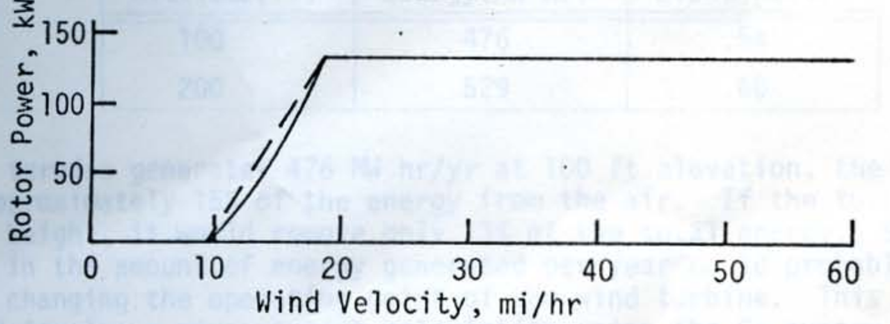

Fig. 8. Power output versus wind speed for the NASA 100 kW wind generator.

The yearly energy output of the 100 kW wind generator can then be calculated using the curve in Fig. 8 and the wind distribution shown in Fig. 4. The number of hours the wind blows at each speed is multiplied by the power produced by the generator at that speed. Using the Wichita data, the annual output of the generator, calculated using the straight line approximation shown in Fig. 8, is 363,000 kw-hr. The average power delivered by the system is 363,000/8760 = 41.4 kW. The plant factor is thus .414.

The wind data which was used to calculate the output of the turbine was taken at an elevation of 25 feet above the ground. The center of the rotor for the NASA system is at an altitude of 100 ft and the blades have a diameter of 125 ft. Over level ground the velocity of the wind normally increases with elevation. A formula which is often used is that the wind speed increases as the one-seventh power of height (Reed, 1975). Therefore, the wind speed seen by the generator would be greater than that measured at 25 ft. The measured wind speeds were adjusted to an altitude of 100 ft using Eq. 4, where V_{100} is the velocity at 100 ft and V_{25} is the velocity at 25 ft. The velocity will actually not be constant over the whole area

$$V_{100} = V_{25}\ (100/25)^{.143} = 1.22\ V_{25} \qquad (4)$$

swept by the rotor; it will be greater than that at 100 ft on the upper part of the swept area and lower below the midpoint of the rotor. The 100 ft data is used as an approximation, however. Using the adjusted data for 100 ft, the energy output is 476,000 kW-hr/yr for an average output power of 54.3 kW or a plant factor of .543. The wind data was also adjusted to an elevation of 200 ft and the output power calculated. The energy output was 529,000 kW-hr/yr for a plant factor of .604. Justus (1975) calculated the energy output for the NASA 100 kW machine at an altitude of 200 ft in Wichita, Kansas, and reports a plant factor of .80. The reason for the difference in the data is not completely clear, but appears to be in the wind data statistics. The energy output and the plant factors for the 100 and 200 ft elevations are summarized in Table VIII.

Table VIII. Total annual energy output and plant factors for a 100 kW system operating in Wichita at an altitude of 100 and 200 ft.

Altitude(ft)	Energy(MW hr)	Plant Factor
100	476	.54
200	529	.60

Since the turbine generates 476 MW hr/yr at 100 ft elevation, the turbine removes approximately 15% of the energy from the air. If the turbine were at 200 ft height, it would remove only 13% of the total energy. Some improvement in the amount of energy generated per year could probably be obtained by changing the operating point of the wind turbine. This optimization would involve a power output calculation using the C_p system curves for each operating point. The operating point that would give the maximum average power output would be chosen. The improvement that would be gained over the present operating point of 40 RPM would probably not be large, however. It might also be advantageous to decrease (or increase) the size of the propellor, depending on the change in total energy generated as a function of propellor size changes and the cost of the propellor as a function of size. As stated before, no optimization will be attempted here since the C_p curves to be used and the cost of the propellor as a function of length are not known by the authors.

SUMMARY, CONCLUSIONS, AND FURTHER RESEARCH IN KANSAS

Over the years 1968 to 1973 the average wind speed at the Wichita NWS station was 12 mi/hr. Of any single direction the wind was most frequently from the south and next most often from the north. There was a considerable hourly and monthly variation in the wind speed; the maximum wind speed usually occurred around 3 p.m. and the minimum speed occurred in the early morning. March and April were the windiest months and July and August were the calmest. A considerable yearly variation in the energy in the wind showed up for this time period. The average power per unit area for each year varied from a low of 14 W/ft^2 to a high of 18.4 W/ft^2.

If the NASA 100 kW machine were installed at the Wichita site or at a similar site it would operate at a plant factor of .54, not counting breakdowns. This plant factor assumes the midpoint of the rotor is at a height of 100 ft and that the wind speed estimated for 100 ft were constant over the rotor area. Installation of the machine at a height of 200 ft would result in a plant factor of .60.

Further research should include, it is thought, wind speed statistics compiled over a longer period of time to average out more completely year to year variations. Sites other than Wichita should also be considered. The authors are presently compiling statistics for several locations in the Western half of Kansas. Wind data over at least a period of ten years will be used for the calculations. Additional data for Wichita is also being used to update the Wichita statistics. NWS data is being used for these statistics. Since meteorological stations are usually not placed at optimum sites for wind generators, it is felt that wind characteristics at some possible turbine sites should be investigated. Several studies have shown that the wind velocity can be higher around hills than it is on nearby level terrain, and that certain types of hills would be optimum for wind generator siting. The Wind Energy Laboratory at Wichita State University is presently selecting sites around Wichita at which it is felt substantially higher wind speeds will be found. The wind speeds at these sites will be monitored for comparison with the wind velocities on level ground.

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