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CLIMATE OF MINNESOTA

IX A Brief Climatology of Solar Radiation and Wind in Minnesota

By Donald G. Baker, Professor of Soils Science

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Climate of Minnesota Part IX

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The sun is the ultimate source of the earth's energy. It is the source of energy for the earth's weather systems and, therefore, responsible for our water supplies and wind systems. The fossil fuels upon which we are now drawing so heavily are a stored form of solar energy and a limited resource. It is tempting to try to harness solar energy directly to conserve coal, oil, gas, and wood since the sun apparently provides such enormous quantities of energy.

The wind, a force created by the sun, is in more or less constant motion, and it seems foolish not to capture and use it also.

To date, most interest in solar and wind energy as alternatives to fossil fuels seems to have centered upon the development of the engineering designs and technological applications required to capture them. There has been relatively little interest shown in the actual availability and dependability of these two elements. The information in this bulletin is a brief outline of the climatology of these two climatic elements: how they vary over time and space. More detailed analyses are planned for the near future.

Solar Radiation

The enormity of the amount of solar energy intercepted each day by the earth can be realized when compared to more familiar quantities of energy. In table 1 the energy of the atomic bomb dropped on Nagasaki in 1945 has been given a value of 1. However, comparisons of this kind can be very deceiving. Several circumstances reduce the amount of solar energy that actually arrives at the earth's surface that can be tapped. These also bear directly on the practical problems of collecting the energy.

Table 1. Relative amounts of energy for various phenomena compared to the solar energy intercepted by the earth each day (After 11).

Atomic bomb exploded over Nagasaki, Japan, August, 1945	1
Average summer thunderstorm	1
Burning of 7000 tons of coal	1
Daily output of Hoover Dam	1
Average hurricane	10,000
World use of energy, 1950	1,000,000
Daily solar energy intercepted by earth*	100,000,000

*The actual amount of energy intercepted equals 3.76×10^{21} calories per day.

Circumstances that reduce solar energy between what is intercepted by the earth and what is actually received at the surface of the earth include:

1. the rotation of the earth about its axis;
2. the revolution of the earth around the sun; and
3. the scattering, absorption, and reflection of the incoming solar radiation by the atmosphere.

The earth rotating on its axis makes a complete rotation each day, creating the day-night effect. Thus the solar radiation received is a discontinuous source of energy. Even if no other reason existed, it is necessary to store energy captured during the day if it is to be available at a later time.

The earth revolving about the sun creates the seasonal effect. Thus the angle of the sun's rays to the earth's surface varies appreciably in the course of a year, as does the day length.

The most efficient absorbing surface of the sun's rays for this area would be one which changes its orientation during the course of a year because the angle of the sun's rays to the earth's surface varies as shown in figure 1 for latitude 45° (just north of St. Paul). A change in orientation on a daily basis would be an advantage as well. However, this introduces an added engineering complexity in solar collector design, so a compromise is often accepted. The absorbing surface is constructed with a permanent tilt from the horizontal always facing south as shown in the lower half of figure 1. With the absorbing surface oriented as shown in figure 1, it is apparent that the rays of the midwinter sun are almost perpendicular to the absorbing surface. In the summer such a tilt of the absorbing surface captures even less energy than a horizontal surface. Figure 2 illustrates that, with respect to the direct rays of the sun, a surface tilted 65° to the horizontal and facing south affects solar energy reception in two ways: (a) the reception is increased in the winter time, and (b) the amount received shows less variation from month to month than that received on a horizontal surface.

As noted previously, a surface with a fixed slope does not always have an advantage in radiation reception compared to that received on a horizontal surface because of the continually changing position of the earth

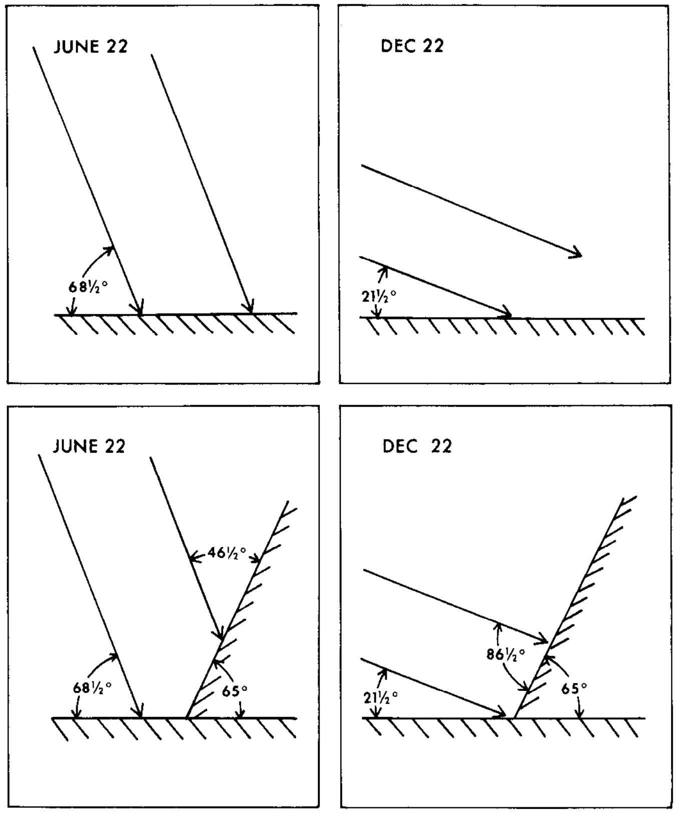

Fig. 1. (Upper) The maximum and minimum angles of the sun's rays to a horizontal surface at 45°N., which occur on June 22, the summer solstice, and December 22, the winter solstice, respectively. (Lower) Comparison of the angle of the rays on a horizontal surface and one tilted 65° from the horizontal and facing south.

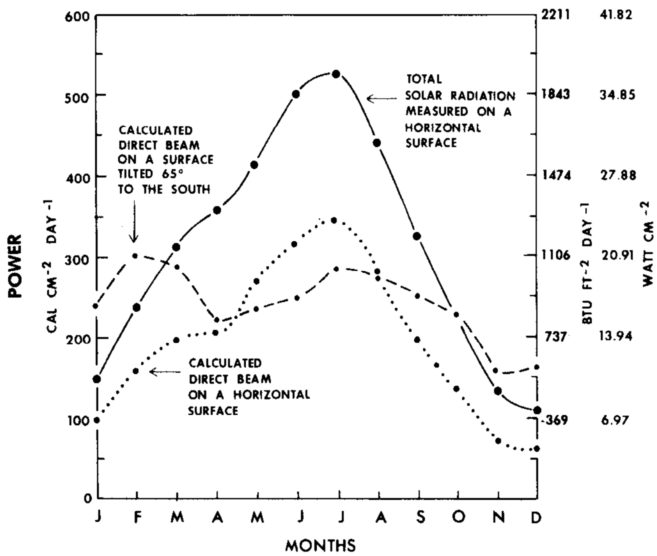

Fig. 2. Comparison of the calculated, direct beam, clear-day radiation incident upon a horizontal surface and one tilted 65° to the south. Calculations are based upon the method of Liu and Jordan (8) using the mean total radiation received on a horizontal surface at St. Paul, 1963-1975.

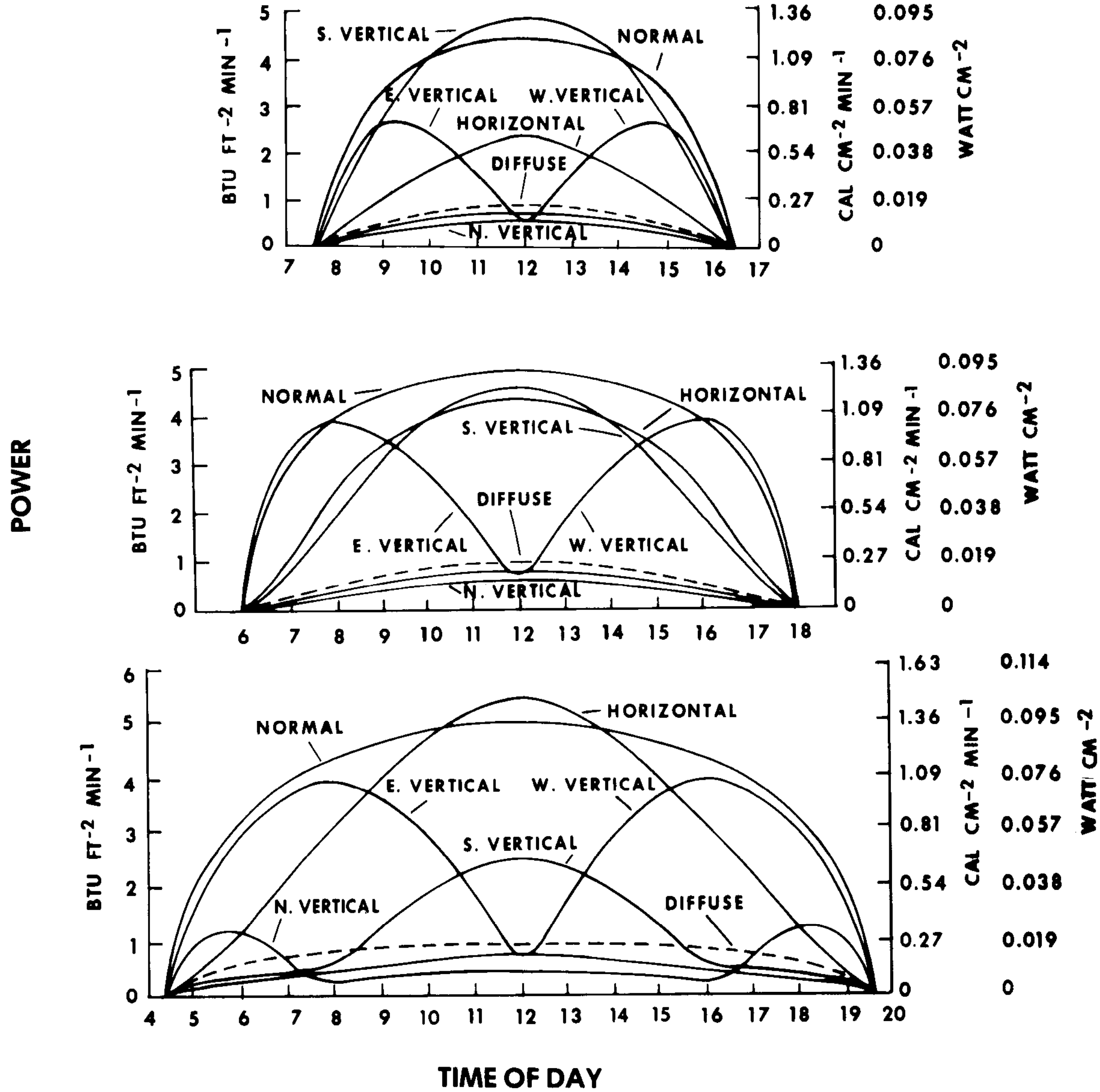

Fig. 3. Relative amounts of clear-day radiation received on a horizontal surface, on vertical surfaces of different facing directions (north, south, east, and west), and a surface always kept normal to the sun's rays at the winter solstice (December 22), the vernal and autumnal equinoxes (March 21 and September 23, respectively), and the summer solstice (June 22). Diffuse radiation on a horizontal surface is also shown. Diffuse radiation is included for all surfaces except the normal surface which includes only the direct radiation. After Brooks (4) and Hand (6).

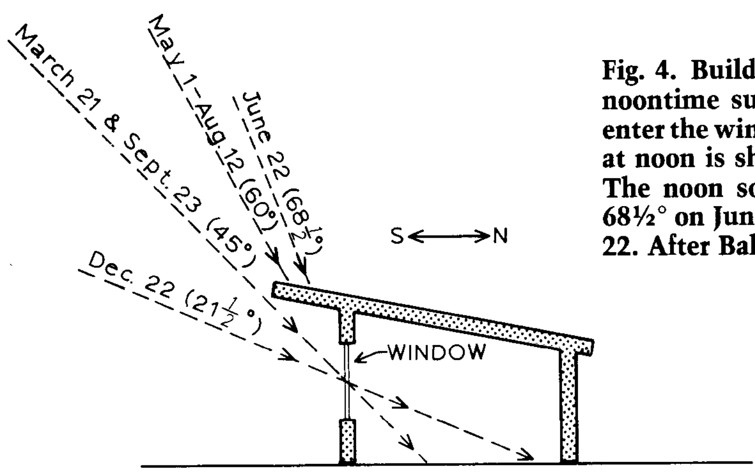

Fig. 4. Building constructed so that direct rays of the noontime sun between May 1 and August 12 do not enter the window. Altitude of the sun above the horizon at noon is shown for indicated dates at 45°N latitude. The noon solar altitude ranges from a maximum of 68½° on June 22 to a minimum of 21½° on December 22. After Baker (2).

relative to the sun. The variability of the total clear-day reception on a horizontal surface, on vertical surfaces of different orientations, and on a surface that tracks the sun such that it is always perpendicular (normal) to the sun's rays is illustrated in figure 3.

Figure 4 shows how the changing altitude of the sun can be used to advantage in building construction. An overhanging eave prevents the strong rays of the midday summer sun from entering a large south-facing window, thus decreasing the heat load on the house, while the low-angle rays of winter can enter the window and help warm the house.

The second effect of the earth's annual revolution about the sun is the changing length of day shown in figure 5. At 45° latitude, for example, the difference between the longest and shortest day is 6 hours 51 minutes, and this difference increases as the latitude increases. Note that the short days occur at the very time when energy needs for heating are high.

Radiation received at the outer limit of the earth's atmosphere, called extraterrestrial radiation, varies throughout the year as shown in figure 6. The variation is a result of the previously defined seasonal effect — the earth's revolution about the sun combined with the constant tilt of the earth from the vertical of nearly 23½°. Upon entering the earth's atmosphere, the radiation is depleted by absorption and scattering. Several atmospheric constituents are responsible for this including oxygen molecules, ozone, and water vapor. More or less transient materials in the atmosphere, such as dust and smoke, cause additional scattering and absorption. Some of the scattered radiation is lost to outer space and some reaches the earth's surface.

This brings up an important distinction with respect to solar radiation within the earth's atmosphere. Figure 7 illustrates that direct beam radiation arrives in a direct path from the sun while, due to scattering, scattered or diffuse radiation arrives at the earth's surface in an indirect path. The concentrator type of solar energy collector can make very little use of the diffuse radiation, whereas the flat plate collector makes use of both the diffuse and direct beam.

On a clear day relatively free of smoke and dust, the proportion of the diffuse radiation to the total amount measured at St. Paul ranges from about 20 percent with the high sun period of the summer solstice, June 22, to about 35 percent at the winter solstice on December 22. The higher proportion of diffuse radiation on December 22 is due to the longer path length, and thus, a greater scattering of the sun's rays as they pass through the atmosphere.

Cloud cover, the last item to be discussed, also reduces radiation received at the earth's surface. This is perhaps the most important factor of all because it is unpredictable, except on a short-term basis, and it frequently severely restricts the radiation received. A large proportion of incoming solar radiation is reflected off the top of the clouds to outer space while the absorption within the cloud is relatively minor. The radiation which penetrates the cloud is diffuse radiation, as shown in figure 7, and is essentially unuseable by the concentrator type of solar energy collector.

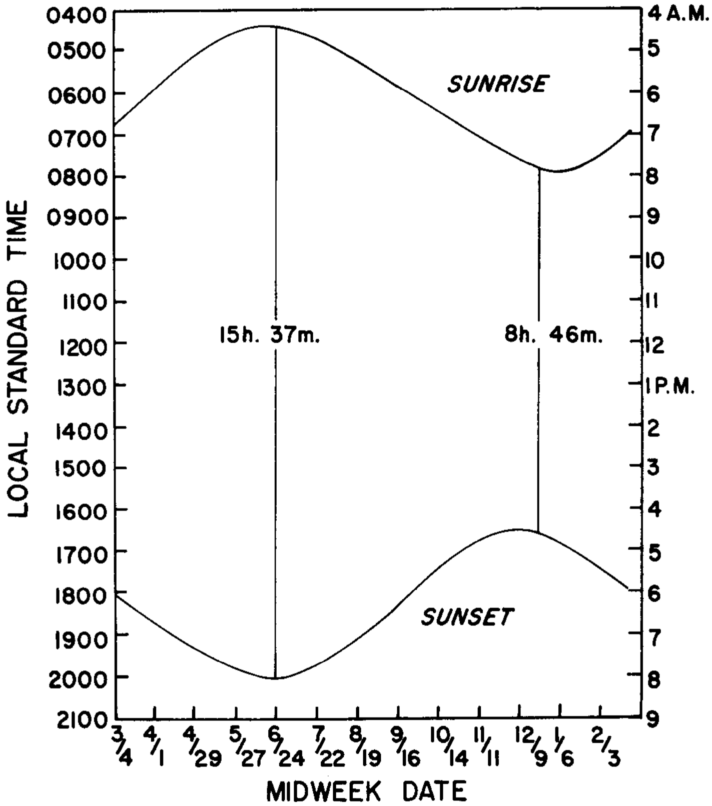

Fig. 5. The variation in sunrise and sunset times during the course of a year at 45°N. The longest day is 15 hours and 37 minutes in duration and the shortest is 8 hours and 46 minutes. After Maxwell (9).

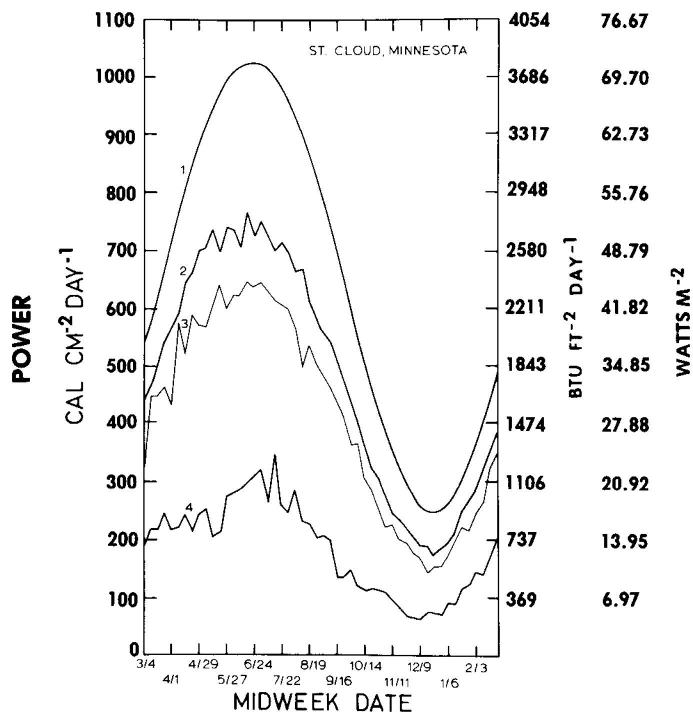

Fig. 6. Total daily extraterrestrial solar radiation (curve 1) and the average measured radiation at St. Cloud under three sky conditions: clear (curve 2), 50 percent cloud cover (curve 3), and 100 percent (overcast) cloud cover (curve 4). Values were plotted at the midweek date of each climatological week. After Baker and Klink (3).

In comparing Minnesota with the rest of the nation, figure 8 provides some interesting information. Cloud cover reduces the amount of sunshine in Minnesota from a possible total of about 4400 hours to an annual total of only approximately 2500 hours. Sunshine, it should be noted, corresponds to direct beam radiation. Minnesota averages more sunshine than the narrow band along the Pacific coast from San Francisco northward, the Great Lakes region, the Appalachian region, and most of New England. However, the total sunshine received in the arid and relatively cloud-free west, and particularly the southwest, greatly exceeds that received in Minnesota.

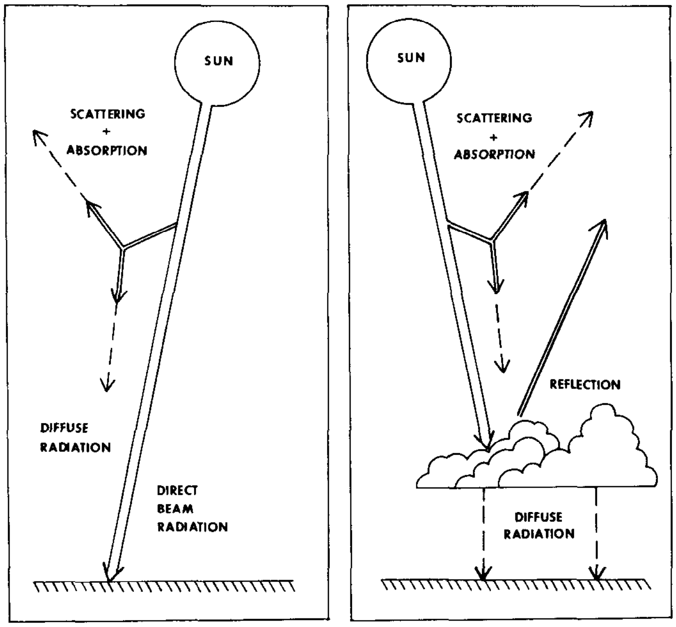

Fig. 7. (Left) Scattering and absorption within the atmosphere deplete the total radiation received at the earth's surface which is comprised of both direct beam and diffuse (scattered) radiation. (Right) Clouds further deplete the radiation received as a result of reflection off the tops and absorption within the clouds. Radiation which passes through a cloud arrives at the surface as diffuse radiation.

The annual march of solar radiation, figure 9, shows that solar radiation as measured at St. Cloud, Minnesota, compares favorably with the mean amount received at 43 United States stations. St. Cloud radiation reception compares favorably during the summer months with Miami but, of course, fails in the winter when Miami receives nearly double the amount at St. Cloud. Throughout the course of the year El Paso averages almost 200 cal $cm^{-2}day^{-1}$ more than St. Cloud.

The distribution of solar radiation across the United States on an annual average basis is shown in figure 10. Because the National Weather Service radiation network consists of approximately one station per state[1], the isolines of radiation can show only general trends. Figure 10 is, of course, very similar to figure 8, which shows the sunshine received. As in figure 8, the gradient in radiation across both Minnesota and north central United States runs approximately from the southwest to the northeast. Minnesota generally receives more radiation than the industrialized east, as much as New Orleans, considerably more than along the northwest Pacific coast, but far less than the southwest receives.

Clouds, as indicated earlier, are responsible for the unpredicted variation in solar radiation reception. However, based upon past records, the expected frequency of varying degrees of cloudiness can be determined, and from this a climatological or probability type forecast can be made. For example, in figure 11 the percent frequency that overcast days (a day with complete cloud

[1] This is true for the solar radiation network as of September, 1972. Since then no data have been published. The network is currently in the process of being reestablished, and sometime in 1977 solar radiation measurements were expected to again be published. However, the network will be reduced to only 35 stations in the contiguous United States, with no National Weather Station located within Minnesota or Iowa.

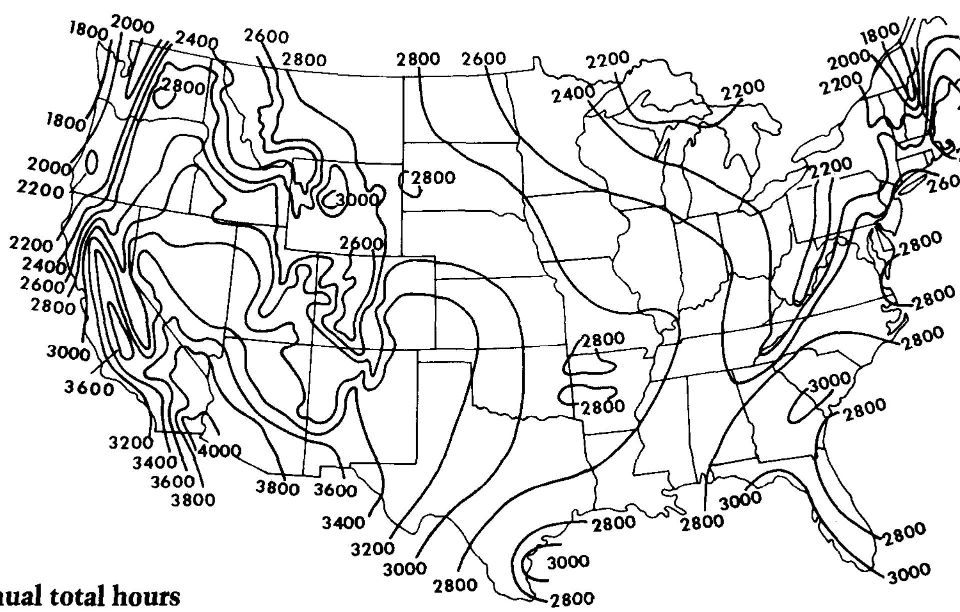

Fig. 8. Average annual total hours of sunshine, 1931-1960 (17).

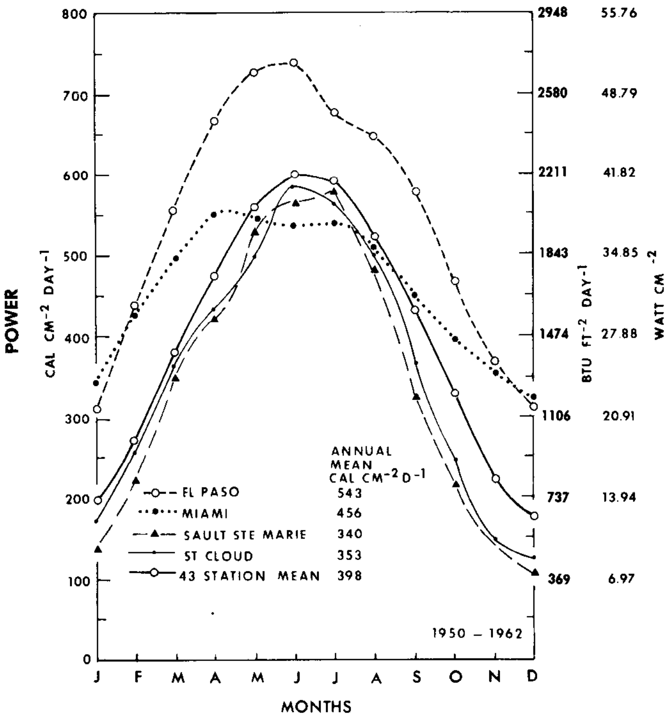

Fig. 9. Average daily total solar radiation received per month on a horizontal surface at St. Cloud compared to El Paso, Texas; Miami, Florida, Sault Ste. Marie, Michigan; and the average of 43 United States stations. Basic data are from (16).

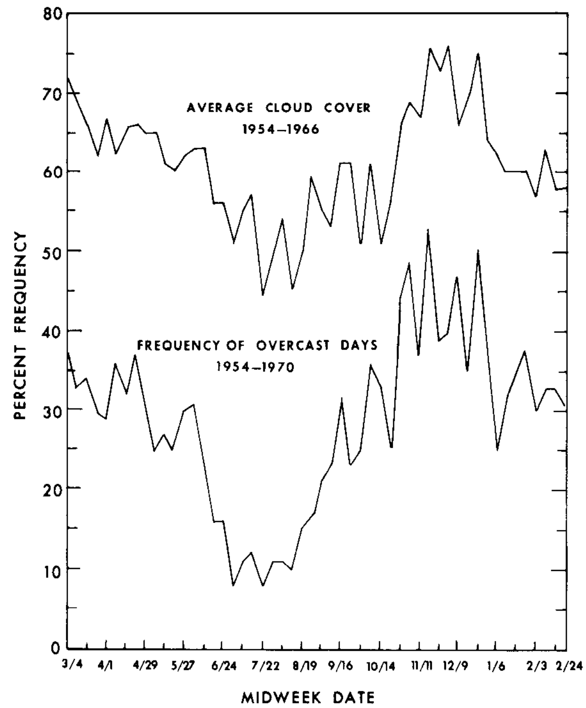

Fig. 11. Average cloud cover, 1954-1966, (1) and average weekly occurrence (in percent) of overcast days (1954-1970) at Minneapolis-St. Paul. The actual values are shown, but for planning purposes a smoothed line is probably very acceptable.

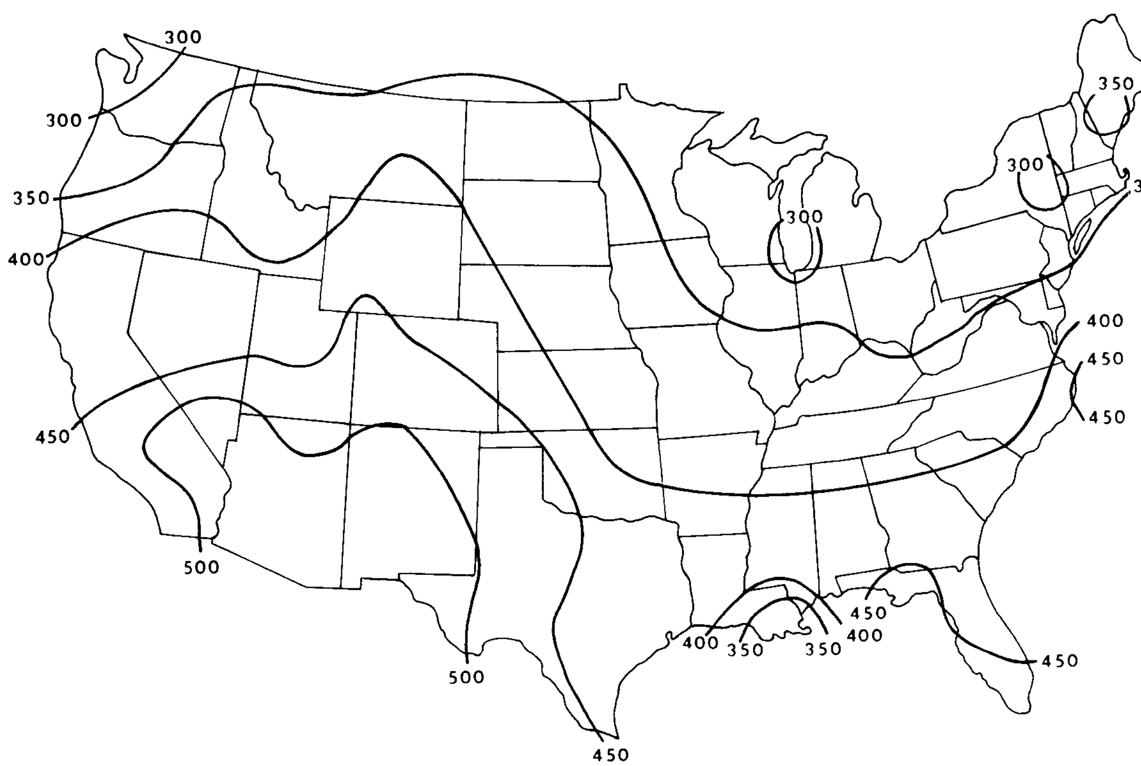

Fig. 10. Average annual total solar radiation in cal cm^{-2} received per day on a horizontal surface. After Harris (5). One hundred cal cm^{-2} day^{-1}=369 BTU ft^{-2} day^{-1}=6.97 watts cm^{-2}.

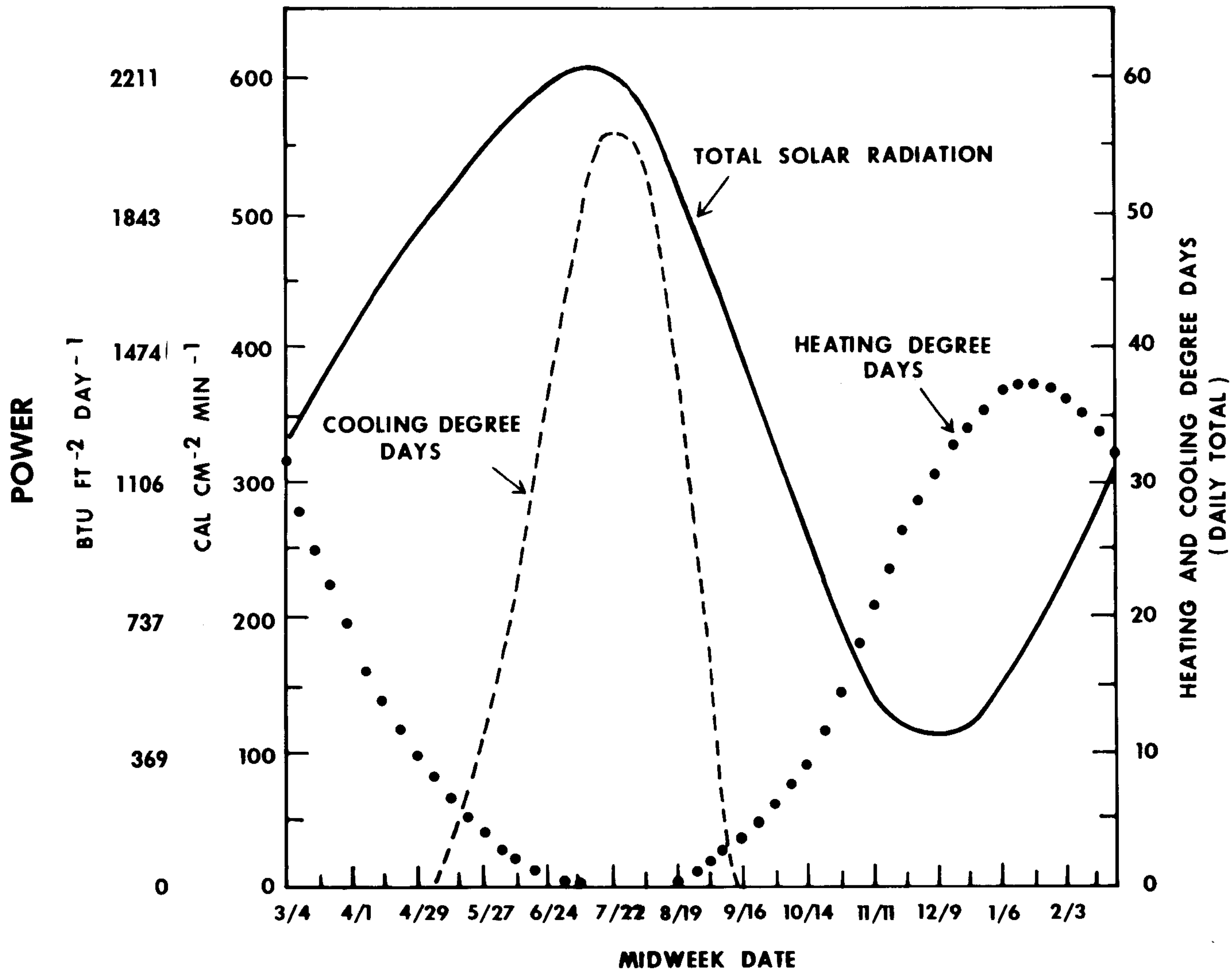

Fig. 12. Heating and cooling degree days, assumed to represent seasonal energy demands at Minneapolis-St. Paul, plotted against the average weekly solar radiation at St. Cloud. All data have been smoothed. The radiation and degree day scales used are for comparative purposes only; there is no direct relationship between the scales shown. Data are from (3, 15).

cover and no sky is visible) occurred at the Twin Cities airport for the period 1954-1970 is shown for each week of the year. The radiation received on such a day is, of course, entirely diffuse in nature. The important thing to note is that the maximum of both average cloud cover and overcast days occurs from late October through December. During this period a day with complete cloud cover can be expected about 43 percent of the time. The high frequency of overcast days occurs at a very inopportune time. At the same time of year the days are rapidly becoming shorter and air temperatures are decreasing, a very disadvantageous combination. Fortunately there is a relatively sharp decrease in the frequency of overcast days between December and January, coinciding with the arrival of the coldest month of the year.

Overcast days are least frequent from about mid-June through August. During this time, which coincides with the longer days and higher air temperatures of summer, overcast days occur only about 15 percent of the time. The minimum average cloud cover of about 50 percent extends only from about mid-July to mid-August.

Figure 12 gives an approximate measure of supply (solar radiation received) versus demand (based upon heating and cooling degree days). Heating degree days

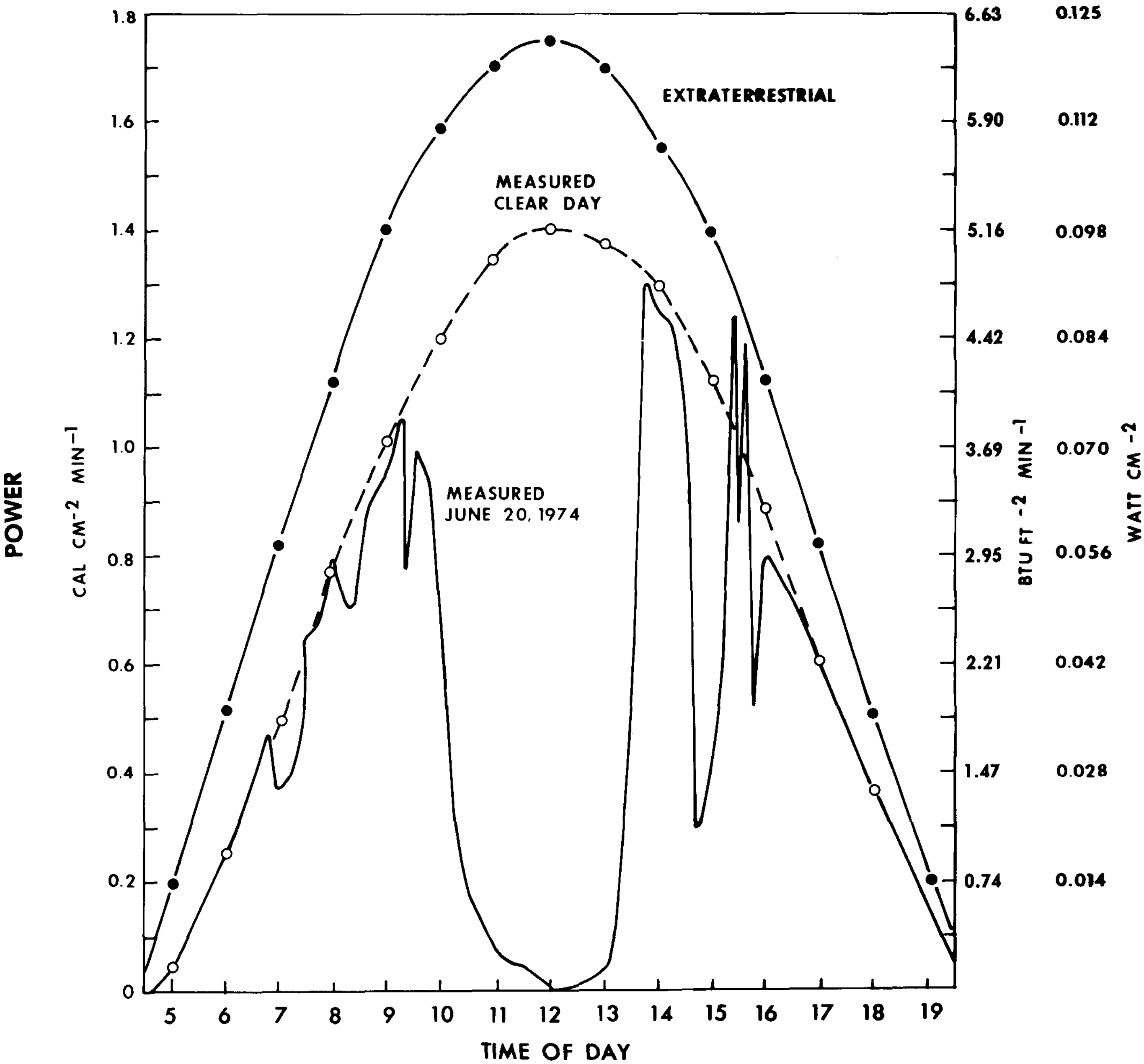

Fig. 13. Solar radiation at St. Paul, June 20, 1974. Outer curve is the extraterrestrial radiation at 45°N, dashed line is the radiation expected on a clear day, and inner solid line is the actual radiation received. An intense storm with dense cloud cover passed over St. Paul between about 1000-1300 hours (10 A.M.-1 P.M.).

are derived from air temperature measurements. Fuel suppliers have found that cumulative heating degree days correlate quite well with fuel consumption for the heating of homes and offices, except in those areas where wind becomes an important factor in heat removal as in the Great Plains. The heating degree days rise to a maximum in mid-January and closely approximate energy requirements for heating. Similarly, cooling degree days are derived from air temperatures, and the number of the calculated cooling degree days correlates with energy demand for the cooling of homes and buildings. The third curve in figure 12 is the smoothed mean weekly radiation values as measured at St. Cloud. It is apparent that the cooling degree days are approximately in phase with incoming solar radiation. It is unfortunate that the heating degree days are out of phase with solar radiation indicating that the solar radiation received may be insufficient to meet the demand.

The two following examples give an idea of the requirements for a "backup" or "reservoir" system if solar radiation is used as the energy source. Figure 13 depicts an admittedly extreme case, but nevertheless a situation that should be reckoned with when planning the energy system. On June 20, 1974, an extremely heavy thunderstorm associated with a squall line passed over the Twin Cities during midday. The storm produced heavy cloud cover which greatly restricted the radiation received from about 1000-1300 hours. Of special note is that the measured radiation dropped to zero at noon and remained at this level for nearly 20 minutes. During this period there was not even any measurable diffuse radiation, and it was so dark that the street lights came on and birds nested as for night. In addition, occasional clouds obscured the sun several times from 1430-1600 hours. This is not unlike what happens on a typical summer day when the solar radiation fluctuates rapidly between diffuse and full sunlight as cumulus clouds pass overhead.

Based upon the solar radiation measured at the University of Minnesota St. Paul Campus weather station, probabilities of certain low values of radiation have been determined for the colder half of the year. The probabilities for the period October-March are shown in table 2. Probabilities such as these should be of value for the design of the energy reserve or backup systems. Special note should be made of December, the month in which the combination of short days and large amount of cloud cover make the reception of adequate amounts of solar radiation highly problematical.

Table 2. Average frequency of occurrence of days with the indicated amounts of total daily solar radiation at St. Paul, 1967-1975.

	Average frequency of radiation equal to or less than					
	50 cal $cm^{-2}day^{-1}$*		100 cal $cm^{-2}day^{-1}$†		150 cal $cm^{-2}day^{-1}$‡	
Month	Days	%	Days	%	Days	%
October	2.9	9.3	7.0	22.6	10.6	34.1
November	6.2	20.7	13.6	45.2	18.9	63.0
December	6.7	21.8	16.4	52.8	22.6	13.0
January	2.9	9.3	8.8	28.3	13.7	44.1
February	0.6	2.0	2.4	8.7	5.7	20.1
March	0.8	2.5	2.9	9.3	5.6	17.9

*50 cal $cm^{-2}day^{-1}$=184 BTU $ft^{-2}day^{-1}$=3.49 Watts cm^{-2}
†100 cal $cm^{-2}day^{-1}$=369 BTU $ft^{-2}day^{-1}$=6.97 Watts cm^{-2}
‡150 cal $cm^{-2}day^{-1}$=553 BTU $ft^{-2}day^{-1}$=10.5 Watts cm^{-2}

November and December constitute the minimum radiation reception months, as is apparent in table 2. This table also shows the rapid change in the frequency of occurrence found between October and November and again between December and January. The latter is more significant, since January is normally the coldest month and heating demands reach a maximum at this time.

Of perhaps even more concern than the probability of certain low radiation values occurring is information indicating the duration of the low values. Tables 3, 4, and 5 provide this information for the same total daily radiation values for which the frequencies shown in table 2 were determined. These three tables show the frequency that runs of days have occurred in which the total daily radiation failed to exceed the indicated amount. In the period available for study, the longest continuous run of days in which the radiation never exceeded 150 cal cm^{-2} was one run of 23 consecutive days in November, 1972. It has already been noted that the months of November and December stand out as months with short days and maximum frequency of overcast conditions. It is no surprise then that the longest runs of days in which the radiation never exceeds certain low daily totals are to be found in these same 2 months.

Table 3. Average occurrence per month of runs of days in which the total daily solar radiation failed to exceed 50 cal $cm^{-2}day^{-1}$* at St. Paul, 1967-1975.

Runs In	Month					
days	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
1	1.1	2.3	2.9	2.2	0.6	0.6
2	0.6	1.1	0.8	0.3	—	0.1
3	0.2	0.6	0.3	—	—	—
4	—	—	0.2	—	—	—

* 50 cal $cm^{-2}day^{-1}$= 184 BTU $ft^{-2}day^{-1}$=3.49 Watt cm^{-2}.

Table 4. Average occurrence per month of runs of days in which the total daily solar radiation failed to exceed 100 cal $cm^{-2}day^{-1}$* at St. Paul, 1967-1975.

Runs In	Month					
days	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
1	2.9	2.1	2.9	5.1	1.7	1.4
2	1.0	1.7	1.2	0.9	0.2	0.6
3	0.6	1.1	0.4	—	0.1	0.1
4	0.1	0.3	0.4	0.1	—	—
5	—	0.2	0.6	0.1	—	—
6	—	0.2	0.1	—	—	—
7	—	—	0.2	—	—	—
8	—	—	—	0.1	—	—
9	—	0.1	—	—	—	—
10	—	—	0.1	—	—	—

* 100 cal $cm^{-2}day^{-1}$=369 BTU $ft^{-2}day^{-1}$=6.97 Watts cm^{-2}.

Table 5. Average occurrence per month of runs of days in which the total daily solar radiation failed to exceed 150 cal $cm^{-2}day^{-1}$* at St. Paul, 1967-1975.

Runs In	Month					
days	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
1	3.0	1.7	1.1	4.3	2.8	1.9
2	0.8	1.1	1.1	2.0	0.9	1.1
3	0.9	1.7	0.4	0.6	0.2	0.3
4	0.7	0.2	0.4	0.2	0.1	0.1
5	—	—	0.6	0.2	—	—
6	0.1	0.2	—	—	—	—
7	—	0.1	0.3	0.1	—	—
8	—	—	0.3	0.1	—	—
9	—	—	0.1	—	—	—
10	—	—	0.2	—	—	—
11	—	0.1	0.1	—	—	—
12	—	0.1	—	—	—	—
13	—	—	0.1	—	—	—
**	—	—	—	—	—	
17	—	0.1	—	—	—	—
**	—	—	—	—	—	—
23	—	0.1	—	—	—	—

* 150 cal $cm^{-2}day^{-1}$=553 BTU $ft^{-2}day^{-1}$=10.5 Watts cm^{-2}.
** Runs of days not listed did not occur during this period.

Wind

Even though wind is measured at many more locations than is solar radiation, (table 6), knowledge of the wind remains unsatisfactory. There are several reasons for this, but the most important is the lack of uniformity with respect to wind measurements. The height of the sensor is a matter of particular concern, as will be noted later; yet the wind seldom is measured at the supposedly standard height of 10 meters. The presence of nearby obstructions, such as trees and buildings, or variations in the local topography, which alter the direction and speed of wind, is an additional reason. Frequently these factors, particularly topography, cannot be controlled.

A factor of less importance is that although the wind may be measured and recorded continuously, the published data of the National Weather Service are based only upon the value registered on the hour. The data are not a mean of the continuous readings.

The Minneapolis-St. Paul International Airport data may serve as an example of problems associated with some of the wind data. During the period 1945-1970 the anemometer height varied as follows (14). It was 73 to 74 feet above ground on top of the control tower from 1945-1952. Through 1970 it was placed at 21 feet above ground (14) adjacent to a runway. Another source (20) indicates that the move to 21 feet was not made until 1958. It remains at this height today. This last position possibly has created a special problem, for the measurements may have been subjected to an added variation with the passage of large jet aircraft along the runway.

Table 6. Location of solar radiation and wind measurement stations in Minnesota and immediate environs.

Climatic Element	Location	Organization and Remarks*
Solar Radiation	St. Cloud Airport	National Weather Service; publication of data ceased September, 1972.
Solar Radiation	St. Paul Campus, St. Paul	University of Minnesota; data unpublished
Wind	Alexandria Airport	Federal Airways Administration (FAA)
Wind	Duluth Airport	National Weather Service (NWS)
Wind	Hibbing Airport	FAA
Wind	International Falls Airport	NWS
Wind	Minneapolis-St. Paul Airport	NWS
Wind	Redwood Falls Airport	FAA
Wind	Rochester Airport	NWS
Wind	St. Cloud Airport	NWS (Recorded only 18 hours per day)
Wind	Fargo, N.D. Airport	NWS
Wind	LaCrosse, Wisconsin Airport	NWS
Wind	Mason City, Iowa Airport	NWS
Wind	Sioux Falls, S.D. Airport	NWS

*Wind data are taken at several other airports but duration and availability of the data remain questionable.

An example of the wind sensor height problem and how it may affect results is illustrated in figures 14 and 15. The monthly mean wind speeds shown in figure 14 have been plotted as published without regard to anemometer height. The data indicate that highest wind speeds occur at Fargo. However, investigation reveals that during most of the 10-year period that the data represent, the wind sensor was 86 feet above the ground at Fargo compared to 53 feet at Duluth and only 21 feet at Minneapolis-St. Paul. Figure 15 shows how little the variation between the stations amounts to on an average monthly wind speed basis when the station data are corrected to a standard height of 10 meters, assuming heights of 86, 53, and 21 feet above the ground at Fargo, Duluth, and Minneapolis respectively. The correction was obtained using the generally accepted power law wind formula $(u_2/u_1)=(Z_2/Z_1)^a$ where $a=0.14$.

With the preceding paragraphs serving as a note of caution with respect to wind data, a general view of wind as a power source in Minnesota follows.

Figure 16 delineates a tentative pattern of the average annual available wind power for the United States. This map indicates about five areas where wind is sufficiently strong that it might be an acceptable power source: the northwestern and northeastern coasts, the western Great Plains from Montana southward to northern Texas, the valley of the Red River of the North, and portions of the Great Lakes area.

For the Minneapolis-St. Paul airport station, the mean power per month available from the wind is shown in figure 17. The data used in the power calculation are from a 1945-1970 summary of the wind data (11). This source shows a lower mean wind speed than the 1951-1960 data upon which figure 16 is based. For this reason the Twin Cities' mean annual power as shown in figure 17 is equal to only about 97 watts m^{-2} (0.14 cal $cm^{-2}min^{-1}$), while in figure 16 the value is close to 150 watts m^{-2} (0.21 cal $cm^{-2}min^{-1}$). Except for the different time periods of the two summaries, the difference in wind speeds cannot be explained at this time.

Figure 17 shows the characteristic maximum of April, the windiest month of the year, with a secondary maximum in November. On the average, the lowest available power occurs in July and August. The maximum and minimum follow the mean monthly wind speed, as is to be expected, although they are accentuated in the case of power. This is because wind power is a cubic function of wind speed. Wind power equals $\frac{1}{2} \rho Au^3$ where ρ is the air density, A the cross-sectional area perpendicular to the air movement, and u the wind speed. Thus, when the wind speed doubles, the power increases eight times. Because of this relationship between wind speed and power, it is important that the wind turbine be placed where the air movement is as free of obstructions as possible. This usually means that

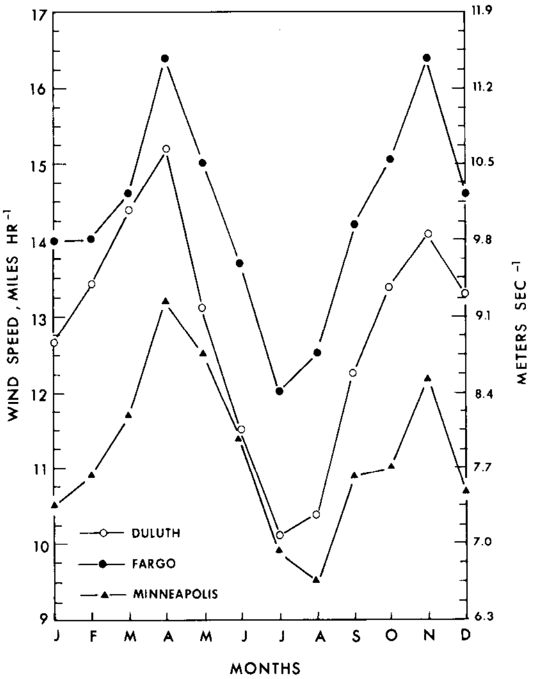

Fig. 14. Average daily wind speed at Duluth, Fargo, and Minneapolis-St. Paul. Data are from (18, 19, 20). The data have not been corrected for anemometer height differences.

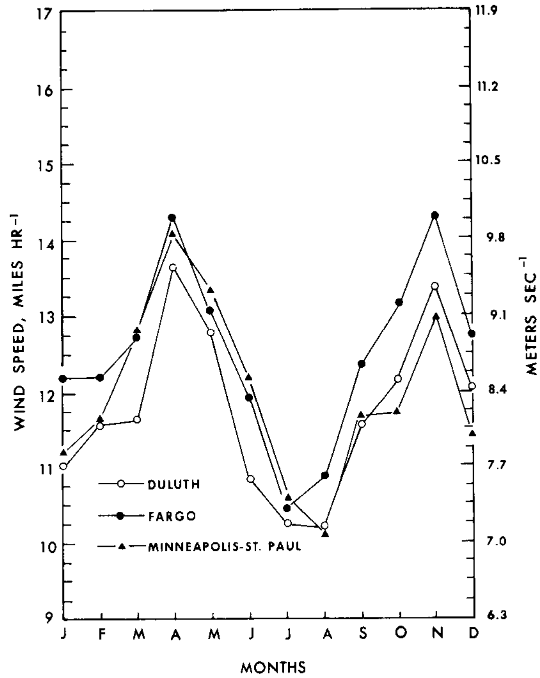

Fig. 15. Average daily wind speed at Duluth, Fargo, and Minneapolis-St. Paul. The basic data (18, 19, 20) have been corrected to the standard 10 meter anemometer height.

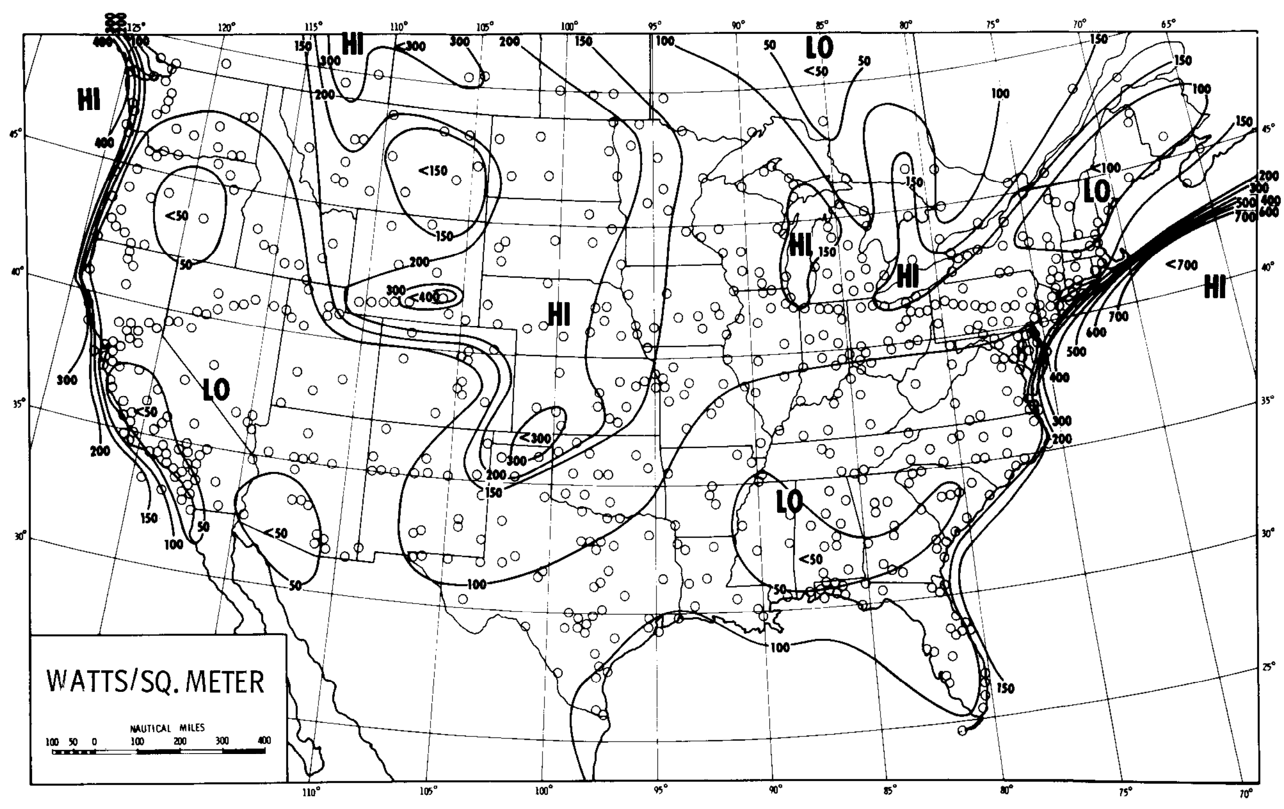

Fig. 16. Average annual wind power in watts m^{-2}. One hundred wm^{-2}=0.14 cal $cm^{-2}day^{-1}$=0.57 BTU $ft^{-2}day^{-1}$. Map based upon wind data for the period 1951-1960 and is from (10).

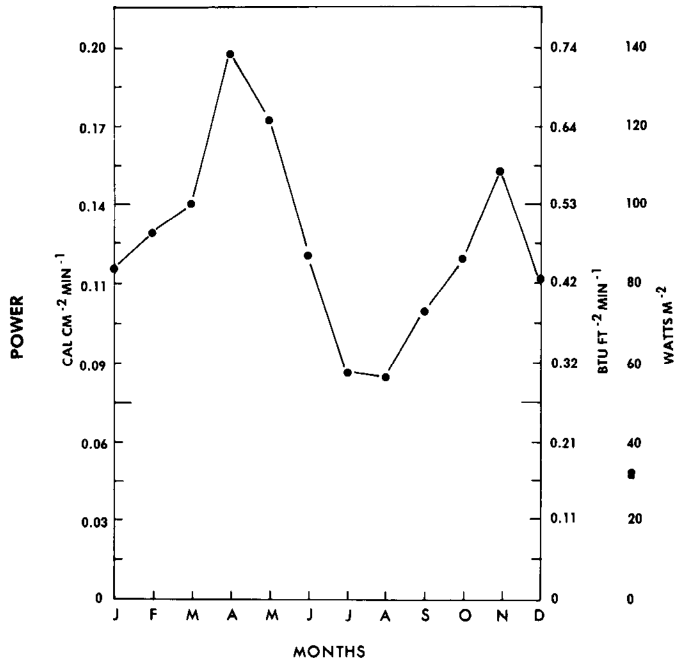

Fig. 17. Average monthly wind power at Minneapolis-St. Paul. The power calculations are based on a wind data summary for the period 1945-1970 (14).

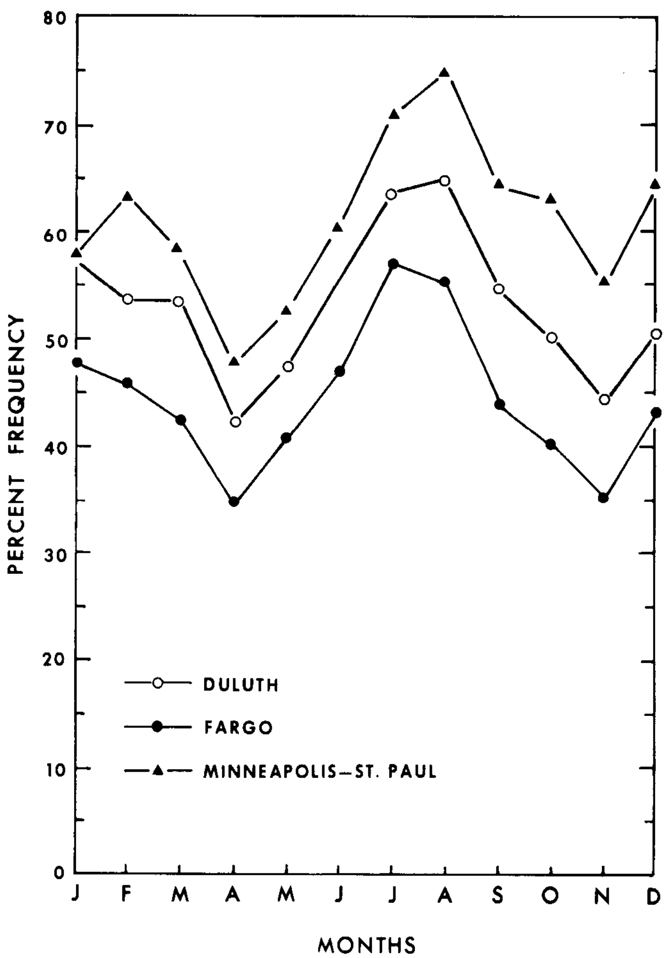

Fig. 18. Average monthly frequency of winds less than 13 miles per hour (9.1 m sec^{-1}) at Duluth, Fargo and Minneapolis-St. Paul. Data are from (18, 19, 20).

the turbine or mill is placed as high above ground as is practical.

Because power is a cubic function of the wind speed, the wind power calculation requires that the frequency distribution of wind speeds be known. The calculation cannot be made using simply the mean wind speed.

Wind speeds of about 10 miles per hour or less are presently impractical as an energy source using the more commonly available mills and turbines (10). Although the frequency distribution of wind speeds in certain climatological summaries (18, 19, 20, 21) do not permit a determination at exactly that speed, the frequencies of speeds at Duluth, Fargo, and Minneapolis-St. Paul less than 13 miles per hour are shown in figure 18. This will give a reasonable approximation of the amount of time when the wind is unavailable as a power source at the three stations. The peak availability of wind occurs March-April-May and again in November.

As mentioned earlier, the wind is a force created by the sun. As such the wind shows, at least in the lower levels of the atmosphere, a marked diurnal effect. This effect is clearly shown in figure 19 where wind speeds of at least 11 miles per hour reach a maximum between 1200 to 1400 hours, normally the warmest hours of the day. With April the month of strongest mean winds and August the month of lowest mean speeds, the other 10 months fit between the frequencies shown for those 2 months.

Just as wind in the lower levels of the atmosphere shows a maximum speed during the daylight hours, an effect that may be observed up to several hundred feet above the earth's surface, the lack of air movement shows a decided maximum in the dark hours. Figure 20 illustrates this phenomenon with respect to the frequency of calm hours during an average day. Normally April has the least number of calm periods, August the most, and the other months have frequencies between these two.

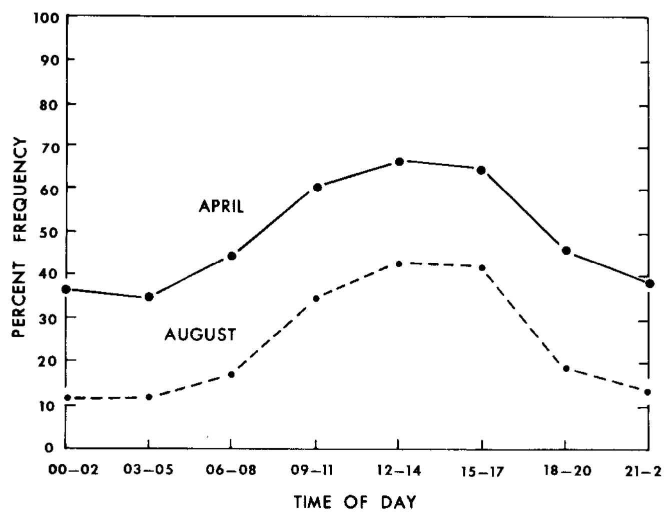

Fig. 19. Average annual frequency of wind speeds of at least 11 miles per hour (7.7 m sec^{-1}) for each 3-hour period of the day in April and August at Minneapolis-St. Paul, 1945-1970. Frequencies of other months fall between the two months shown. Data are from (14).

Figures 19 and 20 illustrate the major drawback to wind as an alternative energy source. It is lacking in persistence, at least at practical heights for most wind mills or turbines. Note a study by Justus, et al. (7) on the capacity factor of a wind-powered generator. (The capacity factor is defined as the fraction of the generator output that could be realized versus its rated output.) For a generator with a cut-in speed of 8 mph, a rated speed of 18 mph, and at a height of 200 feet, the capacity factor was calculated on an average annual basis to be no less than 50 percent over the entire state. A maximum capacity factor of about 70 percent was found for the extreme southwestern part of the state and 60 percent or greater over about two-thirds of the state. For a wind generator with the same characteristics but at one-half the height (100 feet), the capacity factor would be only 30 percent at a site with a mean annual wind speed of 10 mph.

The naturally occurring interruptions in wind are a major drawback which, however, could be overcome with energy storage facilities of sufficient capacity. It is interesting that an investigation has stated that under the climatic conditions of Denmark wind energy can become as dependable as a large nuclear plant, if the associated storage system could replace the average required power output for about a 10-hour period (12).

In this regard the duration of wind power per unit area (wind power density) for certain wind speeds is shown in table 7. The power calculations were made assuming a constant 50°F air density and a wind speed equal to the mid-value of each class. No correction was attempted for anemometer height variations between the stations. The determination of the annual amount of time the wind will provide a given power density can be obtained from the table. For example, during 87 percent of the year, or 7630 hours, the power density will not exceed 3.0×10^{-1} cal cm^{-2}min^{-1} at Des Moines, while at Fargo this low power density occurs somewhat less frequently, or 76 percent of the year.

The expected duration of a given wind power density is shown in greater detail in table 8 for the months of April and August at Duluth, Fargo, and Minneapolis-St. Paul. These data are based upon the 10-year 1951-1960

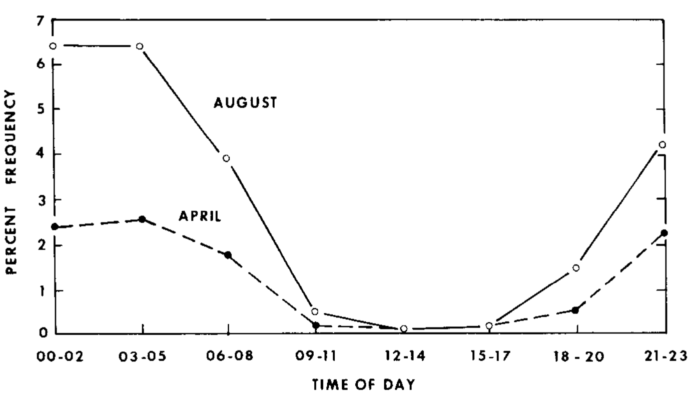

Fig. 20. Average annual frequency of calm periods for each 3-hour period of the day in April and August at Minneapolis-St. Paul, 1945-1970. Frequencies of other months fall between the 2 months shown. Data are from (14).

Table 7. Annual cumulative frequencies of wind speed classes (18, 19, 20, 21) and the associated wind power densities at Des Moines, Duluth, Fargo, and Minneapolis-St. Paul.

Wind speed	Power density	Cumulative frequency of wind speed occurrences			
		Des Moines	Duluth	Fargo	Minneapolis
0 Mi Hr^{-1}	0.0 cal cm^{-2}min^{-1}	1%	1%	1%	1%
1-3	0.7×10^{-3}	3	6	4	8
4-7	1.4×10^{-2}	21	21	17	28
8-12	8.6×10^{-2}	58	54	44	62
13-18	3.0×10^{-1}	87	85	76	89
19-24	8.2×10^{-1}	97	96	91	89
25-31	1.8	99	99	98	100
32-38	3.5	100	100	99	—
39-46	6.3	—	—	100	—

Table 8. The cumulative frequency of wind speed classes and the associated power densities in April and August at Duluth, Fargo, and Minneapolis-St. Paul.

Wind speed	Power density	Cumulative frequency of wind speed occurrences		
		Duluth	Fargo	Minneapolis
		April		
0 Mi hr^{-1}	0.0 cal cm^{-2}min^{-1}	1%	1%	1%
1-3	0.7×10^{-3}	4	2	6
4-7	1.4×10^{-2}	15	11	21
8-12	8.6×10^{-2}	42	35	48
13-18	3.0×10^{-1}	75	65	80
19-24	8.2×10^{-1}	91	85	95
25-31	1.8	98	95	99
32-38	3.5	99	99	100
39-46	6.3	100	100	—
		August		
0	0.0	2	1	2
1-3	0.7×10^{-3}	7	5	12
4-7	1.4×10^{-2}	25	21	36
8-12	8.6×10^{-2}	65	55	75
13-18	3.0×10^{-1}	94	85	96
19-24	8.2×10^{-1}	99	96	100
25-31	1.8	100	99	—
32-38	3.5	—	100	—

wind record at each of the stations (19, 20, 21). The great difference in wind speed occurrences between the 2 months is evident; there being a very small probability that the wind power density will exceed 8.2×10^{-1} cal cm^{-2}min^{-1} during August. There is not a great difference between the stations, though there is an apparent difference in favor of Fargo.

Wind movement adjacent to the earth's surface is retarded due to the friction created by the earth itself as well as obstructions above the surface. The rougher, more variable the surface is with respect to surface features, whether natural or manmade, the greater the reduction in the horizontal air movement. Therefore, in order to obtain equal wind speeds, a wind mill or turbine will have to be placed at a higher elevation in an area where the surface is aerodynamically rough due to the buildings or topographic variation than in an area with a smoother surface.

While wind speed normally increases with height, the frequency of calm periods decreases with height. Therefore, it should be noted that the frequencies shown in figure 18 and 19 would be higher and those in figure 20 would be lower than indicated for elevations higher than the sensors upon which the data in the three figures are based.

Figure 21 shows the calculated variation of wind speed with height based upon the mean wind speed at the Minneapolis-St. Paul International Airport. The results depict very graphically the drag and change in wind speed with height assuming the power law $(u_2/u_1)=(Z_2/Z_1)^a$ — where u is wind speed, Z is height, and a equals 0.14 — holds to a height of 1000 feet. The last point seems to be acceptable as reported by Sutton (13). The wind speed profiles in figure 21 show the two extreme months, August and April, and the annual average. The profiles of the other months fall between those of April and August. It should be understood that actual wind profiles at any moment can diverge greatly

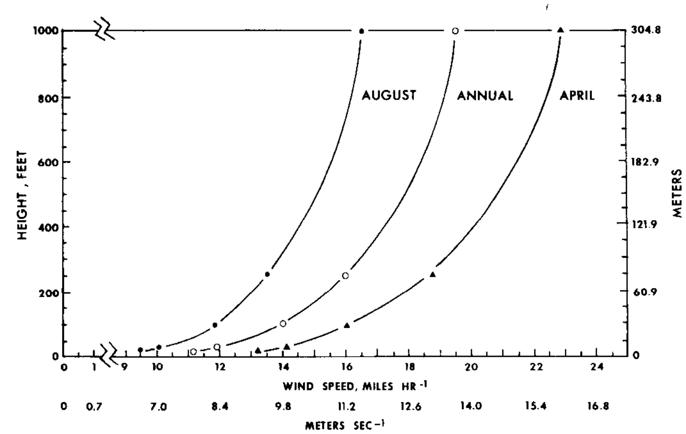

Fig. 21. Calculated average wind speed profile for Minneapolis-St. Paul. Calculations are based on data for the period 1951-1960 (20) as measured at 21 feet (6.4 m).

from what is shown in figure 21, which represents a statistical average over a period of some duration. The calculations indicate that under atmospheric conditions conductive to the power law wind profile, the wind speed measured at 21 feet above the surface will average about 80 percent of the speed at 100 feet, 70 percent of the 250-foot speed, 63 percent of the 500-foot speed, and 58 percent of that at 1000 feet.

Summary

It is evident that Minnesota's solar radiation and wind resources are relatively limited. The maximum availability of radiation occurs on the average in late June, July, and August. The minimum occurs on the average in late October, November, and December. The combination of short days, low sun angle, and cloudiness along with the colder temperatures makes this a most unfortunate combination for Minnesota's winter energy needs. On an optimistic note, the rather sharp decrease in cloudiness in January, making solar radiation a larger and more reliable energy source for the latter part of the winter, should be pointed out.

Wind resources appear to be marginal, with perhaps the best sites for wind turbines located along the upland just west of Lake Superior, in the Red River Valley area, and probably also in the southwestern corner of the state. The intermittent quality of wind in general, plus the relatively low wind speeds, make this form of energy seem to be of a secondary nature for Minnesota under present wind turbine technology.

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