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Solar Radiation in Iowa: The Historical Record

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Historical records spanning over 20 years have been analyzed to determine the long-term monthly average daily solar radiation falling on a horizontal surface in Ames, Iowa. This value has been used to estimate the long-term monthly average daily solar radiation falling on surfaces of other tilts (30°, 60°, and 90° relative to the horizontal) and orientations (at 30° intervals from south to north). Some important features of the results are described. A BASIC computer program is available which can be used to estimate the solar radiation on a surface of arbitrary tilt and orientation.

INDEX DESCRIPTORS: Iowa, solar radiation, insolation.

A variety of solar energy systems are now being installed for use in homes and other buildings in the U.S. Examples of such systems are passive solar space heating systems, active solar space and water heating systems, and photovoltaic systems. The proper design of these solar systems requires good methods of predicting their performance. Performance predictions require detailed knowledge of the physical characteristics of the system and of the climate at the location of the system. A very important type of data needed is solar radiation information.

While there are many existing methods of predicting the performance of solar systems, the most commonly used fall into two groups. The first group consists of detailed computer simulations of solar systems based on hourly (or even more frequent) data on solar radiation; examples are the simulations used to develop the information in Refs. 1 and 2. The second group consists of simpler calculation methods that use monthly averages of solar radiation.

Methods using monthly averages have proven extremely worthwhile, because they give results that are generally in adequate agreement with both experimental data and with the predictions of more sophisticated computer simulations. Two well-known and widely-used methods are the f-chart method for active solar space and water heating systems (1) and the solar load ratio method for passive solar space heating systems (2).

The necessary solar radiation information for a monthly average calculation method is the insolation (incident solar radiation) on the surface of the solar collector. The physical characteristics of the solar system and the nature of the load it is serving are then used to determine the amount of useful solar energy provided by the system.

The insolation needs to be known for surfaces oriented in arbitrary fashion. Surfaces may vary in tilt (angle relative to the horizontal) and in orientation (compass direction). Tilt angles range from 0° (a horizontal surface) to 90° (a vertical surface), while orientations are normally measured from due south (0°), positive westward; thus an east-facing roof with a 1:1 pitch has a tilt of 45° and an orientation of −90°. The nature of the load and local weather and other characteristics determine the optimum tilt and orientation for a solar system. Collectors for winter space heating are usually oriented towards the south in a vertical or nearly-vertical plane. Collectors for year-round domestic water heating are usually oriented in Iowa towards the south at a tilt of about 45 degrees. Collectors for outdoor summer swimming pool heating are usually placed horizontally.

In places where there is no significant east-west asymmetry in insolation, solar collectors are oriented towards the south for maximum solar collection. Thus insolation information for south-facing surfaces should suffice for most purposes and enable the designer of a solar system to carry out performance calculations at several tilt angles in order to determine the optimal tilt.

It is often found, however, that insolation information is required for non-south orientations at a variety of tilt angles. For example, an obstruction (such as a tree or building) may make it desirable to face the solar collector off due south. Or, an excellent view towards the west might dictate orienting a direct gain passive solar home more to the southwest. Or, the existence of a roof facing south-southeast might suggest mounting an active solar collector flush on that roof. All these examples are situations in which insolation data for arbitrary tilt and orientation are desirable.

Unfortunately, experimental information is not available on insolation at arbitrary tilt and orientation, either for Iowa or elsewhere. At many locations (including those in Iowa), insolation has been recorded only on horizontal surfaces. At a few locations in the United States insolation has been recorded on several south-facing surfaces at various tilts in order to develop models which allow the insolation at arbitrary tilt and orientation to be predicted from insolation on horizontal surfaces. These models are generally based on the pioneering work of Liu and Jordan (3). With the renewed interest in solar energy in recent years, there have been many articles published on the Liu-Jordan and later models, particularly in *Solar Energy.*

In order to provide the best possible insolation information for Iowa engineers and designers, a two-part program was begun several years ago. First, the existing insolation data for Iowa were analyzed and developed into a form suitable for use by Iowa engineers and designers. A preliminary analysis using engineering units was published by the Iowa State University Energy Extension Service (4). Second, a program was instituted to record insolation for a variety of tilts and orientations in order to build up a good insolation data base and to compare the results with those obtained from models. This article contains the results of the historical records of horizontal insolation in Ames, Iowa, and the predictions (based on those records) of monthly average daily insolation on surfaces of a variety of tilts and orientations. Future articles will contain data from the solar radiation monitoring program begun in 1981.

HISTORICAL RECORDS OF HORIZONTAL INSOLATION IN AMES

The only long-term records of solar radiation in Iowa are those which have been kept since the 1950s by Professors Robert Shaw, Richard Carlson, and associates in Meteorology-Climatology at Iowa State University in Ames (5). From 1959 to 1972 their daily records were published by the National Weather Service (6), but the records extend to the present day.

Records from July 1959 through May 1981 were analyzed in this study. The solar radiation record is not complete. Daily records are missing for a variety of reasons, such as vandalism and occasional problems with the Eppley pyranometers used as sensors or with the recording system. Nevertheless, good data exist for a minimum of 530 days for each month, equivalent to nearly 18 years of data.

Table 1. Average daily insolation on a horizontal surface in Ames, Iowa using measurements made between July 1959 and May 1981. Based on data from Ref. 5.

Month	Number of Measurements	Daily Average Langleys	Daily Average Btu/ft^2	Daily Average MJ/m^2
January	595	173	637	7.23
February	530	244	900	10.21
March	570	329	1211	13.75
April	530	385	1419	16.12
May	576	474	1746	19.83
June	554	550	2026	23.02
July	630	544	2006	22.78
August	604	465	1714	19.47
September	584	369	1360	15.45
October	613	268	987	11.20
November	560	164	604	6.86
December	574	136	501	5.69

Conversion factors:
1 langley = 1 calorie/cm^2 = 0.04184 MJ/m^2 = 3.686 Btu/ft^2
1 MJ/m^2 = 23.90 langleys = 88.11 Btu/ft^2
1 Btu/ft^2 = 0.01135 MJ/m^2 = 0.2713 langleys

Table 1 shows for each month of the year the number of measurements available and the average daily horizontal insolation in several units, including the Langleys in which the original records were kept. These numbers constitute the best available estimate of monthly average daily horizontal insolation for Iowa. Since they were taken in Ames they may be considered typical of central Iowa. Along the northern border of Iowa, the insolation would be a few percent less, while along the southern border of the state it is probably a few percent more, based on measurements published for other states. "A few percent" in this context means about five percent, but the exact figure will not be known until records are compiled for ten or more years throughout the state.

ESTIMATED INSOLATION ON TILTED SURFACES

The standard Liu-Jordan method for estimating the monthly average daily insolation on a tilted surface proceeds as follows (1, 3):

(1) The monthly average daily horizontal insolation H at a locality is compared to the monthly average daily horizontal extraterrestrial radiation H_o for that locality. The monthly average clearness index $K_T = H/H_o$ is determined from these quantities. Monthly average clearness values are typically in the range of .30 to .70, though the clearness index determined for individual days may range from nearly zero to over .80.

(2) The diffuse fraction of H is determined from the formula

$$H_d/H = 1.39 - 4.03\,K_T + 5.53\,(K_T)^2 - 3.11\,(K_T)^3 \quad \text{[Eq. 1]}$$

This is an empirical formula of Liu and Jordan (3), obtained from insolation data for both total and diffuse radiation. H_d/H is restricted to remain in the range 0 to 1, but for actual values of K_T it never approaches these limits. $K_T = 0.3$ corresponds to $H_d/H = 0.59$ while $K_T = 0.7$ corresponds to $H_d/H = 0.21$.

(3) The ratio R_b of extraterrestrial radiation on the tilted surface to the extraterrestrial radiation H_o on the horizontal surface is determined from geometrical considerations. For this purpose representative days are chosen for each month; these are normally taken to be January 17, February 16, March 16, April 15, May 15, June 11, July 17, August 16, September 15, October 15, November 14, and December 10. Formulas for R_b have been provided by Klein (7) and extended to northern-facing surfaces by Hodges (8).

(4) The monthly average daily insolation on the tilted surface is estimated by:

$$H_T = RH \quad \text{[Eq. 2]}$$

where

$$R = (1 - (H_d/H)R_b + (H_d/H)\,(1 + \cos s)/2 + r(1 - \cos s)/2 \quad \text{[Eq. 3]}$$

where s is the tilt of the surface (measured from the horizontal) and r is the average ground reflectance. This first term in Eq. 3 is the direct (or beam) term, which is taken to be the direct insolation on the horizontal surface multiplied by R_b. The second term is the diffuse term, which is taken to be proportional to the solid angle of sky "seen" by the tilted surface. The third term is the ground-reflection term, which is taken to be proportional to the solid angle of ground "seen" by the tilted surface. The second and third terms are based on the assumption that diffuse and reflected radiation are isotropic.

An interactive BASIC computer program to carry out these calculations has been written for the IBM Personal Computer. Contact the author for a copy or a listing.

The monthly average daily horizontal insolation values shown in Table 1 have been used to compute the monthly average daily insolation on surfaces with tilts of 30°, 60°, and 90° and orientations at 30° intervals from 0° (due south) to 180° (due north). The results are shown in Table 2.

The long-term average values of the clearness index K_T for Ames range from 0.45 in November to 0.57 in July.

In the calculations for Table 2 the average ground reflectance has been taken to be 0.50 in January, 0.45 in February, 0.35 in March, 0.20 in the months April through October, 0.25 in November, and 0.40 in December; these values are estimates based on an average ground reflectance of 0.20 in the absence of snow cover and 0.70 when there is snow cover, using the historical records from 1960 to 1980 for central Iowa. Only the results for west-facing surfaces are given since the model described above has no east-west asymmetry; for negative orientation angles the result is identical to that for the opposite (positive) orientation angle.

INTERESTING ASPECTS OF INSOLATION IN IOWA

Table 3 lists the tilts and orientations for which the maximum and minimum insolation occur each month. The maximum insolation is always on south-facing surfaces (0° orientation), ranging from a near-vertical tilt of 70° in December and January to a horizontal tilt in June. The minimum insolation is on north-facing surfaces (180° orientation) for every month except June, when the model actually predicts a minimum for a vertical south-facing surface. If the June result seems peculiar, remember that in the northern hemisphere south of the Tropic of Cancer, the sun does not even shine on the south side of a building near the June solstice; in central Iowa at the June solstice, the sun shines on the south side for only about 8 of the 15 hours of daylight, and when it does, it is at a very high altitude. When the minimum insolation occurs for a north-facing surface, as it does for every month except June, it is usually for a vertical surface because the diffused sunlight is brighter than ground-reflected sunlight and the vertical surface sees the most ground. In January and February the minimum insolation is at a low tilt because, at least according to the Liu-Jordan model, there is more sunlight reflected from the ground than diffused from the sky; this is due to the partial snow cover during those months.

Some very interesting (and useful) information can be gleaned from the information presented in Table 2. As an example, Table 4 shows the monthly average daily insolation on south-, west-, and north-facing surfaces. This clearly shows the advantages of south windows, which admit much more solar heat in winter than in summer, and the disadvantages of west windows, which admit much more solar heat in summer than in winter.

Table 2. Calculated monthly average daily isolation (in MJ/m^2) on tilted surfaces in Ames, Iowa. Tilt angles are in degrees measured from the horizontal and the orientation is in degrees measured from true south.

		Orientation						
Month	Tilt	0°	30°	60°	90°	120°	150°	180°
January	30°	12.5	11.8	9.9	7.5	5.1	3.1	2.6
	60°	15.3	14.0	11.0	7.6	4.5	2.8	2.8
	90°	14.8	13.3	10.2	7.1	4.3	3.1	3.1
February	30°	15.0	14.3	12.6	10.4	7.9	5.6	4.3
	60°	16.9	15.7	13.3	10.2	6.9	4.2	3.8
	90°	15.4	14.1	11.9	9.2	6.3	4.3	4.1
March	30°	17.1	16.7	15.5	13.6	11.4	9.2	8.0
	60°	17.2	16.7	15.2	12.8	9.7	6.5	4.8
	90°	13.9	13.7	12.9	11.0	8.3	5.8	4.8
April	30°	17.1	17.1	16.6	15.6	14.1	12.7	12.1
	60°	14.9	15.1	15.0	13.8	11.6	8.8	6.4
	90°	10.0	10.9	11.5	10.9	9.1	6.7	5.1
May	30°	19.2	19.3	19.4	19.0	18.0	17.1	17.0
	60°	15.2	16.0	16.8	16.6	14.9	12.1	11.1
	90°	9.2	10.6	12.5	12.9	11.6	9.0	7.3
June	30°	21.3	21.6	22.0	21.9	21.3	20.8	20.8
	60°	16.2	17.1	18.7	19.0	17.7	14.6	14.6
	90°	9.1	10.8	13.6	14.7	13.6	10.9	9.2
July	30°	21.5	21.7	22.0	21.8	20.9	20.1	20.0
	60°	16.6	17.6	18.9	18.9	17.3	14.2	13.5
	90°	9.6	11.3	13.9	14.7	13.4	10.4	8.6
August	30°	19.9	20.0	19.7	18.7	17.2	15.7	15.3
	60°	16.7	17.3	17.5	16.6	14.2	10.8	8.5
	90°	10.6	12.0	13.3	13.0	11.1	8.1	6.1
September	30°	18.0	17.7	16.7	15.1	13.0	10.9	9.9
	60°	16.9	16.7	15.7	13.6	10.6	7.2	4.8
	90°	12.3	12.6	12.4	10.9	8.3	5.6	4.2
October	30°	15.4	14.8	13.2	11.1	8.7	6.4	5.1
	60°	16.3	15.3	13.2	10.3	7.1	4.2	3.5
	90°	13.6	12.6	10.9	8.4	5.6	3.5	3.1
November	30°	10.8	10.2	8.8	6.9	5.0	3.4	2.8
	60°	12.5	11.4	9.2	6.6	4.1	2.6	2.5
	90°	11.4	10.2	8.0	5.6	3.4	2.3	2.3
December	30°	10.0	9.4	7.8	5.9	4.0	2.5	2.3
	60°	12.2	11.1	8.6	5.9	3.4	2.3	2.3
	90°	11.8	10.5	7.9	5.3	3.1	2.3	2.3

Table 3. Monthly extrema of average daily insolation and the tilt and orientation angles at which they occur.

	Maximum			Minimum		
Month	MJ/m^2	Tilt	Orientation	MJ/m^2	Tilt	Orientation
January	15.5	70°	0°	2.6	27°	180°
February	16.9	61°	0°	3.6	36°	180°
March	17.6	46°	0°	4.8	46°	180°
April	17.2	24°	0°	5.1	90°	180°
May	20.0	9°	0°	7.3	90°	180°
June	23.0	0°	0°	9.1	90°	0°
July	22.8	5°	0°	8.6	90°	180°
August	20.2	19°	0°	6.1	90°	180°
September	18.1	36°	0°	4.4	90°	180°
October	16.4	52°	0°	3.9	90°	180°
November	12.5	63°	0°	2.3	90°	180°
December	12.4	70°	0°	2.3	90°	180°

Table 4. Monthly average daily insolation (in MJ/m^2) on north, east (or west), and south vertical surfaces.

Month	North	East/West	South
January	3.1	7.1	14.8
February	4.1	9.2	15.4
March	4.8	11.0	13.9
April	5.1	10.9	10.0
May	7.3	12.9	9.2
June	9.2	14.7	9.1
July	8.6	14.7	9.6
August	6.1	13.0	10.6
September	4.2	10.9	12.3
October	3.1	8.4	13.6
November	2.3	5.6	11.4
December	2.3	5.3	11.8

COMMENTS

The information presented in this article contains the best presently-available data about insolation in central Iowa. It can be used for many purposes, particularly for predicting the performance of solar systems of all types.

Nevertheless, a caveat is in order. For each month, only one datum is experimentally determined: the monthly average daily horizontal insolation. All the other data, including the insolation on vertical surfaces at all compass directions, have been derived using the Liu-Jordan model and its formulas described above. The Liu-Jordan model was developed using experimental information for tilted surfaces facing due south, and it is not known how accurate the model is for non-south orientations.

There is now an experimental program at Iowa State University to collect insolation data for a variety of different tilts and orientations in order to check the Liu-Jordan model and to build up a long-term insolation data base for Iowa. At present this program involves measurements made only in Ames, but it is hoped it will be possible to make similar measurements elsewhere in Iowa in order to check the variability of insolation across the state.

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