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Solar Radiation Availability for New Mexico

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Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29-1)-789

Printed February 1977

Sandia Laboratories
energy report

SF 2900 QQ8(3-74)

Printed in the United States of America

Available from:
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy $3.00; Microfiche $3.00

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SOLAR RADIATION AVAILABILITY FOR NEW MEXICO*

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* This work sponsored by the United States Energy Research and Development Administration

I. Introduction

In order to design a solar system or to make a prediction regarding its performance, we need to know the amount of solar energy which will be available to the system. This article gives an elementary description of the basic geometric considerations and background information on solar radiation availability. In addition, tables giving both average and clear day solar energy availabilities in the four seasons are presented. The solar energy available to a collector depends on the collector type and its orientation. The availabilities are presented for a wide variety of possible surface orientations, including orientations for focusing collectors, tracking collectors, and fixed collectors.

II. Background Information

Solar energy is called solar radiation because it is energy in the form of electromagnetic radiation from the sun. Most of this solar radiation is in the form of light --sunlight-- but a significant portion is invisible, infrared radiation.

The intensity of solar radiation just outside the earth's atmosphere is 1.36 kW/m^2 (431 Btu/ft^2 hr). The intensity of this so-called "extra-terrestrial" solar radiation varies from about 1.40 kW/m^2 in early January to 1.32 kW/m^2, in July due to the variation in the distance between the earth and sun. The average figure, 1.36 kW/m^2, is called the "solar constant," even though the value is almost certainly variable.

As we all know, the solar intensity at the earth's surface is highly variable. The variations are primarily due to (a) the motion of the earth, which causes daily and seasonal variations, and (b) the atmosphere, which absorbs and scatters radiation.

The effects due to the earth's motion are geometric in nature; the angle of incidence of the sun's rays on any surface varies with the motion of the earth, unless that surface is rotated so as to "track the sun." The solar intensity on a surface is greatest when their incidence angle is 90°; in this case, the surface is said to be "normal" to the sun's rays. For other incidence angles, the intensity drops off from this maximum by a factor equal to the sin of the incidence angle.

The largest atmospheric effects on solar radiation intensity are due to clouds. Cloud cover can reduce solar radiation by 90% from clear day intensities. Clouds also produce large variations in the availability of solar radiation from one year to the next.

There are three basic types of solar radiation on earth. Direct radiation is that which comes directly from the sun, the radiation which casts shadows. Diffuse radiation is the radiation which comes from clouds and the sky. Total radiation is the sum of these two. Diffuse radiation is generally only about 10 to 20 percent of total radiation on clear days in the Southwest; 80 or 90 percent is direct. On cloudy days, the total radiation consists entirely of diffuse radiation and is quite low.

Designers of solar energy systems need to know how much solar radiation per square meter will be available to their collectors in order to size the collectors. These solar energy availabilities depend strongly on the season and on the particular orientation of the collectors. For instance, it's obvious that a horizontal collector receives more solar radiation in the summer than in the winter; this is what causes the seasons. It is also obvious that a collector facing North is pretty useless in the Northern hemisphere. Not quite so obvious in the fact that a South facing vertical surface receives nearly twice as much solar radiation as a horizontal surface in the winter in New Mexico.

The <u>intensity</u> of solar radiation on a fixed collector also varies a great deal during the day and depends on the collector's orientation.

III. Geometric Considerations

The sun's apparent paths across the sky in different seasons are illustrated in Figure 3.1. These paths are for a latitude of 34°, which is approximately the latitude of Socorro, New Mexico; the paths are not much different for the rest of the state. To understand these drawings, one must pretend to be an observer located at point O. Note that the paths for June 21 (the summer solstice) and December 21 (the winter solstice) are the extremes; the paths for all other days of the year lie between these.

The sun's position in the sky for different times of day and differ[illegible] is given in Table 3.1. In this table the altitude angle α gives the [illegible]ition above the horizon, and the azimuth angle β is the sun's angular pc[illegible]m South. These solar position angle definitions are displayed in Figure 3.2. The times used in Table 3.1 are <u>solar</u> times; solar time can be conveniently treated as standard time shifted forward or backward sufficiently so that solar noon occurs when the sun is due South.

The latitudes used in Table 3.1 span most of New Mexico; 32° corresponds to the southern border of the eastern part of New Mexico, and 37° is the latitude of the northern border of the state. Interpolation between these latitudes will give reasonably good solar position angles for other points in the state.

It is also possible to calculate the sun's position angle directly using formulas given in the appendix of this article.

Another generally useful formula is the formula giving the incidence angle of direct solar radiation on any surface. This formula uses the sun's position - its altitude α and azimuth β - and the surface's orientation. We describe the orientation

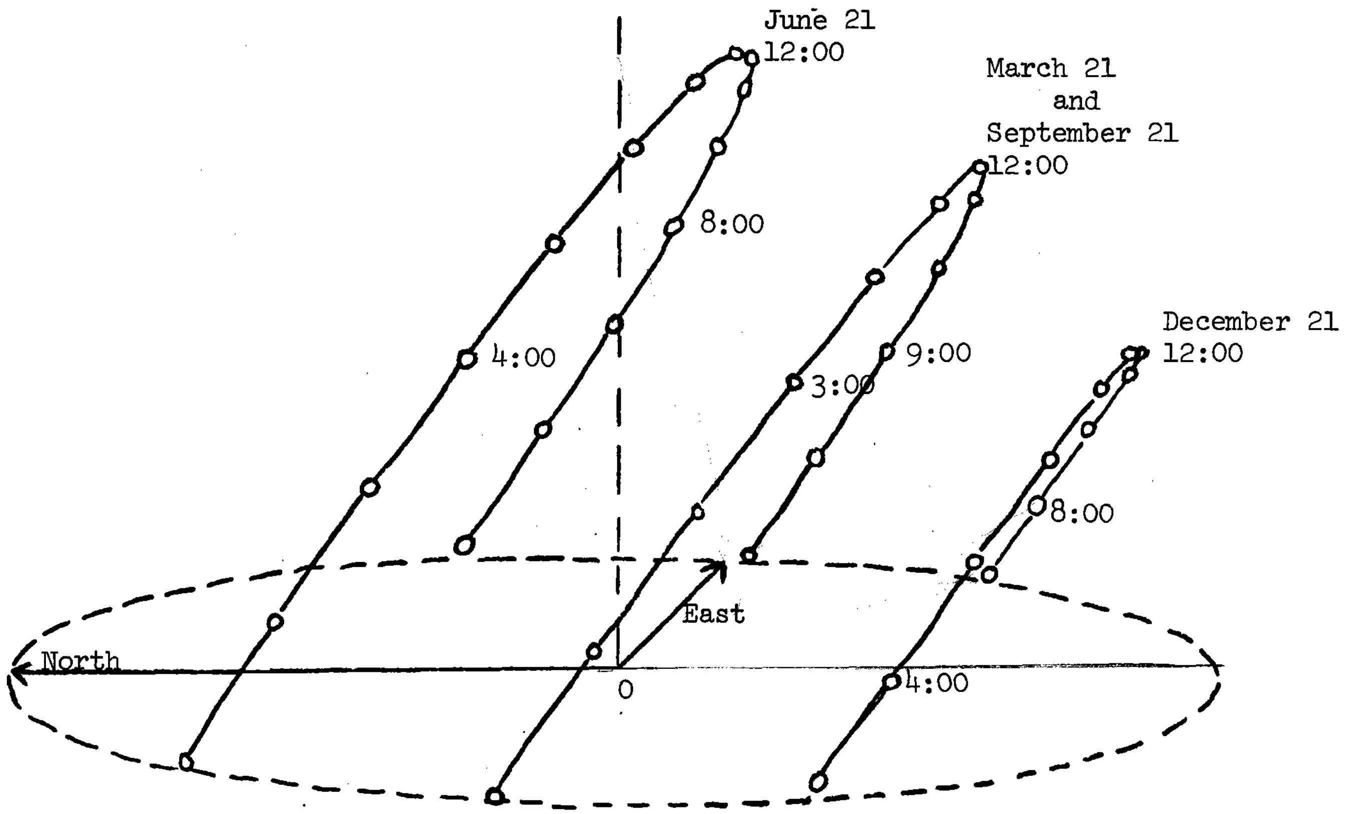

Figure 3.1. The sun's paths across the sky as seen by an observer at point O.

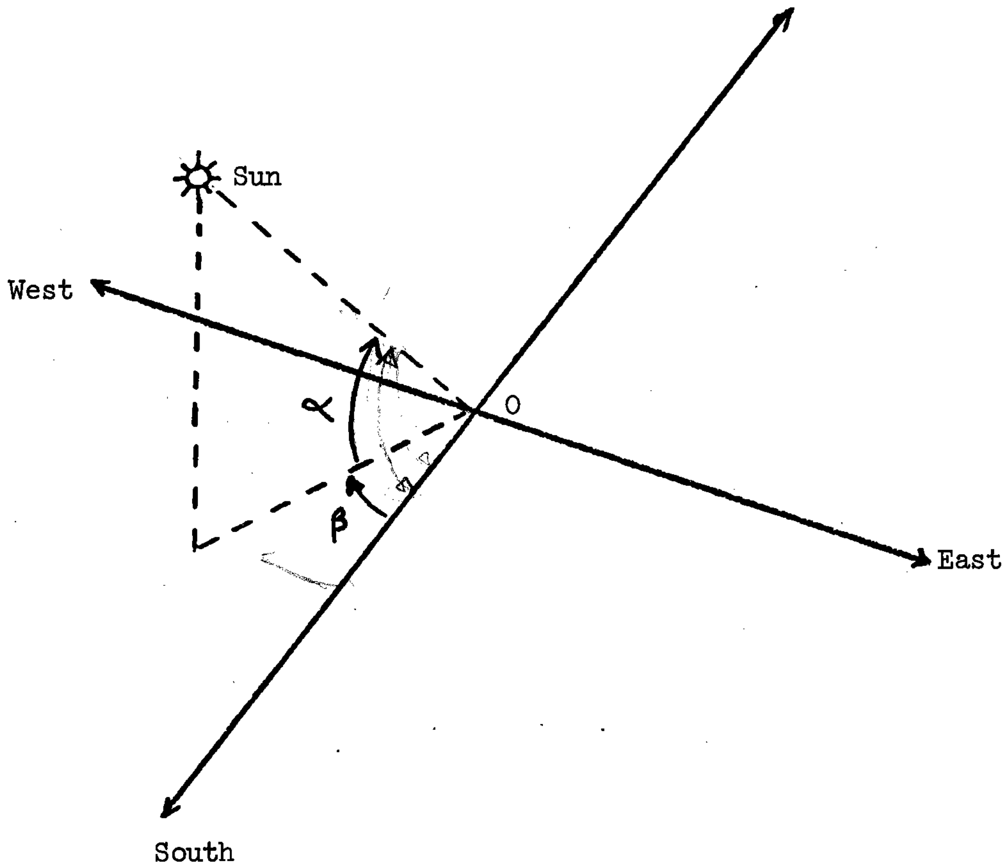

Figure 3.2. Illustration of the solar altitude angle, α, and the solar azimuth angle, β.

Table 3.1 Altitude and Azimuth Angles for 32° and 37° Latitudes

Date and Declination	Solar time AM	Solar time PM	32° Lat. Solar position α	32° Lat. Solar position β		37° Lat Solar position α	37° Lat Solar position β
December 21	Noon		34.5	0	14.5	29.5	0
	11	1	32.7	16.4	36.2	27.9	15.6
-23.5°	10	2	27.6	31.2	40	23.3	29.6
	9	3	19.8	43.6	47	16.2	42.5
	8	4	10.3	53.8	54	7.3	53.2
January 21	Noon		38.1	0	38.1	33.1	0
or	11	1	36.2	17.5	39.7	31.4	16.6
November 21	10	2	30.7	33.1	43.9	26.5	31.7
	9	3	22.6	46.1	50.2	19.0	44.7
-19.9°	8	4	12.6	56.6	57.5	9.8	55.7
	7	5	1.5	65.3	65.3		
February 21	Noon		47.1	0	47.1	42.1	0
or	11	1	44.8	21.0	48.5	40.1	19.4
October 21	10	2	38.4	38.8	52.4	34.4	36.5
	9	3	29.3	52.8	58.2	26.2	50.7
-10.9°	8	4	18.5	63.7	65.2	16.2	62.3
	7	5	6.6	72.6	72.7	5.1	72.2
March 21	Noon		58.0	0	58.0	53.0	0
or	11	1	55.0	26.8	59.2	50.5	24.0
September 21	10	2	47.3	47.5	63.0	43.8	43.8
	9	3	36.9	62.1	68.0	34.4	59.0
0°	8	4	25.1	73.0	74.6	23.5	70.8
	7	5	12.7	81.9	82.1	11.9	80.8
	6	6	0	90.0		0	90.0
April 21	Noon		69.4	0	69.4	64.4	0
or	11	1	65.2	37.3	70.5	61.1	31.6
August 21	10	2	55.6	60.1	73.6	52.8	54.2
	9	3	43.9	74.0	78.5	42.3	69.5
11.4°	8	4	31.4	83.8	84.7	30.7	80.8
	7	5	18.7	92.0	91.9	18.8	90.3
	6	6	6.0	99.7	99.6	6.8	99.2
May 21	Noon		78.0	0	78	73.0	0
or	11	1	72.0	52.0	79	68.6	41.7
July 21	10	2	60.6	73.4	81.9	58.8	65.3
	9	3	48.2	84.7	86.5	47.4	79.2
20.0°	8	4	35.5	92.9	92.4	35.5	89.3
	7	5	22.8	100.1	99.3	23.6	98.0
	6	6	10.5	107.2	106.9	11.9	106.2
						0.7	114.8

Table 3.1 Altitude and Azimuth Angles for 32° and 37° Latitudes
(Continued)

Date and Declination	Solar time AM	Solar time PM	32° Lat. Solar position α	32° Lat. Solar position β		37° Lat. Solar position α	37° Lat. Solar position β
June 21	Noon		81.5	0	81.5	76.5	0
	11	1	74.2	60.9	82.4	71.3	47.8
23.5°	10	2	62.2	79.7	85.2	60.9	70.7
	9	3	49.6	89.5	89.7	49.3	83.6
	8	4	36.9	96.8	95.4	37.3	93.0
	7	5	24.4	103.4	102.2	25.4	101.2
	6	6	12.2	110.2	109.7	13.9	109.1
	5	7	0.6	117.6	117.6	2.9	117.5

of the surface by its azimuth angle γ from South (positive to the West) and its tilt angle to upward from horizontal. As examples, (a) a South-facing roof with a $\frac{1}{2}$ slope has orientation angles $\gamma = 0^{\circ}$ and $t = 27.1^{\circ}$, and (b) a vertical wall facing southeast has $\gamma = 45^{\circ}$ and $t = 90^{\circ}$. If the angle between the sun's rays and the surface is called θ, then

$$\sin \theta = \cos \alpha \cos (\beta - \gamma) \sin t + \sin \alpha \cos t$$

VERTICAL SOUTH FACING WALL $\sin \theta = \cos \alpha \cos \beta$

This formula is useful in calculating the "clear day" intensity of direct radiation on a surface at various times of day on different dates. Assuming there are no clouds near the sun's position, the direct intensity D on a surface is given by

$$D = DN \times \sin \theta$$

where $\sin \theta$ is given above and typical values for DN are given in the next section.

IV. Typical Intensities of Direct Normal Radiation With Clear Skies

Solar system designers frequently want to know the intensity of direct radiation on their collector surface under clear sky conditions. This is useful for calculating the maximum energy ever available to be collected. It is also useful for computing a collector's efficiency - the ratio of the energy collected to the incident energy.

Table 4.1 gives some typical values for DN with clear skies. These intensities, in kilowatts per square meter, are based upon measurements in Albuquerque. They are "typical" values; however, real values can vary by as much as 10% from one day to the next. The values are given for solar noon and for solar altitude angles of 30° and 14.3°; the corresponding times cover most of the daylight hours in each season.

			$\alpha = 30^{\circ}$		$\alpha = 14.3^{\circ}$	
	Time	Intensity	Time	Intensity	Time	Intensity
March	Noon	1.00	8:40a 3:20p	0.90	7:10a 4:50p	0.69
June	Noon	.95	7:25a 4:35p	0.82	6:10a 5:50p	0.63
September	Noon	.99	8:40a 3:20p	0.87	7:10a 4:50p	0.66
December	Noon	1.00	10:50a 1:10p	0.98	8:30a 3:30p	0.81

Table 4.1 Typical values for DN under clear skies (kW/m^2)

Incidentally, these clear day solar radiation intensities are reasonably accurate for the entire state. Slightly higher values will occur at higher elevations, and lower elevations will have slightly lower intensities.

V. Daily Totals of Solar Radiation Available to Various Collector Types

This section contains the information that is of most general interest - the typical amounts of solar energy available to solar collectors per day. Actually the information doesn't refer to the design or construction of the collector; rather, it is presented as the amount of radiation incident on a surface in the same plane as a collector, or using the same tracking scheme as a collector. The data does not include adjustments for collector components, such as the transmission through cover plates, or the absorbtivity of receiver plates, etc.

The solar energy availability information is all given in Table 5.1. The top section of the table lists availabilities of direct radiation available to tracking, focusing collectors. These are average daily amounts, expressed in kilowatt hours per square meter of collector aperture (a square meter equals 10.8 square feet). The collector-radiation type designations are:

DN - direct-normal (full tracking).

DNSP - direct on surface rotating about a polar axis (an axis parallel to earth's axis).

DNSH - direct on a surface rotating about a N-S horizontal axis.

DEW - direct on a surface rotating about an E-W horizontal axis.

DVL - direct on a surface tilted upward latitude degrees and rotating about a vertical axis.

The middle three of these configurations are standard orientation schemes for parabolic trough collectors. As Table 5.1 shows, the last configuration (DVL) is quite good in terms of the total amount of energy collected; over the years, such a surface intercepts 91% of the direct-normal radiation. One problem with this scheme for liquid collectos is that the plumbing connections may be complicated.

The middle section of Table 5.1 gives mean daily amounts of total radiation (direct + diffuse) available to a surface tracking the sun according to these same schemes. These values are appropriate for flat-plate collectors tracking the sun. Of course, focusing collectors would not be able to capture the diffuse radiation.

The final section lists average daily values of solar radiation incident upon various fixed surfaces. The values are in kilowatt-hours per square meter. The designation TH refers to total radiation on a horizontal surface. TT(N) refers to a surface tilted up N degrees from horizontal toward the South. The notation TT(45, ± N) refers to a surface tilted 45 degrees from horizontal and turned N degrees from due South toward either the East or the West. Of course, there are differences in the amounts of radiation available to surfaces depending on whether they face East or West of South. Such differences are caused by prevalence of clouds in the morning or evening. However, these differences are quite small on the average, and they're ignored in this table.

Note that the last row of Table 5.1 refers to East or West walls. In the summer East and West walls receive a great deal more solar radiation, 3.8 kWH/m^2 per day, than does a South wall. But in the winter they receive less than half of the radiation incident upon a South wall.

All of the values given in Table 5.1 are based upon data recorded in Albuquerque. The values for other locations in New Mexico will be generally within about 10% of these. Larger differences may exist for locations which are significantly more cloudy.

A very important fact to keep in mind concerning Table 5.1 is that these are <u>average</u> values. On particular days the <u>actual</u> values which occur may be as low as 20% of these, or they may be almost double these numbers, depending on whether that day is exceptionally cloudy or especially clear. Even the average values for one particular season of one year may be 30% above or below these long term averages. For example, the average daily total-horizontal radiation for September of 1974 in Albuquerque was over 30% below the long-term average daily total-horizontal radiation for Albuquerque for September. That was a particularly cloudy and rainy September for Albuquerque.

Even though actual values may vary from long-term averages by significant amounts, these long term averages are very useful for design purposes. They do indicate the average amounts of radiation that will be available to specific collector orientations by seasons over the years.

Table 5.1 Average Daily Totals of Solar Energy Available to Various Collectors By Seasons

Collector Radiation Types	Spring	Summer	Fall	Winter
	Direct Radiation Available to Tracking Collectors			
	Spring (M,A,M)	Summer (J,J,A)	Fall (S,O,N)	Winter (D,J,F)
DN	8.9	9.5	7.4	6.5
DNSP	8.6	8.9	7.3	6.1
DNSH	8.3	9.3	6.1	4.5
DEW	6.3	7.0	5.7	5.4
DVL	8.2	8.9	6.7	5.6
	Total Radiation Available to Tracking Collectors			
	Spring (M,A,M)	Summer (J,J,A)	Fall (S,O,N)	Winter (D,J,F)
TN	10.2	10.8	8.4	7.3
TNSP	10.0	10.3	8.3	6.9
TNSH	9.7	10.7	7.1	5.4
TEW	7.8	8.5	6.7	6.2
TVL	9.6	10.3	7.8	6.5
	Total Radiation Available to Fixed Collectors			
	Spring	Summer	Fall	Winter
TH	7.1	8.2	5.1	3.8
TT(15)	7.5	8.1	5.9	4.8
TT(30)	7.4	7.6	6.5	5.6
TT(45)	6.9	6.7	6.6	6.1
TT(60)	6.0	5.4	6.3	6.1
TT(75)	4.8	3.9	5.7	5.9
TT(90) = TV	3.4	2.3	4.8	5.2
TT(45,±15)	6.9	6.7	6.5	6.0
TT(45,+30)	6.9	6.8	6.3	5.7
TT(45,±45)	6.8	6.8	5.9	5.2
TT(45,±90)	6.0	6.7	4.4	3.3
TT(90,±15)	3.6	2.5	4.7	5.1
TT(90,±30)	3.7	3.0	4.5	4.7
TT(90,±45)	3.9	3.4	4.1	4.1
TT(90,±90)	3.7	3.8	2.8	2.2

APPENDIX

The location of the sun can be calculated for any day of the year using the formulas of this appendix. The declination δ on the Nth day of the year is given by

$$\delta = \sin^{-1} (.39795 \cos (.98563 (N-172))).$$

The solar altitude angle α is given by

$$\alpha = \sin^{-1} (\cos L \cos \delta \cos H + \sin L \sin \delta),$$

where L = latitude
δ = declination
H = solar hour angle
= 1/4 (number of minutes from solar noon).

The basic equation for the solar azimuth angle β is

$$\sin \beta = \frac{\cos \delta \sin H}{\cos \alpha} .$$

However, to "solve" this equation for β, we must distinguish between the case where the sun is in the Northern half of the sky, and the case where the sun is in the Southern half of the day. The resulting formula for β is:

$$\beta = \begin{cases} \sin^{-1}\left(\dfrac{\cos \delta \sin H}{\cos \alpha}\right) & \text{if } \cos H > \dfrac{\tan \delta}{\tan L} \\ 90^\circ & \text{if } \cos H = \dfrac{\tan \delta}{\tan L} \\ 180^\circ - \sin^{-1}\left(\dfrac{\cos \delta \sin H}{\cos \alpha}\right) & \text{if } \cos H < \dfrac{\tan \delta}{\tan L} \end{cases}$$

This formula measures β from the South, positive toward the West. The value ranges for β are:

-90° to 0°	sun in Southeast
0° to 90°	sun in Southwest
90° to 180°	sun in Northwest
180° to 270°	sun in Northeast

Note that the sun is in the North half of sky when $\cos H < \dfrac{\tan \delta}{\tan L}$.

Finally, sunrise and sunset occur when the hour angle H satisfies the equation

$$\cos H = - \tan L \tan \delta.$$

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