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# Solar Energy Fundamentals

Course No: M04-018

Credit: 4 PDH

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# Solar Energy Fundamentals

*Harlan H. Bengtson, PhD, P.E.*

## COURSE CONTENT

### 1. Introduction

Solar energy travels from the sun to the earth in the form of electromagnetic radiation. In this course properties of electromagnetic radiation will be discussed and basic calculations for electromagnetic radiation will be described. Several solar position parameters will be discussed along with means of calculating values for them. The major methods by which solar radiation is converted into other useable forms of energy will be discussed briefly. Extraterrestrial solar radiation (that striking the earth's outer atmosphere) will be discussed and means of estimating its value at a given location and time will be presented. Finally there will be a presentation of how to obtain values for the average monthly rate of solar radiation striking the surface of a typical solar collector, at a specified location in the United States for a given month. Numerous examples are included to illustrate the calculations and data retrieval methods presented.

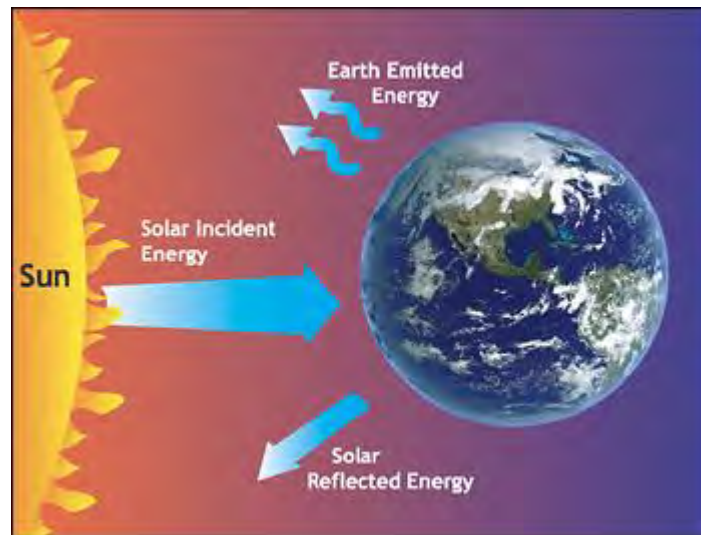


Image Credit: [NOAA, Earth System Research Laboratory](#)

## 2. Learning Objectives

At the conclusion of this course, the student will



- Know the different types of electromagnetic radiation and which of them are included in solar radiation.
- Be able to calculate wavelength if given frequency for specified electromagnetic radiation.
- Be able to calculate frequency if given wavelength for specified electromagnetic radiation.
- Know the meaning of absorbance, reflectance and transmittance as applied to a surface receiving electromagnetic radiation and be able to make calculations with those parameters.
- Be able to obtain or calculate values for solar declination, solar hour angle, solar altitude angle, sunrise angle, and sunset angle.
- Be able to use solar declination, solar hour angle, solar altitude angle, sunrise angle, and sunset angle values in calculations.
- Know the major methods by which solar radiation is converted into other useable forms of energy.
- Be able to obtain an estimated value for monthly averaged extraterrestrial radiation on a horizontal surface for a specified month and latitude between 20 and 65 degrees.
- Be able to obtain values for the average monthly rate of solar radiation striking the surface of a typical solar collector, at a specified location in the United States for a given month.

### 3. Outline of Topics

I. The Nature of Electromagnetic Radiation (Including Solar Radiation)

II. What Happens to Solar Radiation When It Strikes an Object

III. Solar Position Parameters and Calculation of Their Value

- a. Solar Declination
- b. Solar Hour Angle
- c. Solar Altitude Angle
- d. Sunrise Hour Angle
- e. Sunset Hour Angle

IV. Methods of Utilizing Solar Energy

- a. Solar Space Heating
- b. Solar Water Heating
- c. Solar Generation of Electricity

V. Extraterrestrial Solar Radiation

VI. Terrestrial Solar Radiation Quantities or Rates

Information from: *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*

- a. Station Description
- b. Flat-Plate Collector Facing South at a Fixed Tilt
- c. One-Axis Tracking Flat-Plate Collectors with Axis Oriented North-South
- d. Two-Axis Tracking Flat Plate Collectors
- e. Concentrating Collectors
- f. Solar Radiation Graph
- g. Climate Conditions

VII. Summary

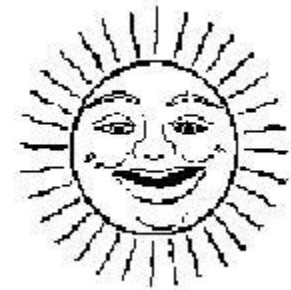
VIII. References

#### 4. The Nature of Electromagnetic Radiation (Including Solar Radiation)

There are many forms of electromagnetic radiation, such as radio waves, infrared radiation (heat), visible light, ultraviolet light, x-rays, and gamma rays. These different forms of electromagnetic radiation are all characterized by their wavelength,  $\lambda$ , and frequency,  $\mu$ . All electromagnetic radiation travels at the speed of light,  $c$ , so the product of wavelength and frequency for any type of electromagnetic radiation equals the speed of light. That is:

$$\lambda\mu = c \quad (1)$$

Thus long wavelength electromagnetic radiation has a low frequency and short wavelength electromagnetic radiation has a high frequency. The different types of electromagnetic radiation listed above are arranged from lowest frequency (radio waves) to highest frequency (gamma waves).



The speed of light in a vacuum is  $3.000 \times 10^8$  m/sec. Thus, if the wavelength of a particular type of electromagnetic radiation is known, its frequency can be calculated and vice versa using equation (1).

**Example #1:** What will be the wavelength of a radio wave with a frequency of 200,000 cycles per second?

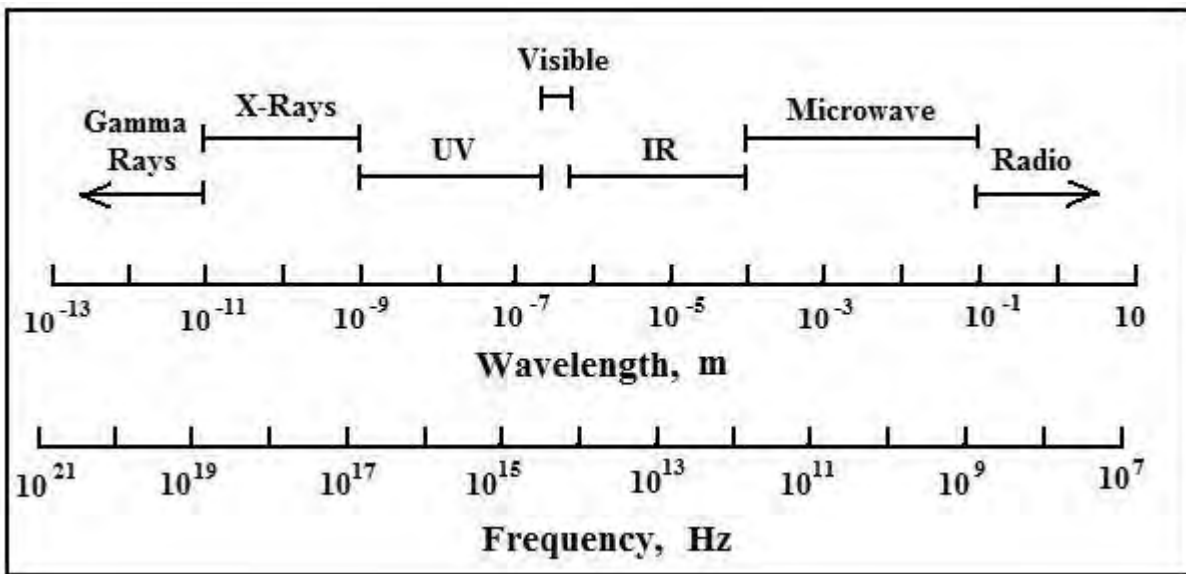
**Solution:** The wavelength can be calculated from equation (1):

$$\lambda = c/\mu = (3 \times 10^8 \text{ m/sec})/(2 \times 10^5 \text{ cycles/sec}) = 1500 \text{ m/cycle}$$

or, as usually expressed, simply: **1500 m**

Figure 1 summarizes the electromagnetic radiation spectrum. It shows the various forms of electromagnetic radiation and the range of wavelength and frequency of each.

**Figure 1. Summary of the Electromagnetic Spectrum**



Solar radiation has most of its energy between wavelengths of  $10^{-7}$  and  $3 \times 10^{-6}$  m. This includes ultraviolet light, visible light and infrared radiation. Visible light and near-infrared (wavelength of  $7 \times 10^{-7}$  to  $4 \times 10^{-7}$  m) make up over 90% of the solar radiation reaching the Earth's atmosphere. Less than 10% of solar radiation is ultraviolet (uv) light (wavelength of  $10^{-9}$  to  $4 \times 10^{-7}$  m). This is illustrated in Figure 2 below.

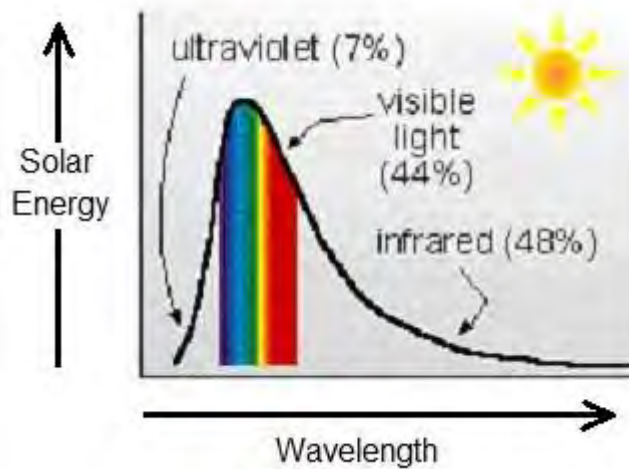
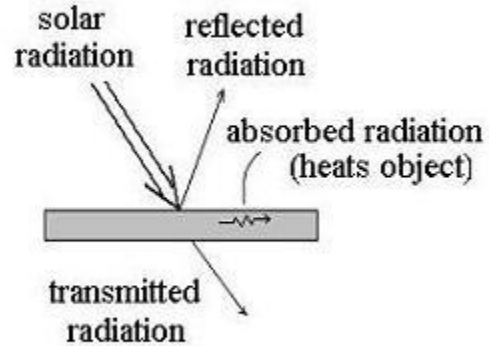


Figure 2. Approximate characteristics of solar radiation reaching the Earth

## 5. What Happens to Solar Radiation when it Strikes an Object ?

When solar radiation strikes any object, one or more of three things must happen to it. The radiation will be absorbed, reflected, and/or transmitted through the object depending upon the nature of the surface. If the object is smooth and shiny like a mirror, then most of the radiation will be reflected. If the surface has a dark-colored, dull, matte finish, then almost all of the radiation will be absorbed, thus



heating the object. If the surface is transparent or translucent to electromagnetic radiation of the wavelength striking it, then it will be completely or partially transmitted through and continue until it strikes something else. The reflected fraction of incident radiation is called the reflectance,  $r$ . The absorbed fraction is called the absorbance,  $a$ , and the transmitted fraction is called the transmittance,  $t$ . All the incident radiation must be accounted for by the sum of these three fractions, thus:

$$a + r + t = 1 \quad (2)$$

An object which allows no electromagnetic radiation of a given wavelength to pass through it is said to be opaque to that electromagnetic radiation and  $t = 0$ . Solar radiation, which is reflected by a surface or transmitted through a surface, will then travel on in a straight line until it strikes another surface and is ultimately absorbed.

**Example #2:** A translucent plastic sheet will transmit 35% of the solar radiation striking it and has an absorbance of 0.5. If 0.7 Kilowatts of solar radiation is striking a sheet of this plastic, what is the rate of reflected solar radiation from the sheet.

**Solution:** The reflectance is calculated as  $r = 1 - a - t = 1 - 0.5 - 0.35 = 0.15$ . The rate of reflected radiation is thus 15% of the incident radiation or  $0.15 \times 0.7$  Kilowatts = **0.105 Kilowatts**.

## 6. Solar Position Parameters and Calculation of their Values



Several solar parameters are used to describe the position of the sun at a specified location, date and time and to make calculations regarding the rate of solar radiation striking the earth at a specified location. Five of those parameters, **solar declination, solar hour angle, solar altitude angle, sunrise hour angle and sunset hour angle** will be discussed in this section.

**Solar declination** is the angle between the sun's rays and a plane passing through the equator. This is illustrated in Figure 3. The solar declination depends only on the day of the year. The declination is also equal to the latitude at which the sun is directly overhead at solar noon on the given day. The declination is positive when the sun is directly overhead north of



the equator (December 21 through June 21) and it is negative when the sun is directly overhead south of the equator (June 21 through December 21). The solar declination,  $\delta$ , can be calculated from the equation:

$$\delta = (23.45^\circ)\sin[360^\circ(284 + n)/365] \quad (3)$$

Where  $n$  is the day number in the year, with January 1 as 1.

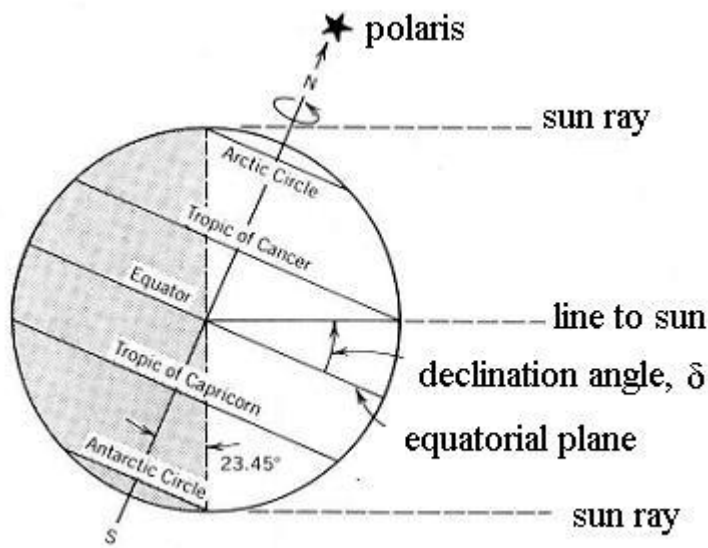
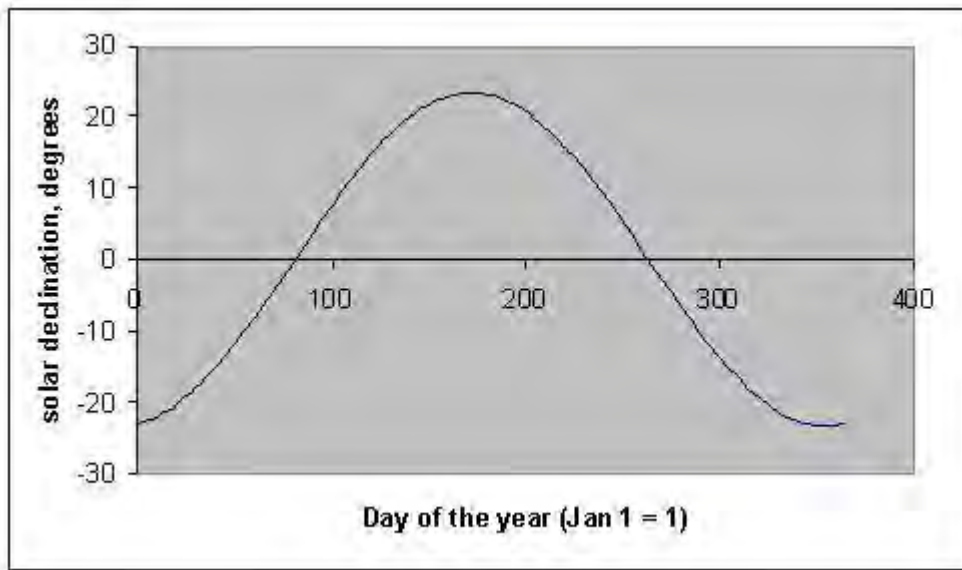


Figure 3. Solar Declination Angle,  $\delta$

The variation of  $\delta$  throughout the year is shown in Figure 4. The solar declination has a maximum value of  $+ 23.45^\circ$  on June 21 and a minimum value of  $- 23.45^\circ$  on December 21.

**Figure 4. Solar Declination vs Day of the Year**



**Example #3:** What is the value of the solar declination on February 15?

**Solution:** The value of n for February 15 is  $31 + 15 = 46$

Equation (3), with the value 46 substituted for n becomes:

$$\delta = (23.45^\circ)\sin[360^\circ(284 + 46)/365] = (23.45^\circ)\sin[325.5^\circ]$$

**NOTE:** If you are using Excel for calculations the argument of the trigonometric functions must be in radians rather than in degrees. The conversion is  $\pi$  radians = 180 degrees, thus the equation above with the angle  $325.5^\circ$  expressed in radians becomes:

$$\delta = (23.45^\circ)\sin[(325.5)(\pi/180)] \text{ or } (23.45^\circ)\sin[(325.5)(\text{pi}()/180)]$$

Proceeding with the calculation:  $\delta = -13.3^\circ$

This appears to be consistent with Figure 4, above.

The **Solar Hour Angle** is a measure of the position of the sun relative to solar noon at a given time at any given location on the earth. The hour angle,  $\omega$ , is zero when the sun is directly overhead (local solar noon). It is negative before local solar noon and is positive in the afternoon. The hour angle changes by  $15^\circ$  each hour, or one degree in 4 minutes. The variation of the solar hour angle with local solar time is summarized in table 1.

**Table 1. Solar hour angle as a function of solar time**

<u>Solar time</u>	<u>Solar hour angle, <math>\omega</math>, in degrees</u>
6 hrs before solar noon	-90
5 hrs before solar noon	-75
4 hrs before solar noon	-60
3 hrs before solar noon	-45
2 hrs before solar noon	-30
1 hr before solar noon	-15
solar noon	0
1 hr after solar noon	15
2 hrs after solar noon	30
3 hrs after solar noon	45
4 hrs after solar noon	60
5 hrs after solar noon	75
6 hrs after solar noon	90

Solar time differs from local standard time (clock time) due to the location of the site relative to the standard time meridian in the time zone, and the irregularity of

the earth's motion around the sun because of the elliptical nature of the earth's orbit, the inclination of the axis of the earth's rotation and perturbations due to the moon and the other planets. Solar time can be calculated from the following equation:

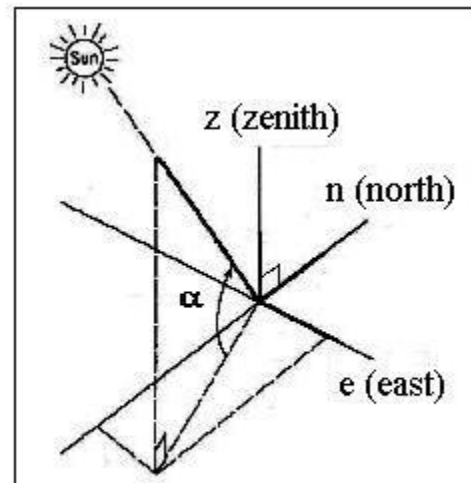
$$\text{Solar Time} = \text{local standard time} + \text{ET} + (l_{\text{st}} - l_{\text{local}})(4 \text{ min/degree}) \quad (4)$$

Where  $l_{\text{st}}$  is the standard time meridian in the local time zone,  $l_{\text{local}}$  is the local meridian, and ET is the equation of time in minutes, given by the equation:

$$\text{ET} = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B) \quad (5)$$

$$\text{Where } B = 360(n - 81)/364 \text{ degrees} \quad (6)$$

The **Solar Altitude Angle** is the angle between the sun's rays and a horizontal plane. when the sun is just rising or setting, the altitude angle is zero. When the sun is directly overhead, the altitude angle is  $90^\circ$ . the solar altitude angle,  $\alpha$ , can be calculated for any location and time from the latitude,  $L$ , solar declination,  $\delta$ , and solar hour angle,  $\omega$ , using the following equation:



Solar Altitude Angle,  $\alpha$

$$\sin \alpha = \sin L \sin \delta + \cos L \cos \delta \cos \omega \quad (7)$$

**Example #4:** Calculate the solar altitude angle,  $\alpha$ , for solar noon on February 15, in St. Louis, MO (latitude:  $38.75^\circ$  N)

**Solution:** From **Example #3**, the solar declination,  $\delta$ , on February 15, is  $-13.3^\circ$ . The hour angle,  $\omega$ , is zero at solar noon, and the latitude is given in the problem statement as  $38.75^\circ$ , so equation (8) becomes:

$$\sin \alpha = \sin(38.75^\circ) \sin(-13.3^\circ) + \cos(38.75^\circ) \cos(-13.3^\circ) \cos(0)$$

Calculating (with conversion of degrees to radians if needed) gives:

$$\sin \alpha = 0.615$$

$$\alpha = \sin^{-1}(0.615) = 0.6624 \text{ radians} = \underline{\underline{37.9^\circ}} = \alpha$$

In some solar calculations, values for the sunset hour angle and sunrise hour angle are needed. The solar altitude angle,  $\alpha$ , will be zero for both sunset and sunrise, so an equation for sunrise and sunset hour angles can be found by setting  $\alpha$  equal to zero in equation (7) above and solving for  $\omega$ . The angle will be negative for sunrise and positive for sunset. This results in the following two equations:

$$\text{Sunrise angle} = \omega_{\text{sr}} = -\cos^{-1}[-(\tan L)(\tan \delta)] \quad (8)$$

$$\text{Sunset angle} = \omega_{\text{ss}} = \cos^{-1}[-(\tan L)(\tan \delta)] \quad (9)$$

If  $\omega_{\text{sr}}$  and  $\omega_{\text{ss}}$  are calculated in degrees from the above equations, they can be converted to radians by multiplying by the factor  $(\pi/180)$ . To calculate clock time before or after solar noon for sunrise or sunset, the conversion is 4 minutes per degree.

**Example #5:** Calculate the sunrise hour angle and sunset hour angle for Kansas City, MO (latitude:  $39.30^\circ$  N), on February 15.

**Solution:** From **Example #3**, the solar declination,  $\delta$ , on February 15, is  $-13.3^\circ$ , and the latitude is given in the problem statement as  $39.30^\circ$ , so equation (9) becomes:

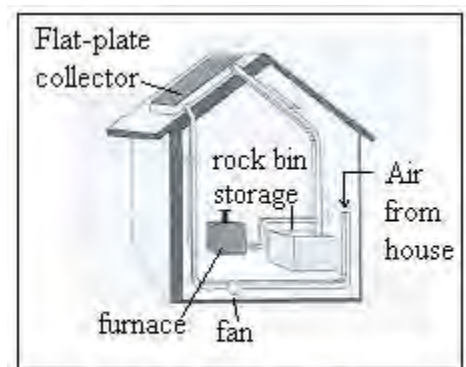
$$\begin{aligned}\text{Sunset angle} &= \omega_{ss} = \cos^{-1}[-\tan(39.30^\circ)\tan(-13.3^\circ)] \\ &= 1.376 \text{ radians} = \underline{78.8^\circ} = \omega_{ss}\end{aligned}$$

$$\text{Sunrise angle} = \omega_{sr} = -\omega_{ss} = \underline{-78.8^\circ} = \omega_{sr}$$

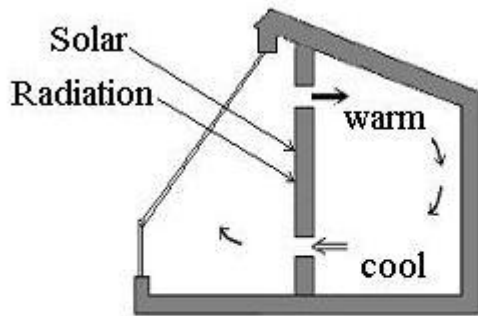
## 7. Methods of Utilizing Solar Energy

There are numerous “behind the scenes” ways that solar energy keeps us alive on the surface of the earth, such as driving photosynthesis, which directly or indirectly produces all of our food; driving the hydrological cycle, which produces precipitation and keeps the rivers running; and simply keeping the temperature within a range at which we can survive on the surface of the earth. The primary intent of this section, however, is to briefly discuss the major ways that solar energy is converted to other usable forms. Three methods of utilizing solar energy will be discussed here: **solar space heating**, **solar water heating** and **solar generation of electricity**.

**Solar space heating** can be accomplished with **active** solar heating systems or **passive** solar heating systems. An active solar heating system uses collectors (usually on the roof of the building) to heat a fluid (usually air). A blower is used to draw the air through the collector, thus heating it. The heated air is used to heat the living space or is sent to a heat storage area, perhaps a bed of rocks. During the night and on cloudy days, heated air is moved from the heat storage area to the space to be heated.



**Active Solar Heating**

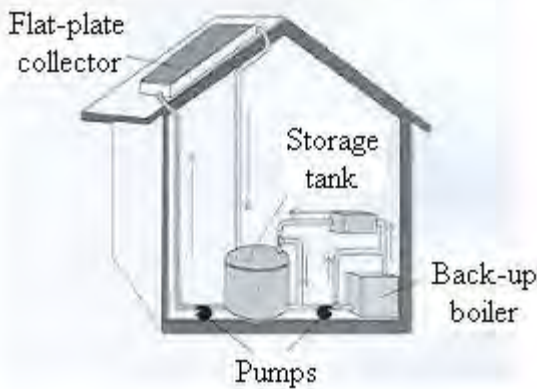


**Attached Sunspace  
Daytime Heat Flow**

A passive solar heating system uses south-facing glazing, such as windows or attached sunspace glazing, to bring the solar radiation into the building. The solar radiation may heat the living space directly and at least some of it is typically stored in components of the building like masonry walls and floors. At night and on cloudy days, the stored heat will be released to the living space. No fans or

blowers are used in a completely passive system. The heat flow is by natural convection (rising of heated air), conduction and radiation.

### **Active Solar Water Heater**



**Solar water heating** has the advantage of being required year round, instead of just during the heating season. Solar water heating systems may be either active or passive also. Either type will use a solar collector to heat water that is stored in a tank for use, much as with a conventional gas or electric water heater. An active solar water heating system uses a pump to move water through the collector and to the storage tank, while a passive system used natural convection (heated water rises) to cause the water flow.



**Solar Generation of Electricity** can be done by two different methods. They are: i) use of photovoltaic cells to generate an electrical current directly and charge a battery, or ii) heating a fluid and using it in a heat engine to generate electricity in a manner much the same as a conventional fossil fuel or nuclear power plant

Image Credit: National Renewable Energy Laboratory website at: <https://www.nrel.gov/workingwithus/re-photovoltaics.html>

The details of these methods are beyond the scope of this introductory course, however, any of these systems uses one or more solar collectors, and design of any of these systems requires information about the average rate of solar radiation striking a solar collector surface at the location of interest, for some appropriate period of time, such as a month. The rest of this course is about how to do that.

## 8. Extraterrestrial Solar Radiation

Solar radiation continuously strikes the earth's outer atmosphere at the rate of  $1.7 \times 10^{17}$  watts. This is referred to as 'extraterrestrial' radiation. Expressed on a per unit area basis, the yearly average rate of solar radiation striking a surface normal to the rays of the sun outside the earth's atmosphere is called the solar constant,  $I_{sc}$ . The solar constant has been estimated by several different groups to be in the range from 1353 to 1394 W/m<sup>2</sup>.





A value of 1367 W/m<sup>2</sup> for the solar constant is now widely accepted. There is a seasonal variation in the extraterrestrial radiation rate due to the variation in distance between the earth and the sun over a year's cycle. An estimate of the actual extraterrestrial solar flux (flux = flow rate per unit area per unit time),  $I_o$ , on any day of the year can be calculated from the following equation:

$$I_o = I_{sc}[1 + 0.034\cos(360n/365.25)^\circ] \quad (10)$$

Where  $n$  is the day number in the year, with January 1 as 1.  $I/I_o$  varies from a maximum of 1.034 at the end of December to a minimum of 0.966 at the end of June.

Using some of the solar parameters discussed earlier in this course ( $\delta$  &  $\omega_{ss}$ ), the average daily extraterrestrial solar flux on a plane parallel to the earth's surface (a horizontal plane) can be calculated for any day of the year and latitude from equation (11) below, along with equation (10).

$$H_{o,h} = (86,400 * I_o / \pi) [\omega_{ss}(\sin L)(\sin \delta) + (\cos \delta)(\cos L)(\sin \omega_{ss})] \quad (11)$$

The latitude of the site is an important parameter because of the effect of latitude on the altitude angle of the sun. The effect of latitude is illustrated by the fact that as one goes north from the equator, the sun is lower in the sky in the winter. Table 2 gives monthly averaged, daily extraterrestrial solar radiation on a horizontal surface,  $H_{oh-ave}$ , for latitudes from 20 to 65 degrees. The values were obtained by calculating daily values of  $H_{o,h}$  from equations (10) and (11), and then calculating the average for each month.

**Table 2. Monthly Averaged extraterrestrial radiation on a horizontal surface, kWhr/day/m<sup>2</sup>**

Latitude (deg)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
20	7.49	8.48	9.65	7.72	10.91	10.98	10.91	10.61	9.89	8.78	7.68	7.15
25	6.72	7.85	9.25	10.42	11.05	11.23	11.10	10.59	9.59	8.21	6.94	6.35
30	5.92	7.16	8.78	10.23	11.11	11.42	11.23	10.50	9.22	7.59	6.17	5.52
35	5.09	6.42	8.24	9.97	11.11	11.54	11.29	10.34	8.78	6.92	5.36	4.67
40	4.24	5.65	7.64	9.64	11.04	11.60	11.28	10.11	8.27	6.19	4.53	3.81
45	3.39	4.85	6.98	9.24	10.90	11.60	11.21	9.81	7.70	5.43	3.68	2.96
50	2.55	4.01	6.27	8.78	10.70	11.55	11.09	9.44	7.07	4.63	2.84	2.12
55	1.73	3.16	5.52	8.26	10.47	11.47	10.94	9.03	6.39	3.81	2.02	1.33
60	0.97	2.32	4.72	7.69	10.20	11.39	10.77	8.57	5.66	2.97	1.26	0.63
65	0.34	1.51	3.90	7.08	9.95	11.39	10.64	8.08	4.90	2.14	0.55	0.10

**Example #6:** What is the average extraterrestrial solar radiation rate (kWhr/day/m<sup>2</sup>) in St. Louis, MO (latitude: 38.75° N), in February?

**Solution:** From Table 1: for latitude 35°, solar rate = 6.42 kWhr/day/m<sup>2</sup>, and

for latitude 40°, solar rate = 5.65 kWhr/day/m<sup>2</sup>

By interpolation, the solar rate at latitude 38.75° is calculated to be:

$$6.42 - [(38.75 - 35)/(40 - 35)](6.42 - 5.65) = \underline{\underline{5.84 \text{ kWhr/day/m}^2}}$$



Approximately 30% of extraterrestrial solar radiation is reflected to space or absorbed by ozone, water vapor and carbon dioxide in the atmosphere. About 23% of the incoming solar energy powers the evaporation/precipitation cycle and less than 0.5% is utilized by plants for photosynthesis. Low level clouds and air pollution will reflect, scatter and absorb additional solar radiation before it reaches the earth's surface. On

average terrestrial solar radiation (at the earth's surface) is about one third of extraterrestrial solar radiation.

Terrestrial solar radiation, that which reaches the earth's surface, is sometimes broken down into two components **beam radiation** (also called direct radiation or direct beam radiation) and **diffuse radiation**. Beam radiation is solar radiation that passes through the atmosphere in essentially a straight line without being reflected, scattered or absorbed by particles or gases in the air. Diffuse radiation is solar radiation, which is scattered, reflected or absorbed by molecules of air, water vapor, aerosols and dust particles, but ultimately still reaches the earth's surface. The diffuse component of solar radiation striking a solar collector also includes solar radiation reflected from the adjacent earth's surface.

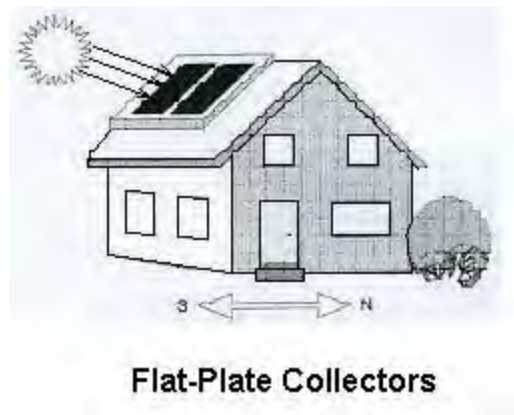
## 9. Terrestrial Solar Radiation Quantities or Rates

Ok, so I now know something about the nature of solar radiation, some solar parameters used to describe the position of the sun, and I can find a value for extraterrestrial solar radiation at any location, but how do I get a value for the quantity or rate of solar radiation striking a given solar collector or photovoltaic surface, at a specified location on the earth's surface?

This is a good question, which will now be answered. There are equations available which can be used to calculate the solar radiation rate on a flat surface

tilted at any specified angle from the horizontal, using values for some of the solar parameters discussed earlier in this course along with a value for the extraterrestrial solar radiation rate at the location of interest, and a value for the terrestrial solar radiation rate on a horizontal surface at that location. Goswami, D. Y., Krieth, Frank, and Kreider, Jan F., *Principles of Solar Engineering*, (reference #1 at the end of this course) provides details and an example for this procedure.

Another alternative, however, is the use of a wide range of solar radiation data for several standard solar collector configurations for locations in the United States and around the world, which are available in printed publications and on the Internet. Use of many of these sources doesn't require calculation of the parameters discussed in the previous section, however, understanding those parameters helps in interpretation of the data. The use of one of these sources, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, will be discussed here, and illustrated with examples.



*Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* is a 259 page publication of the National Renewable Energy Laboratory (NREL), which is out of print, but is available for free download from the website at: <http://rredc.nrel.gov/solar/pubs/redbook/>. This will download the manual and you can save a copy to your computer. It provides solar radiation values for common flat-plate and concentrating collector configurations for 239 stations in the United States and its territories.

The images on pages 21, 22, 24, 26, 28, 29, 30, and 31 came from the NREL website noted above. The figures were prepared by the National Renewable Energy Laboratory for the U.S. Department of Energy. The aforementioned images from NREL's website were authored by an employee of the Alliance for

Sustainable Energy, LLC under Contract No.: DE-AC36-08GO28308 with the U. S. Department of Energy.

The solar radiation values in this manual are expressed as monthly and yearly averages for the period 1961-1990. Minimum and maximum monthly and yearly averages are included to show the variability of the solar radiation at each station. In addition to the solar radiation data, this manual contains climate information, such as average temperatures, average daily minimum and maximum temperatures, average heating and cooling degree days, average relative humidity, and average wind speed.

The data for each station is presented on a single page. The pages are arranged alphabetically by the state or territory two-letter abbreviation, and within each state or territory, the pages are arranged alphabetically by city or island. A map on page 1 of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, and shown as Figure 5 on the next page, shows the locations of the 239 stations used for data in the manual. There are two types of stations in the 1961-1990 database used to prepare this manual. Primary stations are denoted by asterisks on the station map and secondary stations are denoted by dots on the map. There are 56 primary stations, at which solar radiation was measured for a part (from 1 to 27 years) of the 30-year period. The remaining 183 secondary stations made no solar radiation measurements and have modeled solar radiation data that was derived from meteorological data, such as cloud cover. Both primary and secondary stations are National Weather Service stations that collected meteorological data for the entire 1961-1990 period.



Figure 5. Map with locations of the 239 stations used in the NREL manual

A copy of the page for San Antonio, Texas, from the manual, is given on the next page, as an example, to show the information available for each of the stations.

# San Antonio, TX

WBAN NO. 12921

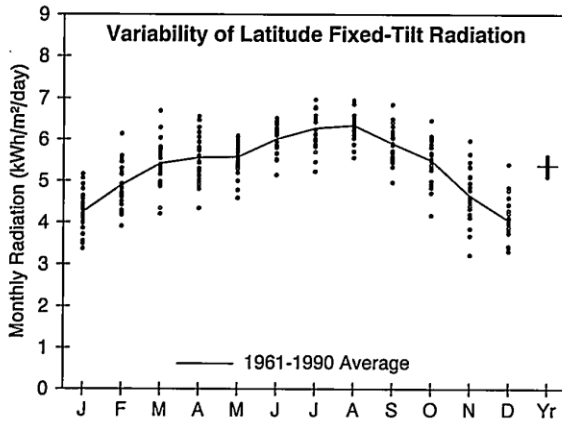
LATITUDE: 29.53° N

LONGITUDE: 98.47° W

ELEVATION: 242 meters

MEAN PRESSURE: 988 millibars

STATION TYPE: Primary



**Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m<sup>2</sup>/day), Uncertainty ±9%**

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.1	3.9	4.8	5.5	6.0	6.7	6.9	6.4	5.4	4.5	3.4	2.9	4.9
	Min/Max	2.6/3.5	3.3/4.6	3.8/5.8	4.3/6.4	4.9/6.5	5.7/7.3	5.6/7.7	5.6/7.1	4.7/6.2	3.6/5.1	2.7/4.1	2.5/3.5	4.7/5.2
Latitude -15	Average	3.7	4.5	5.2	5.7	5.9	6.5	6.7	6.6	5.8	5.1	4.1	3.5	5.3
	Min/Max	3.0/4.5	3.7/5.5	4.1/6.4	4.4/6.7	4.9/6.4	5.5/7.1	5.6/7.5	5.7/7.2	4.9/6.7	4.0/5.9	3.0/5.2	3.0/4.6	5.0/5.5
Latitude	Average	4.3	4.9	5.4	5.6	5.6	6.0	6.3	6.3	5.9	5.5	4.6	4.1	5.4
	Min/Max	3.4/5.2	3.9/6.1	4.2/6.7	4.3/6.6	4.6/6.1	5.1/6.5	5.2/7.0	5.6/6.9	5.0/6.8	4.2/6.5	3.2/6.0	3.3/5.4	5.1/5.6
Latitude +15	Average	4.5	5.0	5.3	5.2	5.0	5.2	5.5	5.8	5.7	5.6	4.9	4.4	5.2
	Min/Max	3.5/5.6	4.0/6.4	4.1/6.6	4.0/6.1	4.1/5.4	4.5/5.6	4.6/6.1	5.1/6.3	4.8/6.6	4.2/6.6	3.3/6.4	3.5/5.9	4.9/5.4
90	Average	3.8	3.8	3.4	2.7	2.1	1.9	2.0	2.6	3.3	4.0	4.0	3.8	3.1
	Min/Max	2.9/4.8	2.9/5.0	2.7/4.2	2.2/3.0	1.9/2.2	1.8/2.0	1.9/2.1	2.4/2.7	2.8/3.8	2.9/4.8	2.5/5.4	2.9/5.3	2.9/3.3

**Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis (kWh/m<sup>2</sup>/day), Uncertainty ±9%**

Axis Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	4.2	5.2	6.3	6.9	7.3	8.4	8.7	8.3	7.1	6.1	4.7	3.9	6.4
	Min/Max	3.3/5.1	4.1/6.6	4.6/8.0	4.9/8.6	5.6/8.2	6.6/9.5	6.6/10.2	6.9/9.5	5.7/8.6	4.4/7.4	3.2/6.1	3.2/5.3	6.0/6.8
Latitude -15	Average	4.7	5.7	6.6	7.1	7.3	8.3	8.7	8.4	7.4	6.6	5.2	4.4	6.7
	Min/Max	3.6/5.8	4.4/7.3	4.9/8.5	5.0/8.8	5.6/8.2	6.5/9.4	6.6/10.1	7.0/9.6	5.9/9.0	4.7/8.0	3.5/6.9	3.5/6.0	6.2/7.1
Latitude	Average	5.1	6.0	6.8	7.0	7.1	7.9	8.4	8.3	7.5	6.9	5.6	4.8	6.8
	Min/Max	3.9/6.3	4.6/7.7	5.0/8.8	4.9/8.7	5.4/8.0	6.2/9.0	6.3/9.7	6.9/9.5	5.9/9.1	4.8/8.4	3.6/7.5	3.8/6.7	6.3/7.2
Latitude +15	Average	5.3	6.1	6.7	6.7	6.7	7.4	7.8	7.9	7.3	6.9	5.8	5.0	6.6
	Min/Max	4.0/6.7	4.6/7.9	4.9/8.7	4.7/8.4	5.0/7.5	5.8/8.4	5.9/9.1	6.6/9.0	5.8/8.9	4.8/8.5	3.7/7.8	4.0/7.1	6.2/7.0

**Solar Radiation for 2-Axis Tracking Flat-Plate Collectors (kWh/m<sup>2</sup>/day), Uncertainty ±9%**

Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
2-Axis	Average	5.3	6.1	6.8	7.1	7.4	8.4	8.8	8.4	7.5	6.9	5.8	5.1	7.0
	Min/Max	4.0/6.7	4.7/7.9	5.0/8.8	5.0/8.8	5.6/8.3	6.6/9.6	6.7/10.3	7.1/9.7	5.9/9.1	4.9/8.5	3.7/7.9	4.0/7.2	6.5/7.4

**Direct Beam Solar Radiation for Concentrating Collectors (kWh/m<sup>2</sup>/day), Uncertainty ±8%**

Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
1-Axis, E-W Horiz Axis	Average	3.0	3.3	3.3	3.2	3.3	4.0	4.4	4.1	3.6	3.7	3.3	3.0	3.5
	Min/Max	2.0/4.2	2.2/4.8	1.9/5.0	1.5/4.5	1.6/4.1	2.5/5.1	2.6/5.8	2.9/5.2	2.2/5.1	2.0/5.0	1.5/5.1	2.1/4.7	3.1/3.9
1-Axis, N-S Horiz Axis	Average	2.7	3.4	4.0	4.2	4.2	5.2	5.7	5.4	4.5	4.1	3.1	2.5	4.1
	Min/Max	1.7/3.8	2.3/5.0	2.3/6.1	1.9/6.0	2.1/5.3	3.1/6.7	3.3/7.6	3.8/6.8	2.8/6.4	2.2/5.7	1.5/4.8	1.7/4.0	3.6/4.6
1-Axis, N-S Tilt=Latitude	Average	3.4	4.1	4.4	4.2	4.1	4.8	5.3	5.3	4.8	4.7	3.9	3.2	4.4
	Min/Max	2.2/4.8	2.7/5.9	2.6/6.7	1.9/6.1	2.0/5.1	2.9/6.2	3.1/7.1	3.8/6.7	3.0/6.9	2.5/6.5	1.8/6.0	2.3/5.2	3.8/4.9
2-Axis	Average	3.7	4.2	4.4	4.3	4.3	5.3	5.7	5.5	4.8	4.8	4.1	3.5	4.5
	Min/Max	2.3/5.1	2.8/6.1	2.6/6.7	1.9/6.2	2.2/5.4	3.2/6.7	3.3/7.7	3.9/6.9	3.0/6.9	2.6/6.6	1.9/6.3	2.4/5.7	4.0/5.1

**Average Climatic Conditions**

Element	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (°C)	9.6	11.9	16.5	20.7	24.2	27.9	29.4	29.4	26.3	21.2	15.8	11.2	20.3
Daily Minimum Temp	3.3	5.2	9.8	14.7	18.7	22.6	23.9	23.6	20.7	14.9	9.3	4.9	14.3
Daily Maximum Temp	16.0	18.7	23.1	26.8	29.6	33.2	35.0	35.2	31.8	27.6	22.2	17.5	26.4
Record Minimum Temp	-17.8	-14.4	-7.2	-0.6	6.1	11.7	16.7	16.1	5.0	0.6	-6.1	-14.4	-17.8
Record Maximum Temp	31.7	36.1	37.8	37.8	39.4	40.6	41.1	42.2	39.4	37.2	34.4	32.2	42.2
HDD, Base 18.3°C	274	184	93	18	0	0	0	0	0	17	100	227	913
CDD, Base 18.3°C	4	6	36	89	181	287	344	343	238	106	23	7	1664
Relative Humidity (%)	67	65	63	66	71	69	65	65	68	67	68	68	67
Wind Speed (m/s)	3.9	4.2	4.5	4.4	4.4	4.3	4.2	3.8	3.8	3.8	3.8	3.8	4.1

Following is information from pages 3, 4, & 5 of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* on the subject of “Interpreting the Data Tables.”

### **Station Description**

Information at the top of each page describes the station with the following information:

- City and state in which the station is located
- Station Weather Bureau Army Navy WBAN ID number
- Latitude (degrees; north)
- Longitude (degrees; east or west)
- Elevation of station (meters)
- Mean atmospheric pressure of station (millibars)
- Type of station (primary or secondary)

### **Solar Radiation Data for Flat-Plate and Concentrating Collectors**

For the period of 1961-1990, tables provide solar radiation data of the following types for flat-plate and concentrating collectors.

- Monthly and yearly averages of solar radiation (kWhr/m<sup>2</sup>/day)
- Minimum and maximum monthly and yearly averages of solar radiation (kWhr/m<sup>2</sup>/day)
- Uncertainty of solar radiation data (± %)

Minimum and maximum monthly and yearly averages are included to show the variability of a station’s solar resource. The uncertainty of the data is presented in the table headings. The manual includes data for flat-plate and concentrating collectors as described in the next few paragraphs.



## Flat-Plate Collectors Facing South at Fixed Tilt

Data are presented for five tilt angles from the horizontal:  $0^\circ$ , latitude minus  $15^\circ$ , latitude, latitude plus  $15^\circ$ , and  $90^\circ$ . Data for a tilt of  $0^\circ$ , referred to as global horizontal solar radiation, show how much solar radiation is received by a horizontal surface such as a solar pond.

Maximum yearly solar radiation can be achieved using a tilt angle approximately equal to a site's latitude. To optimize performance in the winter, the collector should be tilted about  $15^\circ$  greater than the latitude; to optimize performance in the summer, the collector should be tilted about  $15^\circ$  less than the latitude. Data for a tilt of  $90^\circ$  apply to collectors mounted vertically on south-facing walls and apply to south-facing windows for passive solar designs. See Figure 6 below.

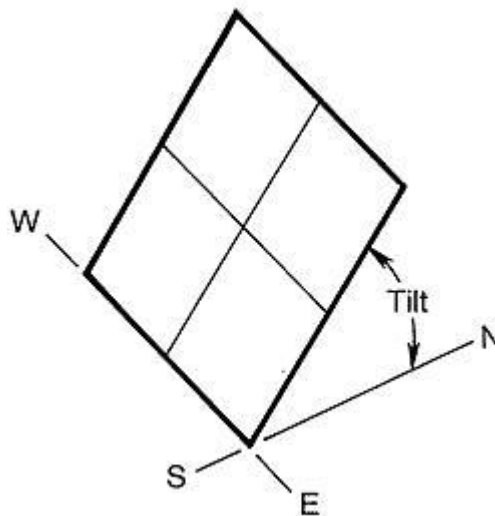


Figure 6. Flat-Plate Collector Facing South at Fixed Tilt

**Example #7:** Using the publication, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, find the average rate at which solar radiation would strike a horizontal flat-plate collector in San Antonio, TX, in March.

**Solution:** The required data is available from page 22 of this course, which is the table for San Antonio, TX, from *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. The result is as follows:

Horiz. flat-plate collector in March: **4.8 kWh/m<sup>2</sup>/day**

**Example #8:** Using the publication, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, compare the average rate at which solar radiation would strike a flat-plate collector in San Antonio, TX, in January for three different tilt angles (from the horizontal): 14.53°, 29.53°, and 44.53°. (Note that San Antonio’s latitude is 29.53°.) Determine the same information for the month of July and also determine the annual average annual solar radiation rate for each of those tilt angles.

**Solution:** The required data is available from page 22 of this course, which is the table for San Antonio, TX, from *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. The results are summarized in the table below:

Tilt Angle <u>From horizontal</u>	<u>Ave. Solar Radiation Rate, kWh/m<sup>2</sup>/day</u>		
	<u>January</u>	<u>July</u>	<u>Annual</u>
14.53° (lat. -15°)	3.7	6.7	5.3
29.53° (latitude)	4.3	6.3	5.4
44.53° (lat. +15°)	4.5	5.5	5.2

**Discussion of Results:** Note that a tilt of “latitude + 15°” receives the greatest average rate of solar radiation for the winter month of January; a tilt of “latitude - 15°” receives the greatest average rate of solar radiation for the summer month of July; and tilt angle equal to the latitude receives the greatest average annual rate of solar radiation. This is consistent with the general statement given above on page 24.

## One-Axis Tracking Flat-Plate Collectors with Axis Oriented North-South

Data are presented for four different axis tilt angles from the horizontal:  $0^\circ$ , latitude minus  $15^\circ$ , latitude, latitude plus  $15^\circ$ . These trackers pivot on their single axis to track the sun, facing east in the morning and west in the afternoon. Large collectors can use an axis tilt angle of  $0^\circ$  to minimize collector height and wind force. Small collectors can have their axis tilted up to increase the solar radiation on the collector. Just as for the flat-plate, fixed tilt collector, the yearly and seasonal solar radiation can be optimized by the choice of tilt angle. The data presented assume continuous tracking of the sun throughout the day. See Figure 7, below.

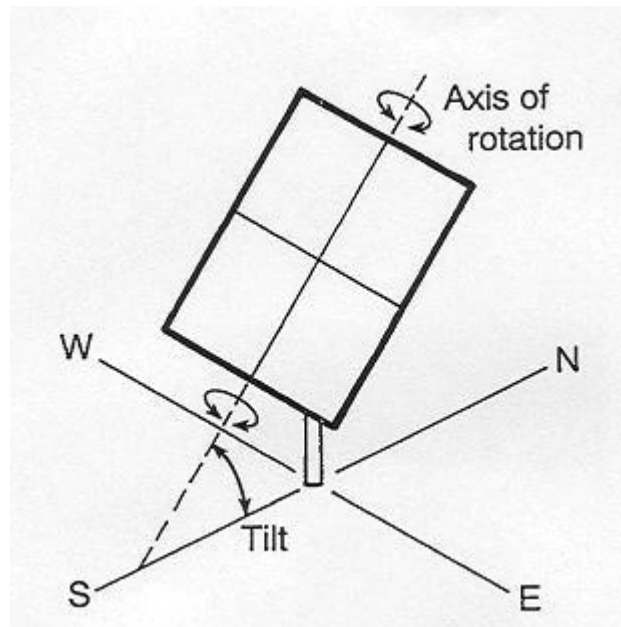


Figure 7. One-Axis Tracking Flat-Plate Collector with North-South Axis

**Example #9:** Using the publication, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, find the average rate at which solar radiation would strike a horizontal, 1-axis, tracking flat-plate collector in San Antonio, TX, in March. Also, for the same location and month, find the average solar rate for a 1-axis, tracking flat-plate collector, with tilt angle equal to  $29.53^\circ$  (the latitude of San Antonio).

**Solution:** The required data is available from page 22 of this course, which is the table for San Antonio, TX, from *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. The result is as follows:

Horiz., 1-axis, tracking flat-plate collector: **6.3 kWh/m<sup>2</sup>/day**

Latitude tilt, 1-axis, tracking flat-plate collector: **6.8 kWh/m<sup>2</sup>/day**

Note that these are both greater than the value for a fixed horizontal collector (**4.8 kWh/m<sup>2</sup>/day**) and for a fixed latitude tilt collector (**5.4 kWh/m<sup>2</sup>/day**) for the same location and month.

## **Two-Axis Tracking Flat-Plate Collectors**

Data for two-axis trackers represent the maximum solar radiation at a site available to a collector. Tracking the sun in both azimuth and elevation, these collectors keep the sun's rays normal to the collector surface throughout the day. See Figure 8 below.

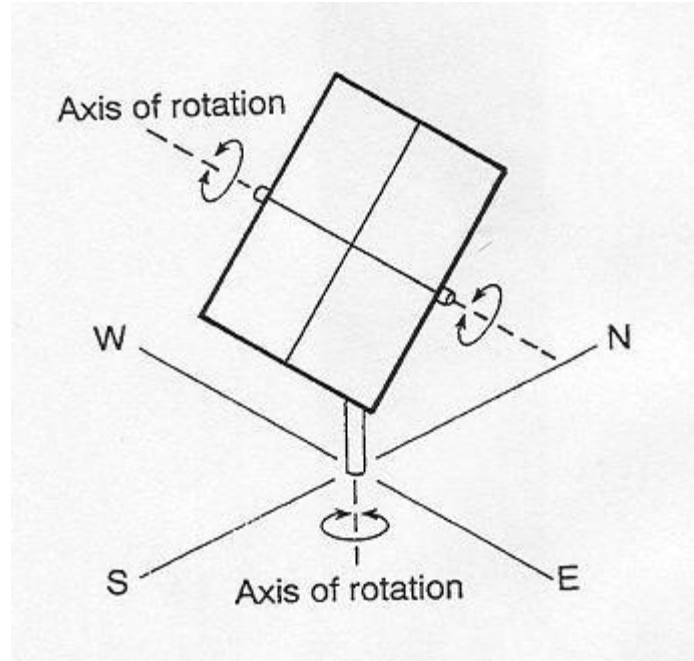


Figure 8. Two-Axis Tracking Flat-Plate Collector

**Example #10:** Using the publication, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, find the average rate at which solar radiation would strike a 2-axis, tracking flat-plate collector in San Antonio, TX, in March.

**Solution:** The required data is available from page 22 of this course, which is the table for San Antonio, TX, from *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. The result is as follows:

2-axis, tracking flat-plate collector: **6.8 kWh/m<sup>2</sup>/day**

**Discussion of Results:** Note that for March, the two-axis, tracking, flat-plate collector receives the same rate of solar radiation as the Latitude tilt, one-axis, tracking flat-plate collector. Throughout the year it is always at least as much as the maximum from a one-axis, tracking flat-plate collector with the three different tilt alternatives presented in the table.

## Concentrating Collectors

Direct beam solar radiation data are presented for four concentrator types: one-axis tracking parabolic troughs with a horizontal east-west axis, one axis tracking parabolic troughs with a horizontal north-south axis, one-axis concentrators with the axis oriented north-south and tilted from the horizontal at an angle equal to the latitude, and two-axis tracking concentrator systems. Direct beam radiation comes in a direct line from the sun and is measured with instruments having a field-of-view of  $5.7^\circ$ . These instruments see only the sun's disk and a small portion of the sky surrounding the sun. See Figures 9 and 10 below.

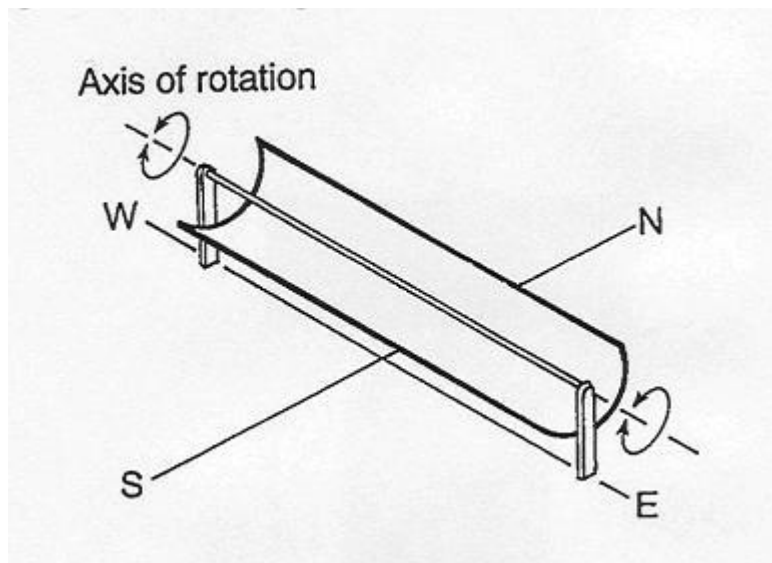


Figure 9. One-Axis Tracking Parabolic Trough with Axis Oriented East-West

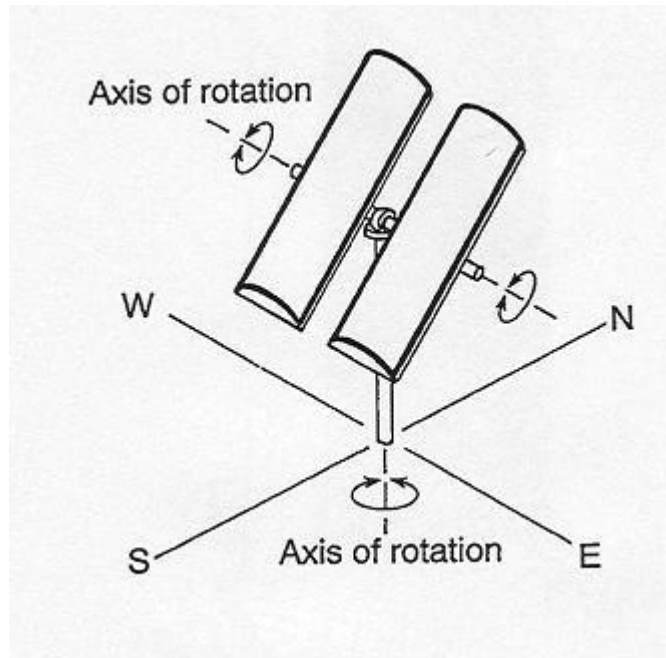


Figure 10. Two-Axis Tracking Concentrator

**Example #11:** Using the publication, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, find the average rate at which direct beam solar radiation would strike each of the four types of concentrating parabolic trough collectors in the data table, in San Antonio, TX, in January.

**Solution:** The required data is available from page 22 of this course, which is the table for San Antonio, TX, from *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. The results are as follows:

Single horizontal, east-west axis:	<b><u>3.0 kWh/m<sup>2</sup>/day</u></b>
Single horizontal, north-south axis:	<b><u>2.7 kWh/m<sup>2</sup>/day</u></b>
Single north-south axis with latitude tilt:	<b><u>3.4 kWh/m<sup>2</sup>/day</u></b>
Two-axis tracking:	<b><u>3.7 kWh/m<sup>2</sup>/day</u></b>

**NOTE:** These results cannot be compared directly with those for the various flat-plate collectors, because the data for flat-plate collectors is total solar radiation striking the collector (beam and diffuse radiation), while the data for the concentrating collectors is beam radiation only. Concentrating collectors are used in order to obtain a high temperature in a fluid, which is passing through the focal point of the parabolic trough. Only the direct beam radiation (that which comes directly from the sun to the collector) will be reflected to the focal point. The rest of the solar radiation (diffuse radiation) is made up of solar radiation which has been scattered or reflected in the atmosphere and then reaches the collector, or has been absorbed in the atmosphere and then reradiated to the collector, or has been reflected to the collector from the surrounding ground.

### **Solar Radiation Graph**

The graph at the top of each data page shows the variability of monthly and yearly solar radiation for a flat-plate collector facing south with a tilt equal to the station's latitude. For each month and year, 30 data values representing each year of the National Solar Radiation Data Base (NSRDB) are plotted along with the 1961-1990 averages for the months and year. The graph shows how the minimum and maximum values compare with the 1961-1990 average. It also shows the distribution of data points with respect to the average, minimum and maximum values.

### **Climate Conditions**

The last table on each page shows average climate conditions at the station, by listing monthly and yearly values for the following parameters.

- Monthly and yearly average temperature (°C)
- Average daily minimum temperature (°C)
- Average daily maximum temperature (°C)
- Record minimum temperature (°C)



- Record maximum temperature (°C)
- Average heating degree days (HDD), base 18.3 °C
- Average cooling degree days (CDD), base 18.3 °C
- Average relative humidity (%)
- Average wind speed (m/s).

Degree days indicate heating and cooling requirements of buildings. They are defined as the difference between the average temperature for the day and a base temperature. If the average for the day (calculated by averaging the maximum and minimum temperature for the day) is less than the base value, then the difference is designated as heating degree days. If the average for the day is greater than the base value, the difference is designated as cooling degree days.

**Example #12:** Using the publication, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, compare the average rate at which solar radiation would strike a flat-plate collector in St. Louis, MO, in January for three different tilt angles (from the horizontal): 23.75°, 38.75°, and 53.75°. (Note that St. Louis's latitude is 38.75°.) Determine the same information for the month of July and also determine the annual average annual solar radiation rate for each of those tilt angles.

**Solution:** You may want to download *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, from the NREL website, <http://www.nrel.gov/docs/legosti/old/5607.pdf>, if you have not already done so. The required data is available on page 119 of the manual, which is reproduced on page 36 of this course. The results are summarized in the table below:

Tilt Angle From horizontal	<u>Ave. Solar Radiation Rate, kWh/m<sup>2</sup>/day</u>		
	<u>January</u>	<u>July</u>	<u>Annual</u>
23.75° (lat. -15°)	3.2	6.3	4.8
38.75° (latitude)	3.6	5.9	4.8
53.75° (lat. +15°)	3.8	5.1	4.6

**NOTE:** The pattern of results for **Example #12** is the same as for **Example #8**, which asked for similar data for San Antonio, TX. The comparable solar radiation rates are all lower for St. Louis than for San Antonio, because St. Louis is farther north and the sun is lower in the sky, especially in the winter.

It sometimes may be convenient to use units other than those used in *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. Table 3 below gives conversion factors for units used in that publication.

To Convert	Into	Multiply by
kilowatt-hours per square meter	megajoules per square meter	3.60
kilowatt-hours per square meter	Btu per square foot	317.2
kilowatt-hours per square meter	Langley	86.04
kilowatt-hours per square meter	calories per square centimeter	86.04
meters	feet	3.281
meters per second	miles per hour	2/237
millibars	pascals	100.0
millibars	atmospheres	0.0009869
millibars	Kilograms per square meter	10.20
millibars	pounds per square inch	0.0145
degrees Centigrade	degrees Fahrenheit	$^{\circ}\text{C} \times 1.8 + 32$
degree days (base 18.3 $^{\circ}$ C)	degree days (base 65 $^{\circ}$ F)	1.8

Table 3. Conversion Factors

**Example #13:** Find the average annual rate of solar radiation striking a flat plate solar collector, with tilt angle equal to the latitude at its location, at San Antonio, TX and at St. Louis, MO. Express the results in kwh/day/m<sup>2</sup> and in Btu/day/ft<sup>2</sup>. Also, what would be the tilt angle from the horizontal for each of those locations for the latitude tilt collector?

**Solution:** For San Antonio, TX, from page 22 of this course, the latitude is  $29.53^\circ$  north, so the tilt angle from the horizontal should be  **$29.53^\circ$** . Also from page 18, the average annual solar radiation rate on a latitude tilt collector at San Antonio is  **$5.4 \text{ kWh/day/m}^2$** . Multiplying this figure by 317.2 gives a value of  **$1713 \text{ Btu/day/ft}^2$** .

For St. Louis, MO, from page 119 of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* (or page 36 of this course), the latitude is  $38.75^\circ$  north, so the tilt angle from the horizontal should be  **$38.75^\circ$** . Also from page 119, the average annual solar radiation rate on a latitude tilt collector at St. Louis is  **$4.8 \text{ kWh/day/m}^2$** . Multiplying this figure by 317.2 gives a value of  **$1523 \text{ Btu/day/ft}^2$** .

The amount of terrestrial solar radiation at a given location can be estimated for different time periods, typically annual, monthly, daily or hourly. In this course only annual and monthly average terrestrial solar radiation has been discussed. Daily and hourly terrestrial solar radiation rates are available from the Renewable Resource Data Center (RREDC) website, which is reference number 6 in the list below. The daily and hourly rates are available only in the form of a database, however, rather than in the form of easy to use tables, as the monthly and annual rates are given in the publication, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, discussed in this course.

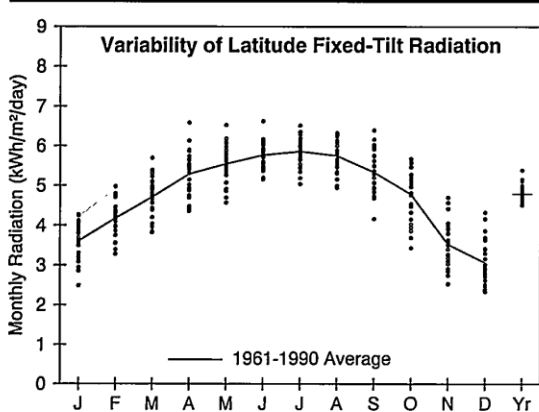
## 10. Summary

Solar energy comes to the earth as electromagnetic radiation. It has properties in common with all other forms of electromagnetic radiation, as for example, in the relationship among its wavelength, its frequency and the speed of light. When electromagnetic radiation strikes an object it must be absorbed, reflected and/or transmitted through the object. Extraterrestrial solar radiation is that reaching the earth's outer atmosphere. The average monthly extraterrestrial solar radiation rate on a horizontal surface can be found for any month, for any latitude between  $20^\circ$  and  $65^\circ$ , from a table provided in this course. Solar declination, solar hour angle, and solar altitude angle are solar parameters, which can be used to describe the sun's position at any location, at any time of the year and time of day. These parameters were discussed and means of calculating them were presented.

Sunrise hour angle and sunset hour angle were also discussed and equations were given for their calculation. Beam radiation and diffuse radiation as two components of terrestrial radiation were described and discussed. The use of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, a publication of the National Renewable Energy Laboratory, was discussed as a source for a wide range of solar radiation data for various solar collector configurations. Numerous examples illustrated the calculations and data retrieval procedures covered in this course.

## 11. References

1. Bengtson, H.H., “Estimating Solar Radiation Rate to the Tilted Surface of a Solar Panel in the U.S.,” BrightHub.com, 2010  
<http://www.brighthouse.com/environment/renewable-energy/articles/68113.aspx>
2. Bengtson, H.H., “What Happens to Solar Radiation When It Reaches the Earth as Electromagnetic Waves,” BrightHub.com, 2009  
<http://www.brighthouse.com/environment/renewable-energy/articles/63714.aspx>
3. Goswami, D. Y., Krieth, Frank, and Kreider, Jan F., *Principles of Solar Engineering*, Philadelphia: Taylor & Francis, 2000.
4. *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* (Provides solar radiation values for common flat-plate and concentrating collectors for 239 stations in the United States and its territories.):  
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# St. Louis, MO

WBAN NO. 13994

LATITUDE: 38.75° N  
 LONGITUDE: 90.38° W  
 ELEVATION: 172 meters  
 MEAN PRESSURE: 997 millibars

STATION TYPE: Secondary

**Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%**

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	2.2	2.9	3.9	5.0	5.9	6.4	6.4	5.7	4.6	3.5	2.3	1.8	4.2
	Min/Max	1.7/2.5	2.5/3.4	3.3/4.5	4.3/6.1	4.9/6.9	5.8/7.4	5.5/7.1	4.9/6.2	3.8/5.3	2.8/3.9	1.9/2.7	1.6/2.3	4.0/4.7
Latitude -15	Average	3.2	3.8	4.6	5.4	5.9	6.3	6.3	6.0	5.3	4.5	3.2	2.7	4.8
	Min/Max	2.3/3.7	3.1/4.5	3.8/5.5	4.5/6.7	4.9/6.9	5.6/7.2	5.4/7.0	5.1/6.6	4.2/6.3	3.3/5.2	2.4/4.1	2.1/3.7	4.5/5.3
Latitude	Average	3.6	4.2	4.7	5.3	5.6	5.8	5.9	5.7	5.3	4.8	3.5	3.1	4.8
	Min/Max	2.5/4.3	3.3/5.0	3.8/5.7	4.4/6.6	4.6/6.5	5.2/6.6	5.0/6.5	4.9/6.3	4.2/6.4	3.4/5.7	2.5/4.7	2.3/4.3	4.5/5.4
Latitude +15	Average	3.8	4.3	4.6	4.9	4.9	5.0	5.1	5.2	5.1	4.8	3.7	3.3	4.6
	Min/Max	2.6/4.6	3.3/5.2	3.7/5.6	4.0/6.1	4.1/5.8	4.5/5.7	4.4/5.7	4.5/5.8	4.0/6.2	3.4/5.8	2.6/5.0	2.4/4.7	4.3/5.1
90	Average	3.5	3.7	3.4	3.1	2.6	2.4	2.6	3.0	3.5	3.8	3.2	3.0	3.2
	Min/Max	2.3/4.3	2.7/4.6	2.7/4.1	2.5/3.7	2.3/2.9	2.3/2.6	2.3/2.7	2.6/3.3	2.7/4.2	2.6/4.7	2.2/4.5	2.2/4.5	2.8/3.5

**Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis (kWh/m²/day), Uncertainty ±9%**

Axis Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.1	4.0	5.1	6.6	7.6	8.3	8.3	7.6	6.2	4.9	3.1	2.5	5.6
	Min/Max	2.2/3.7	3.1/4.8	4.0/6.4	5.2/8.5	6.1/9.4	7.3/10.0	7.2/9.5	6.3/8.4	4.7/7.8	3.4/5.9	2.3/4.2	2.0/3.5	5.3/6.5
Latitude -15	Average	3.8	4.7	5.7	6.9	7.7	8.3	8.4	7.8	6.8	5.6	3.8	3.2	6.1
	Min/Max	2.6/4.6	3.6/5.6	4.3/7.2	5.4/9.0	6.1/9.6	7.2/10.0	7.2/9.5	6.4/8.8	5.0/8.6	3.9/6.8	2.7/5.2	2.4/4.6	5.7/7.0
Latitude	Average	4.2	5.0	5.8	6.8	7.5	7.9	8.1	7.7	6.8	5.9	4.1	3.5	6.1
	Min/Max	2.8/5.1	3.7/6.0	4.4/7.3	5.3/8.9	5.9/9.3	6.9/9.6	6.9/9.2	6.3/8.6	5.0/8.7	4.0/7.2	2.8/5.7	2.6/5.1	5.7/7.1
Latitude +15	Average	4.4	5.1	5.7	6.5	7.0	7.4	7.6	7.3	6.7	5.9	4.2	3.7	6.0
	Min/Max	2.8/5.3	3.8/6.2	4.3/7.3	5.1/8.6	5.5/8.8	6.5/8.9	6.5/8.6	6.0/8.2	4.8/8.5	4.0/7.2	2.8/5.9	2.7/5.4	5.5/6.9

**Solar Radiation for 2-Axis Tracking Flat-Plate Collectors (kWh/m²/day), Uncertainty ±9%**

Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
2-Axis	Average	4.4	5.1	5.8	6.9	7.8	8.5	8.5	7.9	6.9	5.9	4.3	3.7	6.3
	Min/Max	2.9/5.4	3.8/6.2	4.4/7.4	5.4/9.0	6.2/9.7	7.4/10.2	7.3/9.7	6.5/8.8	5.1/8.7	4.0/7.3	2.9/5.9	2.7/5.5	5.9/7.3

**Direct Beam Solar Radiation for Concentrating Collectors (kWh/m²/day), Uncertainty ±8%**

Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
1-Axis, E-W Horiz Axis	Average	2.5	2.6	2.7	3.1	3.5	3.9	4.0	3.7	3.3	3.2	2.4	2.1	3.1
	Min/Max	1.3/3.4	1.7/3.4	1.7/4.0	1.9/4.8	2.3/5.1	3.2/5.5	2.8/5.1	2.6/4.5	2.0/4.7	1.8/4.2	1.2/3.8	1.3/3.6	2.8/3.9
1-Axis, N-S Horiz Axis	Average	1.9	2.4	3.0	4.0	4.7	5.2	5.3	4.9	4.0	3.3	1.9	1.5	3.5
	Min/Max	0.9/2.6	1.5/3.2	1.9/4.6	2.4/6.2	3.1/6.8	4.3/7.2	3.9/6.7	3.5/6.0	2.3/5.9	1.8/4.3	1.0/3.1	0.9/2.5	3.1/4.5
1-Axis, N-S Tilt=Latitude	Average	2.7	3.1	3.6	4.3	4.6	4.9	5.1	4.9	4.5	4.1	2.7	2.2	3.9
	Min/Max	1.4/3.8	2.0/4.2	2.2/5.3	2.5/6.5	3.1/6.7	4.0/6.8	3.7/6.4	3.5/6.1	2.6/6.6	2.3/5.4	1.4/4.3	1.4/3.8	3.5/5.0
2-Axis	Average	2.9	3.2	3.6	4.3	4.8	5.3	5.5	5.1	4.5	4.1	2.9	2.4	4.1
	Min/Max	1.5/4.0	2.0/4.2	2.2/5.3	2.6/6.6	3.2/7.1	4.3/7.4	4.0/6.9	3.6/6.3	2.6/6.6	2.3/5.4	1.4/4.6	1.5/4.2	3.6/5.2

**Average Climatic Conditions**

Element	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (°C)	-1.5	1.1	7.3	13.7	18.9	24.1	26.6	25.3	21.2	14.7	7.9	1.1	13.4
Daily Minimum Temp	-6.2	-3.8	1.9	8.0	13.3	18.7	21.3	19.9	15.8	9.1	3.2	-3.3	8.2
Daily Maximum Temp	3.2	5.9	12.6	19.4	24.5	29.6	31.8	30.7	26.6	20.3	12.6	5.4	18.6
Record Minimum Temp	-27.8	-23.3	-20.6	-5.6	-0.6	6.1	10.6	8.3	2.2	-5.0	-17.2	-26.7	-27.8
Record Maximum Temp	24.4	29.4	31.7	33.9	33.9	38.9	41.7	41.7	40.0	34.4	29.4	24.4	41.7
HDD, Base 18.3°C	615	484	343	148	62	0	0	0	12	132	313	536	2643
CDD, Base 18.3°C	0	0	0	9	81	173	255	217	98	18	0	0	852
Relative Humidity (%)	73	72	68	63	66	67	68	70	72	69	72	76	70
Wind Speed (m/s)	4.9	4.8	5.3	5.2	4.3	4.1	3.8	3.6	3.8	4.1	4.6	4.8	4.4