Solar Energy Fundamentals

By

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Learning Objectives

1. To know the different types of electromagnetic radiation and which of them are included in solar radiation
2. To be able to calculate wavelength if given frequency for specified electromagnetic radiation
3. To be able to calculate frequency if given wavelength for specified electromagnetic radiation

Learning Objectives

4. To be able to obtain or calculate values for solar declination, solar hour angle, solar altitude angle, sunrise angle, and sunset angle.

5. To be able to use solar declination, solar hour angle, solar altitude angle, sunrise angle, and sunset angle values in calculations

Learning Objectives

6. To know the major methods by which solar radiation is converted into other useable forms of energy

7. To 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

Learning Objectives

8. To be able to obtain values for the average monthly rate of solar radiation striking the surface of several types of solar collectors at a specified location in the United States for a specified month

9. To be able to retrieve solar radiation and meteorology data for any location in the world using the NASA POWER website identified and discussed in this course.

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.

Introduction

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, (and for a specified location around the world), for a given month. Numerous examples are included to illustrate the calculations and data retrieval methods presented.

Introduction

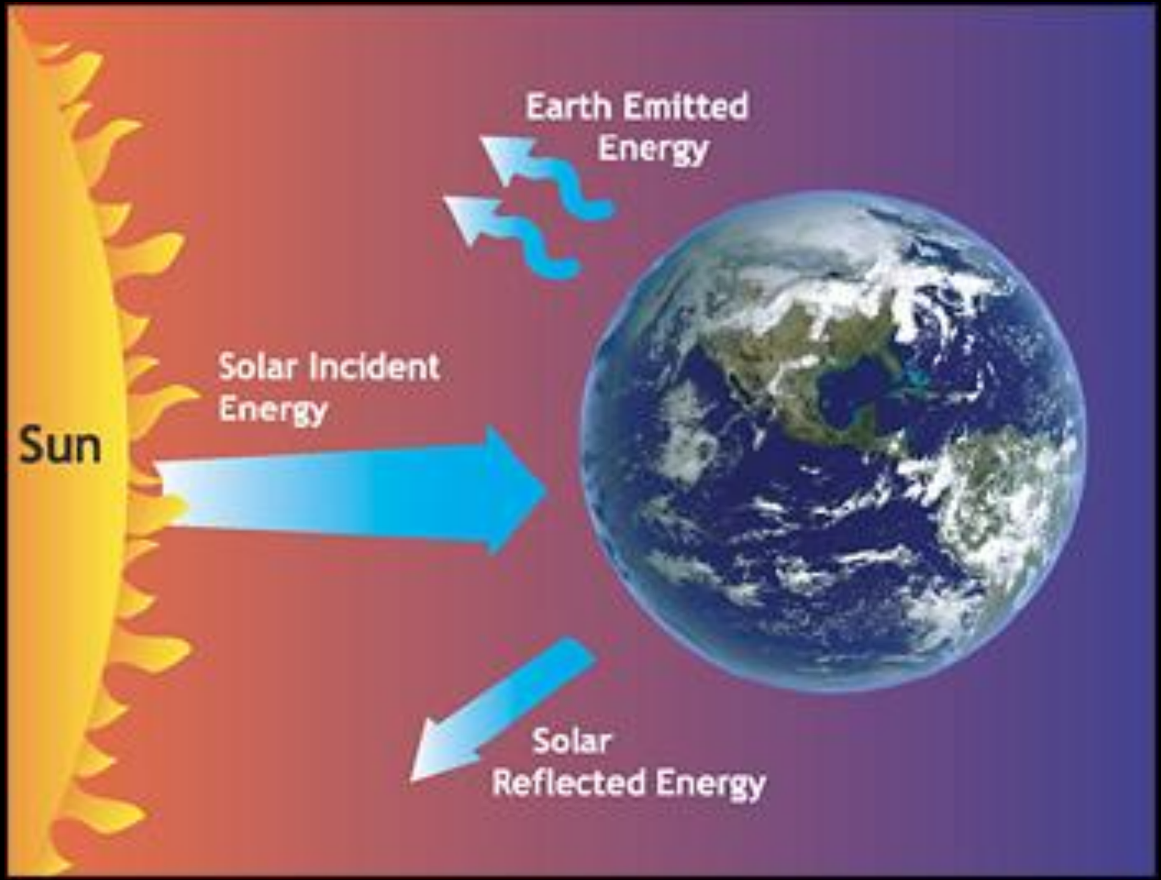


Image Credit: NOAA, Earth Systems Research Laboratory
www.esrl.noaa.gov/gmd/outreach/faq_cat-1.html

The Nature of Electromagnetic 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, λ, and frequency, μ .

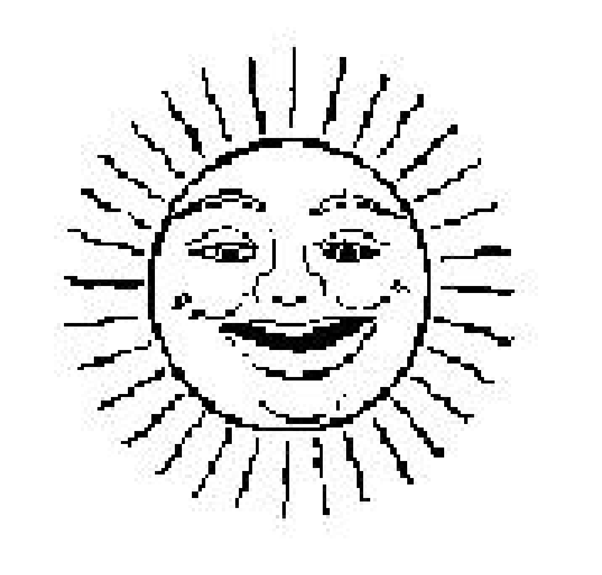
The Nature of Electromagnetic Radiation

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:

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

The speed of light in a vacuum is 3.000 x 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).

The Nature of Electromagnetic Radiation



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 two slides back are arranged from lowest frequency (radio waves) to highest frequency (gamma waves).

The Nature of Electromagnetic Radiation

Example #1:

What will be the wavelength of a radio wave with a frequency of 200,000 cycles per second?

The solution to **Example #1** is shown on the next slide.

The Nature of Electromagnetic Radiation

Example #1 - Solution:

The wavelength can be calculated from **Equation (1)** as follows:

λ **=** $\mathbf{c/\mu}$ = $(3 \times 10^8 \text{ m/sec})/(2 \times 10^5 \text{ cycles/sec})$

= 1500 m/cycle

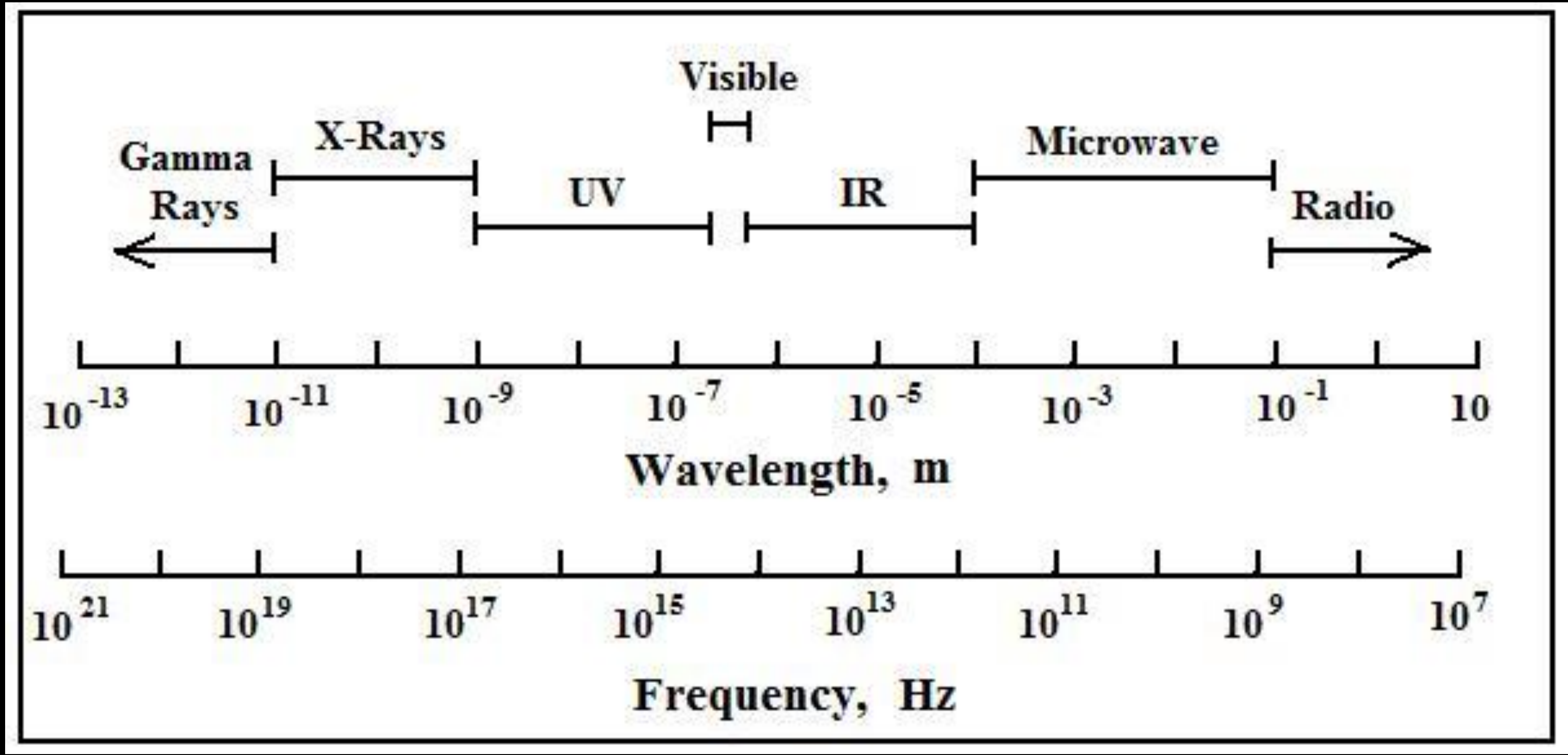
or, as usually expressed, simply: **1500 m**

The Nature of Electromagnetic Radiation

Figure 1, on the next slide, summarizes the electromagnetic radiation spectrum. It shows the various forms of electromagnetic radiation and the range of wavelength and frequency for each of them.

The Nature of Electromagnetic Radiation

Figure 1. Summary of the Electromagnetic Spectrum

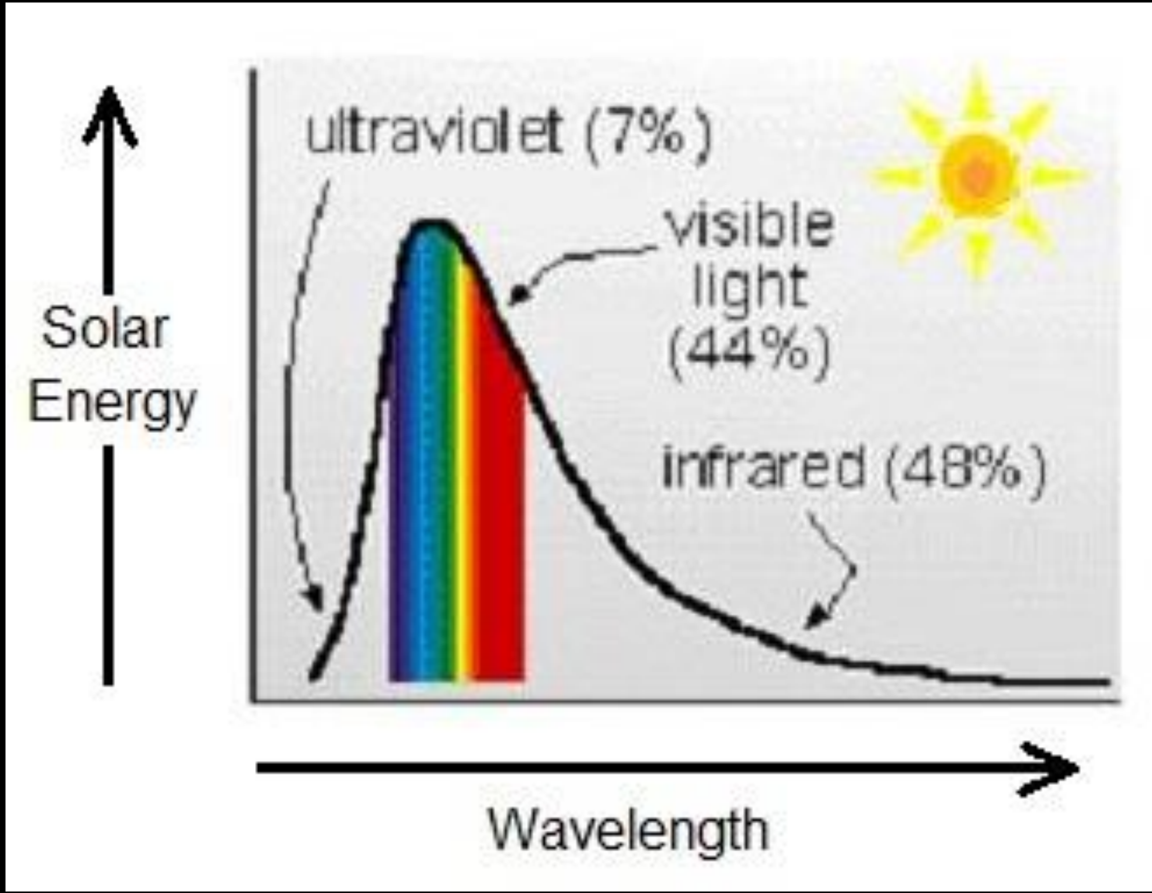


The Nature of Electromagnetic Radiation

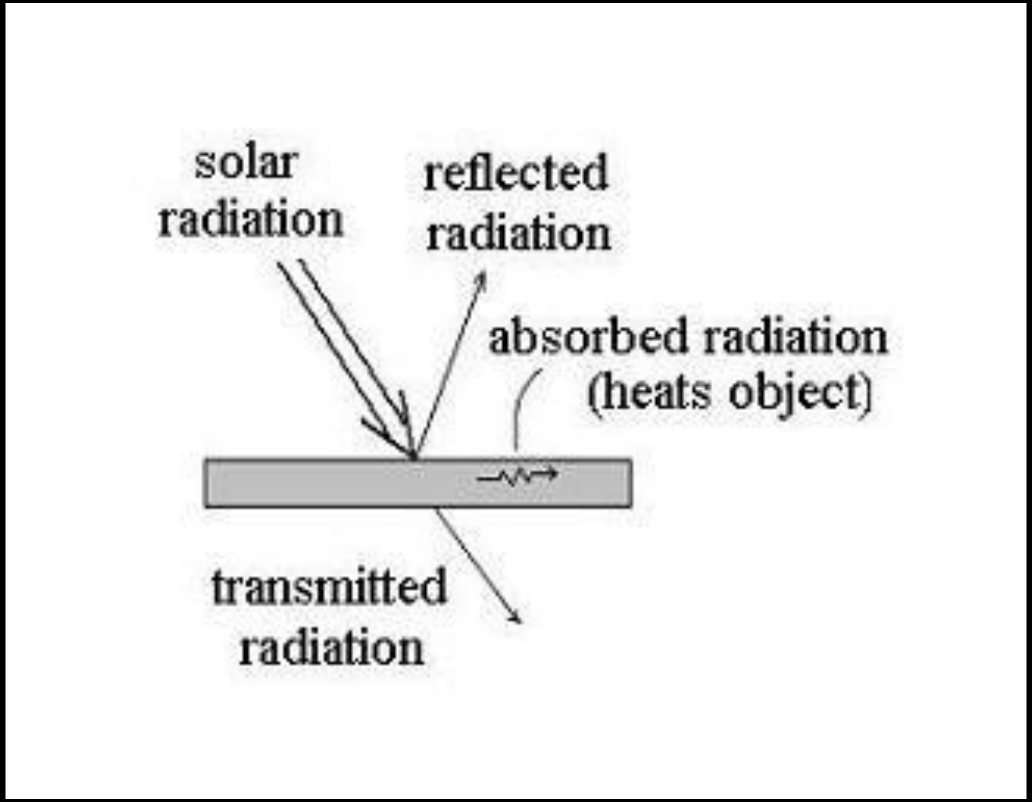
Solar radiation has most of its energy between wavelengths of 10^{-7} and 3×10^{-6} m. This includes ultraviolet light, visible light and infrared radiation. Visible light and near-infrared (wavelength of 7×10^{-7} to 4×10^{-7} m) make up over 90% of the solar radiation reaching the Earth's atmosphere.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

The Nature of Electromagnetic Radiation

Figure 2. Approximate Characteristics of Solar Radiation reaching the Earth



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.

What Happens to Solar Radiation when it Strikes an Object?

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 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.

What Happens to Solar Radiation when it Strikes an Object?

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, as expressed in **Equation (2)** below:

$$\mathbf{a + r + t = 1} \qquad \mathbf{(2)}$$

What Happens to Solar Radiation when it Strikes an Object?

An object which allows no electromagnetic radiation of a given wavelength to pass through it is said to be opaque to electromagnetic radiation of that wavelength, and **t** = 0. Solar radiation, that 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.

What Happens to Solar Radiation when it Strikes an Object?

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.

The solution to **Example #2** is shown on the next slide.

What Happens to Solar Radiation when it Strikes an Object?

Example #2 - 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 x 0.7 Kilowatts = **0.105 Kilowatts**.

Solar Position Parameters and Calculation of their Values

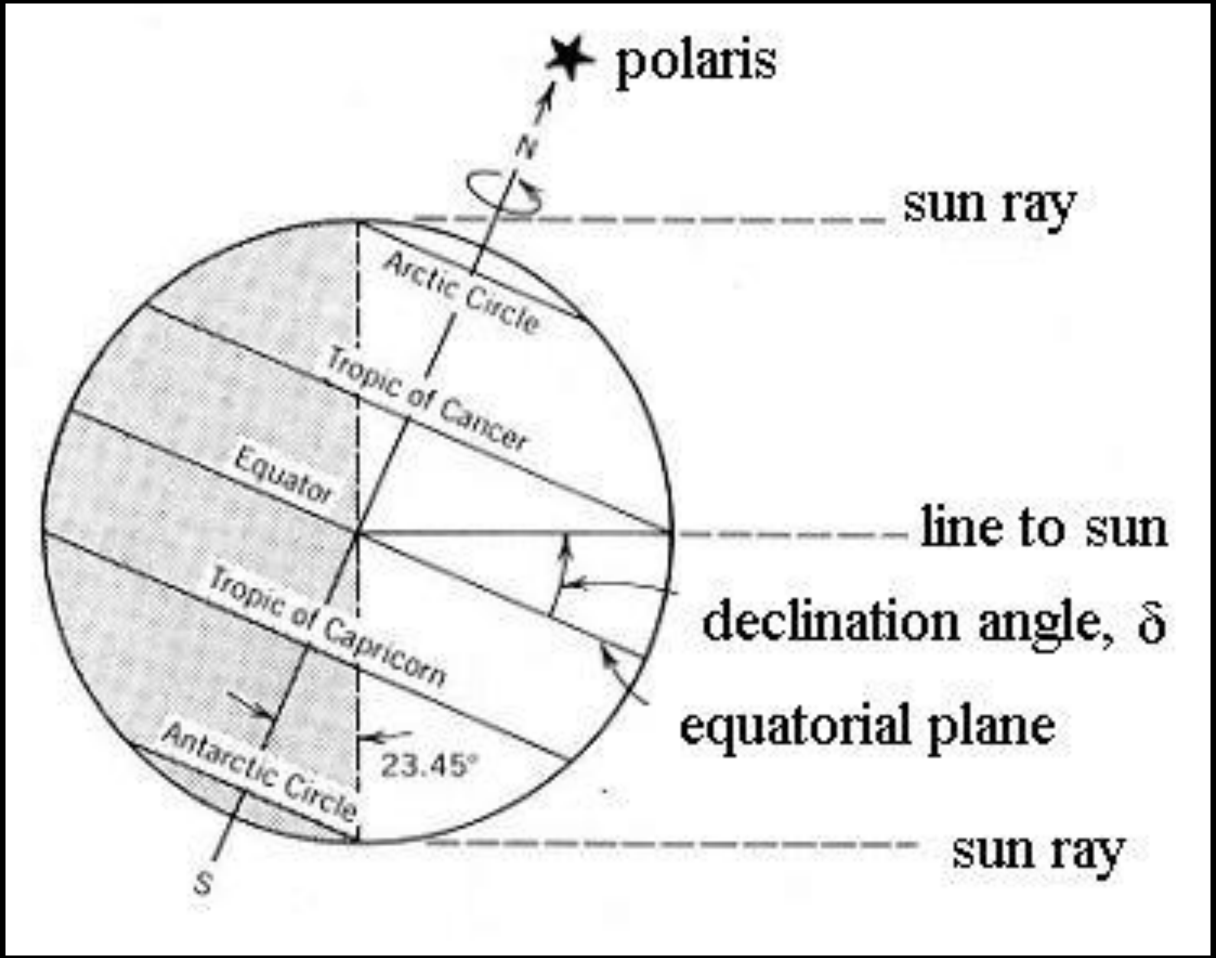
Several solar parameters are used to describe the position of the sun at a specified location, date and time and to make calculations regarding the rate of solar radiation striking the earth at a specified location. Five of those parameters, **solar declination, solar hour angle, solar altitude angle,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

Solar Position Parameters and Calculation of their Values

Solar declination is the angle between the sun's rays and a plane passing through the equator. This is illustrated in **Figure 3** on the next slide. 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).

Solar Position Parameters and Calculation of their Values

Figure 3. Solar Declination Angle, δ



Solar Position Parameters and Calculation of their Values

The solar declination depends only on the day of the year.
The solar declination, δ, can be calculated from the equation:

$$\delta = (23.45^{o})\sin[360^{o}(284 + n)/365] \qquad (3)$$

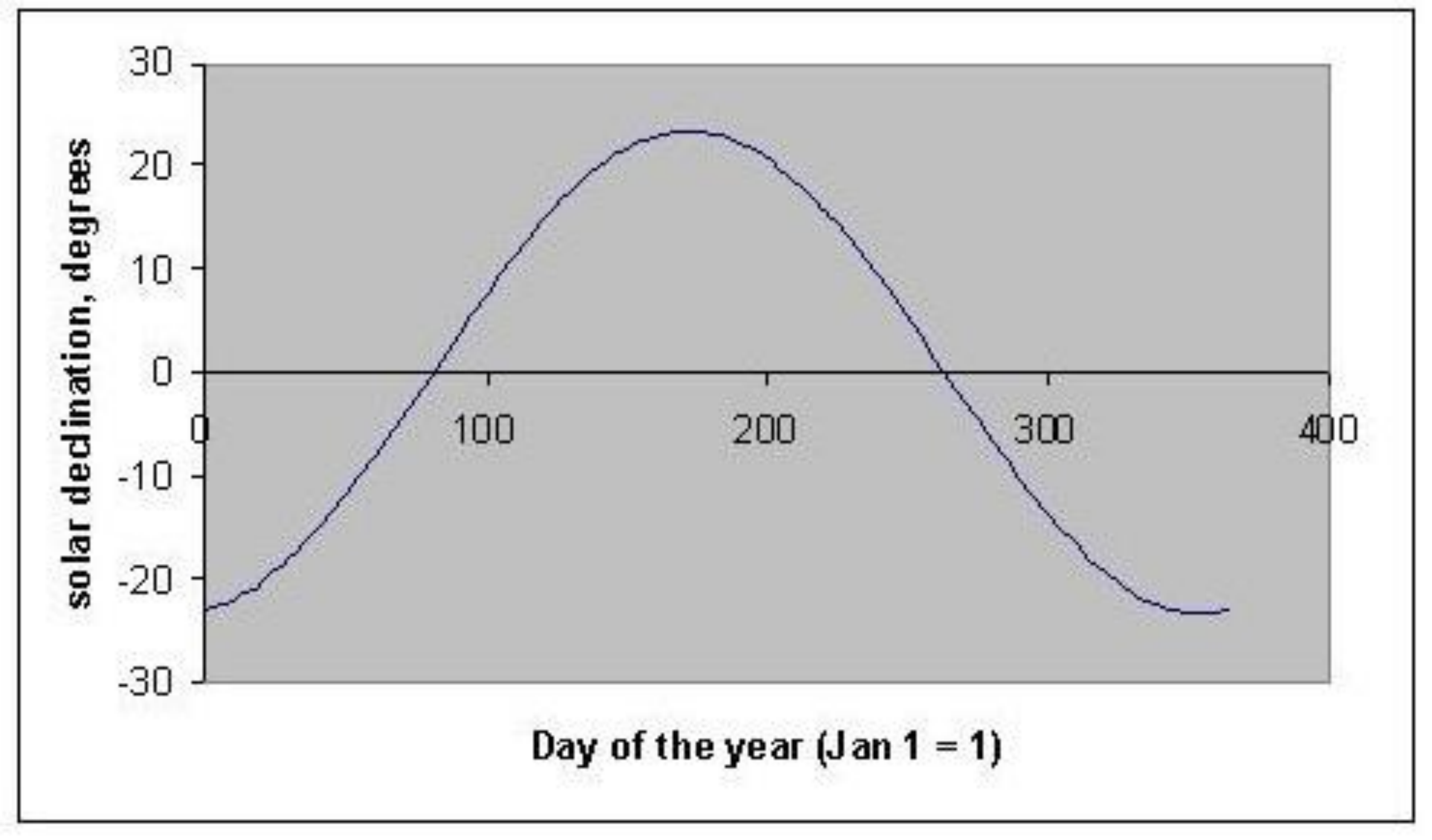
Where **n** is the day number in the year, with January 1 as 1.

Solar Position Parameters and Calculation of their Values

The variation of δ throughout the year is shown in **Figure 4**, on the next slide. The solar declination has a maximum value of + 23.45° on June 21 and a minimum value of – 23.45° on December 21.

Solar Position Parameters and Calculation of their Values

Figure 4. Solar Declination vs Day of the Year



Solar Position Parameters and Calculation of their Values

Example #3:

What is the value of the solar declination on February 15?

The solution to **Example #3** is shown on the next slide.

Solar Position Parameters and Calculation of their Values

Example #3 - Solution:

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

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

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

Solar Position Parameters and Calculation of their Values

Example #3 – Solution (continued):

If you are using Excel for calculations the argument of the trigonometric functions must be in radians rather than in degrees. The conversion is π radians = 180 degrees, thus the equation on the last slide, with the angle 325.5^{o} expressed in radians, is as shown on the next slide.

Solar Position Parameters and Calculation of their Values

Example #3 – Solution (continued):

The equation from the last slide with the angle 325.5^o expressed in radians becomes:

δ = (23.45^o)sin[(325.5)(π/180)] or (23.45^o)sin[(325.5)(pi()/180)]

Proceeding with the calculation: **$\underline{\delta = -13.3^o}$**

Note that this is consistent with **Figure (4),** three slides back.

Solar Position Parameters and Calculation of their Values

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, ω, 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 15º each hour, or one degree in 4 minutes. The variation of the solar hour angle with local solar time is summarized in **Table 1**, on the next two slides.

Solar Position Parameters and Calculation of their Values

Table 1. Solar Hour Angle as a Function of Solar Time – Part 1

Solar time	**Solar hour angle, ω, in degrees**
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**

Solar Position Parameters and Calculation of their Values

Table 1. Solar Hour Angle as a Function of Solar Time – Part 2

Solar time	Solar hour angle, ω, in degrees
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 Position Parameters and Calculation of their Values

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 due to 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 **Equations (4), (5),** and **(6)** given on the next two slides.

Solar Position Parameters and Calculation of their Values

$$\text{Solar Time} = \text{local standard time} + \mathbf{ET} + (\boldsymbol{l}_{\mathbf{st}} - \boldsymbol{l}_{\mathbf{local}})(4\ \text{min/degree}) \qquad \mathbf{(4)}$$

Where $\boldsymbol{l}_{\mathbf{st}}$ is the standard time meridian in the local time zone, $\boldsymbol{l}_{\mathbf{local}}$ is the local meridian, and **ET** is the equation of time in minutes. There is no exact equation for **ET**, but it can be approximated by **Equations (5)** and **(6)** which are shown on the next slide.

Solar Position Parameters and Calculation of their Values

The value for the equation of time, **ET**, can be approximated by **Equations (5)** and **(6)** below, which are presented and discussed at: http://www.susdesign.com/popups/sunangle/eot.php

$$\mathbf{ET} = 9.87 \sin(2\mathbf{B}) - 7.53 \cos(\mathbf{B}) - 1.5 \sin(\mathbf{B}) \qquad \textbf{(5)}$$

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

Solar Position Parameters and Calculation of their Values

For further details about the Equation of Time, see:

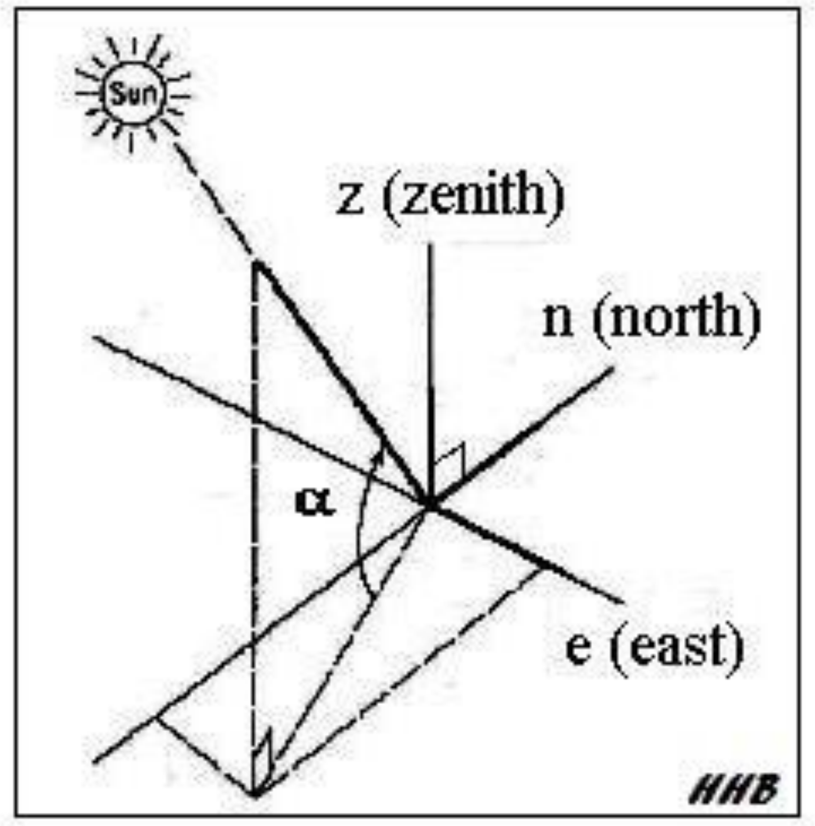
http://www.uwrf.edu/AboutUs/EquationOfTime.cfm

Solar Position Parameters and Calculation of their Values

The **Solar Altitude Angle** is the angle between the sun's rays and a horizontal plane, as shown in the figure on the next slide. When the sun is just rising or setting, the altitude angle is zero. When the sun is directly overhead, the altitude angle is 90º. The solar altitude angle, α, can be calculated for any location and time from the latitude, **L**, solar declination, δ, and solar hour angle, ω, using the following equation:

$$\text{Sin}\,\alpha = \sin L \sin\delta + \cos L \cos\delta \cos\omega \qquad (7)$$

Solar Position Parameters and Calculation of their Values



Solar Altitude Angle, α

Solar Position Parameters and Calculation of their Values

Example #4:

Calculate the solar altitude angle, α , for solar noon on February 15, in St. Louis, MO (latitude: 38.75^{o} N)

The solution to **Example #4** is shown on the next slide.

Solar Position Parameters and Calculation of their Values

Example #4 - Solution:

From **Example #3,** the solar declination, δ , on February 15, is – 13.3^{o}.

The hour angle, ω, is zero at solar noon, and the latitude is given in the problem statement as 38.75^{o}, so **Equation (8)** becomes:

$$\text{Sin}\ \alpha = \sin(38.75^{o})\sin(-13.3^{o}) + \cos(38.75^{o})\cos(-13.3^{o})\cos(0)$$

Solar Position Parameters and Calculation of their Values

Example #4 – Solution (continued):

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

$$\textbf{Sin}\ \alpha = \mathbf{0.615}$$

$$\alpha = \sin^{-1}(0.615) = 0.6624 \text{ radians} = 0.6624*180/\pi \text{ degrees}$$

$$= \underline{\mathbf{37.9^{o} = \alpha}}$$

Solar Position Parameters and Calculation of their Values

In some solar calculations, values for the sunset hour angle and sunrise hour angle are needed. The solar altitude angle, α , will be zero for both sunset and sunrise, so an equation for sunrise and sunset hour angles can be found by setting the value of the solar altitude angle, α**,** equal to zero in **Equation (7)** above and solving for ω. The angle will be negative for sunrise and positive for sunset. This results in **Equation (8)** and **Equation (9)** shown on the next slide.

Solar Position Parameters and Calculation of their Values

This results in the following two equations:

Sunrise Hour Angle $= \omega_{sr} = -\cos^{-1}[-(\tan \mathbf{L})(\tan \boldsymbol{\delta})]$ (8)

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

Solar Position Parameters and Calculation of their Values

If ω_{sr} or ω_{ss} is calculated in degrees from **Equation (8)** or **Equation (9),** they can be converted to radians by multiplying by the factor (π/180). To calculate clock time before or after solar noon for sunrise or sunset, the conversion is 4 minutes per degree.

Solar Position Parameters and Calculation of their Values

Example #5:

Calculate the sunrise hour angle and sunset hour angle for Kansas City, MO (latitude: 39.30º N), on February 15.

The solution to **Example #5** is shown on the next slide.

Solar Position Parameters and Calculation of their Values

Example #5 - Solution:

From **Example #3,** the solar declination, δ, on February 15, is – 13.3^o, and the latitude is given in the problem statement as 39.30^o, so **Equation (9)** becomes:

Sunset angle = ω_{ss} = $\cos^{-1}[- \tan(39.30^o)*\tan(-13.3^o)]$

= 1.376 radians = $\underline{\mathbf{78.8^o = \omega_{ss}}}$

Sunrise angle = ω_{sr} = $- \omega_{ss}$ = $\underline{\mathbf{- 78.8^o = \omega_{sr}}}$

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 a) driving photosynthesis, which directly or indirectly produces all our food; b) driving the hydrological cycle, that is, generating evaporation of water from oceans and other bodies of water, which ends up producing precipitation over land and keeps the rivers running; and c) simply keeping the temperature within a range at which we can survive on the surface of the earth.

Methods of Utilizing Solar Energy

The primary intent of this section, however, is to briefly describe the major ways that solar energy is converted to other usable forms of energy. Three methods of utilizing solar energy will be discussed here: **solar space heating**, **solar water heating** and **solar generation of electricity**.

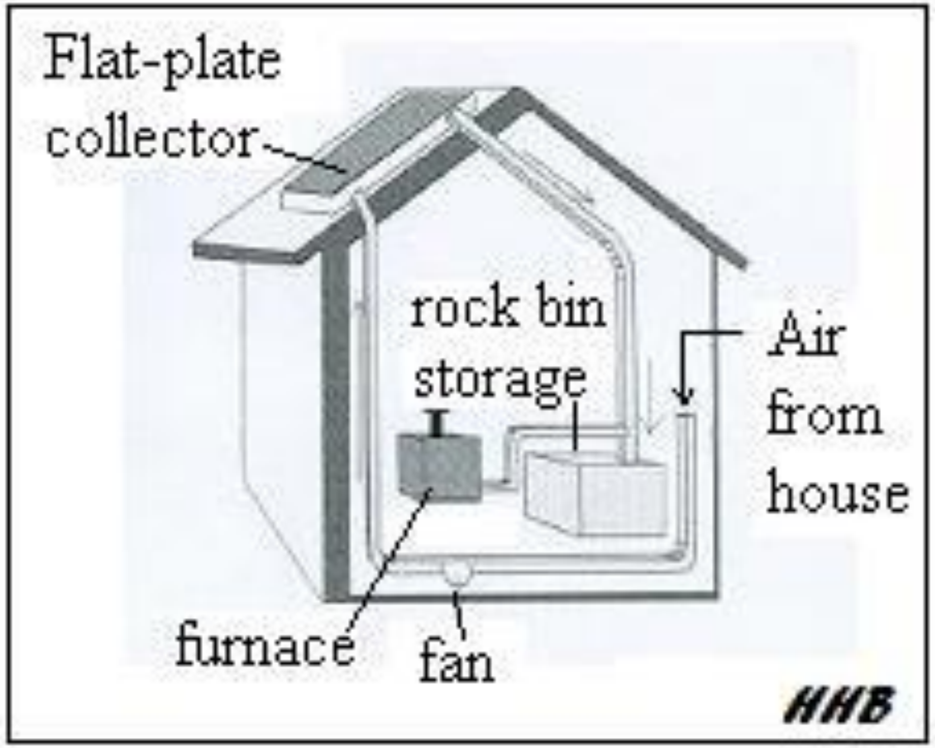
Methods of Utilizing Solar Energy

Solar space heating can be accomplished with **active** solar heating systems or **passive** solar heating systems. The next few slides will describe both active and passive solar heating systems and the differences between them.

Methods of Utilizing Solar Energy

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. A schematic diagram of an active solar heating system is shown on the next slide.

Methods of Utilizing Solar Energy

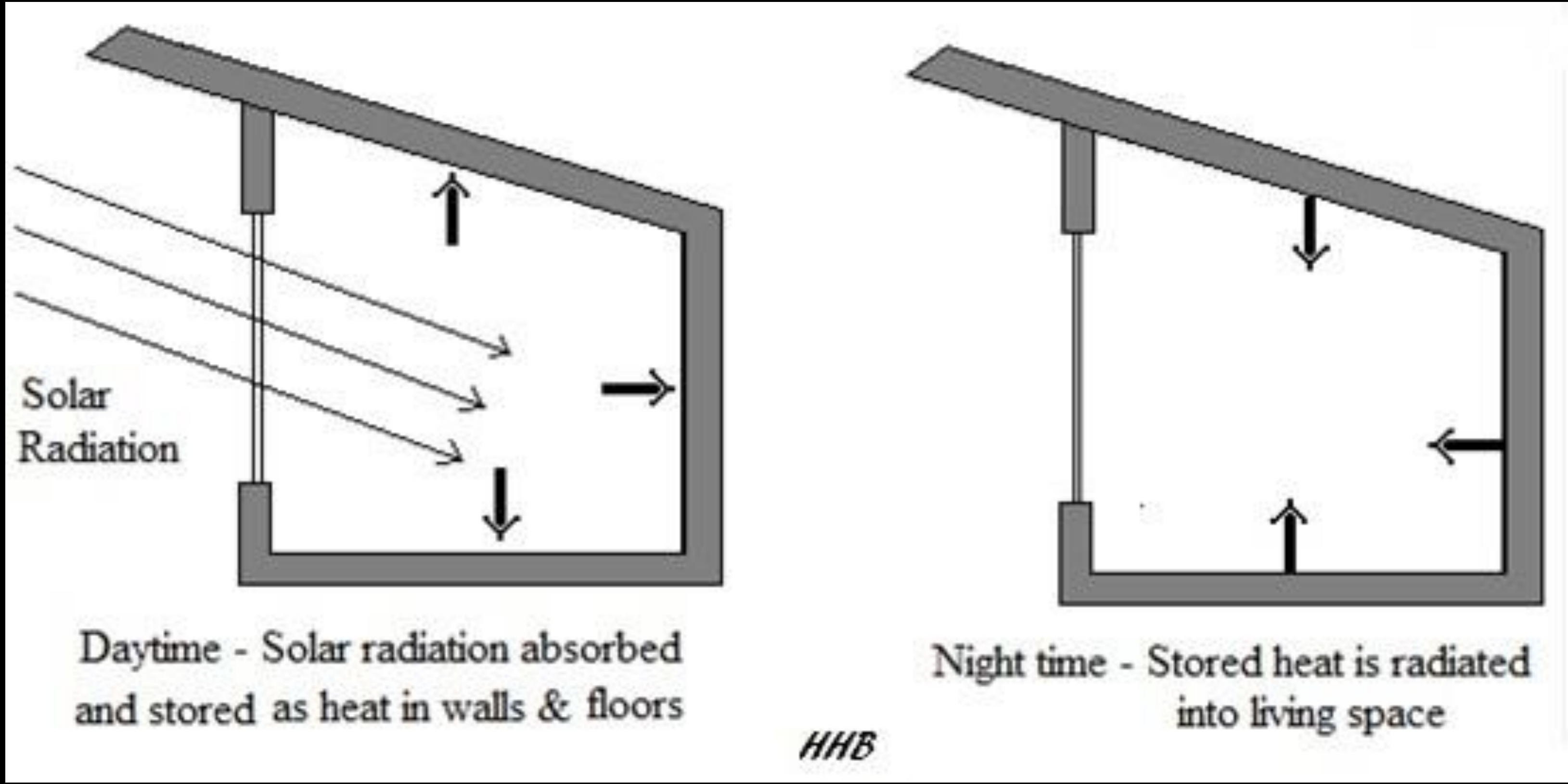


Active Solar Heating

Methods of Utilizing Solar Energy

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. A schematic diagram of a passive solar heating system is shown on the next slide.

Methods of Utilizing Solar Energy

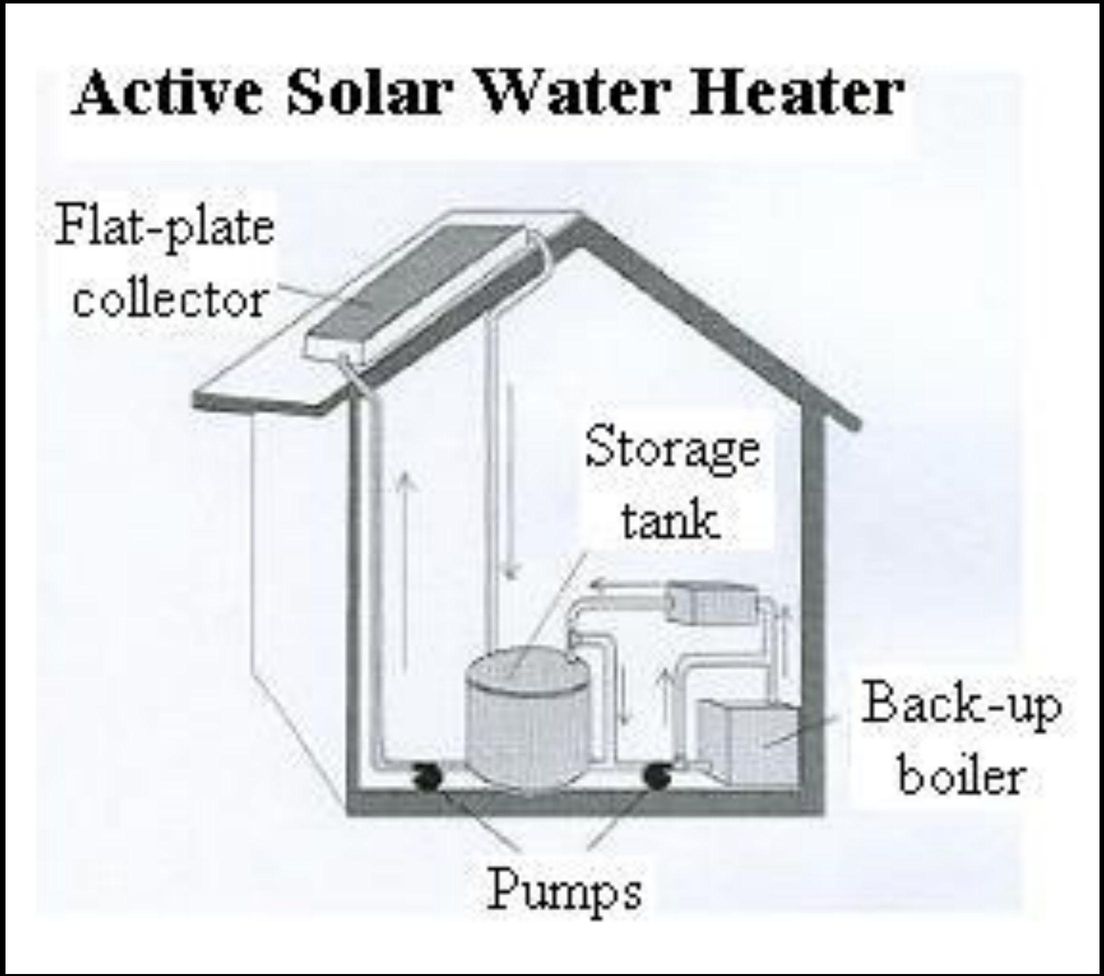


Passive Solar Space Heating

Methods of Utilizing Solar Energy

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. A diagram of an active solar water heater is shown on the next slide.

Methods of Utilizing Solar Energy



Methods of Utilizing Solar Energy

Solar Generation of Electricity can be done by two different methods. They are: i) use of photovoltaic cells to generate an electrical current that can be used directly or used to 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. A picture of a typical array of roof-mounted photovoltaic cell is shown on the next slide.

Methods of Utilizing Solar Energy

An Array of Photovoltaic Cells For conversion of Solar Energy to Electricity

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

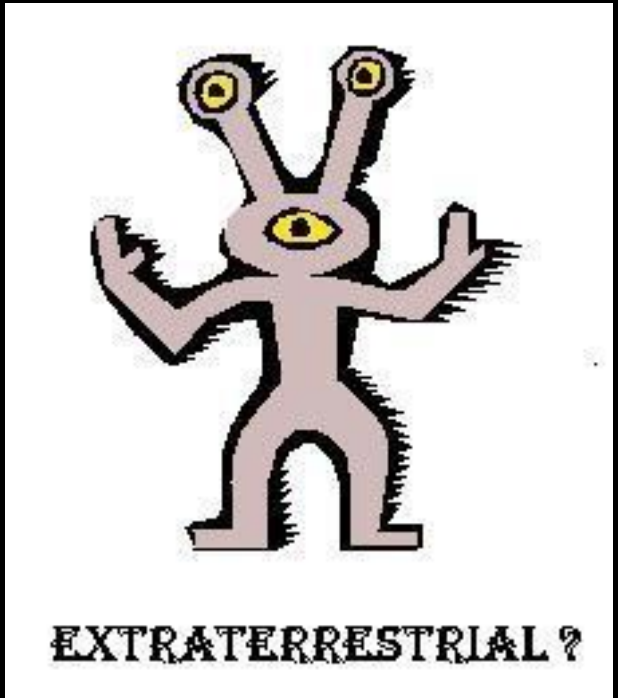
Methods of Utilizing Solar Energy

Solar Generation of Electricity can be done by heating a fluid with solar energy and using the heated fluid in a heat engine to generate electricity. This type of solar generation of electricity requires the use of a concentrating collector in order to heat the fluid to a temperature that high enough to give a reasonable efficiency for the conversion to electricity in the heat engine. There will be more description of concentrating collectors later in this course.

Methods of Utilizing Solar Energy

The details of the methods just described briefly for utilization of solar energy 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, of the type to be used, at the location of interest, for some appropriate time period, such as a month. The rest of this course is about how to obtain such information.

Extraterrestrial Solar Radiation



Solar radiation continuously strikes the earth's outer atmosphere at the rate of 1.7 x 10^{17} watts. This is referred to as 'extraterrestrial' solar 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^2.

Extraterrestrial Solar Radiation

A value of 1367 W/m^2 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 equation given on the next slide.

Extraterrestrial Solar Radiation

The equation for extraterrestrial solar flux, $\mathbf{I_o}$, is:

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

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

Extraterrestrial Solar Radiation

Using some of the solar parameters discussed earlier in this course (δ & ω_{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)** for calculation of $\mathbf{I_o}$.

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

Extraterrestrial Solar Radiation

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** on the next slide gives monthly averaged, daily extraterrestrial solar radiation on a horizontal surface, $\mathbf{H_{oh\text{-}ave}}$, for latitudes from 20 to 65 degrees. The values were obtained by calculating daily values of $\mathbf{H_{o,h}}$ from **Equations (10) and (11),** and then calculating the average for each month.

Extraterrestrial Solar Radiation

Table 2. Monthly Averaged extraterrestrial radiation on a horizontal surface, kWhr/day/m^2

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

Extraterrestrial Solar Radiation

Example #6:

What is the average extraterrestrial solar radiation rate ($kWhr/day/m^2$) in St. Louis, MO (latitude: 38.75^o N), in February?

The solution to **Example #6** is shown on the next slide.

Extraterrestrial Solar Radiation

Example #6 - Solution:

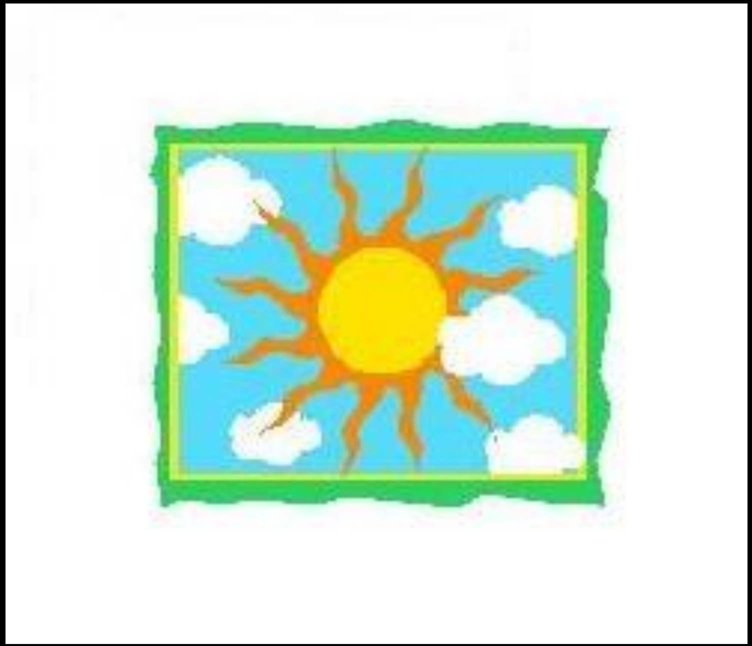
From **Table 1**: for latitude 35^o, solar rate = 6.42 kWhr/day/m^2, and for latitude 40^o, solar rate = 5.65 kWhr/day/m^2

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

$$6.42 - [(38.75 - 35)/(40 - 35)](6.42 - 5.65)$$

= **<u>5.84 kWhr/day/m^2</u>**

Extraterrestrial Solar Radiation



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.

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.

Extraterrestrial Solar Radiation

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.

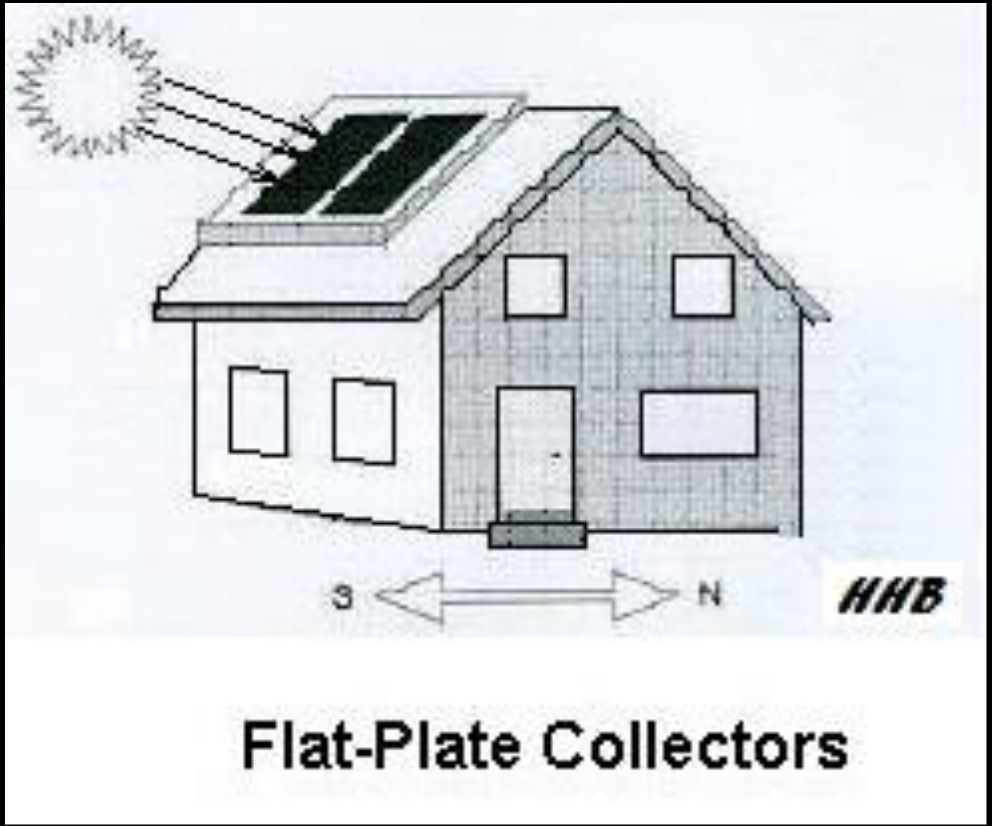
Terrestrial Solar Radiation Quantities or Rates

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 for any month, 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?

Terrestrial Solar Radiation Quantities or Rates

This is a good question, which will now be addressed. 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.

Terrestrial Solar Radiation Quantities or Rates



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.

Terrestrial Solar Radiation Quantities or Rates

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 now be discussed here, and illustrated with examples.

Terrestrial Solar Radiation Quantities or Rates

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: https://www.nrel.gov/docs/legosti/old/5607.pdf
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.

Terrestrial Solar Radiation Quantities or Rates

NREL Images Credit

Several images in these slides came from the NREL website noted on the previous slide. The figures were prepared by the National Renewable Energy Laboratory for the U.S. Department of Energy. The images from the aforementioned 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.

Terrestrial Solar Radiation Quantities or Rates

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.

Terrestrial Solar Radiation Quantities or Rates

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 the Figure on the next slide, shows the locations of the 239 stations used for data in the manual.

Terrestrial Solar Radiation Quantities or Rates

Map showing the 239 NREL Stations

Terrestrial Solar Radiation Quantities or Rates

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.

Terrestrial Solar Radiation Quantities or Rates

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.

Terrestrial Solar Radiation Quantities or Rates

To show the type of information available in the NREL data manual, the tables on the next three slides show data for San Antonio, Texas from page 217 of the NREL *Solar Radiation Data Manual for Flat Plate and Concentrating Collectors*.

Terrestrial Solar Radiation Quantities or Rates

Table 3. San Antonio, TX - Data from p 217, NREL *Solar Radiation Data Manual for Collectors*

	Solar Radiation for Flat-Plate Collectors Facing South at Fixed Tilt (kWh/m²/day), Uncertainty ± 9%												
Tilt (°)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0 (horiz), 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
Minimum	2.6	3.3	3.8	4.3	4.9	5.7	5.6	5.6	4.7	3.6	2.7	2.5	4.7
Maximum	3.5	4.6	5.8	6.4	6.5	7.3	7.7	7.1	6.2	5.1	4.1	4.1	5.2
Latitude - 15, Ave.	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
Minimum	3.0	3.7	4.1	4.4	4.9	5.5	5.6	5.7	4.9	4.0	3.0	3.0	5.0
Maximum	4.5	5.5	6.4	6.7	6.4	7.1	7.5	7.2	6.7	5.9	5.2	4.6	5.5
Latitude, Ave.	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
Minimum	3.4	3.9	4.2	4.3	4.6	5.1	5.2	5.6	5.0	4.2	3.2	3.3	5.1
Maximum	5.2	6.1	6.7	7	6.1	6.5	7	6.9	6.8	6.5	6	5.4	5.6
Latitude + 15, Ave.	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
Minimum	3.5	4	4.1	4	4.1	4.5	4.6	5.1	4.8	4.2	3.3	3.5	4.9
Maximum	5.6	6.4	6.6	6	5.4	5.6	6.1	6.3	6.6	6.6	6.4	5.9	5.4
90 (vert), 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
Minimum	2.6	3.3	3.8	4.3	4.9	5.7	5.6	5.6	4.7	3.6	2.7	2.5	4.7
Maximum	3.5	4.6	5.8	6.4	6.5	7.3	7.7	7.1	6.2	5.1	4.1	4.1	5.2

Terrestrial Solar Radiation Quantities or Rates

Table 4. San Antonio, TX - Data from p 217, NREL *Solar Radiation Data Manual for Collectors*

	Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with N-S Axis ($kWh/m^2/day$)												
Axis Tilt (°)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0 (horiz), 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
Minimum	3.3	4.1	4.6	4.9	5.6	6.6	6.6	6.9	5.7	4.4	3.2	3.2	6.0
Maximum	5.1	6.6	8.0	8.6	8.2	9.5	10.2	9.5	8.6	7.4	6.1	5.3	6.8
Latitude - 15, Ave.	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
Minimum	3.6	4.4	4.9	5.0	5.6	6.5	6.6	7.0	5.9	4.7	3.5	3.5	6.2
Maximum	5.8	7.3	8.5	8.8	8.2	9.4	10.1	9.6	9.0	8.0	6.9	6.0	7.1
Latitude, Ave.	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
Minimum	3.9	4.6	5.0	4.9	5.4	6.2	6.3	6.9	5.9	4.8	3.6	3.8	6.3
Maximum	6.3	7.7	8.8	8.7	8.0	9.0	9.7	9.5	9.1	8.4	7.5	6.7	7.4
Latitude + 15, Ave.	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
Minimum	4.0	4.6	4.9	4.7	5.0	5.8	5.9	6.6	5.8	4.8	3.7	4.0	6.2
Maximum	6.7	7.9	8.7	8.4	7.5	8.4	9.1	9.0	8.9	8.5	7.8	7.1	7.0

	Solar Radiation for 2-Axis Tracking Flat-Plate Collectors ($kWh/m^2/day$)												
2-Axis Tracker	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
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
Minimum	4.0	4.7	5.0	5.0	5.6	6.6	6.7	7.1	5.9	4.9	3.7	4.0	6.5
Maximum	6.7	7.9	8.8	8.8	8.3	9.6	10.3	9.7	9.1	8.5	7.9	7.2	7.4

Terrestrial Solar Radiation Quantities or Rates

Table 5. San Antonio, TX - Data from p 217, NREL *Solar Radiation Data Manual for Collectors*

	Direct Beam Solar Radiation for Concentrating Collectors (kWh/m²/day), Uncertainty ±8%												
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
1-axis, E-W, Ave.	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
Horiz. Axis, Min.	2.0	2.2	1.9	1.5	1.6	2.5	2.6	2.9	2.2	2.0	1.5	2.1	3.1
Max.	4.2	4.8	5.0	4.5	4.1	5.1	5.8	5.2	5.1	5.0	5.1	4.7	3.9
1-axis, N-S, Ave.	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
Horiz. Axis, Min.	1.7	2.3	2.3	1.9	2.1	3.1	3.3	3.8	2.8	2.2	1.5	1.7	3.6
Max.	3.8	5.0	6.1	6.0	5.3	6.7	7.6	6.8	6.4	5.7	4.8	4.0	4.6
1-axis, N-S, Ave.	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
Lat. Tilt, Min.	2.2	2.7	2.6	1.9	2.0	2.9	3.1	3.8	3.0	2.5	1.8	2.3	3.8
Max.	4.8	5.9	6.7	6.1	5.1	6.2	7.1	6.7	6.9	6.5	6.0	5.2	4.9
2-Axis Tracker, Ave.	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
Minimum	2.3	2.8	2.6	1.9	2.2	3.2	3.3	3.9	3.0	2.6	1.9	2.4	4.0
Maximum	5.1	6.1	6.7	6.2	5.4	6.7	7.7	6.9	6.9	6.6	6.3	5.7	5.1

	Average Climatic Conditions												
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Daily Min. Temp (°C)	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 Max. Temp (°C)	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
HDD, Base 18.3°C	274	184	93	18	0	0	0	0	0	17	100	227	913

Terrestrial Solar Radiation Quantities or Rates

The next several slides show 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.”

Terrestrial Solar Radiation Quantities or Rates

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)

Terrestrial Solar Radiation Quantities or Rates

Station Description (continued)

The rest of the list of items at the top of each page describing the station on that page is shown below:

- Elevation of station (meters)
- Mean atmospheric pressure of station (millibars)
- Type of station (primary or secondary)

Terrestrial Solar Radiation Quantities or Rates

Solar Radiation Data for Flat-Plate and Concentrating Collectors

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

- Monthly and yearly averages of solar radiation (kWhr/m^2/day)
- Minimum and maximum monthly and yearly averages of solar radiation (kWhr/m^2/day)
- Uncertainty of solar radiation data ($\pm$ %)

Terrestrial Solar Radiation Quantities or Rates

Solar Radiation Data for Flat-Plate and Concentrating Collectors

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-plat and concentrating collectors as described in the next few paragraphs.

Terrestrial Solar Radiation Quantities or Rates

Flat-Plate Collectors Facing South at Fixed Tilt

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

Terrestrial Solar Radiation Quantities or Rates

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 15º greater than the latitude; to optimize performance in the summer, the collector should be tilted about 15º less than the latitude. Data for a tilt of 90º apply to collectors mounted vertically on south-facing walls and apply to south-facing windows for passive solar designs. See **Figure 5** on the next slide.

Terrestrial Solar Radiation Quantities or Rates

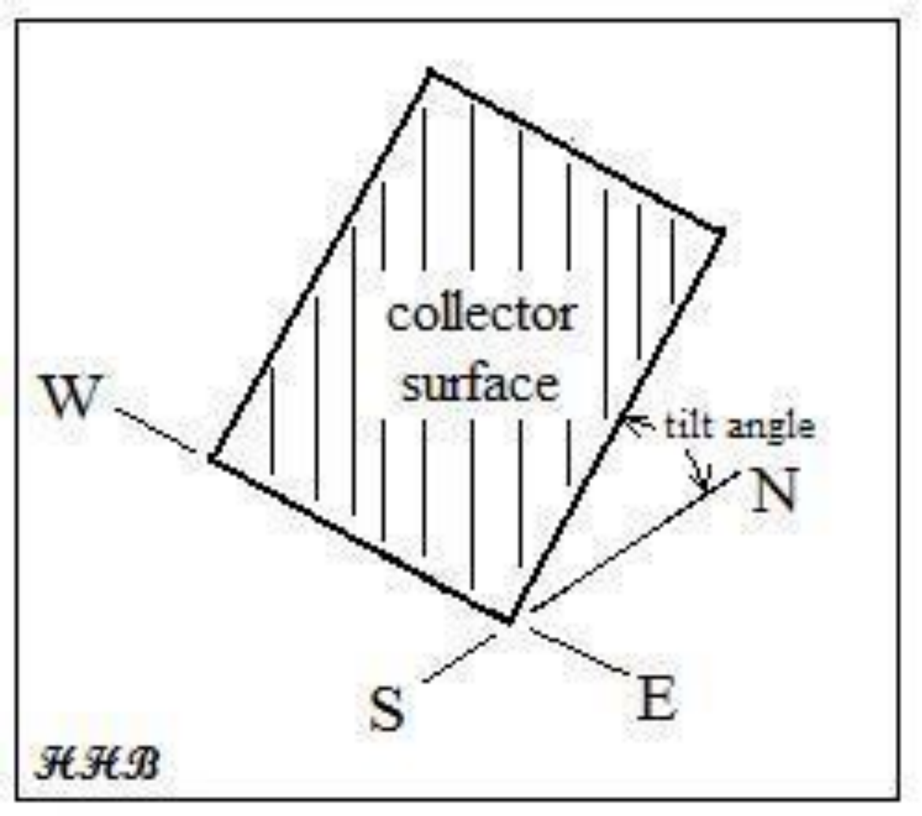


Figure 5. Flat Plate Collector Facing South at Fixed Tilt

Terrestrial Solar Radiation Quantities or Rates

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.

The solution to **Example #7** is shown on the next slide.

Terrestrial Solar Radiation Quantities or Rates

Example #7 - Solution:

The required data is available from **Table 3**, several slides back, which is the top part of the table for San Antonio, TX, from page 217 of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.* The result is as follows:

Horiz. flat-plate collector in March: **4.8 kWh/m²/day**

Terrestrial Solar Radiation Quantities or Rates

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^o, 29.53^o, and 44.53^o. (Note that San Antonio's latitude is 29.53^o.) Determine the same information for the month of July. Also, determine the annual average solar radiation rate for each of those tilt angles.

The solution to **Example #8** is shown on the next slide.

Terrestrial Solar Radiation Quantities or Rates

Example #8 - Solution:

The required data is available from **Table 3**, several slides back, which is the top part of the table for San Antonio, TX, from page 217 of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.* The results are summarized in the table on the next slide.

Terrestrial Solar Radiation Quantities or Rates

Example #8 - Solution:

The table below summarizes the solution to this example:

Tilt Angle From horizontal	Ave. Solar Radiation Rate, $kWh/m^2/day$ January	July	Annual
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

Terrestrial Solar Radiation Quantities or Rates

Example #8 - Discussion:

Note that a tilt of “latitude + 15^o” receives the greatest average rate of solar radiation for the winter month of January; a tilt of “latitude - 15^o” 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 six slides back.

Terrestrial Solar Radiation Quantities or Rates

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

Data are presented for four different axis tilt angles from the horizontal: 0^{o}, latitude minus 15^{o}, latitude, latitude plus 15^{o}. 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^{o} to minimize collector height and wind force.

Terrestrial Solar Radiation Quantities or Rates

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

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 by optimized by the choice of tilt angle. The data presented assume continuous tracking of the sun throughout the day. See **Figure 6**, on the next slide.

Terrestrial Solar Radiation Quantities or Rates

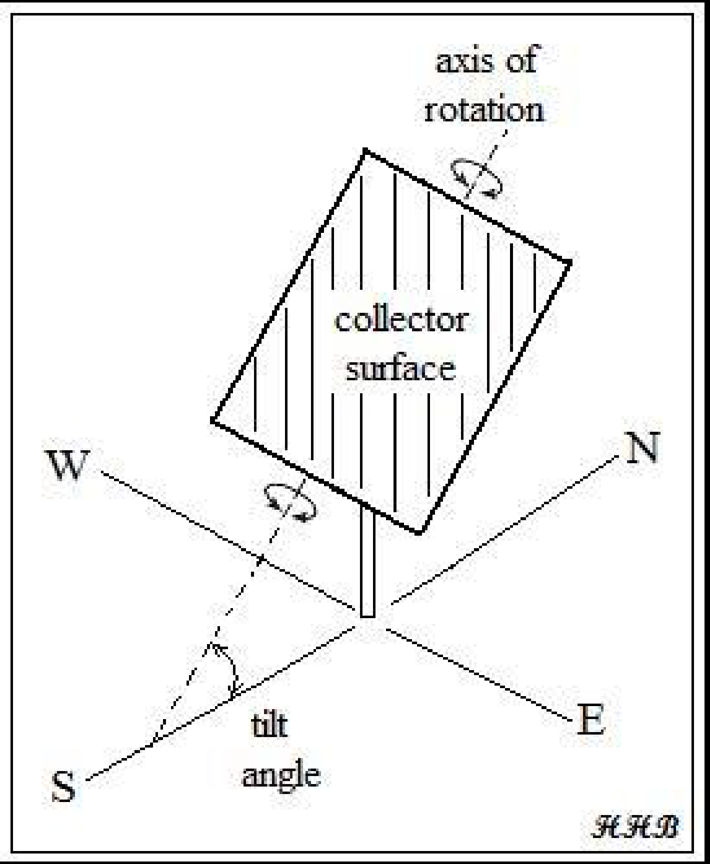


Figure 6. One-Axis Tracking Flat Plate Collector

Terrestrial Solar Radiation Quantities or Rates

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 29.53º (the latitude of San Antonio).

The solution to **Example #9** is shown on the next slide.

Terrestrial Solar Radiation Quantities or Rates

Example #9 - Solution:

The required data is available from **Table 4**, several slides back, which is the middle part of the table for San Antonio, TX, from page 217 of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.* The result is shown below:

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

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

Terrestrial Solar Radiation Quantities or Rates

Example #9 - Discussion:

Note that the values for the Horiz., 1-axis, tracking flat-plate collector and the Latitude tilt, 1- (axis, tracking flat-plate collector are both greater than the value for a fixed horizontal collector (**4.8 kWh/m^2/day)** and for a fixed latitude tilt collector (**5.4 kWh/m^2/day)** for the same location and month.

Terrestrial Solar Radiation Quantities or Rates

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 and throughout the year. See **Figure 7** on the next slide.

Terrestrial Solar Radiation Quantities or Rates

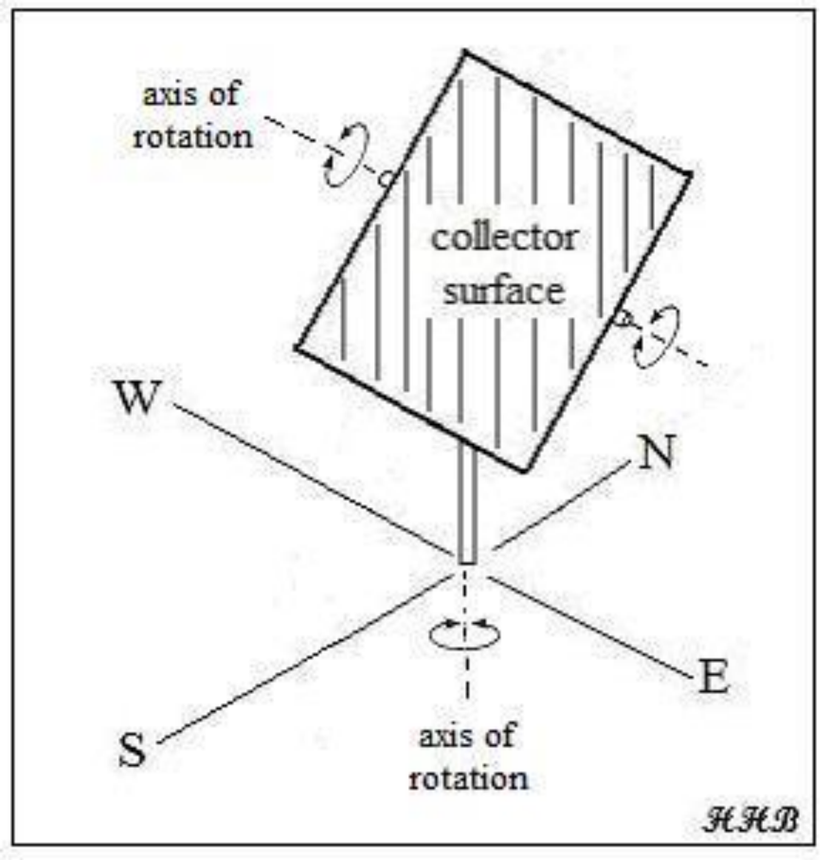


Figure 7. Two-Axis Tracking Flat Plate Collector

Terrestrial Solar Radiation Quantities or Rates

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.

The solution to **Example #10** is shown on the next slide.

Terrestrial Solar Radiation Quantities or Rates

Example #10 - Solution:

The required data is available from **Table 4**, several slides back, which is the middle part of the table for San Antonio, TX, from page 217 of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.* The result is shown below:

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

Terrestrial Solar Radiation Quantities or Rates

Example #10 - Discussion:

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.

Terrestrial Solar Radiation Quantities or Rates

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

Terrestrial Solar Radiation Quantities or Rates

Concentrating Collectors

Direct beam radiation comes in a direct line from the sun and is measured with instruments having a field-of-view of 5.7^o. These instruments see only the sun's disk and a small portion of the sky surrounding the sun. See **Figure 8** and **Figure 9** on the next two slides, showing the two types of concentrating collectors that will be discussed here.

Terrestrial Solar Radiation Quantities or Rates

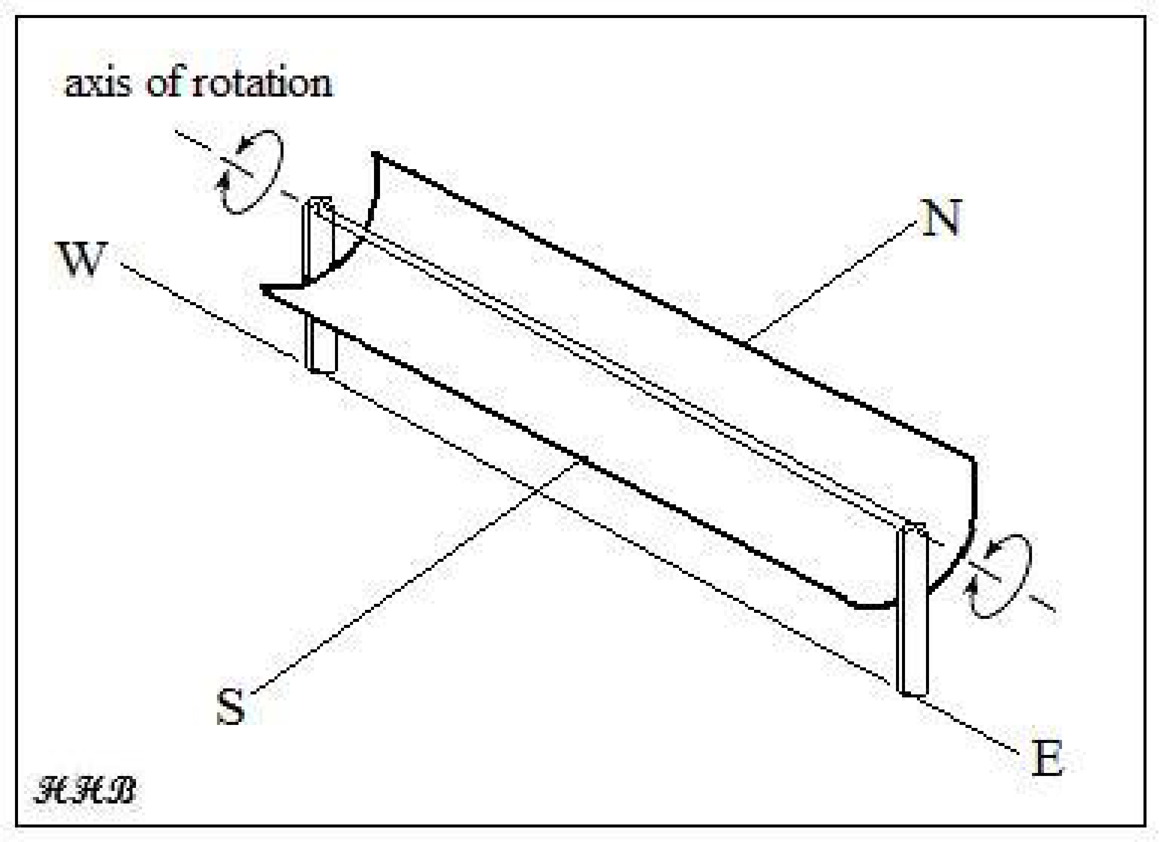


Figure 8. One-Axis Tracking Parabolic Trough with Axis Oriented East-West

Terrestrial Solar Radiation Quantities or Rates

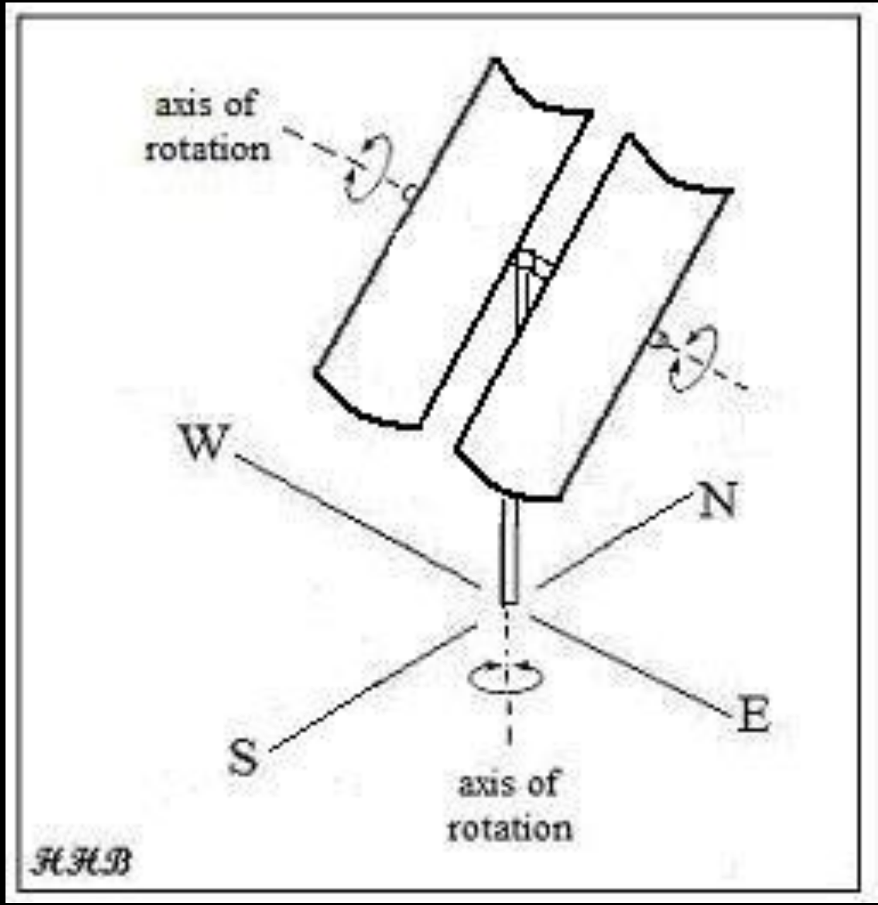


Figure 9. Two-Axis Tracking Parabolic Trough Concentrator

Terrestrial Solar Radiation Quantities or Rates

Example #11:

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

The solution to **Example #11** is shown on the next slide.

Terrestrial Solar Radiation Quantities or Rates

Example #11 - Solution:

The required data is available from **Table 5**, several slides back, which is the bottom part of the table for San Antonio, TX, from page 217 of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.* The results are shown below:

Single horizontal, east-west axis:	**3.0 kWh/m²/day**
Single horizontal, north-south axis:	**2.7 kWh/m²/day**
Single north-south axis with latitude tilt:	**3.4 kWh/m²/day**
Two-axis tracking:	**3.7 kWh/m²/day**

Terrestrial Solar Radiation Quantities or Rates

Example #11 - Discussion:

Note that 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.

Terrestrial Solar Radiation Quantities or Rates

Example #11 – Discussion (continued):

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.

Terrestrial Solar Radiation Quantities or Rates

Example #11 – Discussion (continued):

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 else has been absorbed in the atmosphere and then reradiated to the collector, or else has been reflected to the collector from the surrounding ground.

Terrestrial Solar Radiation Quantities or Rates

Comparison of Solar Radiation for San Antonio, TX and St. Louis, MO

Table 6, which is on the next slide, shows part of page 119 from *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors,* which has solar radiation data for St. Louis, Mo. **Table 6** shows data for flat plate collectors with tilts of horizontal, latitude minus 15º, latitude tilt, and latitude plus 15º. That table will be used for the next example (**Example #12**) and for comparison of the results for San Antonio, TX and for St. Louis, MO.

Terrestrial Solar Radiation Quantities or Rates

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

St. Louis, MO

WBAN NO. 13994

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

Table 6. Top Part of Page 119 from NREL Manual

Terrestrial Solar Radiation Quantities or Rates

Example #12:

Using the publication, ***Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors,*** find 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^{o}, 38.75^{o}, and 53.75^{o}. (Note that St. Louis's latitude is 38.755^{o}.) Determine the same information for the month of July and determine the annual average annual solar radiation rate for each of those tilt angles.

The solution to **Example #12** is shown on the next slide.

Terrestrial Solar Radiation Quantities or Rates

Example #12 - Solution:

The required data is available from **Table 6**, two slides back, which is the top part of the table for St. Louis, MO, from page 119 of *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.* The results are summarized in the table on the next slide.

Terrestrial Solar Radiation Quantities or Rates

Example #12 – Solution (continued):

The results for this example are summarized in the table below:

Tilt Angle From horizontal	Ave. Solar Radiation Rate, $kWh/m^2/day$ January	July	Annual
23.75^o (lat. –15^o)	3.2	6.3	4.8
38.75^o (latitude)	3.6	5.9	4.8
53.75^o (lat. +15^o)	3.8	5.1	4.6

Terrestrial Solar Radiation Quantities or Rates

Solar Radiation Graph

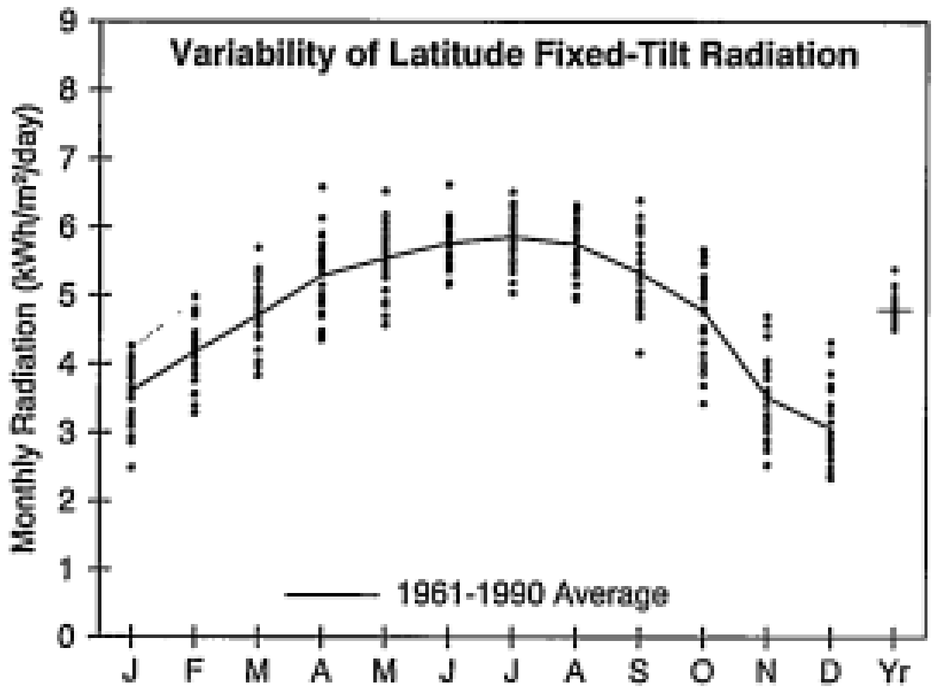
The graph at the top of each data page shows the variability of monthly and yearly solar radiation for a flat-plate collector facing south with a tilt equal to the station's latitude. For each month and year, 30 data values representing each year of the National Solar Radiation Data Base (NSRDB) are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

Terrestrial Solar Radiation Quantities or Rates

Solar Radiation Graph

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. As an example, the next two slides show the graphs from page 119 for St. Louis MO and from page 217 for San Antonio, TX.

Terrestrial Solar Radiation Quantities or Rates



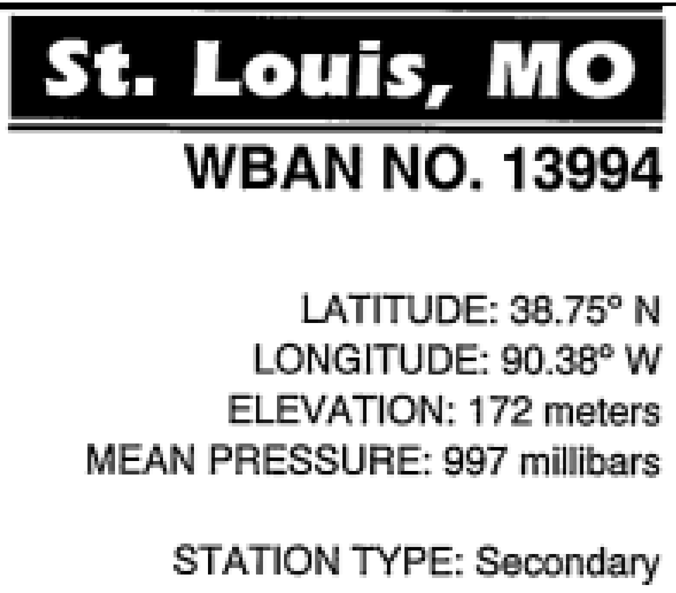


Figure 10. Top Part of St. Louis, MO Page from NREL Manual

Terrestrial Solar Radiation Quantities or Rates

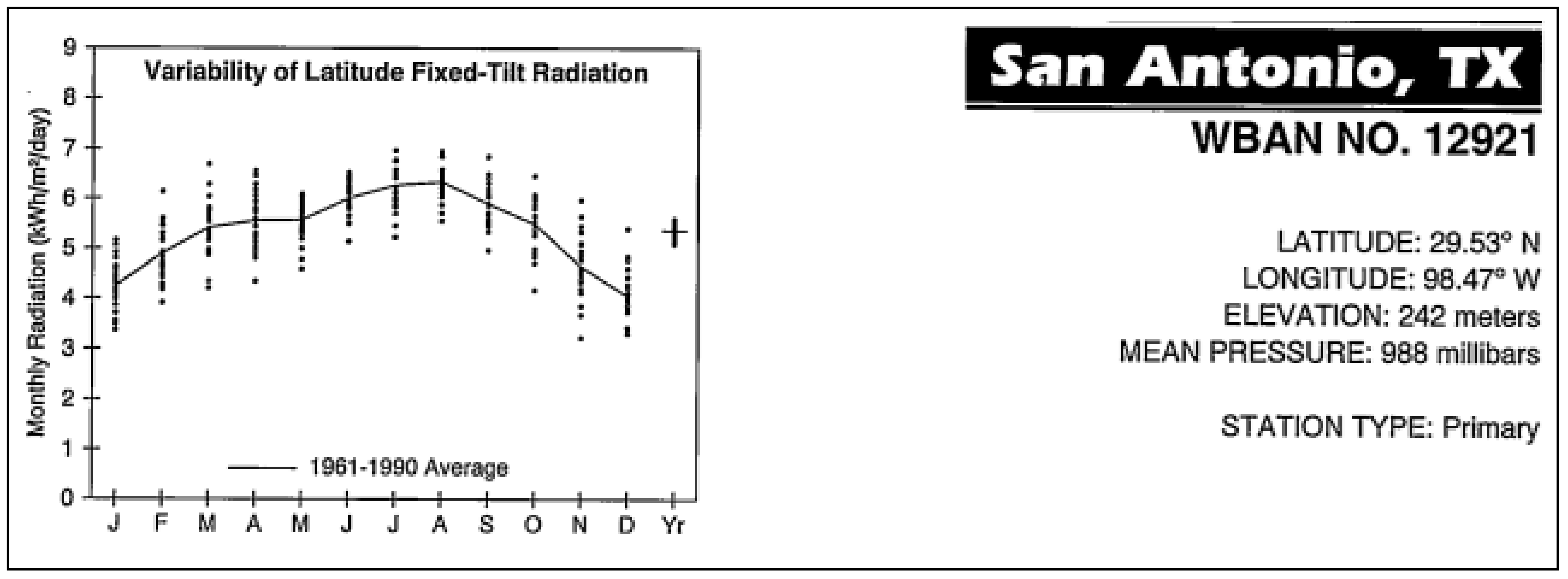


Figure 11. Top Part of San Antonio, TX Page from NREL Manual

Terrestrial Solar Radiation Quantities or Rates

Unit Conversions

It sometimes may be convenient to use units other than those used in *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. **Table 7**, on the next slide, shows conversion factors for units used in that publication.

Terrestrial Solar Radiation Quantities or Rates

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	Langleys	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	°C x 1.8 + 32
degree days (base 18.3° C)	degree days (base 65° F)	1.8

Table 7. Conversion Factors

Terrestrial Solar Radiation Quantities or Rates

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^2 and in Btu/day/ft^2. Also, what would be the tilt angle from the horizontal for each of those locations for the latitude tilt collector?

The solution to **Example #13** is shown on the next two slides.

Terrestrial Solar Radiation Quantities or Rates

Example #13 - Solution:

For San Antonio, TX, from **Figure 10**, 4 slides back, the latitude is 29.53º north, so the tilt angle from the horizontal should be **29.53º**. Also, from **Table 3**, the average annual solar radiation rate on a latitude tilt collector at San Antonio is **5.4 kwh/day/m^2** . Multiplying this figure by 317.2 gives a value of **1713 Btu/day/ft^2.**

Terrestrial Solar Radiation Quantities or Rates

Example #13 – Solution (continued):

For St. Louis, Mo, from **Figure 9**, 6 slides back, the latitude is 38.75^o north, so the tilt angle from the horizontal should be **38.75^o**. Also, from **Table 6**, the average annual solar radiation rate on a latitude tilt collector at St. Louis is **4.8 kwh/day/m^2** . Multiplying this figure by 317.2 gives a value **1523 Btu/day/ft^2.**

Terrestrial Solar Radiation Quantities or Rates

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.

Terrestrial Solar Radiation Quantities or Rates

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 at the end of this course. 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, like the monthly and annual rates given in the publication, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, discussed in this course.

Terrestrial Solar Radiation Quantities or Rates

Climate Conditions

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

- Monthly and yearly average temperature (^oC)
- Average daily minimum temperature (^oC)

Terrestrial Solar Radiation Quantities or Rates

Climate Conditions

Additional parameters listed for each of the NREL locations are:

- Record maximum temperature (^oC)
- Average heating degree days (HDD), base 18.3 ^oC
- Average cooling degree days (CDD), base 18.3 ^oC

Terrestrial Solar Radiation Quantities or Rates

Climate Conditions

The rest of the parameters listed for each of the NREL locations are:

- Average relative humidity (%)
- Average wind speed (m/s)

Terrestrial Solar Radiation Quantities or Rates

Climate Conditions

Degree days are a measure of the 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.

Terrestrial Solar Radiation Quantities or Rates

Climate Conditions

Figure 12, on the next slide, shows the climate data from the bottom of page 119, which is the page for St. Louis, MO, in the NREL *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.*

Terrestrial Solar Radiation Quantities or Rates

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

STATION TYPE: Secondary

St. Louis, MO

WBAN NO. 13994

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

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Figure 12. Climate Data for St Louis, MO from NREL Manual

Terrestrial Solar Radiation Quantities or Rates

Example #14:

The heat loss rate for a **1500 ft²** home in St. Louis, Missouri is **6 Btu/°F-day/ft²**. What is the average total heat input needed for this home in the month of January?

The solution to **Example #14** is shown on the next two slides.

Terrestrial Solar Radiation Quantities or Rates

Example #14 - Solution:

From the climate data at the bottom of the NREL data page for St. Louis (shown in **Figure 12**, two slides back): the value of the heating degree days for January in St. Louis is **615 ºC-days**. Converting units, this is: **(615 ºC-days)(1.8 ºF/ºC)** = **1107 ºF-days** in January.

Terrestrial Solar Radiation Quantities or Rates

Example #14 – Solution (continued):

From the principle of conservation of energy, the rate of heat input needed for the home must be equal to the rate of heat loss from the home. Thus, the heating requirement for January is:

(6 Btu/^{o}F-day/ft^{2})(1500 ft^{2})(1107 ^{o}F-days) = 9,963,000 Btu.

Terrestrial Solar Radiation Quantities or Rates

Example #15:

How much solar collector area would be needed to provide **9,963,000 Btu** to the home of **Example # 14** in St. Louis, MO in January if the efficiency of the solar collector is **80%** ? Assume a fixed flat plate collector tilted at **53.75º** from the horizontal, which is latitude plus 15º.

The solution to **Example #15** is shown on the next two slides.

Terrestrial Solar Radiation Quantities or Rates

Example #15 - Solution:

From the top part of the NREL data page for St. Louis (shown in **Table 6**, several slides back): the value for the solar radiation to a flat plate collector tilted at latitude plus 15^o in January in St. Louis is **3.8 kWh/m^2/d**.

Terrestrial Solar Radiation Quantities or Rates

Example #15 – Solution (continued):

From the table of conversion factors: **1 kWh/m^2 = 317.2 Btu/ft^2**. Thus, the average January insolation in St. Louis is: **(3.8)(317.2) Btu/ft^2/day = 1205 Btu/ft^2/day**, and the required collector area is:

9,963,000 Btu/(1205*31*0.8 Btu/ft^2) = <u>333 ft^2</u>

This is about 22% of the 1500 ft^2 floor area.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

The NREL *Solar Radiation Data Manual for Flat Plate and Concentrating Collectors*, that has been discussed extensively, provides solar radiation data for the United States and its territories. The NASA Prediction of Worldwide Energy Resources website, which will be described on the next several slides, however, gives access to a wide range of meteorology and solar energy parameters for locations all over the world.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

The time periods covered by these two sources for available solar radiation are as follows:

The NREL solar radiation data manual that has been discussed above provides solar insolation data for the period from 1961 - 1990.

The NASA Prediction of Worldwide Energy Resources website provides solar insolation data for the period from 1984 – 2013.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

This website gives access to a wide range of meteorology and solar energy parameters for locations all over the world.

Data for a site of interest can be accessed by following the steps outlined on the next several slides after accessing the website at: https://power.larc.nasa.gov/ .

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

To get started on the website, click on “DATA ACCESS” in the menu along the top of the page.

Then scroll down slightly if necessary and click on the blue button with “POWER DATA ACCESS VIEWER” on it.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

This should take you to a screen with a map in the background and a black rectangle in the middle with a blue rectangular button with "Access Data" on it.

Click on the "Access Data" button, and the black rectangle will disappear, leaving the map in the background a rectangle at the left with the title, "POWER Single Point Data Access" at the top.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

Your entries in the rectangle on the left part of the screen should be as follows in order to obtain data useable for flat-plate solar collectors:

1. **Choose a User Community –** Choose: SSE-Renewable Energy

2. **Choose a Temporal Average –** Choose: Climatology (You need to choose "Climatology" here in order to access data for Tilted Solar Panels.)

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

3. Enter Lat/Long or Add a Point to Map – Here you should either enter the latitude and longitude of the location for which you want data or add a point to the map as follows:

To “Add a Point to Map”, click on the symbol in a box at the left below the heading in order to activate the pointer and use it to select a point on the map.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

3. Enter Lat/Lon or Add a Point to Map (continued):

If entering latitude and longitude, you will probably find Latitude for your site of interest given as XXX° north or XXX° south and Longitude given as XXX° east or XXX° west.

For the NASA site, north latitude should be entered as a positive number, south latitude as a negative number, east longitude as a positive number and west longitude as a negative number.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

4. Select Time Extent – For “Climatology” selected in item **2**, no entry is needed for the time extent.

5. Select Output File Formats – Selecting CSV will give you the output as a file that can be opened as an Excel spreadsheet.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

6. Select Parameters – There is a list of categories from which you should select the data that you want to obtain for the location that you specified in item **3** above.

Double-clicking on a category title will generate a drop-down list of the items available in that category.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

6. Select Parameters (continued) – In order to obtain solar irradiance values for surfaces like those obtainable from the NREL manual, select the first item “Solar Irradiance for Equator Facing Tilted Surfaces (Set of Surfaces) in the last category, “Tilted Solar Panels”.

Terrestrial Solar Radiation Quantities or Rates

NASA POWER Website

7. Submit and Process – After appropriate selections have been made for the first six items as described above, you should click on the “Submit” button.

This will result in a downloaded file, that you can open with Excel, in whatever manner you open downloaded files with your computer.

Terrestrial Solar Radiation Quantities or Rates

Example #16:

Obtain values for the monthly average rate of Solar Insolation on a horizontal surface and on a latitude-tilt flat surface, for St. Louis, MO, from the NASA POWER website.

The solution to **Example #16** is shown on the next two slides.

Terrestrial Solar Radiation Quantities or Rates

Example #16 - Solution:

From the NREL solar data manual, the latitude and longitude for St. Louis, MO are: 38.75º N latitude and 90.38º W longitude. The table on the next slide shows the values for a horizontal surface and for a latitude tilt surface from a CSV (Excel) file obtained as outlined above for St. Louis, MO (Latitude = 38.75 and Longitude = -90.38) for “Solar Irradiance for Equator Facing Tilted Surfaces (Set of Surfaces).

Terrestrial Solar Radiation Quantities or Rates

Example #16 - Solution:

Data from NASA POWER Website – St. Louis

Monthly Average Insolation Incident on a Horizontal Surface (kWh/m²/day) - St. Louis, Mo													
Lat. 38.75 N Long. 90.38 W	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Horizontal	2.08	2.63	3.79	4.85	5.44	5.95	6.08	5.45	4.67	3.35	2.25	1.84	4.03

Monthly Average Insolation Incident on a Latitude Tilt Surface (kWh/m²/day) - St. Louis, Mo													
Lat. 38.75 N Long. 90.38 W	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Latitude Tilt	3.31	3.53	4.44	4.89	4.96	5.19	5.4	5.26	5.26	4.44	3.41	3.05	4.43

Terrestrial Solar Radiation Quantities or Rates

Example #17:

Compare the values for the monthly average rate of Solar Insolation on a horizontal surface and on a latitude-tilt flat surface, for St. Louis, MO, from the NASA POWER website with values from the NREL *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*.

The solution to **Example #17** is shown on the next two slides.

Terrestrial Solar Radiation Quantities or Rates

Example #17 - Solution:

The insolation values for St. Louis, Mo, can be obtained from the top part of page 119 of the NREL solar data manual, which is shown on page 120 of this course. The results for St. Louis, MO from both the NREL manual and from the NASA POWER website are shown in the table on the next slide.

Terrestrial Solar Radiation Quantities or Rates

Example #17 - Solution:

Data from NREL Manual and from NASA website – St. Louis

Monthly Average Insolation Incident on a **Horizontal** Surface (kWh/m^2/day) - **St. Louis, Mo**													
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
NASA POWER	2.08	2.63	3.79	4.85	5.44	5.95	6.08	5.45	4.67	3.35	2.25	1.84	4.03
NREL Manual	2.2	2.9	3.9	5.0	5.9	6.4	6.4	5.7	4.6	3.5	2.5	1.8	4.2

Monthly Average Insolation Incident on a **Latitude Tilt** Surface (kWh/m^2/day) - **St. Louis, Mo**													
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
NASA POWER	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
NREL Manual	3.31	3.53	4.44	4.89	4.96	5.19	5.4	5.26	5.26	4.44	3.41	3.05	4.43

Terrestrial Solar Radiation Quantities or Rates

Example #17 – Solution - Discussion:

The insolation values for St. Louis, Mo, from the two sources are similar, but they are not quite the same. The time period for the data in the NREL *Solar Radiation Data Manual for Flat Plate and Concentrating Collectors* is 1961 – 1990, while the time period for the data from the NASA POWER website is 1984 – 2013.

Terrestrial Solar Radiation Quantities or Rates

Example #18:

In order to illustrate retrieval of solar insolation data for a location outside the U.S., this example will obtain the values for the monthly average rate of Solar Insolation on a horizontal surface and on a latitude-tilt flat surface, for Melbourne, Austrailia, from the NASA POWER website.

The solution to **Example #18** is shown on the next two slides.

Terrestrial Solar Radiation Quantities or Rates

Example #18 - Solution:

The latitude and longitude for Melbourne, Australia (from a Google search) are: Latitude = 37.83º S and Longitude = 145.0º E. (in NASA format: Latitude = - 37.83 and Longitude = 145.0) Following the steps outlined above for data access, using latitude = - 37.83 and longitude = 145.0, and selecting "Solar Irradiance for Equator Facing Tilted Surfaces (Set of Surfaces) under the "Tilted Solar Panels" category, should allow you to a download a CSV (Excel) file, from which the values in the table on the next page can be extracted.

Terrestrial Solar Radiation Quantities or Rates

Example #18 - Solution:

Data from NASA website – Melbourne, Australia

Monthly Average Insolation for Melborne, Austalia (kWh/m^2/day)													
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Horizontal	6.36	5.59	4.51	3.24	2.23	1.79	1.94	2.60	3.58	4.80	5.74	6.23	4.05
Latitude Tilt	5.67	5.43	5.01	4.23	3.34	2.89	3.00	3.50	4.12	4.82	5.24	5.46	4.39

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.

Summary

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. The terms, sunrise hour angle and sunset hour angle, were defined and equations were given for their calculation.

Summary

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^o and 65^o, from a table provided in this course.

Summary

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 locations in the United States, for various solar collector configurations. Numerous examples illustrated the calculations and data retrieval procedures covered in this course.

Summary

The NASA POWER Website at http://power.larc.nasa.gov/ was described, along with information about how to obtain solar radiation data for any location in the world based on the latitude and longitude of the location of interest.

References

1. Goswami, D. Y., Krieth, Frank, and Kreider, Jan F., *Principles of Solar Engineering,* Philadelphia: Taylor & Francis, 2000.

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5. Fundamentals of Solar Energy: http://www.radiantsolar.com/pdf/fundamentals.pdf

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6. U.S. Department of Energy: http://apps1.eere.energy.gov/consumer/renewable_energy/solar/index.cfm/mytopic=50012

7. ***Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*** (Provides solar radiation values for common flat-plate and concentrating collector configurations for 239 stations in the United States and its territories.): http://rredc.nrel.gov/solar/pubs/redbook/

References

8. National Renewable Energy Laboratory:
   http://www.nrel.gov/

9. Part of a chapter from the on-line text, "*The Good Earth*" with information about solar radiation and the atmosphere:
http://www.mhhe.com/earthsci/geology/mcconnell/atm/solrad.htm

References

10. Source for the approximate formula for the Equation of Time: http://www.susdesign.com/popups/sunangle/eot.php

11. NASA POWER Website (a source for worldwide solar insolation data)

http://power.larc.nasa.gov/