Solar Energy Introduction

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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, three websites from which solar irradiance data can be obtained will be presented and discussed, including description of how to obtain solar irradiance data for a location of interest and examples of data retrieval for a city or cities from each of the websites. Numerous examples are included to illustrate the calculations and data retrieval methods presented.

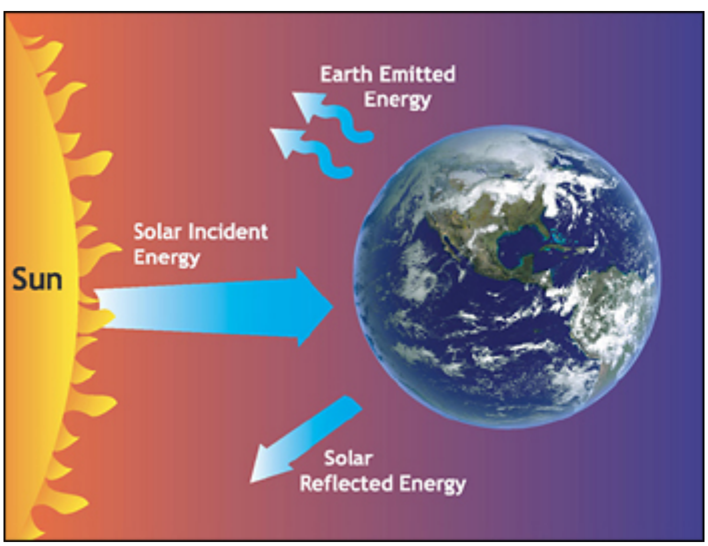

Image Credit: NOAA, Earth System Research Laboratory

2. Learning Objectives

At the conclusion of this course, the student will

- Know the differrent 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.

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- 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 horizontal, vertical or tilted flat plate solar collector, at a specified location in the United Stated or anywhere in the world for a given month, using the NASA POWER website.

- Be able to obtain values for Solar Irradiance and projected Photovoltaic panel performance anywhere in the world, using the Global Solar Atlas website

- Be able to obtain hourly values for Direct Normal Irradiance and Global Horizontal Irradiance for a specified year at a specified location anywhere in the world, using the NREL NSRDB Data Viewer website.

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

VII. Solar Irradiance Data from the NASA POWER Project

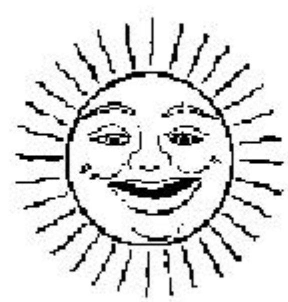
VIII. Solar Irradiance Data from the Global Solar Project

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, λ, and frequency, μ. 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:

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

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 3.000×10^8 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?

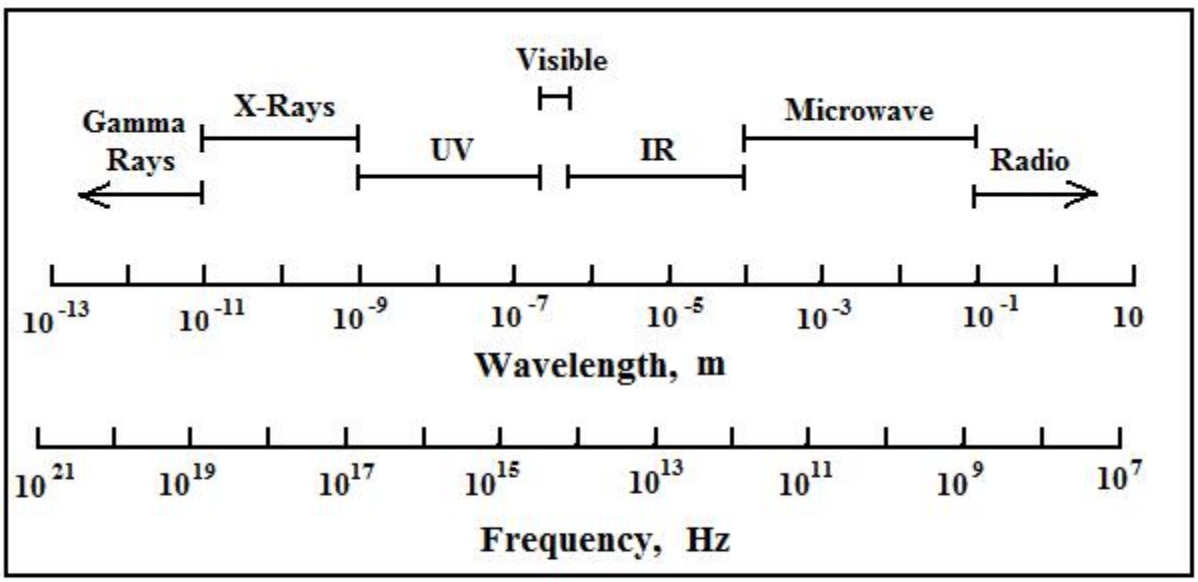
Solution: The wavelength can be calculated from equation (1):

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

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 3×10^{-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 below.

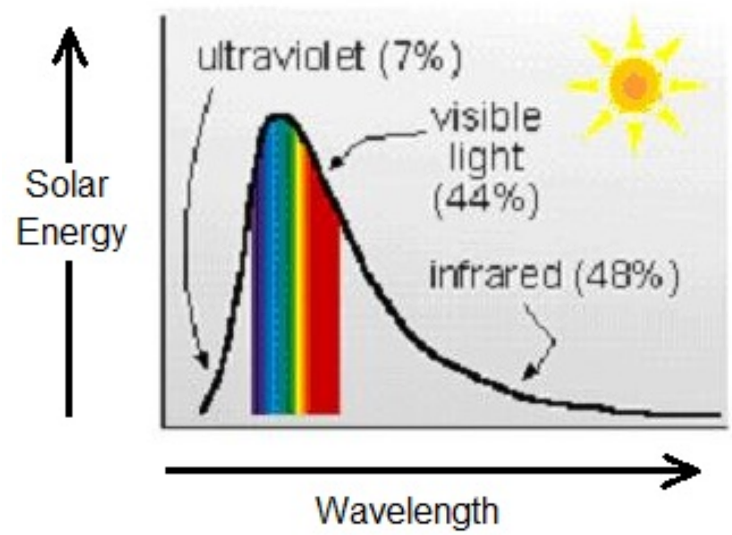
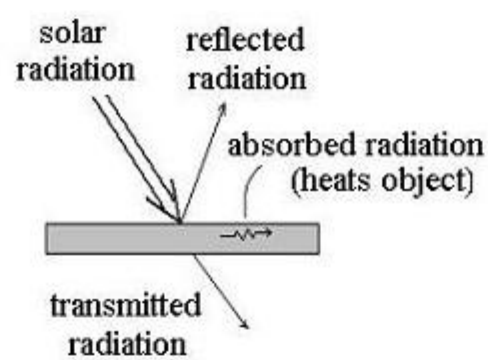


Figure 2. Approximate characteristics of solar radiation reaching the Earth

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:

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

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 x 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, 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.

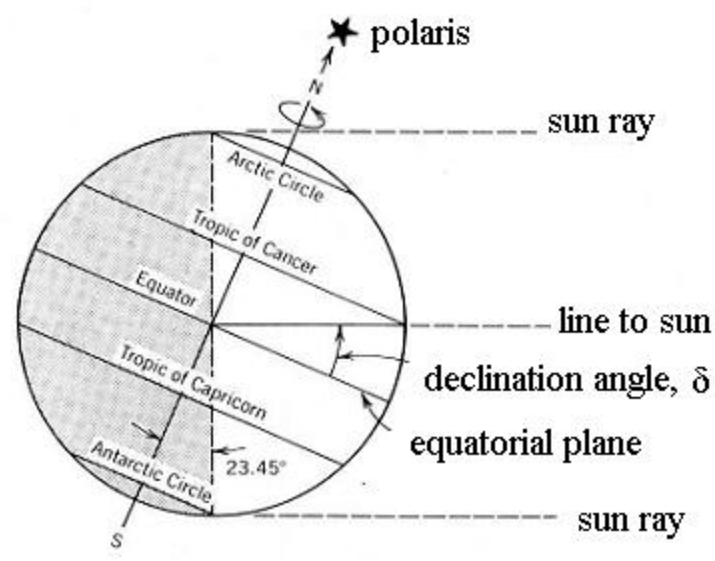
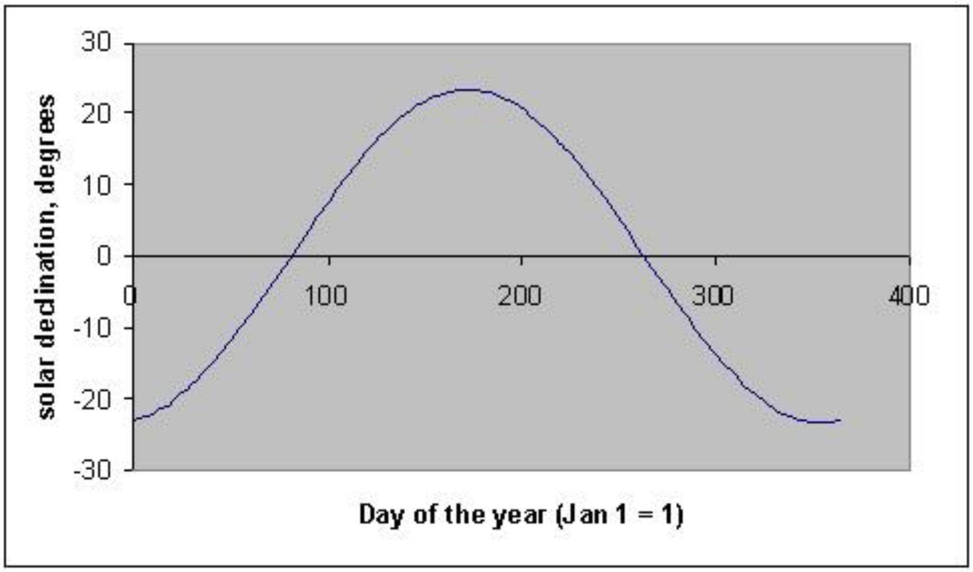


Figure 3. Solar Declination Angle, δ

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

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

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 π radians = 180 degrees, thus the equation above with the angle 325.5° expressed in radians becomes:

$\delta = (23.45^o)\sin[(325.5)(\pi/180)]$ or $(23.45^o)\sin[(325.5)(pi()/180)]$

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

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, 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 15^o 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

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
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:

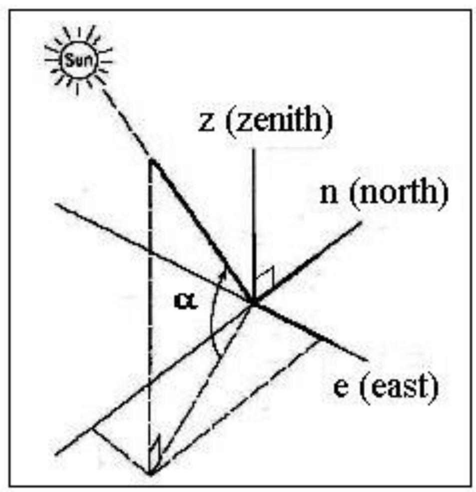
$$\text{Solar Time} = \text{local standard time} + ET + (l_{st} - l_{local})(4\ \text{min/degree}) \qquad (4)$$

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

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

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

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 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:



Solar Altitude Angle, α

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

Example #4: Calculate the solar altitude angle, α , for solar noon on February 15, in St. Louis, MO (latitude: 38.75° N)

Solution: From **Example #3,** the solar declination, δ , on February 15, is – 13.3°. The hour angle, ω, is zero at solar noon, and the latitude is given in the problem statement as 38.75°, so equation (8) becomes:

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

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

$$\text{Sin}\ \alpha = 0.615$$

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

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 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 the following two equations:

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

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

If ω_{sr} and ω_{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° N), on February 15.

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

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

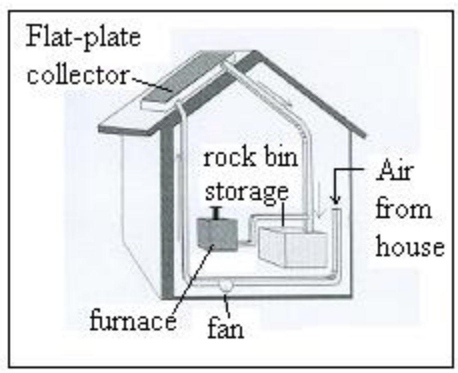
$= 1.376$ radians $=$ **$78.8^o = \omega_{ss}$**

Sunrise angle $= \omega_{sr} = - \omega_{ss} =$ **$- 78.8^o = \omega_{sr}$**

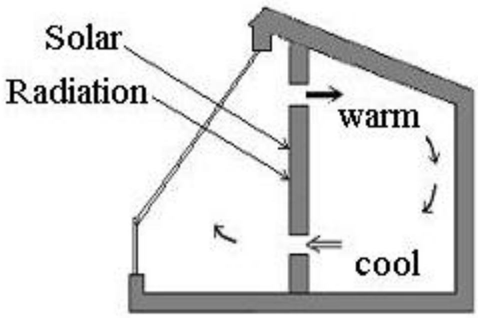
7. Methods of Utilizing Solar Energy

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.

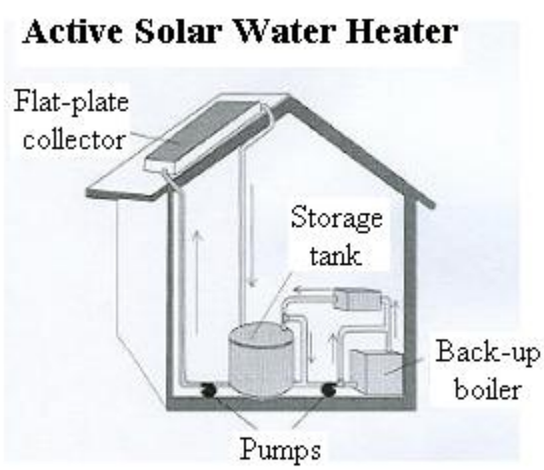


Active Solar Heating



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.



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.

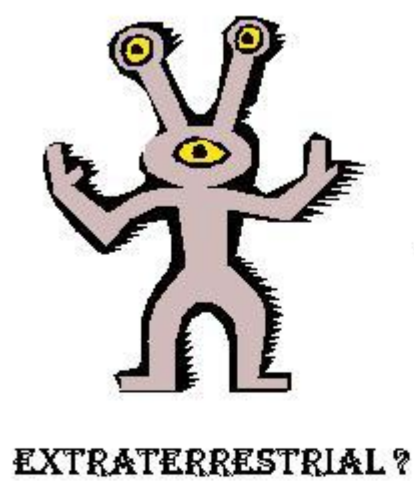
Solar Generation of Electricity can be done by two different methods. They are: i) use of photovoltaic cells to generate an electrical current directly and charge a battery, or ii) heating a fluid and using it in a heat engine to generate electricity in a manner much the same as a conventional fossil 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 x 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^2.



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 following equation:

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

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 (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).

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

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, $H_{oh\text{-}ave}$, 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^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

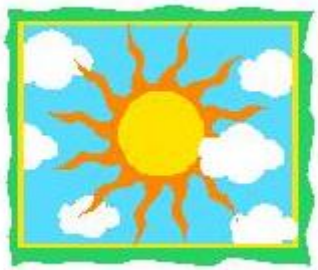
Example #6: What is the average extraterrestrial solar radiation rate (kWhr/day/m^2) in St. Louis, MO (latitude: 38.75^o N), in February?

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:

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



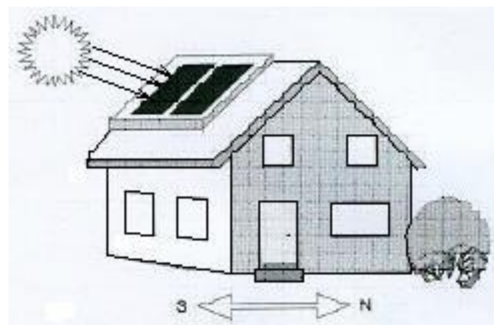
Approximately 30% of extraterrestrial solar radiation is reflected to space or absorbed by ozone, water vapor and carbon dioxide in the atmosphere. About 23% of the incoming solar energy powers the evaporation/ precipitation cycle and less than 0.5% is utilized by plants for photosynthesis. Low level 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.

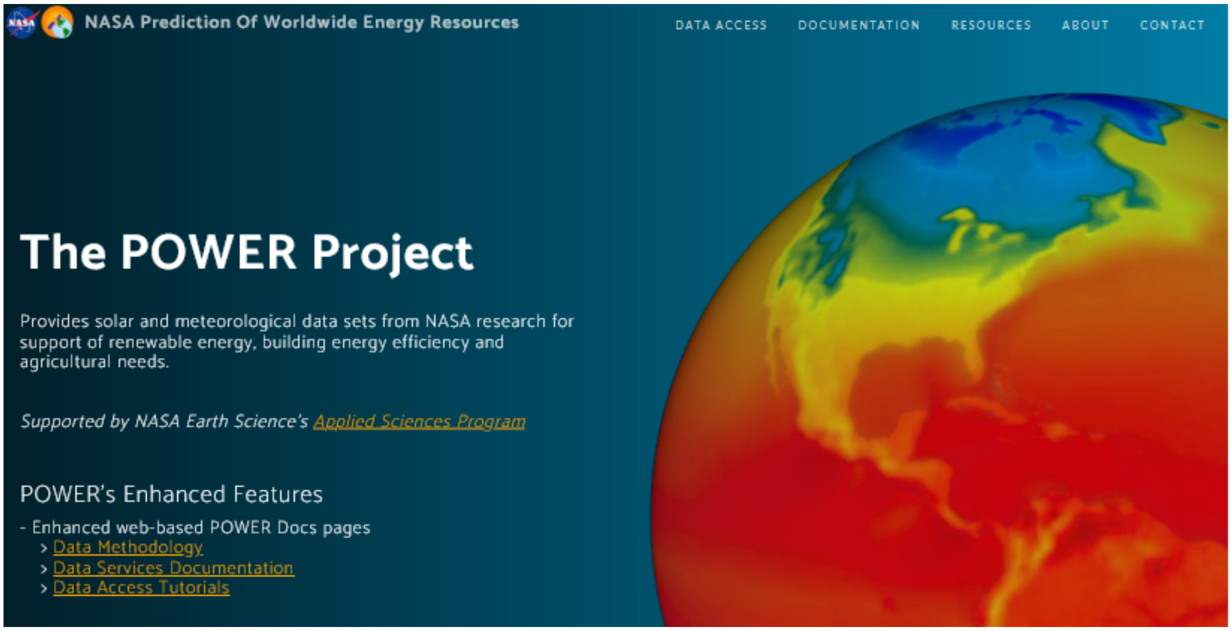


Flat-Plate Collectors

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 from several sources online. Use 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 three of these sources, will be discussed here, and illustrated with examples. The first source is a website provided by the National Aeronautics and Space Administration (NASA). The second source is a website called the Global Solar Atlas, that provides information about the photovoltaic power output attainable at a selected site anywhere in the world. The third source is a website provided by the National Renewable Energy Laboratory (NREL).

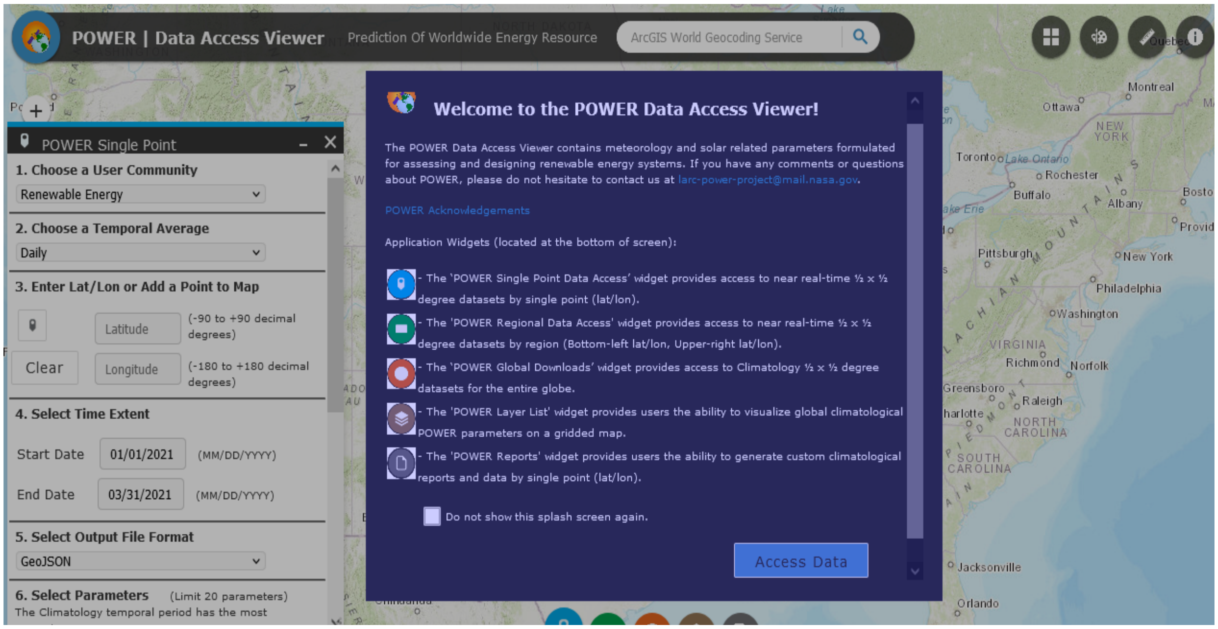
10. Solar Irradiance Data from the NASA POWER Project

The title of the website for the NASA POWER Project is: NASA Prediction of Worldwide Energy Resources. It is available at https://power.larc.nasa.gov . 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 entering the latitude and longitude of the site or by clicking on the location of interest on a map. If you go to the NASA POWER website noted above, you will get the screen shown below:



To get started on the website, click on "DATA ACCESS" in the menu along the top of the page. That will take you to the screen shown below.

To proceed, you should click on the blue bar with "POWER DATA ACCESS VIEWER" on it. This will take you to the following screen:



Next you should click on the "Access Data" light blue button on the dark blue portion of the screen. This will leave a map on the screen with the menu shown on the left in the screen shot above remaining on the screen.

Next you should enter your selections in the menu on the left side of the screen.

For **1. Choose a User Community**- you should choose "Renewable Energy".

For **2. Choose a Temporal Average** - you should choose "Climatology" in order to obtain data for tilted solar panels.

For **3. Enter Lat/Lon or add a Point to Map** - 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.

If you want to enter the Latitude and Longitude for your site, 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.

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

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

For 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. In order to obtain solar irradiance values for solar panels, select the first item "Solar Irradiance for Equator Facing Tilted Surfaces (Set of Surfaces) in the last category, "Tilted Solar Panels".

For 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.

Example #7: Obtain a table with monthly averaged solar radiation incident on a south facing vertical window and on horizontal, latitude tilt, latitude – 15^o tilt and latitude + 15^o tilt surfaces for Denver, CO, from the NASA POWER website.

Solution: In the menu on the left side of the screen, "Renewable Energy" is selected for **item 1** and "Climatology" is selected for **item 2**. For **item 3**, an online search shows that the latitude of Denver, Colorado is 39.74^o N and the longitude is 104.99^o W. so the latitude is entered as 39.74 and the longitude is entered as -104.99. No entry is needed for **item 4**, since Climatology was selected for **item 3**. For **item 5**, "CSV" is selected for the output. For **item 6**, first double click on "Parameters for Tilted PV Panels", then click on "Solar Irradiance for Equator Facing Tilted Surfaces (Set of Surfaces)". At this point clicking on the "Submit" button and then on the blue "CSV" button will allow you to open an Excel file containing the data, shown in the image below.

The top part of the Excel sheet shown below gives information about the parameters for which values are given in the bottom part of the sheet. All of the numbers in the Excel printout are solar irradiance in kw-hr/m^2/day for flat plate solar panels inclined at the specified angle from horizontal and are average values for the 30-year period from January 1990 through December 2019, except that the last row is the optimal angle of inclination from horizontal in degrees for the flat plate for each month.

NASA/POWER CERES/MERRA2 Native Resolution Climatology Climatologies												
30-year Meteorological and Solar Monthly & Annual Climatologies (January 1990 - December 2019)												
Location: Latitude 39.74 Longitude -104.99												
Elevation from MERRA-2: Average for 0.5 x 0.625 degree lat/lon region = 2094.96 meters												
Parameter(s):												
SI_EF_TILTED_SURFACE_HORIZONTAL	SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Horizontal Surface (kW-hr/m^2/day)											
SI_EF_TILTED_SURFACE_LAT_MINUS15	SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Latitude Minus 15 Tilt (kW-hr/m^2/day)											
SI_EF_TILTED_SURFACE_LATITUDE	SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Latitude Tilt (kW-hr/m^2/day)											
SI_EF_TILTED_SURFACE_LAT_PLUS15	SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Latitude Plus 15 Tilt (kW-hr/m^2/day)											
SI_EF_TILTED_SURFACE_VERTICAL	SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Vertical Surface (kW-hr/m^2/day)											
SI_EF_TILTED_SURFACE_OPTIMAL	SRB V4/CERES SYN1deg Solar Irradiance Optimal (kW-hr/m^2/day)											
SI_EF_TILTED_SURFACE_OPTIMAL_ANG	SRB V4/CERES SYN1deg Solar Irradiance Optimal Angle (Degrees)											
PARAMETER	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
SI_EF_TILTED_SURFACE_HORIZONTAL	2.58	3.48	4.72	5.76	6.49	7.2	6.94	6.2	5.26	4	2.82	2.31
SI_EF_TILTED_SURFACE_LAT_MINUS15	3.83	4.56	5.56	6.12	6.44	6.93	6.76	6.38	6.03	5.19	4.07	3.6
SI_EF_TILTED_SURFACE_LATITUDE	4.34	4.93	5.71	5.94	5.98	6.28	6.19	6.05	6.07	5.55	4.55	4.14
SI_EF_TILTED_SURFACE_LAT_PLUS15	4.61	5.03	5.55	5.48	5.28	5.4	5.37	5.45	5.77	5.59	4.78	4.46
SI_EF_TILTED_SURFACE_VERTICAL	4.25	4.24	4.1	3.42	2.85	2.61	2.68	3.07	3.89	4.46	4.23	4.19
SI_EF_TILTED_SURFACE_OPTIMAL	4.66	5.03	5.71	6.12	6.58	7.23	6.99	6.42	6.1	5.61	4.79	4.53
SI_EF_TILTED_SURFACE_OPTIMAL_ANG	63	53	39	23	11	5.5	7.5	17.5	33.5	49	59.5	65.5

Example #8: Compare the average values over the period from January 1990 – December 2019 for solar irradiance on latitude tilt, latitude – 15^o tilt and latitude + 15^o tilt surfaces in January and in July for Denver, CO.

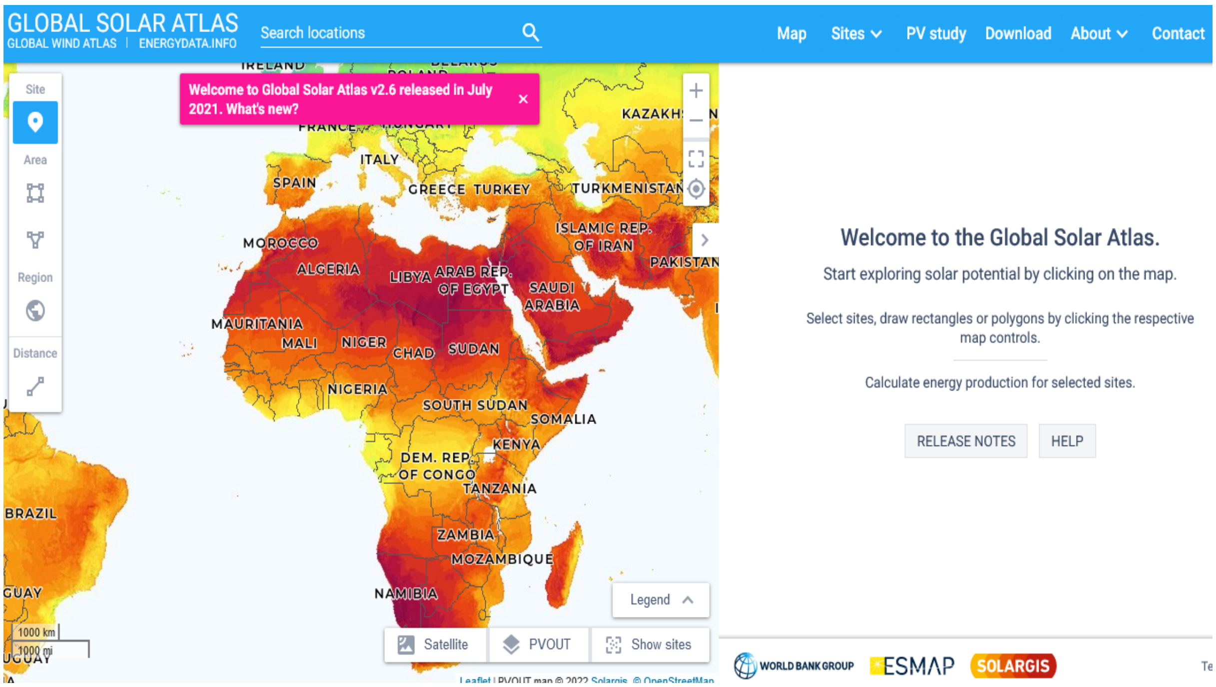
Solution: From the table above, which was obtained from the NASA POWER website, the solar irradiance values in kw-hr/m^2/day are as follows:

	Latitude Tilt	Latitude – 15^o	Latitude + 15^o
January	4.34	3.83	4.61
July	6.19	6.78	5.4

Note that a general rule of thumb is that the maximum solar irradiance in the winter will be on a flat plate inclined at approximately Latitude + 15^o from the horizontal and the maximum solar irradiance in the summer will be on a flat plate inclined at approximately Latitude -15^o from the horizontal. This makes sense because the sun is lower in the southern sky in the winter and higher in the southern sky in the summer in the northern hemisphere. The results shown above for Denver are consistent with this.

11. Solar Irradiance Data from the Global Solar Atlas

The second source for solar insolation data is the Global Solar Atlas, which can be accessed at: https://globalsolaratlas.info/map . The screen that comes up when you go to this web address is shown below:



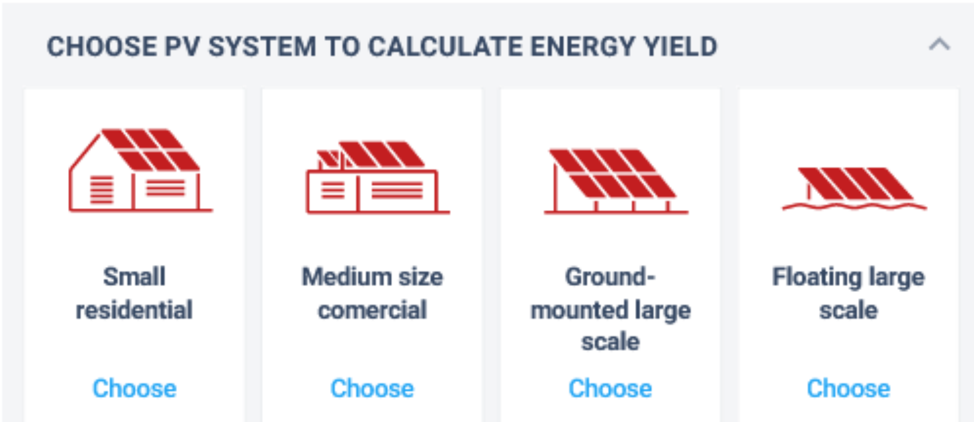
Clicking on "About" in the menu at the top of the page and then on "Introduction" leads you to information about the World Bank Group made up of the World Bank and the International Finance Corporation, which is the provider of the Global Solar Atlas. There is also information in the "About" tab on how to get started and obtain information from the site. This site is oriented particularly towards providing information on the capacity to generate electricity with photovoltaic cells. There have been significant decreases in the cost of photovoltaic cell and significant increases in their efficiency, since they were first developed quite a few years ago. Today photovoltaic cells are quite a viable method of generating electricity from the sun's incoming solar energy.

In order to illustrate the extraction of information from the Global Solar Atlas, information will be obtained about the solar photovoltaic generating capability at three locations, St. Louis, Missouri; Denver, Colorado; and Phoenix, Arizona.

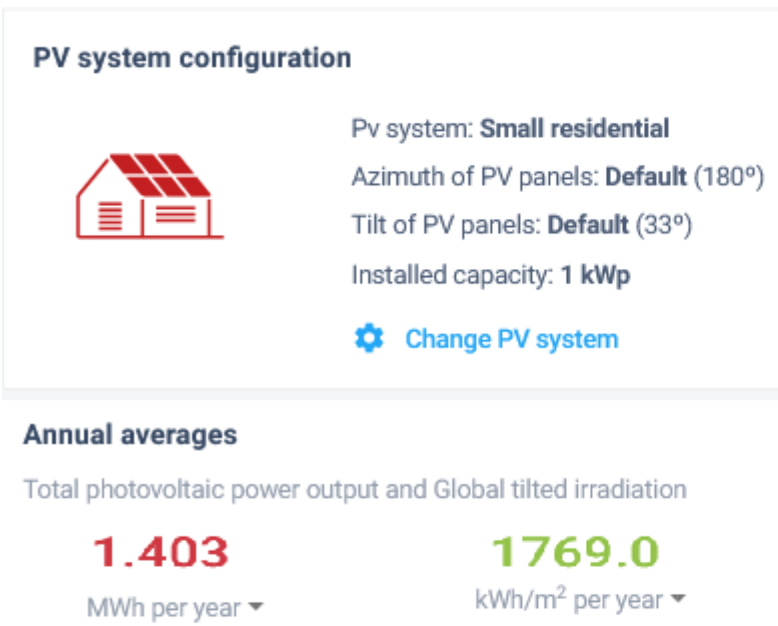
St. Louis, Missouri: To get started on the Global Solar Atlas site, you can start typing the name of the location for which you want to obtain solar information in the space where it says "Search locations" on the blue bar along the top of the screen. As you start typing in "St. Louis, Missouri", you will get a dropdown menu with "St. Louis, Missouri, United States of America" as one of the options. Clicking on that will get you to information about solar insolation at St. Louis, Missouri. The map on the left side of the screen will have zeroed in on St. Louis, Missouri and the immediate surrounding area. On the upper part of the right side of the screen will be the latitude and longitude of St. Louis, Mo and its time zone. On the bottom right will be information about solar irradiation and photovoltaic power output at St. Louis, MO, as follows: (Note that the first item, Specific photovoltaic power output is the annual kWh generated per kW of installed PV peak capacity over the long term.)

Specific photovoltaic power output	PVOUT specific	1477.1	kWh/kW
Direct normal irradiation	DNI	1641.7	$(kWh/m^2)/yr$
Global horizontal irradiation	GHI	1566.8	$(kWh/m^2)/yr$
Diffuse horizontal irradiation	DIF	603.8	$(kWh/m^2)/yr$
Global tilted irradiation at optimum angle	GTI opta	1804.1	$(kWh/m^2)/yr$
Optimum tilt of PV modules	OPTA	33 / 180°	
Air temperature	TEMP	13.7 °C	
Terrain elevation	ELE	147 m	

Scrolling down on this screen will show the four types of PV systems below to choose from:



Choosing “Small residential” for St. Louis, leads to the following information:



Denver, Colorado: Following a similar procedure to obtain data for Denver Colorado yields the following results:

Specific photovoltaic power output	PVOUT specific	1717.9	kWh/kW
Direct normal irradiation	DNI	2170.9	$(kWh/m^2)/yr$
Global horizontal irradiation	GHI	1745.1	$(kWh/m^2)/yr$
Diffuse horizontal irradiation	DIF	519.9	$(kWh/m^2)/yr$

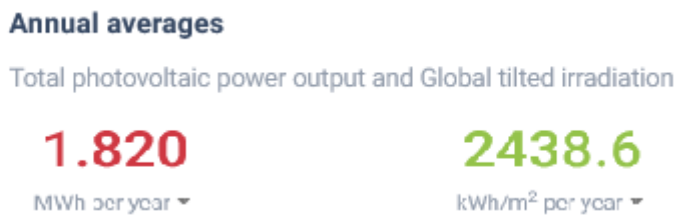
Global tilted irradiation at optimum angle	GTI opta	2101.6	$(kWh/m^2)/yr$
Optimum tilt of PV modules	OPTA	37 / 180°	
Air temperature	TEMP	8.8 °C	
Terrain elevation	ELE	1636 m	

Choosing "Small residential" for the type of solar photovoltaic system for Denver, Colorado, shows the following values for Annual Averages:

Phoenix, Arizona: Following a similar procedure to obtain data for Phoenix, Arizona yields the following results:

Specific photovoltaic power output	PVOUT specific	1898.3	kWh/kW
Direct normal irradiation	DNI	2720.0	$(kWh/m^2)/yr$
Global horizontal irradiation	GHI	2129.5	$(kWh/m^2)/yr$
Diffuse horizontal irradiation	DIF	483.2	$(kWh/m^2)/yr$
Global tilted irradiation at optimum angle	GTI opta	2455.0	$(kWh/m^2)/yr$
Optimum tilt of PV modules	OPTA	33 / 180°	
Air temperature	TEMP	23.6 °C	
Terrain elevation	ELE	354 m	

Choosing "Small residential" for the type of solar photovoltaic system for Phoenix, Arizona, shows the following values for Annual Averages:



Comparison of Results for St. Louis, Denver and Phoenix - The following table shows a comparison of the Photovoltaic generating capabilities at St. Louis, Denver, and Phoenix.

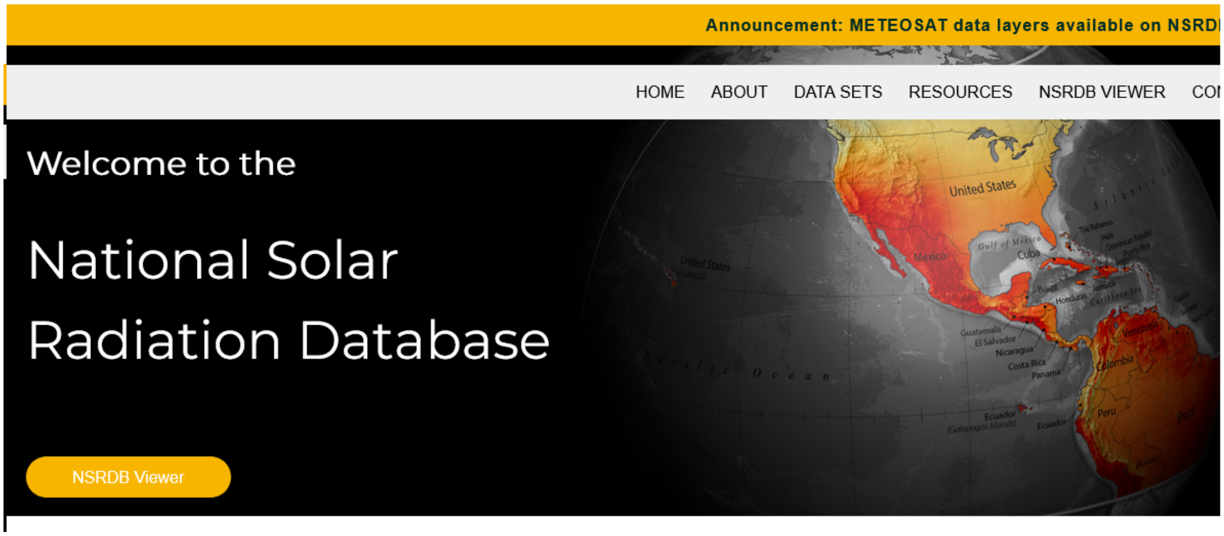
Location	**$PVOUT_{spec}$** kWhr/kW	**Ann. Ave PV Output** MWh/year	**Global Tilted Irradiation** kWh/m^2/yr
St. Louis, MO	**1477.1**	**1.403**	**1769.0**
Denver, CO	**1717.9**	**1.635**	**2068.2**
Phoenix, AZ	**1898.3**	**1.820**	**2438.6**

As would be expected, Phoenix, Arizona, which is in the sunny southwestern United States, receives the largest amount of annual solar irradiation and has the capability of generating the most electricity from a given area photovoltaic panel. St. Louis, Missouri, which has more cloudy and rainy weather and is somewhat farther north, receives the least annual solar irradiation of these three cities, and would generate the least electricity from a given area photovoltaic panel. The results for Denver, Colorado are between those for Phoenix and St. Louis. Similar information could be obtained for any location in the U.S. or around the world in the way described above for these three locations.

12. Solar Irradiance Data from The National Solar Radiation Database

The third source for solar insolation data is the National Solar Radiation Database, which is available through a website of the National Renewable Energy

Laboratory (NREL) with the web address: https://nsrdb.nrel.gov/. The screen that comes up when you go to that web address is shown below:



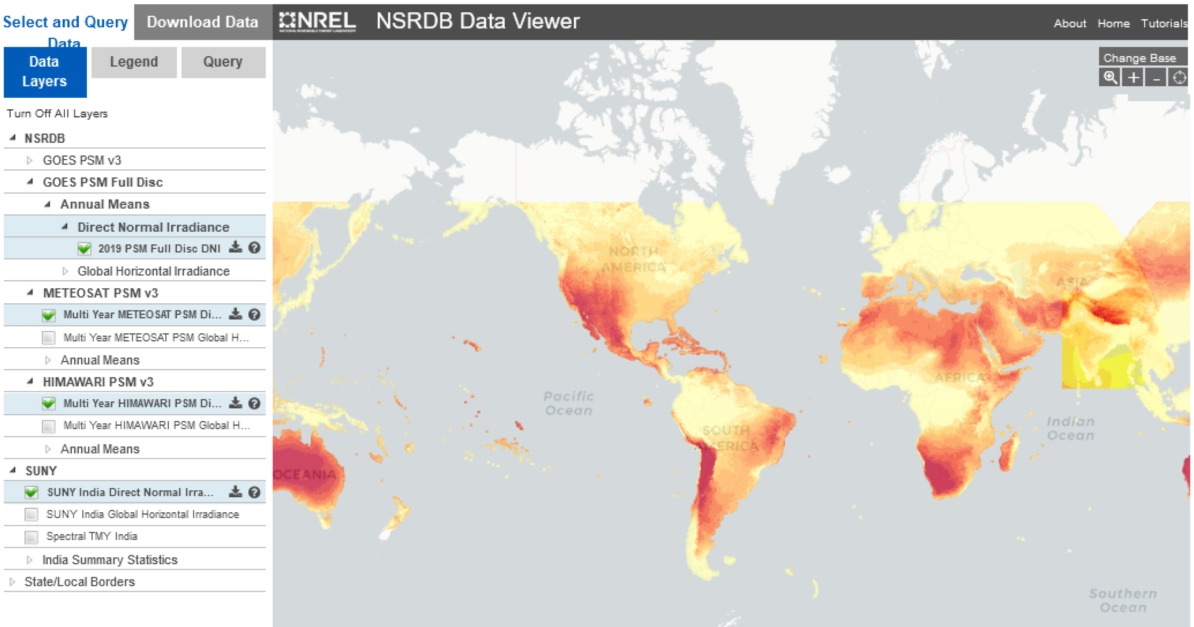
If you click on "Data Sets: in the menu across the top and then click on "Download Instructions" in the drop-down menu, you will get the instructions shown below:

NSRDB Viewer Direct Download Instructions

Use the following steps to download data from the NSRDB Viewer:

- Click "Download Data" in the top left corner of the application
- Click "Download Solar Resource Data by Point or by Region"
- Click or draw your area of interest on the map
- input your name and email address (NOTE: A valid email is required in order to receive your download link)
- Customize your download parameters within the Data Download Wizard

Clicking on "NSRDB Viewer" on the lower left corner of the screen will take you to the following screen:



The instructions shown above were used to download data for solar irradiance for Denver, Colorado, from the NRSDB Data Viewer. Note that the + and – in the upper right corner of the screen can be used to increase or decrease the scale of the map, so you can zero in on a particular location. Also, the colored shading on the map shows the amount of annual solar irradiance at the various locations, and it can be removed by clicking on "Turn Off All Layers" just below the blue box in the upper left corner that says "Data Layers" on it. With the data layers turned off, you can see the locations of larger cities, in order to click on one to identify it as the location for which you want to download data. This was done in order to click on Denver as the location for the data download. DHI (direct horizontal irradiance) and DNI (direct normal irradiance) were identified as the parameter to be downloaded for Denver, Colorado in the year 2020.

The downloaded data is in a very large file, because hourly values of DNI and DHI are provided for every day of the year. Thus, the downloaded file is in a zip format, that must be opened by PeaZip, WinZip, or some such program that can open zip files. The resulting file after unzipping will be a csv file that can be opened with Excel. The table below shows a small portion of the data for 2020 DHI and DNI for Denver from that downloaded file. The table shows the DHI and DNI values for January 1 and for July 1, for the part of those days for which solar irradiance is shown on July 1. As would be expected, there is solar irradiance for a significantly larger part of the 24-hour day on July 1 than on January 1. Also, the total amount of solar irradiance for the day is much greater on July 1 than on January 1. Similar information is available for each of the other 363 days of 2020.

	Source:NSRDB			Location: Denver, CO, USA				Lat.	39.73		Long.	-105.02		
Year	Month	Day	Hour	Minute	DHI	DNI		Year	Month	Day	Hour	Minute	DHI	DNI
					w/m^2	w/m^2							w/m^2	w/m^2
2020	1	1	4	30	0	0		2020	7	1	4	30	0	0
2020	1	1	5	30	0	0		2020	7	1	5	30	38	494
2020	1	1	6	30	0	0		2020	7	1	6	30	58	738
2020	1	1	7	30	6	3		2020	7	1	7	30	70	854
2020	1	1	8	30	62	208		2020	7	1	8	30	78	919
2020	1	1	9	30	97	420		2020	7	1	9	30	85	957
2020	1	1	10	30	131	36		2020	7	1	10	30	86	982
2020	1	1	11	30	160	67		2020	7	1	11	30	86	997
2020	1	1	12	30	146	11		2020	7	1	12	30	86	998
2020	1	1	13	30	94	614		2020	7	1	13	30	84	988
2020	1	1	14	30	67	692		2020	7	1	14	30	83	962
2020	1	1	15	30	35	757		2020	7	1	15	30	81	918
2020	1	1	16	30	15	239		2020	7	1	16	30	74	852
2020	1	1	17	30	0	0		2020	7	1	17	30	65	727
2020	1	1	18	30	0	0		2020	7	1	18	30	48	444
2020	1	1	19	30	0	0		2020	7	1	19	30	5	39
2020	1	1	20	30	0	0		2020	7	1	20	30	0	0

13. Discussion of the Three Sources for Solar Irradiance Data

The third source for solar

14. Conversion of Units

It sometimes may be convenient to use units other than those used for date downloaded from the three websites discussed in this course. Table 3 below from an NREL publication, *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors,* gives conversion factors for units used for some of the parameters in this course.

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 3. Conversion Factors

15. 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^o and 65^o, 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 three websites for accessing solar radiation data was covered. Those three websites are: (i) NASA Prediction of Worldwide Energy Resources, available at https://power.larc.nasa.gov , (ii) the Global Solar Atlas, which can be accessed at: https://globalsolaratlas.info/map , and the National Solar Radiation Database, which is available through a website of the National Renewable Energy Laboratory (NREL) with the web address: https://nsrdb.nrel.gov/. These three websites were discussed as sources for solar radiation data for various flat plate solar collector configurations. Numerous examples illustrated the calculations and data retrieval procedures covered in this course.

16. 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.brighthub.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.brighthub.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. NASA Prediction of Worldwide Energy Resources website, available at https://power.larc.nasa.gov

5. The Global Solar Atlas, which can be accessed at: https://globalsolaratlas.info/map

6. The National Solar Radiation Database, which is available through a website of the National Renewable Energy Laboratory (NREL) with the web address: https://nsrdb.nrel.gov/

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