PDHonline Course E286 (2 PDH)

Solar Energy Basics I - Fundamentals

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Solar Energy Basics I - Fundamentals

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COURSE CONTENT

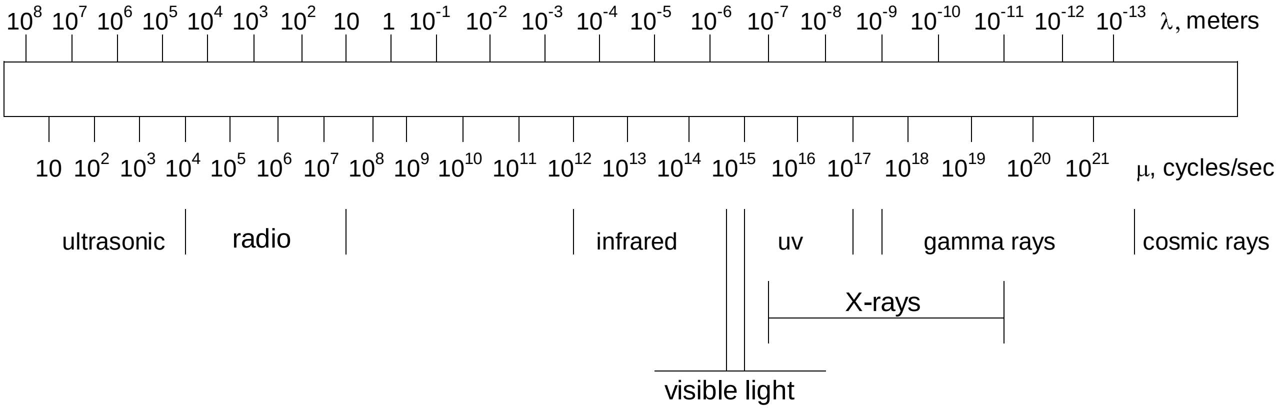
1. The Nature of Solar Radiation

Solar energy travels from the sun to the earth in the form of electromagnetic radiation. There are many forms of electromagnetic radiation, such as ultrasonic waves, radio waves, infrared radiation (heat), visible light, ultraviolet light, x-rays, gamma rays, and cosmic rays. Electromagnetic radiation is characterized by its wavelength, λ, and frequency, μ. Since all electromagnetic radiation travels at the speed of light, c, 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 short wavelength electromagnetic radiation has a high frequency and long wavelength electromagnetic radiation has a low frequency. The different types of electromagnetic radiation listed above are arranged from lowest frequency (ultrasonic waves) to highest frequency (cosmic waves). The figure below summarizes the electromagnetic radiation spectrum.

Figure 1. Summary of the Electromagnetic Spectrum



The speed of light in a vacuum is 3.000×10^{8} m/sec. Thus, if the wavelength of electromagnetic radiation is known, its frequency can be calculated and vice versa. For example a radio wave with a frequency of 100,000 cycles per second will have a wavelength of $\lambda = c/\mu = 3 \times 10^8/10^5$ m = 3×10^3 m = 3000 m.

Solar radiation has most of its energy between wavelengths of 10^{-7} and 3×10^{-6} m. This includes infrared radiation, visible light and ultraviolet light. Over 90% of the solar radiation reaching the Earth's atmosphere is visible light and near-infrared (wavelength of 7×10^{-7} to 1.5×10^{-6} m). Less than 10% of solar radiation is ultraviolet (uv) light (wavelength of 10^{-8} to 4×10^{-7} m). This is illustrated in Figure 2 below.

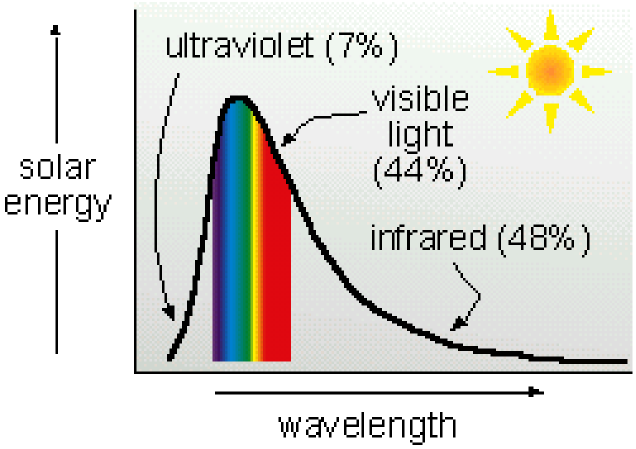
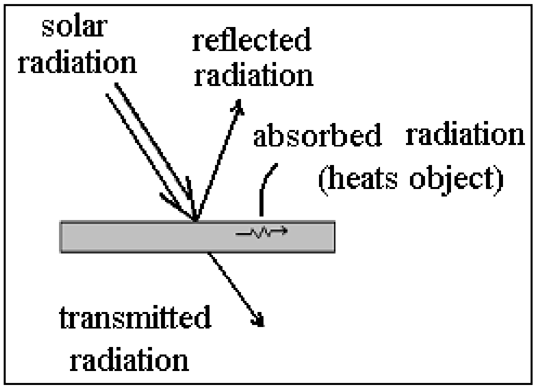


Figure 2. Approximate characteristics of solar radiation reaching the Earth

2. 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, ρ. The absorbed fraction is called the absorbance, α, and the transmitted fraction is called the transmittance, τ. All the incident radiation must be accounted for by the sum of these three fractions, thus:

$$\alpha + \rho + \tau = 1 \qquad (2)$$

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 $\tau = 0$. Solar radiation, which is reflected by a surface or transmitted through it, will then travel on in a straight line until it strikes another surface and is ultimately absorbed.

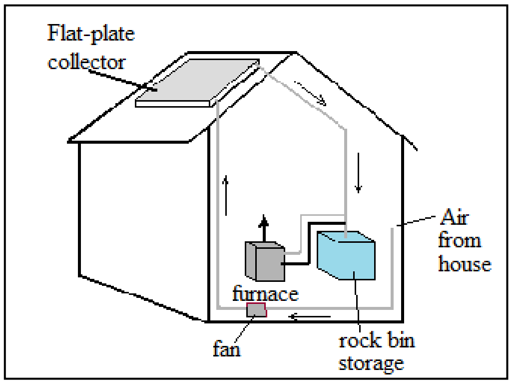
Example #1: A translucent plastic sheet will transmit 30% of the solar radiation striking it and has an absorbance of 0.6. If 0.5 Kilowatts of solar radiation is striking a sheet of this plastic, what is the rate of reflected solar radiation from the sheet.

Solution: The reflectance is calculated as $\rho = 1 - \alpha - \tau = 1 - 0.6 - 0.3 = 0.1$. The rate of reflected radiation is thus 10% of the incident radiation or 0.1 x 0.5 Kilowatts = 0.05 Kilowatts.

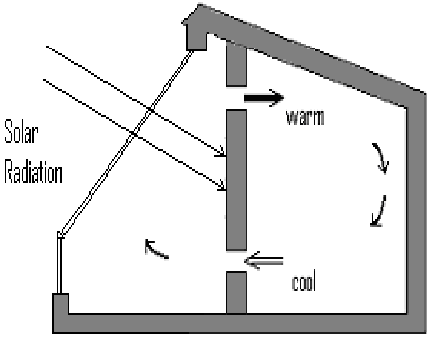
3. Methods of Putting Solar Energy to Work

There are numerous ways that solar energy works “behind the scenes” to keep us alive on the surface of the earth. These ways include powering 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 suitable for our survival on the surface of the earth. The intention of this section, however, is to briefly discuss three major ways that solar energy is converted to other usable forms: **solar space heating**, **solar water heating** and **solar generation of electricity**.

Solar space heating can be done with **active** or **passive** solar heating systems. An active solar heating system makes use of solar collectors, usually on the roof of the building. The collectors heat a fluid (usually air). A blower draws air through the collectors. The heated air is then 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 heated living space.

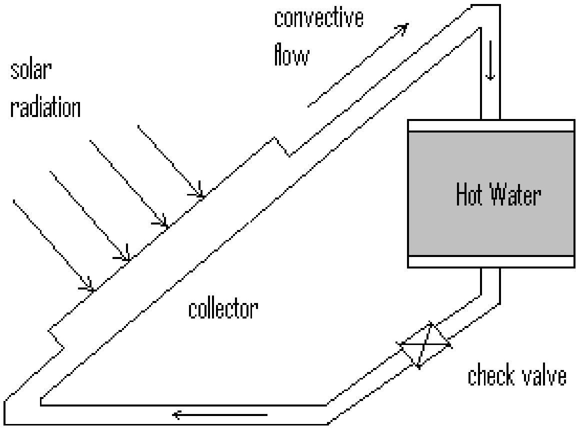


Active Solar Heating System



Attached Sunspace - daytine heat flow

A passive solar heating system uses south-facing glass, such as windows or attached sunspace glazing, to bring the sun's rays into the building. The solar radiation will heat the living space directly and some of the thermal energy will be stored in parts of the building such as masonry walls and floors. At night and on cloudy days, the stored heat will heat 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.



Passive Solar Water Heater

A positive point for **Solar Water Heating** is that it is needed all year around, not just during the heating season. Active or passive solar systems can be used for water heating. In either case, a solar collector will be used to heat water, which is stored in a tank for use. Active solar water heating systems use a pump to move water around, while a passive system uses natural convection (heated water rises) to move water.

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 much the same as in a conventional fossil fuel or nuclear power plant.

photovoltaic cells

4. Solar Position Parameters

There are several parameters that can be used to describe the position of the sun at a specified date, time, and location. The five parameters that will be discussed here are **solar declination, solar altitude angle, solar hour angle, sunrise hour angle, and sunset hour angle**.

Solar declination is a function of the day of the year. It is the angle between the sun's rays and a plane passing through the equator, as shown in Figure 3. 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 increasing when the sun is directly overhead north of the equator (December 21 through June 21) and it is decreasing when the sun is directly overhead south of the equator (June 21 through December 21).

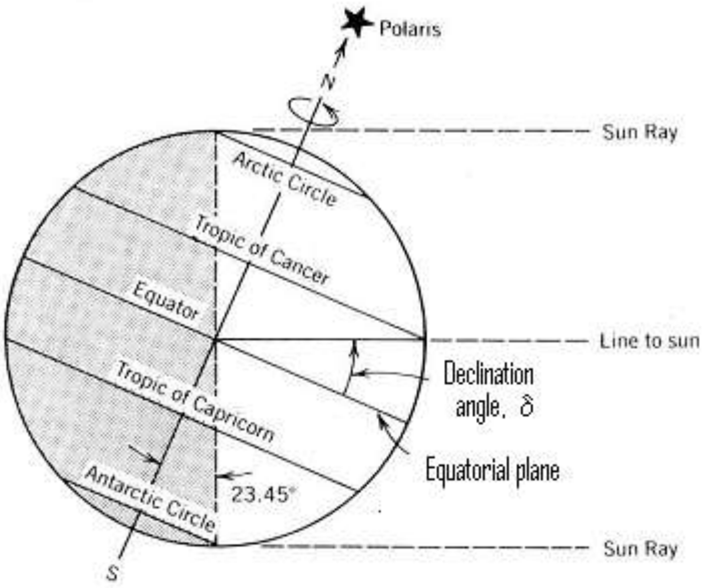


Figure 3. Solar Declination Angle, δ

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.

The variation of δ throughout the year is shown in the diagram below. The solar declination is a maximum of + 23.45^{o} on June 21 and is a minimum of – 23.45^{o} on December 21.

Example #2: What is the value of the solar declination on March 5?

Solution: The value of n for March 5 is $31 + 28 + 5 = 64$

Equation (3), with the value 64 substituted for n becomes:

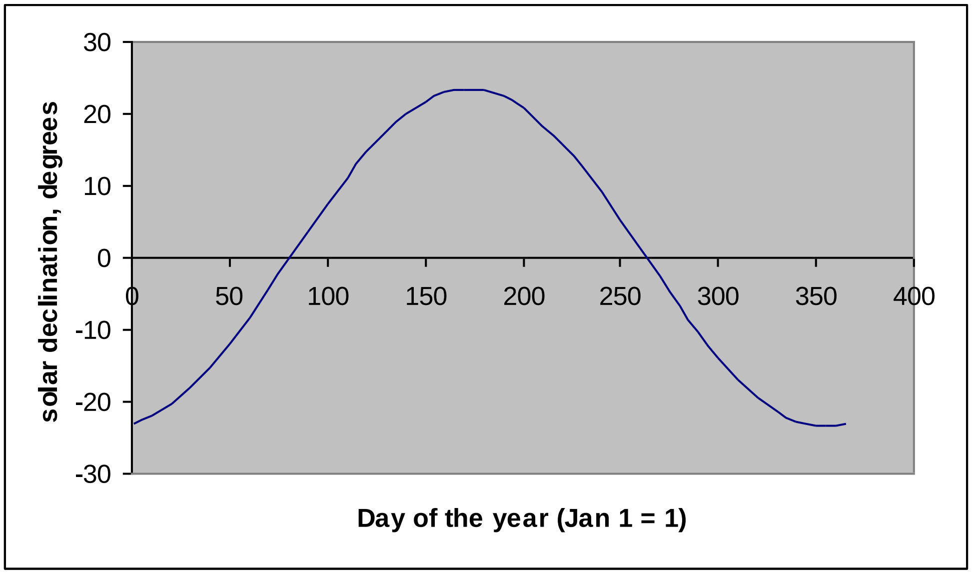
$$\delta = (23.45^{o})\sin[360^{o}(284 + 64)/365] = (23.45^{o})\sin[343.2^{o}]$$

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 343.2^{o} expressed in radians becomes:

$$\delta = (23.45^{o})\sin[(343.2)(\pi/180)] \text{ or } (23.45^{o})\sin[(343.2)(pi()/180)]$$

Proceeding with the calculation: $\underline{\boldsymbol{\delta = -6.78^{o}}}$

Figure 4. Solar Declination

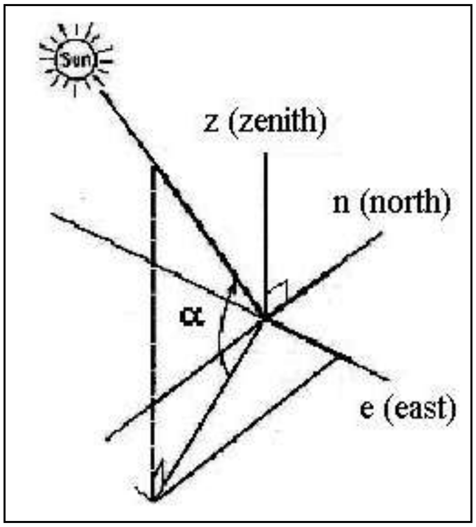


The **Solar Altitude Angle** is the angle between the sun's rays and a horizontal plane. When the sun is just rising or setting, the altitude angle is zero. When the sun is directly overhead, the altitude angle is 90°. The diagram below illustrates the altitude angle. The solar altitude angle, α, can be calculated for any location and time from the latitude, L, solar declination, δ, and solar hour angle, h_s, using the following equation.

$$\text{Sin}\alpha = \sin L \sin\delta + \cos L \cos\delta \cosh_s \qquad (4)$$

Example #3: Calculate the solar altitude angle, α, for solar noon on March 5, in Albuquerque, NM (latitude 35.05° N).

Solution: From **Example #2,** the solar declination, δ, on March 5, is - 6,78°. The hour angle, h_s, is zero at solar noon, and the latitude is given in the problem statement as 35.05°, so equation (4) becomes:



Solar Altitude Angle, α

$$\text{Sin}\ \alpha = \sin(35.05^o)\sin(-6.78^o) + \cos(35.05^o)\cos(-6.78^o)\cos(0)$$

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

$$\text{Sin}\ \alpha = 0.745$$

$$\alpha = \sin^{-1}(0.745) = 0.8407 \text{ radians} = \underline{\mathbf{48.2^o = \alpha}}$$

The **Solar Hour Angle** is a measure of the position of the sun relative to solar noon at any given location and time on the earth. The hour angle, h_s, 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 solar hour angle as a function of local solar time is summarized in Table 1 below.

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

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

$$\text{Solar Time} = \text{local standard time} + \text{ET} + (l_{st} - l_{local})(4\ \text{min/degree}) \qquad (5)$$

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:

$$\text{ET} = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B) \qquad (6)$$

$$\text{Where} \quad B = 360(n - 81)/364 \ \text{degrees} \qquad (7)$$

For some solar calculation, 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 (4) and solving for h_s. The angle will be negative for sunrise and positive for sunset. This results in the following two equations:

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

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

If h_{sr} and h_{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 #4: Calculate the sunrise hour angle and sunset hour angle for St. Louis, MO (latitude: 38.75^o N), on March 5.

Solution: From **Example #3,** the solar declination, δ, on March 5, is -6.78^o, and the latitude is given in the problem statement as 38.75^o, so equation (9) becomes:

$$\text{Sunset hour angle} = h_{ss} = \cos^{-1}[-\tan(38.75^o)*\tan(-6.78^o)]$$

$$= 0.2975 \text{ radians} = \underline{\mathbf{17.0^o = h_{ss}}}$$

$$\text{Sunrise hour angle} = h_{sr} = -h_{ss} = \underline{\mathbf{-17.0^o = h_{sr}}}$$

3. Extraterrestrial Solar Radiation

Solar radiation continuously strikes the earth's outer atmosphere at the rate of 1.7×10^{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_o. The solar constant has been estimated by several different groups to be in the range from 1353 to 1394 W/m^2. There is a seasonal variation in amount of extraterrestrial radiation due to the variation in distance between the earth and the sun over a year's cycle. An estimate of the solar radiation, I, on any day of the year can be estimated from the following equation:

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

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.

Equation (11) can be used along with equation (10) to calculate the average daily extraterrestrial solar flux on a horizontal plane, $H_{o,h}$, for any day of the year and latitude, using the previously discussed parameters, solar declination, δ, and sunset hour angle, h_{ss}, and latitude, L.

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

The latitude of the site is an important parameter because of the effect of latitude on the altitude angle of the sun. 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), (using I_o = 367 W/m^2) 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 #5: What is the average extraterrestrial solar radiation rate (kWhr/day/m^2) in Albuquerque, NM (latitude: 35.05° N), in March?

Solution: From Table 2: for latitude 35°, solar rate = 8.24 kWhr/day/m^2, and

for latitude 40°, solar rate = 7.64 kWhr/day/m^2

By interpolation, the solar rate at latitude 35.05° is calculated to be:

$$8.24 - [(35.05 - 35)/(40 - 35)](8.24 - 7.64) = \underline{\mathbf{8.23\ kWhr/day/m^2}}$$

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

6. Terrestrial Solar Radiation

Although this information about extraterrestrial solar radiation is interesting, what we usually want is the rate of solar radiation striking a solar collector or photovoltaic panel at the earth's surface, right? Right! And… that is what this section is about.

Terrestrial solar radiation is solar radiation reaching the earth's surface. It is sometimes convenient to break it down into two components **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. Beam radiation is also sometimes called direct radiation. Diffuse radiation is solar radiation that is scattered or reflected by molecules of air, water vapor, aerosols and dust particles, but ultimately still reaches the earth's surface.

A couple different approaches that can be used for estimating the rate of solar radiation striking a solar collector at a given location will be discussed briefly here. These estimates can be made for a variety of time periods, such as monthly daily, or hourly. Monthly average rates are widely used.

One of these approaches uses a set of equations that can be used to calculate the solar radiation rate on a flat surface tilted at any specified angle from the horizontal. The data needed for this type of calculation includes the latitude of the collector location and values for some of the solar parameters discussed earlier in this course (δ, h_{ss}, & h_{sr}) 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.

The other approach makes use of print and/or internet resources containing data on average rate of solar radiation striking solar collectors of a variety of configurations and tilt angles. Data for monthly average solar radiation rate for the collector of interest to you will usually be available directly from one of the sources. The course, E287 "Solar Energy Basics II – Estimation of Solar Radiation on a Collector ", provides details about some of these sources of solar data.

7. Summary

Solar energy reaches the earth in the form of electromagnetic radiation. It can be absorbed by an object that it strikes, and thus be converted to thermal energy (heat). Typical methods of utilizing solar energy include, space heating, water heating and generation of electricity. Several parameters that are used in solar energy calculations were presented and discussed. Means of estimating monthly average extraterrestrial and terrestrial solar radiation rates at a specified location were also discussed.

8. Related Links and References

References:

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

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