Sunlight and its Properties

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The Sun

- The sun is a hot sphere of gas whose internal temperatures reach over 20 million deg. K.
- Nuclear fusion reaction at the sun's core converts hydrogen to helium.
- A nuclear fusion releases a tremendous amount of thermal energy according to Einstein's formula:

$$E = mC^2$$

• The radiation from the inner core is not visible since it is absorbed by a layer of hydrogen atoms closer to the sun's surface.



Plank's Black Body Formula

• The energy at the surface of the sun is estimated according to Plank's formula:

$$w_{\lambda} = \frac{2\pi h\lambda^{-5}}{e^{\frac{hc}{\lambda kT}} - 1}$$

- *w*: Energy density (W/m²/unit wavelength in m)
- h: Plank's constant = $6.63 \times 10^{-34} \text{ Ws}^2$
- c: speed of light = 3×10^8 m/s
- T: temperature of black body (K)
- K: Boltzmann's constant = $1.38 \times 10^{-23} (J/K)$
- At the surface of the sun, T \approx 5,800 K, resulting in w = 5.961 x10⁷ W/m².

Solar radiation in space

- The energy radiated on an object in space decreases as the object moves further away from the sun.
- The energy density *w* on an object some distance D from the sun is found by

$$w_o = \left(\frac{R}{D}\right)^2 w$$

where $R = 6.955 \times 10^8$ m is the radius of the sun.



How much solar radiation doe the earth receive?

- By the time this energy travels 150,000,000 km to the earth's outer atmosphere, it is reduced to nearly 1,367 W/m².
- By the time this energy travels through the earth's atmosphere to the earth's surface, it is reduced to nearly 1,000 W/m²
- In one hour, the earth receives enough energy from then sun to meet its energy needs for nearly one year.

Solar radiation intensity of other planets

Planet	Distance D (x 10 ⁹ m)	Solar Radiation w _o (W/m ²)					
Mercury	57	9228					
Venus	108	2586					
Earth	150	1367					
Mars	227	586					
Jupiter	778	50					
Saturn	1426	15					
Uranus	2868	4					
Neptune	4497	2					
Pluto	5806	1					

Effect of Atmosphere on Sunlight

- As sunlight enters the earth's atmosphere, some of it gets absorbed, some is scattered and some passes through and reaches the earth's surface.
- Different molecules in the atmosphere absorb significant amounts of sunlight at certain wavelengths
 - Water vapor and carbon dioxide absorb sunlight in the visible and infrared region
 - Ozone absorbs sunlight in the UV region



Scattering of incident light

 Blue light has a wavelength similar to the size of particles in the atmosphere – thus scattered.



 Red light has a wavelength that is larger than most particles – thus unaffected



Types of Radiations

- Scattered sunlight (what makes the sky blue) is responsible for the light entering the northfacing windows. It is referred to as *diffuse radiation*.
- *Direct or beam radiation* is sunlight that reaches the earth's surface without scattering.
- Sunlight that is reflected from the ground is called *albedo radiation*.
- The sum of the all three components above is called *global radiation*

Solar Radiation Spectrum



Comparison of solar radiation outside the Earth's atmosphere with that reaching the Earth.



Air Mass (AM)

- **Air Mass** (AM) is the optical path length through Earth's atmosphere for sunlight.
- As it passes through the atmosphere, light is attenuated by scattering and absorption;
 - the more atmosphere through which it passes, the greater the attenuation.
 - Consequently, the sun at the horizon appears less bright than when at the zenith (angle measured between the direct beam and the vertical).
- AM normally indicates *relative airmass*, the path length relative to that at the zenith at sea

х

$$AM \approx \frac{1}{\cos \theta} = \frac{y}{x}$$

Air Mass

 An easy method to determine the AM is from the shadow s of a vertical object. Air mass is the length of the hypotenuse k divided by the object height h:



Air Mass

- By definition, the sea-level AM at the zenith is 1 (denoted AM1).
- AM increases as the angle between the sunbeam and the zenith increases, reaching a value of approximately 38 at the horizon.
- AM can be less than one at an elevation greater than sea level;
- The region above Earth's atmosphere, where there is no atmospheric attenuation of solar radiation, is considered to have "air mass zero" (AM0).
- Global solar radiation at AM0 is \$1,367 W/m², and nearly 1,000 W/m² at AM1 (i.e., about 70% of that corresponding to AM0)
- Note that AM0 and AM1 have different spectral content.

Air Mass

• Approximate formula of solar radiation as a function of air mass:

$$I = 1367(0.7)^{(AM)^{0.678}}$$

• AM1.5 is chosen as the standard calibration spectrum for PV Cells.

Standard Solar Spectrum for Testing PV Cells (Excel file available)



Some Facts

- The hours of sunlight over a year are the same for every point on the earth (provided only the hours between sunrise and sunset are counted)
- Why are the earth's poles cold? Because sunlight reaching these areas carries less energy, since it must pass through a greater air mass.

Irradiance and Irradiation

- Irradiance: power density of sunlight (W/m2).
 Often referred to as intensity of sunlight.
- Irradiation is a measure of energy density of sunlight (kWh/m²). It is the integral of irradiance over a period of time (usually 1 day)
- Irradiation is usually expressed in *peak sun hours (psh)*, i.e., the length of time at an irradiance of 1kW/m² needed to produce the daily irradiation obtained from integration of irradiance over a day. (see Fig. 2.3).

Earth's orbit

 The earth revolves around the sun in an elliptical orbit once per year. The variation in distance between the sun and earth is given by

$$d = 150\{1 + 0.017\sin[\frac{360(n-93)}{365}]\} Mkm$$

• The maximum distance (152 Mkm) occurs at summer solstice, and the minimum distance (147 Mkm) occurs at winter solstice.



Earth Rotation

- The earth also rotates about its own axis once per day.
- The polar axis of the earth is inclined by an angle of 23.45° to the plane of the earth's orbit.



Convenient Reference:

fixed earth spinning around its north-south axis

- This causes the sun to move up and down as the seasons progress (higher in the sky during the summer, and lower during the winter).
- On summer solstice, the sun appears vertically above the Tropic of Cancer (which is at 23.45° latitude above the equator)
- On winter solstice, the sun appears vertically above the Tropic of Capricorn (which is at 23.45° latitude below the equator)
- At the two equinoxes, the sun appears vertically above the equator (which is at 0° latitude)



Declination Angle

- The declination angle δ is the angle of deviation of the sun from directly above the equator.
- If angles north of the equator are considered positive and those below the equator are considered negative, then at any given nth day of the year, this angle can be calculated by the following formula.

$$\delta = 23.45^{\circ} \sin[\frac{360(n-81)}{365}]$$



Month: Jan Feb Mar Apr May Jun July Aug Sept Oct Nov Dec δ: -20.1 -11.2 0.0 11.6 20.1 23.4 20.4 11.8 0.0 -11.8 -20.4 -23.4

Longitude and Latitude Angles



Solar Noon:

An important reference point for solar calculations

- Solar noon is the moment when the sun appears the highest in the sky, compared to its positions during the rest of the day.
- Solar noon occurs when the sun is directly over the local meridian (line of longitude).
- The Sun is directly overhead at solar noon in
 - the equator on the two equinoxes;
 - the Tropic of Cancer on the summer solstice;
 - the Tropic of Capricorn on the winter solstice.
 - Mexico City (19° latitude) on \dots n = 139, and n = 208
 - Key West (24.5° latitude) on ... n/a

Sun Altitude Angle

- The altitude angle α is the angle between the sun beam and the local horizon directly beneath the sun.
- The altitude angle is largest at solar noon:

$$\alpha_{N} = 90 - \phi + \delta$$

where ϕ and δ are the latitude and declination angles.



Illustration

- **Problem:** Find the optimum tilt angle for a south facing PV module in Tucson, AZ (32.1° latitude) at solar noon on March 1.
- Solution:
 - March 1 corresponds to n = 60
 - Declination angle: $\delta = -8.3^{\circ}$
 - Altitude angle at solar noon: $\alpha_N = 49.6^{\circ}$
 - Tilt angle that would make the sun's rays perpendicular to the module surface at solar noon: Tilt = $90^{\circ} \alpha_N = 40.4^{\circ}$



Sun Position

- The sun position at any time of day is described in terms of its altitude angle α and azimuth angle ψ(which measures that sun's angular position east or west of south).
- These angles depend on the latitude, day number, and most importantly, time of day.
- For the Northern Hemisphere, the azimuth angle is
 - Positive in the morning with the sun in the east
 - Zero at solar noon
 - Negative win the afternoon with the sun in the west
- For solar work in the Southern Hemisphere, azimuth angles are measured relative to the north.

Sun Position



Hour angle

- The hour angle is the number of degrees that the earth must rotate before the sun is directly above the local solar meridian (line of longitude).
- The hour angle is the difference between the local meridian and the sun's meridian, with positive values occurring in the morning and negative values in the afternoon.



Hour Angle and Solar Time

 Since the earth rotates 360° in 24 hrs, or 15° per hour, the hour angle can be described by

 $\omega = 15^{\circ}(12 - ST)$

where ST is the time of day with respect to solar midnight on a 24 clock. For most solar work, it is common to deal with Solar Time (ST): the time before the sun crosses the local meridian. e.g., 11:00 am solar time means 1 hour before the sun reaches the local meridian.

- Examples:
 - At 11:00 am solar time (ST = 11), the hour angle is 15° .
 - At 2:00 pm solar time (ST=14), the hour angle is -30°
 - At midnight solar time (ST = 0 or 24), the hour angle is \pm 180°.

Sun Location Formulas

 The sun's altitude and azimuth angles can be determined in terms of the hour angle, declination angle, and latitude angle by the following formulas:

$$\sin \alpha = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega$$
$$\cos \psi = \frac{\sin \alpha \sin \phi - \sin \delta}{\cos \alpha \cos \phi}, \quad or \quad \sin \psi = \frac{\cos \delta \sin \omega}{\cos \alpha}$$

Note about the azimuth angle

- During the equinoxes, the sun rises directly from the east (+90°) and sets directly to the west (-90°) in every place on earth.
- During spring and summer in the early morning and late afternoon, the sun's azimuth angle is liable to be more than 90° from south (this never happens in the fall and winter).
- Since the inverse of a sin is ambiguous, we need a test to determine whether the azimuth angle is greater or less than 90°

Test: if
$$\cos \omega \ge \frac{\tan \delta}{\tan \phi}$$
, then $|\psi| \le 90^\circ$ otherwise, $|\psi| > 90^\circ$

Example: Where is the Sun?

- Question: Find the sun altitude and azimuth angles of the sun at 3:00 pm solar time (ST) in Boulder, CO (latitude: 40°) on the summer solstice.
- Answer:
 - the declination angle δ = 23.45°
 - The time of day (with respect to solar midnight) T = 15,
 - the hour angle ω = 45°.
 - The altitude angle α = 48.8°.
 - Sin Ψ = -0.985, the Ψ = -80° (80° west of south) or 260° (110° west of south)
 - Test: $\cos \omega = 0.707$, $\tan \delta / \tan \Phi = 0.517$, then $\psi = -80^{\circ}$ (i.e., 80° west of south)

Sun rise and sunset

• The sun's azimuth angle at sunrise and can be determined by setting the altitude angle to zero:

$$\omega_s = \cos^{-1}\{-\tan\delta\tan\phi\}$$

- Which implies that the azimuth angle at sunset is given by ω_s .
- Theses angles are converted to solar time of sunrise and sunset using

$$ST = 12:00 - \frac{\omega_s}{15}$$

• The daylight hours DH are then determined by

$$DH = \frac{2}{15}\omega_s$$
 hours

Sun Path Diagram (plot of sun altitude versus azimuth for specific latitude and days of the year)



Sun position on polar plot: (radial = azimuth, concentric: elevation) Las Vegas NV: longitude (115^o 10' W), latitude (36^o 10' N),

- d = 21, ST: 15:05
- \rightarrow Altitude: 23°
- \rightarrow Azimuth: -40°

- d = 81, ST: 11:13
- \rightarrow Altitude: 50°
- \rightarrow Azimuth: 50°



- →Altitude: 27°
- \rightarrow Azimuth: -100°





Sun position on polar plot: (radial = azimuth, concentric: elevation) Fairbanks, AK: longitude (147° 43' W), latitude (64° 50' N)

- d = 356, ST: 11:00 •
- \rightarrow Altitude: 2.5° •
- \rightarrow Azimuth: 2.5°



- d = 173, ST: 17:13 •
- →Altitude: 21°
- \rightarrow Azimuth: -100°

in in

Solar Time (ST) and Civil (clock) Time (CT)

- There are two adjustments that need to be made to ST in order to convert to CT:
 - The first is the Longitude adjustment (see how the world is divided into 24 1-hour time zones, each spanning 15° of longitude)
 - All clocks within a time zone are set to the same time
 - Each time zone is defined by a local time meridian located ideally in the middle of the zone (with the origin of this time system passing through Greenwich, UK at 0° longitude)
 - The longitude correction between local clock time and solar time is based on the time it takes for the sun to travel between the local time meridian and the observer's line of longitude (4 minutes/degree)
 - Example: San Francisco (longitude 122°) will have solar noon 8 minutes after the sun crosses the 120° local time meridian for the pacific time zone

Time Zones

Solar Time (ST) and Civil (clock) Time (CT)

- There are two adjustments that need to be made to ST in order to convert to CT:
 - The second is a fudge factor that takes into account the uneven way in which the earth moves around the sun
 - This is a result of the earth's elliptical orbit which causes the length of a solar day (solar noon to solar noon) to vary throughout the year.
 - The difference between a 24-hour day and a solar day changes according to the following *equation of time* (where E is in minutes):

$$E = 9.87 \sin(2B) - 7.53 \cos B - 1.5 \sin B$$

$$B = \frac{360}{364}(n-81)$$

Analemma

- Analemma: Variation in solar noon due to the elliptical earth orbit and declination
- Ways of describing Analemma:
 - Plot the position of the sun at each clock noon
 - Plot the clock time at which solar noon occurs over a period of a year (Equation of Time)

Final Relationship between ST and CT

ST = CT+4x(Local Time Meridian – Local Longitude) + E

- When daylight savings Time is in effect, one hour must be added to the local CT.
- Example: Find Eastern Daylight Time for solar noon (ST = 12:00) in Boston (longitude: 71.1° west) on July 1st. The Local Time Meridian is 75°
- Answer:
 - n=182
 - B = 99.89°
 - E = -3.5 min
 - Longitude adjustment: 4(75-71.1)=15.6 min
 - CT = 12:00 15.6 (-3.5) = 12:00 12.1 = 11:48 am (EST)
 - Add daylight savings: solar noon will occur at 12:48 pm (EST)

Measuring Sunlight

- Pyranometers are designed to accurately measure the global solar irradiance (respond to all wavelengths)
- **Pyrheliometers** (shaped like long narrow tubes) are designed to measure the direct (or normal incident) irradiance.
- Other instruments which are less expensive (but less accurate) are available. Examples include silicon photodiodes and cadmium sulfide photocells.

Capturing Sunlight - Types of PV Arrays

with axis oriented south.

Capturing Sunlight (Fixed Array)

- $S_{module} = S_{incident} \times sin(\alpha + \beta)$
- Therefore, maximum power is captured when $\beta = 90^{\circ}$ α
- Since a solar noon, $\alpha = 90^{\circ}-\Phi+\delta$, then the optimal tilt angle is $\beta = \Phi \delta$

Optimal Tilt Angle of Fixed Array

- For optimal yearly performance, choose the average value of δ during the year (which is 0°).
 Hence β = Φ.
- For optimal seasonal performance, choose the average value of δ during that season. For summer, the average value is 15°. Hence $\beta = \Phi 15^{\circ}$. For winter, the average value is -15°. Hence $\beta = \Phi + 15^{\circ}$.
- Many irradiation tables are available for Φ , Φ 15°, and Φ + 15°.

Las Vegas, NV

WBAN NO. 23169

LATITUDE: 36.08° N LONGITUDE: 115.17° W ELEVATION: 664 meters MEAN PRESSURE: 938 millibars

STATION TYPE: Primary

Tilt (")		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.0	4.0	5.4	6.9	7.8	8.4	7.9	7.2	6.2	4.7	3.4	2.8	5.7
	Min/Max	2.3/3.4	3.4/4.5	4.8/6.1	6.1/7,4	7.2/8.3	7.8/8.9	6.6/8.4	6.0/7.8	5.4/6.7	4.0/5.1	3.0/3.7	2.2/3.1	5.3/5.8
Latitude -15	Average	4,4	5.3	6.4	7.5	7.8	8.1	7.7	7.5	7.1	6.1	4.8	4.2	6.4
	Min/Max	3.2(5.3	4.4/6.1	5.6/7.3	6.4/8.0	7.2/8.3	7.6/8.6	6.5/8.2	6.2/8.2	6.1/7.7	5.0/6.7	4.0/5.4	3.1/4.8	5.9/6.7
Latitude	Average	5.1	5.9	6.7	7.4	7.3	7.4	7.1	7.1	7.2	6.6	5.5	4.9	6.5
	Min/Max	3.6/6.2	4.8/6.8	5.8/7.7	6.2(7.9	6.7/7.8	7.0/7.8	6.1/7.5	6.0/7.9	6.1/7.9	5.3/7.3	4.5/6.3	3.6/5.7	5.9/6.8
Latitude +15	Average	5.6	6.1	6.6	6/8	6.5	6.3	6.2	6.5	7.0	6.8	5,9	5.4	6.3
	Min/Max	3.8/6.8	4.9/7.2	5.7/7.6	5.7/7.3	5.9/6.8	6.0/6.7	5.3/6.5	5.5(7.2	5.9/7.6	5.4/7.5	4,7/6.8	3.8/6.2	5.7/6.6
90	Average	5.0	5.1	4.7	3.9	3.0	2.6	2.6	3,4	4.5	5.3	5.2	5.0	4,1
	Min/Max	3.4/6.2	4.0/6.0	4.0/5.4	3.344.1	2.8/3.1	2.4/2.7	2.4/2.7	2.9/3.7	3.8/4.9	4.2/5.9	4.1/6.1	3.5/5.8	3.7/4.5

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

Axis Tilt (*)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average Min/Max	4.6 3.3(5.6	5.9 4.6/7.0	7.8 6.2/9.3	9.8 8.2/10.9	10.9	11.6	10.6 8.2,11.8	10.1 8.1/11.3	9.0 7.1/10.1	7,1 5,7/7.9	5.1 4.1/6.0	4.2 3.0/4.9	8.1 7.2/8.5
Latitude -15	Average Min/Max	5.7 3.9/6.9	6.9 5.3/8.2	8.5 6.9/10.2	10.3 8.5(11.4	11.0 9.9/12.0	11.5	10.8 8,2/11.8	10.4 8.4/11.7	9.7 7.7/10.9	8.1 6.4/9.1	6.2 4.9/7.3	5.3 3.7/6.2	8.7 7.7/9_1
Latitude	Average Min/Max	6.2 4.3(7.7	7.3 5.6/8.7	8.8 7.1/10.5	10.2 8.4/11.3	10.6 9.6/11.6	11.1 10.0/11.9	10.4 7.8/11.4	10.3 8.2/11.5	9.8 7.8/11.1	8.6 6.7/9.5	6.7 5.3/7.9	5.9 4.1/6.9	8.8 7.8/9_3
Latitude +15	Average Min/Max	6.5 4,4/8.1	7.5 5.7/9.0	8.7 7.0/10.4	9.8 8.1/10.9	10.0 9.0/11.0	10.3 9.3/11.1	9.8 7.3/10.7	9.8 7.8/11.0	9.6 7.6/10.9	8.7 6.7/9.7	7.0 5.4/8.3	6.2 4.3/7.3	8.7 7.6/9.1

Solar Radiation for 2-Axis Tracking Flat-Plate Collectors (kWh/m²/day), Uncertainty ±9%	
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Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
2-Axis	Average Min/Max	6.6 4.5/8.2	7.5 5.7/9.0	8.8 7.1/10.5	10.3 8.5911.4	11.1 10.0/12.1	11.8 10.6/12.7	11.0 8.3/12.1	10.5	9,8 T.8/11.1	8.7 6.7/9.7	7.1 5.5/8.3	6.3 4.3/7.4	9.1 8.1/9.6

Shading

 The impact of shades on PV modules will be covered will be covered in detail at a later time.

