Lecture 4 – Solar Radiation

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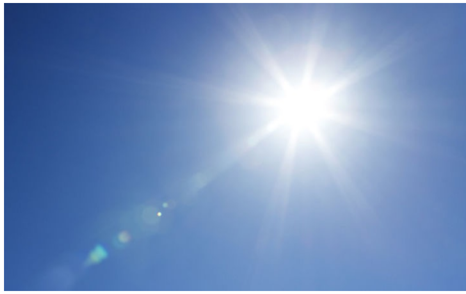
ECE180J

Outline

- The Sun's Structure and Composition
- Sunlight and Spectrum
- The Earth's Revolution and Seasons
- Solar Irradiance & Irradiation
- Optimize Tilt Angle of Solar Collectors

B1 Chap 4; B3 Chap 3

The Sun: Ultimate Source of Renewable Energy




- Solar – directly from sunlight
- Winds – caused by uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth
- Hydro – winds and the sun's heat cause water to evaporate → rain/snow and flows downhill into rivers or streams
- Biomass – along with rain & snow, sunlight causes plants to grow. The organic matter that makes up plants is known as biomass.
- Tidal wave – gravitational pull of Moon & Sun upon the Earth.

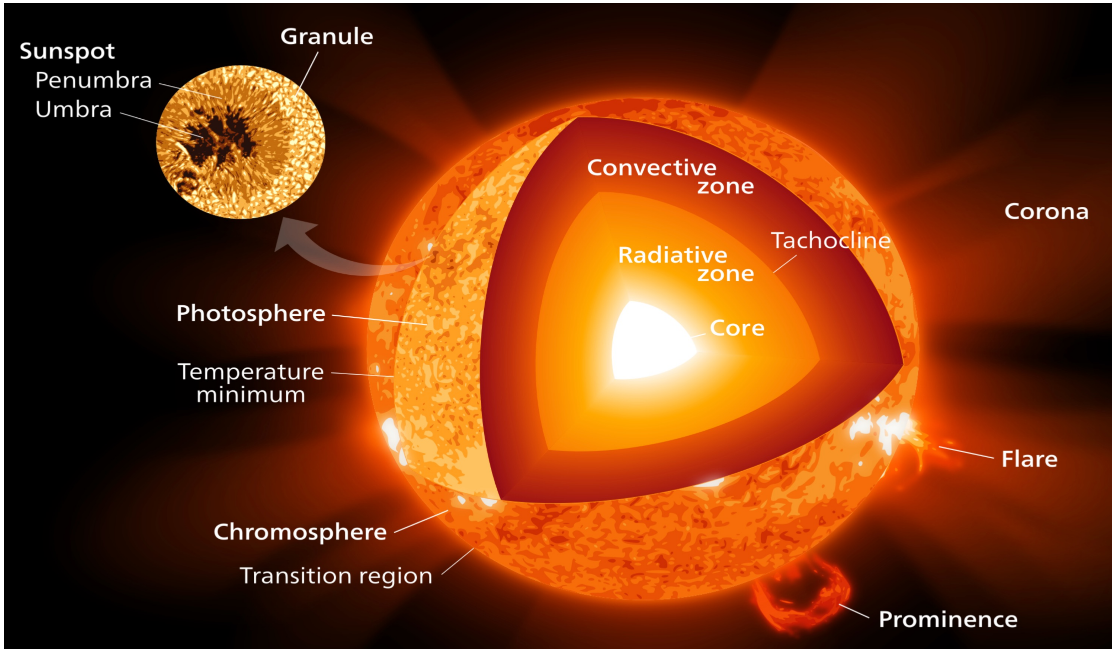
Data of the Sun

Observation data	
Mean distance from Earth	1 au ≈ 1.496×10^8 km[1] 8 min 19 s at light speed
Visual brightness (*V*)	−26.74[2]
Absolute magnitude	4.83[2]
Spectral classification	G2V[3]
Metallicity	$Z = 0.0122$[4]
Angular size	31.6–32.7 minutes of arc[5]

Physical characteristics	
Equatorial radius	695,700 km,[7] 696,342 km[8] 109 × Earth[9]
Equatorial circumference	4.379×10^6 km[9] 109 × Earth[9]
Flattening	9×10^{-6}
Surface area	6.09×10^{12} km^2[9] 12,000 × Earth[9]
Volume	1.41×10^{18} km^3[9] 1,300,000 × Earth
Mass	1.9885×10^{30} kg[2] 333,000 × Earth[2]
Average density	1.408 g/cm^3[2][9][10] 0.255 × Earth[2][9]

Source: Wikipedia

Layers of The Sun



- **Core**: the innermost 20-25% of the Sun's radius, where temperature/pressure are sufficient for nuclear fusion to occur.
- **Radiative zone**: between 20-25% to 70% of the radius, energy transfer occurs by means of radiation (photons) rather than by convection.
- **Tachocline**: boundary region between the radiative & convective zones.
- **Convective zone**: between about 70% of the Sun's radius and a point close to the visible surface; the primary means of outward heat transfer.
- **Photosphere**: the deepest part which we can directly observe with visible light.
- **Atmosphere**: a gaseous 'halo' surrounding the Sun, comprising the chromosphere, solar transition region, corona and heliosphere.

Composition of the Sun

Photospheric composition (by mass)	
Hydrogen	73.46%[14]
Helium	24.85%
Oxygen	0.77%
Carbon	0.29%
Iron	0.16%
Neon	0.12%
Nitrogen	0.09%
Silicon	0.07%
Magnesium	0.05%
Sulfur	0.04%

Source: Wikipedia

The Sun’s Nuclear Fusion

- The solar energy (both heat and light) originates from a nuclear fusion process.
- This proton-proton fusion process begins with protons (simply a lone hydrogen nucleus) and through a series of steps, these protons fuse together and are turned into helium.

1. 2 protons fuse. One of them transforms into a neutron via the weak nuclear force, which forms a positron and neutrino (deuterium).
2. A 3rd proton collides with deuterium resulting in a helium-3 nucleus and a gamma ray (sunlight).
3. 2 helium-3 nuclei collide, creating a helium-4 nucleus plus 2 extra protons that escape as 2 hydrogen.

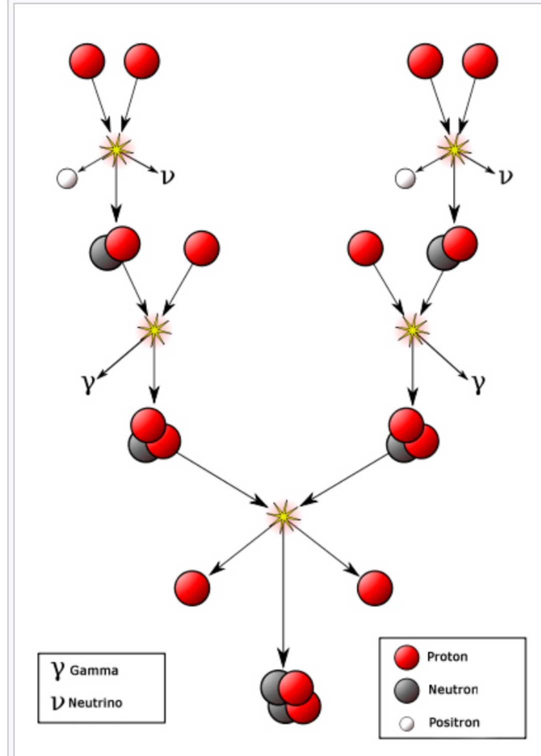
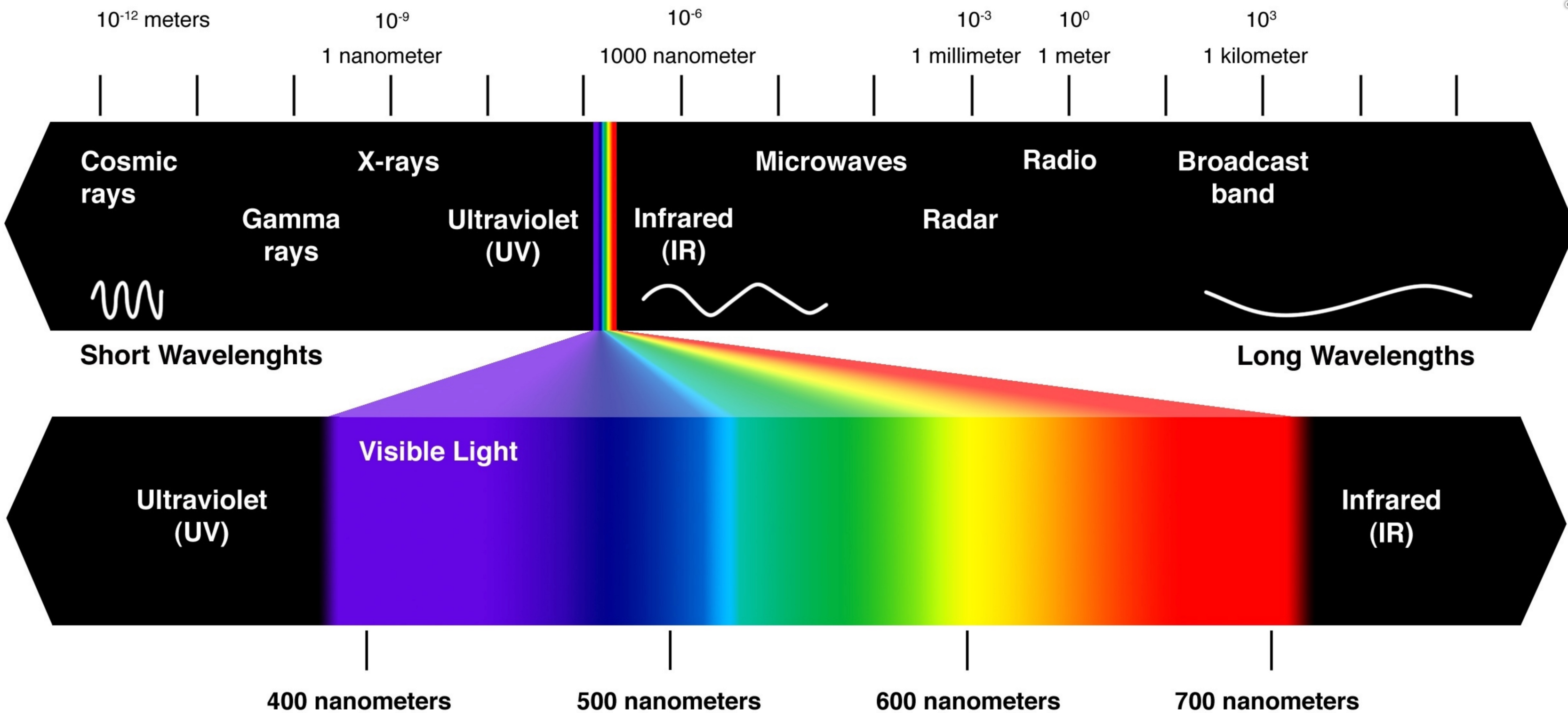


Figure 1. The proton-proton fusion process that is the source of energy from the Sun.[1]

- The core is the only part of the Sun that produces any significant amount of heat through fusion (it contributes about 99%).
- The rest of the Sun is heated by energy transferred outward from the core.

https://energyeducation.ca/encyclopedia/Nuclear_fusion_in_the_Sun

Light Spectrum



frequency

$$f = \frac{c}{\lambda}$$

speed of light (3×10^8 m/s)

wavelength

Blackbody Radiation

A blackbody is be a perfect emitter and a perfect absorber.

- As a perfect emitter: it radiates more energy per unit of surface area than any real object at the same temperature.
- As a perfect absorber: it absorbs all radiation that impinges upon it.
- There is no net flow of matter or energy between the body and its environment.

The spectral radiance of a blackbody is given by Planck's law:

$$E_\lambda = \frac{3.74 \times 10^8}{\lambda^5 \left[\exp\left(\frac{14{,}400}{\lambda T}\right) - 1\right]} \tag{4.1}$$

E_λ: emissive power intensity per unit area per unit wavelength $(W/m^2/\mu m)$

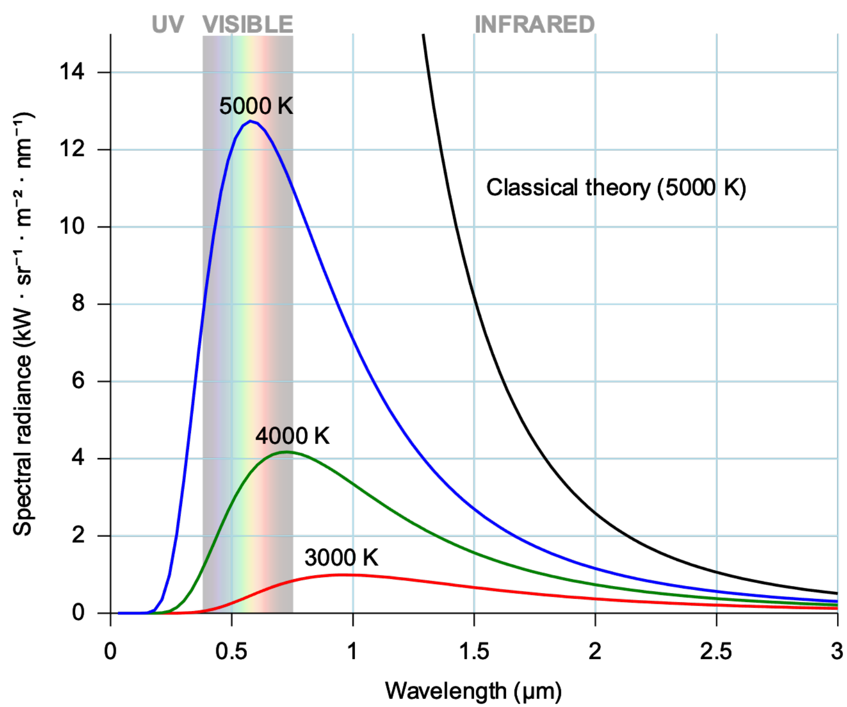
T: absolute temperature of the body (K)

λ: wavelength (μm)

https://en.wikipedia.org/wiki/Planck_constant

Planck's Law

- Planck's law describes the electromagnetic radiation emitted by a black body in the thermal equilibrium at a given temperature.
- It was heuristically derived by German physicist Max Planck in 1900. This discovery was a pioneering insight of modern physics and is of fundamental importance to quantum theory.
- The emissive power intensive is a function of wavelength, parameterized by temperature.



Source: Wiki

The Spectrums of the Earth & the Sun

➢ The wavelength at which the intensity reaches its maximum:

$$\lambda_{\max}(\mu\mathrm{m}) = \frac{2898}{T(\mathrm{K})}$$

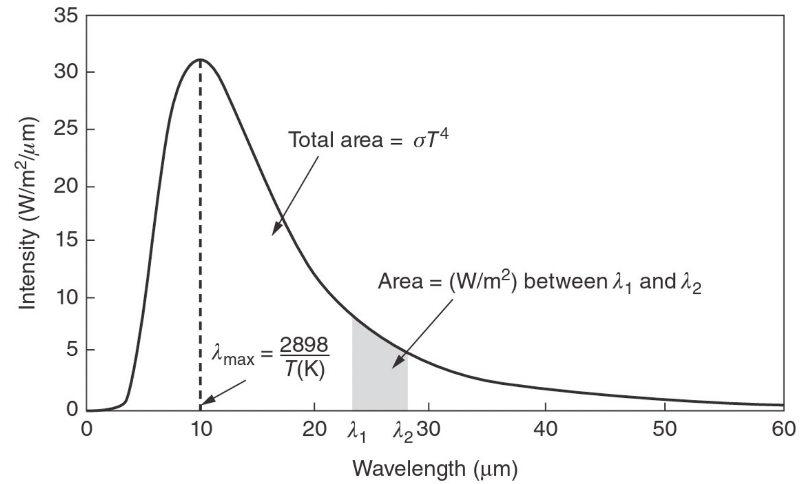


FIGURE 4.1 The spectral emissive power of the earth modeled as a 288 K blackbody.

➢ The total radiant power emitted:

$$E = \sigma A T^4$$

where σ is the Stefan–Boltzmann constant 5.67×10^{-8}, T is the absolute temperature (K), and A is the surface area (m^2).

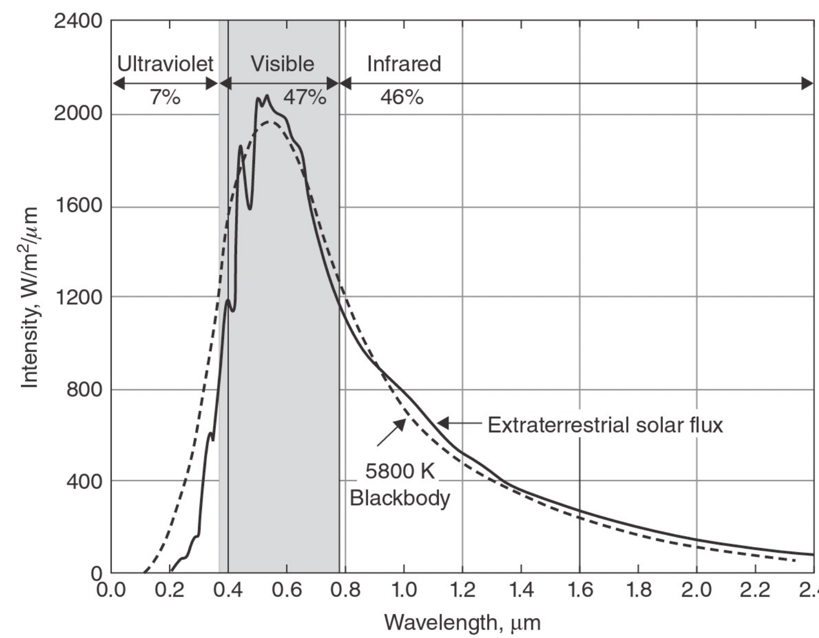


FIGURE 4.2 The extraterrestrial solar spectrum compared with a 5800 K blackbody.

An Example

Example 4.1 The Earth's Spectrum. Consider the earth to be a blackbody with average surface temperature 15°C and area equal to 5.1×10^{14} m^2. Find the rate at which energy is radiated by the earth and the wavelength at which maximum power is radiated. Compare this peak wavelength with that for a 5800 K blackbody (the sun).

Solution. Using Equation 4.2, the earth radiates

$$E = \sigma A T^4 = (5.67 \times 10^{-8} \mathrm{W/m^2/K^4}) \times (5.1 \times 10^{14} \mathrm{m^2}) \times (15 + 273\ \mathrm{K})^4$$

$$= 2.0 \times 10^{17}\ \mathrm{W}$$

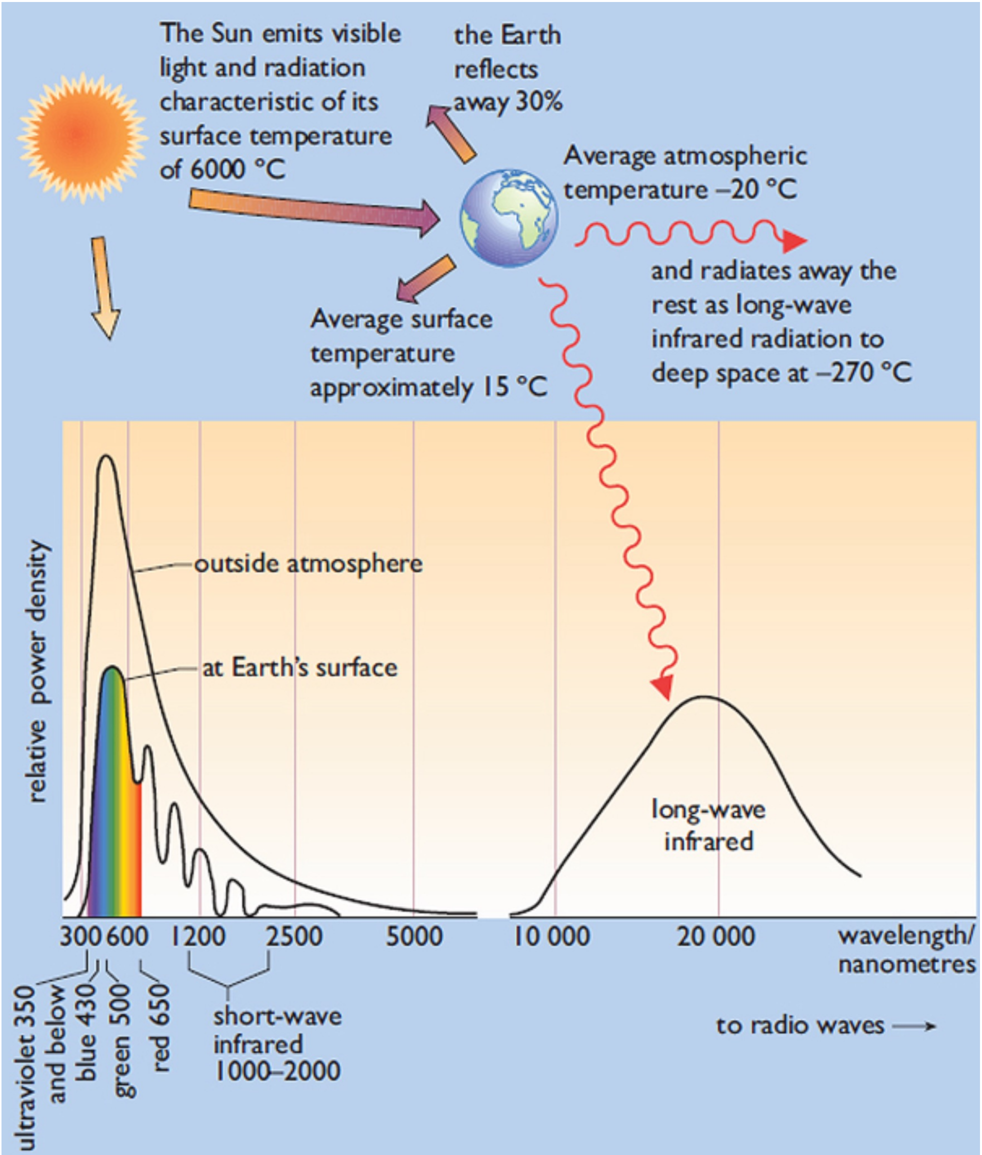
The wavelength at which the maximum power is emitted is given by Equation 4.3:

$$\lambda_{\max}(\text{earth}) = \frac{2898}{T(\mathrm{K})} = \frac{2898}{288} = 10.1\ \mu\mathrm{m}$$

For the 5800 K sun,

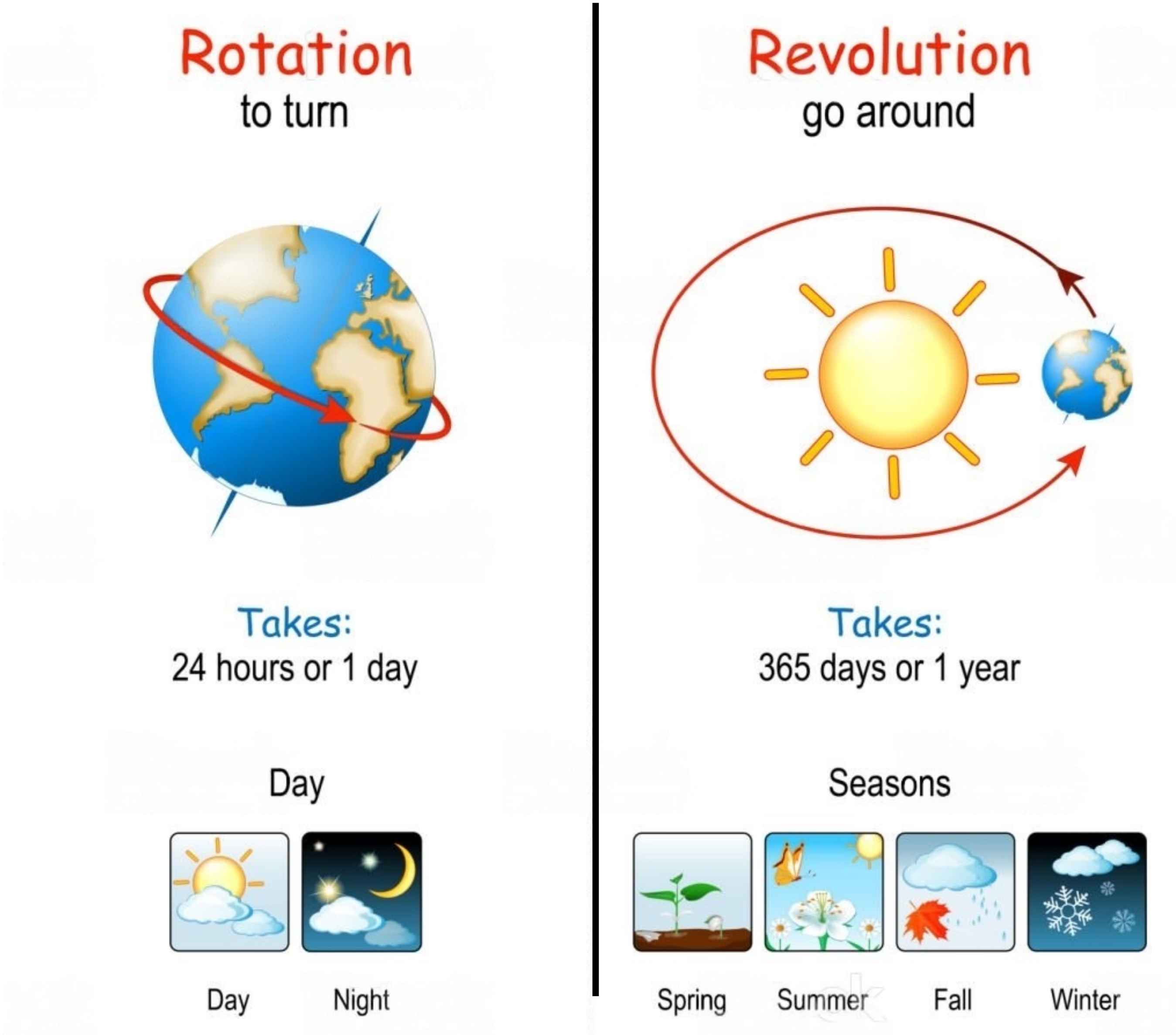
$$\lambda_{\max}(\text{sun}) = \frac{2898}{5800} = 0.5\ \mu\mathrm{m}.$$

Solar Irradiation



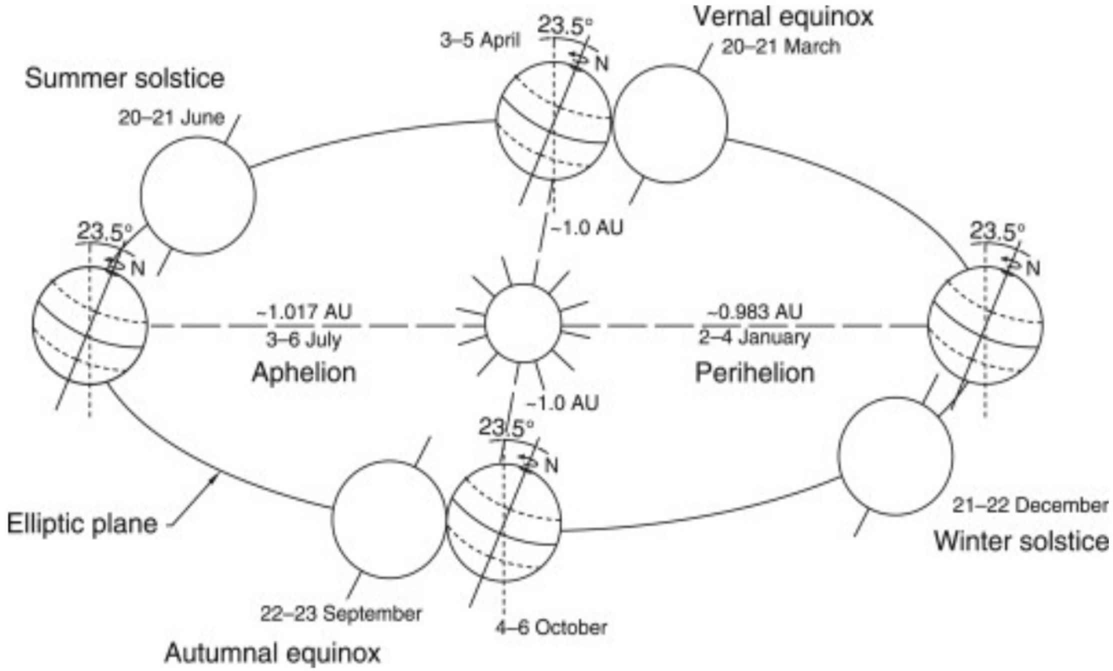
- The Sun is an enormous nuclear fusion reactor: hydrogen atoms fuse to form helium at rate of 4 million tons per second.
- This fusion reaction causes the Sun to radiate energy, due to the high surface temperature (6000°C).
- This fusion has been continuing reliably for the past 4 or 5 billion years and is expected to continue for another 4 or 5 billion years.

The Earth's Rotation and Revolution



Source: www.istockphoto.com

Earth to Sun Distance



Earth-to-Sun distance:

n: day #: 1~365

$$d = 1.5 \times 10^8 \left\{1 + 0.017 \sin \left[\frac{360\,(n-93)}{365}\right]\right\} \text{ km}$$

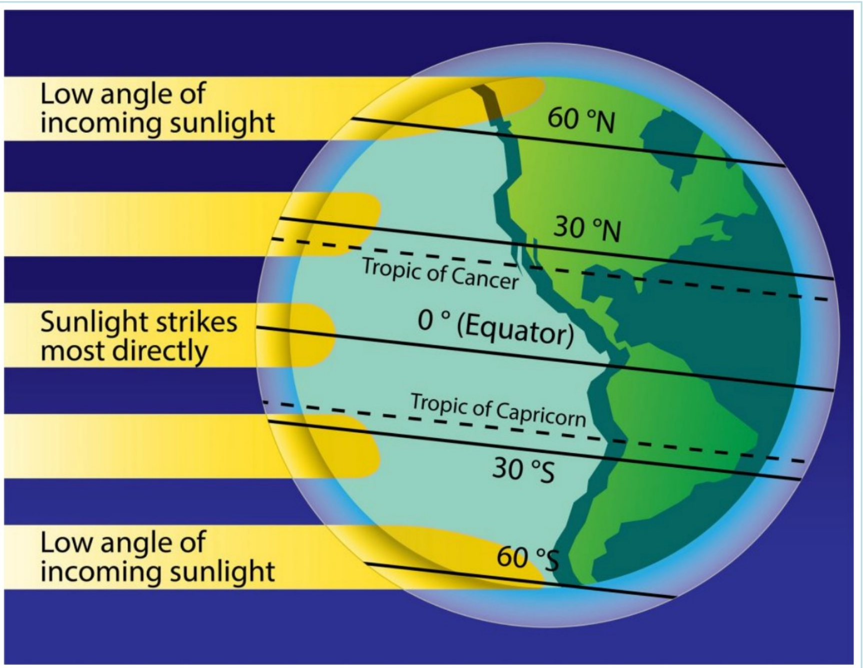
Mean distance :=
1astronomical unit (AU)

Eccentricity of Earth

Angle measured
in degrees

The above formula is derived based on Kepler's first law and an approximation; see details at https://bit.ly/3jEyHup

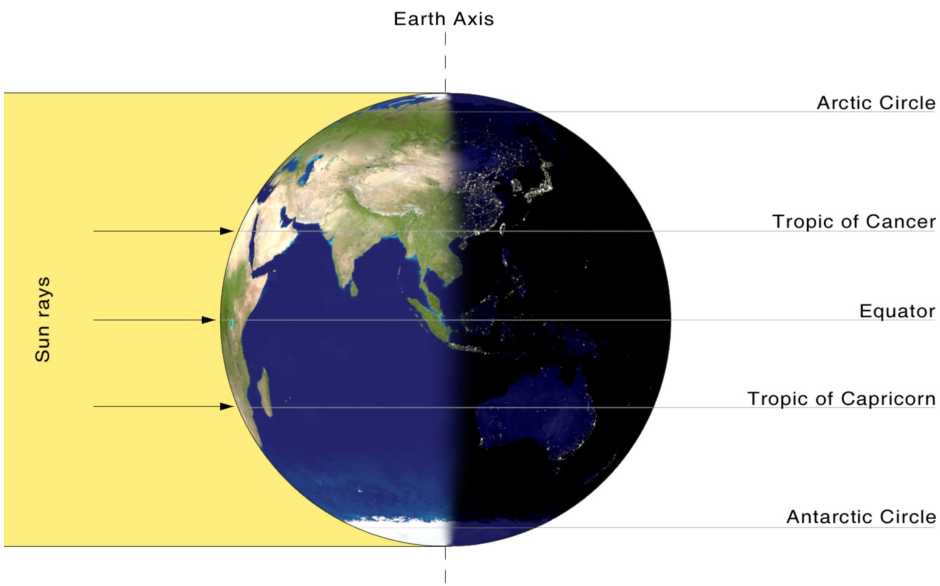
Unequal Distribution of Solar Radiation



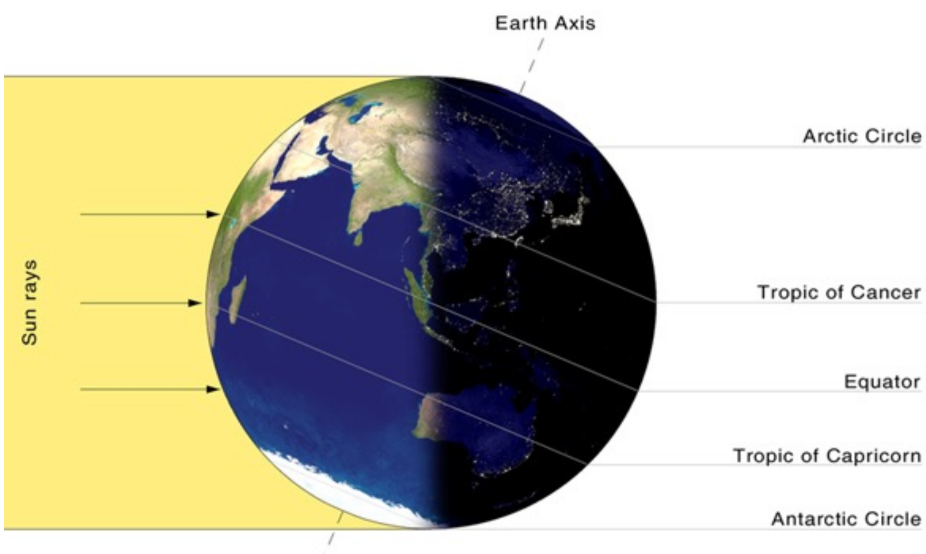
- Because Earth is a sphere, not all part of the Earth receives the same amount of solar radiation.
- Near the equator, the Sun's rays strike the Earth most directly, while at the poles the rays strike at a steep angle.
- This means that less solar radiation is absorbed per square meter of surface area at higher latitudes than at lower latitudes, and that the tropics are warmer than the poles.
- This temperature difference shapes global atmospheric and ocean circulation patterns.

Source: ugc.berkeley.edu/background-content/reflection-absorption-sunlight/

The Angle of Sun Rays

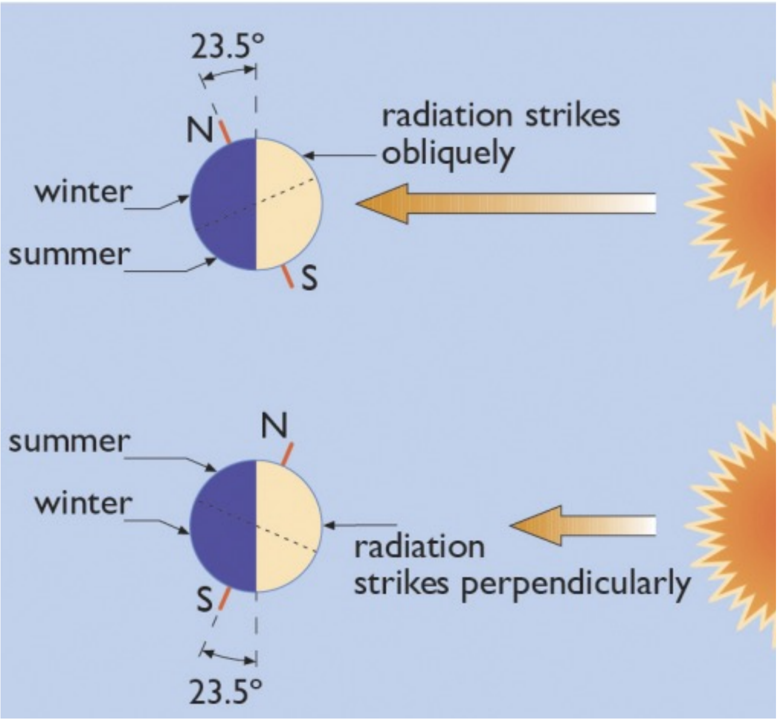


If the Earth if not tilted, the sun rays always strike perpendicularly onto the Equator.



During the Summer time of Southern Hemisphere, the sun rays strike perpendicularly onto the Tropic of Capricorn.

Different Seasons

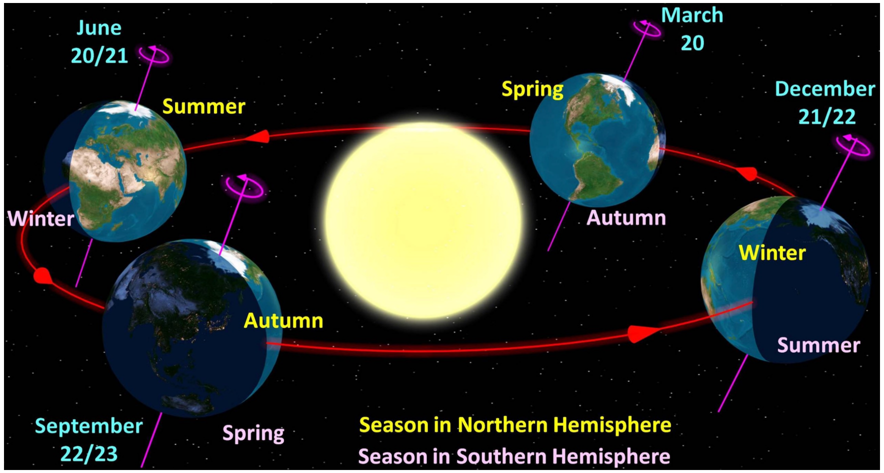


The Earth circles the Sun with its polar axis tilted towards the plane of rotation.

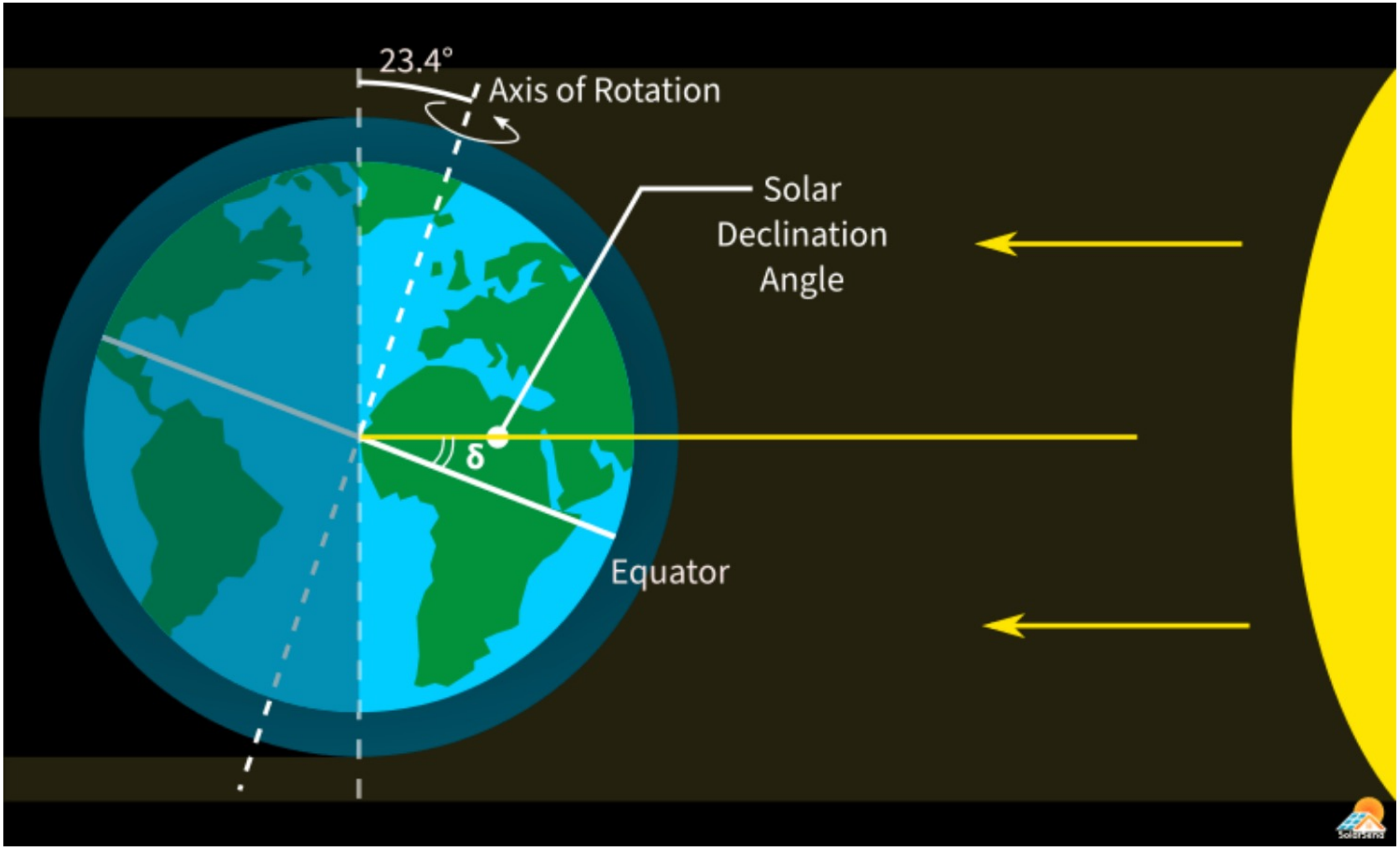
- In Dec., the North Pole is tilted away from the Sun, resulting in fewer kilowatt-hours reaching per square meter.

- In June, the North Pole is tilted towards the Sun therefore its rays strike the northern hemisphere more perpendicularly and the Sun appears higher in the sky.

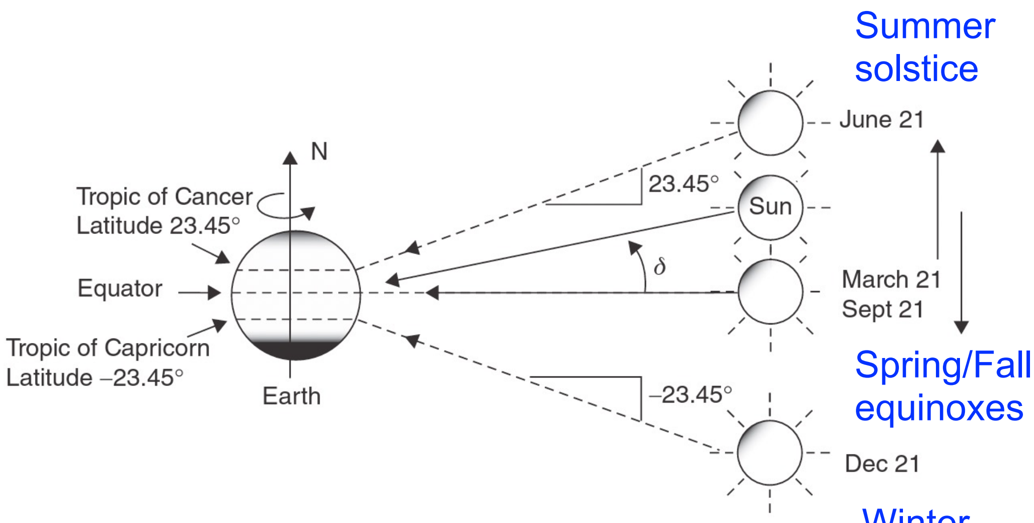
Tilt (at 23.45°) of the Earth's axis creates different seasons.



Solar Declination



Solar Declination (cont'd)



Alternative View: Fixed Earth and Sun Moves

n: day #: 1~365

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

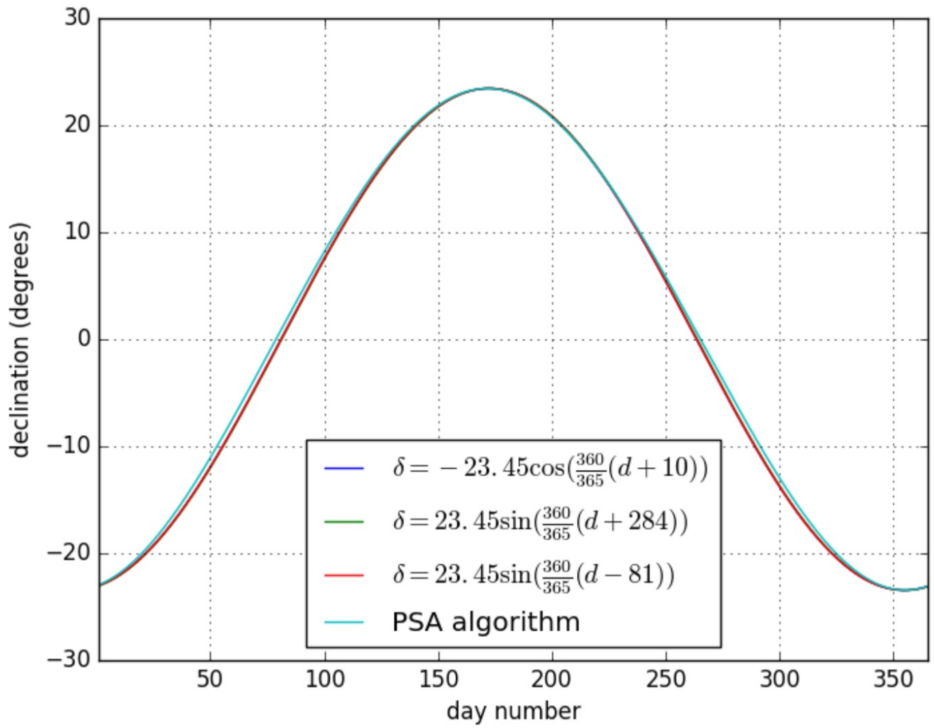
angle measured
in degrees

Solar declination δ: the angle between the Earth-Sun line and the earth's equatorial plane. It describes the latitude of Earth where the sun is directly overhead at noon.

The solar declination angle is an important factor in determining

1) the amount of solar radiation that a particular location receives.
2) the path of the Sun across the sky and the length of daylight hours at a particular location.

More Accurate Formula

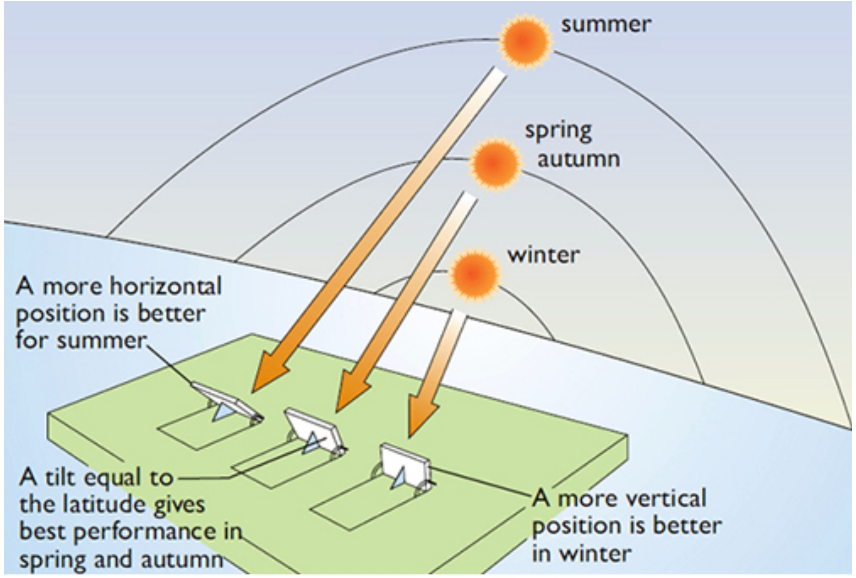


$$\delta = \sin^{-1}\left[\sin(-23.44^{\circ})\cos\left(\frac{360}{365.24}(d+10)+\frac{360}{\pi}\times 0.0167\sin\left(\frac{360}{365.24}(d-2)\right)\right)\right]$$

There are many algorithms for more accurate determinations of declination angle to account for the elliptic and yearly movement of the earth's orbit. These are only needed for concentrators that require more accurate tracking

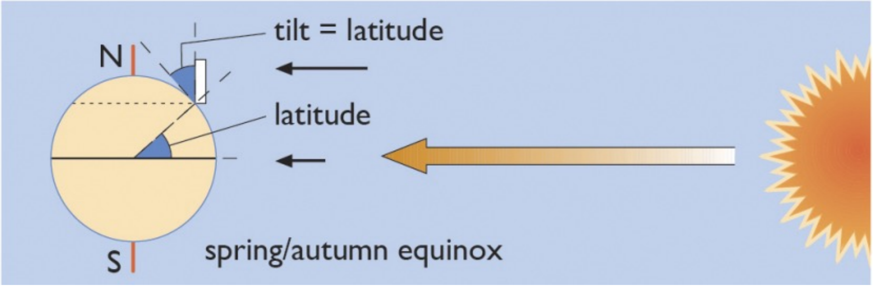
Source: pveducation.org

Optimizing the Tilt



- In the northern hemisphere, a surface should face south to collect as much radiation as possible.

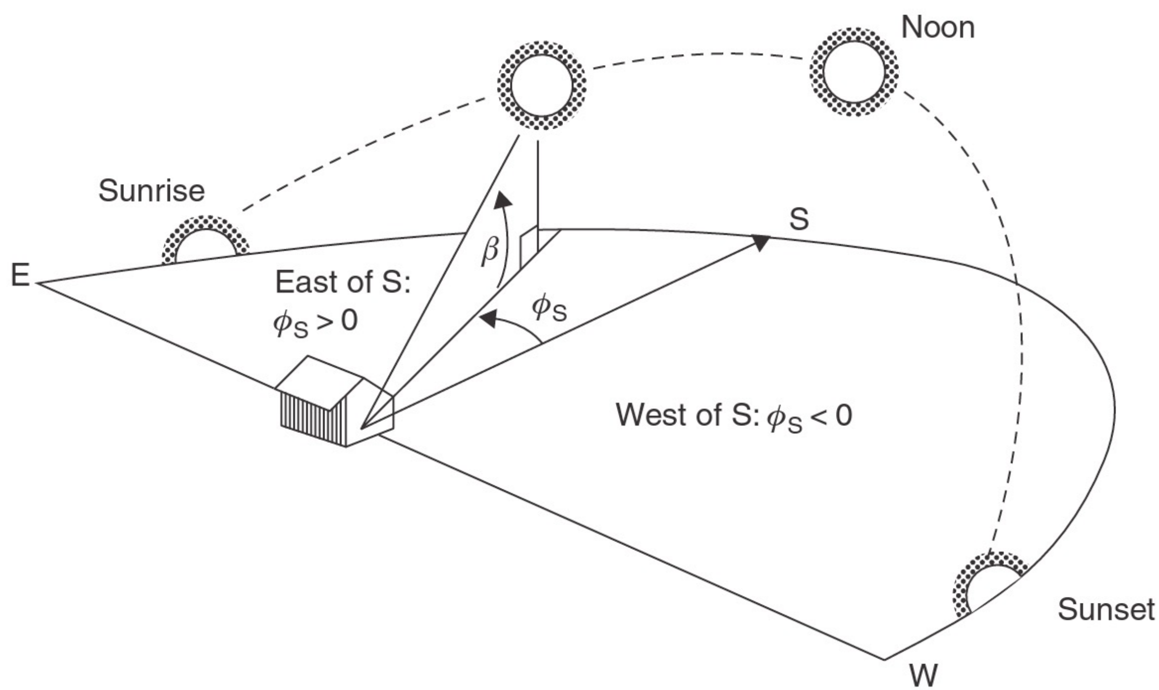
- Be tilted towards the Sun at an angle depending on the latitude and the time of year.



A surface tilted at the latitude angle will be perpendicular to the Sun's rays at mid-day on the Spring or Autumn equinox.

Position of the Sun

Tracking the Sun at Any Time



The location of the sun can be described by two angles:

- Solar altitude (elevation) angle β: the angle between the sun and the local horizon directly beneath the sun. Its complementary angle is the Solar zenith angle.
- Solar azimuth angle φs: the book uses the south-anticlockwise convention (for the Northern Hemisphere): due south as the reference and positive angles if anticlockwise.

Computing the Two Solar Angles

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta$$

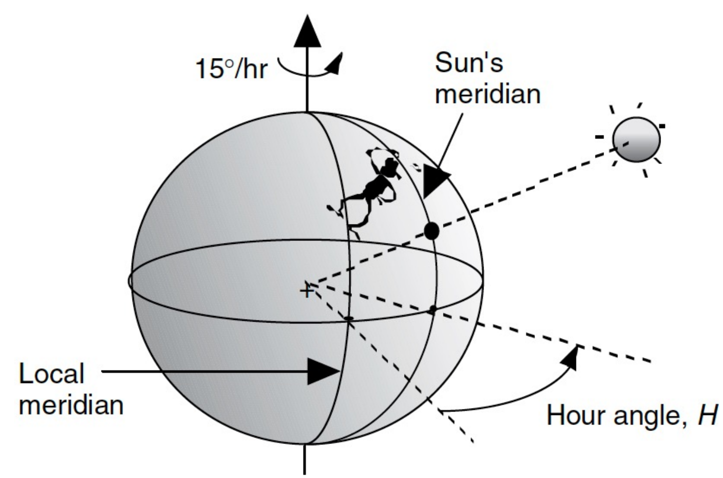
$$\sin\phi_S = \frac{\cos\delta \sin H}{\cos\beta}$$

$$\text{Hour angle } H = \left(\frac{15^\circ}{\text{hour}}\right) \cdot (\text{hours before solar noon})$$

- L: Latitude of the location
- δ: Solar declination
- H: hour angle

Hour angle: the number of degrees the Earth must turn before the Sun is directly over the local meridian. H = 0 at solar noon.

Solar noon: the moment when the Sun passes a location's meridian (on the line of longitude), reaching its highest position above the horizon and casting the shortest shadow.
At this time, the Sun appears due south in the Northern Hemisphere. In most cases, it doesn't happen at 12pm sharp.



Special Cases

$$\boxed{\sin\ \beta = \cos\ L \cos\ \delta \cos\ H + \sin\ L \sin\ \delta}$$

- At solar noon (H = 0):

$$\sin \beta = \cos L \cos \delta + \sin L \sin \delta = \cos(L - \delta) \implies \boxed{\beta_N = 90 - L + \delta}$$

- At solar noon (H = 0) &
  Sun is directly overhead:

$$\beta_N = 90 \implies \delta = L$$

- Solar hour at sunrise/sunset:

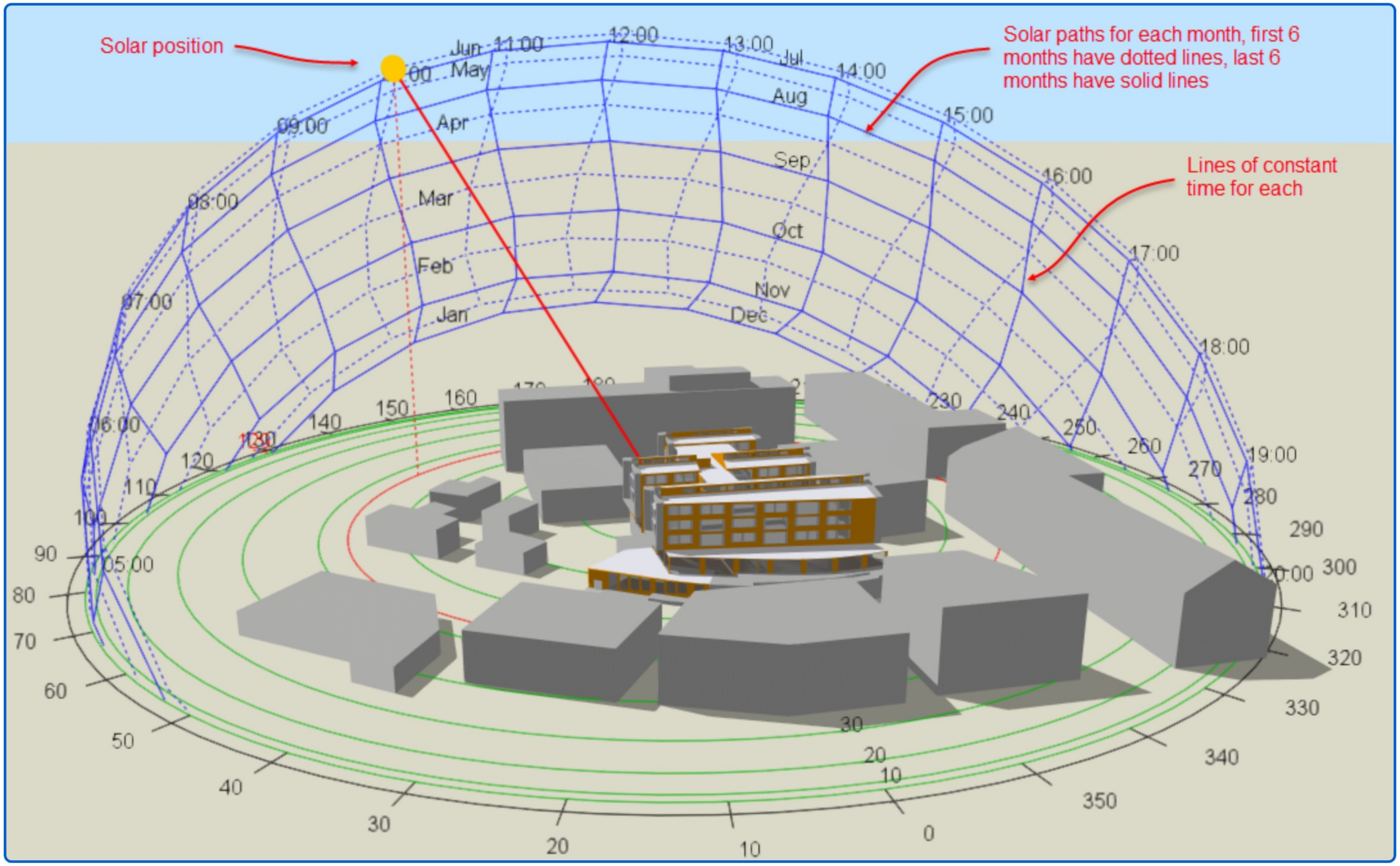
$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta = 0$$

$$\cos H = -\frac{\sin L \sin \delta}{\cos L \cos \delta} = -\tan L \tan \delta$$

$$H_{SR} = \cos^{-1}(-\tan L \tan \delta) \qquad (+\text{ for sunrise}) \implies$$

$$\text{Sunrise(geometric)} = 12{:}00 - \frac{H_{SR}}{15°/h}$$

Sun Path Diagram



The Sun path diagram helps visualize the paths as it moves through the sky at all times of the year: the green circles are the contour lines for the solar latitude angles. The black circle shows solar azimuth angles (North as reference).

Source: designbuilder.co.uk

An Example

Example 4.2 Tilt Angle of a PV Module. Find the optimum tilt angle for a south-facing photovoltaic module in Tucson (latitude 32.1°) at solar noon on March 1.

Solution. From Table 4.1, March 1st is the 60th day of the year so the solar declination (Eq. 4.6) is

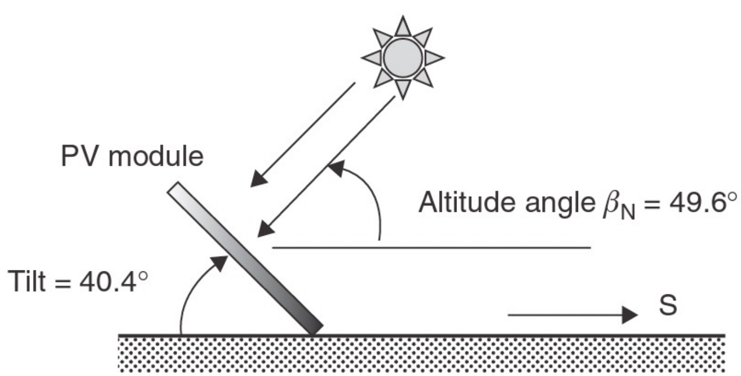
$$\delta = 23.45 \sin\left[\frac{360}{365}(n - 81)\right] = 23.45^\circ \sin\left[\frac{360}{365}(60 - 81)^\circ\right] = -8.3^\circ$$

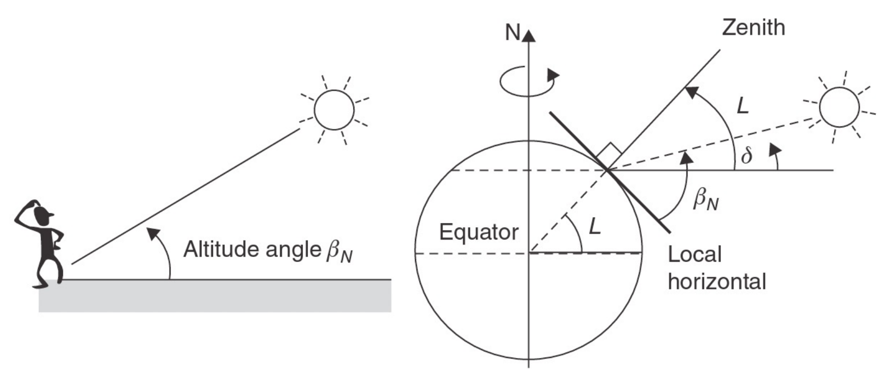
which, from Equation 4.7, makes the altitude angle of the sun equal to

$$\beta_N = 90 - L + \delta = 90 - 32.1 - 8.3 = 49.6^\circ$$

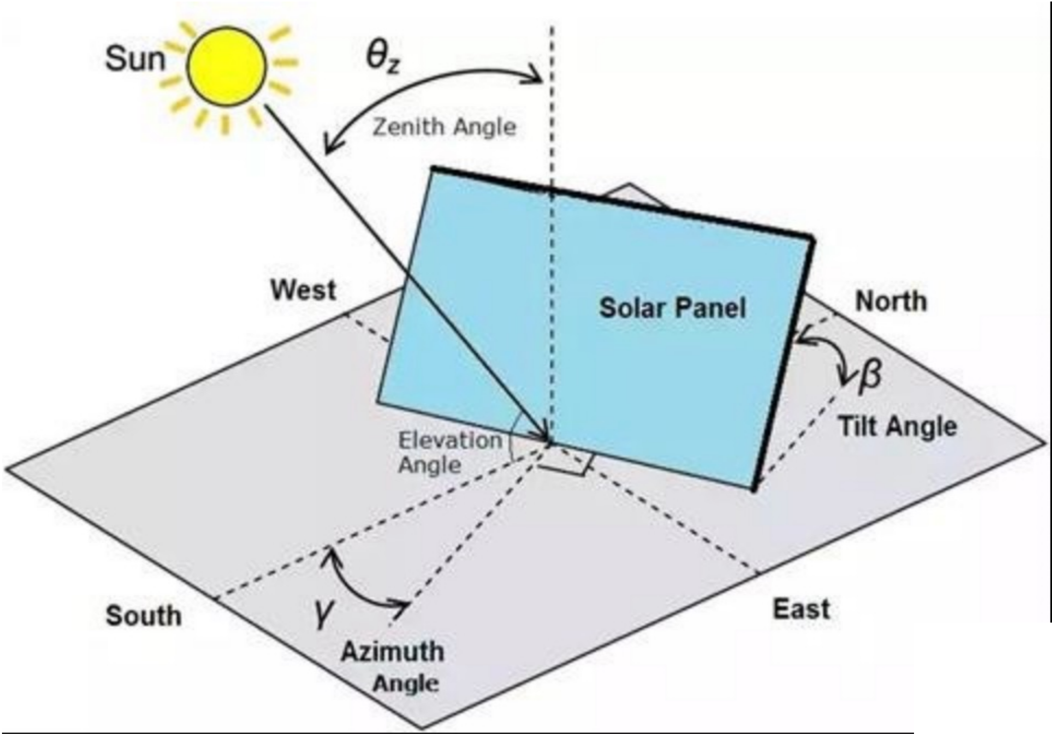
The tilt angle that would make the sun's rays perpendicular to the module at noon would therefore be

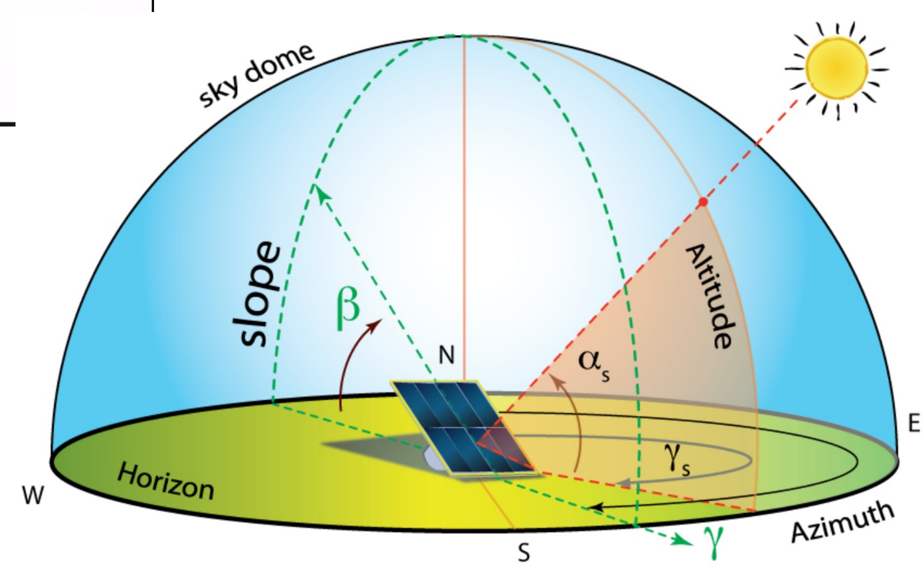
$$\text{Tilt} = 90 - \beta_N = 90 - 49.6 = 40.4^\circ$$





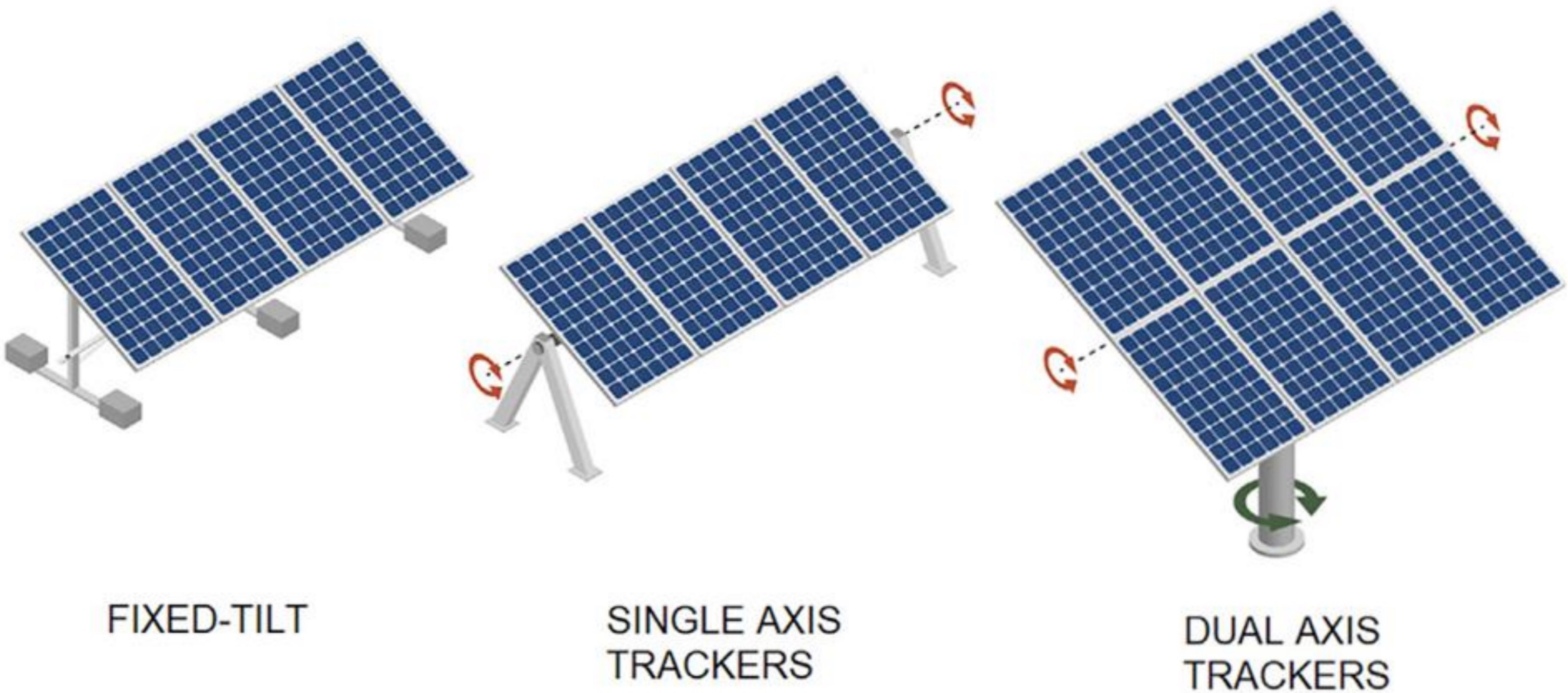
Solar and Collector Angles in 3-D





Credit: Jeffrey Brownson © Penn State University

Solar Trackers



Credit: forbes.com

Solar Irradiance & Insolation

- Solar irradiance: The power per unit area (W/m^2) received from the Sun in the form of electromagnetic radiation.

- Solar insolation (aka solar exposure/ irradiation): Solar irradiance integrated over a given period (kWh/m^2).

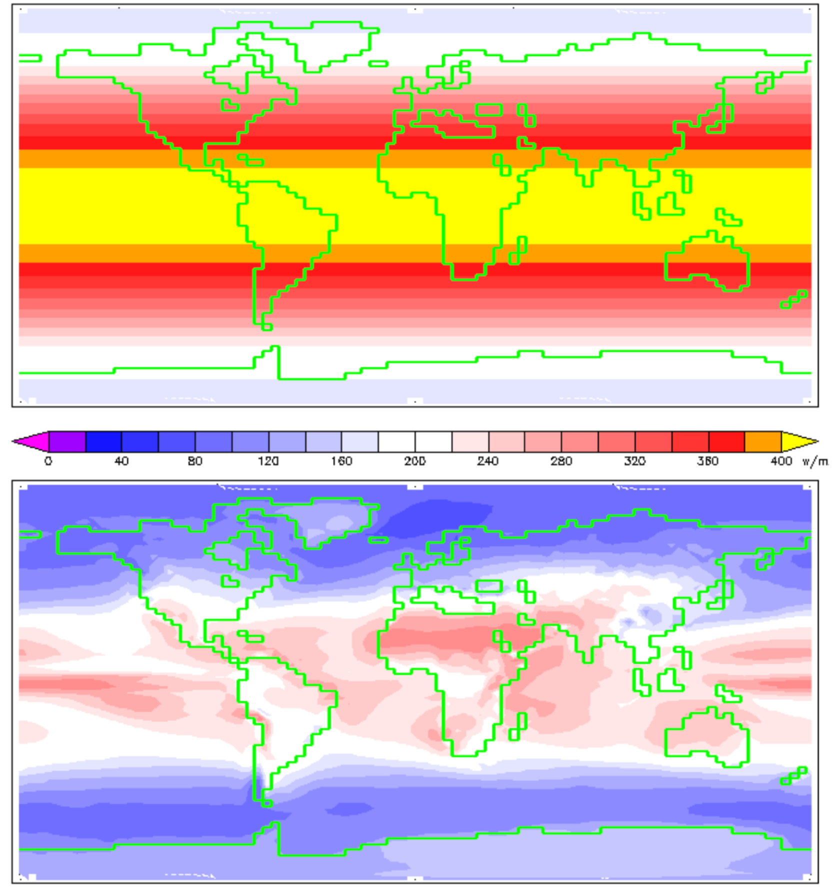


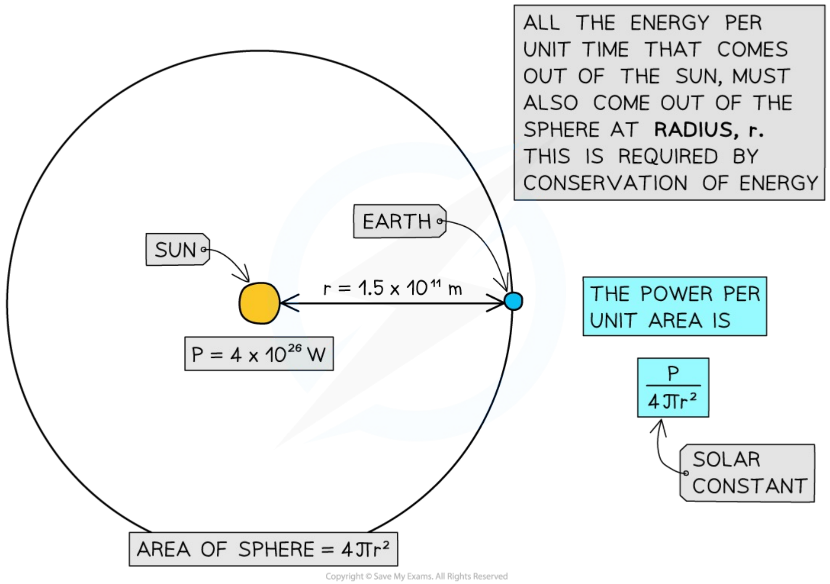
Fig: The shield effect of Earth's atmosphere on solar irradiation.
Top: at the top of Earth's atmosphere
Bottom: reaching the Earth's surface

Important applications:

1) prediction of solar energy generation.
2) heating/cooling loads of buildings.
3) climate modeling and weather forecasting.

Source: Wikipedia

Solar Constant



The solar constant (SC ≈ 1361 W/m²) is a flux density measuring mean solar electromagnetic radiation (total solar irradiance) per unit area. It is measured on a surface perpendicular to the rays, 1 AU from the Sun.

Extraterrestrial (ET) solar irradiance I_0, which passes perpendicularly through an imaginary surface just outside of the earth's atmosphere, depends on the distance between the Earth and the Sun, which varies with the time of year.

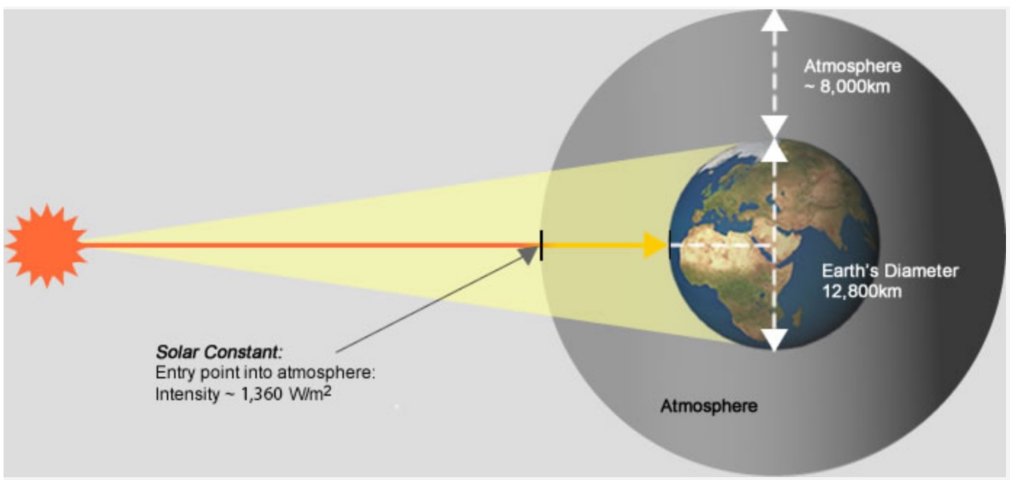
$$I_0 = \mathrm{SC} \cdot \left[1 + 0.034 \cos\left(\frac{360n}{365}\right)\right] \qquad (\mathrm{W/m^2})$$

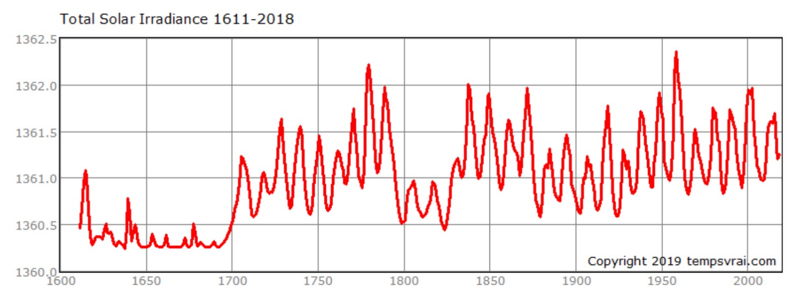
Source: Wiki

Total Solar Irradiance

Total solar irradiance (TSI) is a measure of the amount of solar radiation received at the top of the earth's atmosphere, averaged over a period of time (usually a year) and over the entire surface of the earth facing the sun.

- The average value for TSI is about 1361 W/m². It has been measured by satellites over the entire solar cycle (about 11 years).
- TSI can vary over shorter time scales due to solar activity and other factors. However, over longer time scales, the average TSI is relatively constant.



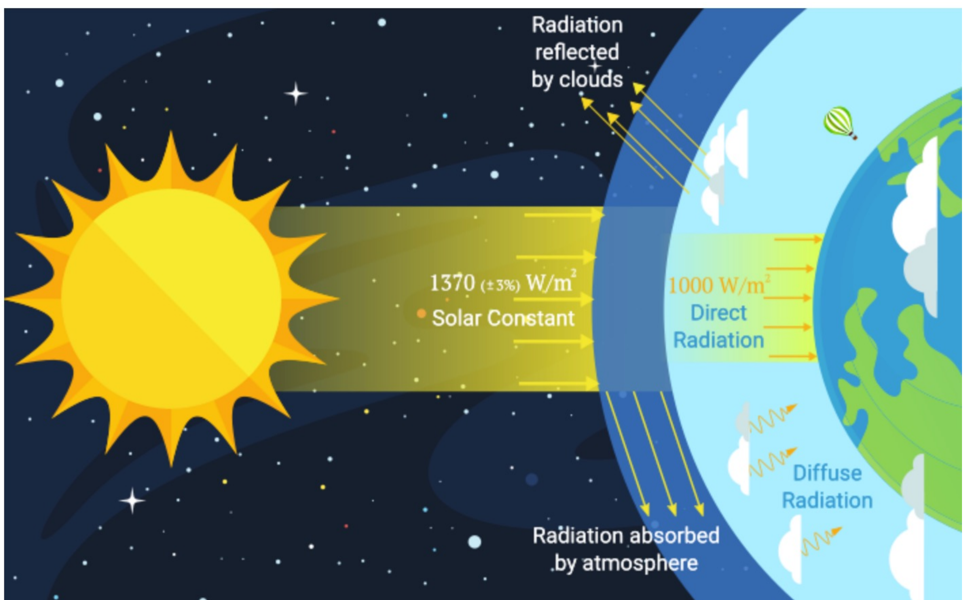


This entry point into the atmosphere is called “Air Mass – 0 (AM-0)”, where “0” means no air mass.

Source: www.greenrhinoenergy.com

Solar Irradiance (cont'd)

- Solar irradiance varies depending on a number of factors, including the time of day, season, and location.
- Atmospheric attenuation: Earth's atmosphere absorbs some of the sun's radiation, particularly in the ultraviolet and infrared portions.
- Clouds, smoke, and air pollution can all reduce the amount of solar irradiance that reaches the surface.
- The average solar irradiance on the Earth's surface is approximately 1kW/m². The solar irradiance at solar noon can be as high as 1.4 kW/m², while it can drop to as low as 0.2 kW/m² during sunrise and sunset.



Beam portion of the radiation reaching the Earth's surface:

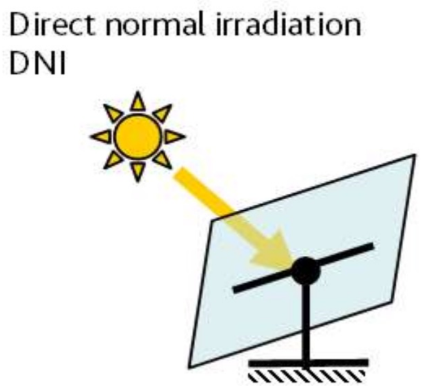
$$I_B = Ae^{-km}$$

Air mass ratio $\quad m = \dfrac{1}{\sin\beta}$

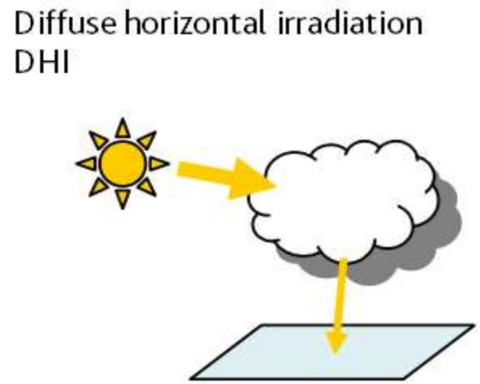
$$A = 1160 + 75\sin\left[\frac{360}{365}(n-275)\right] \qquad (\mathrm{W/m^2})$$

$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n-100)\right]$$

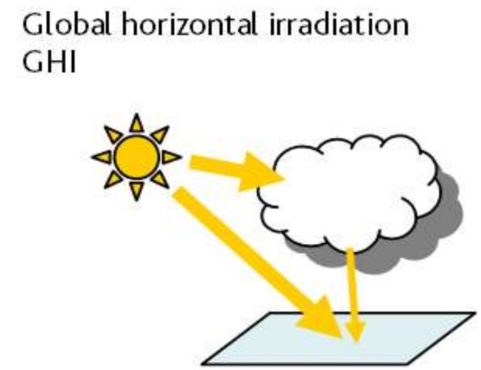
DNI, DHI and GHI



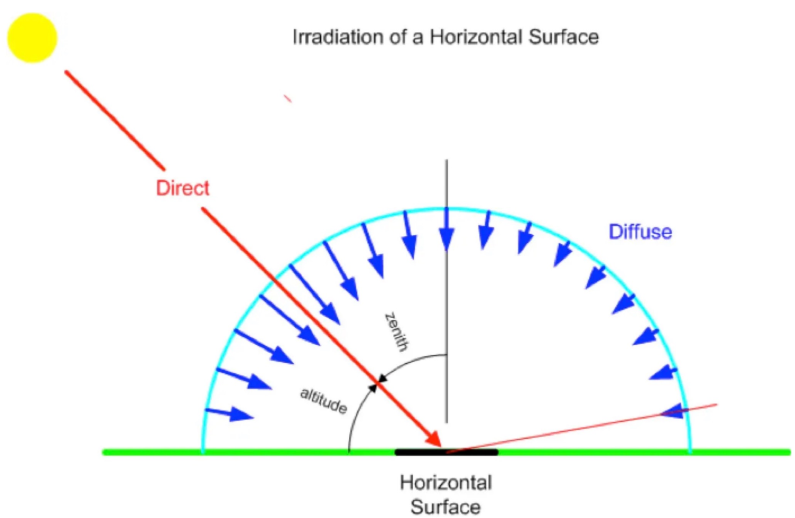
Direct Normal Irradiance (DNI): measured at a surface element perpendicular to the Sun



Diffuse Horizontal Irradiance (DHI): measured on a horizontal surface with radiation coming from all particles in the sky.



Global Horizontal Irradiance (GHI): the total irradiance on a horizontal surface



GHI is calculated as

$$GHI = DHI + DNI \times \cos(\theta_z)$$

θ_z : Solar zenith angle

Source: www.ecosmartsun.com/

Plane of Array (PoA) Irradiance

POA irradiance (aka Global Tilted Irradiance (GTI)): Quantify the incident irradiance on a given solar array. It is used extensively in PV modeling and performance analysis.

The bifacial POA can be calculated as follows, where the angle of incidence (AoI) is the angle between the sun's rays and the normal on PV panel.

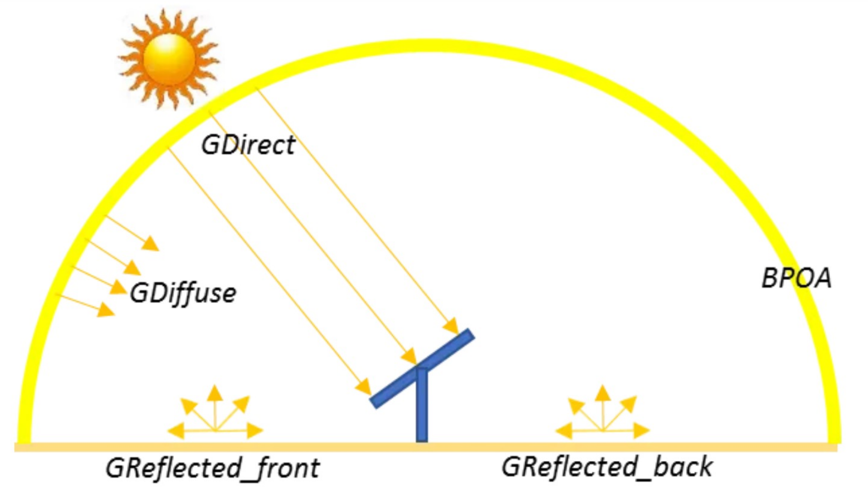


Figure 1. Modelling Irradiance, Including Albedo, on a Bifacial PV Module (Corbellini and Medici, 2015)

$$\mathrm{POA_b} = G_{\mathrm{direct}} + G_{\mathrm{diffuse}} + G_{\mathrm{reflected-front}} + G_{\mathrm{reflected-back}}$$

$$G_{\mathrm{direct}} = \mathrm{DNI} \times \cos(\mathrm{AoI})$$

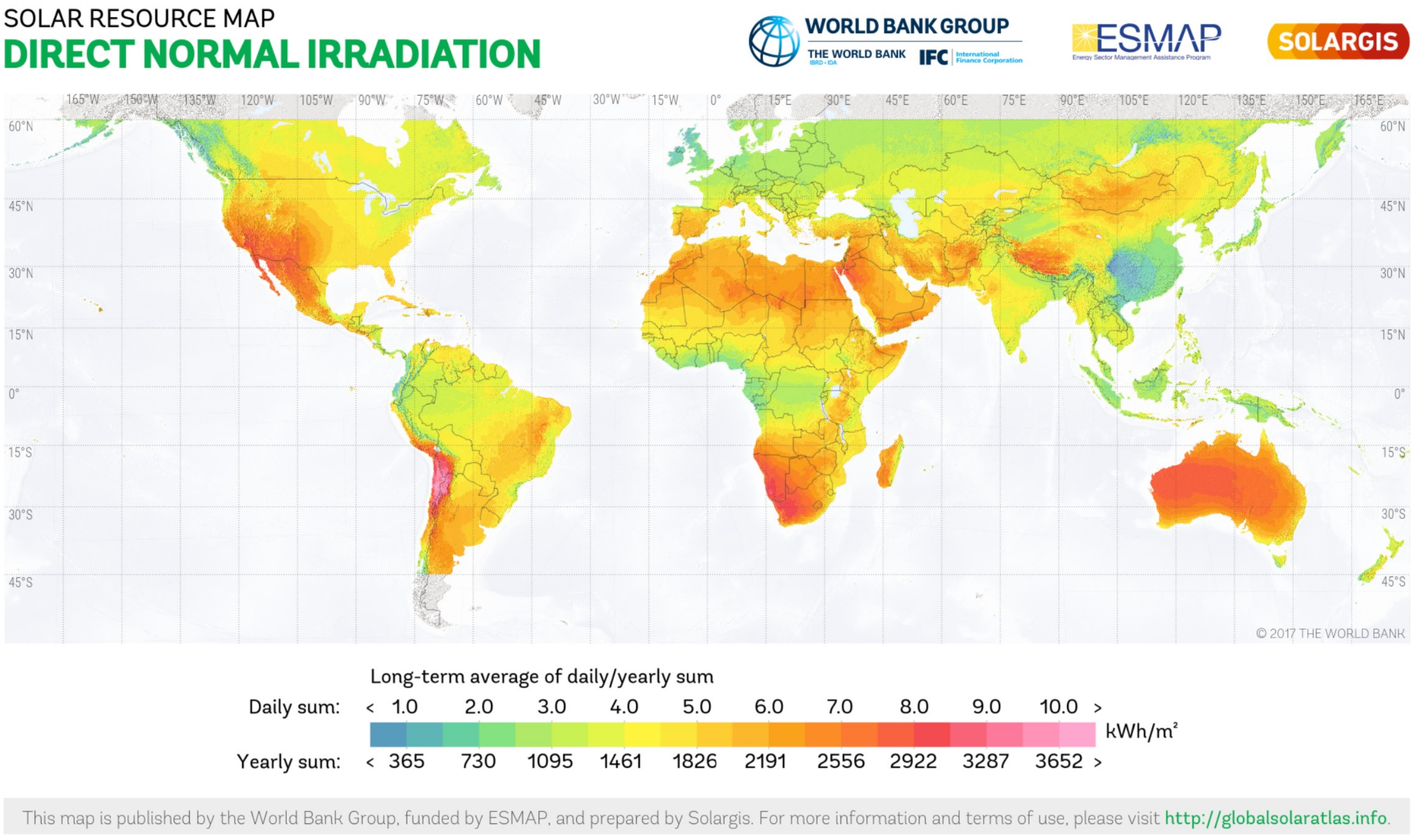
$$G_{\mathrm{diffuse}} = \mathrm{DHI} \times \frac{1 + \cos(\mathrm{tilt})}{2}$$

$$G_{\mathrm{reflected-front}} = \mathrm{GHI} \times \mathrm{Albedo} \times \frac{1 - \cos(\mathrm{tilt})}{2}$$

$$G_{\mathrm{reflected-back}} = \mathrm{GHI} \times \mathrm{Albedo} \times \frac{1 - \cos(\pi - \mathrm{tilt})}{2}$$

Source: campbellsci.cc

DNI


SOLAR RESOURCE MAP
DIRECT NORMAL IRRADIATION
WORLD BANK GROUP
THE WORLD BANK
IFC
ESMAP
SOLARGIS
165°W 150°W 135°W 120°W 105°W 90°W 75°W 60°W 45°W 30°W 15°W 0° 15°E 30°E 45°E 60°E 75°E 90°E 105°E 120°E 135°E 150°E 165°E
60°N
45°N
30°N
15°N
0°
15°S
30°S
45°S
© 2017 THE WORLD BANK
Long-term average of daily/yearly sum
Daily sum: < 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 >
kWh/m²
Yearly sum: < 365 730 1095 1461 1826 2191 2556 2922 3287 3652 >
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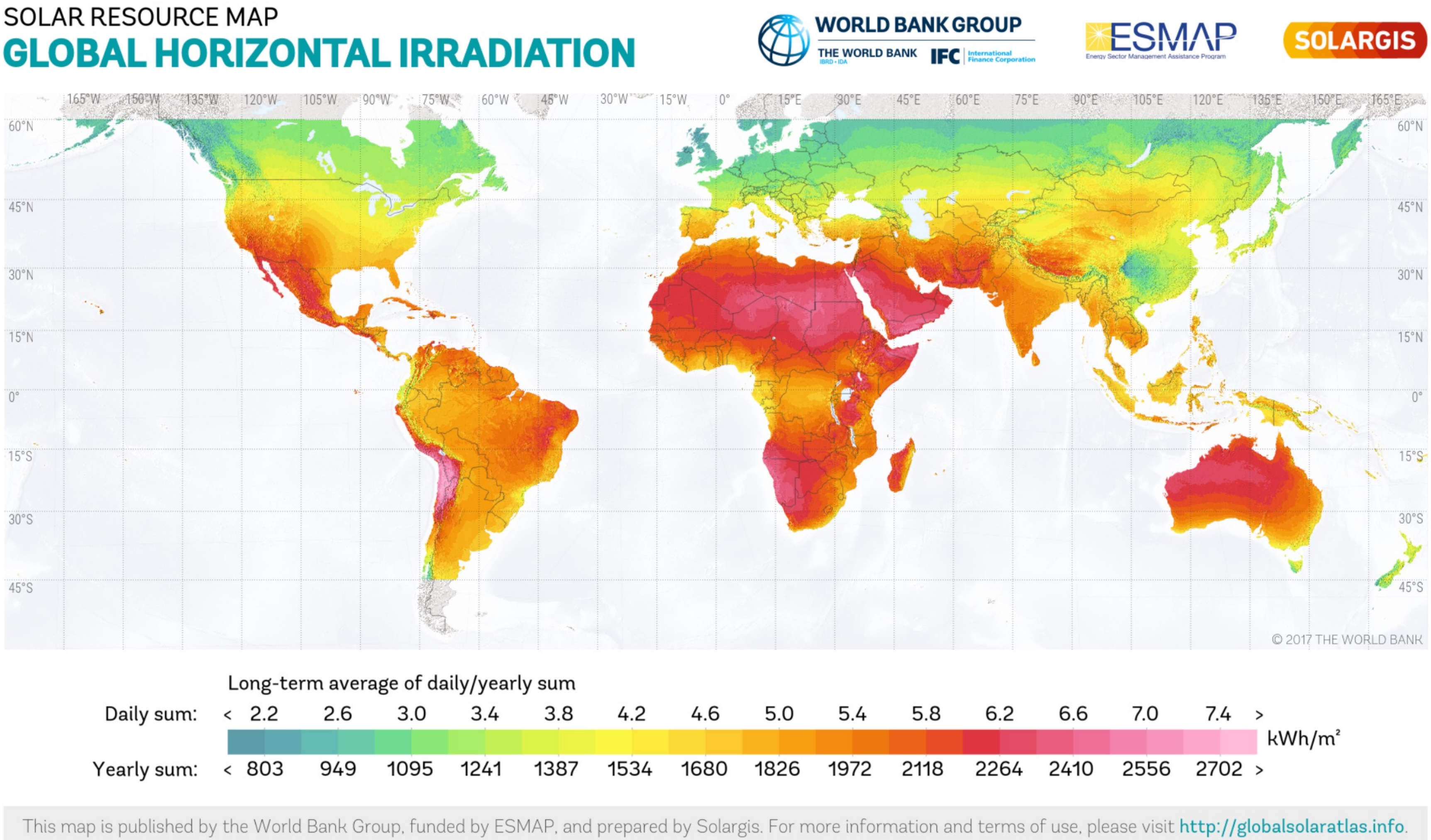
GHI


SOLAR RESOURCE MAP
GLOBAL HORIZONTAL IRRADIATION
WORLD BANK GROUP
THE WORLD BANK
IFC International Finance Corporation
ESMAP
SOLARGIS
© 2017 THE WORLD BANK
Long-term average of daily/yearly sum
Daily sum: < 2.2 2.6 3.0 3.4 3.8 4.2 4.6 5.0 5.4 5.8 6.2 6.6 7.0 7.4 >
kWh/m²
Yearly sum: < 803 949 1095 1241 1387 1534 1680 1826 1972 2118 2264 2410 2556 2702 >
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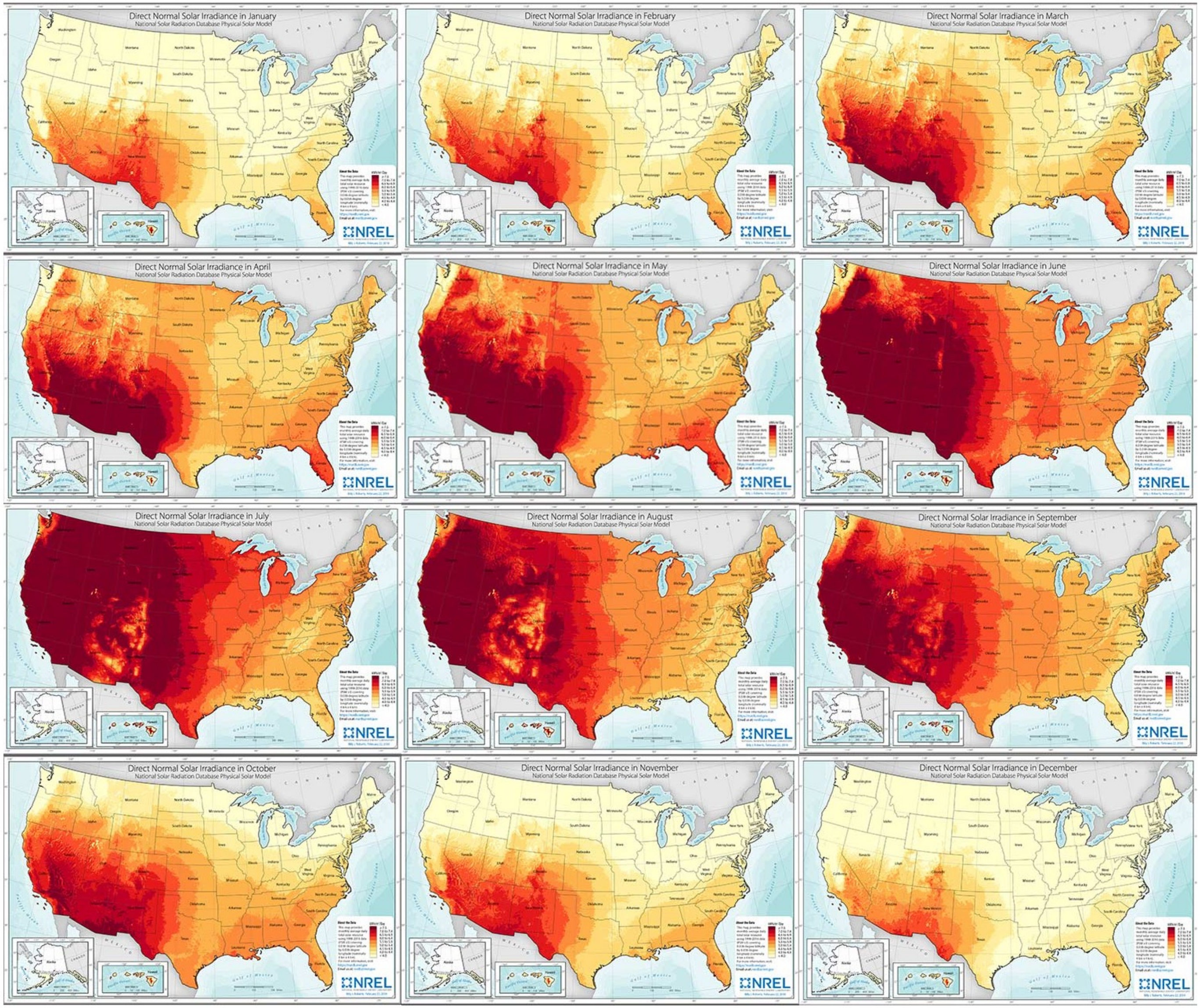
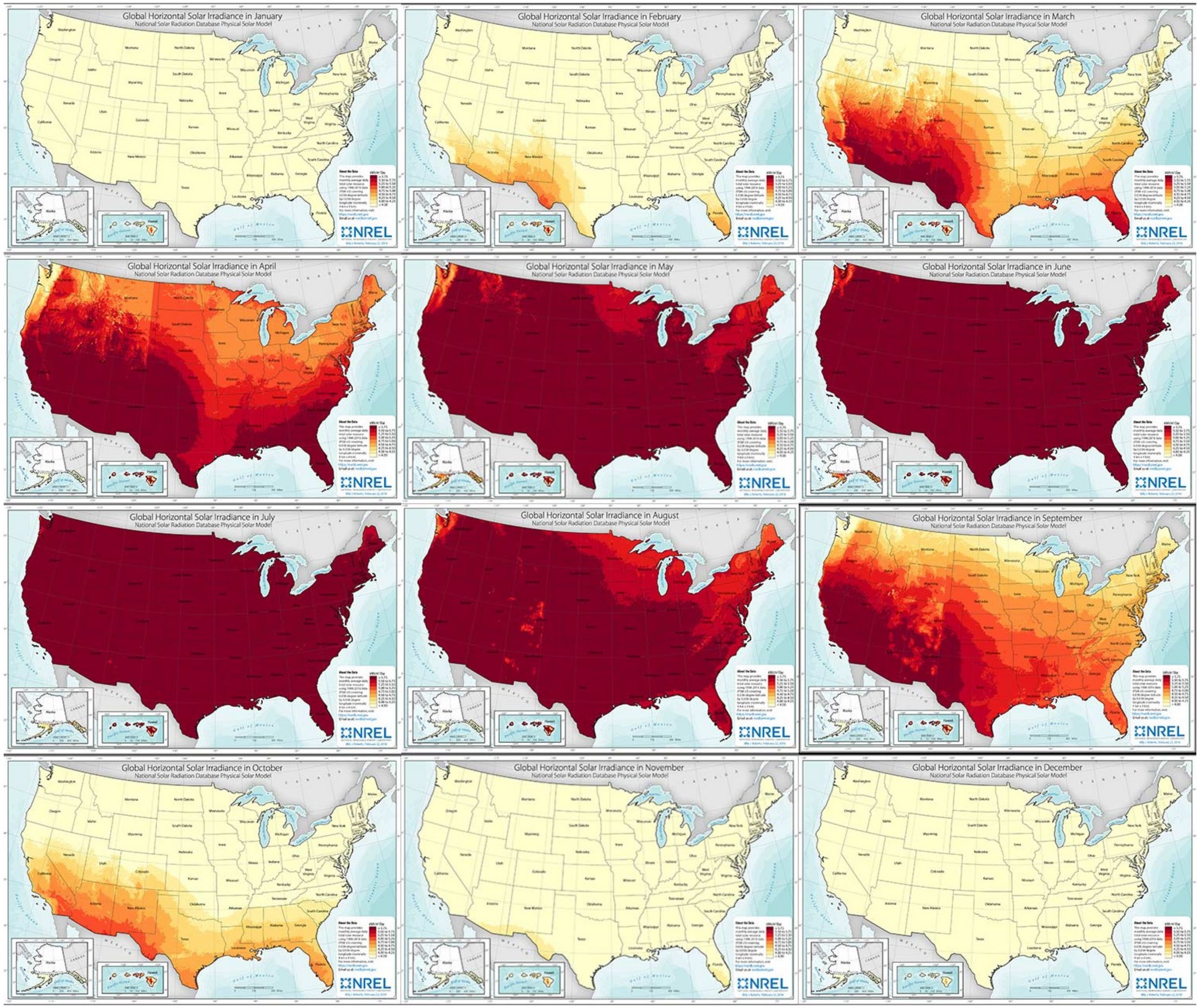
U.S. Monthly Averages of DNI



https://www.nrel.gov/gis/solar.html

U.S. Monthly Averages of GHI



https://www.nrel.gov/gis/solar.html