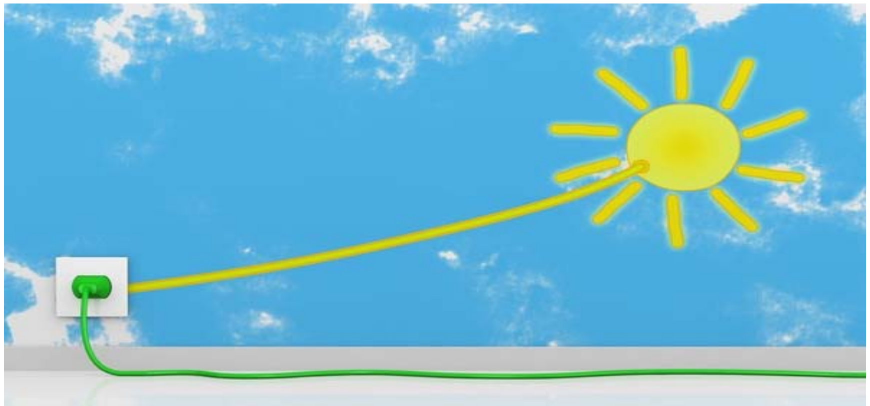
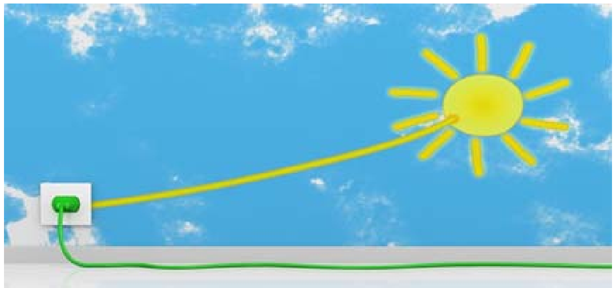
Chapter 7. Solar Resource

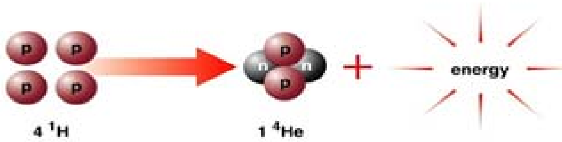


Solar Resource

- What do we have to know to design a solar system?
  - How much ( ) is available?
  - Where is the sun in the sky at any ( ) of the day?
  - Solar intensity ("( )" = Incident Solar Radiation)
  - ( ) Daily Insolation
  - Insolation on ( ) surfaces



Solar Spectrum

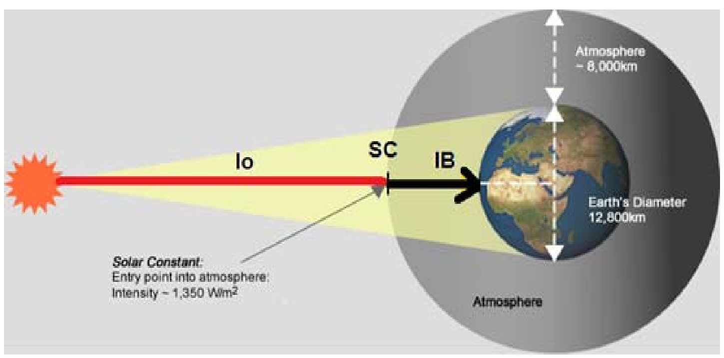


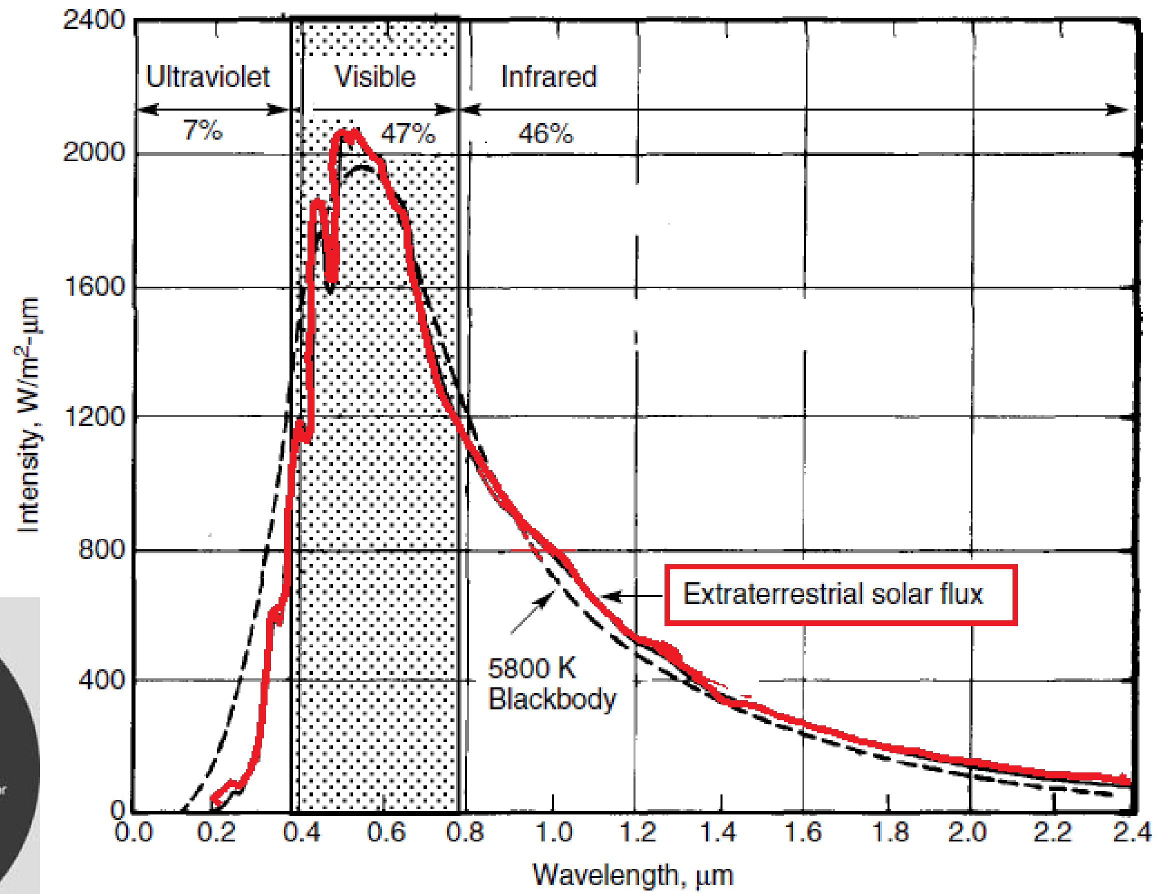
- Sun
  - 1.4 million kilometer diameter

    $4\ {}^{1}H + 2\ e \dashrightarrow {}^{4}He + 2$ neutrinos $+ 6$ photons
  - Thermonuclear furnace fusing hydrogen atoms into helium
  - 3.8×10^{20} MW electromagnetic energy radiation into space
  - Solar Spectrum (scaled to have the total area under the curve is 1.37 kW/m^2, which is the solar insolation just outside the earth's atmosphere: > 8000 km)
    - UV (   ) %
    - Visible Light (   ) %
      - (wavelength: 0.38 um (violet) – 0.78 um (Red))
    - IR (   ) %

Solar Spectrum

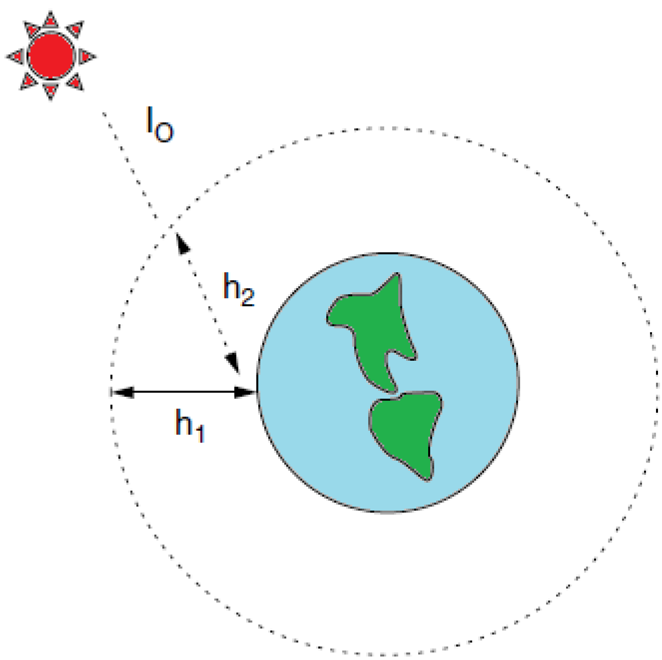
- Extraterrestrial Solar Spectrum (scaled to have the total area under the curve is 1.37 kW/m^2, which is the solar insolation just outside the earth's atmosphere)

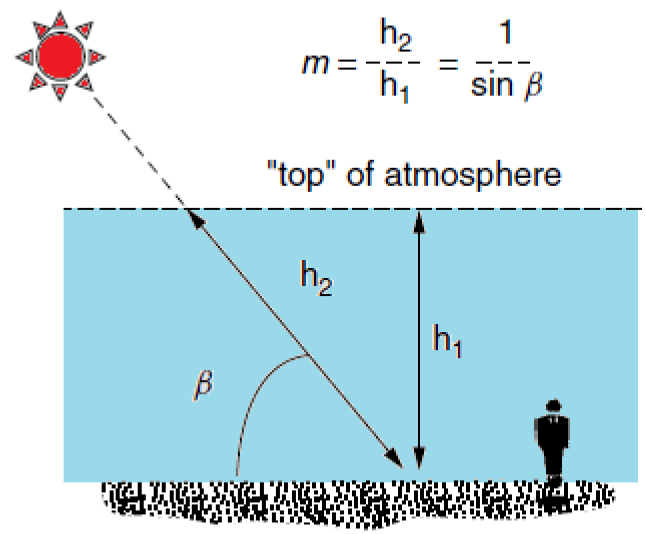




Solar Spectrum

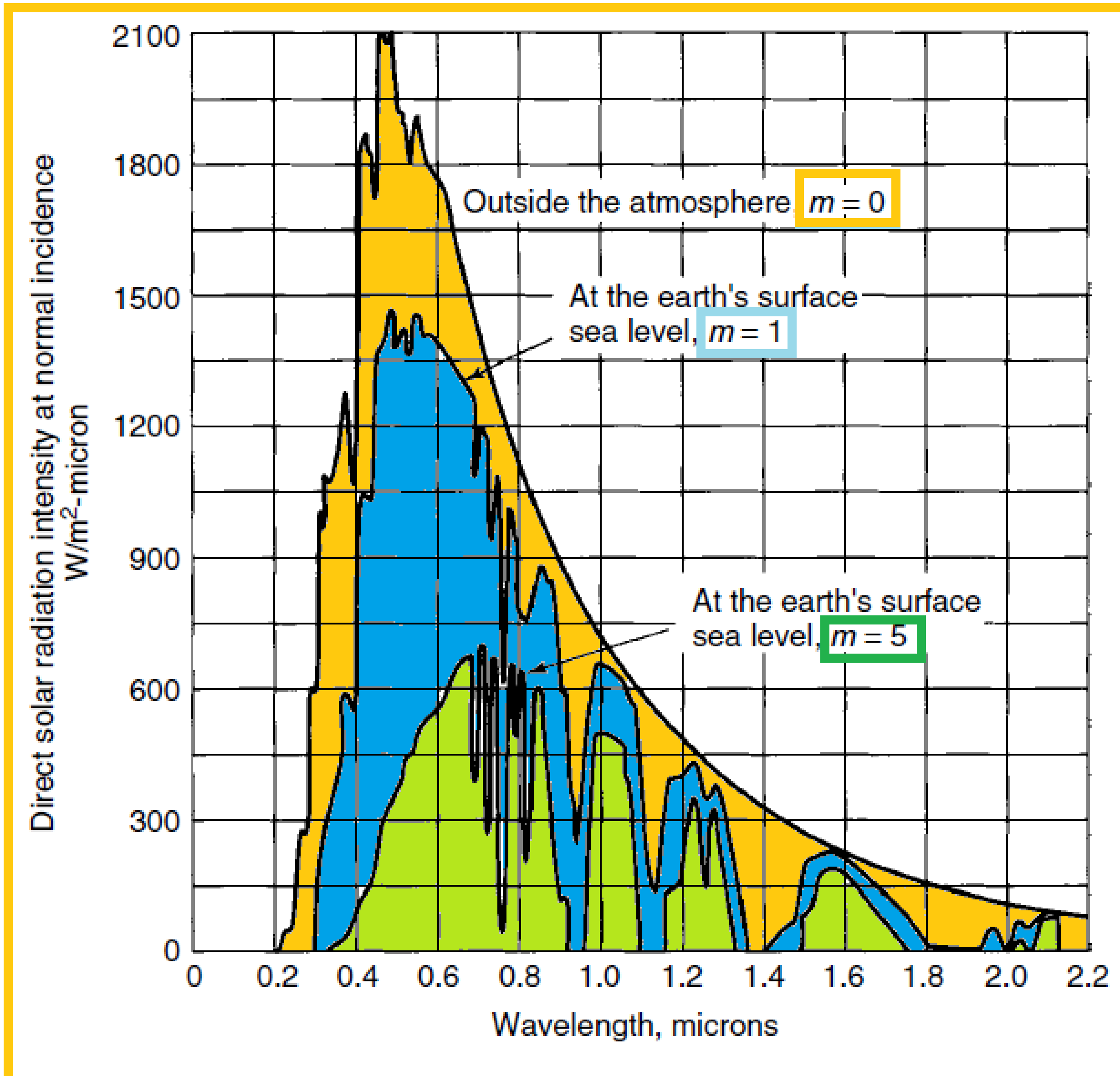
- Extraterrestrial Solar radiation is absorbed in the atmosphere
- Length of path of sun's rays has to be considered
  - h2: actual path length
  - h1: minimum possible length (when sun is directly overhead)
  - Air Mass Ratio (**m**) & Sun's Altitude Angle (β)





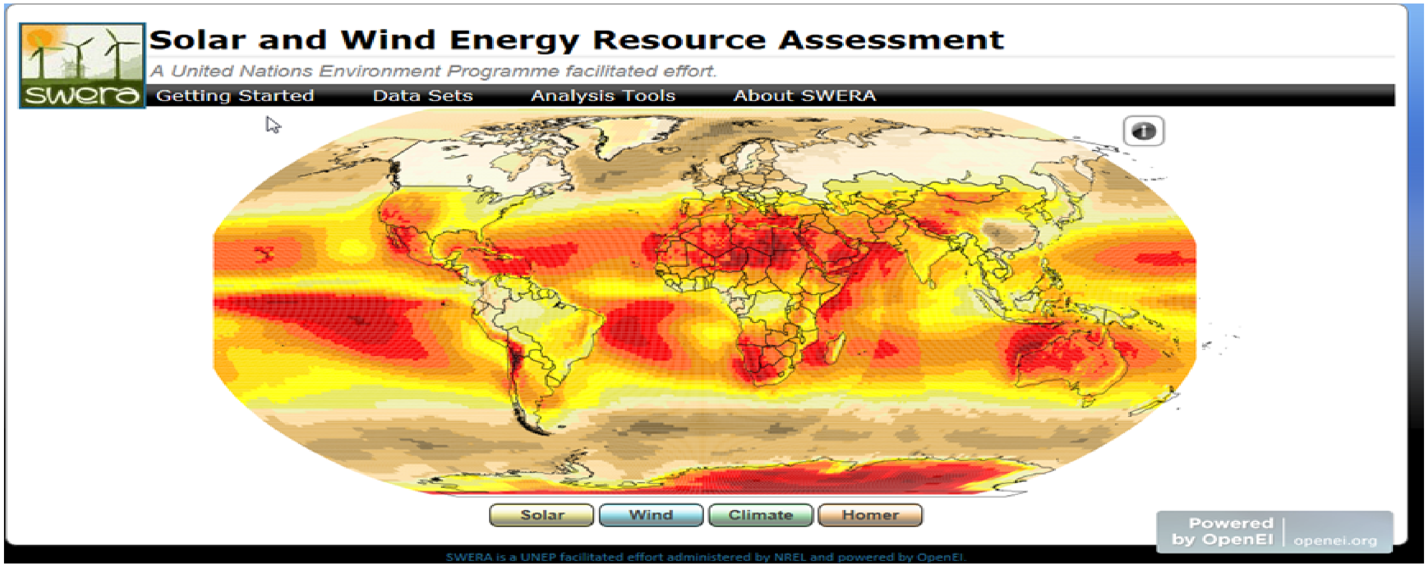
Solar Spectrum

- AM0: (Outside the atmosphere) Extraterrestrial solar spectrum
- AM1: Air mass ratio of 1 --- Sun is directly overhead
- AM1.5: Average solar spectrum at the earth's surface
  - UV 2%, Visible 54%, IR 44%
  - Spectrum shifts some toward longer wavelength
  - **What angle?**



Solar Energy Resources

- SWERA(Solar and Wind Energy Resource Assessment)
- https://openei.org/wiki/Solar_and_Wind_Energy_Resource_Assessment_(SWERA)
- http://maps.nrel.gov/re-atlas



- SWERA

The Earth's Orbit

- Earth revolves around the sun in an elliptical orbit
- One revolution per very 365.25 days
- Nearest point to Sun ("Perihelion"): 147 million km on (   ) 2
- Farthest point from Sun ("Aphelion"): 152 million km on (   ) 3
- Distance between Sun and Earth on a given day
  - n: day number (1: Jan 1, 365: Dec 31)
  - Angle in **degrees**

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

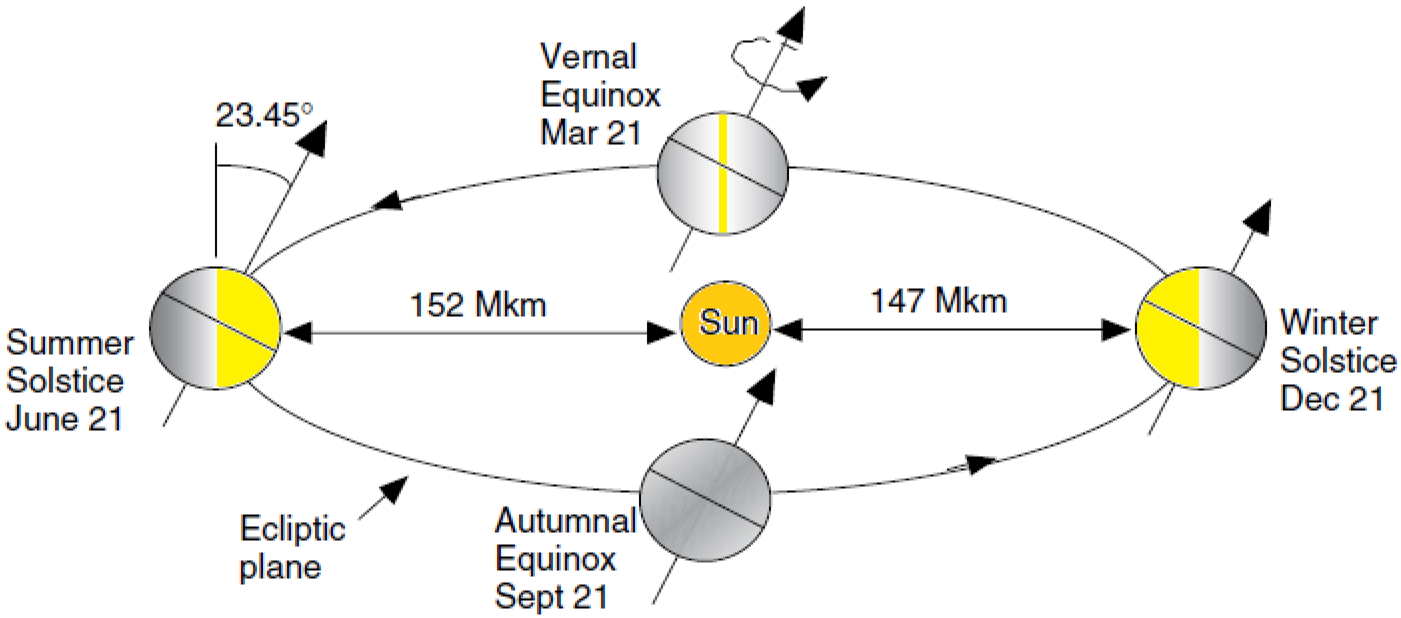
d for Apr 15?

Day Numbers for the First Day of Each Month

January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
March	$n = 60$	September	$n = 244$
April	$n = 91$	October	$n = 274$
May	$n = 121$	November	$n = 305$
June	$n = 152$	December	$n = 335$

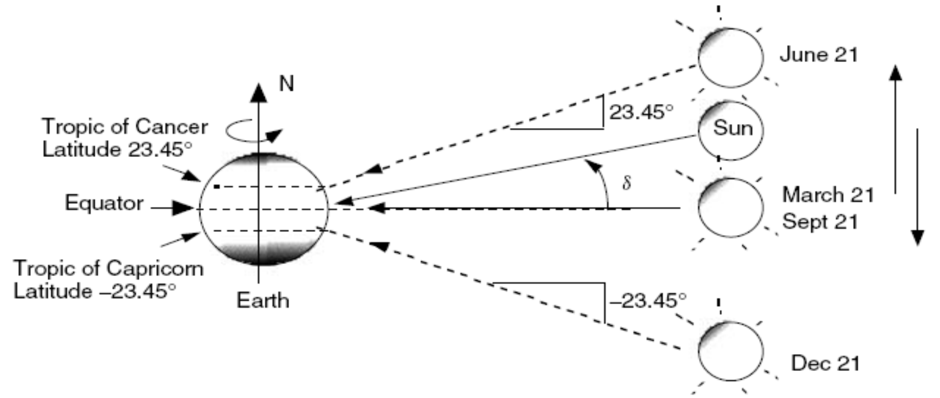
The Earth's Orbit

- Earth's Spin Axis: 23.45 degrees
- Equinox (Equal day and night): 12 hours each for March 21 and September 21
- Winter Solstice: December 21 – axis angle ("Inclination" of North Pole) is highest away from the sun
- Summer Solstice: June 21 – Inclination is closest to the sun.



Solar Declination

- Solar angles as seen from the surface of the earth → Ancient perspective: *Fixed Earth and Sun Moving Up and Down View*
- Solar declination: **"angle between the sun's rays and the earth's <u>equatorial plane</u>, the latitude at which the sun is directly overhead at <u>midday</u>.** Declination values are positive when the sun is north of the equator (March 21 to September 23) and negative when the sun is south of the equator. Maximum and minimum values are +0.409 radians (+23.45 degrees) and -0.409 radians (-23.45 degrees)."



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

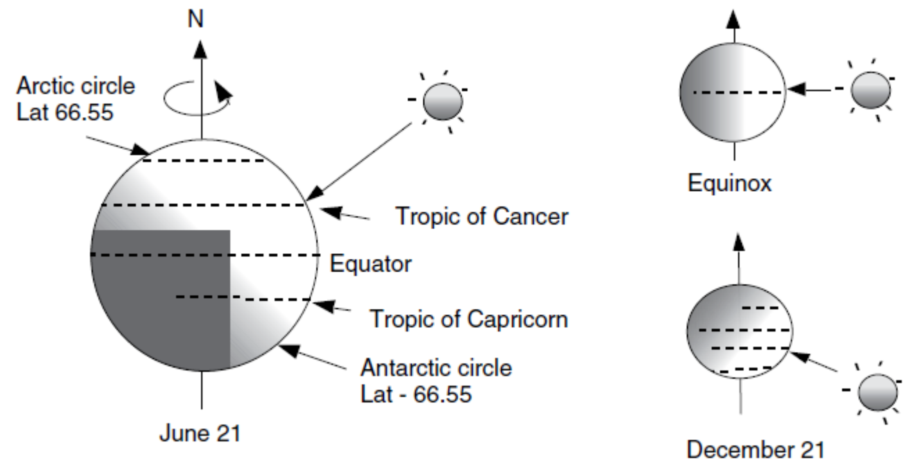
$$\delta = \sin^{-1}\left\{\sin(23.45°)\sin\left[\frac{360}{365}(n-81)\right]\right\}$$

Solar Declination δ for the 21st Day of Each Month (degrees)

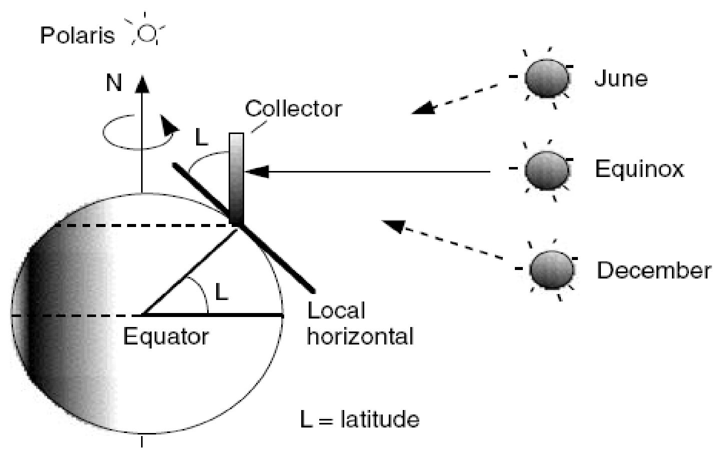
Month:	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
δ:	−20.1	−11.2	0.0	11.6	20.1	23.4	20.4	11.8	0.0	−11.8	−20.4	−23.4

Solar Declination

- "Solar Noon": Sun is directly over the local meridian (longitude)



- A good rule of thumb of solar panel for the best annual performance
  - Face it **south**
  - **Tilt it up at an angle equal to the local latitude**



Altitude Angle of the Sun and Solar Declination

β_N altitude angle of the sun

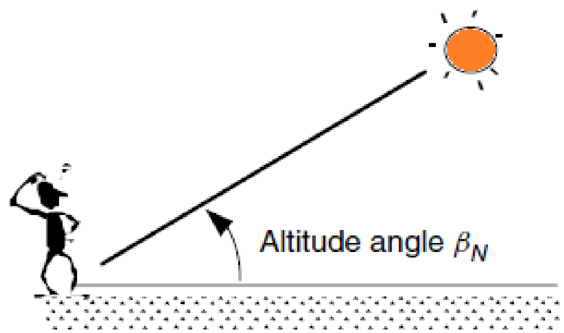
δ solar declination

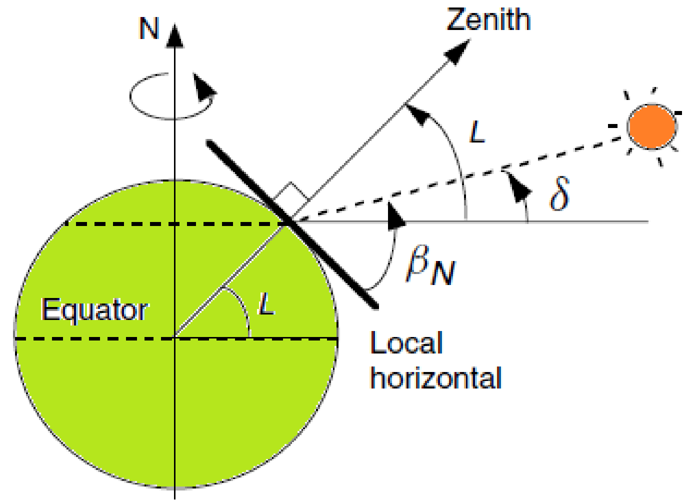
L latitude of the site

$$\beta_N = 90^\circ - L + \delta$$

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

$$\delta = \sin^{-1}\left\{\sin(23.45^\circ)\sin\left[\frac{360}{365}(n-81)\right]\right\}$$





Example

- Find the optimum tilt angle for a south-facing PV module in Tucson (latitude 32.1°) at solar noon on March 1.

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

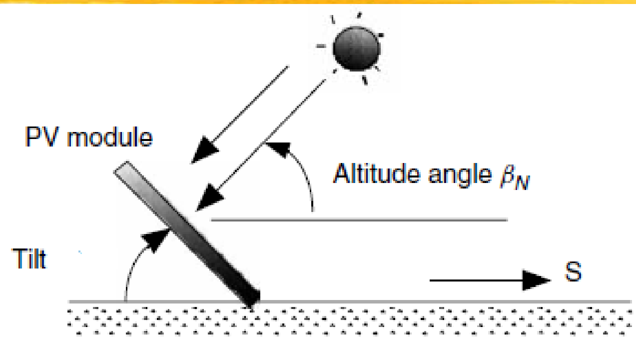
$$\delta = \sin^{-1}\left\{\sin(23.45°)\sin\left[\frac{360}{365}(n-81)\right]\right\}$$

β_N altitude angle of the sun

δ solar declination

L latitude of the site

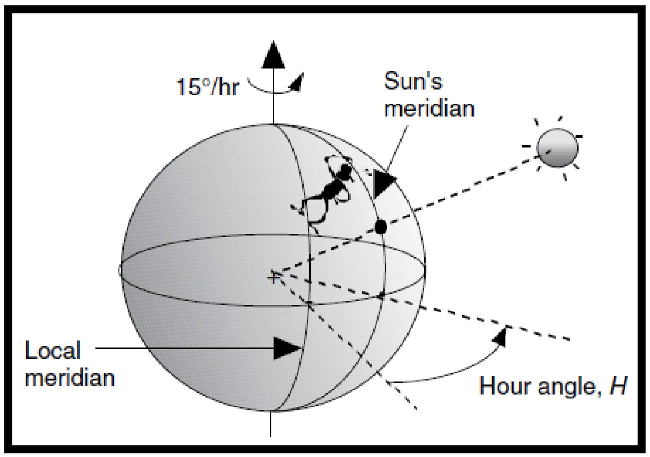
$$\beta_N = 90° - L + \delta$$

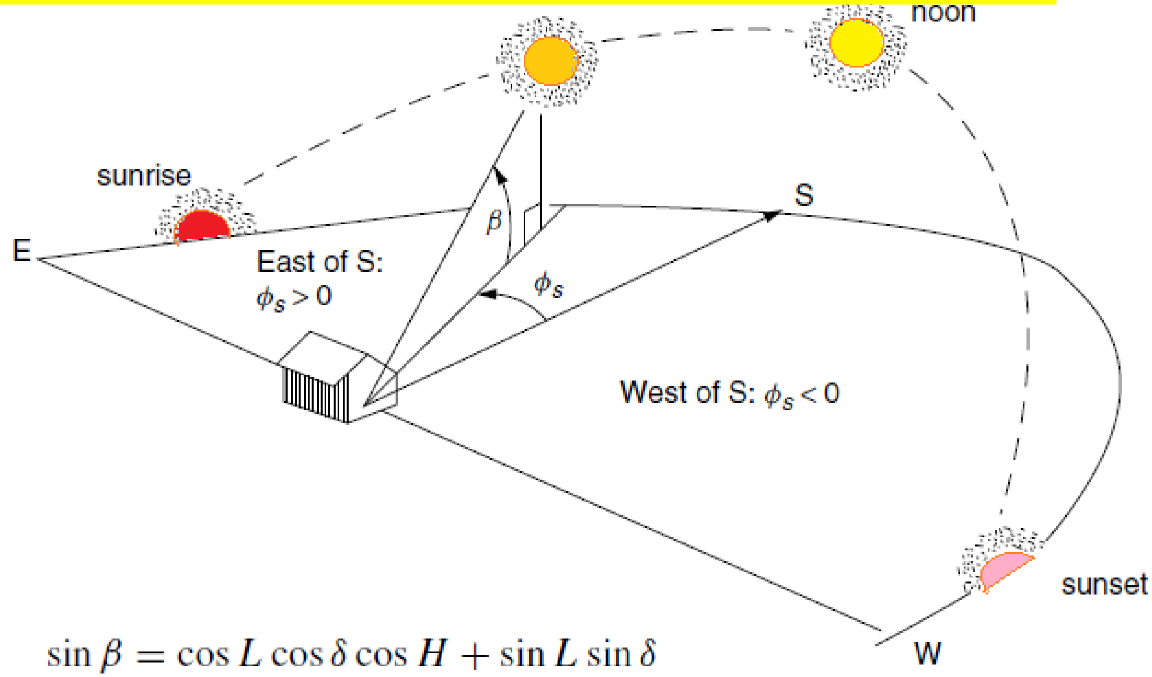


Solar Position at Any Time of Day (Reference: True South)

β	Altitude Angle
ϕ	Azimuth Angle
H	Hour Angle

- H = 15° at 11:00am
- H = - 30° at 2:00pm





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

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

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

$$\text{if} \quad \cos H \geq \frac{\tan\delta}{\tan L}, \quad \text{then } |\phi_S| \leq 90^\circ; \quad \text{otherwise } |\phi_S| > 90^\circ$$

Solar Position at Any Time of Day: Example

⌘ Question: Find the altitude angle (β) and azimuth angle(ϕ) for the sun at 3:00PM in Boulder, CO (Lat = 40°) on the summer solstice.

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

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

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

$$\text{if} \quad \cos H \geq \frac{\tan\delta}{\tan L}, \qquad \text{then } |\phi_S| \leq 90^\circ;$$

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

$$\delta = \sin^{-1}\left\{\sin(23.45^\circ)\sin\left[\frac{360}{365}(n-81)\right]\right\}$$

Solar Position at Any Time of Day: SOLUTION

- Question: Find the altitude angle (β) and azimuth angle(ϕ) for the sun at 3:00PM in Boulder, CO (Lat = 40°) on the summer solstice.
- **Answer:**

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

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

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

$$\text{if} \quad \cos H \geq \frac{\tan\delta}{\tan L}, \qquad \text{then } |\phi_S| \leq 90^\circ;$$

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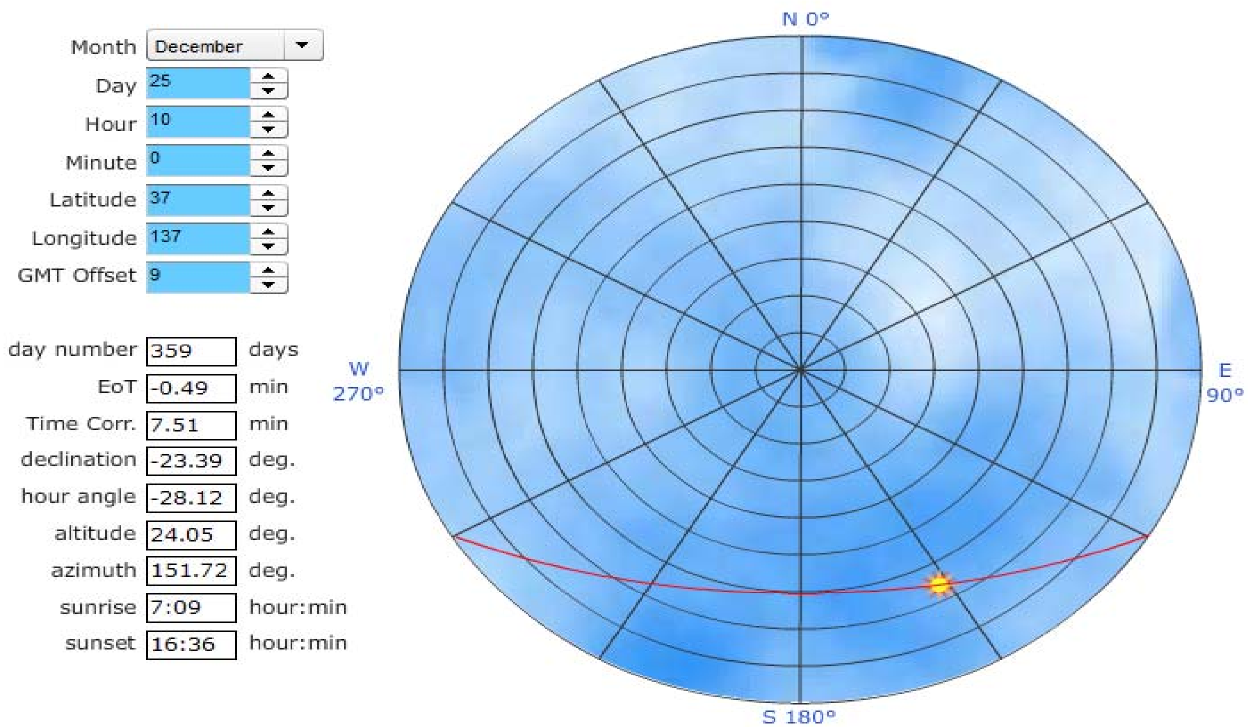
$$\delta = 23.45^\circ \sin\left[\frac{360}{365}(n-81)\right]$$

$$\delta = \sin^{-1}\left\{\sin(23.45^\circ)\sin\left[\frac{360}{365}(n-81)\right]\right\}$$

Sun Position Calculator

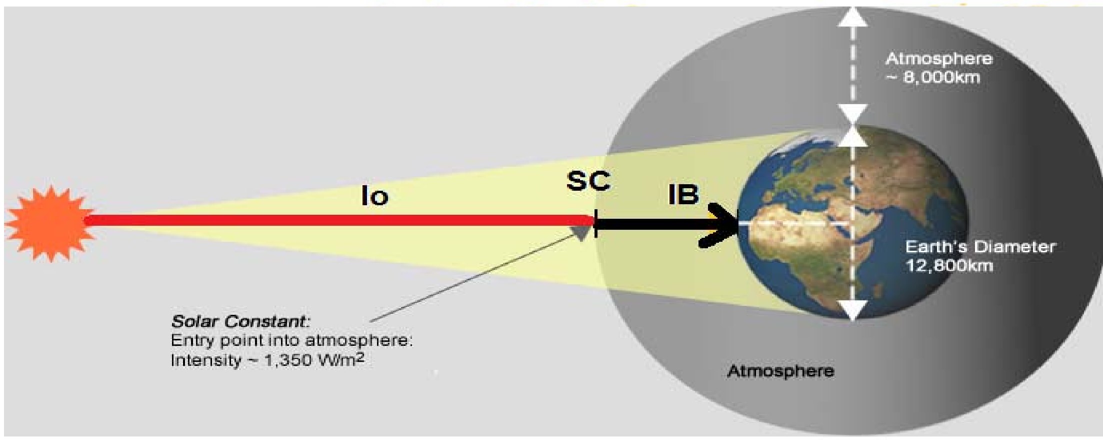
PV EDUCATION.ORG
PV CDROM
Christiana Honsberg
and Stuart Bowden

- Sample Example
- Weblink: http://pveducation.org/pvcdrom/properties-of-sunlight/sun-position-calculator



Solar Radiation in Space and on Earth Surface

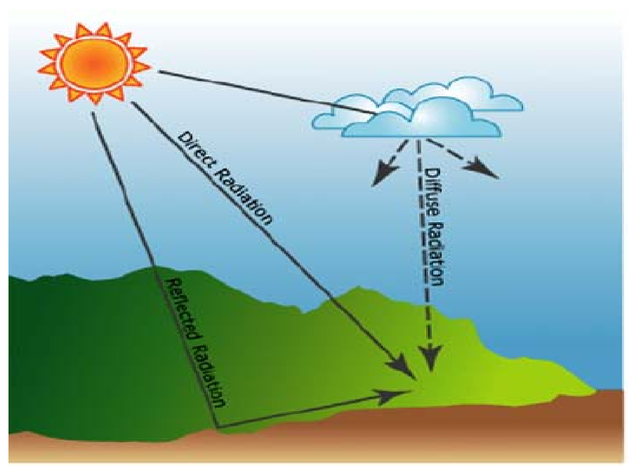
- Space



- Units:
  - ✓ kWh per square meter (preferred)
  - ✓ British Thermal Units
  - ✓ Kilocalories
  - ✓ Langleys

1 kW/m^2	=	316.95 $Btu/h\text{-}ft^2$
	=	1.433 langley/min
1 kWh/m^2	=	316.95 Btu/ft^2
	=	85.98 langleys
	=	3.60×10^6 $joules/m^2$
	=	1 cal/cm^2
	=	41.856 $kjoules/m^2$
	=	0.01163 kWh/m^2
	=	3.6878 Btu/ft^2

- Earth Surface - 3 components:
  - Direct Beam Radiation: I_B
  - Diffuse Radiation: I_D
  - Reflected Radiation: I_R



Source: esri.com

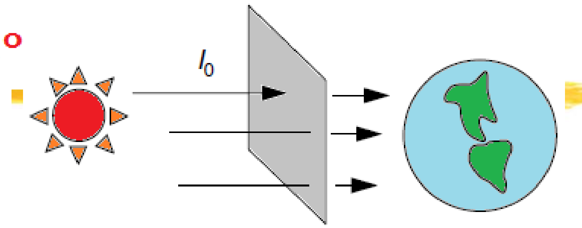
Clear Sky Beam Radiation

- Extraterrestrial Solar Insolation (I_o)

$$I_0 = \mathrm{SC} \cdot \left[1 + 0.034 \cos\left(\frac{360n}{365}\right)\right]$$

degree°

(W/m²)



  - *SC*: Solar constant $1.377\ \mathrm{kW/m^2}$
  - *n*: day number

- Portion of the beam reaching the earth surface ("horizontal surface") (I_B)

January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
March	$n = 60$	September	$n = 244$
April	$n = 91$	October	$n = 274$
May	$n = 121$	November	$n = 305$
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$$I_B = Ae^{-km}$$

  - A: Apparent extraterrestrial flux

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

  - *k* : optical depth $\quad k = 0.174 + 0.035 \sin\left[\frac{360}{365}(n - 100)\right]$
  - *m*: air mass ratio
  - *β*: altitude angle of the sun $\quad m = \dfrac{1}{\sin\beta}$

Clear Sky Beam Radiation

- A: Apparent extraterrestrial flux
- *k* : optical depth
- *m*: air mass ratio
- *β*: altitude angle of the sun

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$$m = \frac{1}{\sin\beta}$$

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Optical Depth *k*, Apparent Extraterrestrial Flux *A*, and the Sky Diffuse Factor *C* for the 21st Day of Each Month

Month:	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
A (W/m^2):	1230	1215	1186	1136	1104	1088	1085	1107	1151	1192	1221	1233
k:	0.142	0.144	0.156	0.180	0.196	0.205	0.207	0.201	0.177	0.160	0.149	0.142
C:	0.058	0.060	0.071	0.097	0.121	0.134	0.136	0.122	0.092	0.073	0.063	0.057

Source: ASHRAE (1993).

Clear Sky Beam Radiation – Example

- Question: Find the direct beam solar radiation normal to the sun's rays ("horizontal surface") at solar noon on a clear day on Howard University campus (latitude ???? degrees) on May 21.

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

$$\delta = \sin^{-1}\left\{\sin(23.45^\circ)\sin\left[\frac{360}{365}(n-81)\right]\right\}$$

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

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

January	$n = 1$	July	$n = 182$
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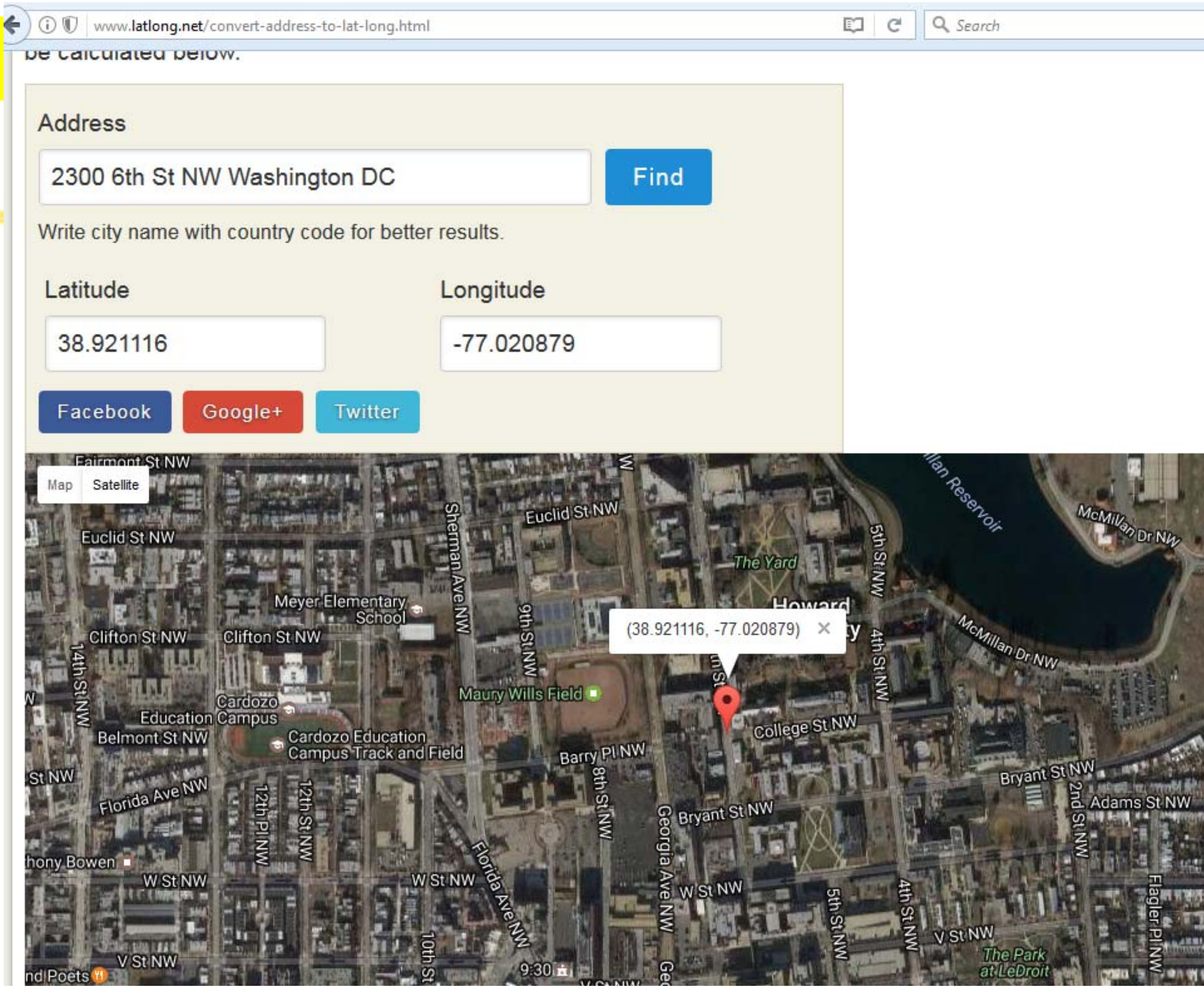
$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n-100)\right]$$

altitude angle of the sun at solar noon.

$$\beta_N = 90^\circ - L + \delta$$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Search
be calculated below.
Address
2300 6th St NW Washington DC
Find
Write city name with country code for better results.
Latitude
38.921116
Longitude
-77.020879
Facebook
Google+
Twitter
Map
Satellite
(38.921116, -77.020879)
Fairmont St NW
Euclid St NW
Clifton St NW
Meyer Elementary School
Sherman Ave NW
9th St NW
The Yard
Howard
McMillan Dr NW
Maury Wills Field
Cardozo Education Campus
Cardozo Education Campus Track and Field
Belmont St NW
College St NW
Barry Pl NW
Florida Ave NW
Bryant St NW
Adams St NW
Georgia Ave NW
W St NW
V St NW
The Park at LeDroit
Flagler Pl NW

Clear Sky Beam Radiation – Example

- Question: Find the direct beam solar radiation normal to the sun's rays ("horizontal surface") at solar noon on a clear day on Howard University campus (latitude 38.92116 degrees) on May 21.

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

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

$$\delta = \sin^{-1}\left\{\sin(23.45°)\sin\left[\frac{360}{365}(n - 81)\right]\right\}$$

January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
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Air mass ratio $m = \dfrac{1}{\sin\beta}$

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

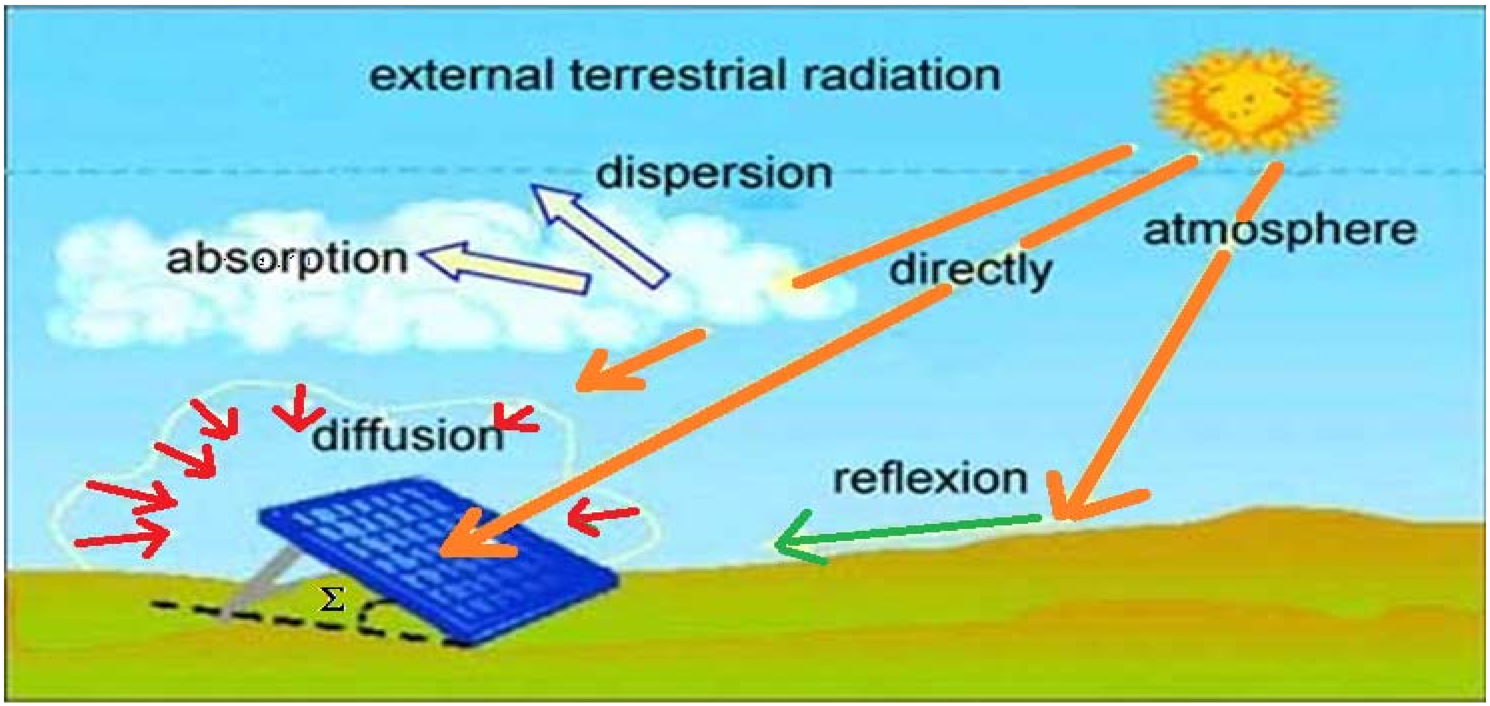
$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n - 100)\right]$$

altitude angle of the sun at solar noon.

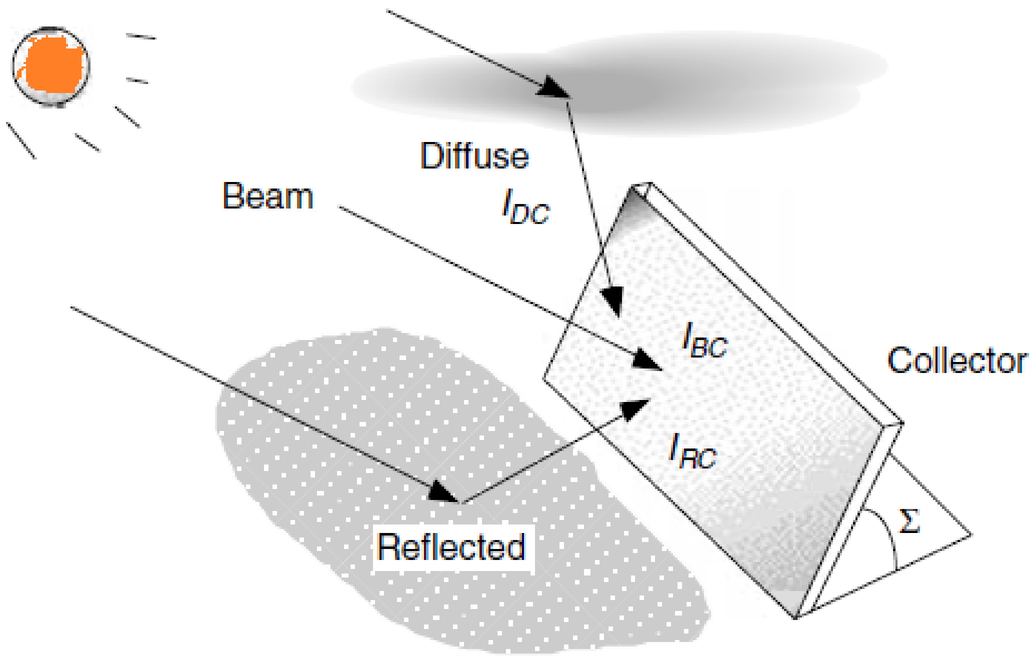
$$\beta_N = 90° - L + \delta$$

Radiation on collector

- **C**ollector Surface:
  - Beam radiation: I_{BC}
  - Diffuse radiation: I_{DC}
  - Reflected radiation: I_{RC}



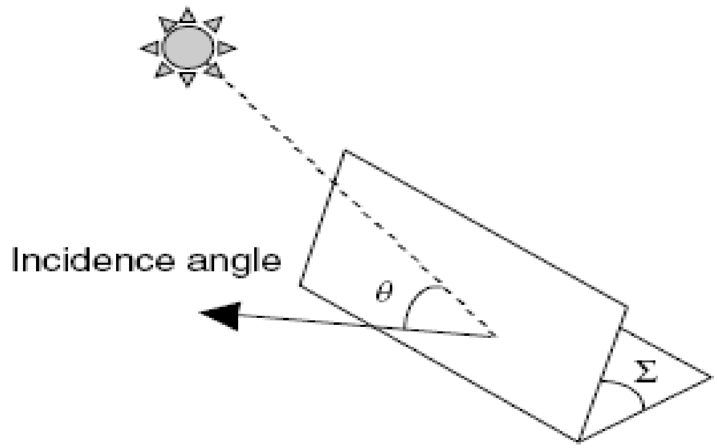
Total Clear Sky Insolation on **Collector Surface**



Beam Radiation on **Collector – Simple Case**

incidence angle θ

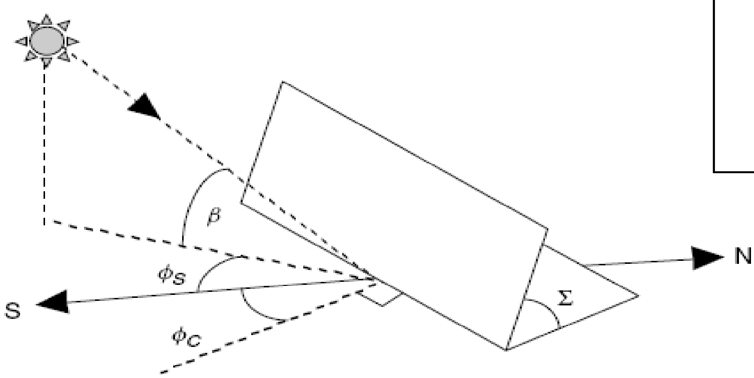
tilt angle Σ

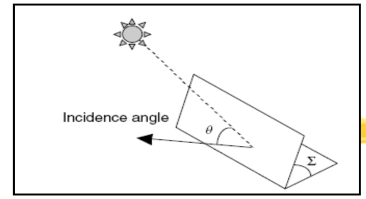


$$I_{BC} = I_B \cos\theta$$

Beam Radiation on **Collector - Complicated**

incidence angle θ
collector azimuth angle ϕ_C
altitude angle β
solar azimuth angle ϕ_S
tilt angle Σ





- Solar altitude: β
- Normal to vertical surface: ϕ_c

$$I_{BC} = I_B \cos\theta$$

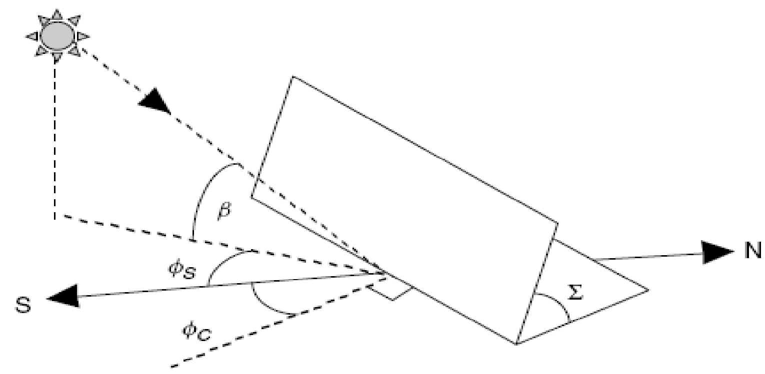
$$\cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma$$

beam insolation on a horizontal surface I_{BH}

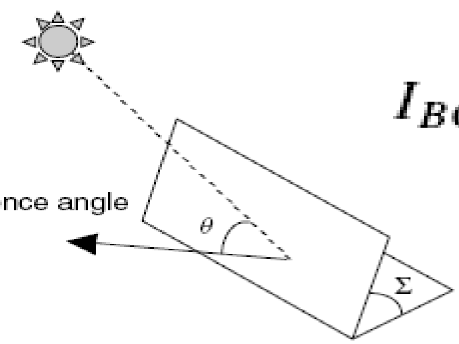
$$I_{BH} = I_B\cos(90^\circ - \beta) = I_B\sin\beta$$

Beam Radiation on **Collector - Example**

- Question: At solar noon in Atlanta (latitude 33.7) on May 21, the altitude angle of the sun was found to be 76.4 degrees and the clear-sky beam insolation was found to be 902 W/m^2. Find the beam insolation at that time on a collector that faces 20 degrees toward the southeast with tipped angle at 52 degrees.



$$\cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma$$

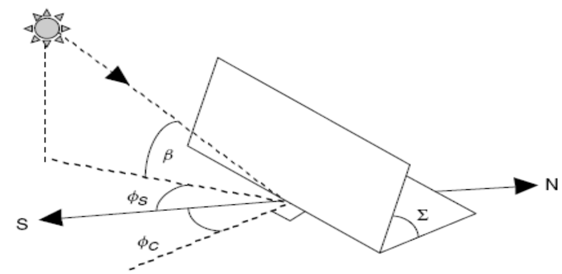


$$I_{BC} = I_B \cos\theta$$

incidence angle θ
collector azimuth angle ϕ_C
altitude angle β
solar azimuth angle ϕ_S
tilt angle Σ

Beam Radiation on **Collector - Example**

- Question: At solar noon in Atlanta (latitude 33.7) on May 21, the altitude angle of the sun was found to be 76.4 degrees and the clear-sky beam insolation was found to be 902 W/m^2. Find the beam insolation at that time on a collector that faces 20 degrees toward the southeast with tipped angle at 52 degrees.



$$\cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma$$

$$I_{BC} = I_B \cos\theta$$

Diffuse Radiation on Collector

- Sky diffuse factor (C)

$$C = 0.095 + 0.04 \sin\left[\frac{360}{365}(n - 100)\right]$$

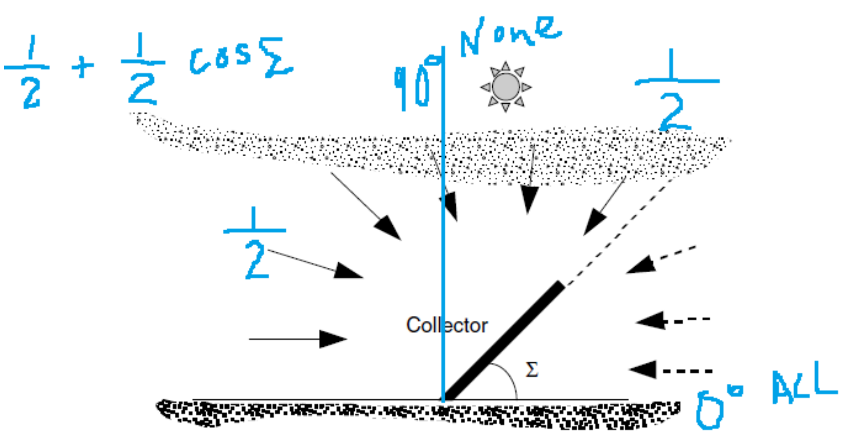
January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
March	$n = 60$	September	$n = 244$
April	$n = 91$	October	$n = 274$
May	$n = 121$	November	$n = 305$
June	$n = 152$	December	$n = 335$

- n: day number
- Diffuse insolation on a Horizontal surface is proportional to the direct radiation

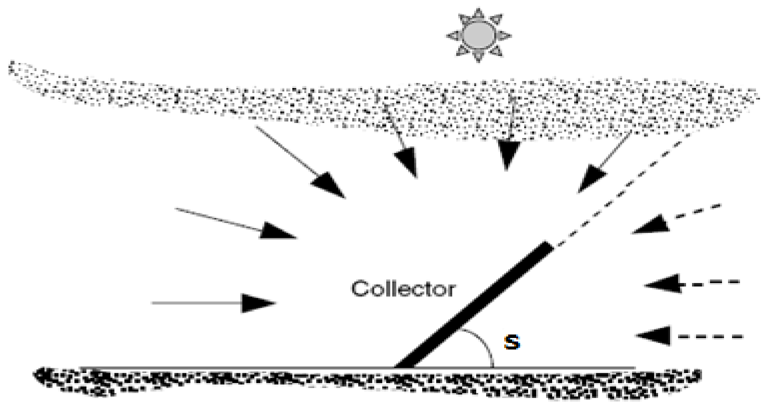
$$I_{DH} = C\, I_B$$

- Diffuse Radiation on collector

$$I_{DC} = I_{DH}\left(\frac{1+\cos\Sigma}{2}\right) = C\, I_B\left(\frac{1+\cos\Sigma}{2}\right)$$



I_{DC}



I_{DH} all the surface 180 degrees

I_{DC} Only the portion of collector surface (180 - s) degrees

If S=0; Collector gets full diffuse radiation.

If S=90; collecter gets 1/2 of the diffuse radiation.

mathematical expression $\frac{1 + \sin(90-S)}{2}$

sin (X-Y)=sinX*cosY - cosX*sinY

sin (90-S)=sin90*cosS - cos90*sinS
=cosS

Finally, $I_{DC} = \frac{1 + \cos S}{2}$

Diffuse Radiation on Collector - Example

- Question: At solar noon in Atlanta (latitude 33.7) on May 21, the altitude angle of the sun was found to be 76.4 degrees and the clear-sky beam insolation was found to be 902 W/m². Find the **diffuse radiation** at that time on a collector that faces 20 degrees toward the southeast with tipped angle at 52 degrees.
- **Find the Diffuse Radiation** (I_{DC})

January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
March	$n = 60$	September	$n = 244$
April	$n = 91$	October	$n = 274$
May	$n = 121$	November	$n = 305$
June	$n = 152$	December	$n = 335$

$$C = 0.095 + 0.04 \sin\left[\frac{360}{365}(n - 100)\right]$$

$$I_{DH} = C\ I_B$$

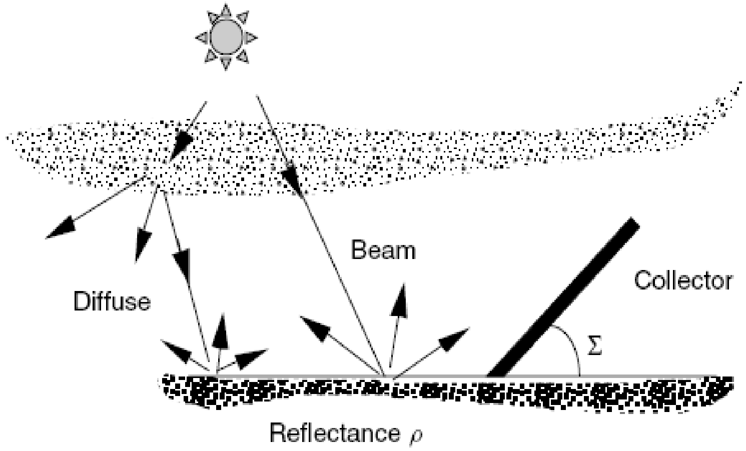
$$I_{DC} = I_{DH}\left(\frac{1 + \cos\Sigma}{2}\right) = C\ I_B\left(\frac{1 + \cos\Sigma}{2}\right)$$

$$\cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma$$

Reflected Radiation on Collector

- Reflection from ground with reflectance (snow, water, etc.)

ground reflectance ρ



$$I_{RC} = \rho(I_{BH} + I_{DH})\left(\frac{1-\cos\Sigma}{2}\right)$$

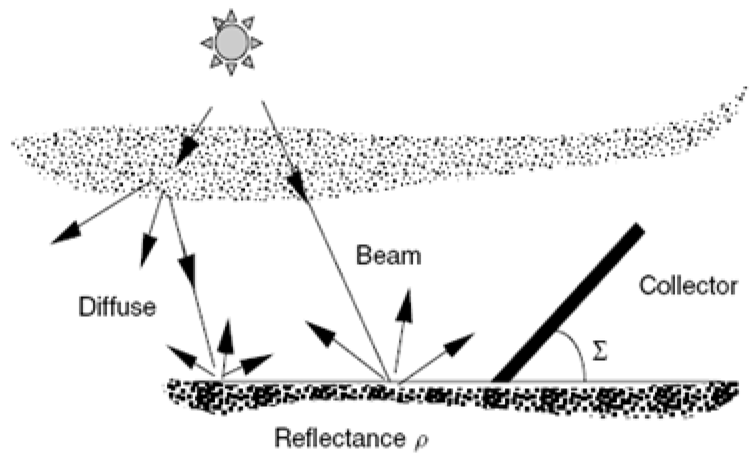
$$I_{RC} = \rho I_B(\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right)$$

Reflected Radiation on Collector: Example

- Question: At solar noon in Atlanta (latitude 33.7) on May 21, the altitude angle of the sun was found to be 76.4 degrees and the clear-sky beam insolation was found to be 902 W/m^2. Find the **reflected radiation** at that time on a collector that faces 20 degrees toward the southeast with tipped angle at 52 degrees, if the reflectance of the surfaces in front of the panel is 0.2.

ground reflectance ρ

$$I_{RC} = \rho I_B (\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right)$$

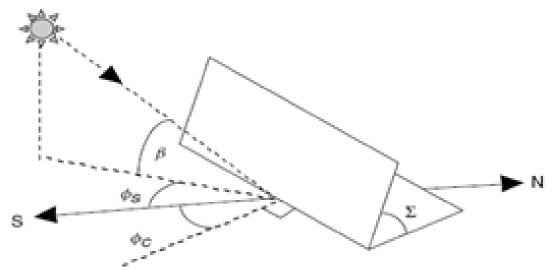


Total Radiation on Collector

- **Combination** of all three: Radiation striking a collector on a clear day

$$I_C = I_{BC} + I_{DC} + I_{RC}$$

$$I_C = Ae^{-km}\left[\cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma + C\left(\frac{1+\cos\Sigma}{2}\right) + \rho(\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right)\right]$$



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

$$I_{BC} = I_B\cos\theta$$

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

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

$$C = 0.095 + 0.04\sin\left[\frac{360}{365}(n - 100)\right]$$

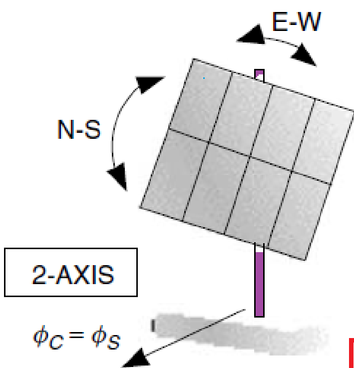
$$\beta_N = 90^\circ - L + \delta$$

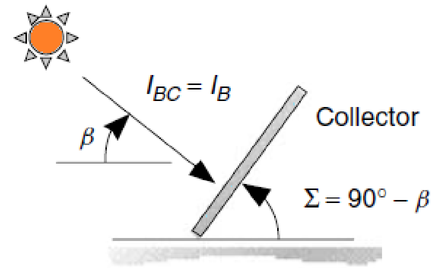
$$\cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma$$

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

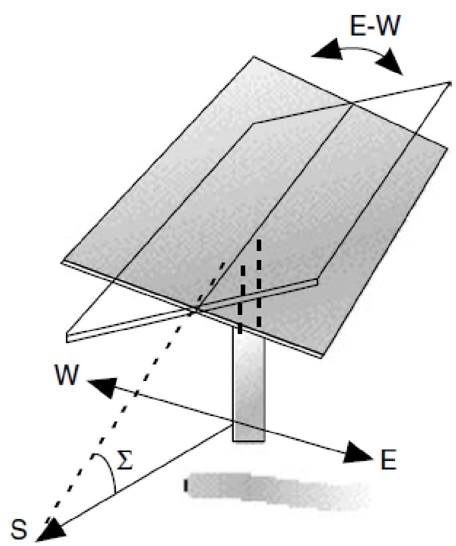
$$\delta = \sin^{-1}\left\{\sin(23.45^\circ)\sin\left[\frac{360}{365}(n - 81)\right]\right\}$$

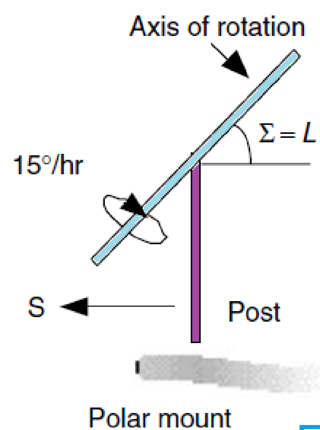
Tracking System





Two-axis tracking angular relationships.



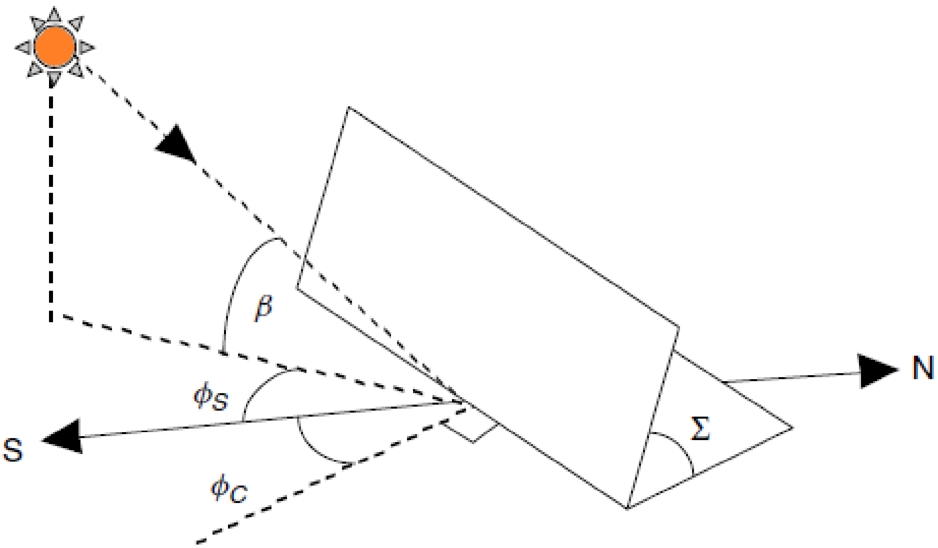


A single-axis tracking

Class Activity - 7

- Compare the 40° latitude, clear sky insolation on a collector at solar noon on the summer solstice for (a) fixed titled angle of 40° facing south, (b) single axis polar mount, and (c) two-axis tracking. Ignore the reflected insolation.
- Answer:
  - (a) Ic (fixed) = [ ] W/m^2
  - (b) Ic (1-axis) = [ ] W/m^2
  - (c) Ic (2-axis) = [ ] W/m^2

Fixed Collector (No Tracking)



$$I_{BC} = I_B \cos\theta \qquad \cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma$$

$$I_{DC} = C I_B \left(\frac{1 + \cos\Sigma}{2}\right)$$

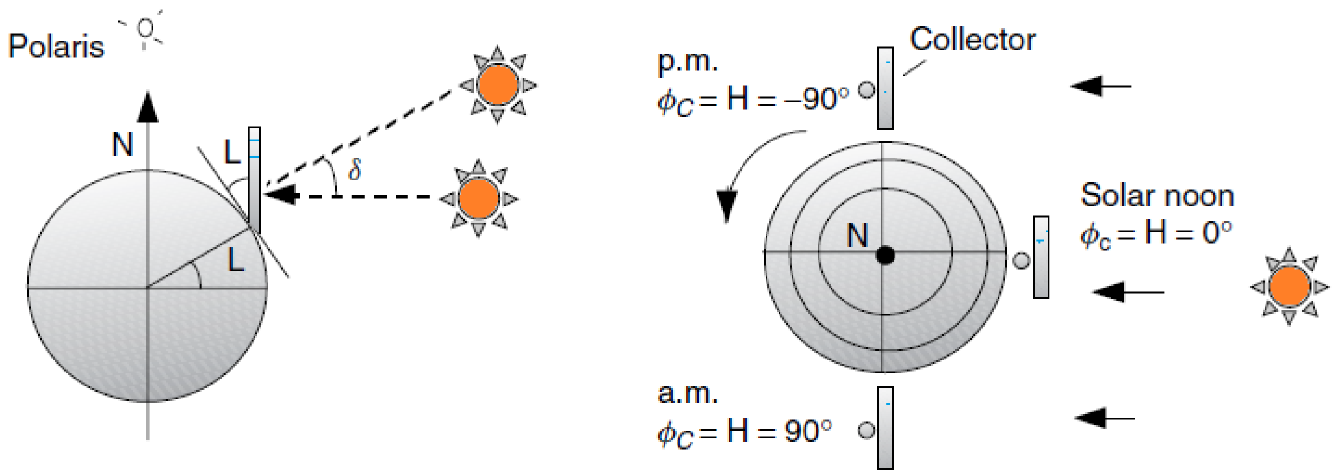
$$I_{RC} = \rho(I_{BH} + I_{DH})\left(\frac{1 - \cos\Sigma}{2}\right)$$

$$I_{BH} = I_B \cos(90^\circ - \beta) = I_B \sin\beta$$

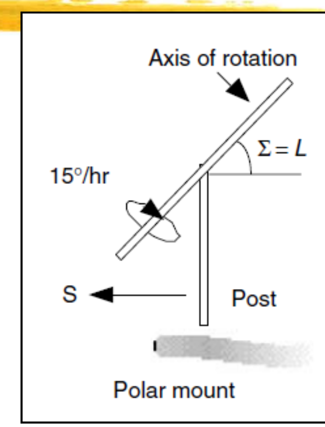
$$I_{DH} = C I_B$$

One-Axis Polar Mount Tracking

One-Axis, Polar Mount:



(a) (b)



(a) Polar mount for a one-axis tracker showing the impact of a 15°/h angular rotation of the collector array.

(b) Looking down on North Pole.

$$I_{BC} = I_B \cos\delta$$

$$I_{DC} = C I_B \left[\frac{1 + \cos(90° - \beta + \delta)}{2}\right]$$

$$I_{RC} = \rho(I_{BH} + I_{DH}) \left[\frac{1 - \cos(90° - \beta + \delta)}{2}\right]$$

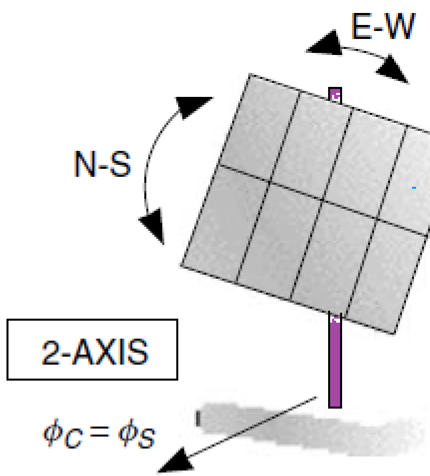
$\Sigma = L$

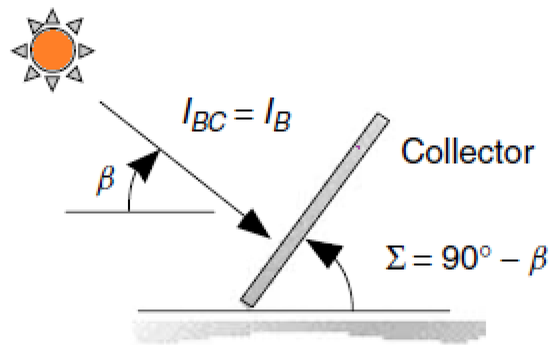
$\Sigma = L$

$\beta = 90 - L + \delta$

Two-Axis Tracking

Two-Axis Tracking:





$$I_{BC} = I_B$$

$$I_{DC} = CI_B\left[\frac{1+\cos(90^\circ-\beta)}{2}\right]$$

$$I_{RC} = \rho(I_{BH}+I_{DH})\left[\frac{1-\cos(90^\circ-\beta)}{2}\right]$$

Summary of Clear-Sky Solar Insolation Equations

I_0 = extraterrestrial solar insolation
m = air mass ratio
I_B = beam insolation at earth's surface
A = apparent extraterrestrial solar insolation
k = atmospheric optical depth
C = sky diffuse factor
I_{BC} = beam insolation on collector
θ = incidence angle
Σ = collector tilt angle
I_H = insolation on a horizontal surface
I_{DH} = diffuse insolation on a horizontal surface
I_{DC} = diffuse insolation on collector
I_{RC} = reflected insolation on collector
ρ = ground reflectance
I_C = insolation on collector
n = day number
β = solar altitude angle
δ = solar declination
ϕ_S = solar azimuth angle ($+ =$ AM)
ϕ_C = collector azimuth angle ($+ =$ SE)

Summary of Clear-Sky Solar Insolation Equations

$$I_0 = 1370\left[1 + 0.034\cos\left(\frac{360n}{365}\right)\right] \text{ (W/m}^2\text{)}$$

$$m = \frac{1}{\sin\beta}$$

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

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

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

$$I_{BC} = I_B\cos\theta$$

$$\cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma$$

$$I_{BH} = I_B\cos(90^\circ - \beta) = I_B\sin\beta$$

$$I_{DH} = CI_B$$

Summary of Clear-Sky Solar Insolation Equations

$$C = 0.095 + 0.04 \sin\left[\frac{360}{365}(n - 100)\right]$$

$$I_{DC} = I_{DH}\left(\frac{1 + \cos\Sigma}{2}\right) = I_B C\left(\frac{1 + \cos\Sigma}{2}\right)$$

$$I_{RC} = \rho I_B(\sin\beta + C)\left(\frac{1 - \cos\Sigma}{2}\right)$$

$$I_C = I_{BC} + I_{DC} + I_{RC}$$

$$I_C = Ae^{-km}\left[\cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma + C\left(\frac{1 + \cos\Sigma}{2}\right) + \rho(\sin\beta + C)\left(\frac{1 - \cos\Sigma}{2}\right)\right]$$

Summary of Clear-Sky Solar Insolation Equations

Two-Axis Tracking:

$$I_{BC} = I_B$$

$$I_{DC} = C I_B \left[\frac{1 + \cos(90^\circ - \beta)}{2} \right]$$

$$I_{RC} = \rho (I_{BH} + I_{DH}) \left[\frac{1 - \cos(90^\circ - \beta)}{2} \right]$$

One-Axis, Polar Mount:

$$I_{BC} = I_B \cos \delta$$

$$I_{DC} = C I_B \left[\frac{1 + \cos(90^\circ - \beta + \delta)}{2} \right]$$

$$I_{RC} = \rho (I_{BH} + I_{DH}) \left[\frac{1 - \cos(90^\circ - \beta + \delta)}{2} \right]$$

Class Activity - 7

- Compare the 40° latitude, clear sky insolation on a collector at solar noon on the summer solstice for (a) fixed titled angle of 40° facing south, (b) single axis polar mount, and (c) two-axis tracking. Ignore the reflected insolation.
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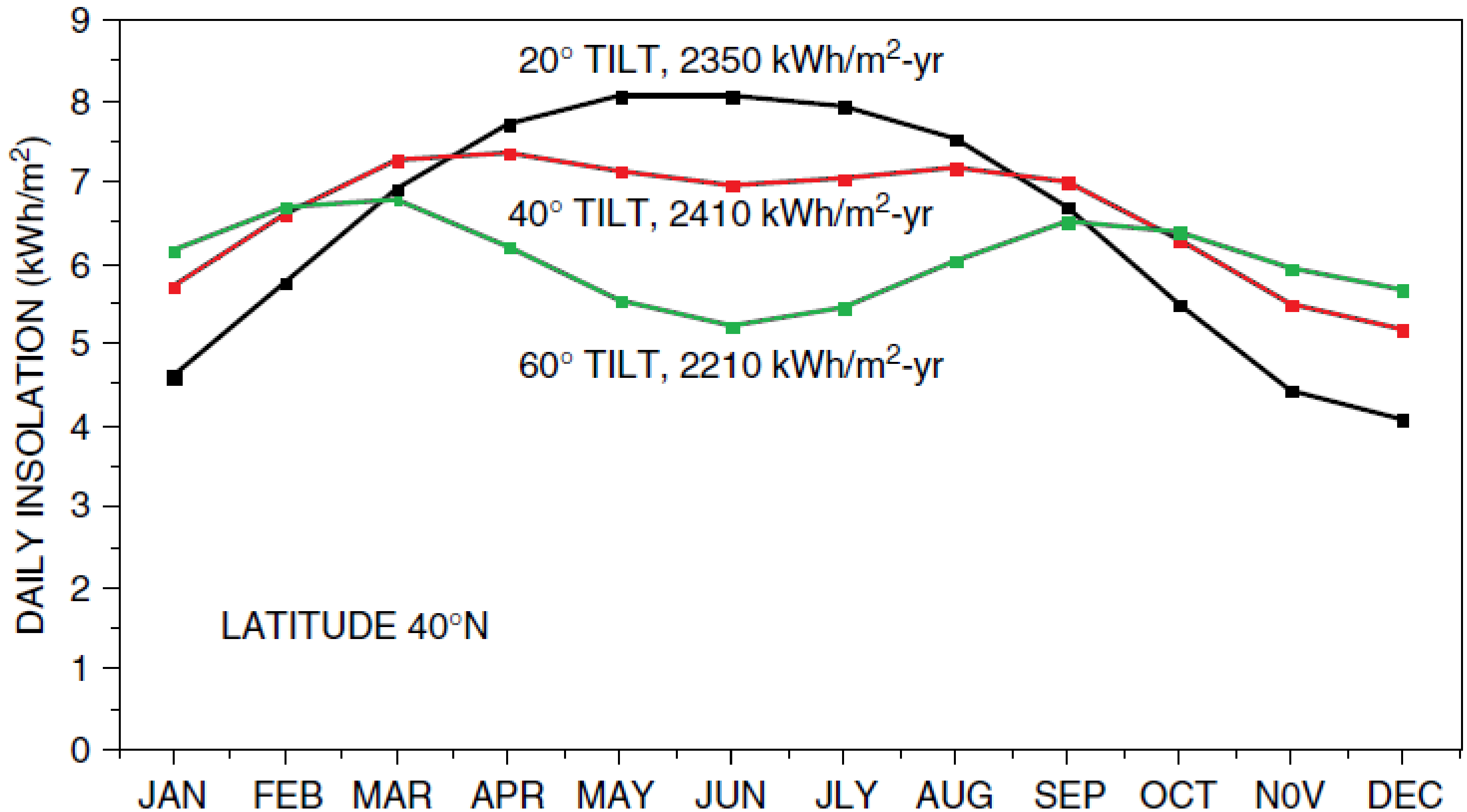
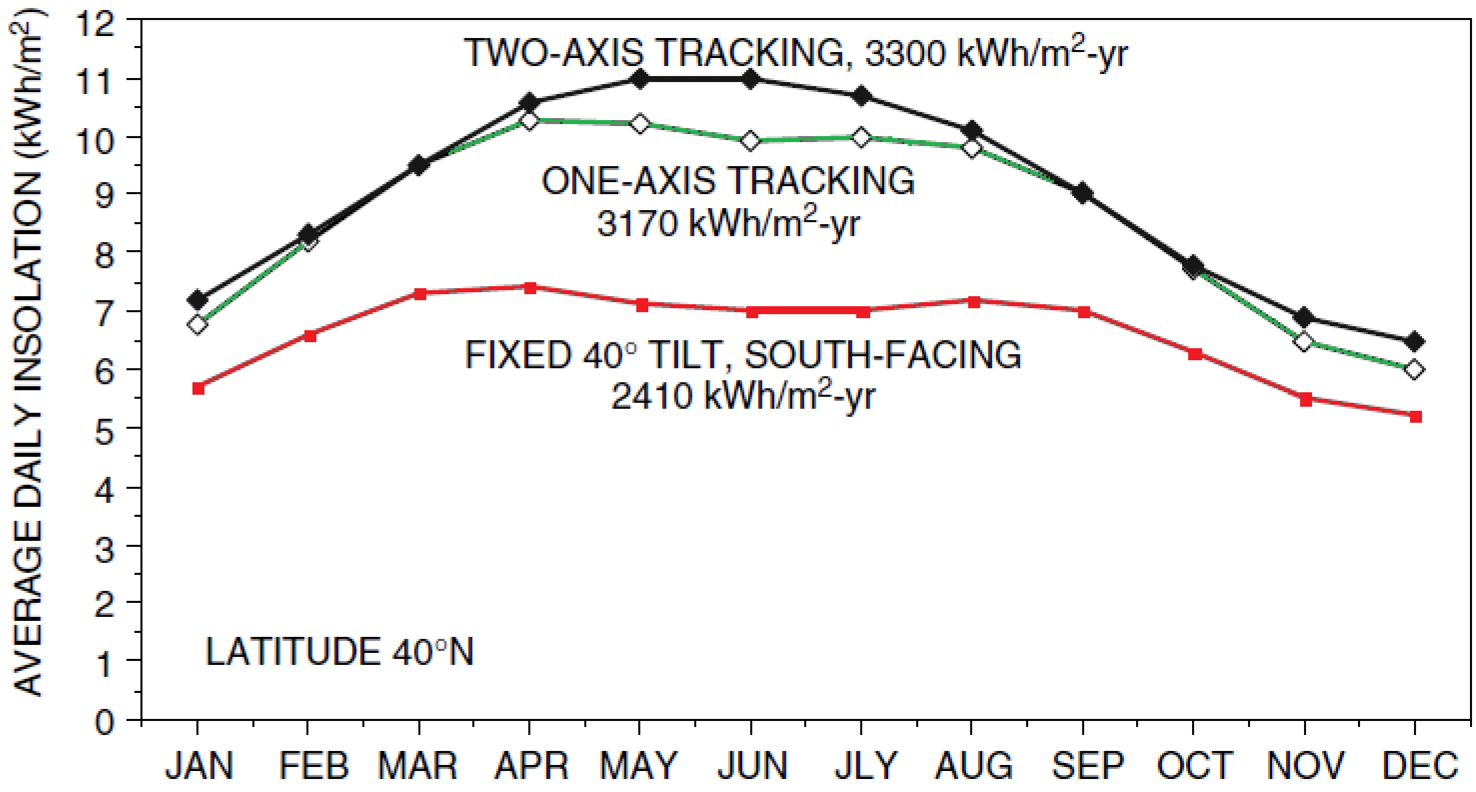
Monthly Clear-Sky Insolation

- What we have calculated so far? **Instantaneous insolation**
- Daily (and Yearly) Insolation on South-Facing Collectors



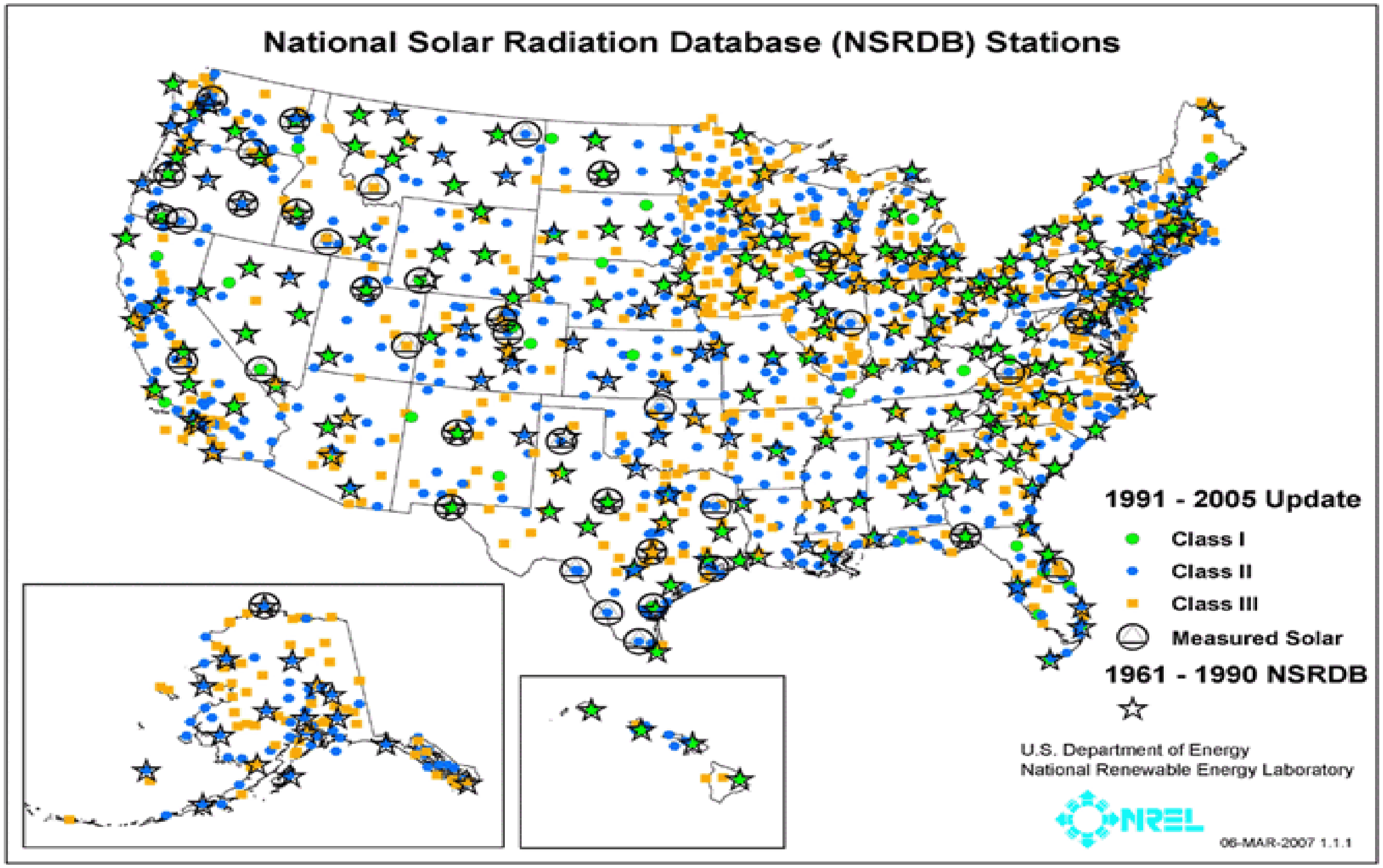
Monthly Clear-Sky Insolation

- Daily (and Yearly) Insolation on Tracking & South-Faced Collectors



Solar Radiation Measurement Stations

- 239 National Solar Radiation Database Stations (NSRDB)



Pyranometer and Pyrheliometer

- **Pyranometer**: measures total radiation arriving from all directions, direct and diffuse component

- **Pyrheliometer**: measures only direct radiation

Average Daily Insolation

- Sky is not always clear
- Estimate of average insolation that strikes a tilted collector under real conditions at a particular site
  - Atmospheric clearness
  - Solar hour angle from sunrise to sunset
  - Average Tilt Factor
  - $I_C=I_{BC}+I_{DC}+I_{RC}$ (direct + Diffuse + reflection) on collector surface
- **Starting Point**: Working on horizontal insolation (on horizontal surface) (since primary measurement data is on horizontal insolation I_H)
- $\mathbf{I_H = I_{DH} + I_{BH}}$ (Horizontal Insolation = Horizontal Diffuse + Horizontal Beam)
- $I_{DC} \leftarrow I_{DH}$ & $I_{RC} \leftarrow I_H$ (already discussed)
- Question is how to get I_{BC} from I_H
  - We decompose the total horizontal insolation in to its **diffuse component** and **beam components**
  - Clearness index K_T

Decomposition of Total Horizontal Insolation (I_H)

- **Clearness index** (K_T): Ratio of **average horizontal insolation at a site** (I_H) to the **extraterrestrial insolation** on a horizontal surface above the site and just outside the atmosphere (I_o)

$$K_T = \frac{\overline{I}_H}{\overline{I}_0}$$

- Average value of I_o: averaging the product of normal radiation and the SIN of the solar hour angle from sunrise and sunset:
- Correlation between Clearness Index and Diffuse Radiation

SC: Solar constant 1.377 kW/m²

$$\overline{I}_0 = \left(\frac{24}{\pi}\right) \mathrm{SC}\left[1 + 0.034\cos\left(\frac{360n}{365}\right)\right](\cos L \cos\delta \sin H_{SR} + H_{SR}\sin L \sin\delta)$$

- Diffuse and Reflected Radiation on a tilted collector surface

$$\frac{\overline{I}_{DH}}{\overline{I}_H} = 1.390 - 4.027K_T + 5.531{K_T}^2 - 3.108{K_T}^3$$

$$\overline{I}_{DC} = \overline{I}_{DH}\left(\frac{1+\cos\Sigma}{2}\right) \qquad \overline{I}_{RC} = \rho\overline{I}_H\left(\frac{1-\cos\Sigma}{2}\right)$$

$$H_{SR} = \cos^{-1}(-\tan L \tan\delta)$$

SUNRISE HOUR ANGLE - The sunrise hour angle is the hour angle, expressed in degrees, when the sun's center reaches the horizon.

Conversion to Beam Radiation on Collector

- The **average beam radiation** on a horizontal surface (I_{BH}) can be found by subtracting the diffuse portion (I_{DH}) from the total (I_H):

$$\overline{I}_H = \overline{I}_{DH} + \overline{I}_{BH} \longrightarrow \overline{I}_{BH} = \overline{I}_H - \overline{I}_{DH}$$

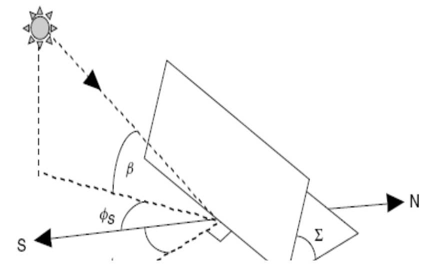
- Conversion of horizontal beam radiation (I_{BH}) to the beam radiation on collector (I_{BC}):

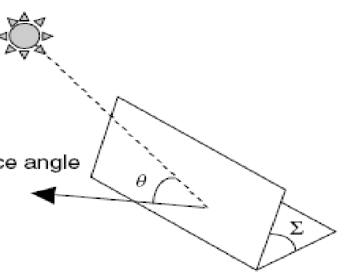
$$I_{BH} = I_B \sin\beta$$
$$I_{BC} = I_B \cos\theta$$
$$\longrightarrow \quad I_{BC} = I_{BH}\left(\frac{\cos\theta}{\sin\beta}\right) = I_{BH} R_B$$

θ is the incidence angle between the collector and beam

β is the sun's altitude angle

R_B is *beam tilt factor*





- Average value of Beam Tilt Factor (R_B):

Instantaneous beam tilt factor

$$R_B = \left(\frac{\cos\theta}{\sin\beta}\right)$$

Average value of Beam Tilt Factor (R_B)

- We need Average value of R_B
- For South-Facing Collectors:

Radian value

$$\overline{R}_B = \frac{\cos(L-\Sigma)\cos\delta\sin H_{SRC} + H_{SRC}\sin(L-\Sigma)\sin\delta}{\cos L\cos\delta\sin H_{SR} + H_{SR}\sin L\sin\delta}$$

Radian value

$$H_{SR} = \cos^{-1}(-\tan L\tan\delta) \quad \text{sunrise hour angle (in radians)}$$

$$H_{SRC} = \min\{\cos^{-1}(-\tan L\tan\delta), \cos^{-1}[-\tan(L-\Sigma)\tan\delta]\}$$

sunrise hour angle for the collector

L is the latitude

Σ is the collector tilt angle.

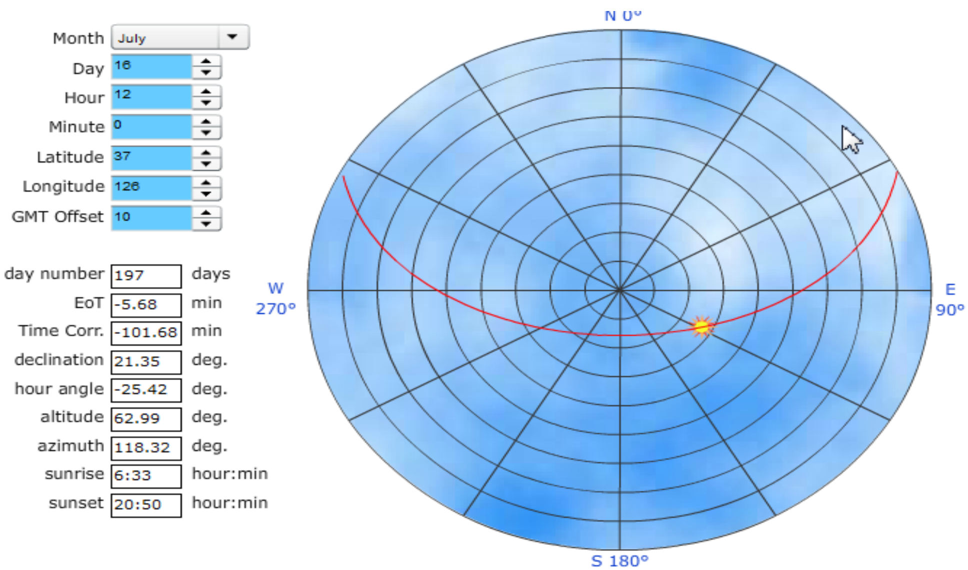
δ is the solar declination

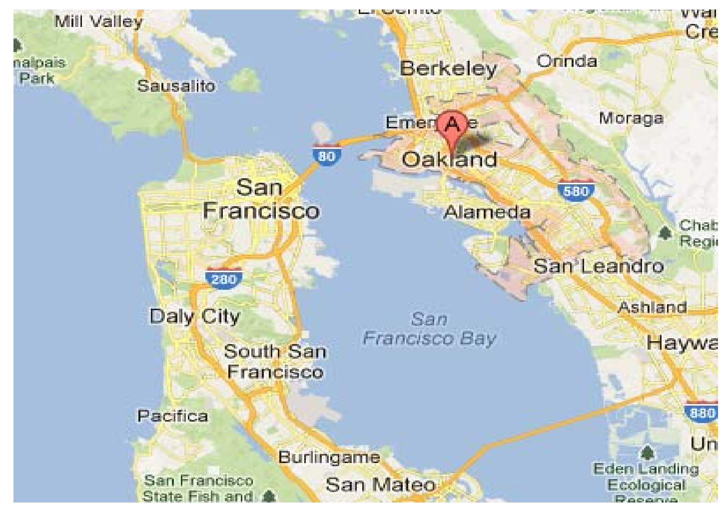
- **Final Equation for Insolation striking a collector** $\overline{I}_C = \overline{I}_{BC} + \overline{I}_{DC} + \overline{I}_{RC}$

$$\overline{I}_C = \overline{I}_H\left(1 - \frac{\overline{I}_{DH}}{\overline{I}_H}\right)\cdot\overline{R}_B + \overline{I}_{DH}\left(\frac{1+\cos\Sigma}{2}\right) + \rho\overline{I}_H\left(\frac{1-\cos\Sigma}{2}\right)$$

Calculation of Average Daily Insolation

- Average Monthly Insolation on a Tilted Collector
- Average horizontal insolation (I_H) in Oakland, California (latitude 37.73°N) in July 16 is 7.32 kWh/m^2-day. Assume ground reflectivity of 0.2.
- **Question**: Estimate the average insolation on a south-facing collector at a tilt angle of 30° with respect to the horizontal.





Calculation of Average Daily Insolation

- 0. Target
- 1. Sun declination (δ) for July 16 (n=197)
- 2. Sunrise Hour Angle (H_{SR}) using L=37.73^o
- 3. Extraterrestrial Insolation (I_o) (with SC=1.37 kW/m^2)
- 4. Clearness Index (K^T)
- 5. Horizontal Diffuse Radiation (I_{DH})
- 6. Diffuse Radiation on the Collector (I_{DC})
- 7. Reflected Radiation on the Collector (I_{RC})
- 8. Horizontal Beam Radiation (I_{BH})
- 9. Sunrise Hour Angle on the Collector (H_{SRC})
- 10. Beam Tilt Factor (R_B)
- 11. Beam Radiation on the Collector (I_{BC})
- 12. Total Insolation on the Collector (I_C)

Solution - Details

July 16 ($n = 197$):

$$\delta = 23.45 \sin\left[\frac{360}{365}(n-81)\right] = 23.45 \sin\left[\frac{360}{365}(197-81)\right]$$
$$= 21.35^\circ$$

$$H_{SR} = \cos^{-1}(-\tan L \tan\delta)$$
$$= \cos^{-1}(-\tan 37.73^\circ \tan 21.35^\circ) = 107.6^\circ = 1.878 \text{ radians}$$

$$\overline{I}_0 = \left(\frac{24}{\pi}\right)\text{SC}\left[1 + 0.034\cos\left(\frac{360n}{365}\right)\right](\cos L \cos\delta \sin H_{SR} + H_{SR} \sin L \sin\delta)$$
$$= \left(\frac{24}{\pi}\right)1.37\left[1 + 0.034\cos\left(\frac{360\cdot 197}{365}\right)^\circ\right](\cos 37.73 \cos 21.35^\circ \sin 107.6^\circ$$
$$+ 1.878 \sin 37.73^\circ \sin 21.35^\circ)$$
$$= 11.34 \text{ kWh/m}^2\text{-day}$$

$$K_T = \frac{\overline{I}_H}{\overline{I}_0} = \frac{7.32 \text{ kWh/m}^2\cdot\text{day}}{11.34 \text{ kWh/m}^2\cdot\text{day}} = 0.645$$

$$\frac{\overline{I}_{DH}}{\overline{I}_H} = 1.390 - 4.027K_T + 5.531{K_T}^2 - 3.108{K_T}^3$$
$$= 1.390 - 4.027\ (0.645) + 5.531\ (0.645)^2 - 3.108\ (0.645)^3 = 0.258$$

Solution- Details (Continued)

$$\overline{I}_{DH} = 0.258 \cdot 7.32 = 1.89 \text{ kWh/m}^2\text{-day}$$

$$\overline{I}_{DC} = \overline{I}_{DH}\left(\frac{1+\cos\Sigma}{2}\right) = 1.89\left(\frac{1+\cos 30^\circ}{2}\right) = 1.76 \text{ kWh/m}^2\text{-day}$$

$$\overline{I}_{RC} = \rho\,\overline{I}_{H}\left(\frac{1-\cos\Sigma}{2}\right) = 0.2 \cdot 7.32\left(\frac{1-\cos 30^\circ}{2}\right) = 0.10 \text{ kWh/m}^2\text{-day}$$

$$\overline{I}_{BH} = \overline{I}_{H} - \overline{I}_{DH} = 7.32 - 1.89 = 5.43 \text{ kWh/m}^2\text{-day}$$

$$\begin{aligned} H_{SRC} &= \min\{\cos^{-1}(-\tan L \tan\delta),\ \cos^{-1}[-\tan(L-\Sigma)\tan\delta]\} \\ &= \min\{\cos^{-1}(-\tan 37.73^\circ \tan 21.35^\circ),\ \cos^{-1}[-\tan(37.73-30)^\circ \tan 21.35^\circ]\} \\ &= \min\{107.6^\circ, 93.0^\circ\} = 93.0^\circ = 1.624 \text{ radians} \end{aligned}$$

$$\begin{aligned} \overline{R}_B &= \frac{\cos(L-\Sigma)\cos\delta\sin H_{SRC} + H_{SRC}\sin(L-\Sigma)\sin\delta}{\cos L\cos\delta\sin H_{SR} + H_{SR}\sin L\sin\delta} \\ &= \frac{\cos(37.73-30)^\circ\cos 21.35^\circ\sin 93^\circ + 1.624\sin(37.73-30)^\circ\sin 21.35^\circ}{\cos 37.73^\circ\cos 21.35^\circ\sin 107.6^\circ + 1.878\sin 37.73^\circ\sin 21.35^\circ} \\ &= 0.893 \end{aligned}$$

$$\overline{I}_{BC} = \overline{I}_{BH}\overline{R}_B = 5.43 \cdot 0.893 = 4.85 \text{ kWh/m}^2\text{-day}$$

$$\overline{I}_{C} = \overline{I}_{BC} + \overline{I}_{DC} + \overline{I}_{RC} = 4.85 + 1.76 + 0.10 = 6.7 \text{ kWh/m}^2\text{-day}$$

Smath Solutio

1 Sun Declination (δ)

$IH := 7.32$ kWh /m^2-day average horizontal insolation

Collector tilt angle $\Sigma := 30$ deg

$L := 37.73$ $n := 197$

Day number of May 21

Solar Declination Angle (δ)

$$\delta := 23.45 \cdot \sin\left(\frac{360}{365} \cdot (n - 81) \cdot \frac{\pi}{180}\right) = 21.3537 \quad \text{deg}$$

2 Sun Rise Hour Angle (HSR)

$$H_{SR} = \cos^{-1}(-\tan L \tan \delta)$$

$$HSR := acos\left(-\tan\left(L \cdot \frac{\pi}{180}\right) \cdot \tan\left(\delta \cdot \frac{\pi}{180}\right)\right) = 1.8781 \quad \text{rad}$$

3 Extraterrestrial Insolation (I0) with SC= 1.37 kW/m^2

$SC := 1.37$

$$I0 := \left(\frac{24}{\pi}\right) \cdot SC \cdot \left(1 + 0.034 \cdot \cos\left(\frac{360 \cdot n}{365} \cdot \frac{\pi}{180}\right)\right) \cdot \left(\cos\left(L \cdot \frac{\pi}{180}\right) \cdot \cos\left(\delta \cdot \frac{\pi}{180}\right) \cdot \sin(HSR) + HSR \cdot \sin\left(L \cdot \frac{\pi}{180}\right) \cdot \sin\left(\delta \cdot \frac{\pi}{180}\right)\right)$$

$$I0 = 11.3417 \quad \frac{kW}{m^2}$$

Smath Soluti

4 Clearness Index (KT)

$$KT := \frac{IH}{I0} = 0.6454$$

$$\frac{\overline{I}_{DH}}{\overline{I}_H} = 1.390 - 4.027 K_T + 5.531 K_T^2 - 3.108 K_T^3$$

5 Horizontal Diffuse Radiation (IDH)

$$IDH := IH \cdot \left(1.390 - 4.027 \cdot KT + 5.531 \cdot KT^2 - 3.108 \cdot KT^3\right) = 1.8982$$ kWh /m^2-day

6 Diffuse Radiation on the Collector (IDC)

$$\overline{I}_{DC} = \overline{I}_{DH} \left(\frac{1 + \cos \Sigma}{2}\right)$$

$$IDC := IDH \cdot \left(\frac{1 + \cos\left(\Sigma \cdot \frac{\pi}{180}\right)}{2}\right) = 1.771$$ kWh /m^2-day

7 Reflected Radiation on the Collector (IRC)

$$\rho := 0.2$$

$$\overline{I}_{RC} = \rho\, \overline{I}_H \left(\frac{1 - \cos \Sigma}{2}\right)$$

$$IRC := \rho \cdot IH \cdot \left(\frac{1 - \cos\left(\Sigma \cdot \frac{\pi}{180}\right)}{2}\right) = 0.0981$$ kWh /m^2-day

Smath Solution

8 Horizontal Beam Radiation (IBH)

$$\overline{I}_{BH} = \overline{I}_H - \overline{I}_{DH}$$

IBH := IH − IDH = 5.4218 kWh /m^2-day

9 Sunrise Hour Angle on the Collector (HSRC)

$$H_{SRC} = \min\{\cos^{-1}(-\tan L \tan\delta), \cos^{-1}[-\tan(L-\Sigma)\tan\delta]\}$$

$$HSRC1 := \operatorname{acos}\left(-\tan\left(L \cdot \frac{\pi}{180}\right) \cdot \tan\left(\delta \cdot \frac{\pi}{180}\right)\right) = 1.8781$$

$$HSRC2 := \operatorname{acos}\left(-\tan\left((L-\Sigma) \cdot \frac{\pi}{180}\right) \cdot \tan\left(\delta \cdot \frac{\pi}{180}\right)\right) = 1.6239$$

$$HSRC := \min\left(\left(HSRC1 \quad HSRC2\right)\right) = 1.6239$$

$$A := \left(2 \quad 5\right)$$

$$\min(A) = 2$$

10 Beam Tilt Factor (RB)

$$\overline{R}_B = \frac{\cos(L-\Sigma)\cos\delta\sin H_{SRC} + H_{SRC}\sin(L-\Sigma)\sin\delta}{\cos L\cos\delta\sin H_{SR} + H_{SR}\sin L\sin\delta}$$

$$RB := \frac{\cos\left((L-\Sigma)\cdot\frac{\pi}{180}\right)\cdot\cos\left(\delta\cdot\frac{\pi}{180}\right)\cdot\sin(HSRC) + HSRC\cdot\sin\left((L-\Sigma)\cdot\frac{\pi}{180}\right)\cdot\sin\left(\delta\cdot\frac{\pi}{180}\right)}{\cos\left(L\cdot\frac{\pi}{180}\right)\cdot\cos\left(\delta\cdot\frac{\pi}{180}\right)\cdot\sin(HSR) + HSR\cdot\sin\left(L\cdot\frac{\pi}{180}\right)\cdot\sin\left(\delta\cdot\frac{\pi}{180}\right)}$$

RB = 0.8934

11 Beam Radiation on the Collector (IBC)

$$\overline{I}_{BC} = \overline{I}_{BH}\overline{R}_B$$

IBC := IBH · RB = 4.8438 kWh /m^2-day

12 Total Insolation on the Collector

$$\overline{I}_C = \overline{I}_{BC} + \overline{I}_{DC} + \overline{I}_{RC}$$

IC := IBC + IDC + IRC = 6.7129 kWh /m^2-day

Calculation is complex, so we need

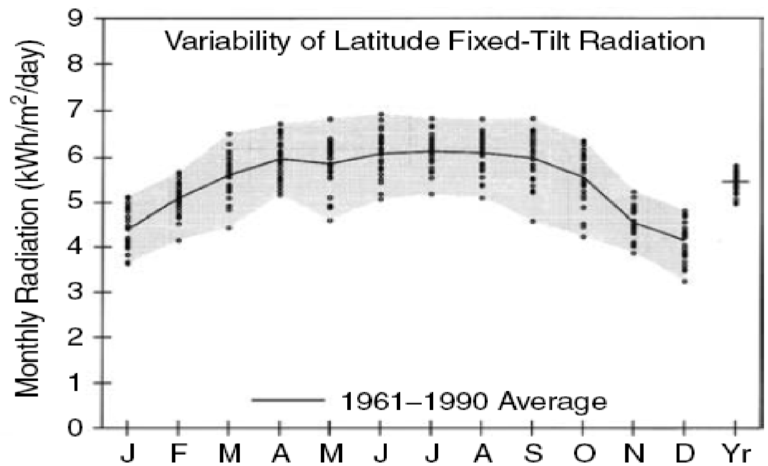
- Spreadsheet or Computer Analysis → Complex
- Pre-computed Data such as ***Solar Radiation Data Manual for Flat-Place and Concentrating Collectors*** (NREL, 1994): **AVERAGE DAILY INSOLATION Per MONTH**

Boulder, CO

WBAN NO. 94018

LATITUDE: 40.02° N
LONGITUDE: 105.25° W
ELEVATION: 1634 meters
MEAN PRESSURE: 836 millibars

STATION TYPE: Primary



Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m² /day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	2.4	3.3	4.4	5.6	6.2	6.9	6.7	6.0	5.0	3.8	2.6	2.1	4.6
	Min/Max	2.1/2.7	2.8/3.5	3.7/5.0	4.8/6.1	5.1/7.2	5.7/7.8	5.6/7.4	5.2/6.6	4.0/5.5	3.1/4.2	2.3/2.8	1.9/2.3	4.3/4.8
Latitude −15	Average	3.8	4.6	5.4	6.1	6.2	6.6	6.6	6.3	5.9	5.1	4.0	3.5	5.4
	Min/Max	3.2/4.4	3.8/5.1	4.3/6.2	5.3/6.8	4.9/7.3	5.5/7.6	5.6/7.4	5.3/7.1	4.6/6.7	4.0/5.8	3.4/4.6	2.8/4.1	4.9/5.7
Latitude	Average	4.4	5.1	5.6	6.0	5.9	6.1	6.1	6.1	6.0	5.6	4.6	4.2	5.5
	Min/Max	3.6/5.1	4.2/5.7	4.4/6.5	5.2/6.7	4.6/6.8	5.1/6.9	5.2/6.8	5.1/6.8	4.6/6.8	4.2/6.4	3.9/5.2	3.2/4.8	5.0/5.8
Latitude +15	Average	4.8	5.3	5.6	5.6	5.2	5.2	5.3	5.5	5.8	5.7	4.8	4.5	5.3
	Min/Max	3.9/5.6	4.3/5.9	4.4/6.5	4.8/6.2	4.1/6.0	4.4/5.9	4.5/5.9	4.6/6.2	4.4/6.6	4.2/6.5	4.1/5.6	3.5/5.3	4.8/5.6
90	Average	4.5	4.6	4.3	3.6	2.8	2.6	2.7	3.2	4.0	4.6	4.4	4.3	3.8
	Min/Max	3.6/5.4	3.7/5.2	3.5/5.0	3.0/4.0	2.3/3.1	2.2/2.8	2.3/2.9	2.7/3.6	3.1/4.6	3.4/5.3	3.7/5.1	3.4/5.2	3.4/4.1

Solar Radiation Data Manual for Flat-Place and Concentrating Collectors (NREL)

rredc.nrel.gov/solar/pubs/redbook/

Search

Solar Radiation Data Manual
for
Flat-Plate and Concentrating Collectors

The ***Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*** is available on the RReDC in HTML and PDF format. Individual PDF files are available for the main body of the manual and for each of the 50 states, the Pacific Islands (Guam) and Puerto Rico. Compressed files containing the individual PDFS for the manual and the site data tables can be downloaded in three compression formats: PC, Macintosh and Unix. Maps derived of the data represented in the tables are also available for viewing.

- Individual PDFs
  - Manual (5.5MB)
  - State/Territoy Data Tables
    Tables include the "Averages of solar radiation for each of the 360 months during the period of 1961-1990" and "30-year (1961-1990) average of monthly solar radiation".
    - Alabama (3.5MB)
    - Alaska (14MB)
    - Arizona (3.5MB)
    - Arkansas (2MB)
    - California (8.5MB)
    - Colorado (5.5MB)
    - Connecticut (5MB)
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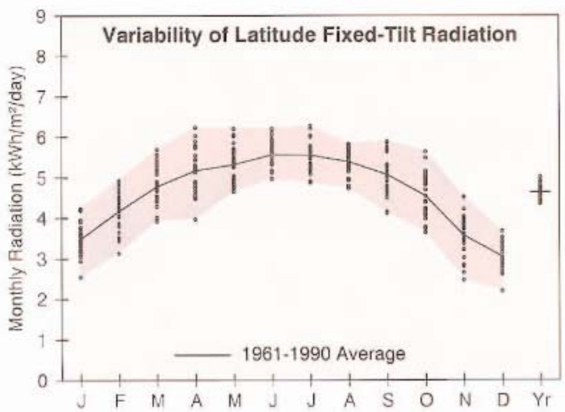
    - South Carolina (2.5MB)
    - South Dakota (3.5MB)
    - Tennessee (4.5MB)

Solar Radiation Data Manual for Flat-Place and Concentrating Collectors (NREL)

- Average Daily Insolation per month



Baltimore, MD

WBAN NO. 93721

LATITUDE: 39.18° N
LONGITUDE: 76.67° W
ELEVATION: 47 meters
MEAN PRESSURE: 1012 millibars

STATION TYPE: Secondary

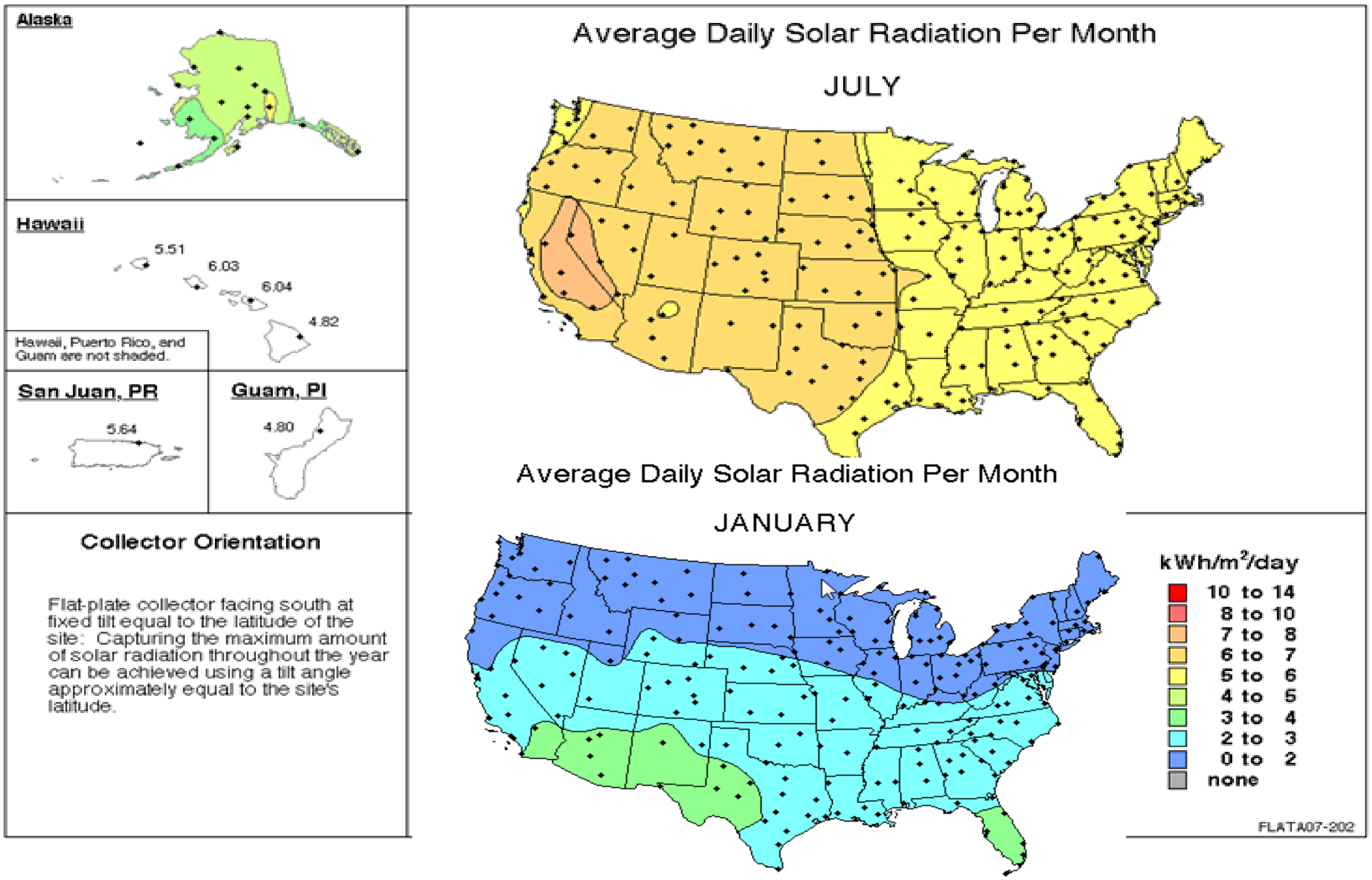
Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	2.1	2.9	3.9	4.9	5.6	6.2	6.0	5.3	4.4	3.3	2.2	1.8	4.0
	Min/Max	1.7/2.4	2.4/3.2	3.4/4.5	3.9/5.8	5.0/6.5	5.5/6.9	5.3/6.8	4.7/5.7	3.7/5.0	2.9/3.9	1.8/2.6	1.5/2.0	3.8/4.3
Latitude -15	Average	3.1	3.8	4.6	5.3	5.7	6.0	6.0	5.6	5.0	4.3	3.2	2.7	4.6
	Min/Max	2.3/3.7	3.0/4.4	3.8/5.4	4.1/6.3	5.0/6.6	5.4/6.7	5.2/6.7	4.9/6.0	4.1/5.8	3.5/5.2	2.3/4.0	2.0/3.2	4.3/4.9
Latitude	Average	3.5	4.2	4.8	5.2	5.3	5.6	5.5	5.4	5.1	4.6	3.6	3.1	4.6
	Min/Max	2.5/4.2	3.1/4.9	3.9/5.7	4.0/6.2	4.7/6.2	5.0/6.2	4.9/6.3	4.7/5.8	4.1/5.9	3.6/5.6	2.5/4.5	2.2/3.7	4.4/5.0
Latitude +15	Average	3.7	4.3	4.7	4.8	4.7	4.8	4.9	4.9	4.8	4.6	3.7	3.3	4.4
	Min/Max	2.6/4.6	3.2/5.1	3.8/5.6	3.7/5.8	4.1/5.5	4.3/5.3	4.3/5.5	4.3/5.3	3.9/5.7	3.6/5.7	2.5/4.8	2.3/4.0	4.1/4.8
90	Average	3.4	3.7	3.5	3.0	2.6	2.4	2.5	2.9	3.3	3.7	3.3	3.0	3.1
	Min/Max	2.3/4.4	2.7/4.5	2.8/4.2	2.4/3.6	2.3/2.9	2.2/2.6	2.3/2.8	2.6/3.1	2.7/3.9	2.8/4.6	2.2/4.3	2.0/3.7	2.9/3.4

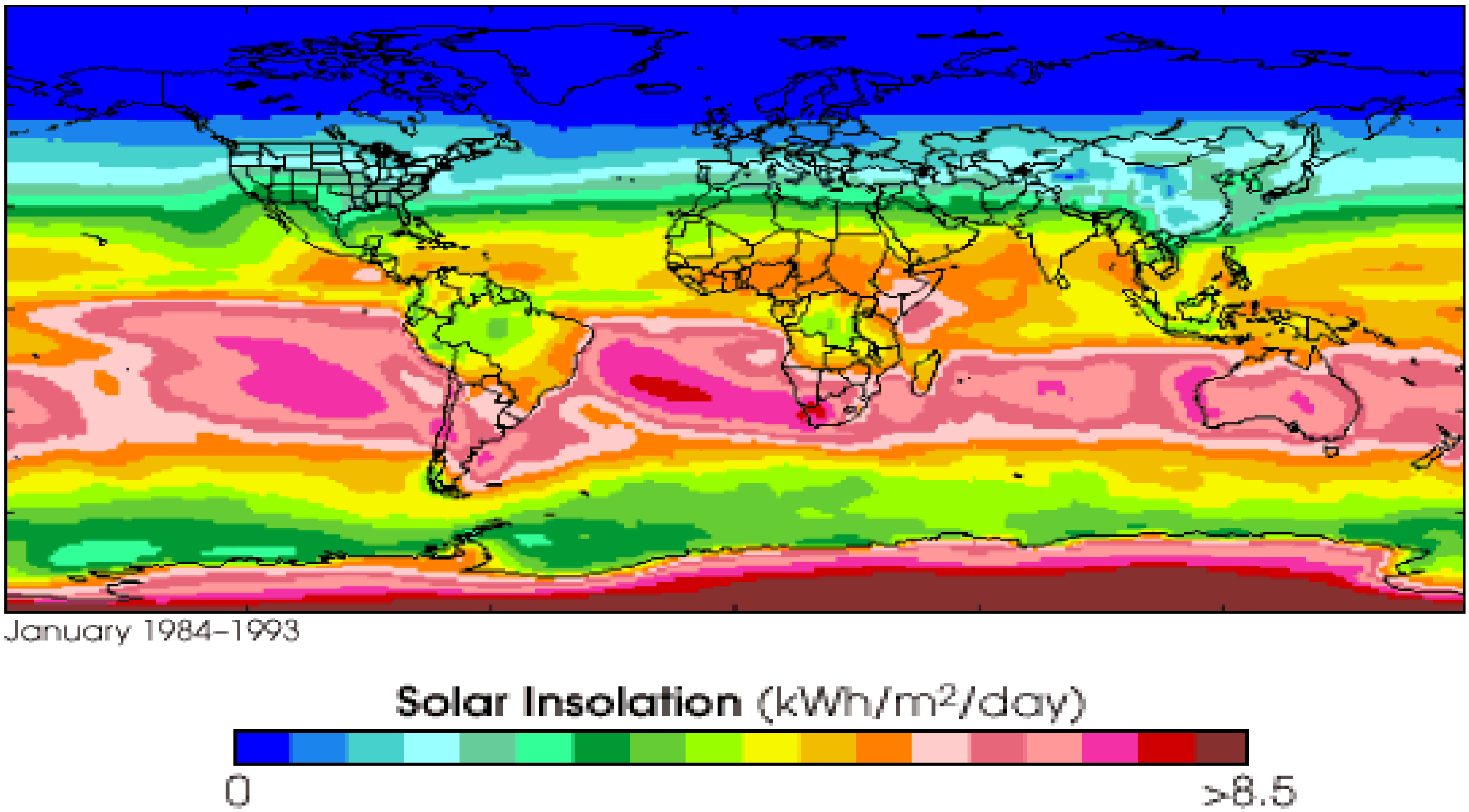
Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis (kWh/m²/day), Uncertainty ±9%

Axis Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.0	4.0	5.3	6.4	7.1	7.8	7.7	6.9	5.8	4.6	3.2	2.5	5.4
	Min/Max	2.3/3.7	3.0/4.8	4.2/6.4	4.8/8.1	6.1/8.5	6.5/9.0	6.3/8.9	5.7/7.5	4.7/6.9	3.6/5.7	2.2/4.0	1.9/3.0	5.0/5.9
Latitude -15	Average	3.7	4.7	5.9	6.8	7.2	7.8	7.7	7.1	6.3	5.3	3.9	3.2	5.8
	Min/Max	2.7/4.6	3.4/5.7	4.6/7.2	4.9/8.6	6.1/8.6	6.5/9.0	6.3/9.0	5.9/7.8	5.1/7.5	4.2/6.7	2.6/5.0	2.3/3.9	5.4/6.4
	Average	4.1	5.0	6.0	6.7	7.0	7.5	7.4	7.0	6.4	5.5	4.2	3.5	5.9

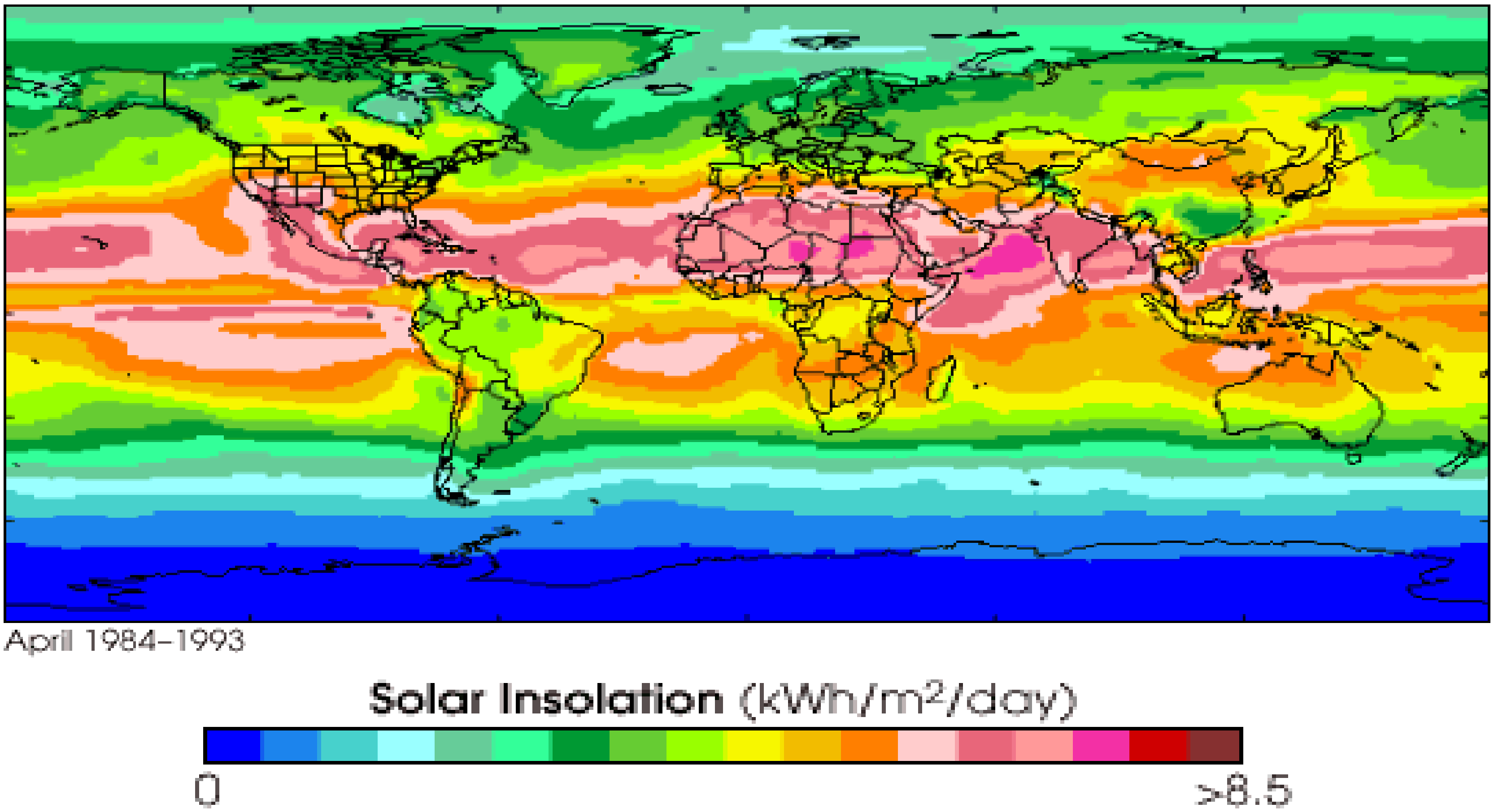
Average Solar Radiation, Jan/July, Flat, South Facing, Tilted Latitude



Solar Insolation Map - January

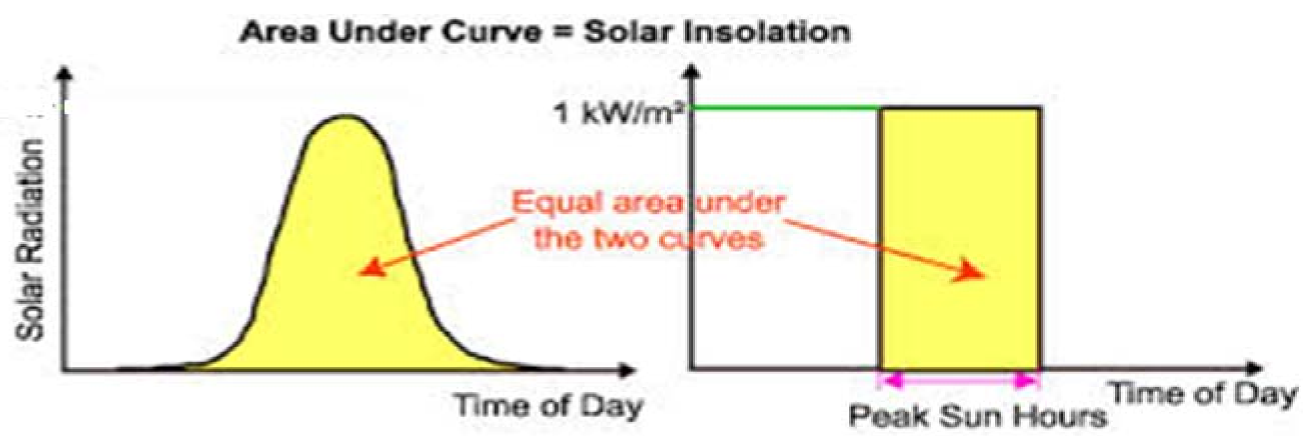


Solar Insolation Map - April



Peak Sun Hours

- Unit in the solar maps is *average kWh/m²-day* of insolation.
- Much simpler approach for PV
- "Peak Sun Hours": Total number of hours per day in which solar irradiance averages 1 kW/m² in **worst month**.



ENERGY = Rated_Power * Conversion_Efficiency * Peak_Sun_Hour/Day * 365 Day/Year

Peak Sun Hour Map

- http://www.oynot.com/solar-insolation-map.html
- The amount of solar energy in hours ("**peak sun**" hours) received each day on an optimally tilted surface during the **worst month** ("design month") of the year at 1 kW/m^2.

ENERGY = Rated_Power * Conversion_Efficiency * Peak_Sun_Hour/Day * 365 Day/Year