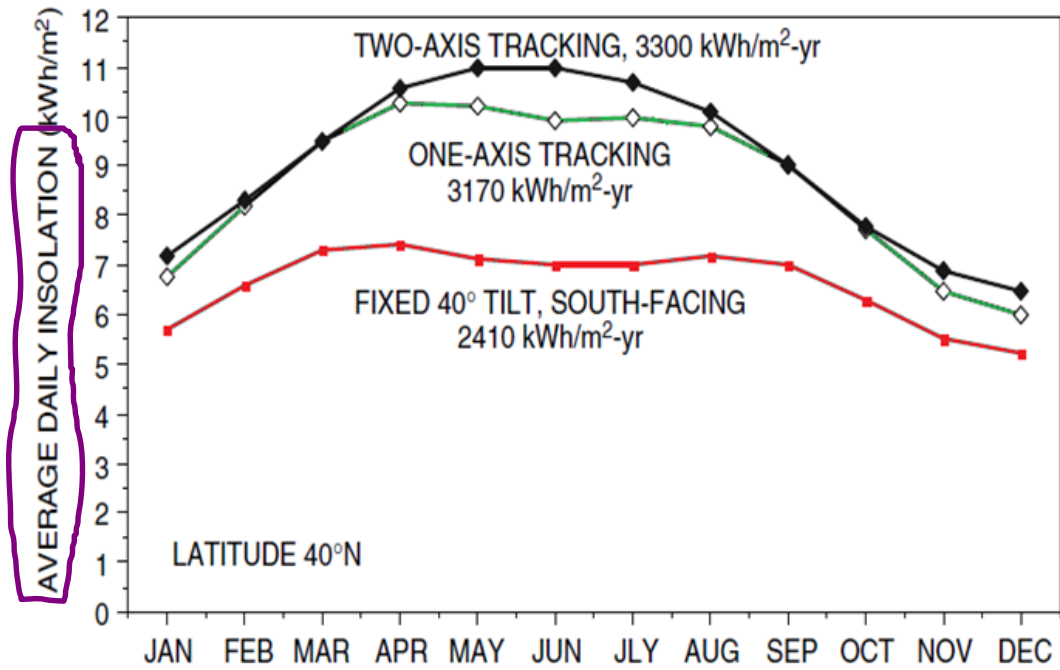


Average Daily Insolation

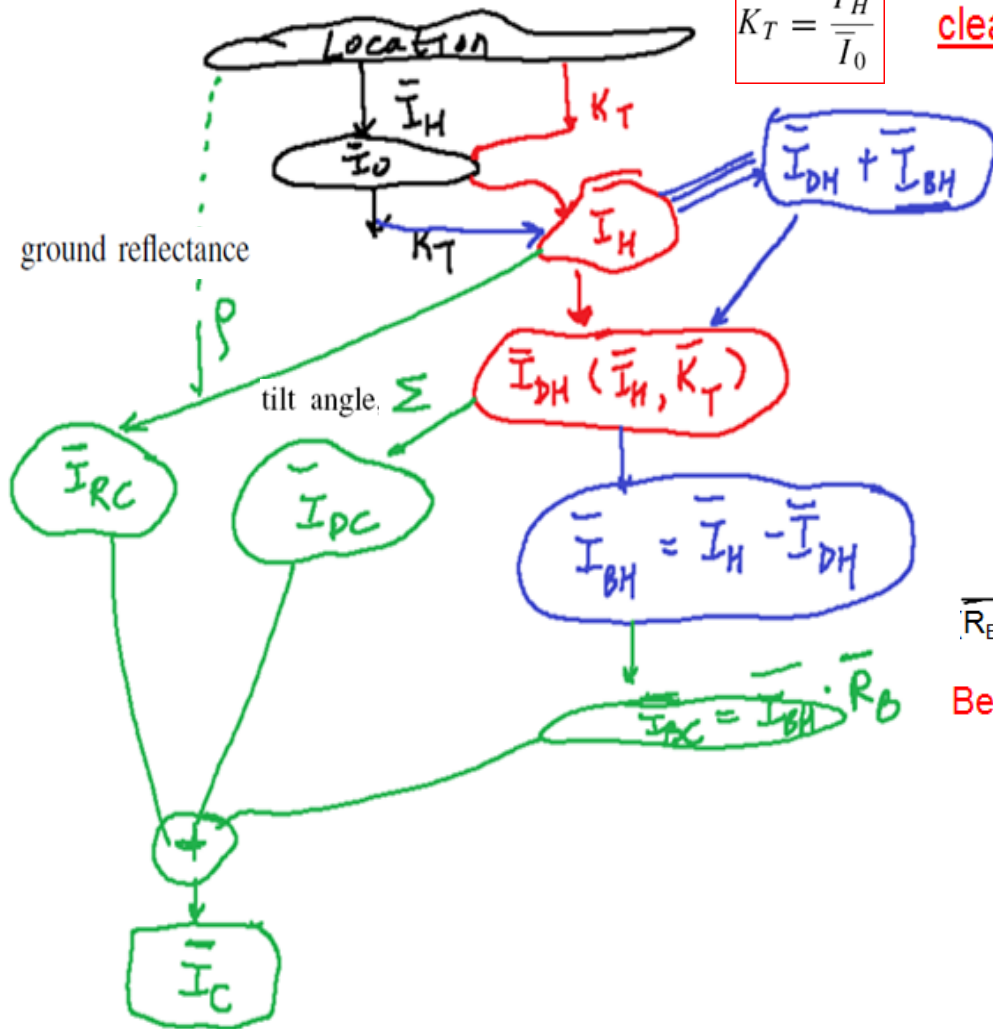


Average Daily Insolation

total average insolation
on a collector

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

clearness Index K_T



$\bar{R}_B$
Beam Tilt Factor

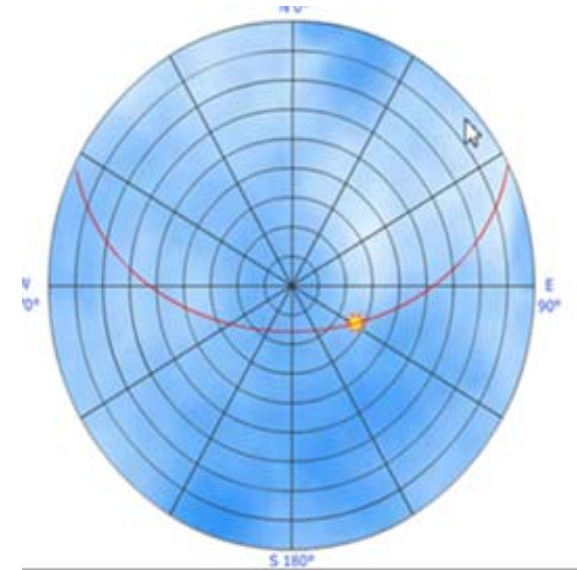
Average of I_o and I_H

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

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

⌘ Relationship between Diffuse Radiation & Horizontal Insolation via K_T :

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



⌘ Diffuse and Reflected Radiation on a tilted collector surface

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

Beam Radiation on horizontal surface → Beam Radiation on Collector

Average value of Beam Tilt Factor ($\overline{R_B}$)

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

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

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

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

sunrise hour angle for the collector

Total Average Insolation on Collector $\overline{I}_C$ (With given average horizontal insolation $\overline{I}_H$)

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

$$K_T = \frac{\overline{I}_H}{\overline{I}_0} \quad \frac{\overline{I}_{DH}}{\overline{I}_H} = 1.390 - 4.027 K_T + 5.531 K_T^2 - 3.108 K_T^3$$

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

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

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

$$\overline{I}_{BC} = \overline{I}_H \left(1 - \frac{\overline{I}_{DH}}{\overline{I}_H} \right) \cdot \overline{R}_B$$

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

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

sunrise hour angle for the collector

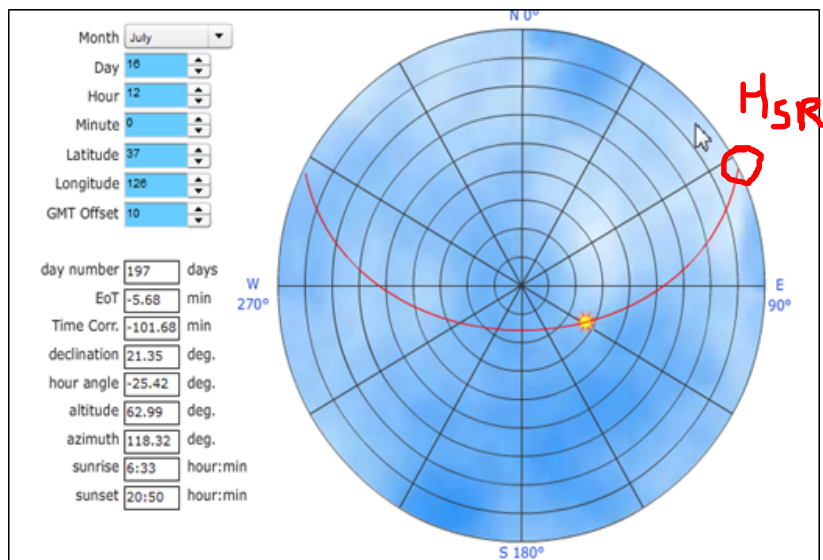
$$\overline{I}_C = \overline{I}_{BC} + \overline{I}_{DC} + \overline{I}_{RC}$$

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

$$\begin{aligned} \overline{I}_{BC} &= \overline{I}_H \overline{R}_B \\ &= (\overline{I}_H - \overline{I}_{DH}) \overline{R}_B \\ &= \overline{I}_H \left(1 - \frac{\overline{I}_{DH}}{\overline{I}_H} \right) \overline{R}_B \end{aligned}$$

Calculation of Average Daily Insolation - Example

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



Calculation is complex, so we need

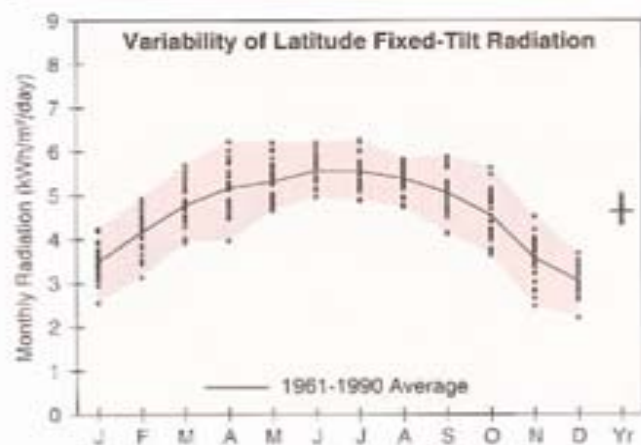
- ❖ Pre-computed Data such as ***Solar Radiation Data Manual for Flat-Place and Concentrating Collectors*** (NREL, 1994): **AVERAGE DAILY INSOLATION Per MONTH**



Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors

The *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* Individual PDF files are available for the main body of the manual. Compressed files containing the individual PDFS are available in PC, Macintosh and Unix. [Maps](#) derived of the

The screenshot shows the OSTI.GOV website interface. The browser address bar displays the URL: <https://www.osti.gov/biblio/10169141-solar-radiation>. The page title is "Solar radiation data manual for flat-plate and concentrating collectors". Below the title, there are tabs for "Full Record" and "Related Research". The "Full Record" tab is selected. On the left side, under "TECHNICAL REPORT:", there is a green button labeled "View Technical Report" and a link to the DOI: <https://doi.org/10.2172/10169141>. Below this, there is a "SAVE / SHARE:" section with options to "Export Metadata" and "Save to My Library". On the right side, under "Abstract", the text reads: "For designers and engineers of solar energy-related systems, the Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors gives the solar resource available for various types of collectors for the US and its territories. The data in the manual were modeled using hourly values of direct beam and diffuse horizontal solar radiation from the National Solar Radiation Data Base (NSRDB). The NSRDB contains modeled (93%) and measured (7%) global horizontal, diffuse horizontal, and direct beam solar radiation for 1961-1990."



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%

Average Daily Solar Radiation Per Month

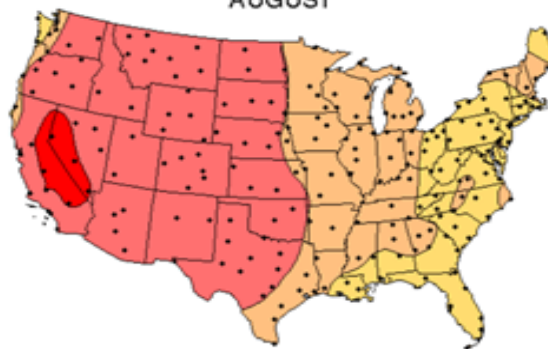
JANUARY



North-South Axis Tracking Flat Plate Tilted at Latitude

Average Daily Solar Radiation Per Month

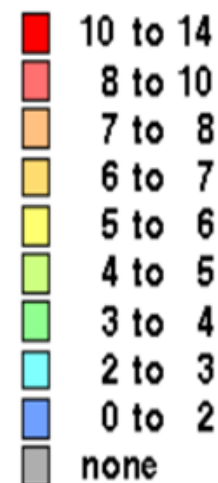
AUGUST



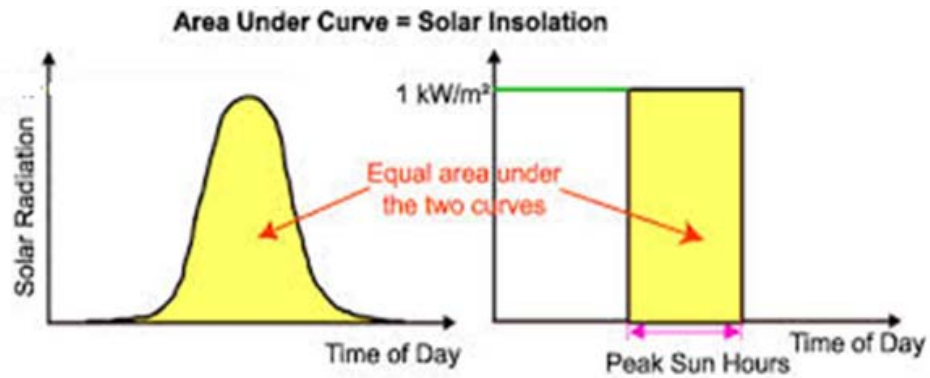
North-South Axis Tracking Flat Plate Tilted at Latitude

Solar Map

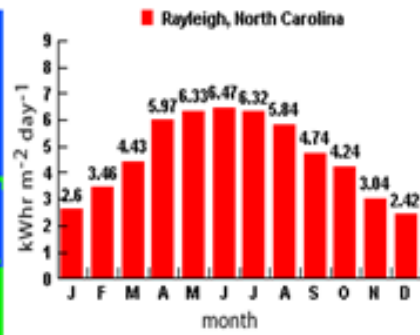
kWh/m²/day



Peak Sun Hours



move the mouse over a city to see the average daily solar radiation measured on the horizontal in units of $\text{kWhr m}^{-2}\text{day}^{-1}$



Energy Calculation with **Rated Power** and **Peak Sun Hour**

PV Energy Delivery Calculation - Example

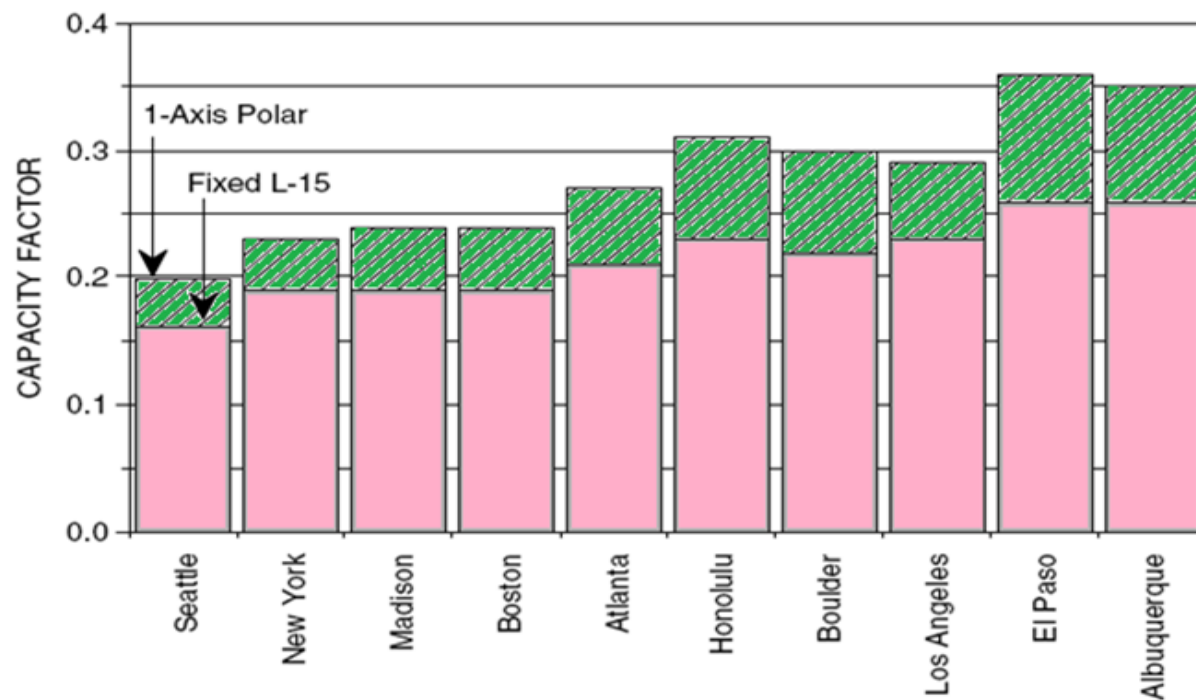
⌘ Estimate the annual energy delivered by the 1-kW (dc) array in Madison, WI, which south-facing, and has a tilt angle equal to its latitude minus 15°. Assume the dc-to-ac conversion efficiency at 72%.

⌘ Insolation Table for Madison, WI

	Madison, WI												
	Latitude 43.13°N												
Tilt	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Year
Lat − 15	3.0	3.9	4.5	5.1	5.8	6.2	6.2	5.7	4.8	3.8	2.5	2.3	4.5
Lat	3.4	4.3	4.7	5.0	5.5	5.7	5.8	5.5	4.8	4.0	2.8	2.6	4.5
Lat + 15	3.6	4.4	4.6	4.6	4.8	4.9	5.0	5.0	4.6	4.0	2.9	2.8	4.3
90	3.5	4.0	3.7	3.2	2.9	2.8	2.9	3.2	3.4	3.3	2.6	2.7	3.2
1-Axis (Lat)	3.9	5.0	5.8	6.4	7.3	7.8	7.7	7.1	6.0	4.8	3.2	3.0	5.7
Temp. (°C)	−4.0	−1.1	5.3	13.7	20.5	25.7	28.0	26.4	21.9	15.5	6.7	−1.2	13.1

$$\text{Capacity Factor} = [\text{"Peak Sun Hour"} / 24]$$

CFs for a number of U.S. cities



Example Problem

- ✚ A PV system is installed on top of the Engineering building (Latitude: 38.9°). The PV system is composed of fifteen (15) 150 W (dc) solar panels, and is installed south-facing, tilted with an angle to its latitude. A DC-to-AC converter is installed which has a conversion efficiency of 75%. Calculate the annual energy the PV system can deliver (ac kWh) if the annual insolation is $4.5 \text{ kWh/m}^2\text{-day}$.

