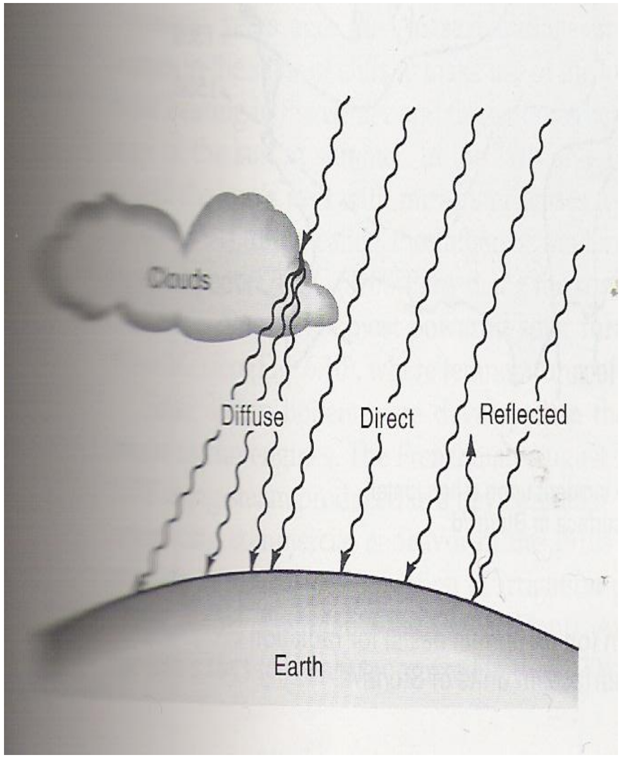
ELG4126
Solar Energy
The Ultimate Renewable Resource

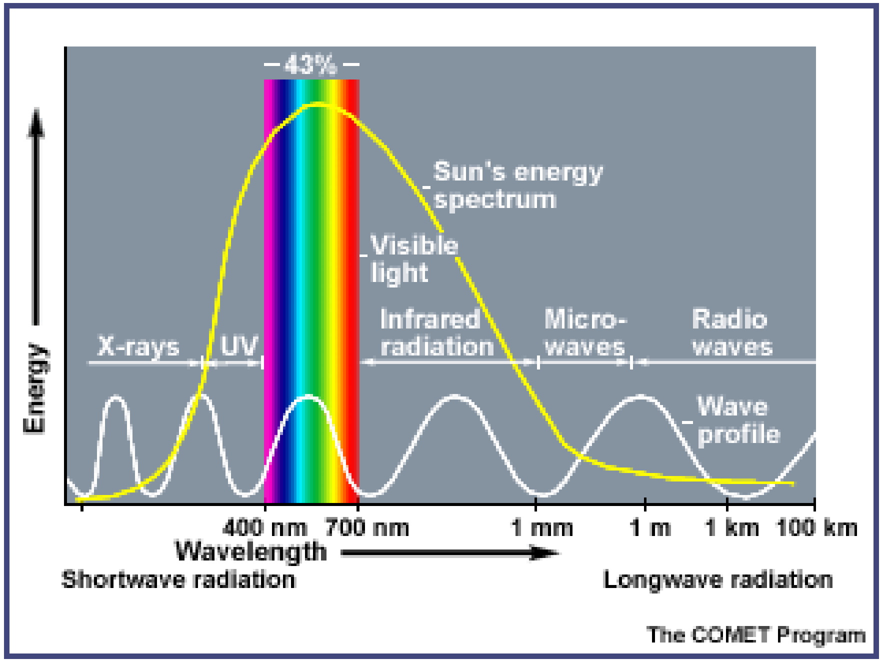


Based Partially on Renewable and Efficient Electric Power System, Gilbert M. Masters, Wiely

What is Solar Energy?

1.4 million kilometer diameter, thermonuclear furnace fusing hydrogen atoms into helium.

The resulting loss of mass is converted into about 3.8 × 1020 MW of electromagnetic energy that radiates outward from the surface into space.



Advantages and Disadvantages

Advantages:

- All chemical and radioactive polluting byproducts of the thermonuclear reactions remain behind on the sun, while only pure radiant energy reaches the Earth.
- Energy reaching the earth is incredible. By one calculation, 30 days of sunshine striking the Earth have the energy equivalent of the total of all the planet's fossil fuels, both used and unused!

Disadvantages:

- Sun does not shine consistently.
- Solar energy is a diffuse source. To harness it, we must concentrate it into an amount and form that we can use, such as heat and electricity.
- Addressed by approaching the problem through collection, conversion, and storage.

Blackbody

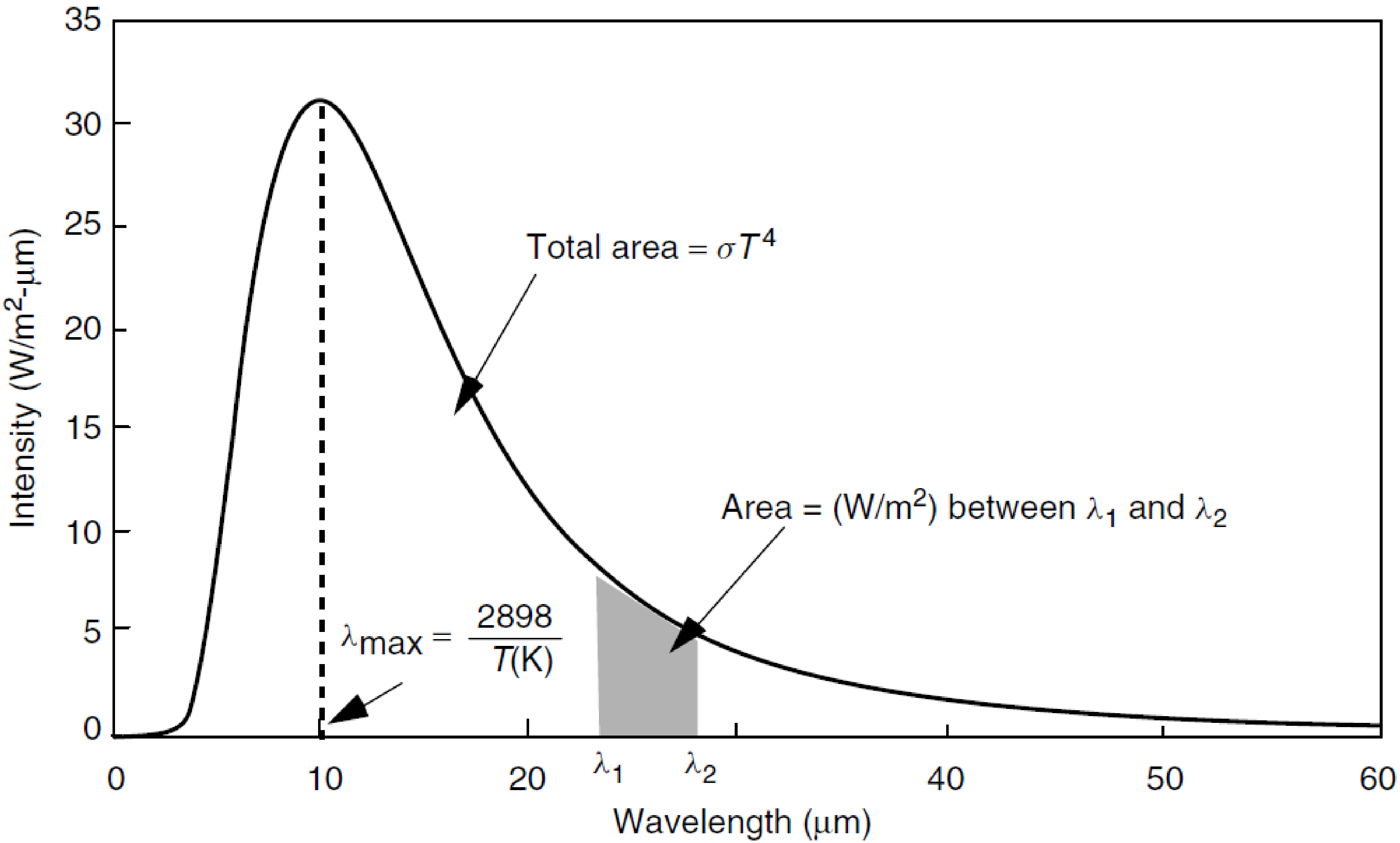
- Every object emits radiant energy in an amount that is a function of its temperature. The usual way to describe how much radiation an object emits is to compare it to a theoretical abstraction called a **blackbody**.
- A blackbody is defined to be a perfect emitter as well as a perfect absorber. As 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; that is, none is reflected and none is transmitted through it.

- The wavelengths emitted by a blackbody depend on its temperature as described by **Planck's law**.

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

- where E_λ is the emissive power per unit area of a blackbody (W/m2 μm), T is the absolute temperature of the body (K), and λ is the wavelength (μm).
- Modeling the earth itself as a 288 K (15◦C) blackbody results in the emission spectrum plotted

The Spectral Emissive Power of a 288 K Blackbody



- The area under Planck's curve between any two wavelengths is the power emitted between those wavelengths, so the total area under the curve is the total radiant power emitted. That total is conveniently expressed by the **Stefan–Boltzmann law of radiation**:

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

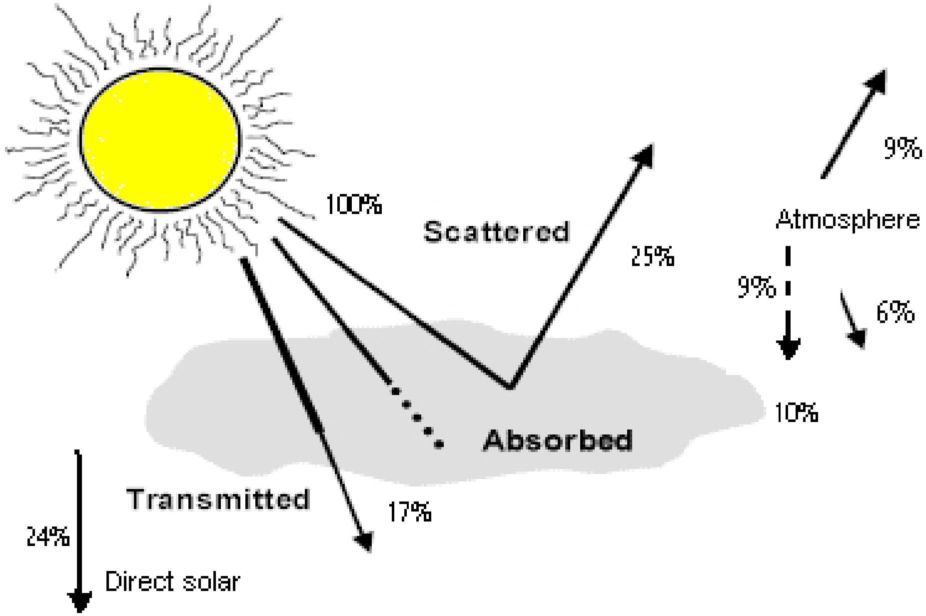
- where *E* is the total blackbody emission rate (W), *σ* is the Stefan–Boltzmann constant = 5.67 × 10^{-8} W/m^2-K^4, *T* is the absolute temperature of the blackbody (K), and *A* is the surface area of the blackbody (m^2).

- Another convenient feature of the blackbody radiation curve is given by **Wien's displacement rule**, which tells us the wavelength at which the spectrum reaches its maximum point:

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

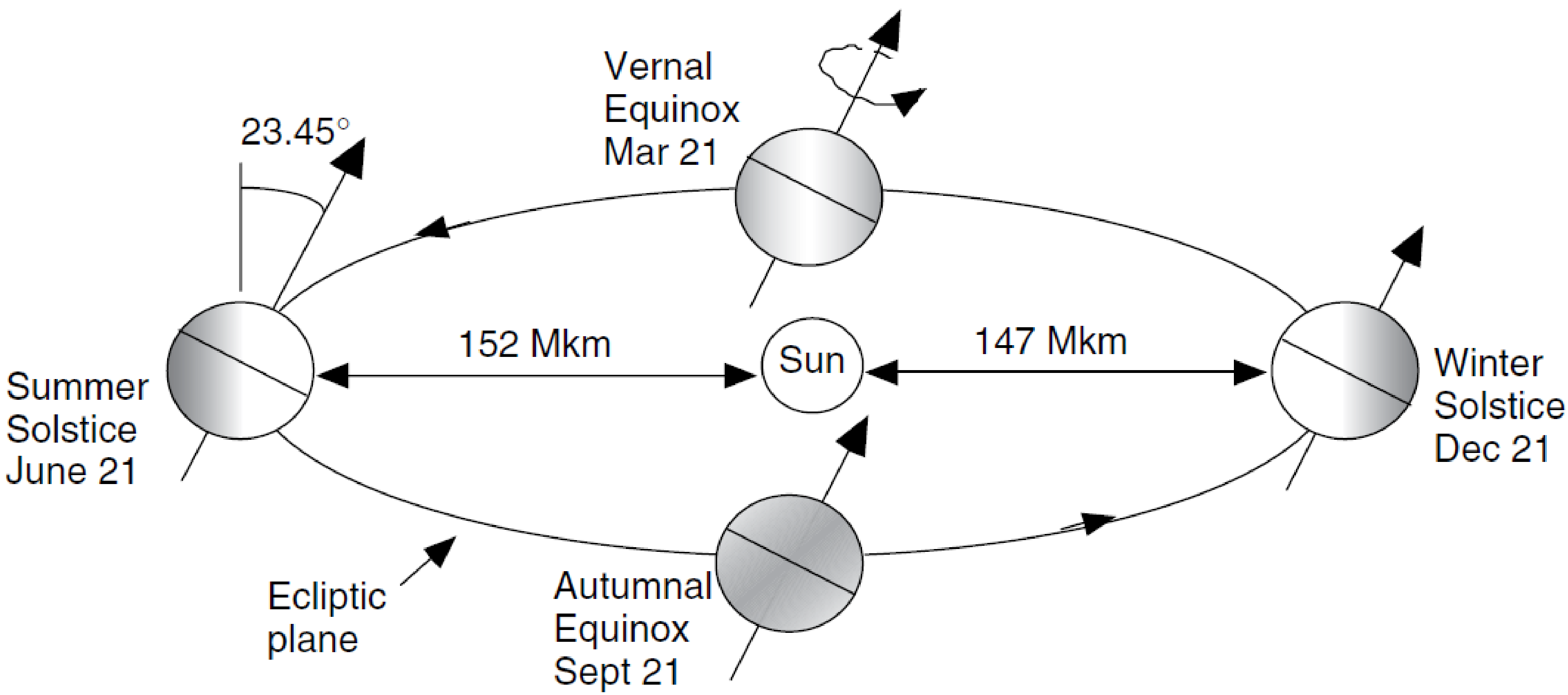
- where the wavelength is in microns (µm) and the temperature is in kelvins.

How Much Solar Energy?



The surface receives about 47% of the total solar energy that reaches the Earth. Only this amount is usable.

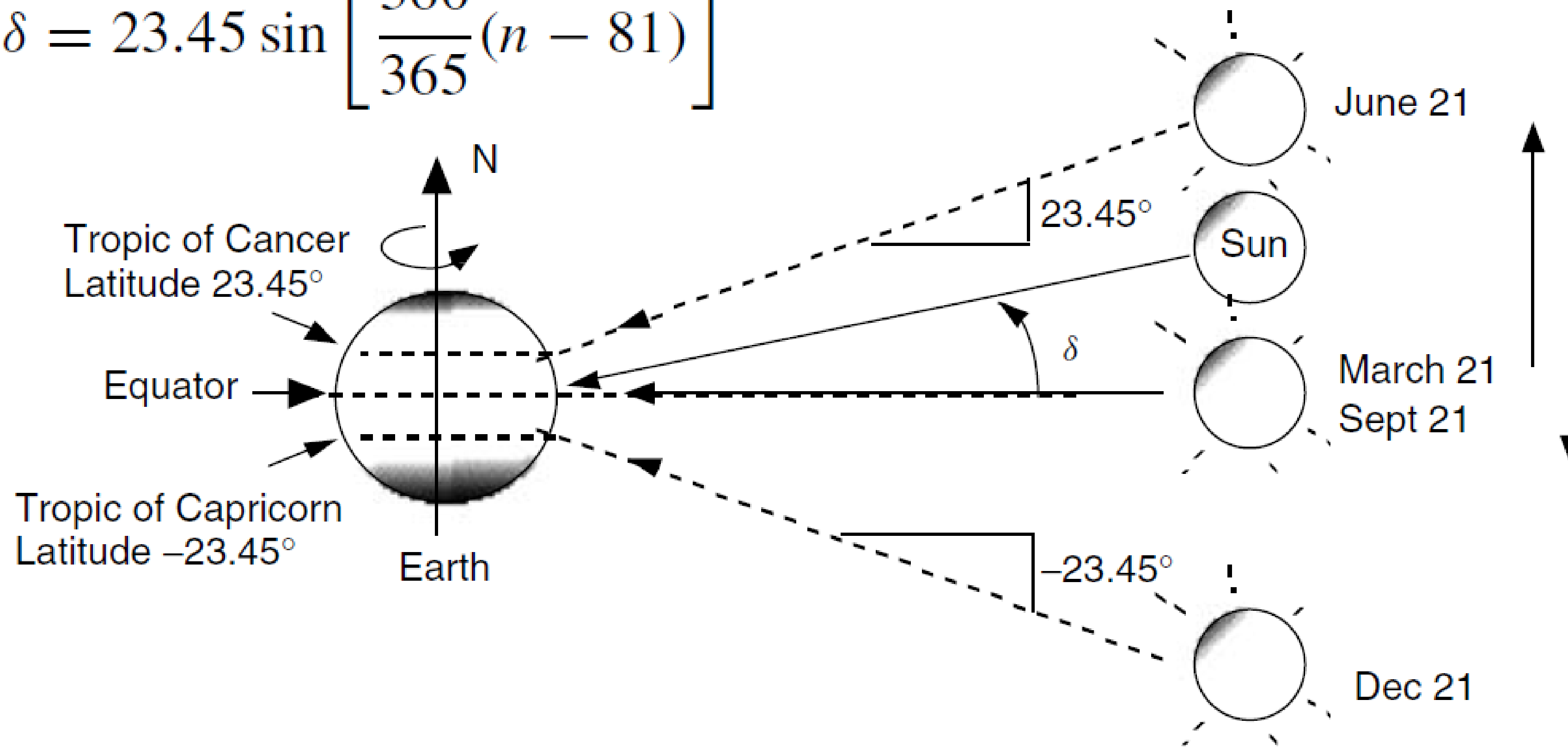
Winter and Summer are Designations for the Solstices in the Northern Hemisphere



Altitude Angle of the Sun at Solar Noon

Solar Declination. δ

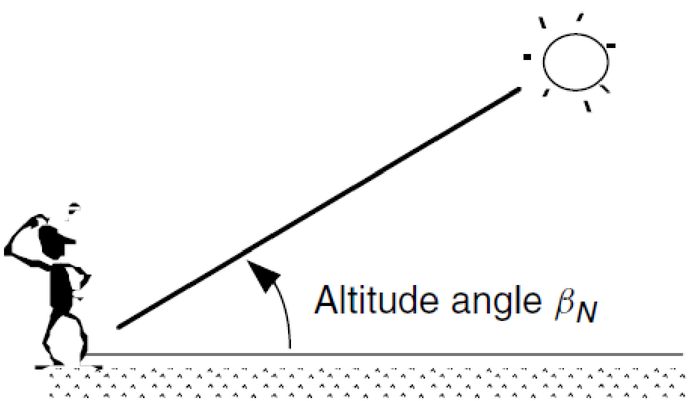
$$\delta = 23.45 \sin\left[\frac{360}{365}(n - 81)\right]$$

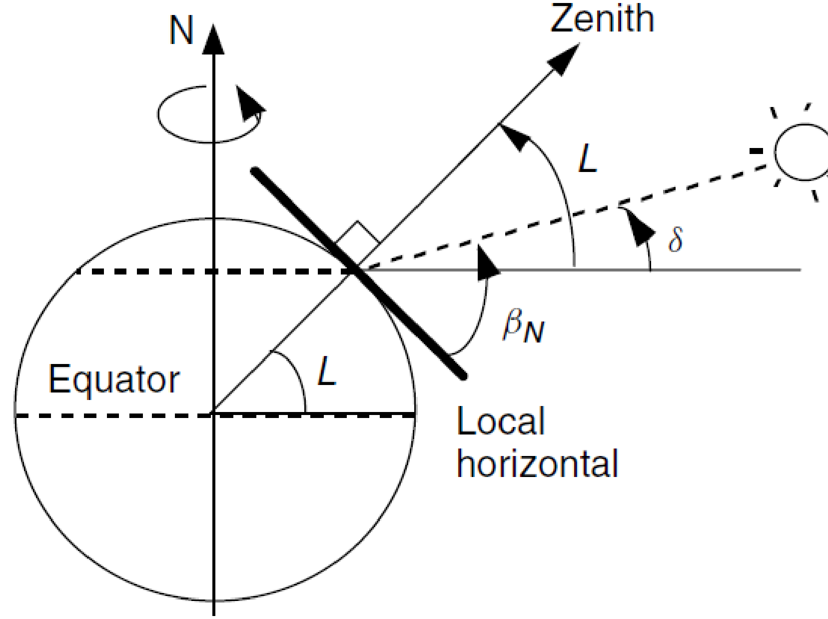


Solar Declination δ for the 21st Day of Each Month (degrees)

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

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





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 7.1, March 1 is the sixtieth day of the year so the solar declination (7.6) is

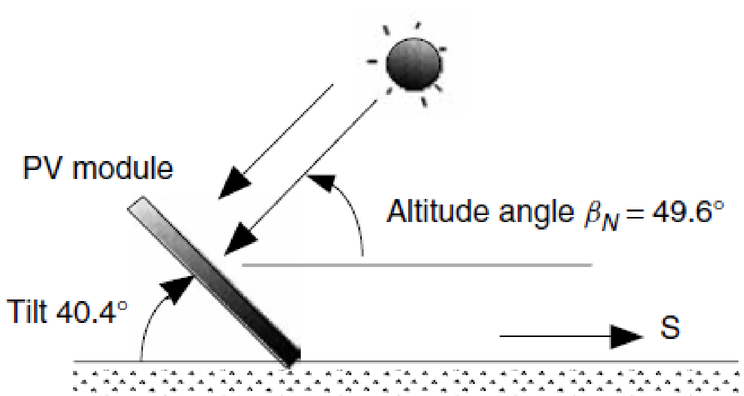
$$\delta = 23.45 \sin\left[\frac{360}{365}(n-81)\right] = 23.45^\circ \sin\left[\frac{360}{365}(60-81)^\circ\right] = -8.3^\circ$$

which, from (7.7), makes the altitude angle of the sun equal to

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

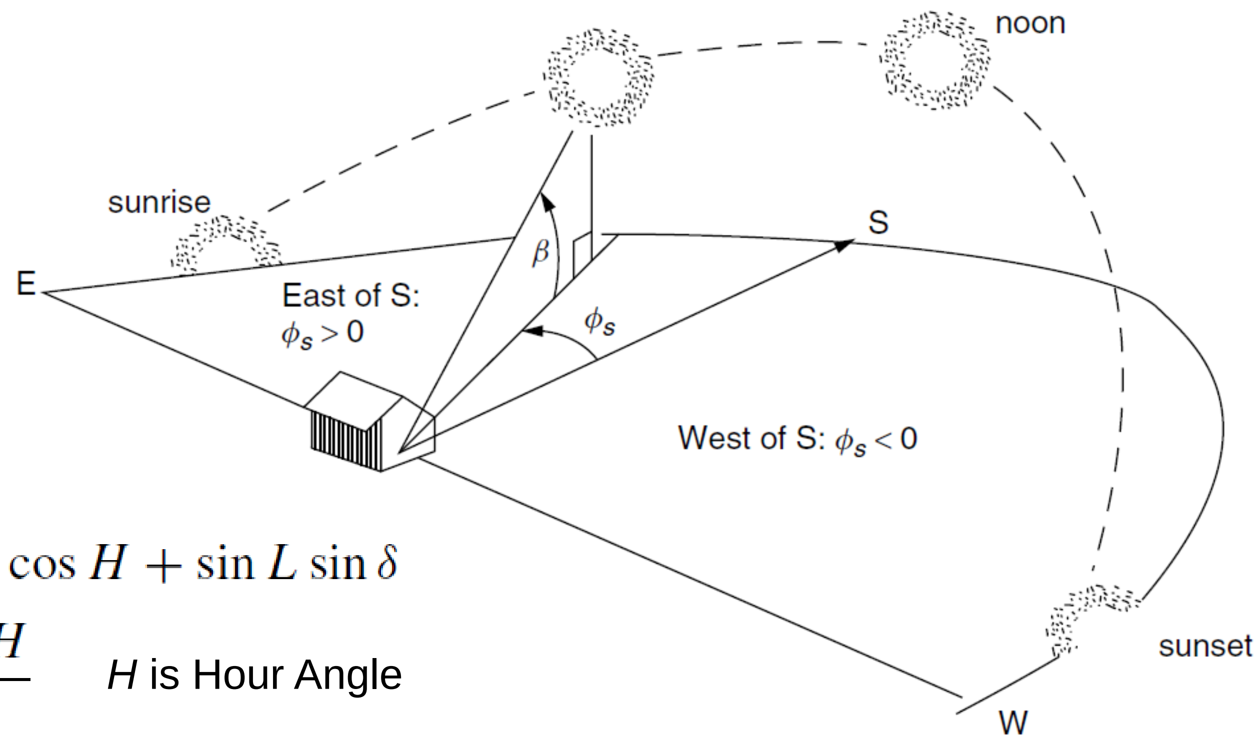
The tilt angle that would make the sun's rays perpendicular to the module at noon would therefore be

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



Solar Position at any Time of the Day

- The location of the sun at any time of day can be described in terms of its altitude angle β and its azimuth angle *φs* as shown in the following figure.
- The subscript *s* in the azimuth angle helps us remember that this is the azimuth angle of the sun.
- By convention, the azimuth angle is positive in the morning with the sun in the east and negative in the afternoon with the sun in the west.
- The azimuth angle shown in the figure uses true south as its reference, and this will be the assumption in this text unless otherwise stated.



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

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

H is Hour Angle

Where Is the Sun? Find the altitude angle and azimuth angle for the sun at 3:00 P.M. solar time in Boulder, Colorado (latitude 40°) on the summer solstice.

Solution. Since it is the solstice we know, without computing, that the solar declination δ is 23.45°. Since 3:00 P.M. is three hours after solar noon

$$H = \left(\frac{15^\circ}{\text{h}}\right) \cdot (\text{hours before solar noon}) = \frac{15^\circ}{\text{h}} \cdot (-3\ \text{h}) = -45^\circ$$

Using (7.8), the altitude angle is

$$\begin{aligned}\sin\beta &= \cos L \cos\delta \cos H + \sin L \sin\delta \\ &= \cos 40^\circ \cos 23.45^\circ \cos(-45^\circ) + \sin 40^\circ \sin 23.45^\circ = 0.7527 \\ \beta &= \sin^{-1}(0.7527) = 48.8^\circ\end{aligned}$$

the sine of the azimuth angle is

$$\begin{aligned}\sin\phi_S &= \frac{\cos\delta \sin H}{\cos\beta} \\ &= \frac{\cos 23.45^\circ \cdot \sin(-45^\circ)}{\cos 48.8^\circ} = -0.9848\end{aligned}$$

But the arcsine is ambiguous and two possibilities exist:

$$\phi_S = \sin^{-1}(-0.9848) = -80^\circ \qquad (80^\circ \text{west of south})$$

$$\text{or} \quad \phi_S = 180 - (-80) = 260^\circ \qquad (100^\circ \text{west of south})$$

To decide which of these two options is correct, we apply (7.11):

$$\cos H = \cos(-45^\circ) = 0.707 \qquad \text{and} \qquad \frac{\tan\delta}{\tan L} = \frac{\tan 23.45^\circ}{\tan 40^\circ} = 0.517$$

Since $\cos H \geq \dfrac{\tan\delta}{\tan L}$ we conclude that the azimuth angle is

$$\phi_S = -80^\circ \qquad (80^\circ \text{west of south})$$

Clear Sky Beam Plus Diffuse Insolation at 40° Latitude in January for South-Facing Collectors with Fixed Tilt Angle and for Tracking Mounts (hourly W/m^2 and daily kWh/m^2-day)

Solar Time	Tracking		Tilt Angles				Latitude 40°		
	One-Axis	Two-Axis	0	20	30	40	50	60	90
			January 21					(W/m^2)	
7, 5	0	0	0	0	0	0	0	0	0
8, 4	439	462	87	169	204	232	254	269	266
9, 3	744	784	260	424	489	540	575	593	544
10, 2	857	903	397	609	689	749	788	803	708
11, 1	905	954	485	722	811	876	915	927	801
12	919	968	515	761	852	919	958	968	832
kWh/d:	6.81	7.17	2.97	4.61	5.24	5.71	6.02	6.15	5.47

Sustainability through Heating Living Spaces

- Best design of a building is for it to act as a solar collector and storage unit. This is achieved through three elements: insulation, collection, and storage.
- Efficient heating starts with proper insulation on external walls, roof, and the floors. The doors, windows, and vents must be designed to minimize heat loss.
- **Collection:** south-facing windows and appropriate landscaping.
- **Storage:** Thermal mass—holds heat.
    - Water= 62 BTU per cubic foot per degree F.
    - Iron=54, Wood (oak) =29, Brick=25, concrete=22, and loose stone=20.

Heating Living Spaces

- A passively heated home uses about 60-75% of the solar energy that hits its walls and windows.
- The Center for Renewable Resources estimates that in almost any climate, a well-designed passive solar home can reduce energy bills by 75% with an added construction cost of only 5-10%.
- About 25% of energy is used for water and space heating.
- Major factor discouraging solar heating is low energy prices.

Solar-Thermal Electricity: Power Towers

- General idea is to collect the light from many reflectors spread over a large area at one central point to achieve high temperature.
- Example is the 10-MW solar power plant in Barstow, CA.
  - 1900 heliostats, each 20 feet by 20 feet
  - a central 295 feet tower
- An energy storage system allows it to generate 7 MW of electric power without sunlight.
- Capital cost is greater than coal fired power plant, despite the no cost for fuel, ash disposal, and stack emissions.
- Capital costs are expected to decline as more and more power towers are built with greater technological advances.
- One way to reduce cost is to use the waste steam from the turbine for space heating or other industrial processes.

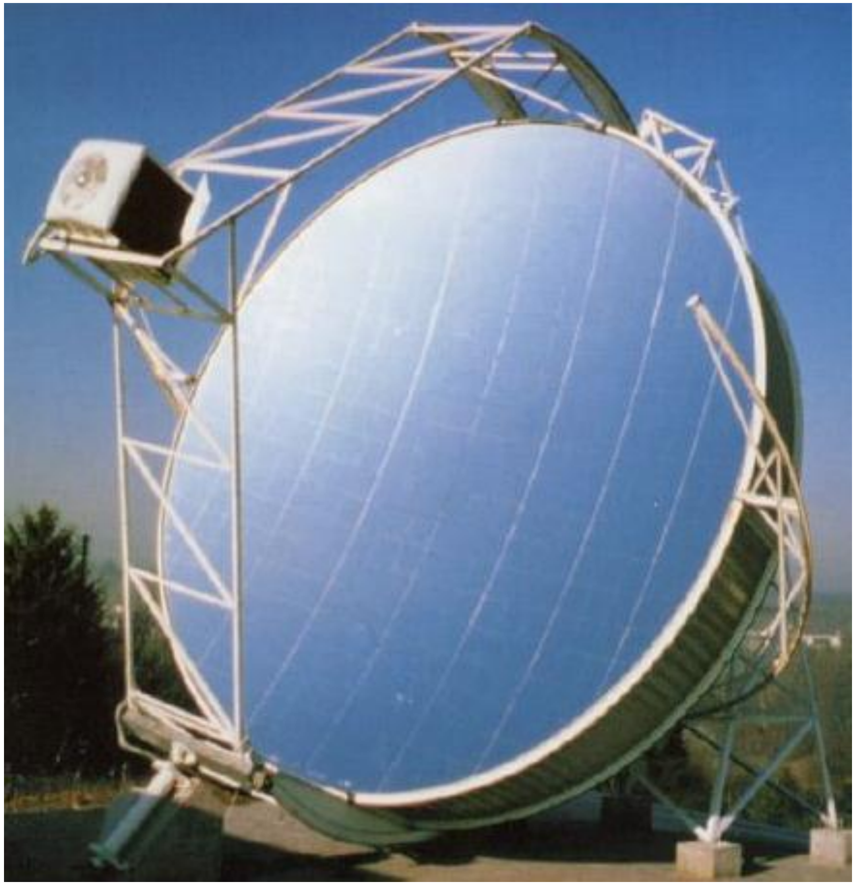
Power Towers

Power tower in Barstow, California.

Solar-Thermal Electricity: Parabolic Dishes and Troughs

- Focus sunlight on a smaller receiver for each device; the heated liquid drives a steam engine to generate electricity.
- The first of these Solar Electric Generating Stations (SEGS) was installed in California by Luz International.
- Output was 13.8 MW; cost was $6,000/peak kW and overall efficiency was 25%.
- Through federal and state tax credits, Luz was able to build more SEGS, and improved reduced costs to $3,000/peak kW and the cost of electricity from 25 cents to 8 cents per kWh, barely more than the cost of nuclear or coal-fired facilities.
- The more recent facilities converted a remarkable 22% of sunlight into electricity.

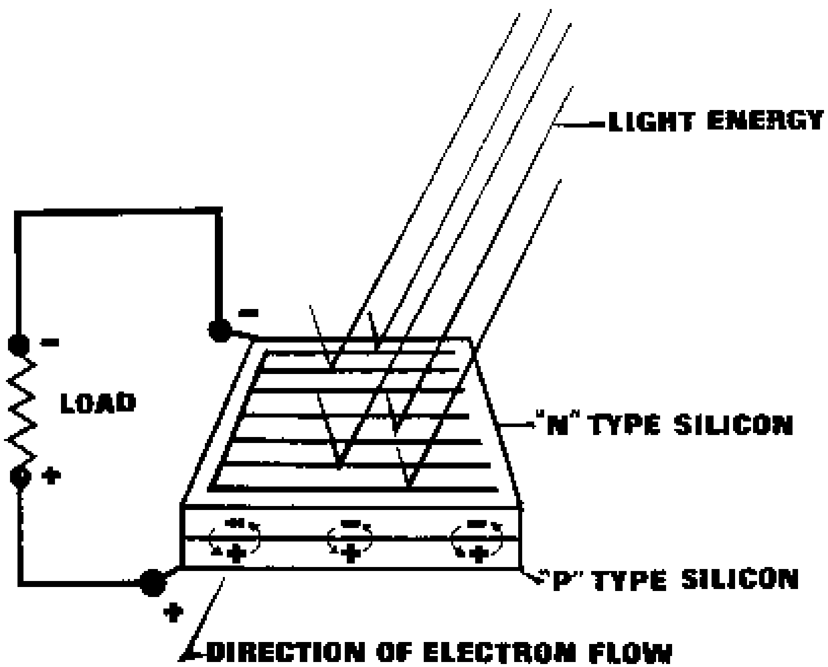
Parabolic Dishes and Troughs



Collectors in southern CA.

Because they work best under direct sunlight, parabolic dishes and troughs must be steered throughout the day in the direction of the sun.

Direct Conversion into Electricity



- Photovoltaic cells are capable of directly converting sunlight into electricity.
- A simple wafer of silicon with wires attached to the layers. Current is produced based on types of silicon (n- and p-types) used for the layers. Each cell=0.5 volts.
- Battery needed as storage
- No moving parts→do no wear out, but because they are exposed to the weather, their lifespan is about 20 years.

Solar Panels in Use

- Because of their current costs, only rural and other customers far away from power lines use solar panels because it is more cost effective than extending power lines.
- Note that utility companies are already purchasing, installing, and maintaining PV-home systems (Idaho Power Co.).
- Largest solar plant in US, sponsored by the DOE, served the Sacramento area, producing 2195 MWh of electric energy, making it cost competitive with fossil fuel plants.

Efficiency and Disadvantages

- Efficiency is far lass than the 77% of solar spectrum with usable wavelengths.
- 43% of photon energy is used to warm the crystal.
- Efficiency drops as temperature increases (from 24% at 0°C to 14% at 100°C.)
- Light is reflected off the front face and internal electrical resistance are other factors.
- Overall, the efficiency is about 10-20%.
- Cost of electricity from coal-burning plants is anywhere b/w 8-20 cents/kWh, while photovoltaic power generation is anywhere b/w $0.50-1/kWh.
- Does not reflect the true costs of burning coal and its emissions to the nonpolluting method of the latter.
- Underlying problem is weighing efficiency against cost.
  - Crystalline silicon-more efficient, more expensive to manufacture
  - Amorphous silicon-half as efficient, less expensive to produce.