The Path of the Sun

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Mechanical Engineering 483

Alternative Energy Engineering II

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California State University Northridge

Outline

- Review radiation properties for solar collectors
- Orientation of earth and sun
- Earth-based solar path
  - Definition of angles
  - Calculation of path
- Optimum tilt angles for solar collectors
- Solar air mass

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From last lecture

TABLE 12–3

Comparison of the solar absorptivity α_s of some surfaces with their emissivity ε at room temperature

Surface	α_s	ε
Aluminum		
Polished	0.09	0.03
Anodized	0.14	0.84
Foil	0.15	0.05
Copper		
Polished	0.18	0.03
Tarnished	0.65	0.75
Stainless steel		
Polished	0.37	0.60
Dull	0.50	0.21
Plated metals		
Black nickel oxide	0.92	0.08
Black chrome	0.87	0.09
Concrete	0.60	0.88
White marble	0.46	0.95
Red brick	0.63	0.93
Asphalt	0.90	0.90
Black paint	0.97	0.97
White paint	0.14	0.93
Snow	0.28	0.97
Human skin (Caucasian)	0.62	0.97

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Emissivity and Absorptivity

- Data on previous chart are due to difference in radiation properties associated with radiation temperature
  - For solar collector incoming radiation has source temperature about 5800 K
  - Outgoing radiation from collector has source temperature just over 300K
  - Kirchoff's Law says $\alpha_\lambda = \varepsilon_\lambda$, but this is true only at individual wavelengths
  - What is average over all wavelengths?

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Average Radiation Properties

- Integrated average properties over all wavelengths

$$\bar{\varepsilon} = \frac{1}{\sigma T^4}\int_0^\lambda \varepsilon_\lambda E_{b\lambda} d\lambda' \qquad \bar{\alpha} = \frac{1}{\sigma T^4}\int_0^\lambda \alpha_\lambda E_{b\lambda} d\lambda'$$

- Look at simple example where $\varepsilon_\lambda = \varepsilon_1$ for $\lambda < \lambda_1$ and $\varepsilon_\lambda = \varepsilon_2$ for $\lambda > \lambda_1$

$$\bar{\varepsilon} = \frac{1}{\sigma T^4}\int_0^\lambda \varepsilon_\lambda E_{b\lambda} d\lambda' = \frac{1}{\sigma T^4}\int_0^{\lambda_1} \varepsilon_1 E_{b\lambda} d\lambda' + \frac{1}{\sigma T^4}\int_{\lambda_1}^\infty \varepsilon_2 E_{b\lambda} d\lambda'$$

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Average Radiation Properties II

- Rearrange to get f_λ, the fraction of black body radiation between 0 and λ

$$\bar{\varepsilon} = \frac{\varepsilon_1}{\sigma T^4}\int_0^{\lambda_1} E_{b\lambda} d\lambda' + \frac{\varepsilon_2}{\sigma T^4}\int_{\lambda_1}^\infty E_{b\lambda} d\lambda' = \varepsilon_1 f_{\lambda_1} + \varepsilon_2\left(1 - f_{\lambda_1}\right)$$

- Similar equation for absorptivity ($\alpha_\lambda = \varepsilon_\lambda$)

$$\bar{\alpha} = \frac{\alpha_1}{\sigma T^4}\int_0^{\lambda_1} E_{b\lambda} d\lambda' + \frac{\alpha_2}{\sigma T^4}\int_{\lambda_1}^\infty E_{b\lambda} d\lambda' = \alpha_1 f_{\lambda_1} + \alpha_2\left(1 - f_{\lambda_1}\right)$$

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Example

- Data: ε_λ = 0.9 for λ < 3 μm and ε_λ = 0.2 for λ > 3
  - Solar T = 5800 K, λT = 17,400 μm·K, f_λ(17,400 μm·K) = 0.980155, find α
    - Use $\alpha_\lambda = \varepsilon_\lambda$

$$\overline{\alpha}_{5800\,K} = \alpha_1 f_{\lambda_1} + \alpha_2\left(1 - f_{\lambda_1}\right) = 0.9(0.980) + 0.2(1 - 0.980) = 0.886$$

  - Earth T = 300 K, λT = 900 μm·K, f_λ(17,400 μm·K) = 0.001, find ε

$$\overline{\varepsilon}_{300\,K} = \varepsilon_1 f_{\lambda_1} + \varepsilon_2\left(1 - f_{\lambda_1}\right) = 0.9(0.001) + 0.2(1 - 0.001) = 0.201$$

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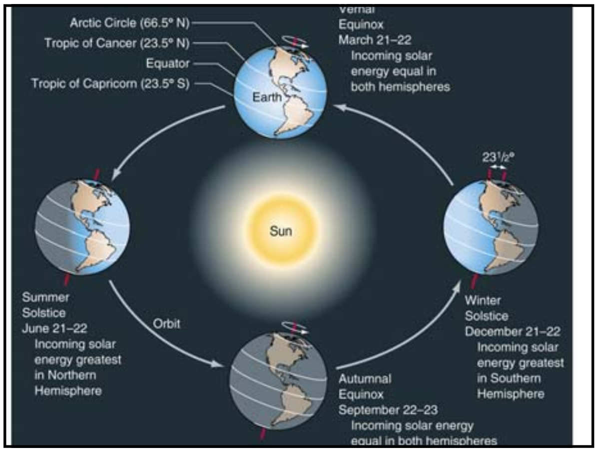
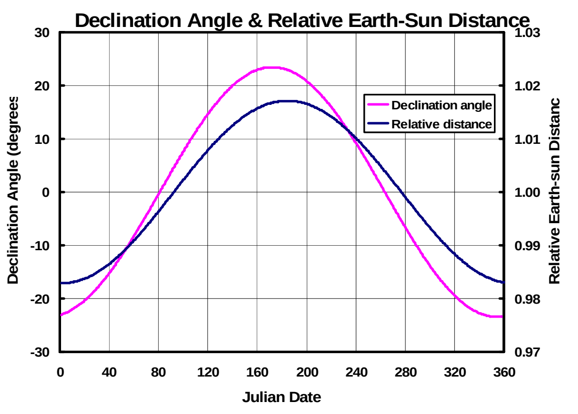
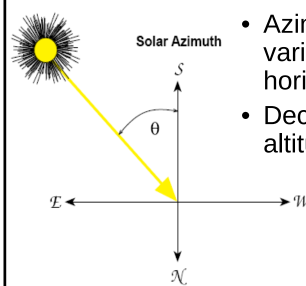
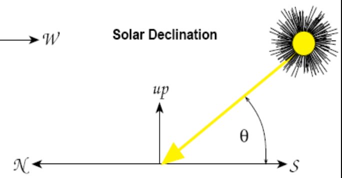




Solar Angles



- Azimuth is daily variation around horizon
- Declination is annual altitude variation



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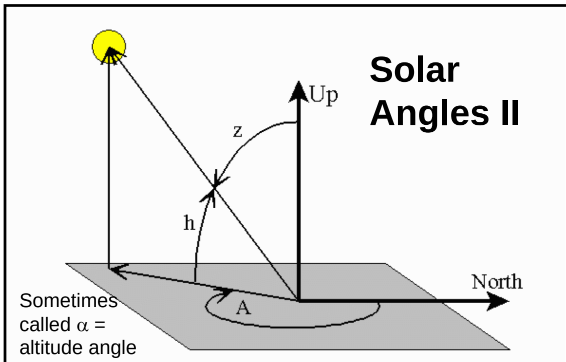
Solar Angles II

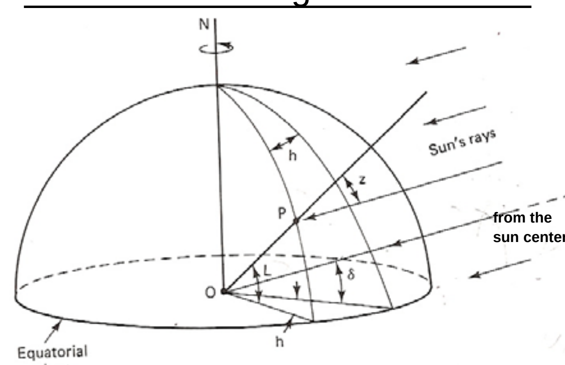


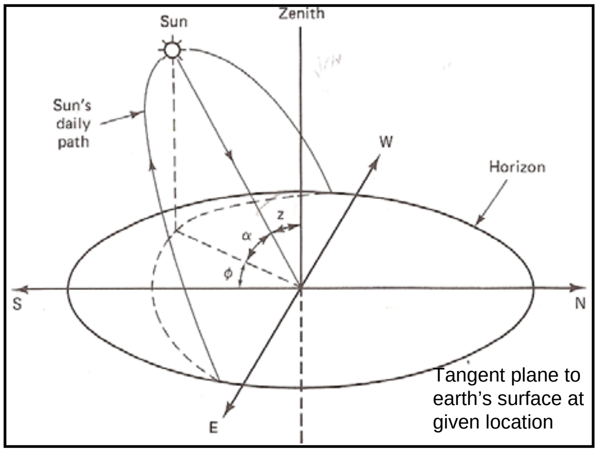
h = elevation angle, measured up from horizon

z = zenith angle, measured from vertical

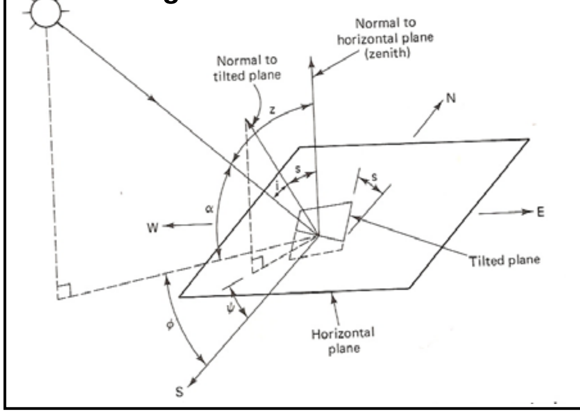
A = Azimuth angle, measured clockwise from North = $\phi = \alpha_s$

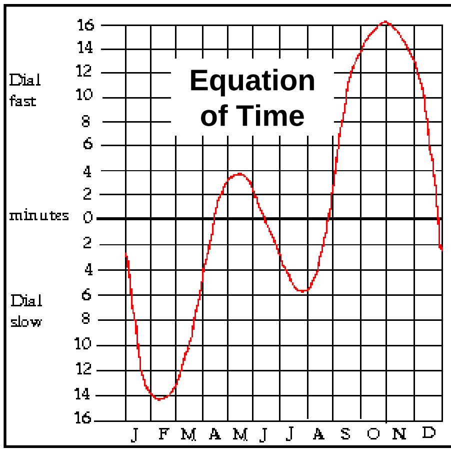
Solar Angles III





Angles for Tilted Collector





Solar Time = Standard Time + Equation of Time + (4 min/°) * (Standard Longitude – Local Longitude)

Standard Time = DST – 1 hour

Computing the Sun Path

- Input data: Latitude, L, date, hour h
- Find declination from serial date, n

$$\delta = (23.45^o)\sin\left[\frac{360}{365}(284+n)\frac{\pi}{180}\right] \quad (\delta \textbf{ in degrees})$$

- Two angles: altitude (α) and azimuth (ϕ)
  - $\sin(\alpha) = \sin(L)\sin(\delta) + \cos(L)\cos(\delta)\cos(h)$
  - $\sin(\alpha_s) = \sin(\phi) = \cos(\delta)\sin(h) / \cos(\alpha)$
  - Sun path is plot of α *vs.* $\phi = \alpha_s$ for one day
  - Plot is symmetric about solar noon
  - Typically plot data for 21st of month

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Path Calculation Problem

- Angles given as sin(angle) = x require arcsin function calculation
- Typical arcsine function returns angle between –90º and 90º
  - Limits correspond to range for sine between –1 and +1
  - Special calculation for hour angle limit
    - $h_{limit} = \pm\tan(\delta) / \tan(L)$
    - $\phi = \pm[\pi - \arcsin(\sin\phi)]$ for $|h| > |h_{limit}|$

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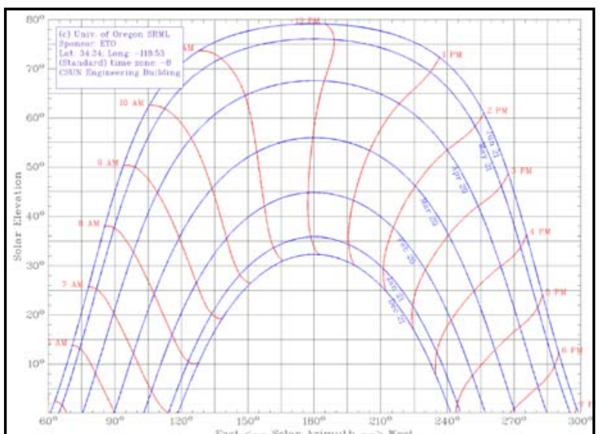
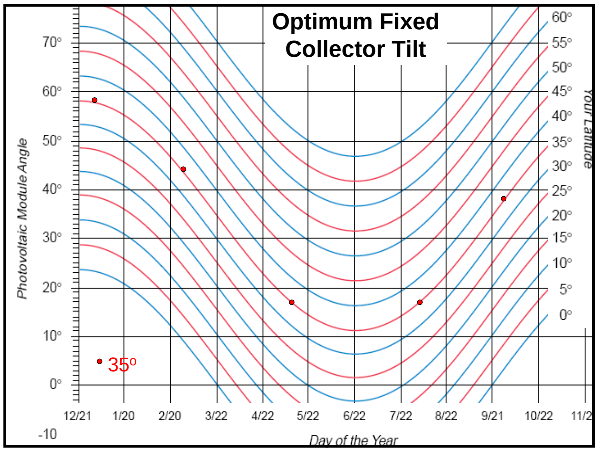
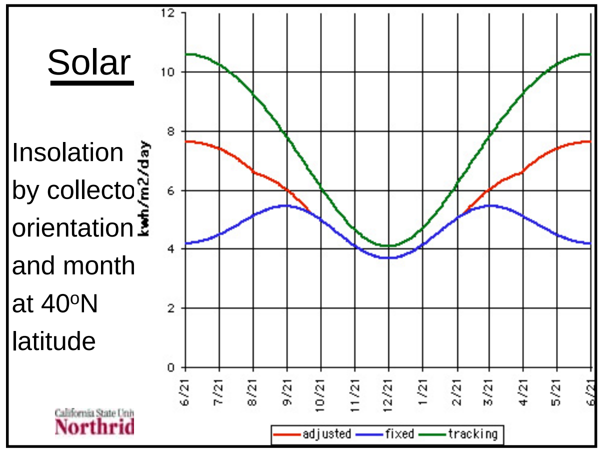
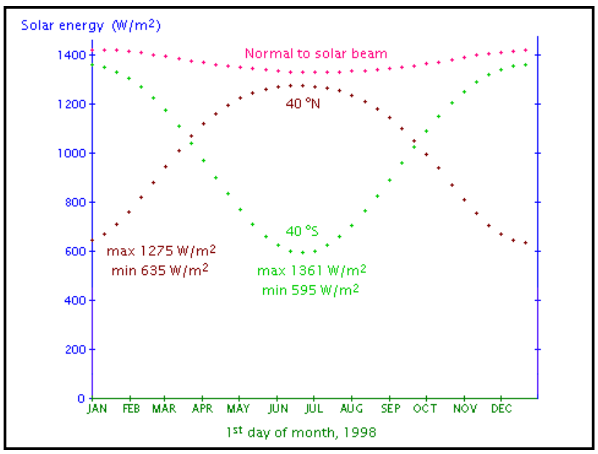
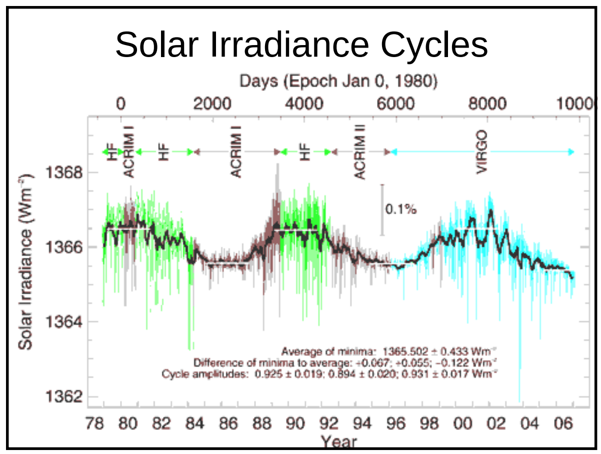
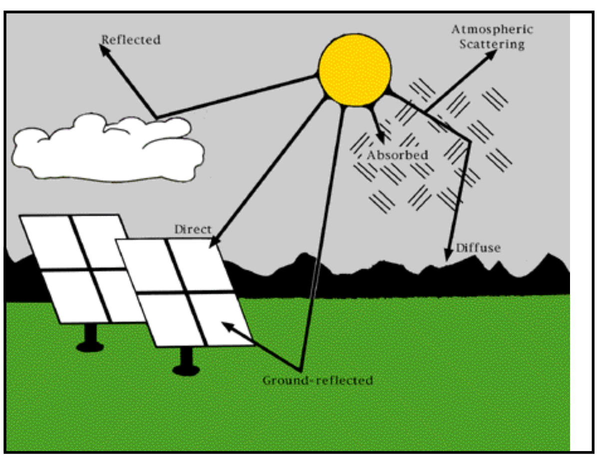


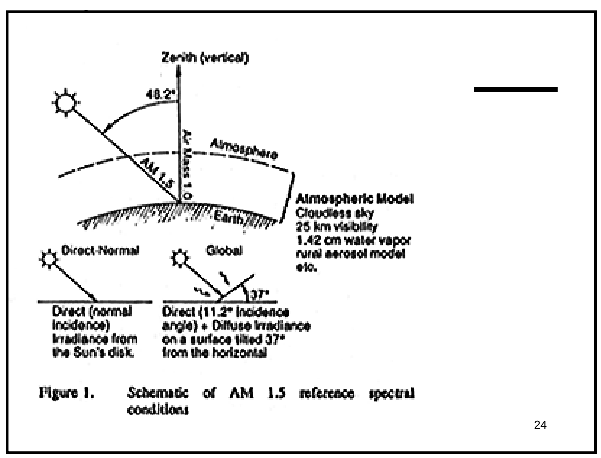

Optimum Fixed
Collector Tilt
Photovoltaic Module Angle
Your Latitude
Day of the Year
35º


Solar
Insolation
by collecto
orientation
and month
at 40ºN
latitude
kwh/m2/day
adjusted
fixed
tracking


Solar energy (W/m2)
Normal to solar beam
40 °N
40 °S
max 1275 W/m2
min 635 W/m2
max 1361 W/m2
min 595 W/m2
1st day of month, 1998


Solar Irradiance Cycles
Days (Epoch Jan 0, 1980)
Solar Irradiance (Wm-2)
Year
VIRGO
0.1%


Reflected
Atmospheric
Scattering
Absorbed
Direct
Diffuse
Ground-reflected


Zenith (vertical)
48.2°
Atmosphere
Air Mass 1.0
AM 1.5
Earth
Atmospheric Model
Cloudless sky
25 km visibility
1.42 cm water vapor
rural aerosol model
etc.
Direct-Normal
Global
37°
Direct (normal incidence) irradiance from the Sun's disk
Direct (11.2° incidence angle) + Diffuse irradiance on a surface tilted 37° from the horizontal
Figure 1. Schematic of AM 1.5 reference spectral conditions
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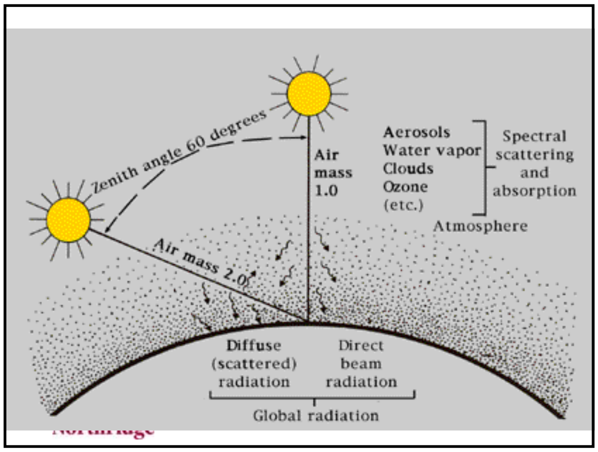
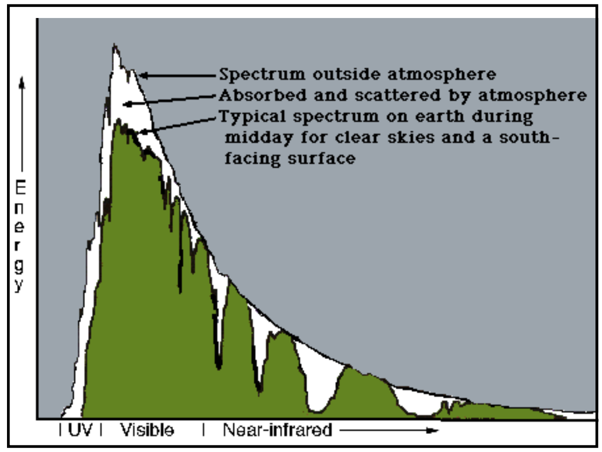
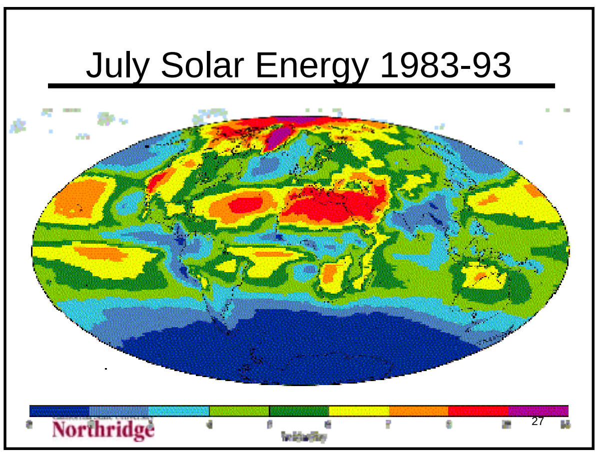

Zenith angle 60 degrees
Air mass 1.0
Aerosols
Water vapor
Clouds
Ozone
(etc.)
Spectral scattering and absorption
Atmosphere
Air mass 2.0
Diffuse (scattered) radiation
Direct beam radiation
Global radiation


Spectrum outside atmosphere
Absorbed and scattered by atmosphere
Typical spectrum on earth during midday for clear skies and a south-facing surface
Energy
UV
Visible
Near-infrared


July Solar Energy 1983-93
Northridge
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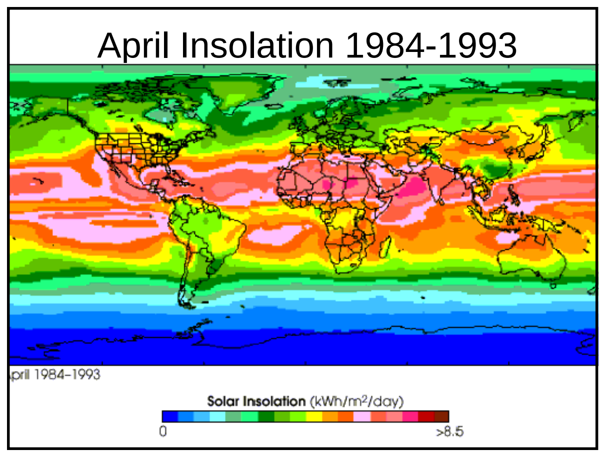
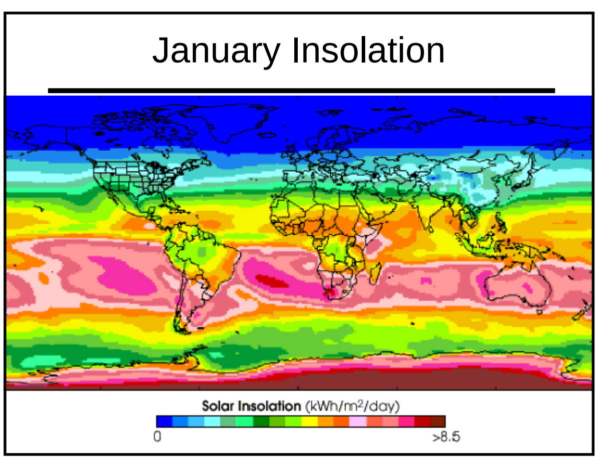
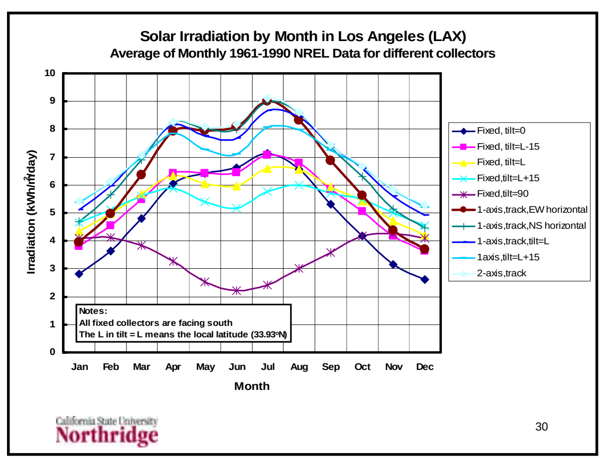

April Insolation 1984-1993
pril 1984-1993
Solar Insolation (kWh/m²/day)
0
>8.5


January Insolation
Solar Insolation (kWh/m²/day)
0
>8.5


Solar Irradiation by Month in Los Angeles (LAX)
Average of Monthly 1961-1990 NREL Data for different collectors
Irradiation (kWh/m²/day)
Month
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Fixed, tilt=0
Fixed, tilt=L-15
Fixed, tilt=L
Fixed,tilt=L+15
Fixed,tilt=90
1-axis,track,EW horizontal
1-axis,track,NS horizontal
1-axis,track,tilt=L
1axis,tilt=L+15
2-axis,track
Notes:
All fixed collectors are facing south
The L in tilt = L means the local latitude (33.93°N)
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