EELE408 Photovoltaics

Lecture 04: Apparent Motion of the Sum

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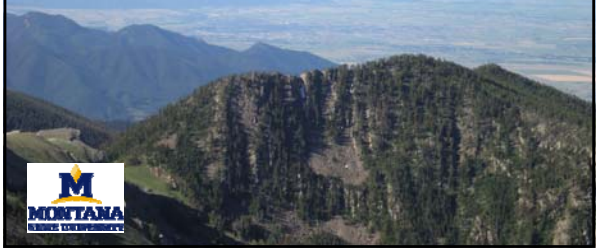
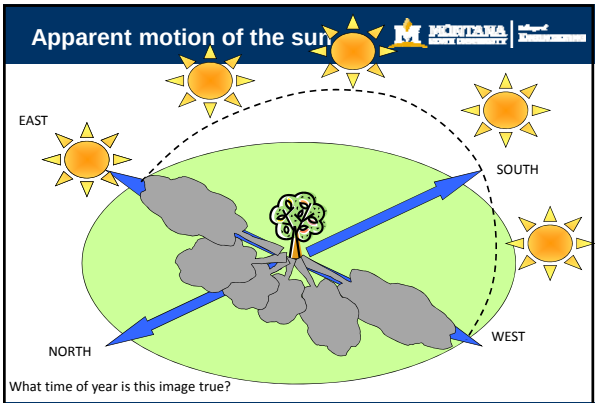


Apparent motion of the sun



What time of year is this image true?

March 22: Spring Equinox
Sept 23: Fall Equinox

Capturing the Light

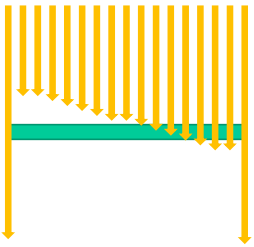
- The power capture by a surface is going to be a function of the angle between the normal to the surface and the light

Angle Effects 0º

$\Theta = 0^{\circ} \quad \cos\Theta = 1$

All the power is incident on the surface

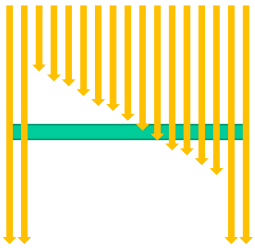
Angle Effects 15º



$\Theta = 15^{\circ} \qquad \cos\Theta = 0.9659$

96.6% of the power is incident on the surface

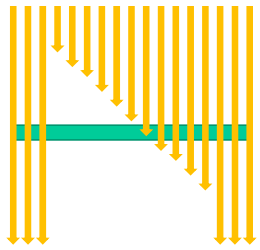
Angle Effects 30º



$\Theta = 30^{\circ} \cos\Theta = 0.8660$

86.6% of the power is incident on the surface

Angle Effects 45º



$$\Theta = 45^{\circ} \cos\Theta = 0.7071$$

70.7% of the power is incident on the surface

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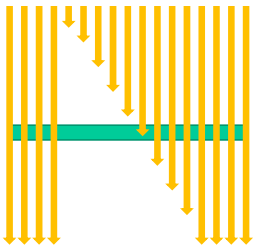
Angle Effects 60º



$$\Theta = 60^{\circ} \cos\Theta = 0.5000$$

50.0% of the power is incident on the surface

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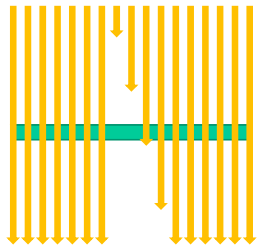
Angle Effects 75º



$$\Theta = 75^{\circ} \cos\Theta = 0.2588$$

25.9% of the power is incident on the surface

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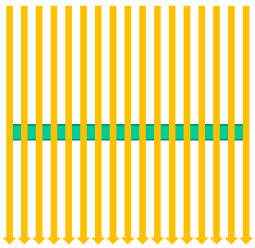
Angle Effects 90º



$$\Theta = 90^{\circ} \cos\Theta = 0.0000$$

None of the power is incident on the surface

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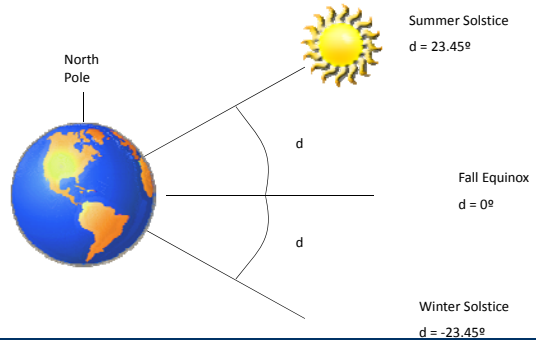
Declination Angle of Sun



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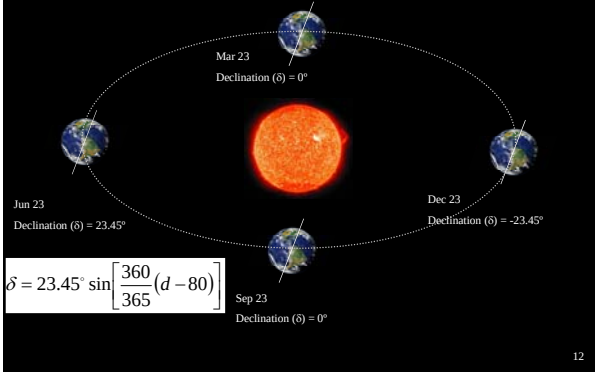
Declination Angle



$$\delta = 23.45^{\circ} \sin\left[\frac{360}{365}(d-80)\right]$$

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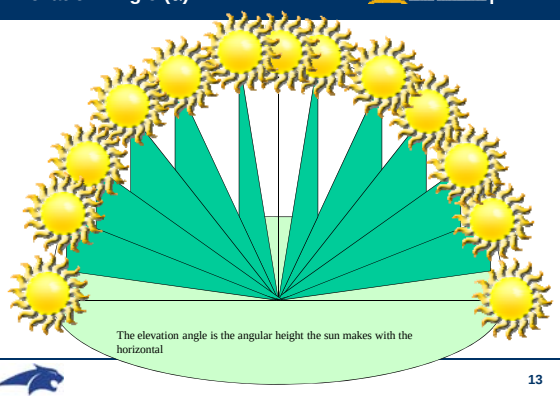
Elevation Angle (α)



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Solar Time

- Local Time (LT): varies with time zones and day light savings
- Solar noon Local Solar Time (LST): time when sun is highest in the sky = 0º
- Hour Angle (HRA)=15º(LST-12)
  - Zero at solar noon
  - Negative in the morning
  - Positive in the afternoon

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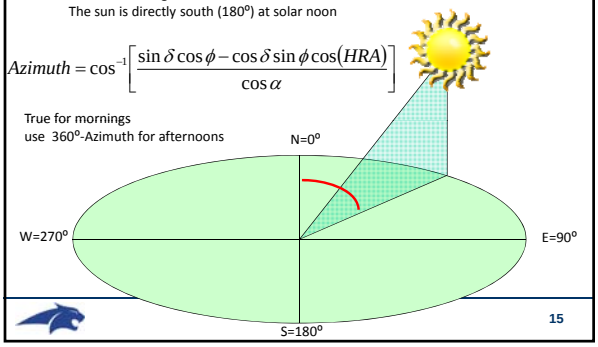
Azimuth Angle

Azimuth angle is the angle direction of the sun.
North is at 0 degrees
The sun is directly south (180º) at solar noon

f = latitude (Bz@ 45.68º)

$$Azimuth = \cos^{-1}\left[\frac{\sin\delta\cos\phi - \cos\delta\sin\phi\cos(HRA)}{\cos\alpha}\right]$$

True for mornings
use 360º-Azimuth for afternoons



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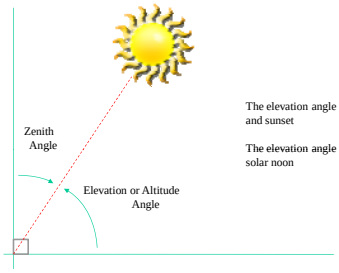
Elevation and Zenith Angles



The elevation angle is zero at sunrise and sunset

The elevation angle is a maximum at solar noon

$$Elevation = \sin^{-1}\left[\sin\delta\sin\phi + \cos\delta\cos\phi\cos(HRA)\right]$$

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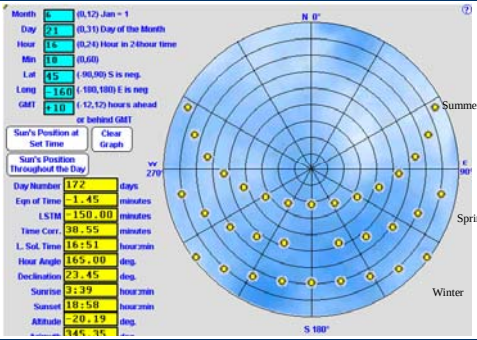
Polar Plot of Sun Position for Bozeman



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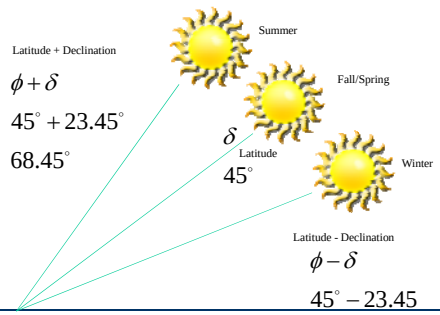
Peak Elevation Angle (Bozeman)



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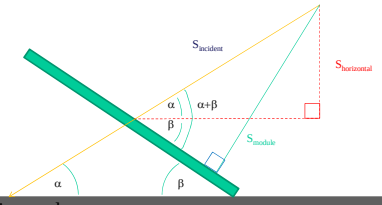
Solar Radiation on a Tilted Surface



α = elevation angle
β = tilt angle of panel
δ = declination angle
ϕ = latitude
$\alpha = 90^\circ - \phi + \delta(\text{at solar noon})$

$$S_{horizontal} = S_{incident} \sin\alpha$$
$$S_{module} = S_{incident} \sin(\alpha+\beta)$$
$$S_{module} = \frac{S_{horizontal} \sin(\alpha+\beta)}{\sin\alpha}$$

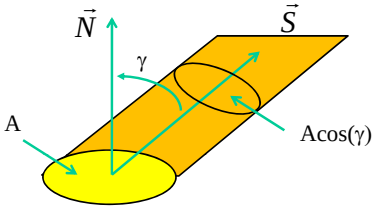
Arbitrary Angles

$$S_{module} = S_{incident}\left[\cos\alpha \sin\beta \cos(\psi - \Theta) + \sin\alpha \cos\beta\right]$$

a: sun elevation angle
b: module tilt angle
y: azimuth angle the panel faces
Q: sun azimuth angle

- Most fixed panels are facing toward the equator (south in northern Hemisphere) → $\psi = 180^o$
- Tracking Modules
  - $\beta(t) = 90^o - \alpha$
  - $\Psi(t) = \Theta$

Arbitrary Angles



$$S_{module} = S_{incident} \cos\gamma = S_{incident} \vec{S} \cdot \vec{N}$$

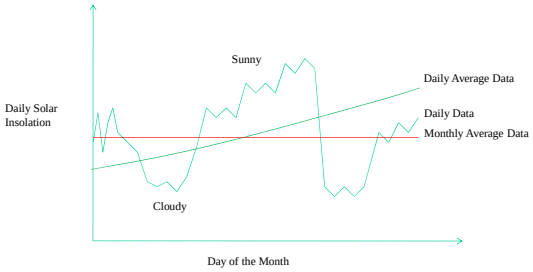
$\vec{S}$: Unit vector pointing towards sun

$\vec{N}$: Unit vector normal to surface

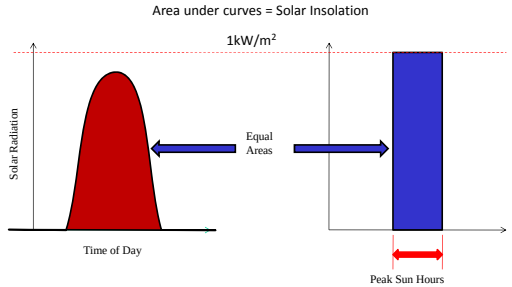
Measuring Solar Radiation

Pyranometers

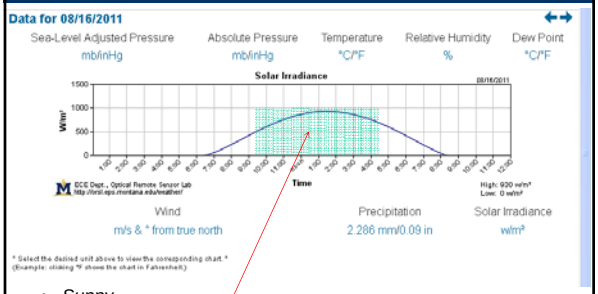
Solar Irradiance Data



Peak Sun Hours

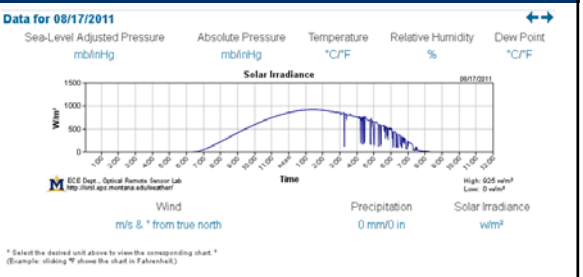


MSU Weather Station 1



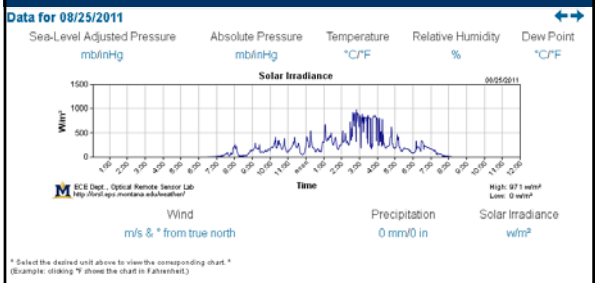
- Sunny
- (7 peak sun hours)

MSU Weather Station 2



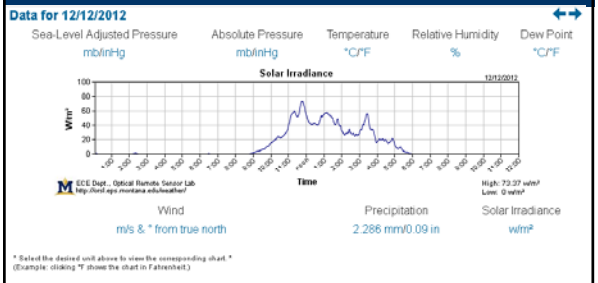
- Afternoon Clouds

MSU Weather Station 3



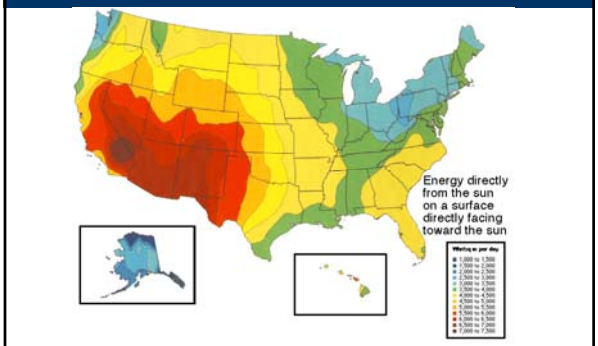
- Mostly Cloudy

MSU Weather Station 4



- Overcast: note the scale change

Isoflux Contour Plots



The number of hours the sun is shining

- d = day of the year
- ϕ = latitude
- δ = declination angle

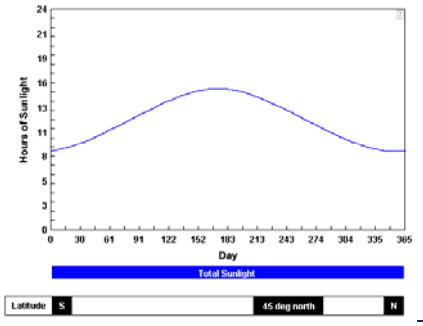
$$\delta = 23.45^{\circ}\sin\left[\frac{360}{365}(284+d)\right]$$

$$\text{sunrise} = 12 - \frac{1}{15^{\circ}}\cos^{-1}\left[\frac{\sin(\phi)\sin(\delta)}{\cos(\phi)\cos(\delta)}\right]$$

$$\text{sunset} = 12 + \frac{1}{15^{\circ}}\cos^{-1}\left[\frac{\sin(\phi)\sin(\delta)}{\cos(\phi)\cos(\delta)}\right]$$

(In solar time)

Hours of Sunlight(Latitude & Day)



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Daily Solar Irradiance

- HRA = hour angle
- α = elevation angle
- h = hour of the day

$$HRA = 15^{\circ}(h-12)$$

$$\alpha = \sin^{-1}[\sin(\delta)\sin(\phi)+\cos(\delta)\cos(\phi)\cos(HRA)]$$

$$H(d,\phi) = 1.367\left(0.7^{AM}\right)^{0.678}$$

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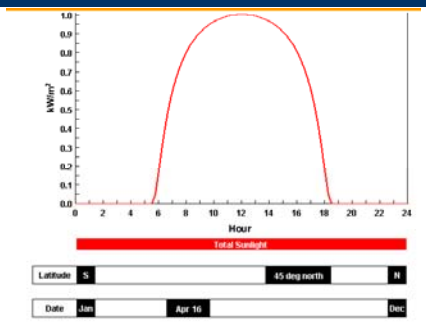
Power Density (Latitude & Day)



The power density throughout a given day at a particular location.

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Solar Insolation (latitude & tilt)

$$S_{module} = S_{incident}\left[\cos\alpha \sin\beta \cos(\psi - \Theta) + \sin\alpha \cos\beta\right]$$

a: sun elevation angle
b: module tilt angle
y: azimuth angle the panel faces
Q: sun azimuth angle

$$H = \sum_{h=sunrise}^{sunset} 1.367\left(0.7^{AM}\right)^{0.678}$$

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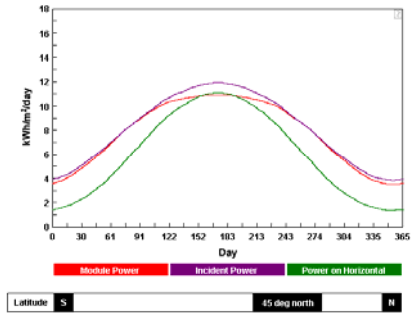
Solar Isolation (latitude & tilt)



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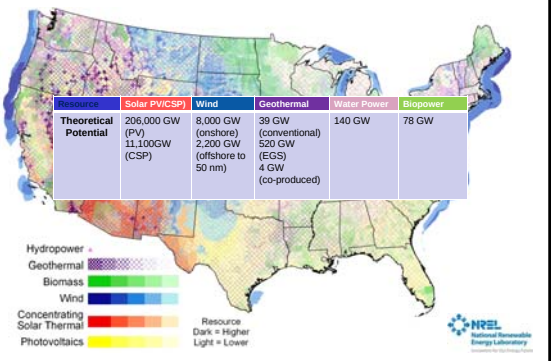
Renewable Energy Technology Resource Maps for the United States

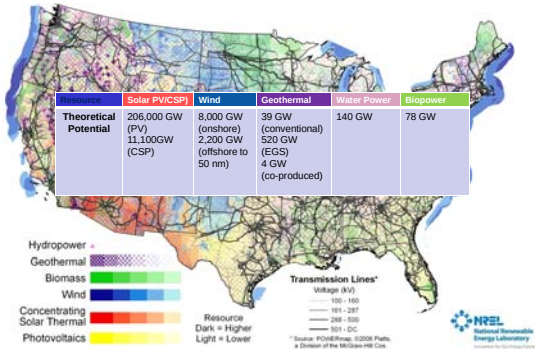
- Updated August 2009

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

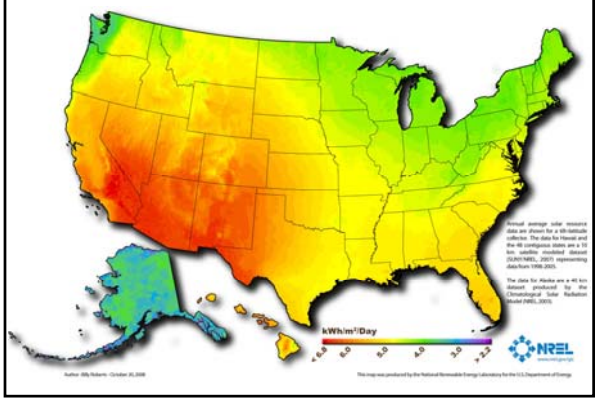
U.S. Renewable Resources



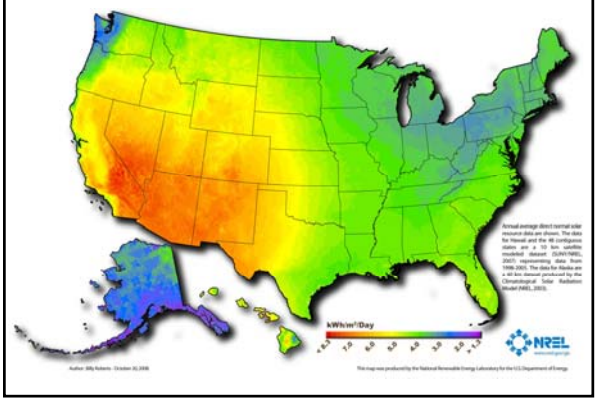
Including Transmission Lines



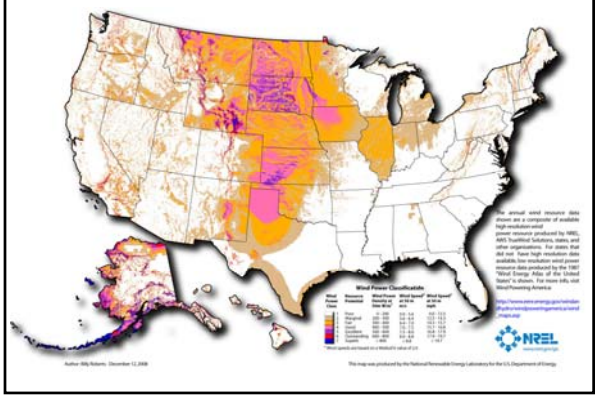
U.S. Photovoltaic Solar Resource



U.S. Concentrating Solar Resource



U.S. Wind Resource (50m)



U.S. Biomass Resource