The Solar Resource

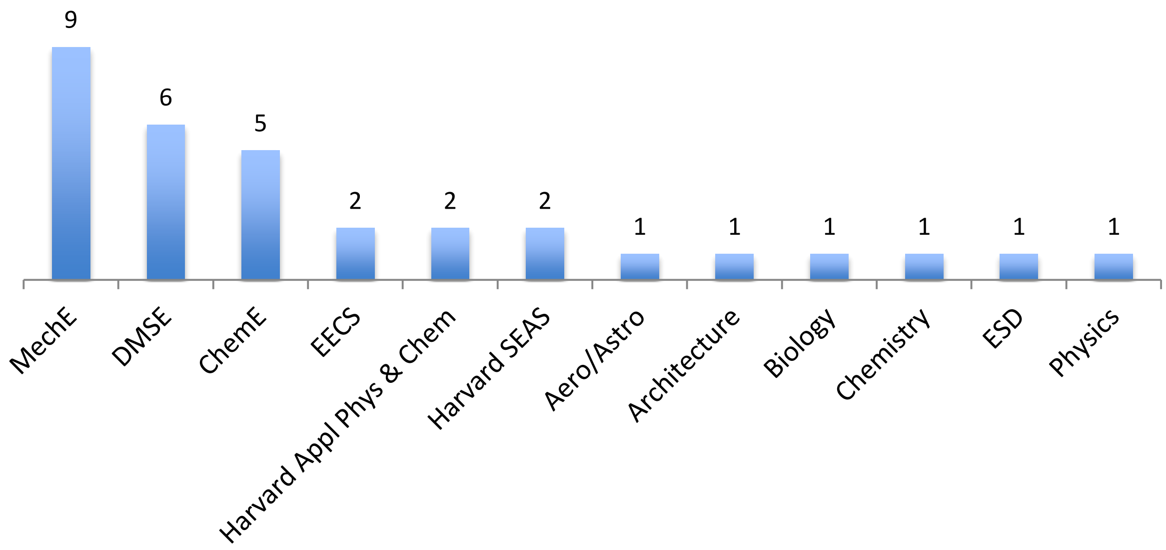
Lecture 2 – 9/13/2011

MIT Fundamentals of Photovoltaics 2.626/2.627 – Fall 2011

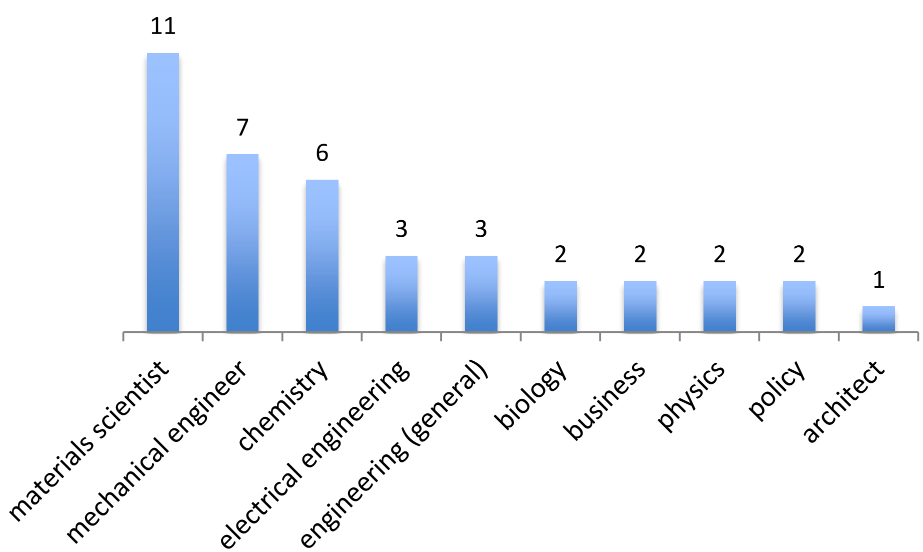
Prof. Tonio Buonassisi

2.626/2.627 Census 2011

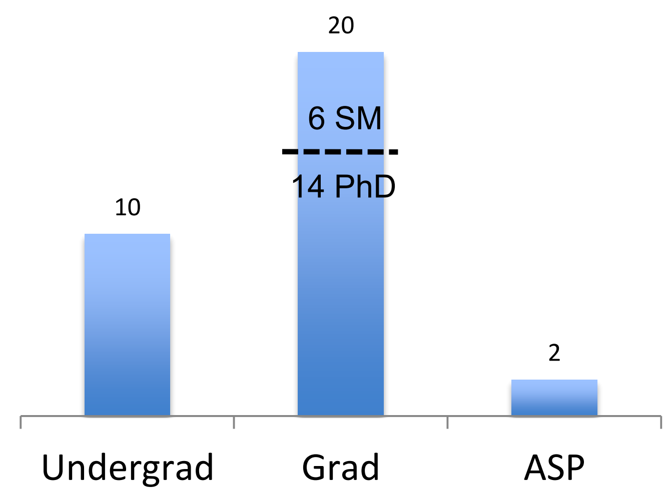
Department Affiliation

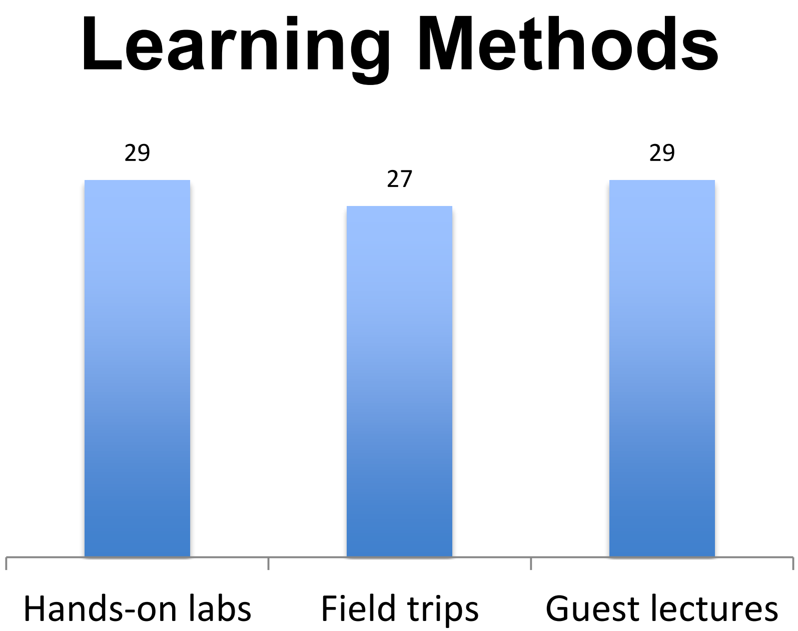


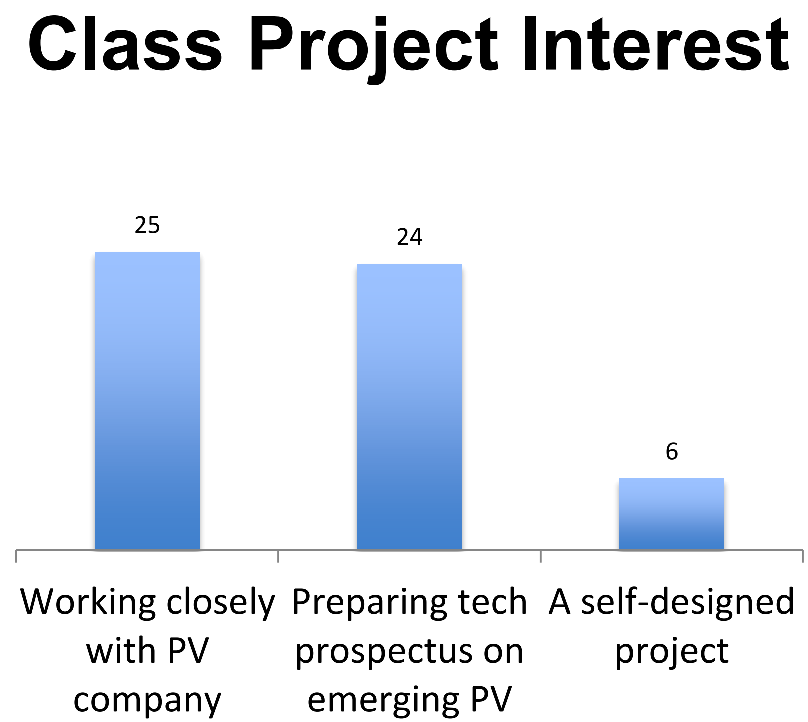
Self-Defined Expertise



Degree in Progress







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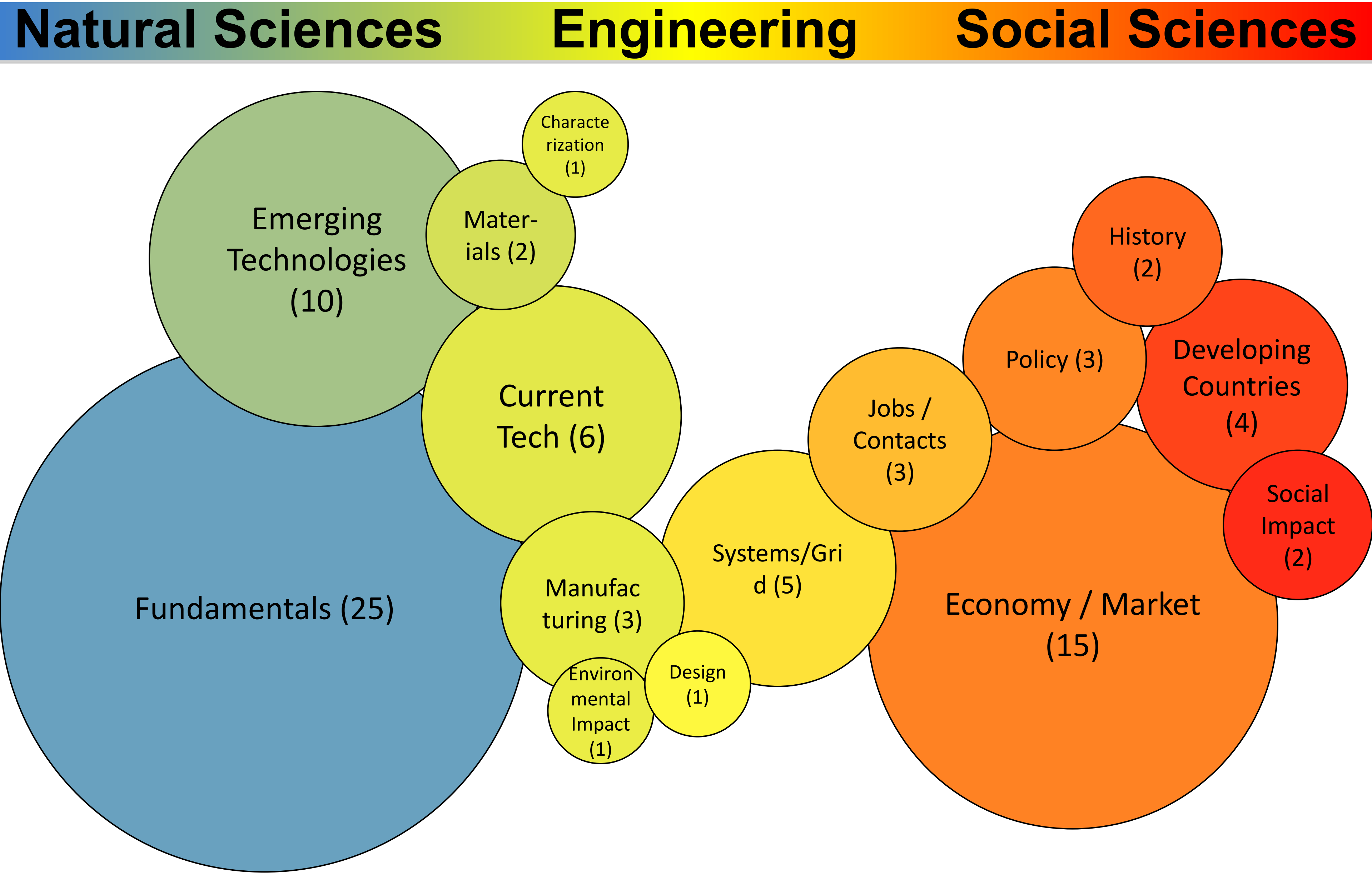
Learning Objectives



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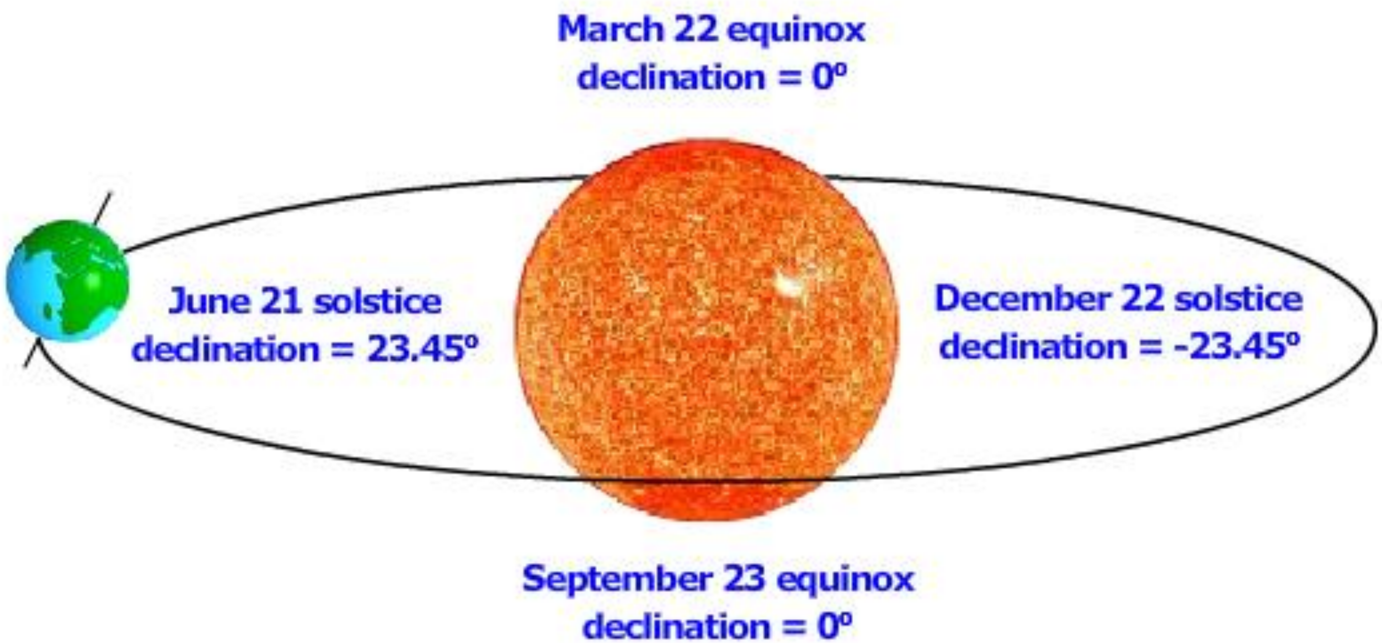
Before we begin… Review of Readings



Courtesy of PVCDROM. Used with permission.

http://pveducation.org/pvcdrom/properties-of-sunlight/declination-angle

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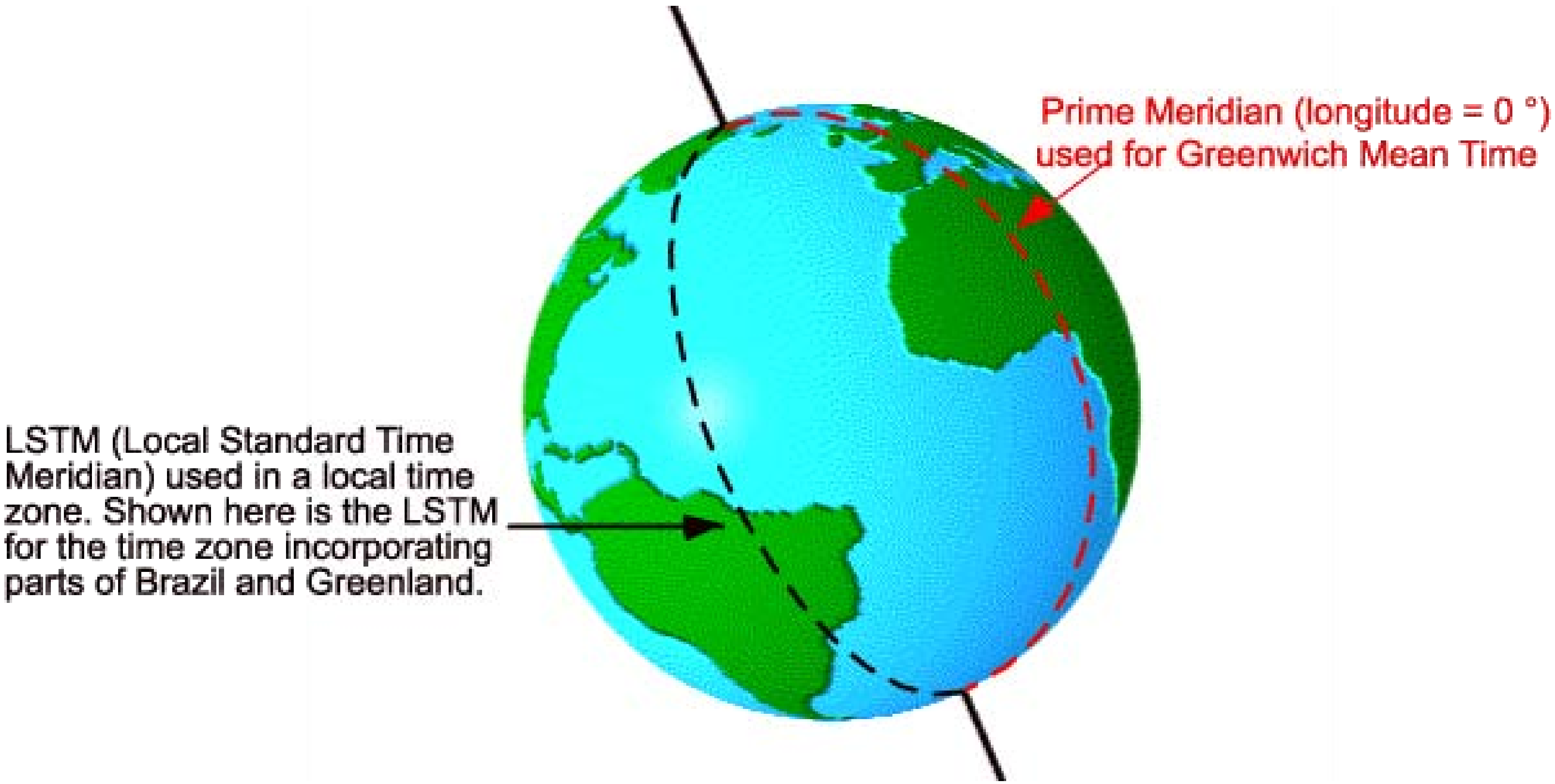

Courtesy of PVCDROM. Used with permission.

http://pveducation.org/pvcdrom/properties-of-sunlight/solar-time

Before we begin… a touch of History

Working together, to understand the Sun

16th-17th Century: Johannes Kepler
Refines predictive astronomy with elliptical orbital model, *Astronomia Nova*.

←

10th-11th Century: Abu Rayhan al-Bīrunī
Applies cartographic methods to aid astronomical observation, *Indica*.

↑

3rd Century BCE: Aristarchus of Samos
Confirms Yajnavalkya's principles, estimates interstellar distances via heliocentric model.

←

9th-8th Centuries BCE: Yajnavalkya
Solar calendar, relative sizes of Earth, Sun, and Moon, possibly first heliocentric model.

International collaboration essential to development of modern scientific models.

Many scientists were well-traveled polyglots.

Parallel astronomical developments in Far East (China), Mesoamerica.

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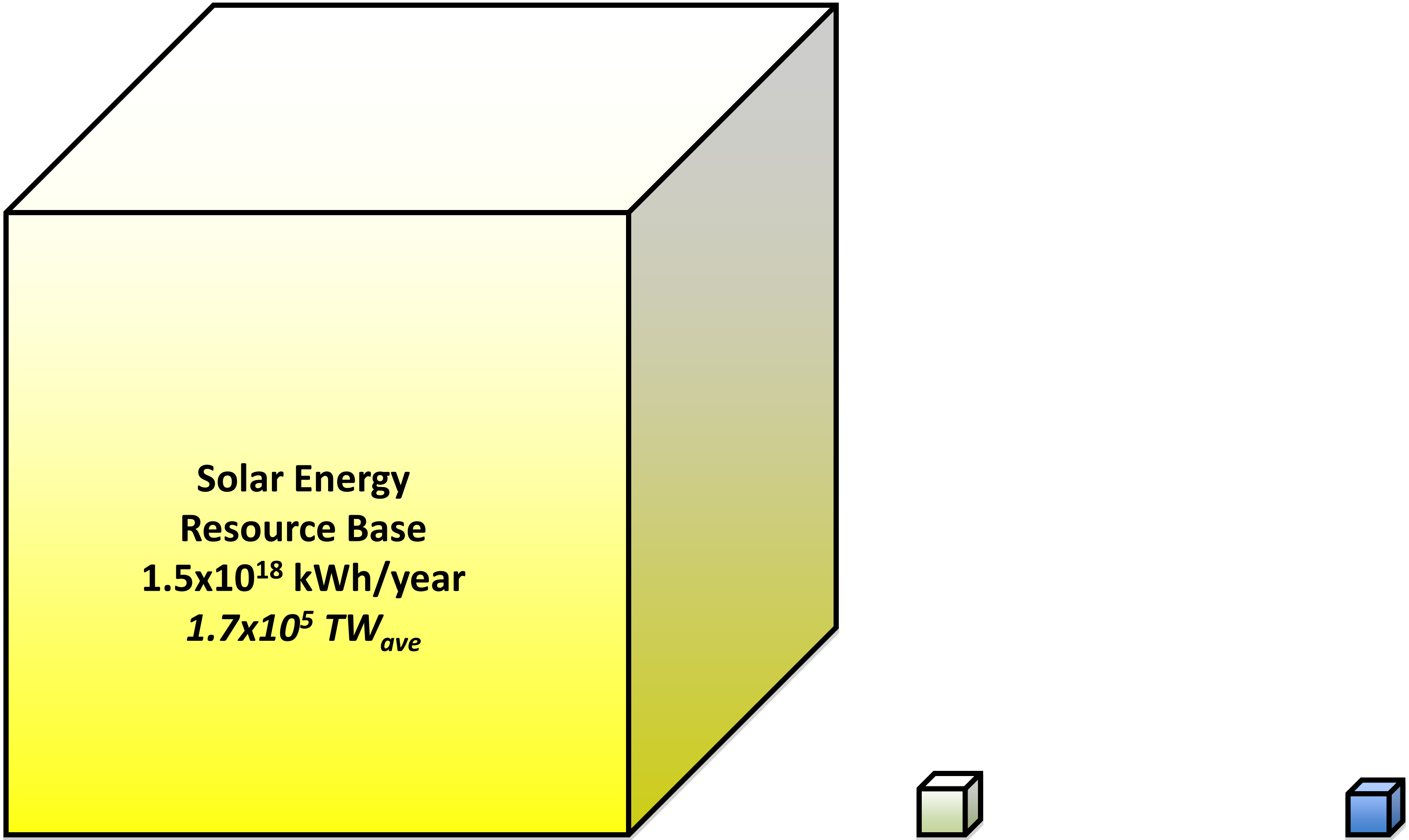
Solar Resource is VAST!



Wind Energy Resource Base
6×10^{14} kWh/year
72 TW_{ave}

Human Energy Use (mid- to late-century)
4×10^{14} kWh/year
50 TW_{ave}

References:
Wind Energy: C.L. Archer and M.Z. Jacobson, *J. Geophys. Res.* **110**, D12110 (2005).

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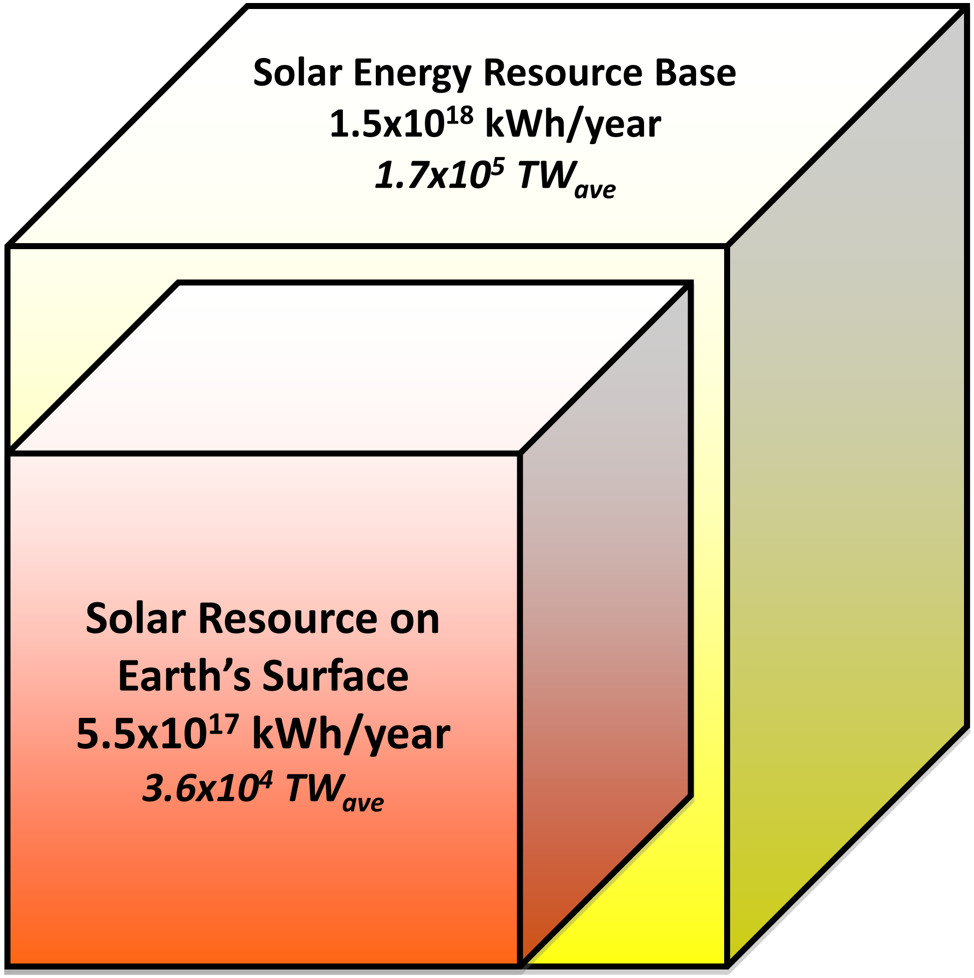

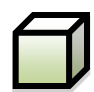

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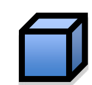

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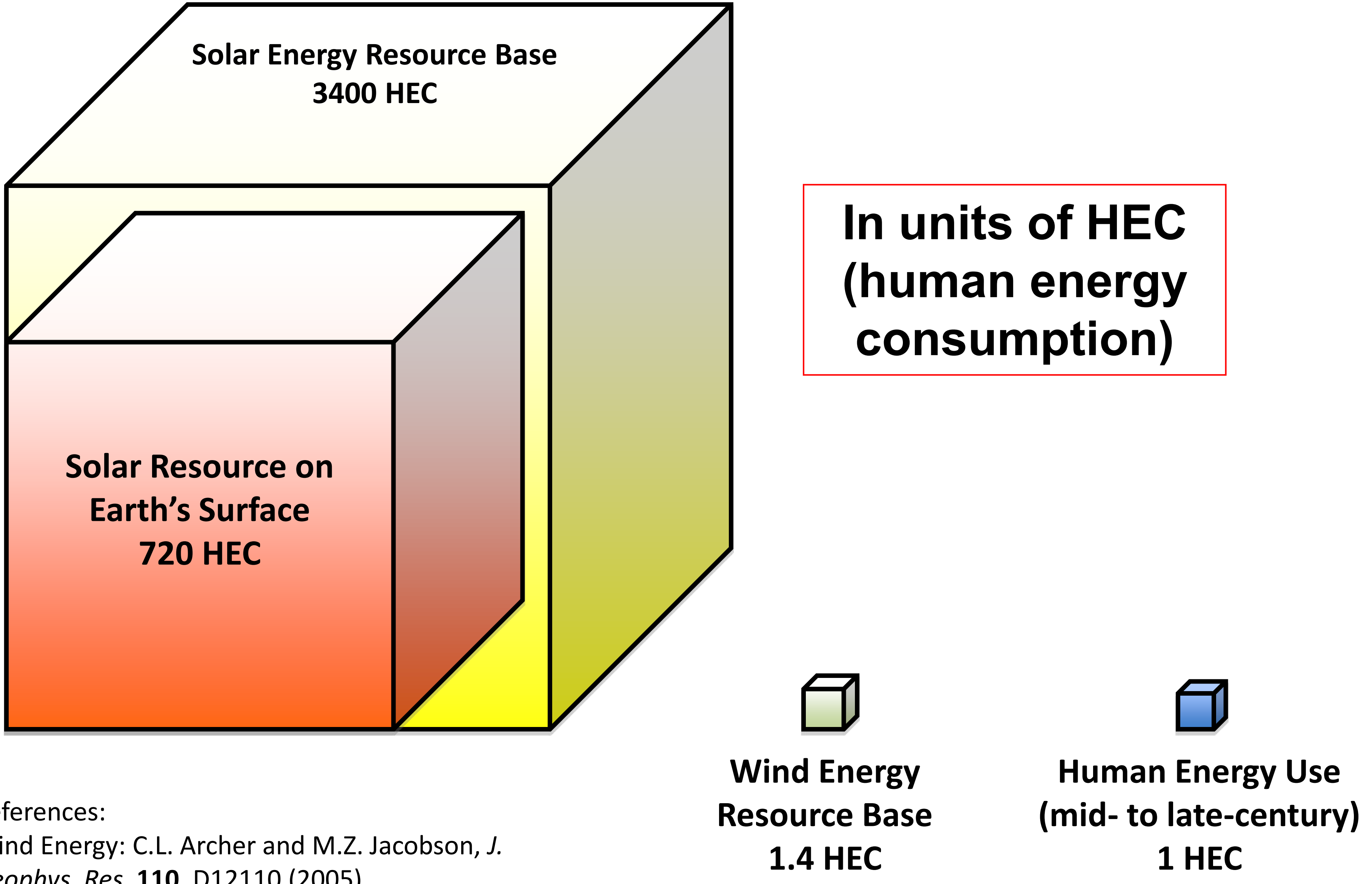

In units of HEC (human energy consumption)

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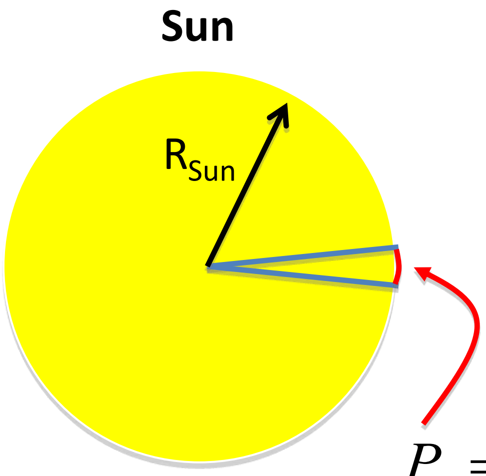
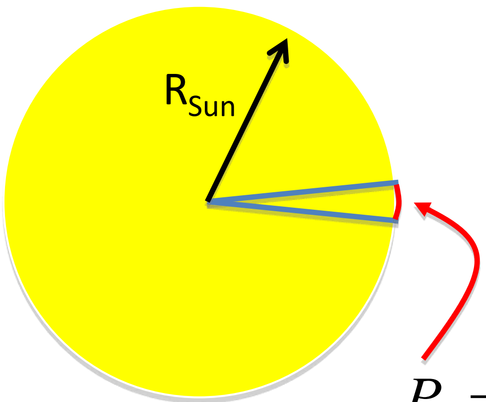
Quantifying Solar Power



$$P_o = \sigma \cdot T^4$$

Quantifying Solar Power

Sun



$$P_o = \sigma \cdot T^4$$

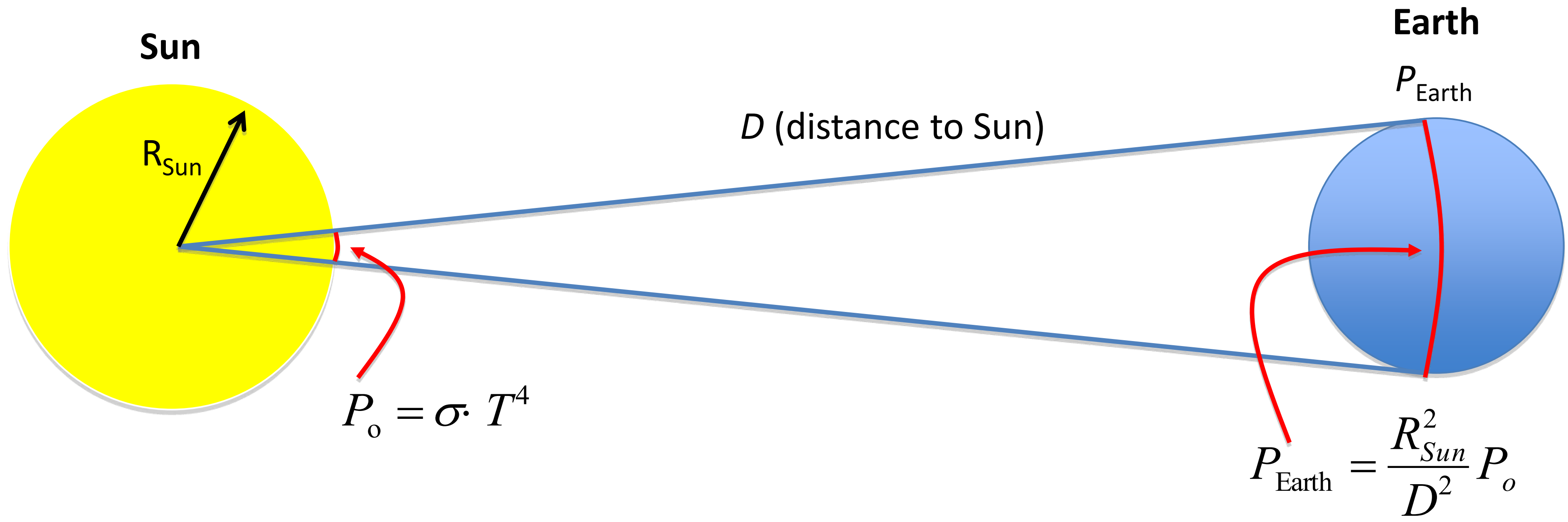
Total Radiative Power of Sun (from Stefan-Boltzman law, T =5762±50K)

Power radiated per unit area 6.250×10^7 W/m^2

Assumes Sun is a "black body."

Quantifying Solar Power

not to scale!



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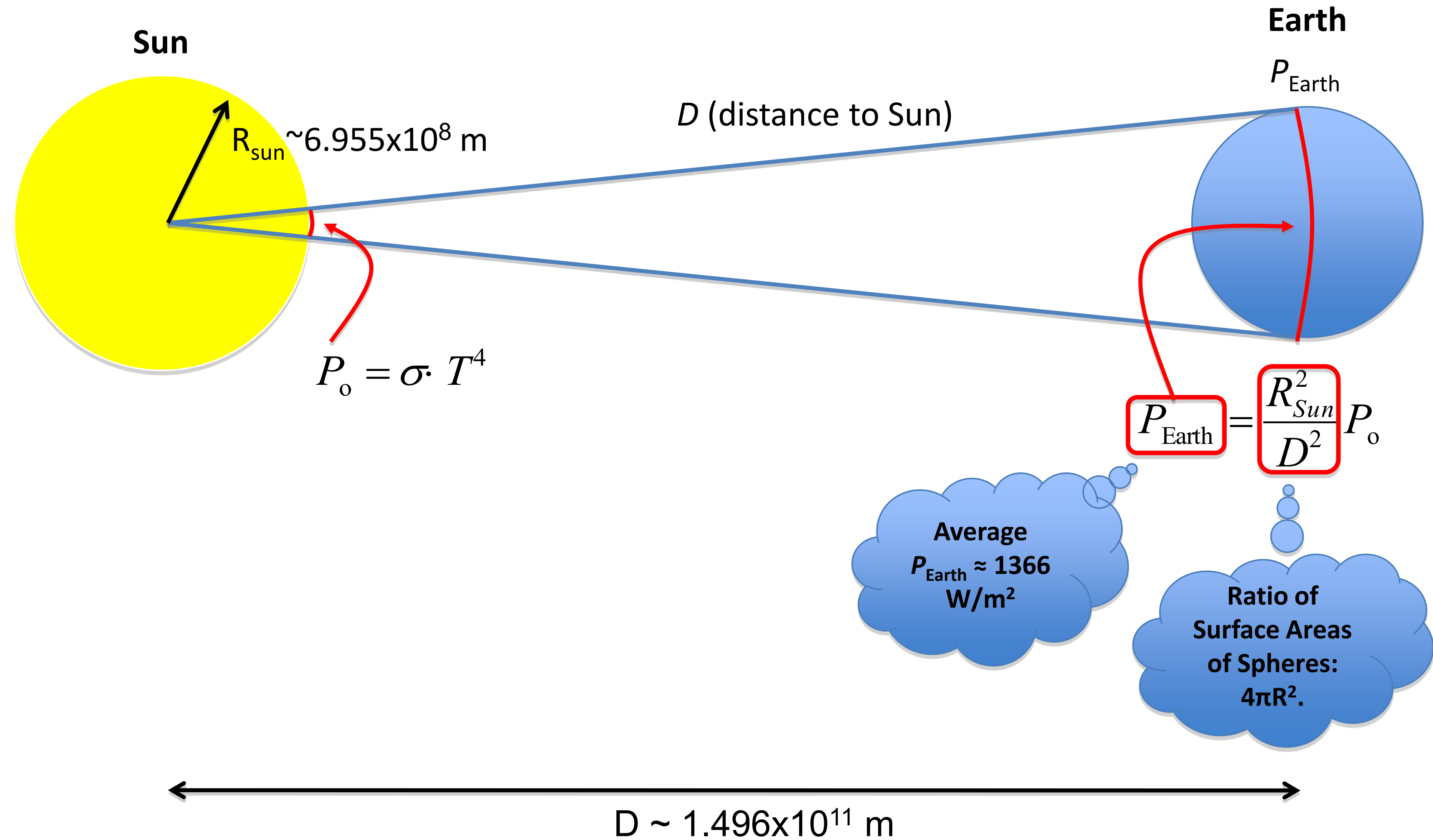

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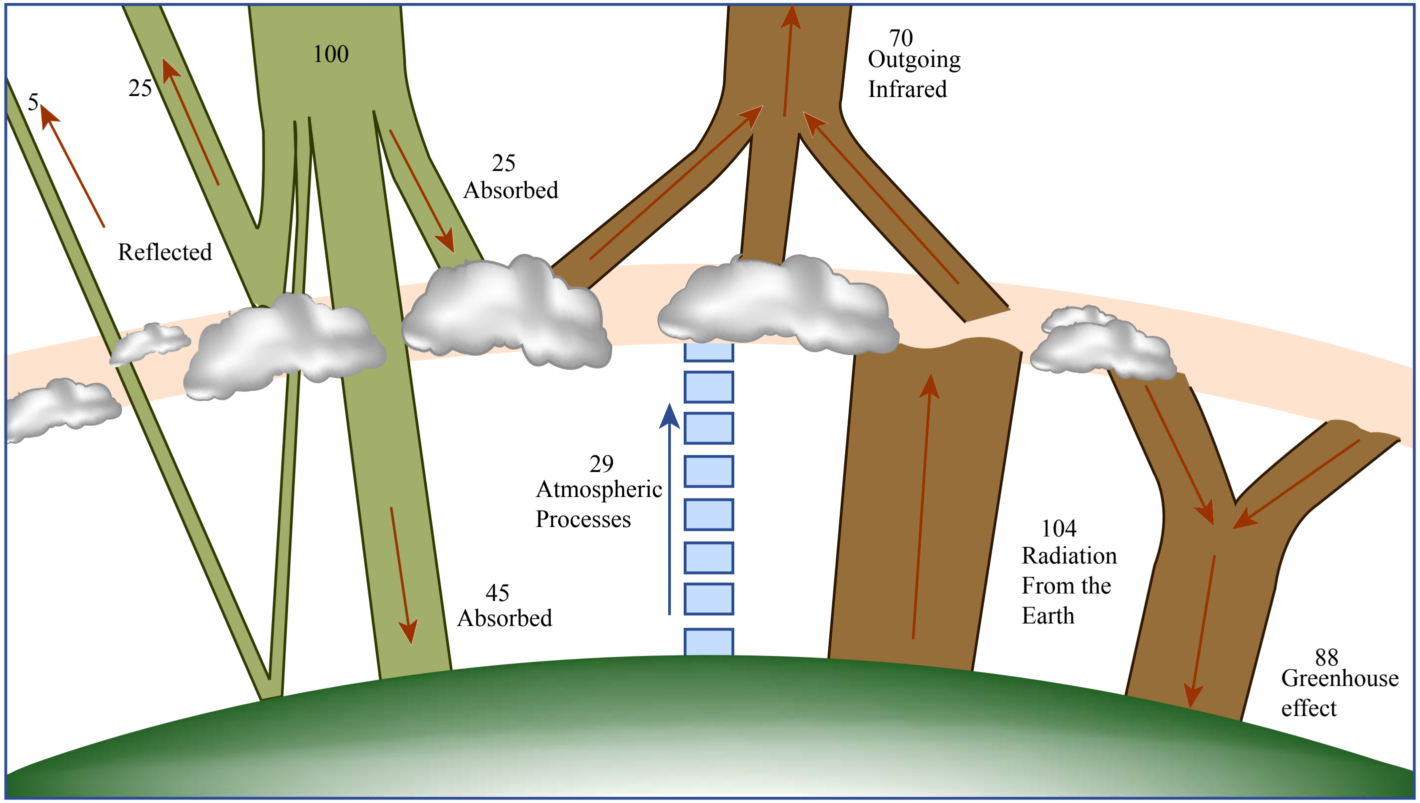
Atmospheric Absorption

Source: NASA (public domain)

ATMOSPHERIC EFFECTS

IPCC's assessment on the quantity of insolation (incoming solar radiation) reaching the Earth's surface.



Heat trapping in the atmosphere dominates the earth's energy balance. Some 30% of incoming solar energy is reflected (left), either from clouds and particles in the atmosphere or from the earth's surface; the remaining 70% is absorbed. The absorbed energy is reemitted at infrared wavelengths by the atmosphere (which is also heated by updrafts and cloud formation) and by the surface. Because most of the surface radiation is trapped by clouds and greenhouse gases and returned to the earth, the surface is currently about 33 degrees Celsius warmer than it would be without the trapping.

Image by MIT OpenCourseWare.

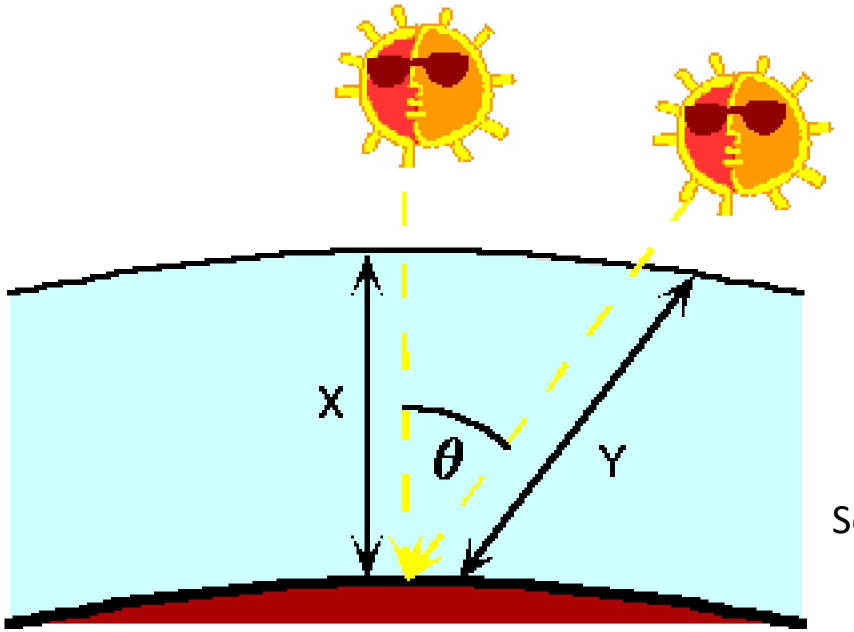
Source: IPCC, from J. T. Houghton et al., *Climate Change 1995: The Science of Climate Change* (Cambridge Univ. Press, Cambridge, 1996), p. 58.; data from Kiehl and Trenberth (1996).

AIR MASS

The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead). The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The Air Mass is defined as:

$$AM = \frac{1}{\cos(\theta)}$$

Valid for small to medium θ



AM1: Sun directly overhead

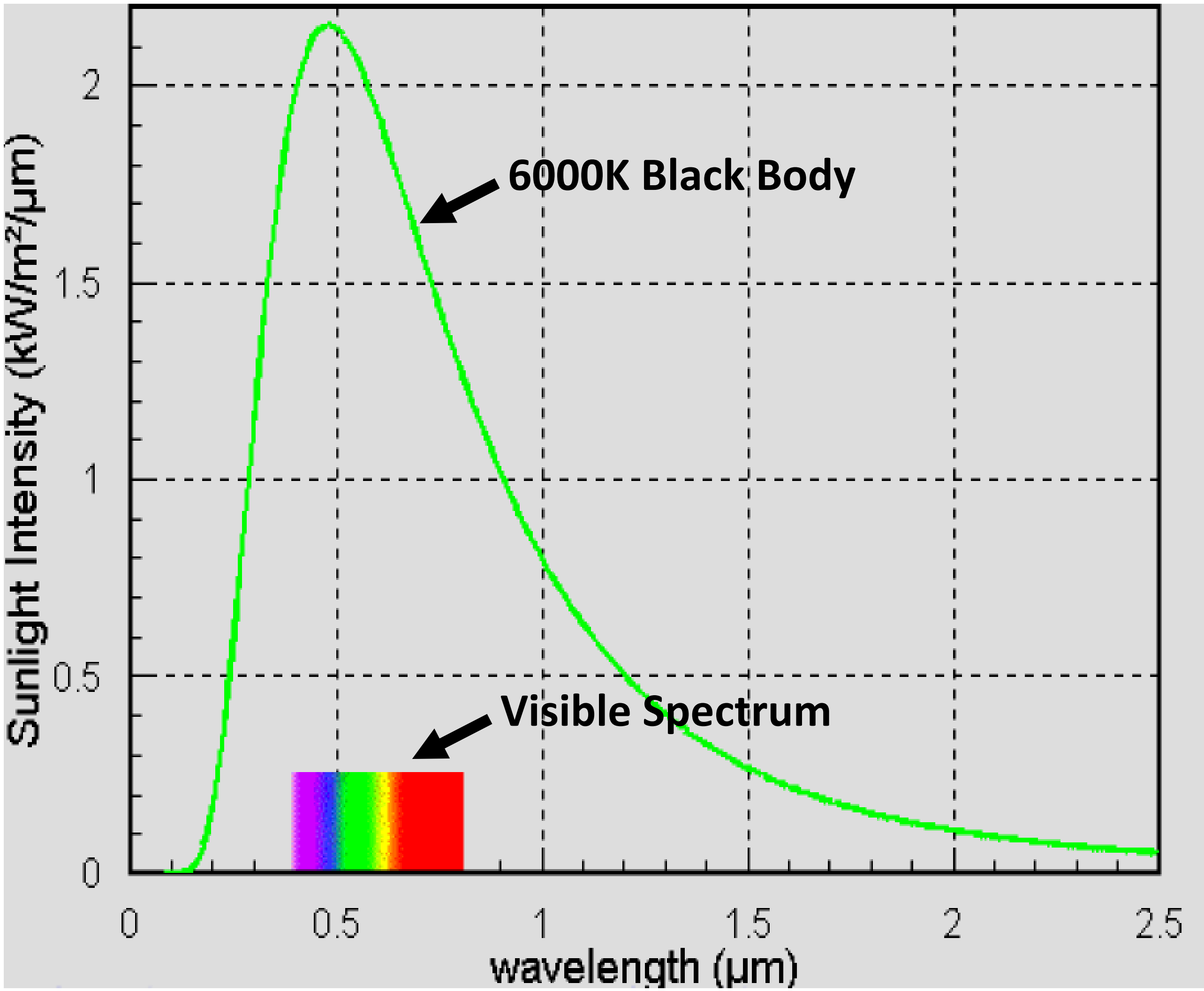
AM1.5G: "Conventional"
G (Global): Scattered and direct sunlight
D (Direct): Direct sunlight only

AM0: Just above atmosphere (space applications)

Source: http://www.pveducation.org/pvcdrom

Courtesy of PVCDROM. Used with permission.

SOLAR SPECTRUM



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From: http://www.pveducation.org/pvcdrom
Standard Solar Spectra Downloadable from: http://rredc.nrel.gov/solar/spectra/am1.5/

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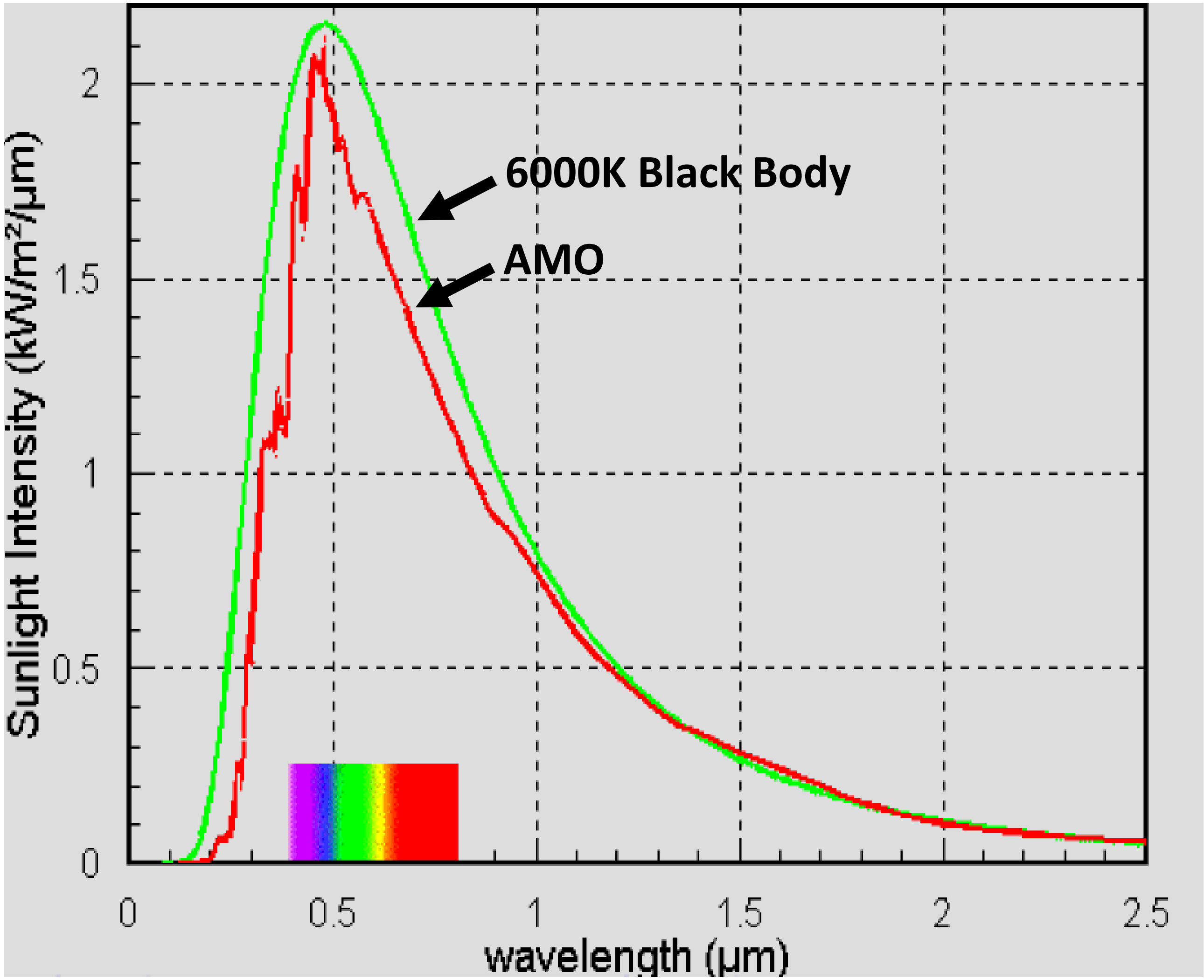

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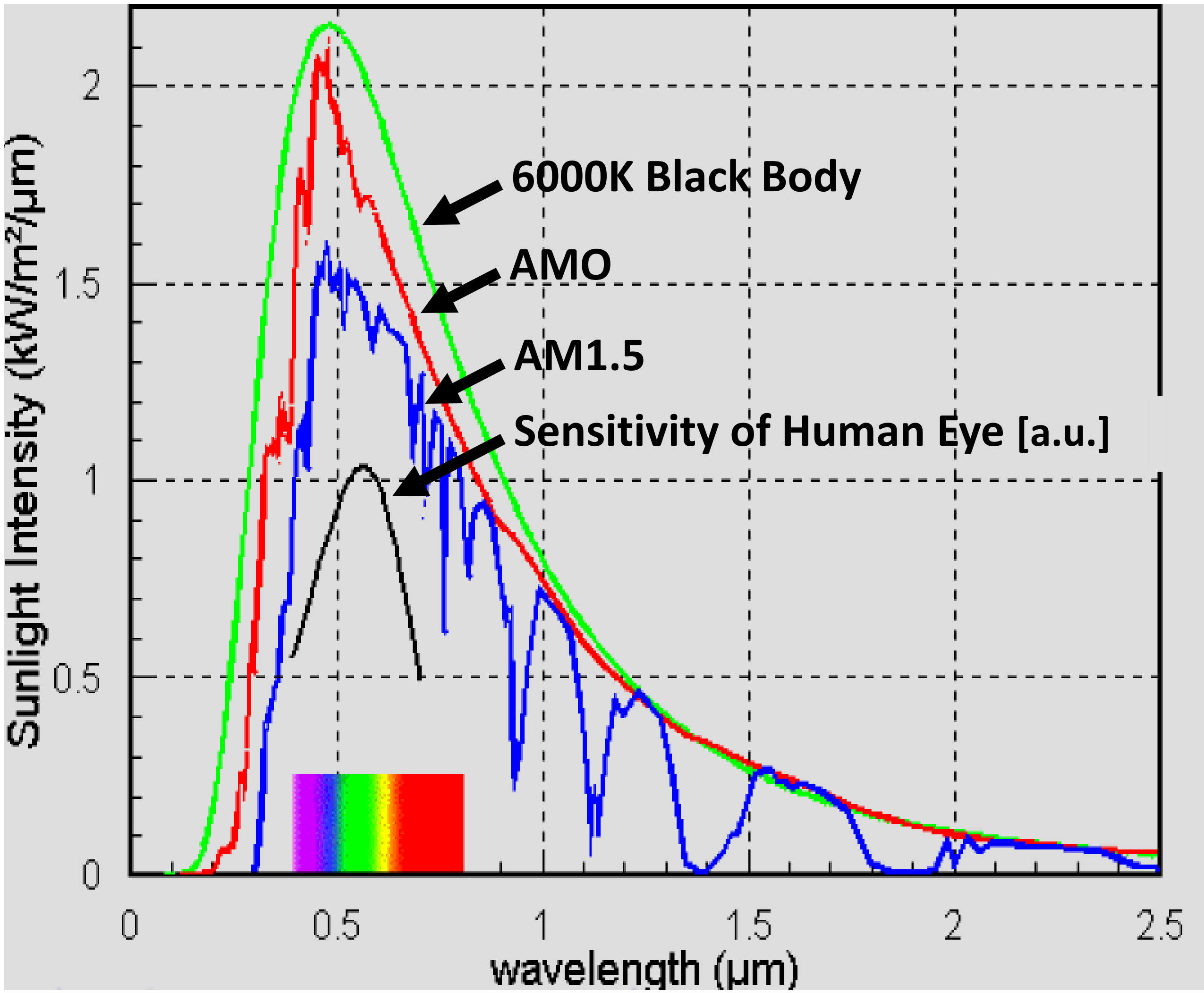


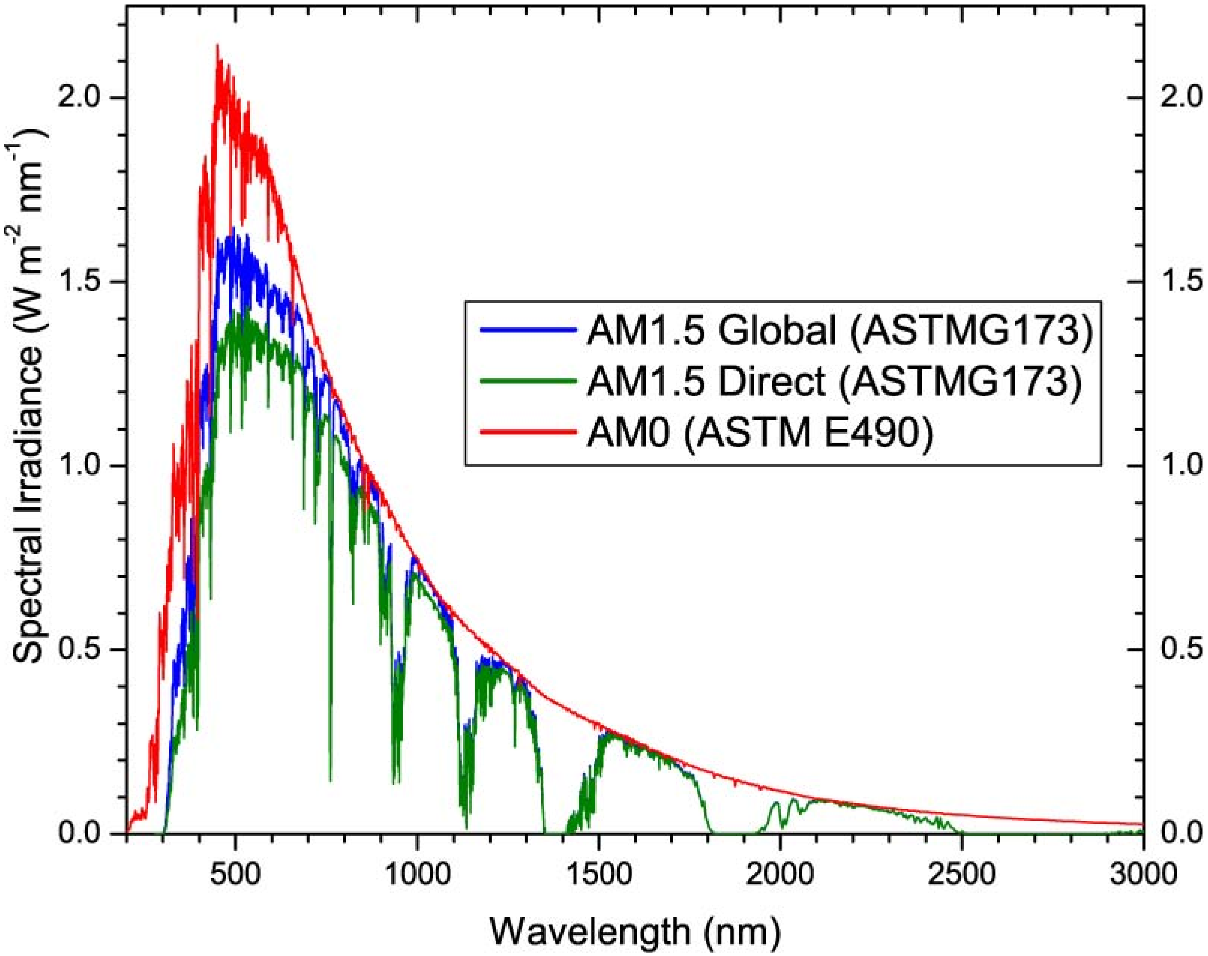
Courtesy of PVCDROM. Used with permission.

From: http://www.pveducation.org/pvcdrom

Sekuler R. and Blake, R., "Perception", *Alfred A. Knopf Inc, New York, 1985.*

SOLAR SPECTRUM

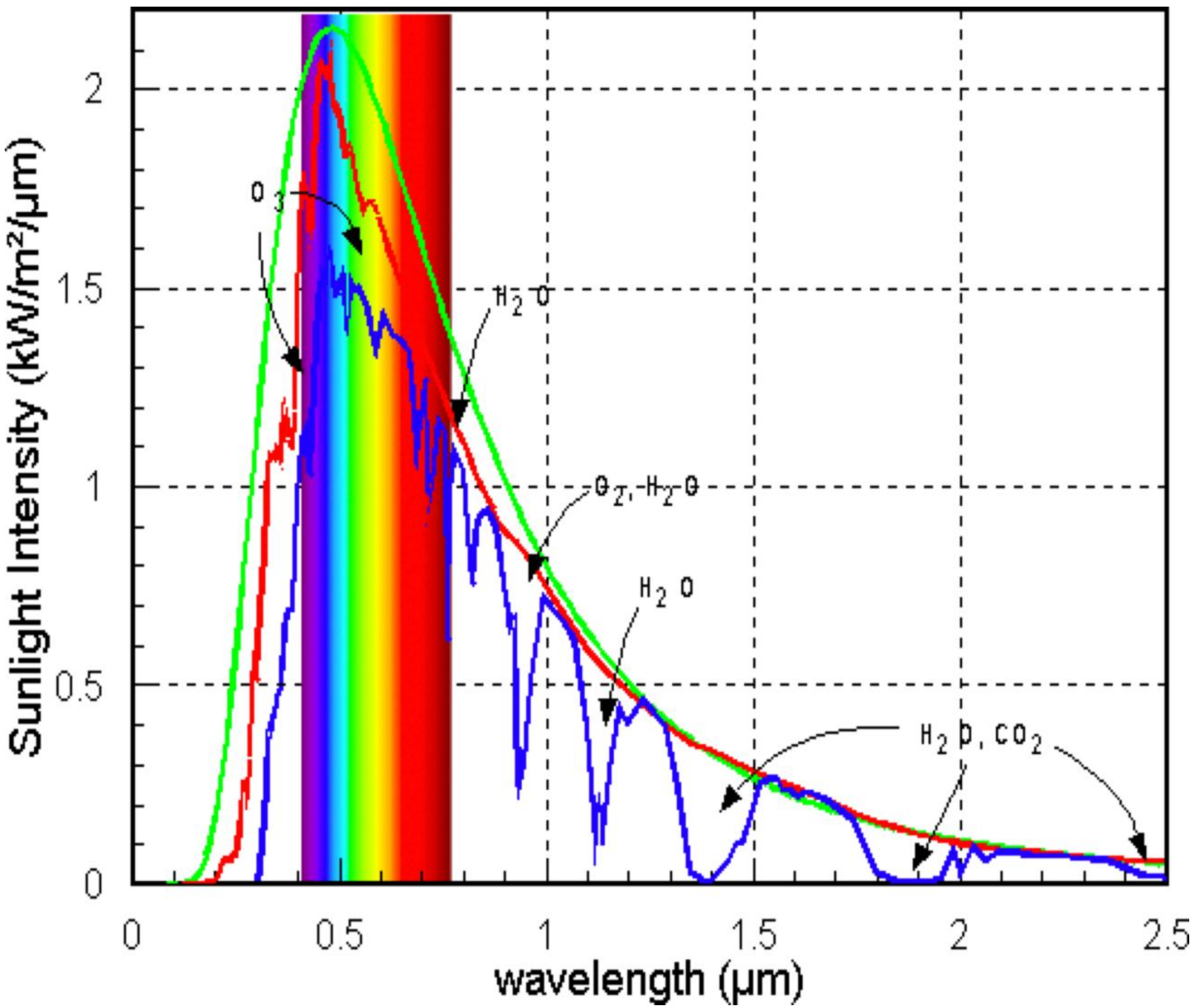
AM1.5 Global: Used for testing of Flat Panels (Integrated power intensity: 1000 W/m^2)
AM1.5 Direct: Used for testing of concentrators (900 W/m^2)
AM0: Outer space (1366 W/m^2)



Source of data:
http://www.nrel.gov/rredc/smarts/

The above charts, in Excel files:
http://www.pveducation.org/pvcdrom/appendicies/standard-solar-spectra

SOLAR SPECTRUM



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INSOLATION

Insolation: Incomming Solar Radiation

Typically given in units of:

Energy per Unit Area per Unit Time

(kWh/m^2/day)

Helpful when designing or projecting PV systems: Expected yield

Affected by: latitude, local weather patterns, etc.

Global/Direct Insolation: Ground Measurements

pyranometer

Equipment for solar irradiance measurements http://www.nrel.gov/data/pix/searchpix_visual.html

Insolation: Satellite Measurements

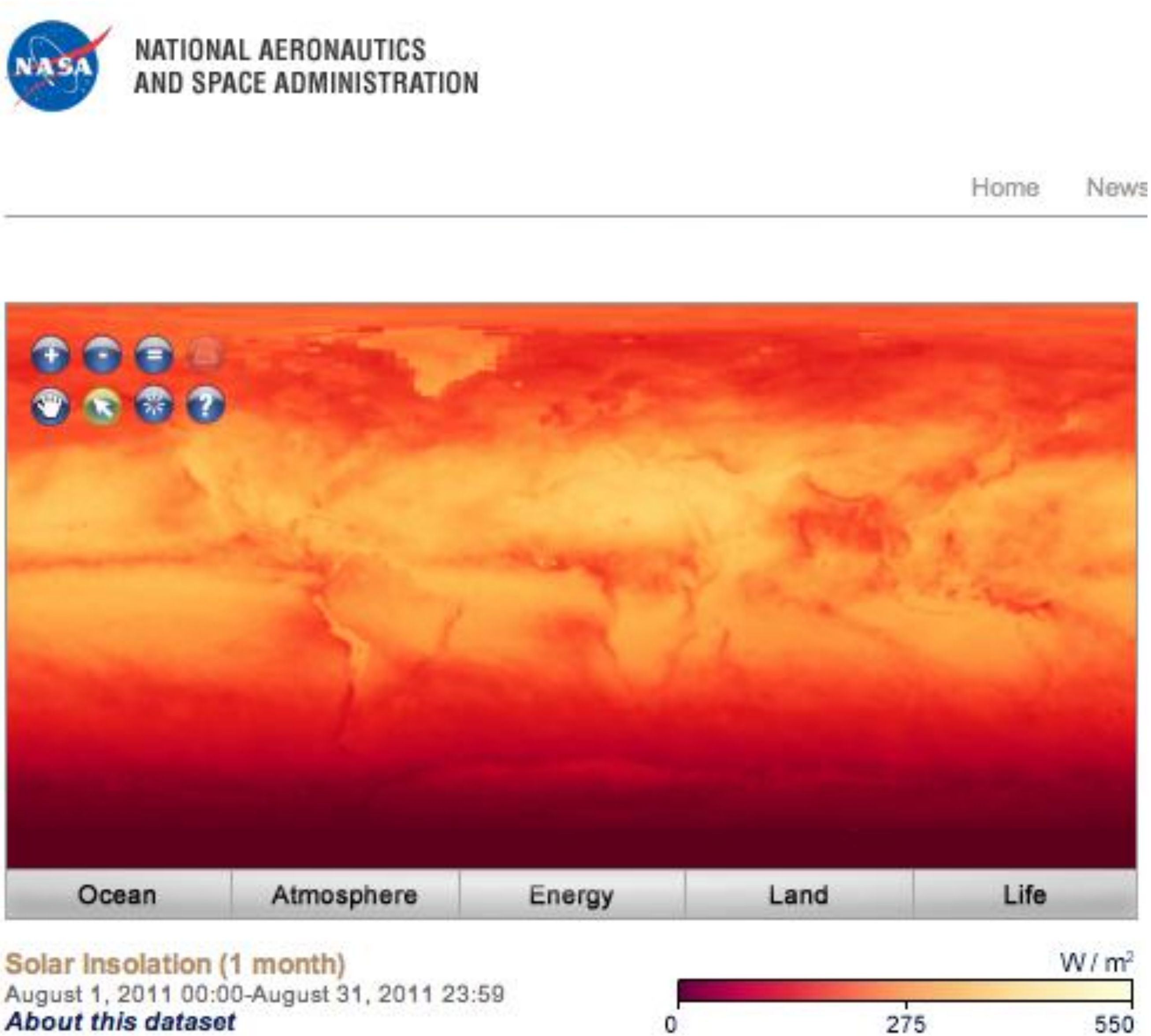
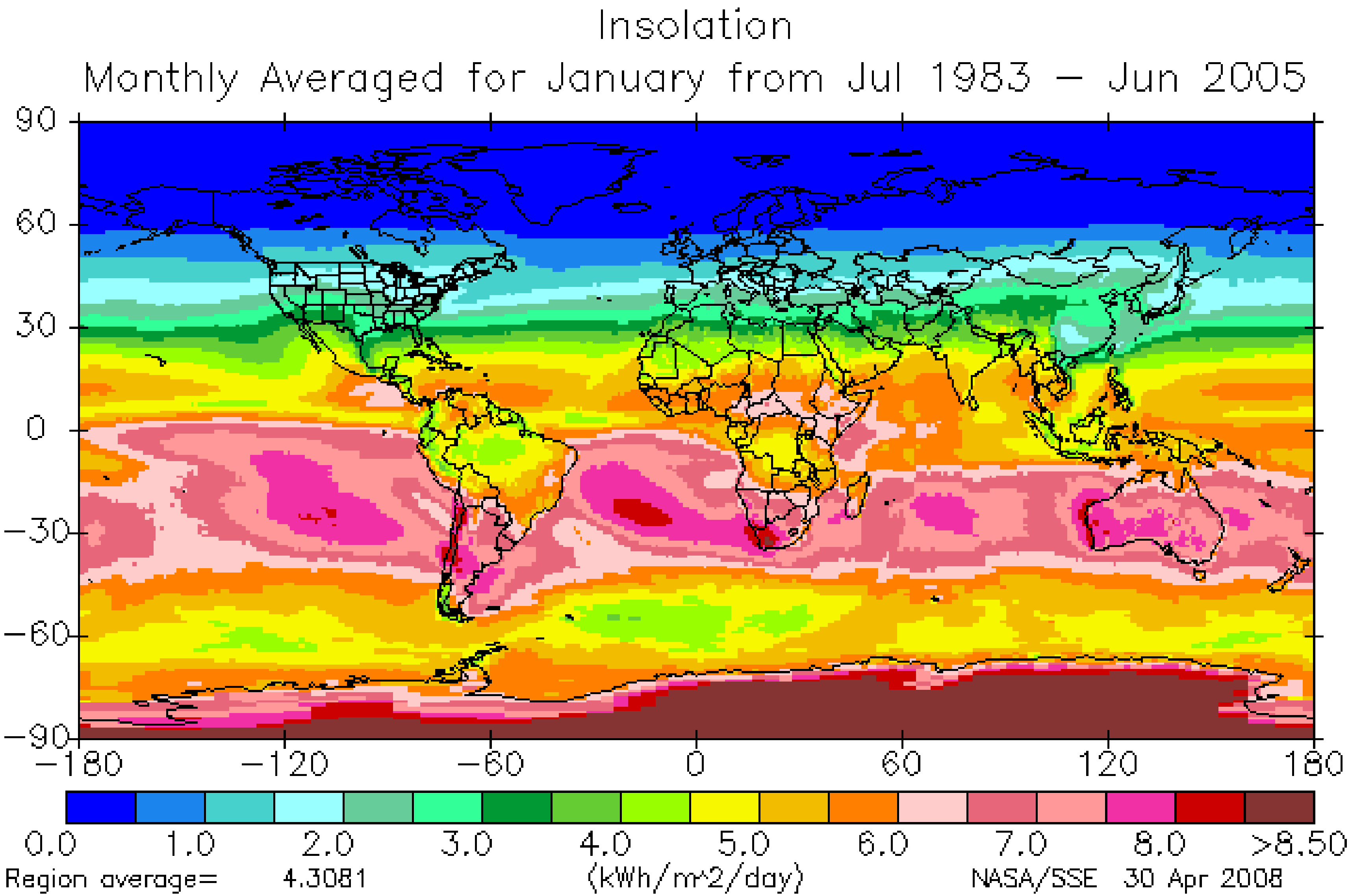


Image by NASA Earth Observatory. http://neo.sci.gsfc.nasa.gov → Energy tab → Solar Insolation

Global Insolation Data



http://eosweb.larc.nasa.gov/sse/

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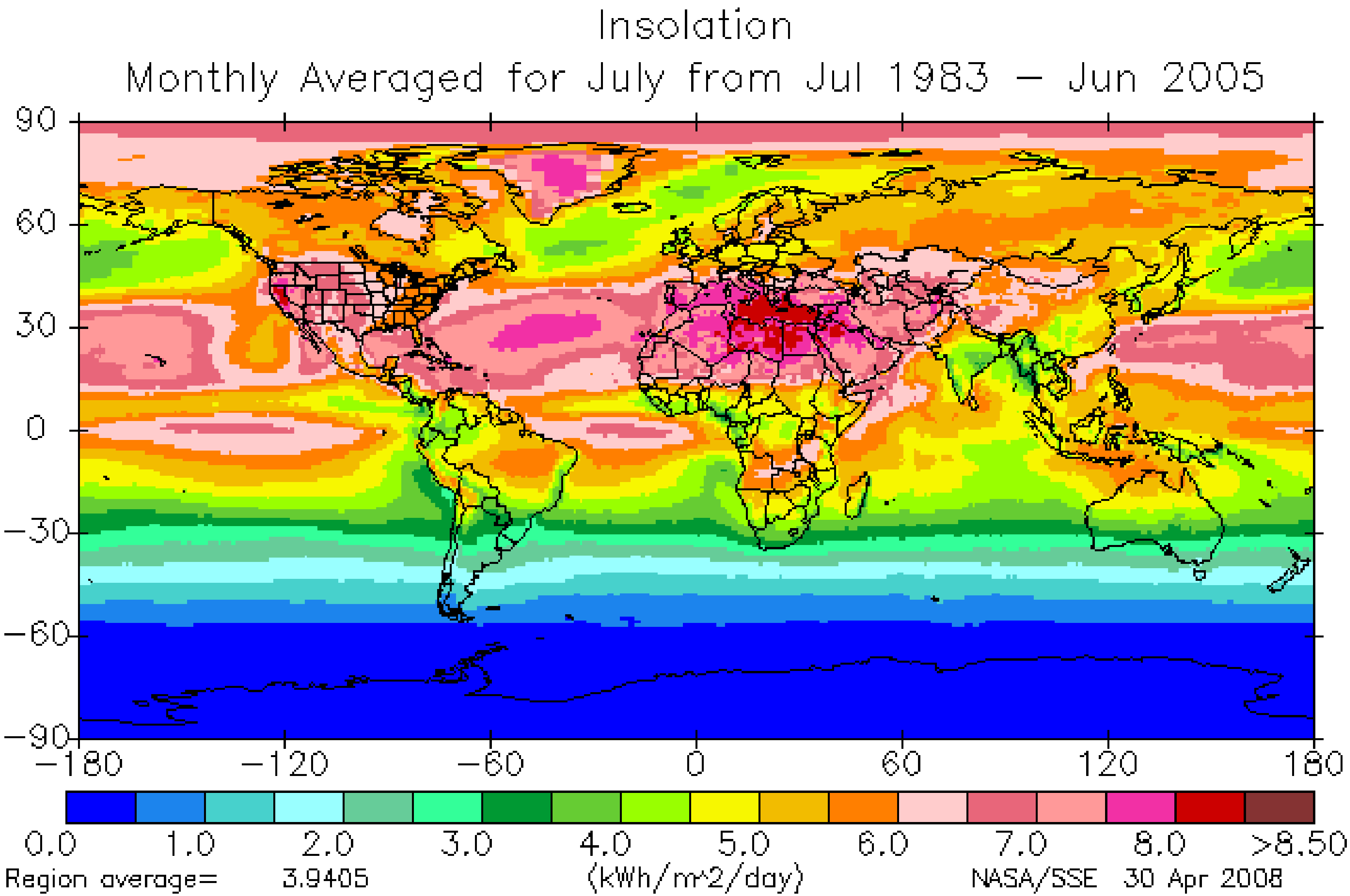

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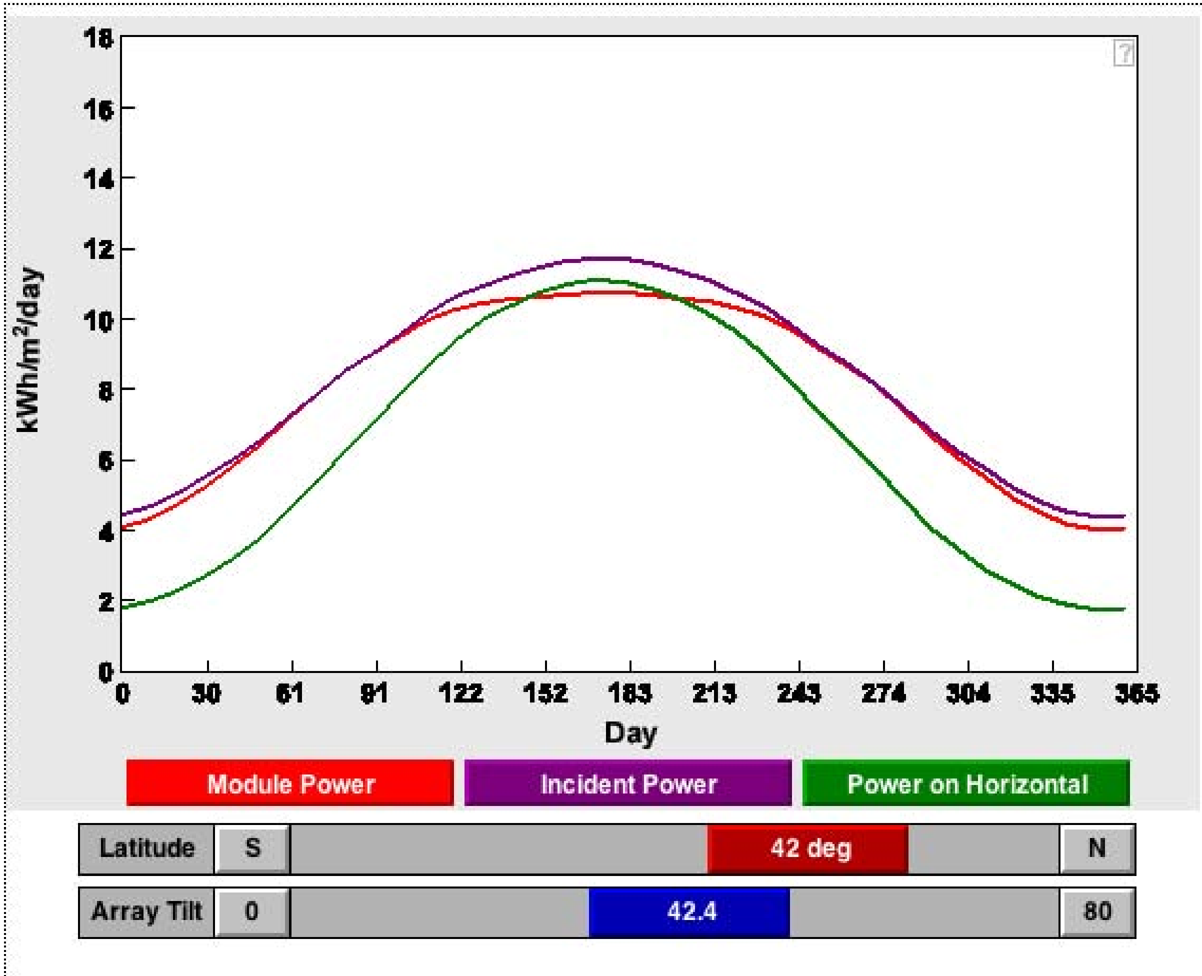
Seasonal Variation of Insolation



Courtesy of PVCDROM. Used with permission.

http://pveducation.org/pvcdrom/properties-of-sunlight/calculation-fo-solar-insolation

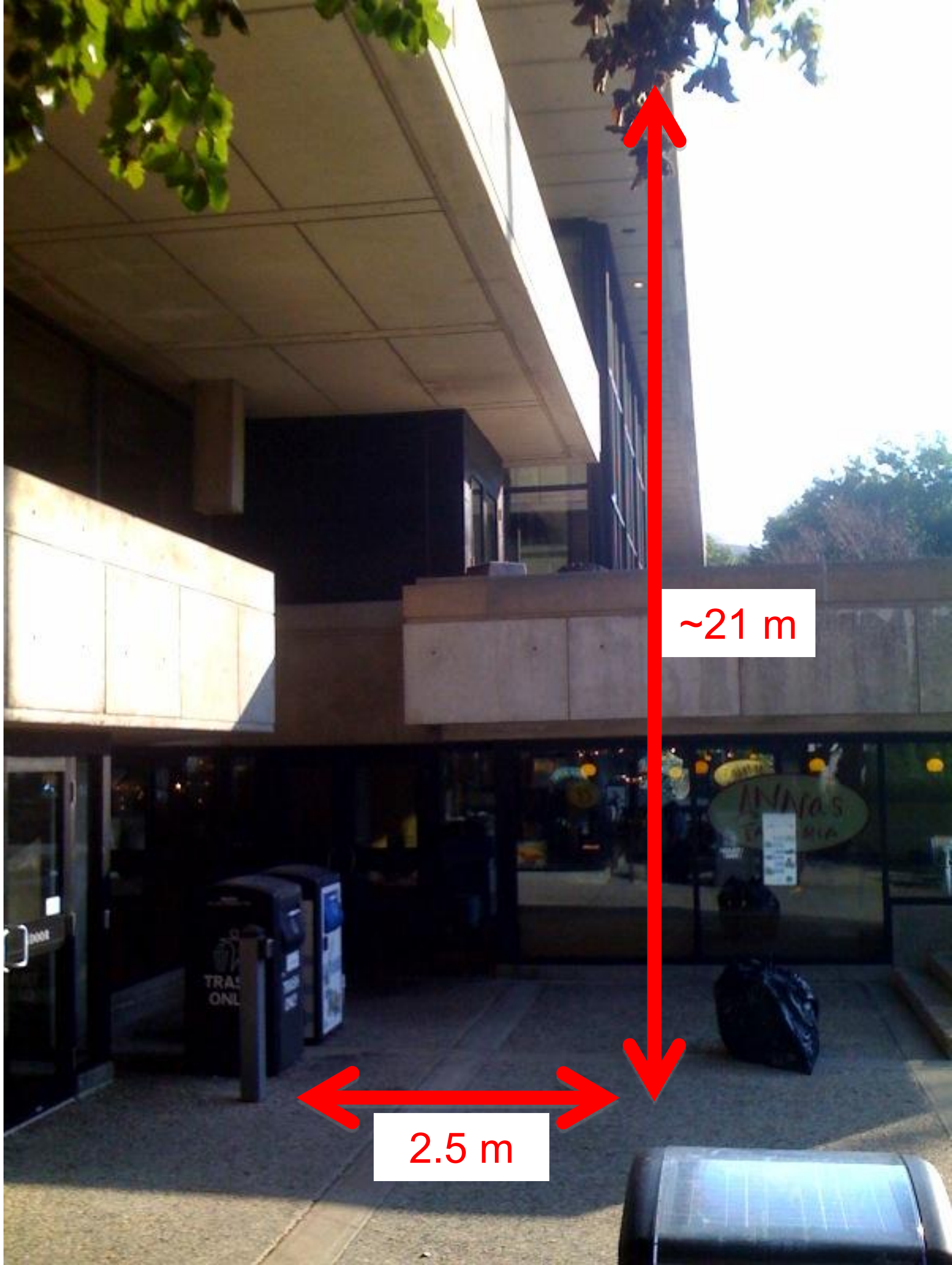
Seasonal & Diurnal Variations

- The trajectory of the sun relative to a fixed ground position is important when mounting a fixed solar array.
- Local weather patterns may limit exposure of sun at certain times of day.
- When do you want more power? Summer vs. winter?
- Not only does the length of the day change, but so does the position of the sun in the sky throughout the seasons.
- Important when considering shading effects!

Really awesome app:
http://astro.unl.edu/naap/motion3/animations/sunmotions.html

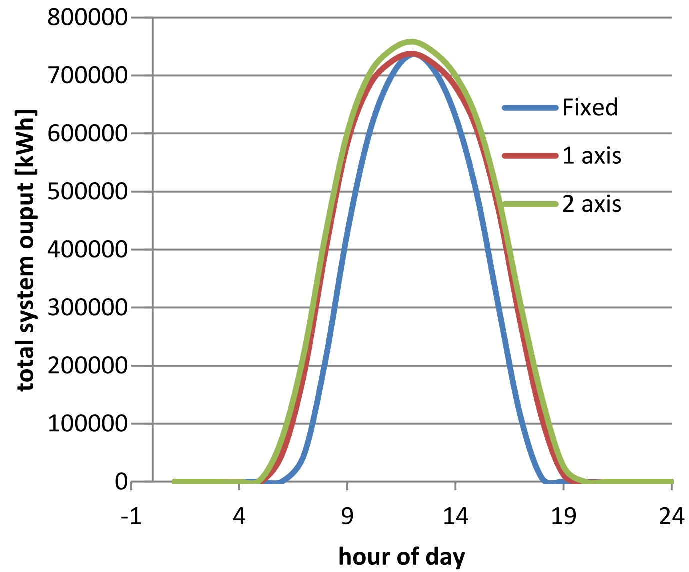

TRASH
ONLY
TRASH
ONLY
Single Stream
RECYCLING
Single Stream
RECYCLING


Single Stream
RECYCLING
TRASH ONLY
TRASH
ONLY

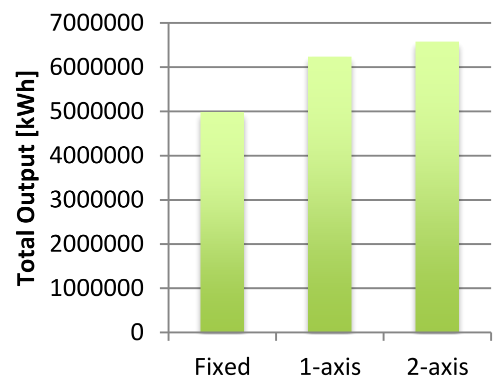

~21 m
2.5 m

Fixed vs. Tracking Systems

- As mentioned in previous slide, the sun moves through the sky. Panels that are able to constantly move and follow the sun, can increase their output per day!
- Of course added cost of building a concentrator may not make this idea a good one…

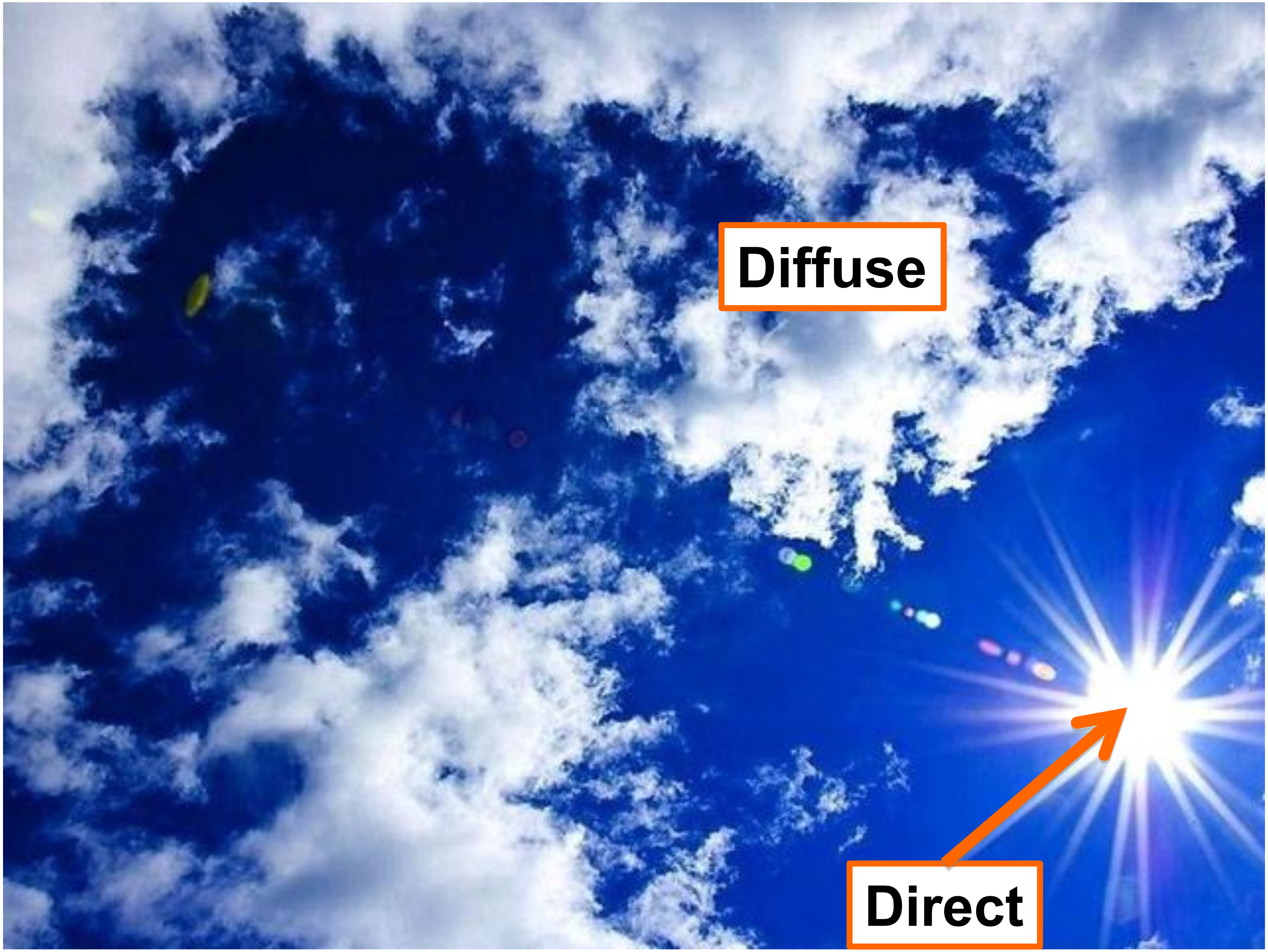


Total Annual System Output

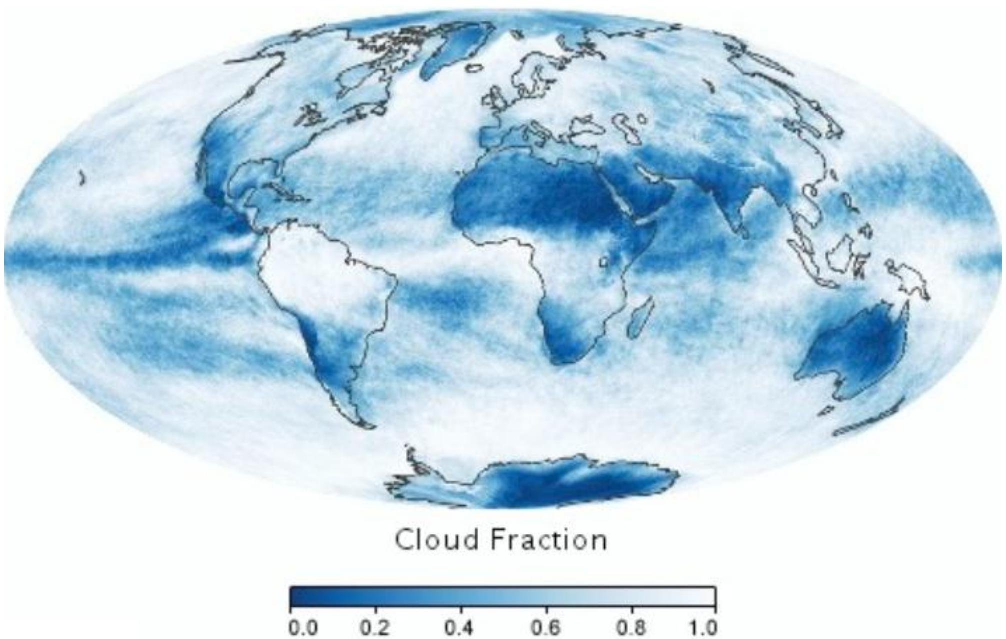


From PVWatts for Boston

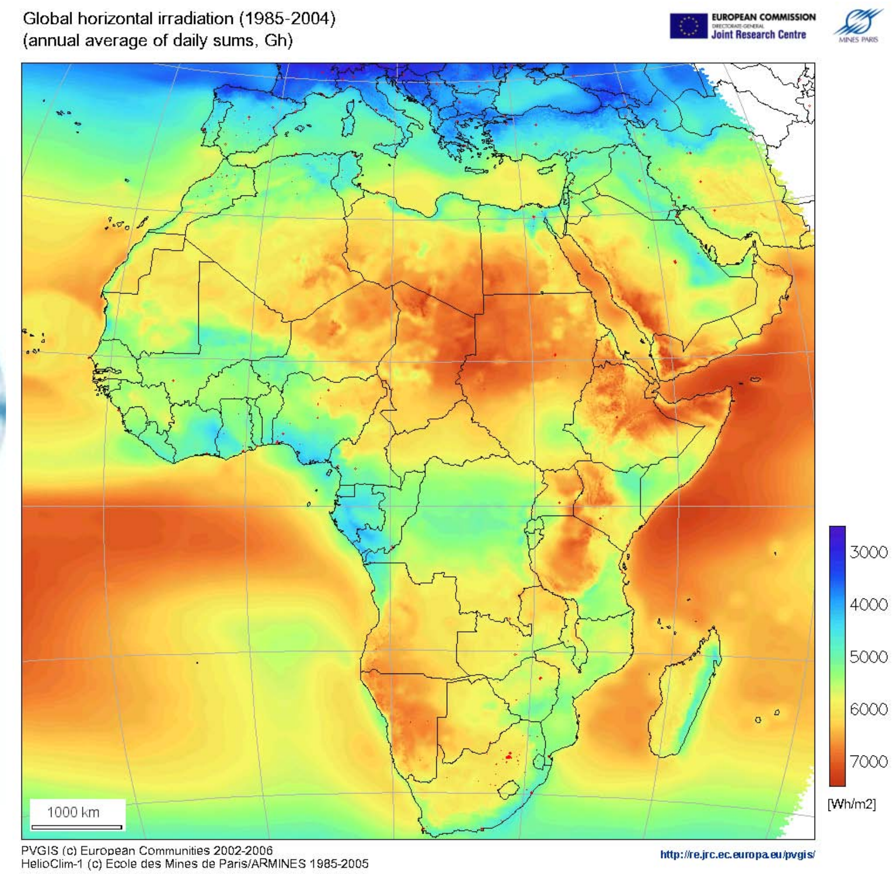
Direct vs. Diffuse Sunlight



Local Weather Patterns: Long Time Constant



http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=CERES_NETFLUX_M&d2=MODAL2_M_CLD_FR



http://sunbird.jrc.it/pvgis/countries/countries-non-europe.htm

Local Weather Patterns: Short Time Constant

Please see lecture video or go to the links below to see the explanatory cartoon images:
http://www.newport.com/images/web150w-EN/images/1069.gif
http://www.newport.com/images/web150w-EN/images/1070.gif

- Question: Why do many solar panels in the San Francisco Bay Area point south or south-west, instead of south-east?

Intermittency

Please see lecture video or go to the links below to see the explanatory cartoon images:
http://www.newport.com/images/web150w-EN/images/1069.gif
http://www.newport.com/images/web150w-EN/images/1070.gif

1. Short time constant (less predictable): Cloud cover. Relevant to predicting power supply reliability.

2. Long time constants (more predictable): Diurnal & seasonal variations. Relevant to calculating total annual energy output.

Germany & U.S. : A quick comparison

Please see lecture video for comparative insolation between Germany and the US.

One out of every two installed solar panels is in Germany…

Yet we have much more sun! Conclusion: Solar resource is part but not all of the equation.

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Units 101

- Basic Units Check: Assign Appropriate Units

- Energy
- Power
- Current
- Voltage

- Amps (A)
- Kilowatt Hours (kWh)
- Kilowatts (kW)
- Volts (V)

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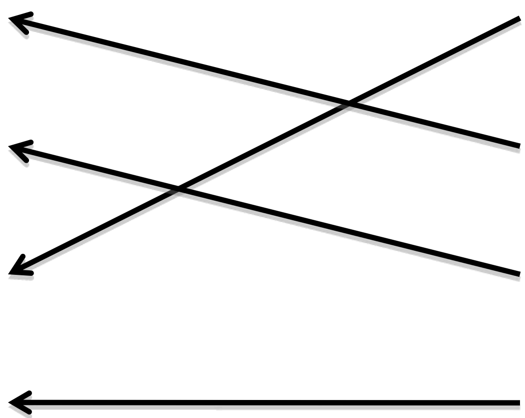


- Amps (A)
- Kilowatt Hours (kWh)
- Kilowatts (kW)
- Volts (V)

Unit Check

- Current, voltage, power, and energy.
  - Example: Hairdrier vs. Fridge.
    - Which is more likely to blow a fuse?
    - Which is more likely to blow your budget?

$0.044\ kW_{ave}$
$\sim 1\ kWh/day$

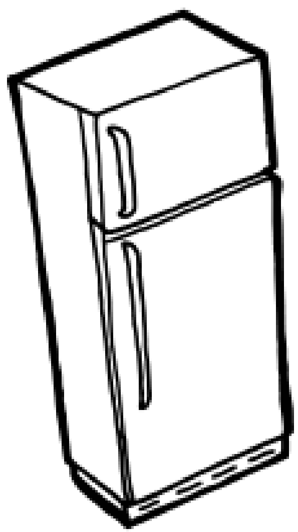


Photo courtesy of Niels van Eck on Flickr.

$1.88\ kW_{peak}$
$\sim 0.5\ kWh/day$

Why “Peak Power”?

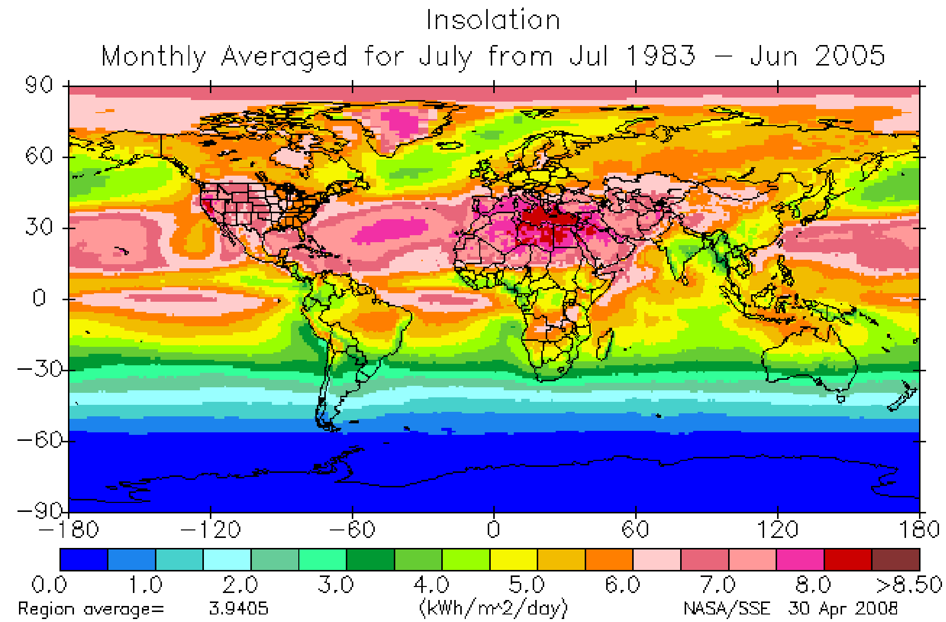
- Why is “peak power” (kW_p) useful?
  - *Because it is a location (resource) neutral rating of output power. A PV module will have the same* kW_p *in Arizona or Alaska, although the* kW_{ave} *will be very different! Useful spec when designing systems.*

Estimating System Output from Insolation Maps

Q: Let's say I have a 2.2 kW_p photovoltaic array. How much energy will it produce in a year?

A: Let's say our location receives, on average, 4 $kWh/m^2/day$ from the Sun. The calculation is then straightforward:

$$\text{Energy Output} = \frac{(2200\ W_p) \times (4.0\ kWh/m^2/day)}{1000\ W_p/m^2} = 8.8\ kWh/day \approx 3200\ kWh/year$$



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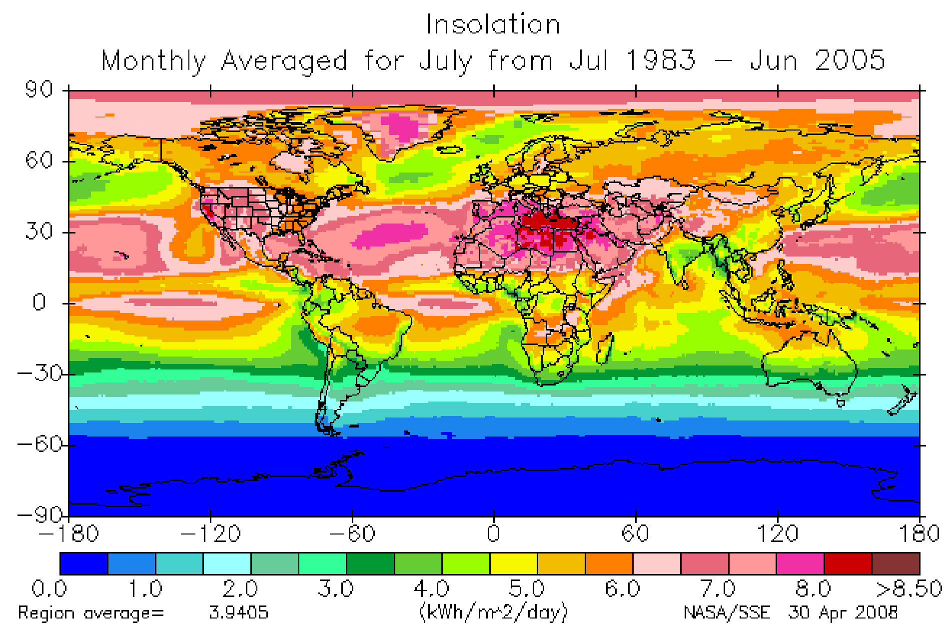
System size

Insolation at site of installation

$$\text{Energy Output} = \frac{(2200\ \text{W}_p) \times (4.0\ \text{kWh/m}^2\text{/day})}{1000\ \text{W}_p\text{/m}^2} = 8.8\ \text{kWh/day} \approx 3200\ \text{kWh/year}$$

AM 1.5G



More Accurate Predictions

PVWatts: Tapping into the NREL database

http://www.pvwatts.nrel.gov/

SAM (Solar Advisor Model)

https://www.nrel.gov/analysis/sam/

Actual System Outputs

Actual system outputs may be significantly lower, due to suboptimal system performance, design, installation, shading losses, etc.:

Source (outdated):
https://web.archive.org/web/20081025200657/http://soltrex.masstech.org/systems.cfm

Material Helpful for Homework Problems

Estimating Solar Land Area Requirements

Here's the equation to use, when calculating the area of land needed to produce a certain amount of energy over a year, given a technology with a certain conversion efficiency.

$$\text{Land Requirements (m}^2\text{)} = \frac{\text{Energy Burn Rate (kWh/yr)}}{\text{Solar Resource}\left(\dfrac{\text{kWh}}{\text{m}^2\cdot\text{yr}}\right) \times \text{Conversion Efficiency}}$$

Estimating Solar Land Area Requirements

Here's the equation to use, when calculating the area of land needed to produce a certain amount of energy over a year, given a technology with a certain conversion efficiency.

How much energy (kWh) will be produced by the solar system over the course of a year.

How much land is needed

$$\text{Land Requirements (m}^2\text{)} = \frac{\text{Energy Burn Rate (kWh/yr)}}{\text{Solar Resource}\left(\frac{\text{kWh}}{\text{m}^2 \cdot \text{yr}}\right) \times \text{Conversion Efficiency}}$$

How much energy from the Sun is available (read values off insolation maps in previous slides for a particular location. (Watch units: days^{-1} vs. years^{-1})

The ability of a given technology to convert sunlight into a usable form. NB: This is the conversion efficiency for the entire system, not just the device.

Test Case

Given:

1. An energy burn rate of 4 TW_{ave} ($3.5x10^{13}$ kWh/yr)
   (forward-projected U.S. energy consumption, including waste heat)
2. An insolation value of 6 $kWh/m^2/day$
   (typical year-average value for flat panel in Nevada; CPV ~ 7 $kWh/m^2/day$)
3. System conversion efficiency of 12%
   (including all system losses)

Using:

$$\text{Land Requirements } (\text{m}^2) = \frac{\text{Energy Burn Rate (kWh/yr)}}{\text{Solar Resource}\left(\frac{\text{kWh}}{\text{m}^2 \cdot \text{yr}}\right) \times \text{Conversion Efficiency}}$$

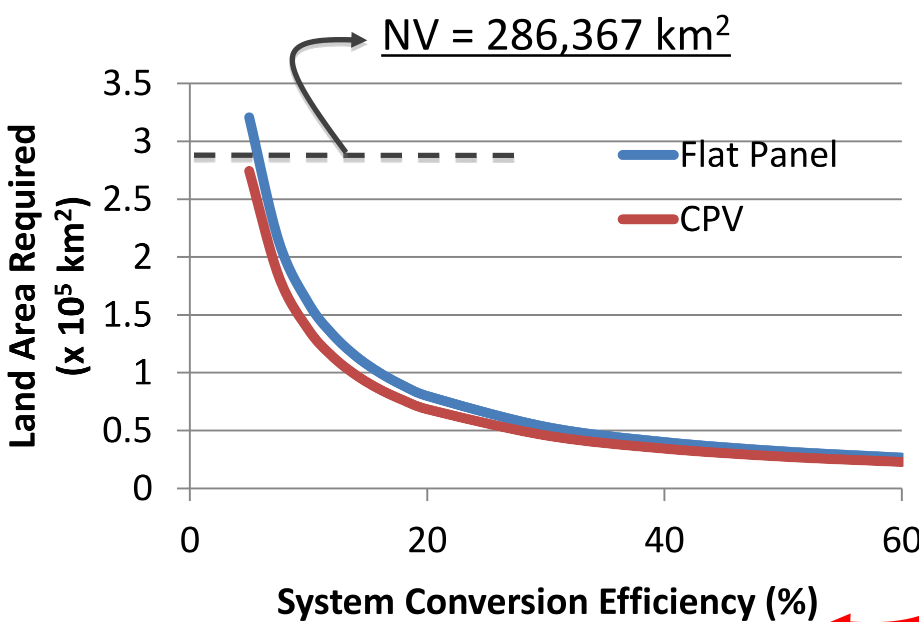
$$= \frac{\left(3.5 \times 10^{13} \text{ kWh/yr}\right)}{\left(2192 \ \frac{\text{kWh}}{\text{m}^2 \cdot \text{yr}}\right) \times (0.12)} \approx 1.3 \times 10^5 \text{ km}^2$$

Compare land requirement to power entire U.S. on today's solar technology (~130,000 km^2), to total area of Nevada (286,367 km^2).

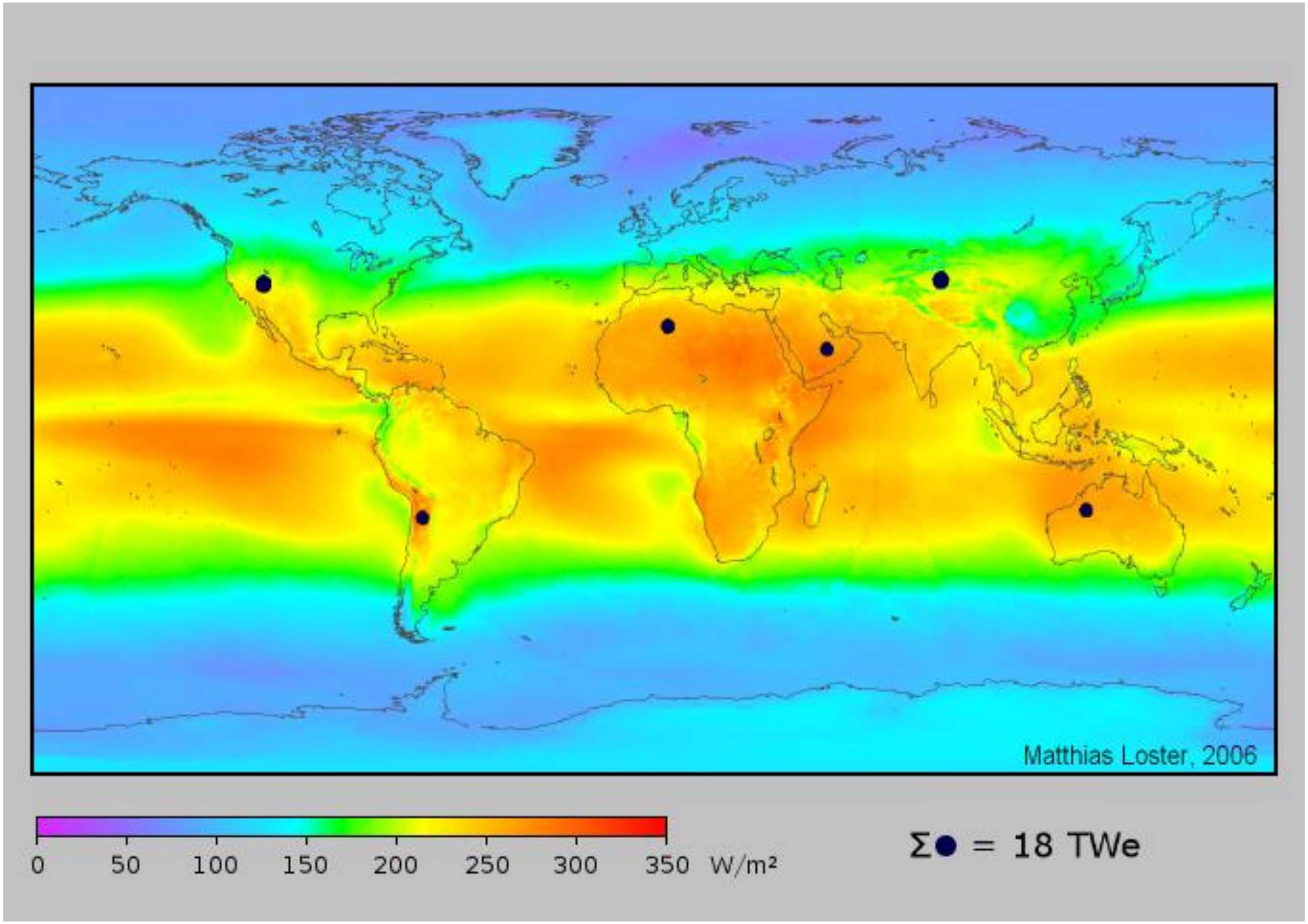
Test Case

Note that the land area requirement is a hyperbolic function of system conversion efficiency.

$$\text{Land Requirements (m}^2\text{)} = \frac{\text{Energy Burn Rate (kWh/yr)}}{\text{Solar Resource}\left(\frac{\text{kWh}}{\text{m}^2\cdot\text{yr}}\right)\times\text{Conversion Efficiency}}$$



Estimating Solar Land Area Requirements



6 Circles at 3 TW_e Each = 18 TW_e http://www.answers.com/topic/solar-power-1

2.627 / 2.626 Fundamentals of Photovoltaics
Fall 2013