2.626 Fundamentals of Photovoltaics

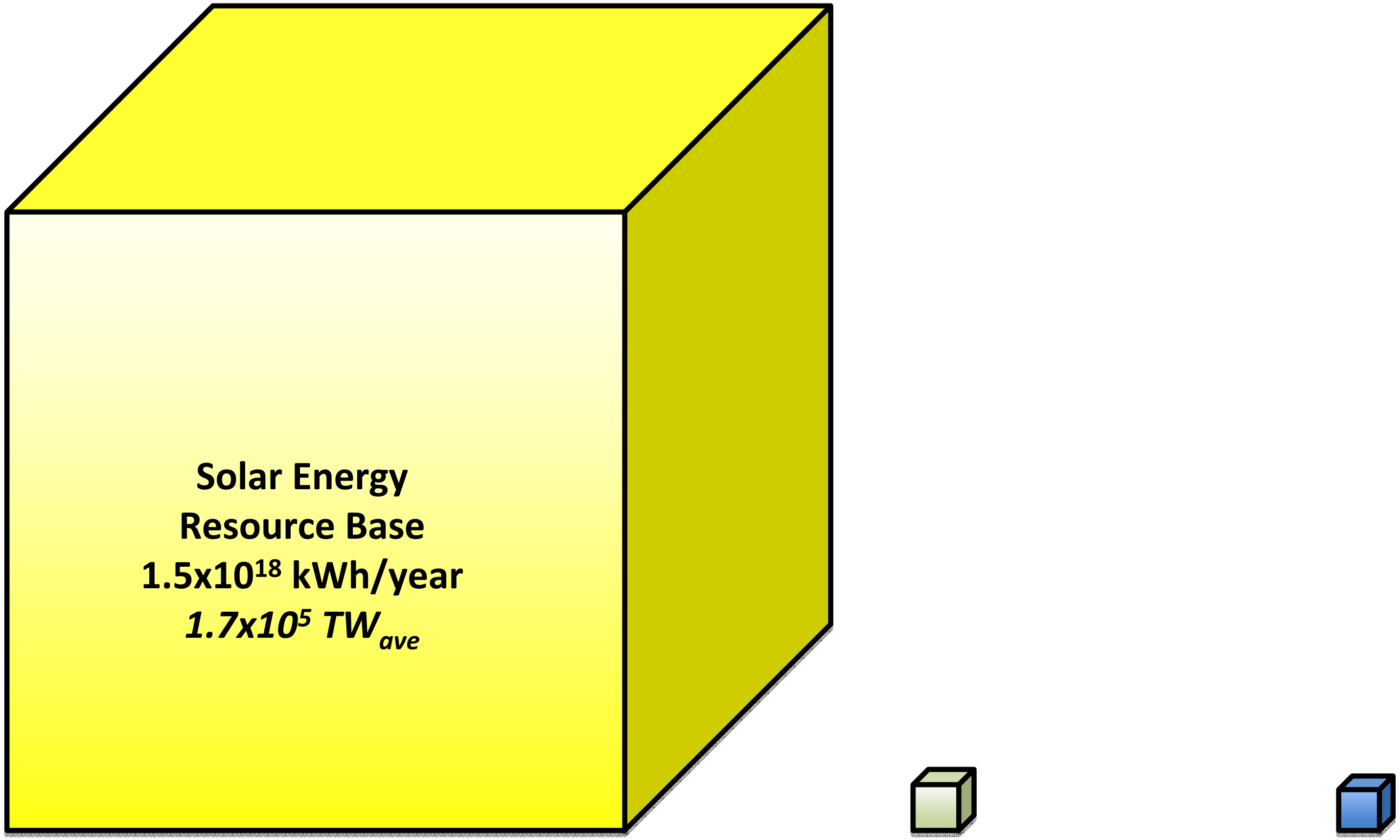
Fall 2008

Solar Resource

Lecture 1 – 2.626

Tonio Buonassisi

Solar Resource Base



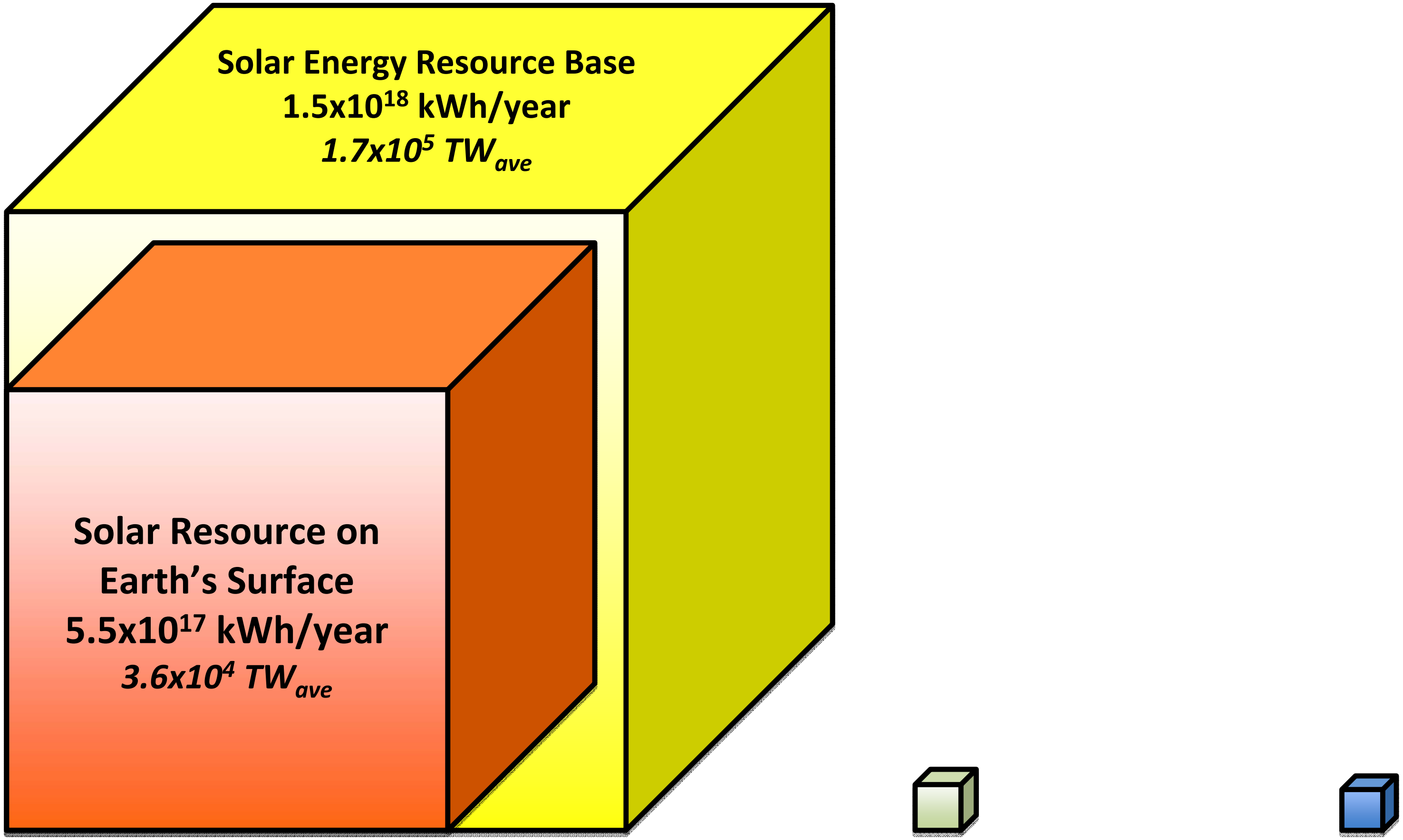
Solar Energy
Resource Base
$1.5x10^{18}$ kWh/year
$1.7x10^{5}$ TW$_{ave}$

Wind Energy
Resource Base
$6x10^{14}$ kWh/year
72 TW$_{ave}$

Human Energy Use
(mid- to late-century)
$4x10^{14}$ kWh/year
50 TW$_{ave}$

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

Solar Resource Base



Solar Energy Resource Base
$1.5x10^{18}$ kWh/year
$1.7x10^{5}\ TW_{ave}$

Solar Resource on Earth's Surface
$5.5x10^{17}$ kWh/year
$3.6x10^{4}\ TW_{ave}$

Wind Energy Resource Base
$6x10^{14}$ kWh/year
$72\ TW_{ave}$

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$4x10^{14}$ kWh/year
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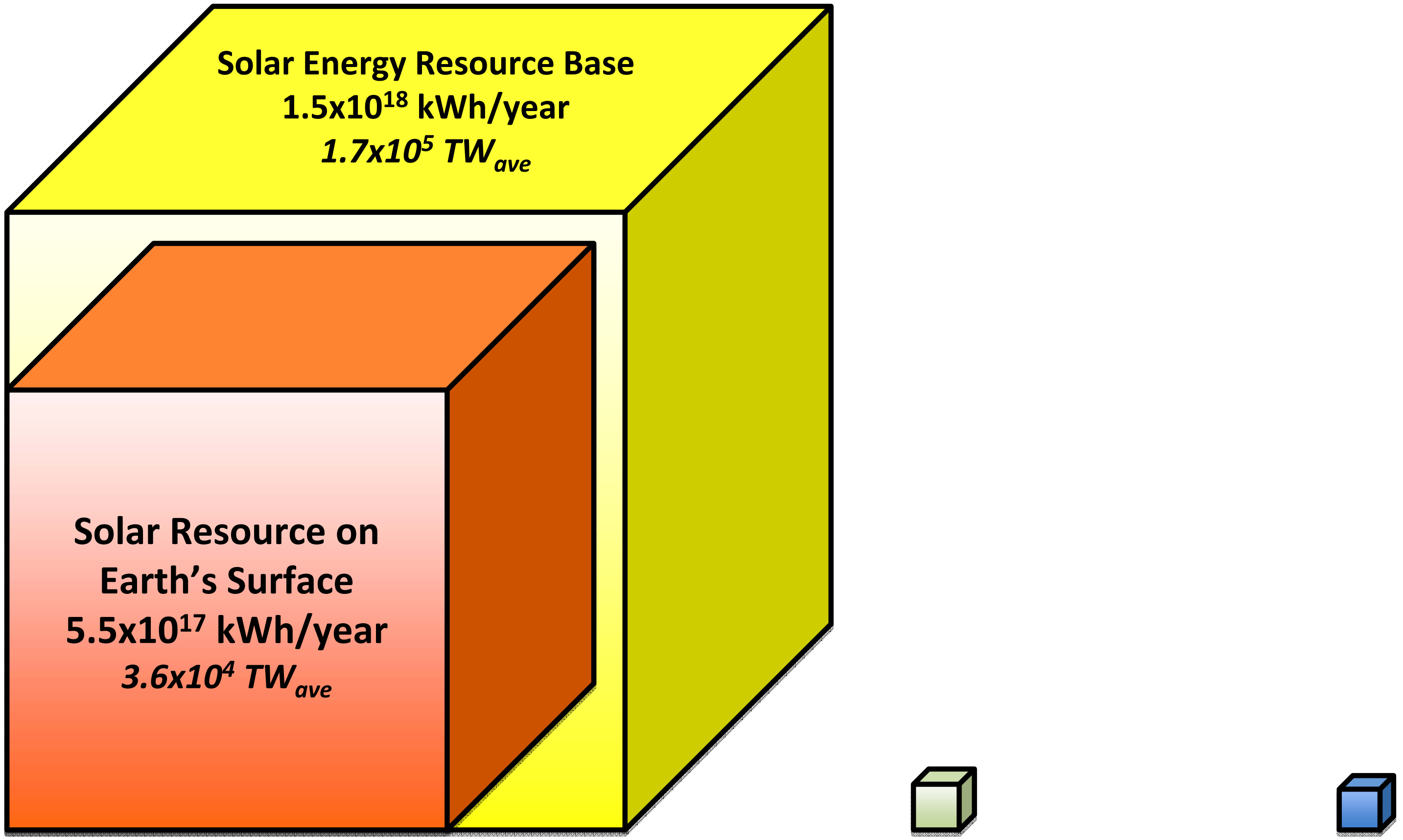
Solar Resource Base



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References:
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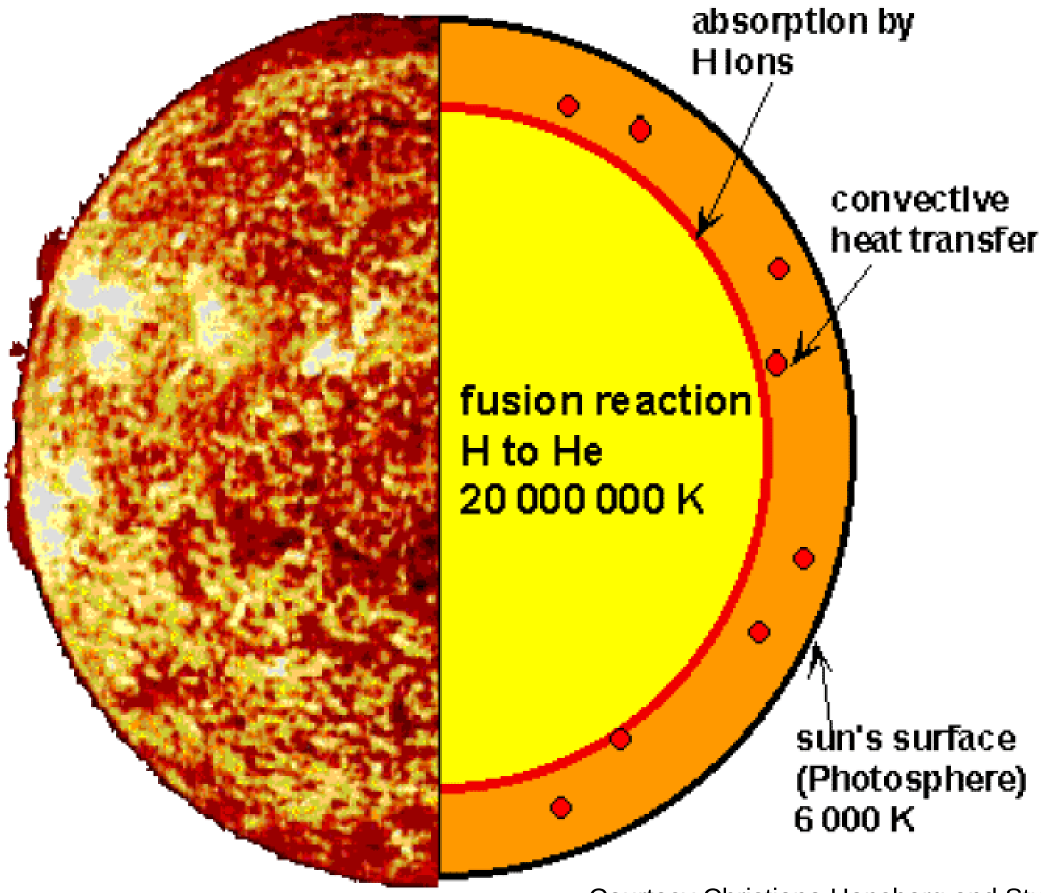
The Sun

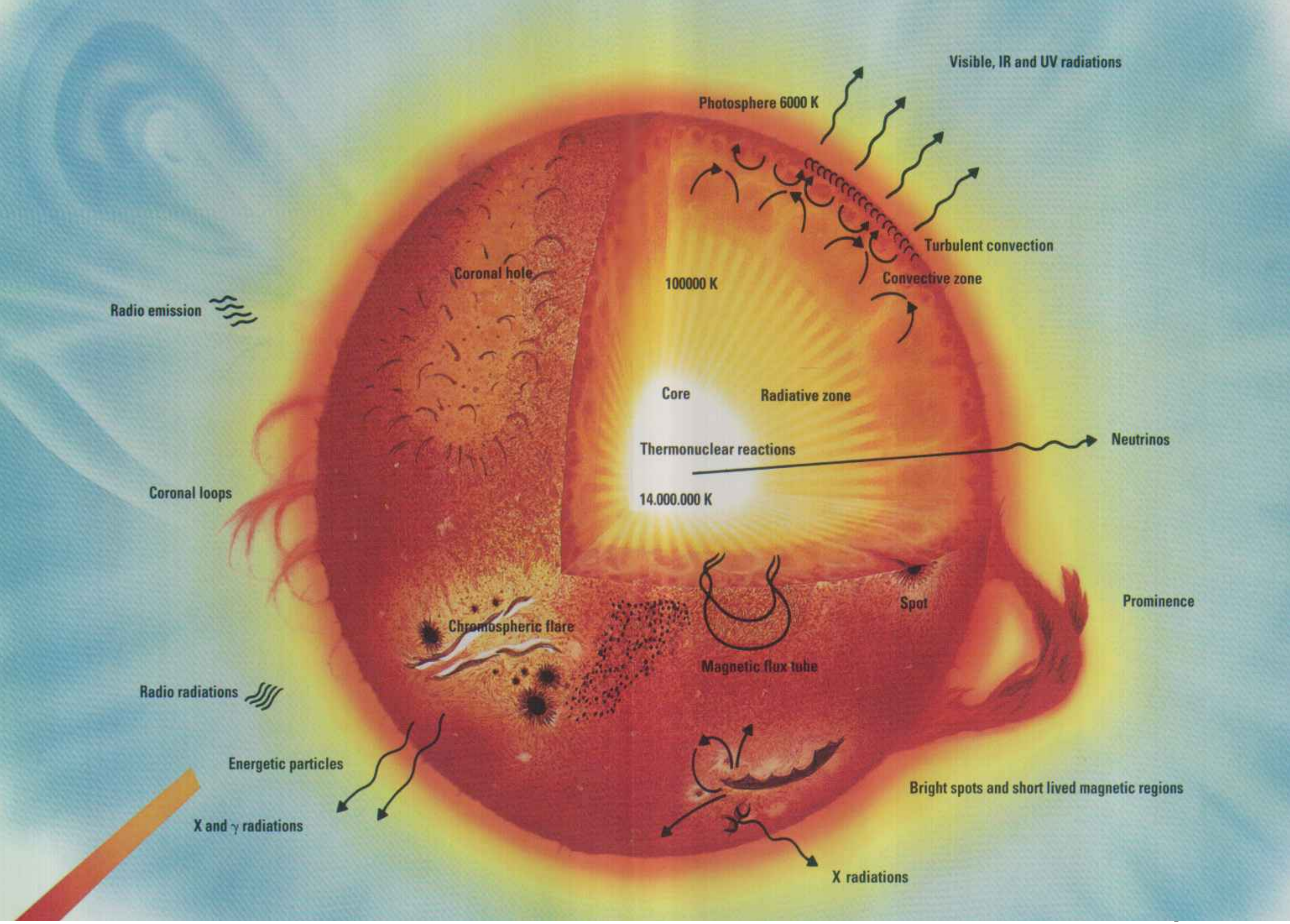
A nuclear fusion power plant ca. $1.5\text{x}10^8$ km ($9.3\text{x}10^7$ miles) away.

All power and life on Earth, from photosynthesis to fossil fuels, originates from the Sun.



Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

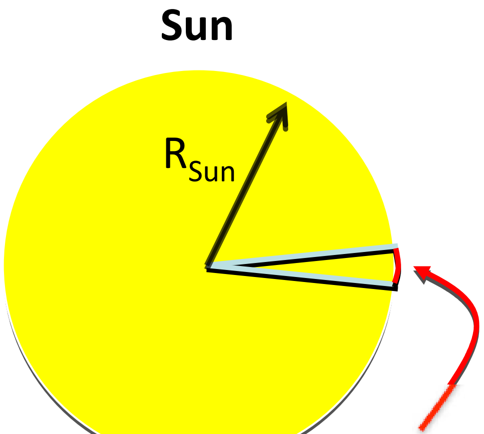
http://www.udel.edu/igert/pvcdrom/index.html



Courtesy NASA.

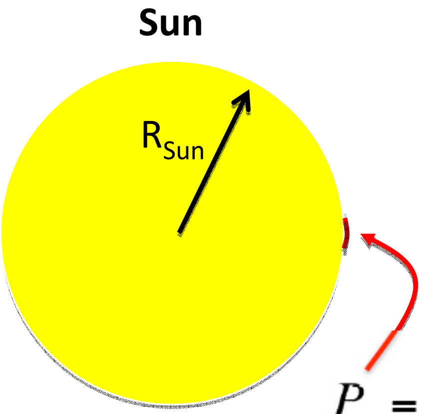
http://www.solarviews.com/cap/sun/sundiag.htm

Quantifying Solar Power



$$P_o = \frac{\sigma \cdot T^4}{4\pi R_{sun}^2}$$

Quantifying Solar Power



$$P_o = \frac{\boxed{\sigma \cdot T^4}}{\boxed{4\pi R_{sun}^2}}$$

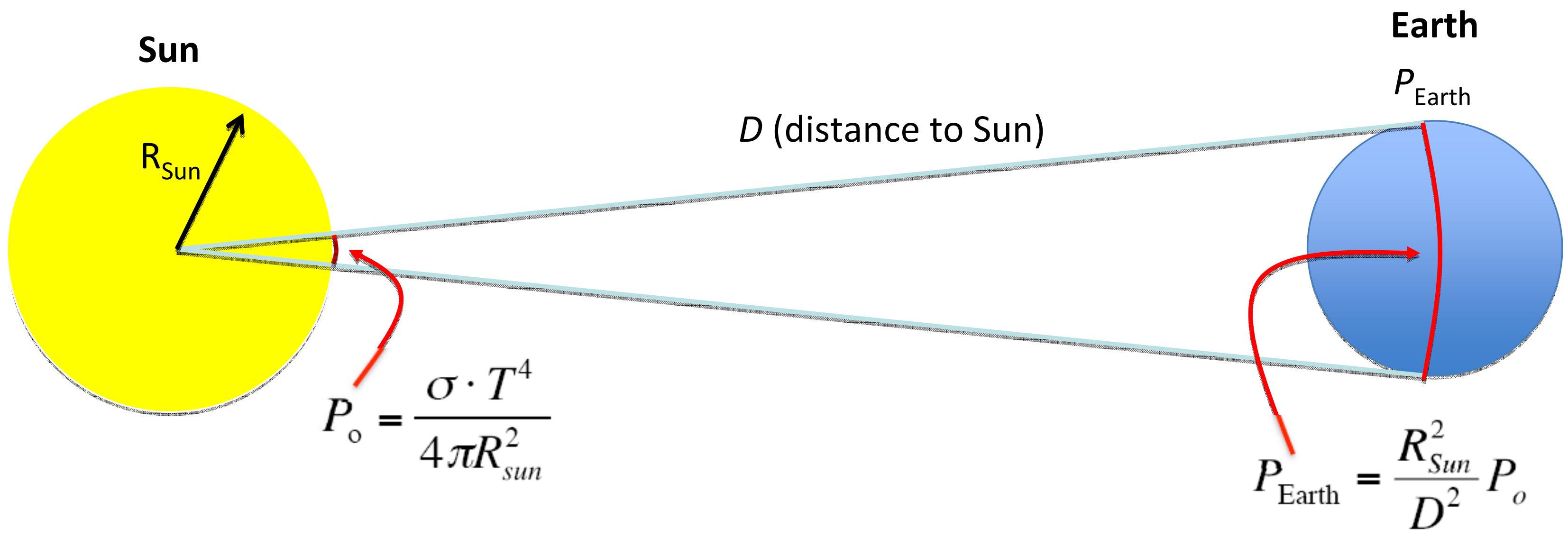
Total Radiative Power of Sun (from Stefan-Boltzmann law, T =5762±50K)

Power radiated per unit area 5.961×10^7 W/m^2

Surface Area of Sun

Quantifying Solar Power

not to scale!



Sun

R_{Sun}

D (distance to Sun)

Earth

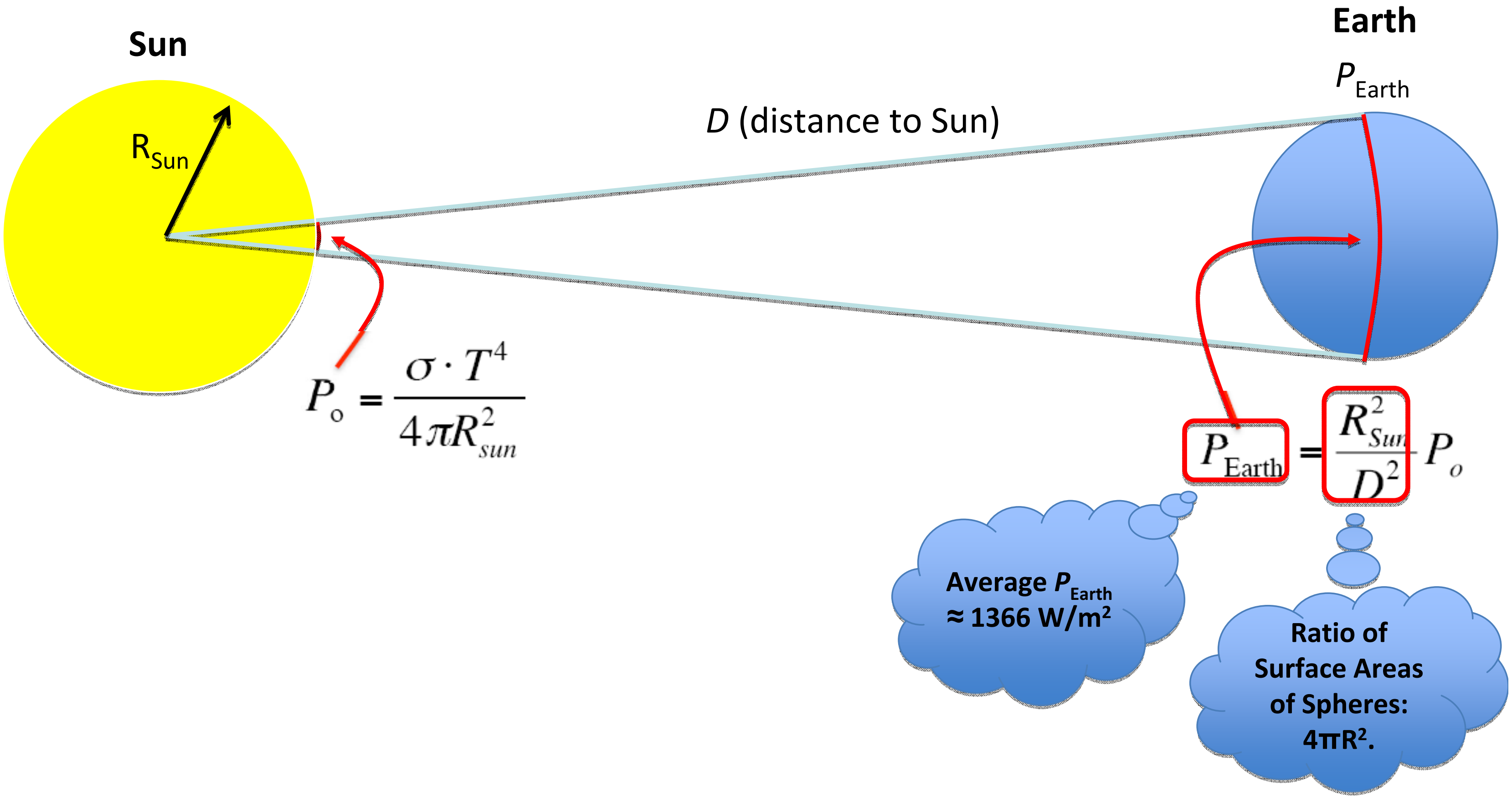
P_{Earth}

$$P_o = \frac{\sigma \cdot T^4}{4\pi R_{sun}^2}$$

$$P_{Earth} = \frac{R_{Sun}^2}{D^2} P_o$$

Quantifying Solar Power

not to scale!



$$P_o = \frac{\sigma \cdot T^4}{4\pi R_{sun}^2}$$

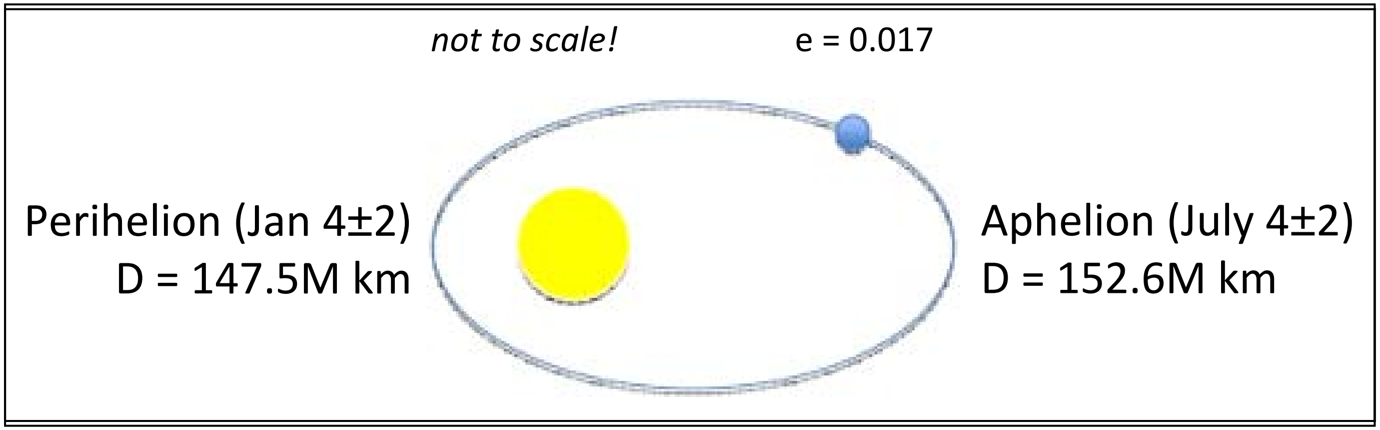
$$\boxed{P_{\text{Earth}}} = \boxed{\frac{R_{Sun}^2}{D^2}}\, P_o$$

Average P_{Earth} ≈ 1366 W/m^2

Ratio of Surface Areas of Spheres: $4\pi R^2$.

Orbit Ellipticity

The Earth's orbit around the Sun is slightly elliptical…



not to scale!

e = 0.017

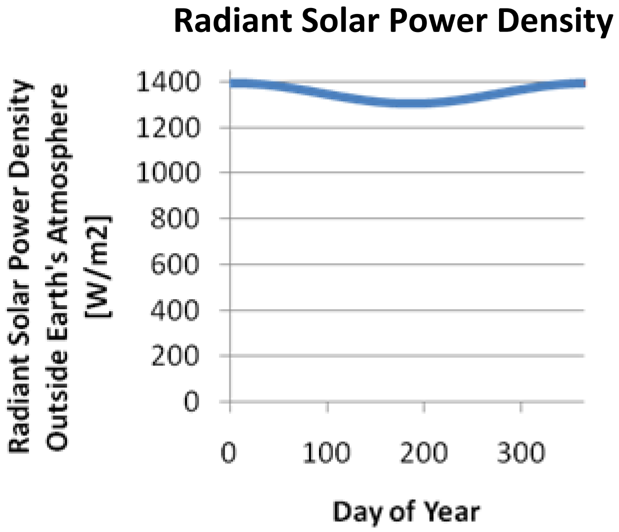
Perihelion (Jan 4±2)
D = 147.5M km

Aphelion (July 4±2)
D = 152.6M km

… resulting in a slight periodic change in the radiant solar power density as a function of season.

$$\frac{P}{P_{\text{Earth}}} = 1 + 0.033 \cdot \cos\left(\frac{2\pi \cdot (n-4)}{365}\right)$$

$P_{\text{Earth}} \approx$ **1366 W/m²**



G.D. Rai, "Solar Energy Utilisation," p. 44, Khanna Publishers, (1980).

Orbit Ellipticity

Other planets can have greater orbital ellipticity, greater variability in solar irradiance.

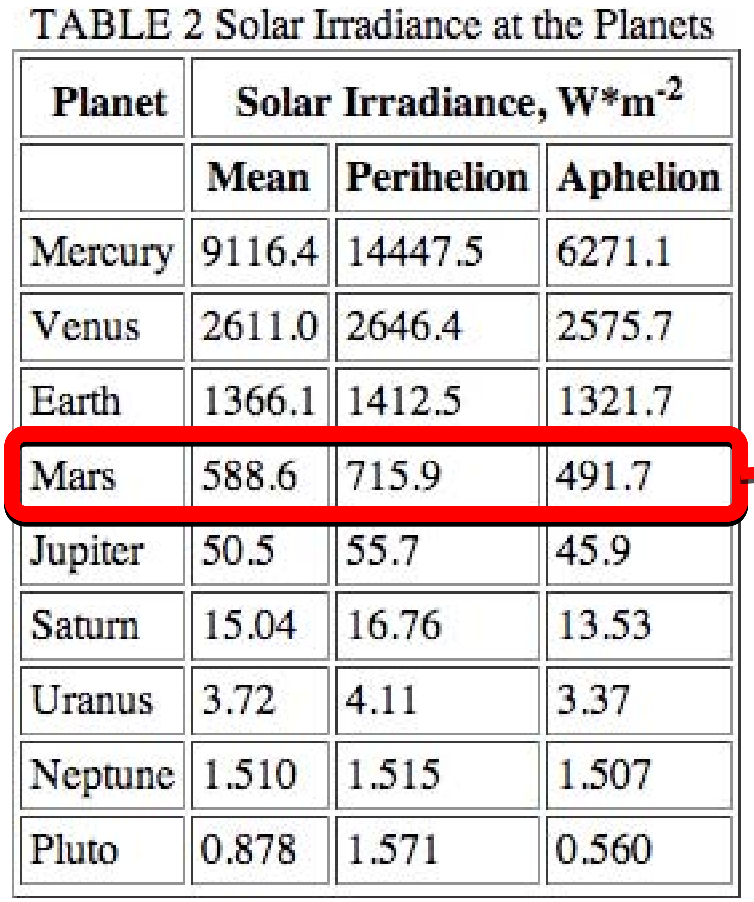


TABLE 2 Solar Irradiance at the Planets

Planet	**Solar Irradiance, W*m^{-2}**		
	Mean	**Perihelion**	**Aphelion**
Mercury	9116.4	14447.5	6271.1
Venus	2611.0	2646.4	2575.7
Earth	1366.1	1412.5	1321.7
Mars	588.6	715.9	491.7
Jupiter	50.5	55.7	45.9
Saturn	15.04	16.76	13.53
Uranus	3.72	4.11	3.37
Neptune	1.510	1.515	1.507
Pluto	0.878	1.571	0.560

Courtesy NASA.

http://rredc.nrel.gov/solar/spectra/am0/ASTM2000.html

Comprehensive Model

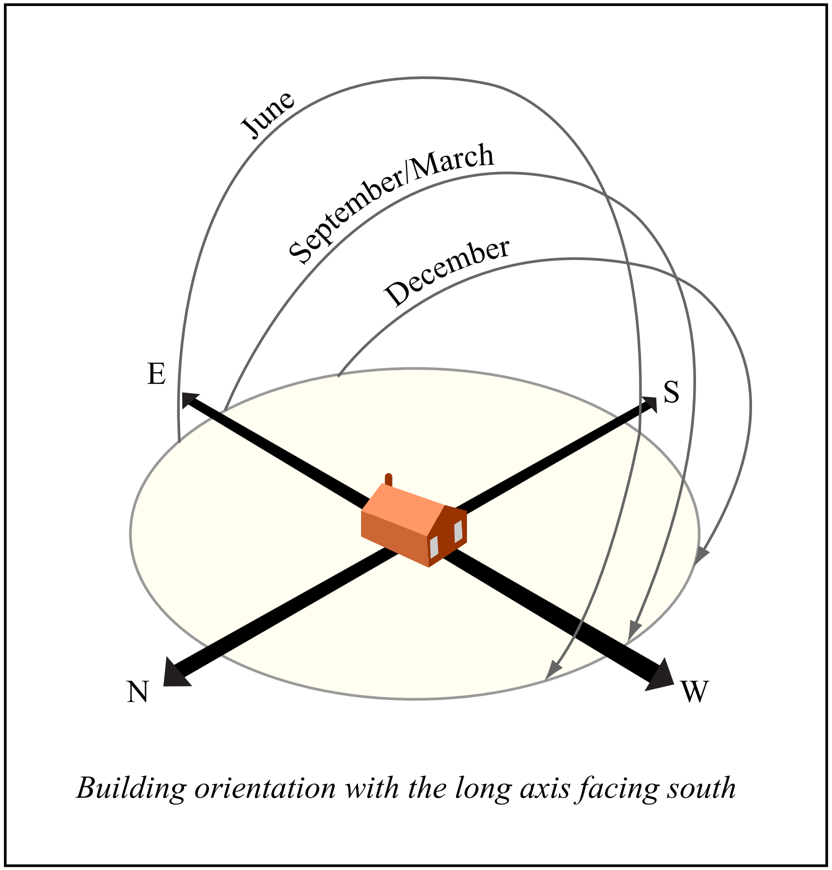
For our friends following along by phone, please access:

http://pvcdrom.pveducation.org/

Click:
- Chapter 2: Properties of Sunlight
  - *Terrestrial Solar Radiation*
    - *Motion of the Sun*

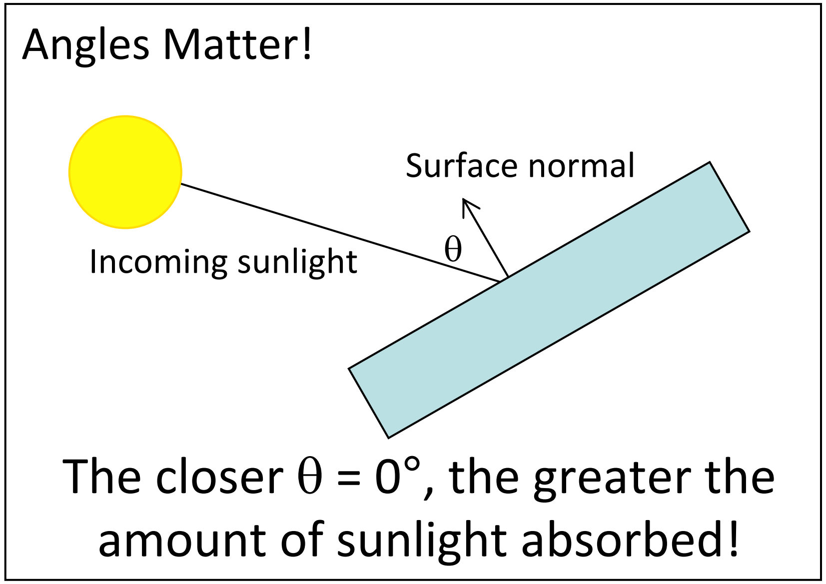
Question: How do I angle my solar panels?

Incidence of sunlight changes depending on location, time of year, local weather.



Building orientation with the long axis facing south

Figure by MIT OpenCourseWare.



The closer $\theta = 0°$, the greater the amount of sunlight absorbed!

Atmospheric Absorption

- Causes.
- Estimating the effects.
- The solar spectrum on Earth.

Atmospheric Absorption

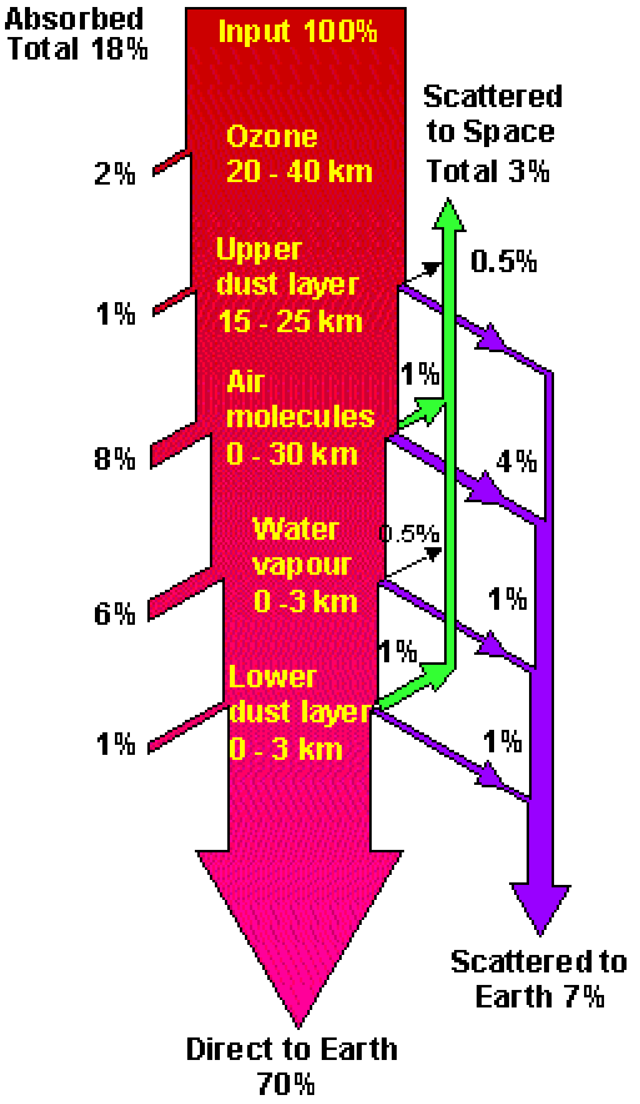
Courtesy NASA.

http://www.gsfc.nasa.gov/gsfc/earth/pictures/2002/1203apollo17/earth.jpg

ATMOSPHERIC EFFECTS

Atmospheric effects have several impacts on the solar radiation at the Earth's surface. The major effects for photovoltaic applications are:

- A reduction in the power of the solar radiation due to absorption, scattering and reflection in the atmosphere;
- A change in the spectral content of the solar radiation due to greater absorption or scattering of some wavelengths;
- The introduction of a diffuse or indirect component into the solar radiation; and
- Local variations in the atmosphere (such as water vapor, clouds and pollution) which have additional effects on the incident power, spectrum and directionality.

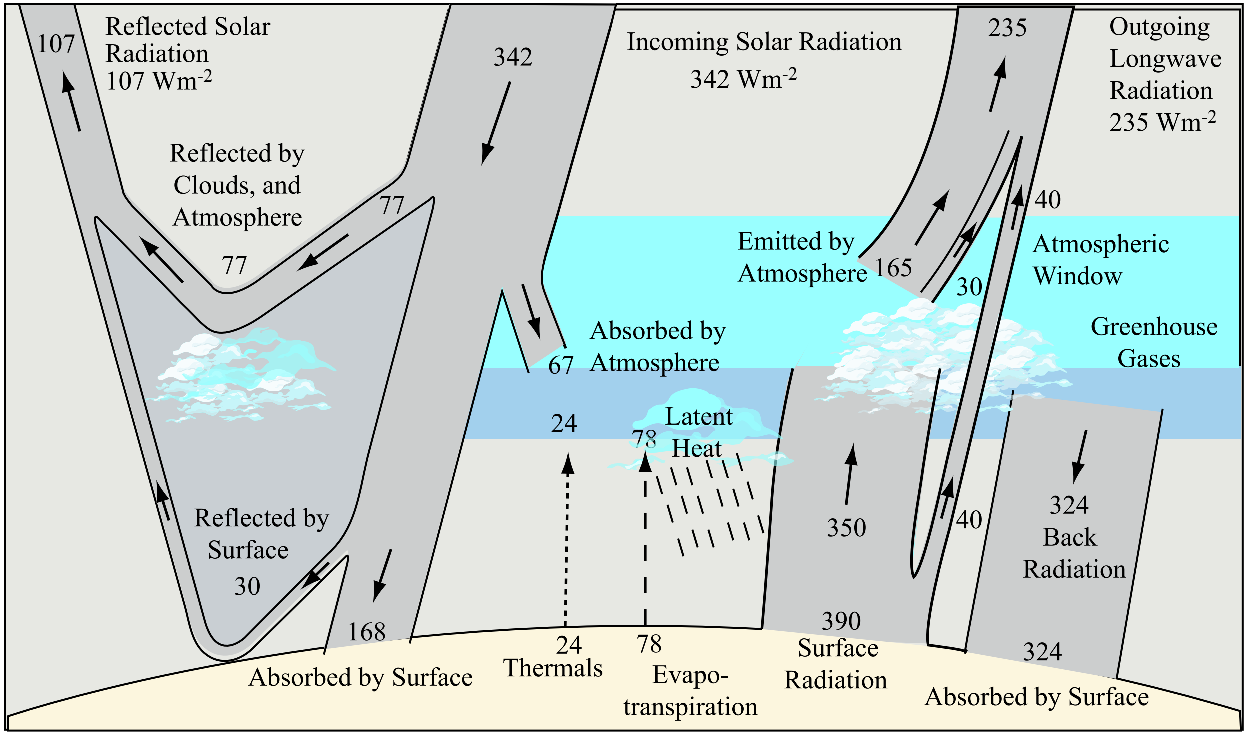


Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

Typical clear sky absorption and scattering of incident sunlight (after Hu and White, 1983).

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.

Figure 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).

ATMOSPHERIC EFFECTS

Perhaps more intuitive means of demonstrating insolation evolution (figure courtesy of Spencer Ahrens).

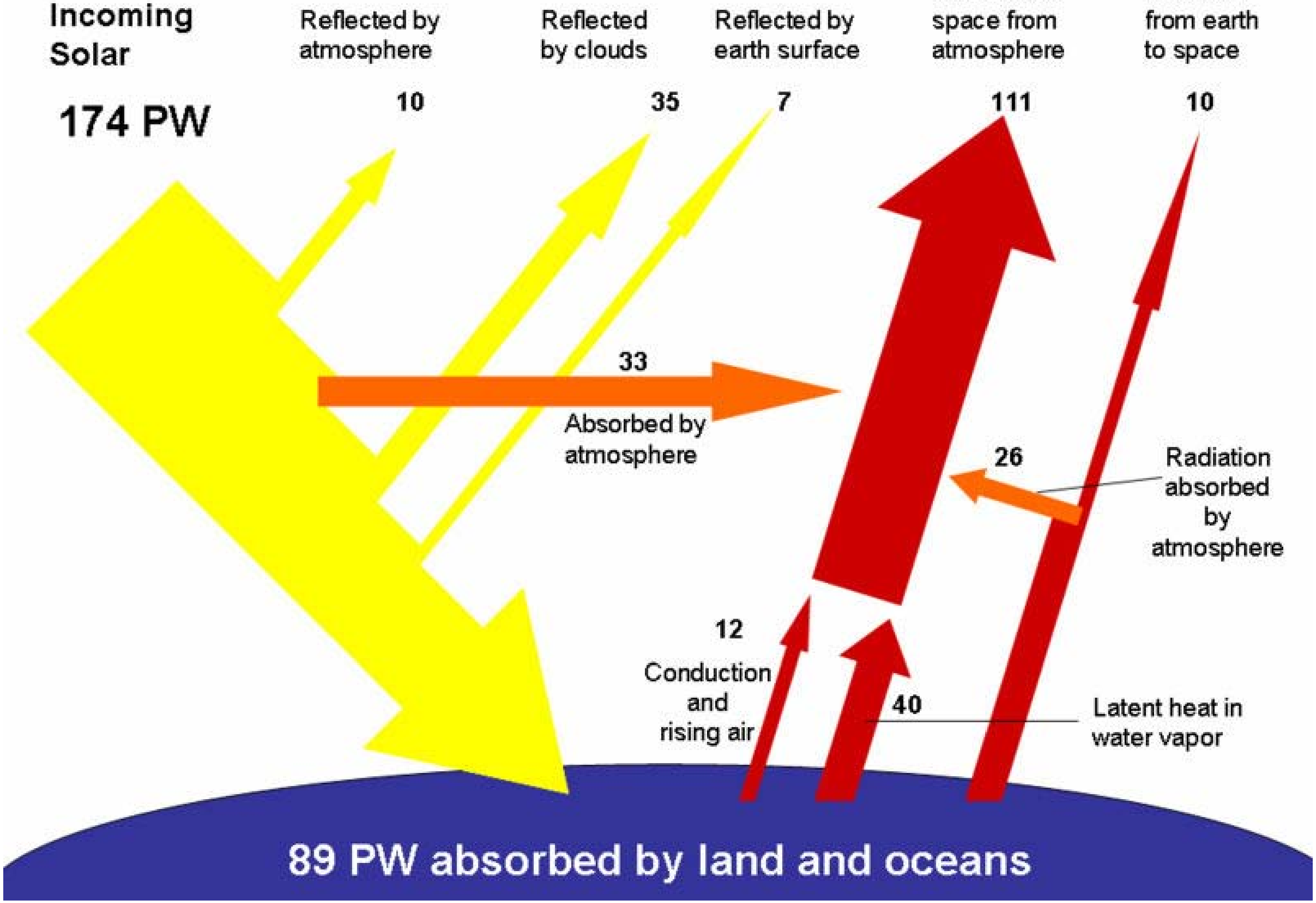


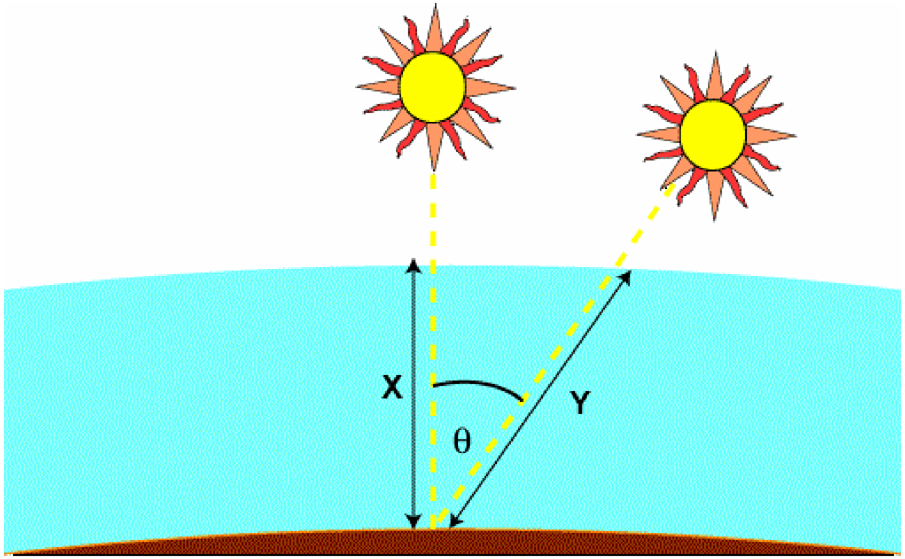
Image by Frank van Mierlo.

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



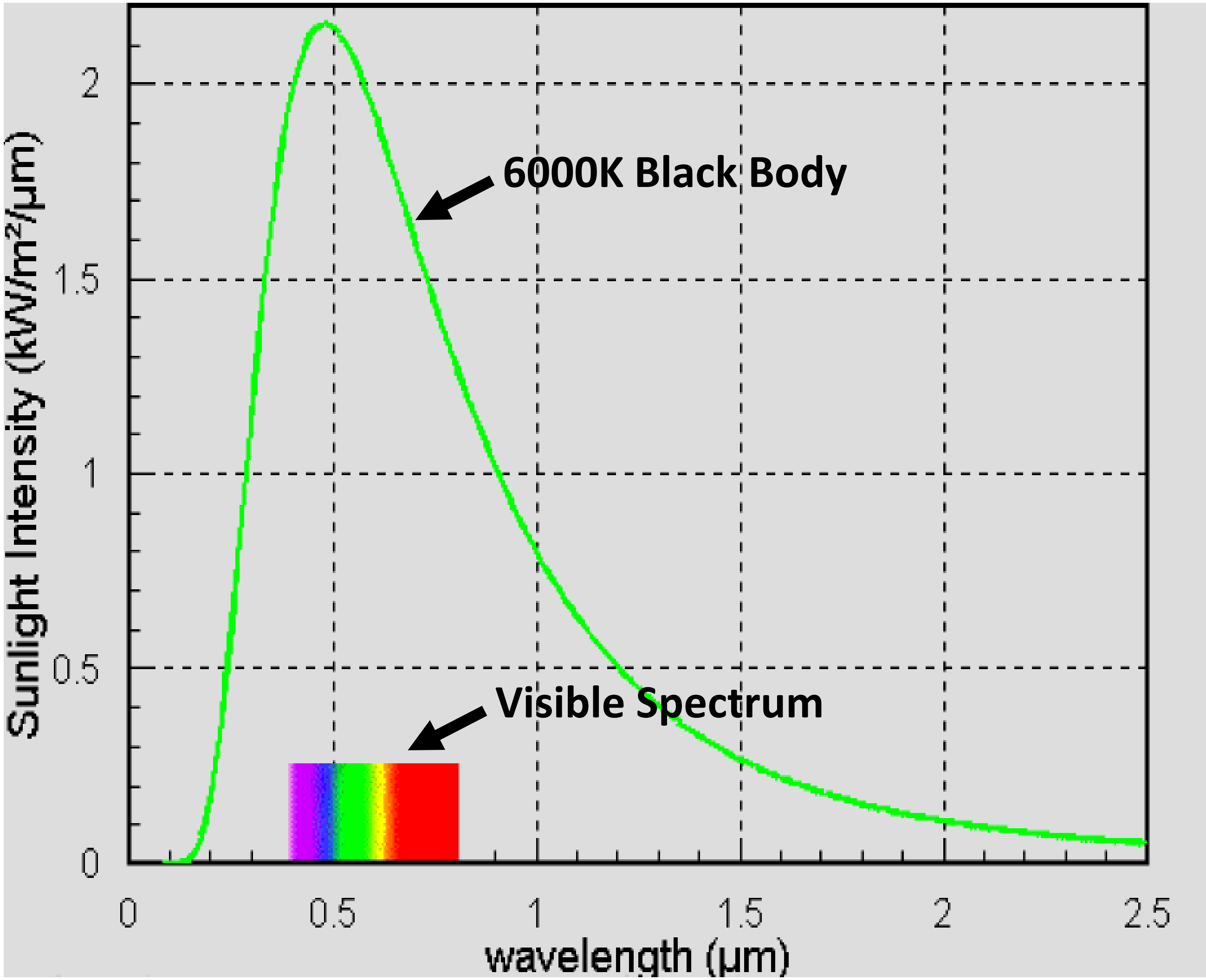
Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

AM1: Sun directly overhead

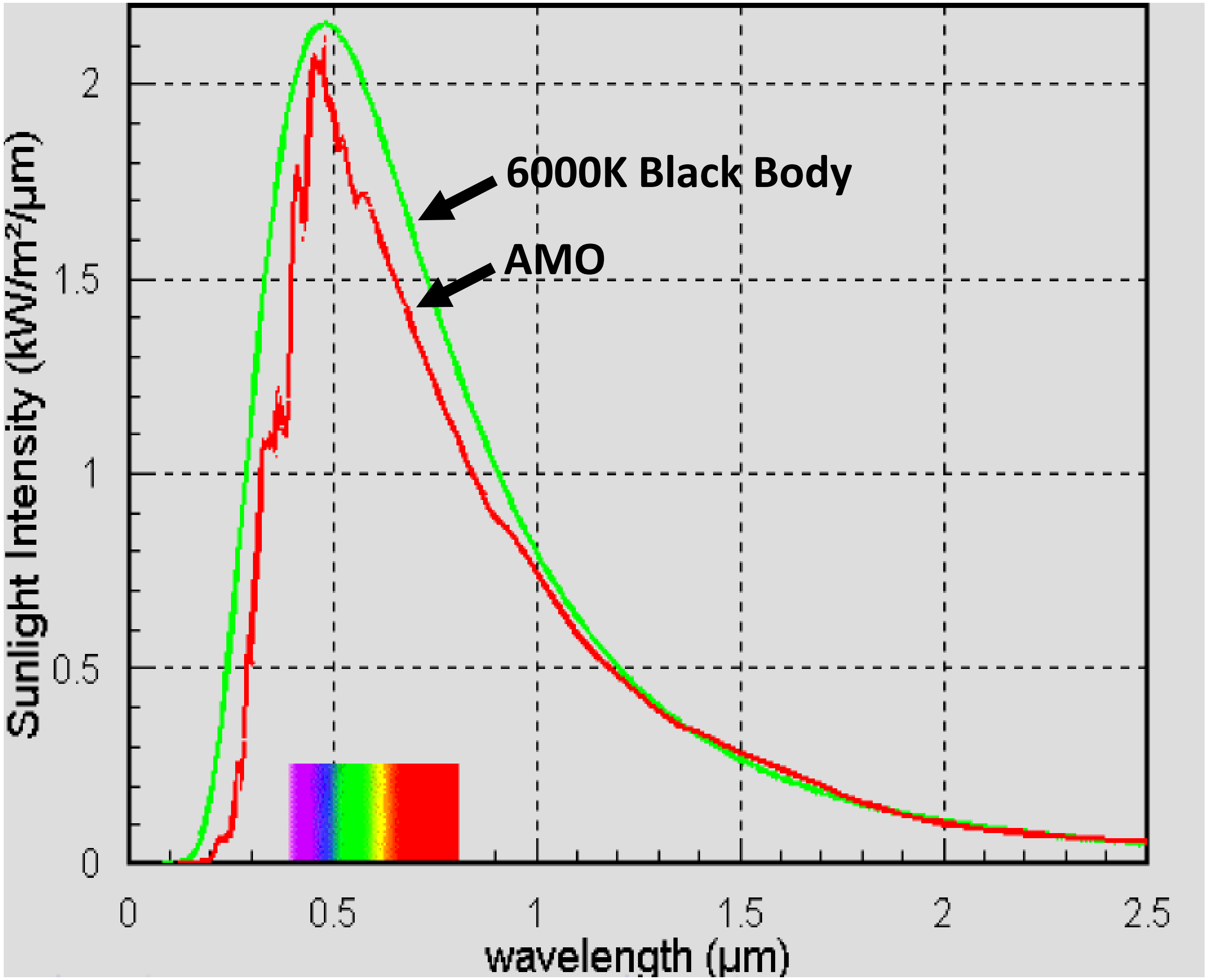
AM1.5G: “Conventional”
G (Global): Scattered and direct sunlight
D (Direct): Direct sunlight only

AM0: Just above atmosphere (space applications)

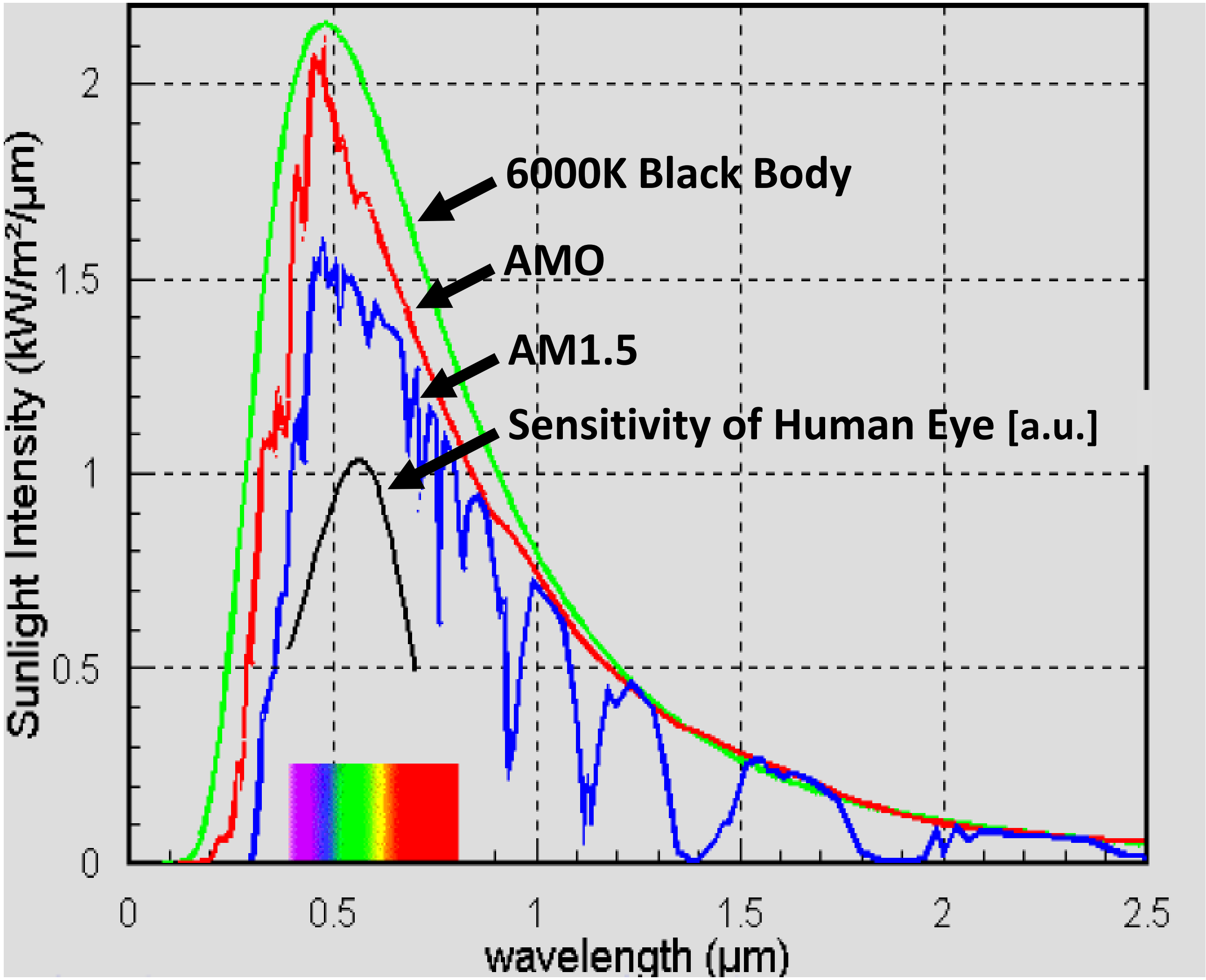
SOLAR SPECTRUM



SOLAR SPECTRUM



SOLAR SPECTRUM



6000K Black Body

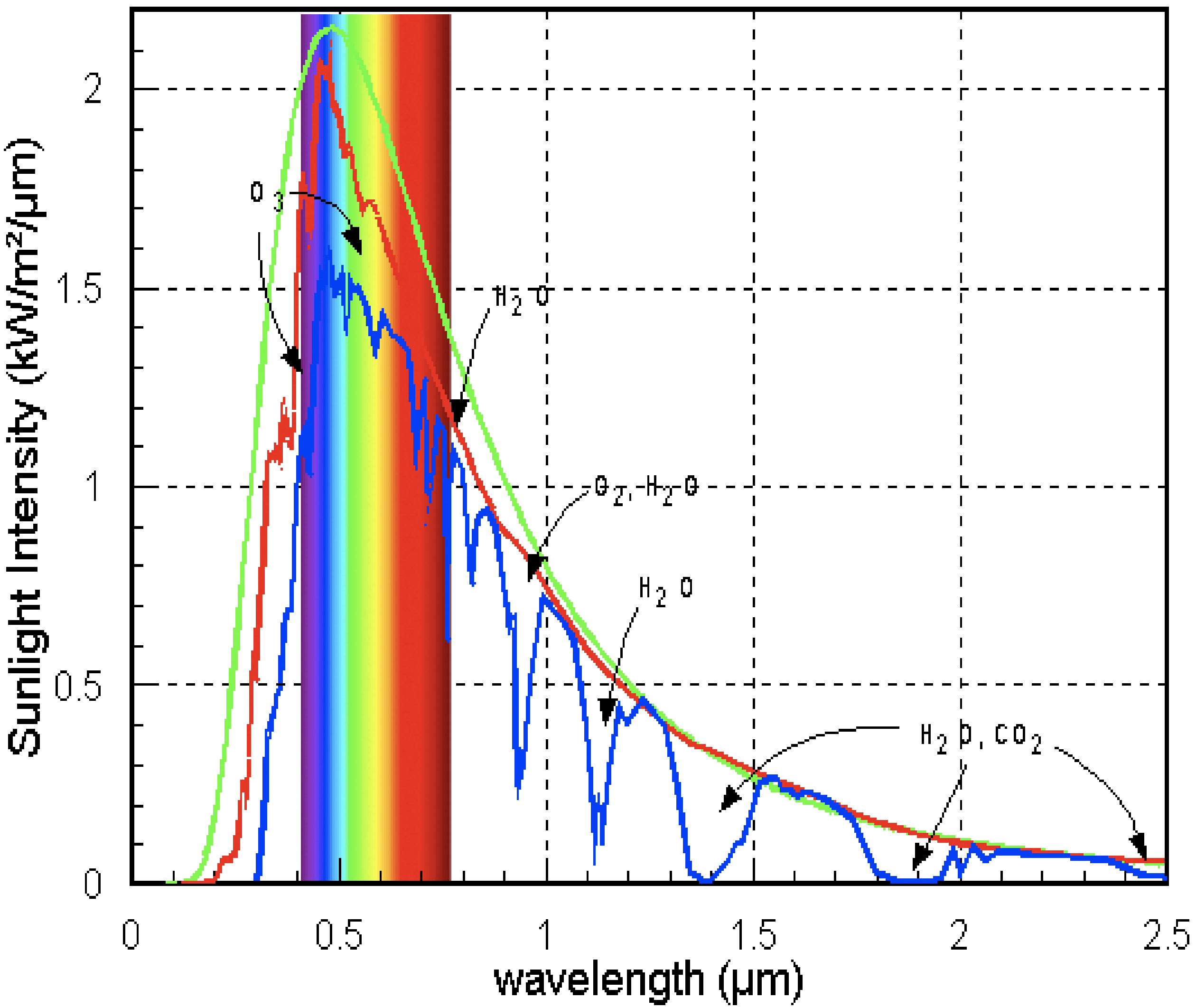
AMO

AM1.5

Sensitivity of Human Eye [a.u.]

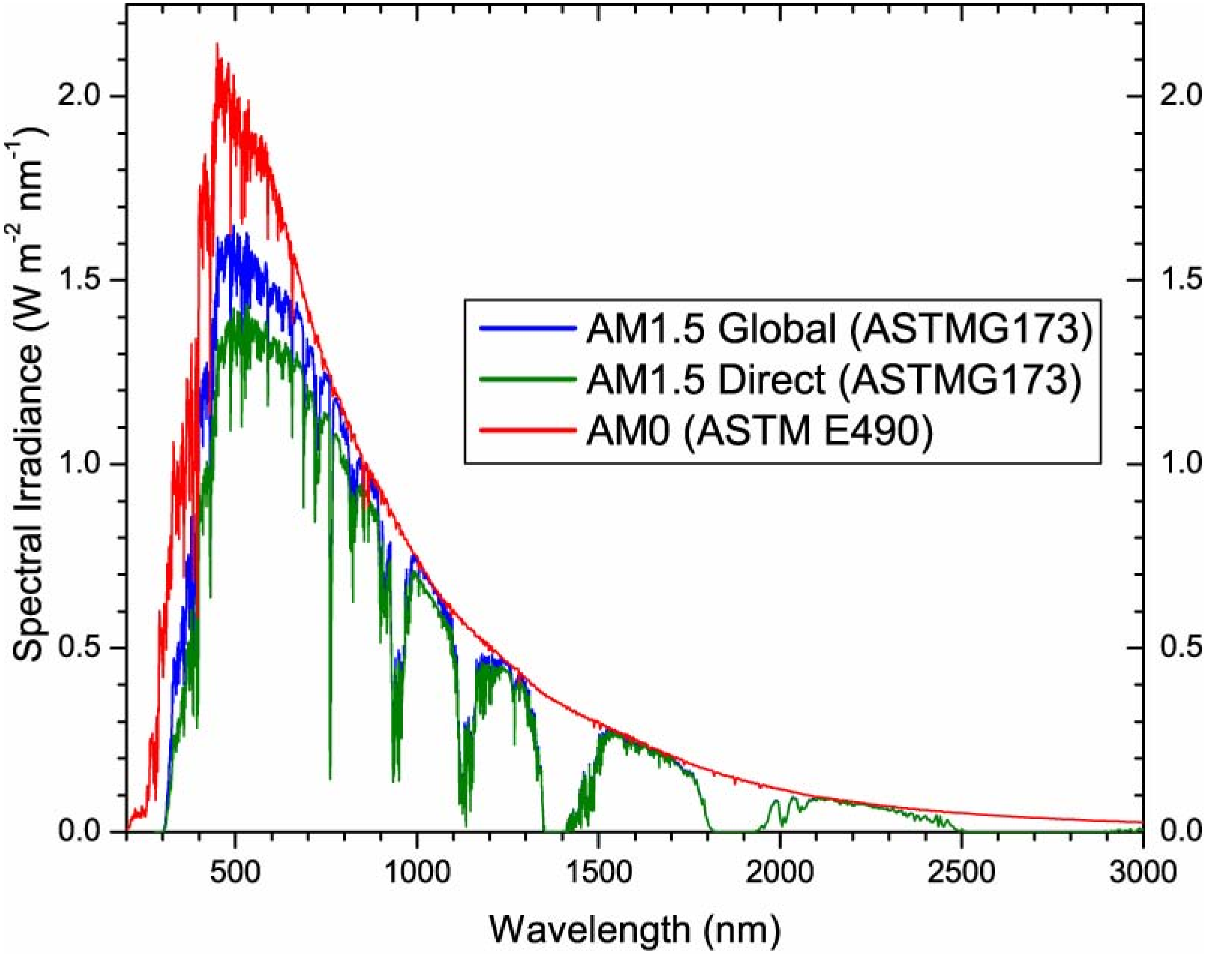
Sekuler R. and Blake, R., "Perception", *Alfred A. Knopf Inc, New York, 1985.*

SOLAR SPECTRUM



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)



The above charts, in Excel files:
http://www.udel.edu/igert/pvcdrom/APPEND/AM0AM1_5.xls

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

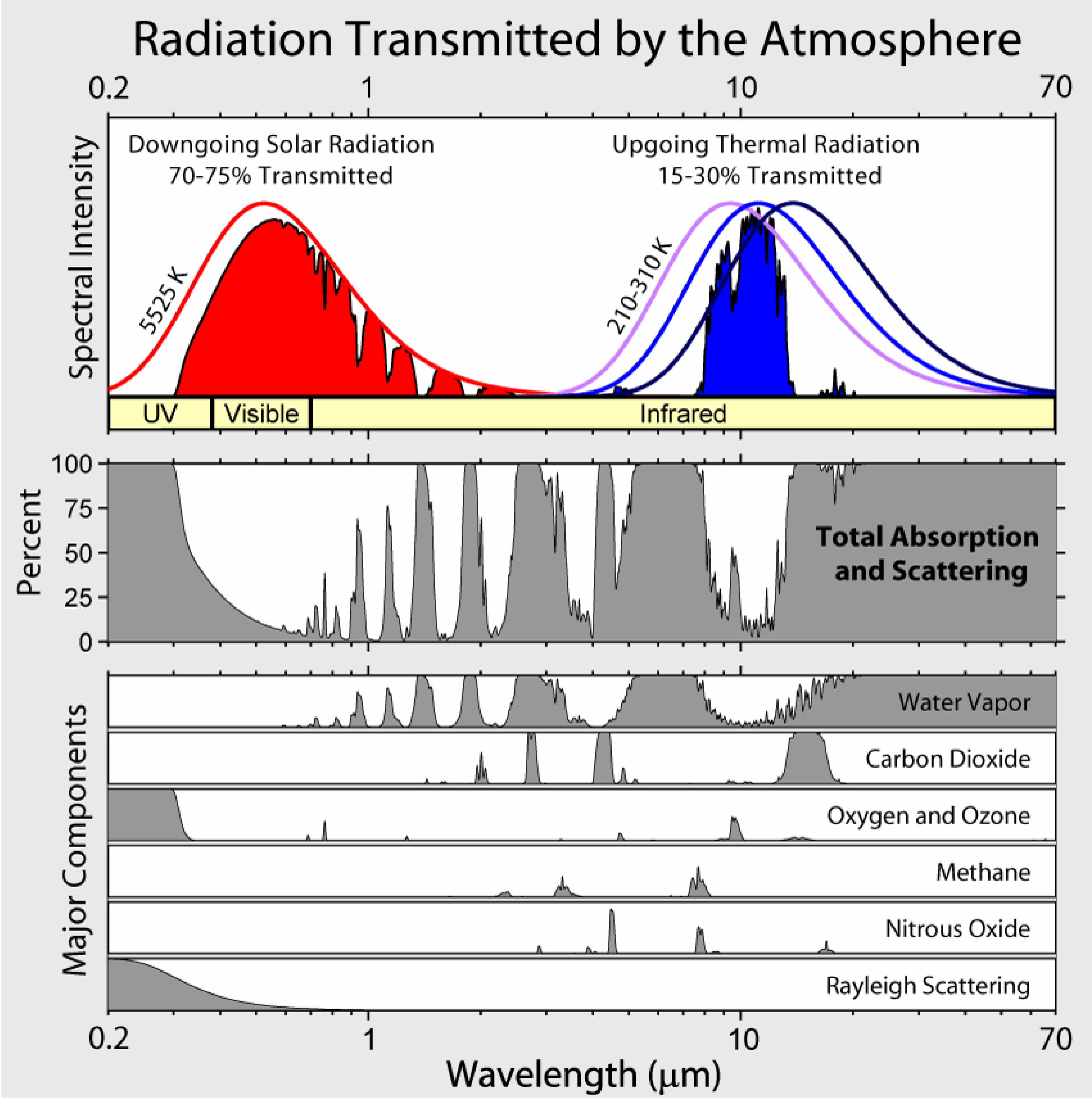


Image created by Robert A. Rohde / Global Warming Art.

INSOLATION

Insolation: Incoming 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.

Measuring Global/Direct Insolation

Courtesy DOE/NREL, Credit – David Parsons.

Courtesy DOE/NREL, Credit – Tom Stoffel.

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

Solar Insolation Maps

- United States
- Europe
- Africa
- World

Map removed due to copyright restrictions. Please see PV Solar Radiation (Flat Plaste, Facing South, Latitude Tilt), [January], NREL.

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Map removed due to copyright restrictions. Please see PV Solar Radiation (Flat Plaste, Facing South, Latitude Tilt), [December], NREL.

The difference between concentrating and non-concentrating solar resources

(concentrating solar power requires direct sunlight!)

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Map removed due to copyright restrictions. Please see [PV Solar Radiation (Flat Plate, Facing South, Latitude Tilt), January], NREL.

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Map removed due to copyright restrictions. Please see [PV Solar Radiation (Flat Plate, Facing South, Latitude Tilt),July], NREL.

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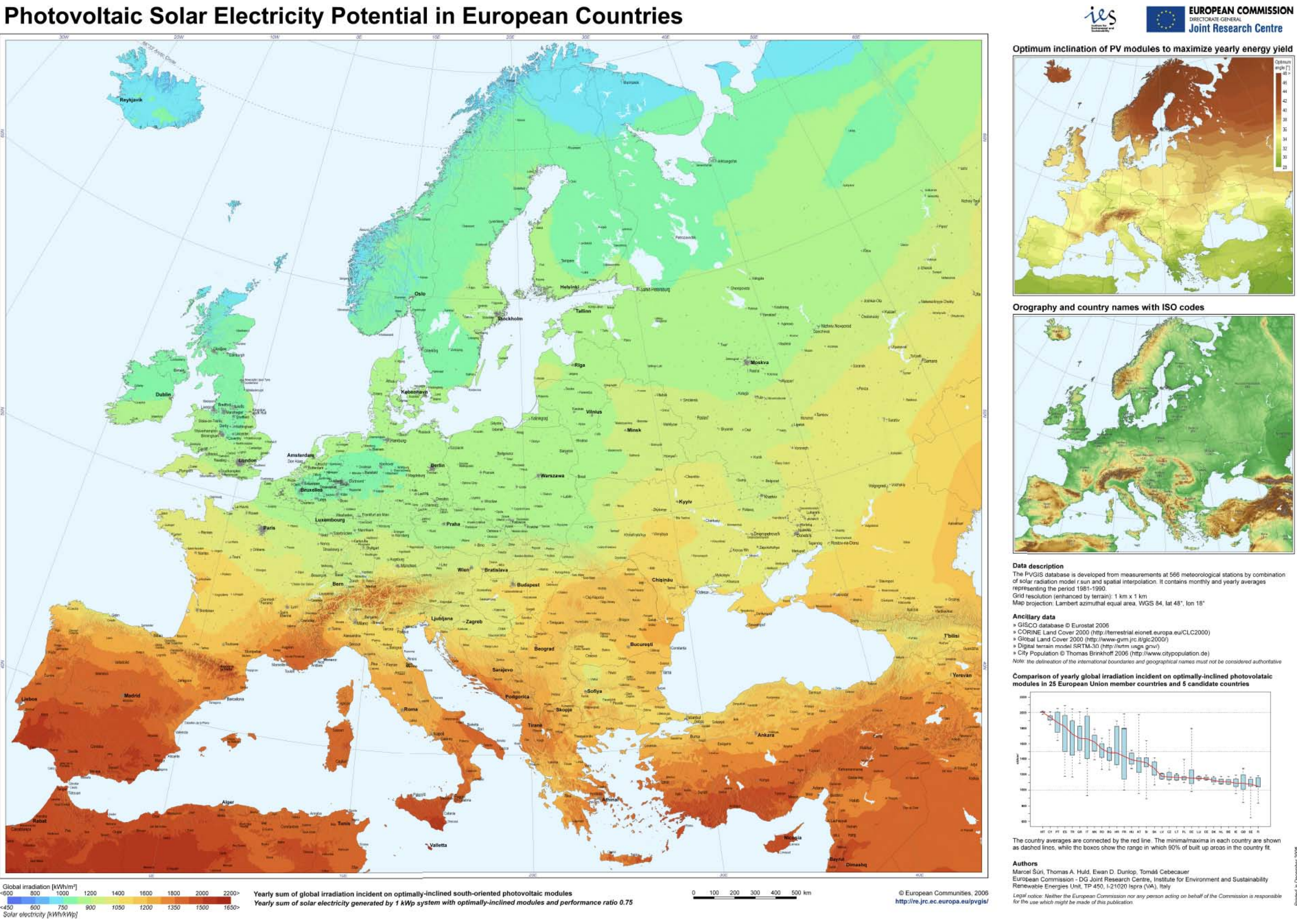

Photovoltaic Solar Electricity Potential in European Countries

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules

Yearly sum of solar electricity generated by 1 kWp system with optimally-inclined modules and performance ratio 0.75

© European Communities, 2006
http://re.jrc.ec.europa.eu/pvgis/

Optimum inclination of PV modules to maximize yearly energy yield

Orography and country names with ISO codes

Data description

The PVGIS database is developed from measurements at 566 meteorological stations by combination of solar radiation model r.sun and spatial interpolation. It contains monthly and yearly averages representing the period 1981-1990.
Grid resolution (enhanced by terrain): 1 km x 1 km
Map projection: Lambert azimuthal equal area, WGS 84, lat 48°, lon 18°

Ancillary data

- GISCO database © Eurostat 2006
- CORINE Land Cover 2000 (http://terrestrial.eionet.europa.eu/CLC2000)
- Global Land Cover 2000 (http://www-gvm.jrc.it/glc2000/)
- Digital terrain model SRTM-30 (http://srtm.usgs.gov/)
- City Population © Thomas Brinkhoff 2006 (http://www.citypopulation.de)

Note: the delineation of the international boundaries and geographical names must not be considered authoritative

Comparison of yearly global irradiation incident on optimally-inclined photovolataic modules in 25 European Union member countries and 5 candidate countries

The country averages are connected by the red line. The minima/maxima in each country are shown as dashed lines, while the boxes show the range in which 80% of built up areas in the country fit.

Authors

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Renewable Energies Unit, TP 450, I-21020 Ispra (VA), Italy

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Printed in December 2006

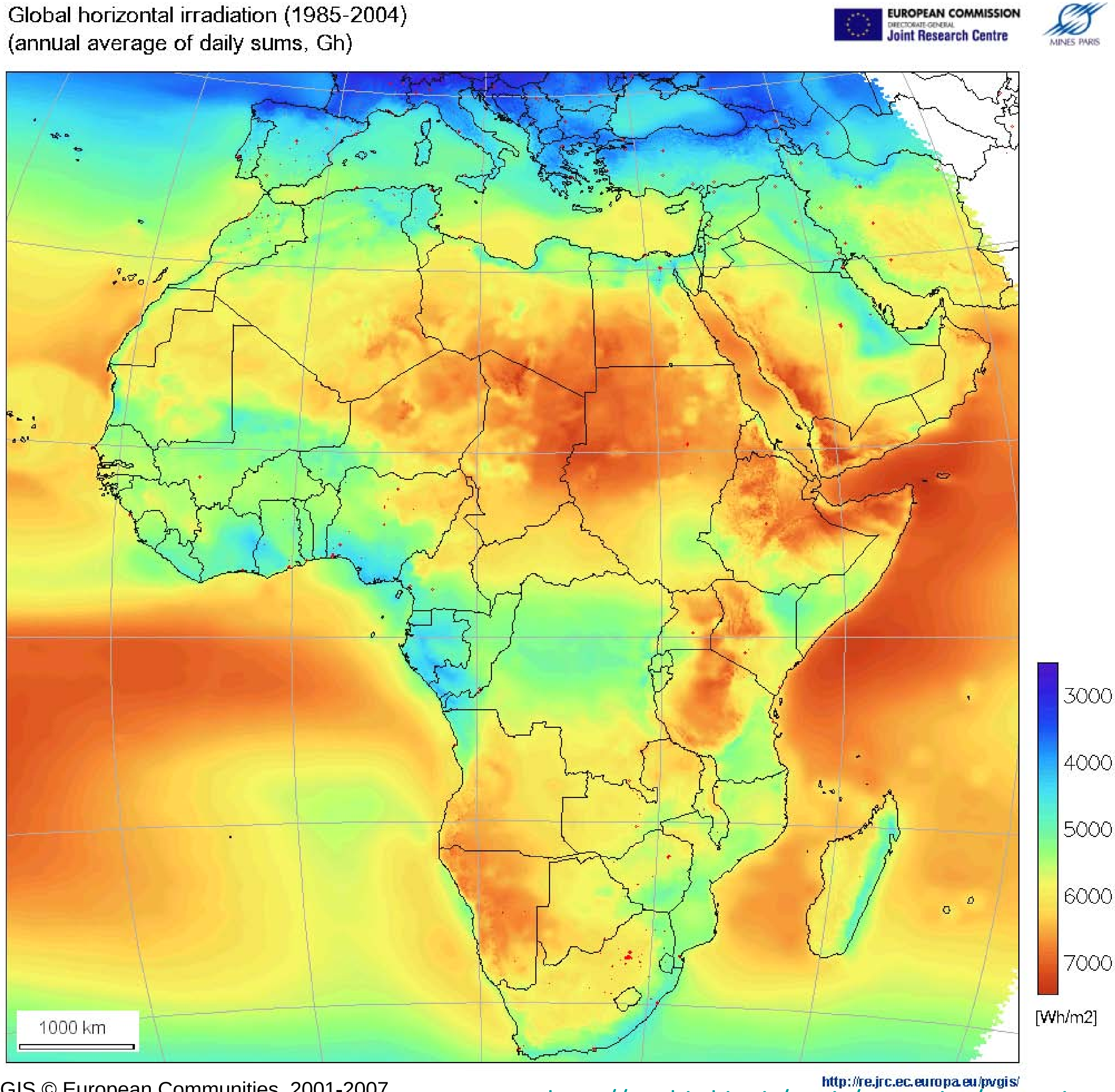
Image by PVGIS © European Communities, 2001-2007

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

Germany & U.S. : A quick comparison

Image removed due to copyright restrictions. Please see
http://citysustainable.com/images/SEIA_compare_germany_us.jpg

About half of all modules installed last year were installed in Germany…

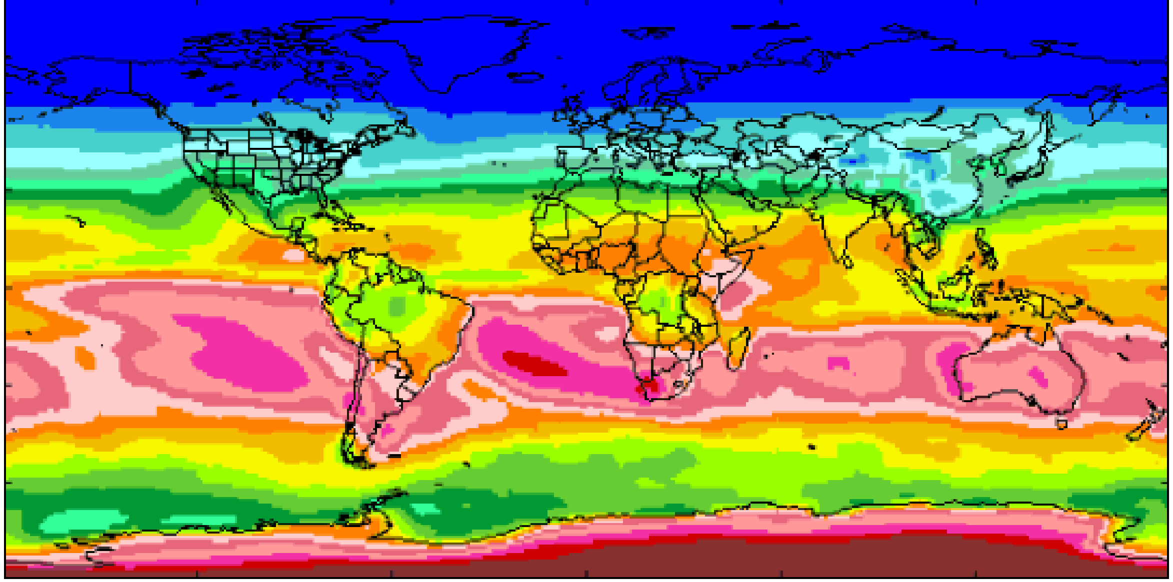

Global horizontal irradiation (1985-2004)
(annual average of daily sums, Gh)

http://re.jrc.ec.europa.eu/pvgis/

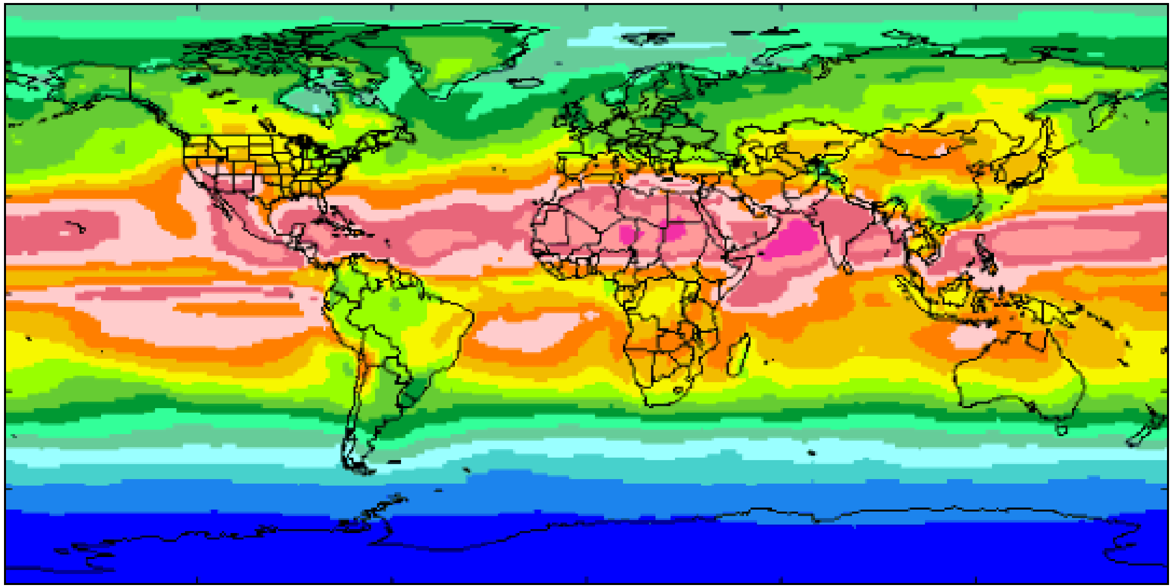
Image by PVGIS © European Communities, 2001-2007

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

Global Insolation Data



January 1984–1993



April 1984–1993

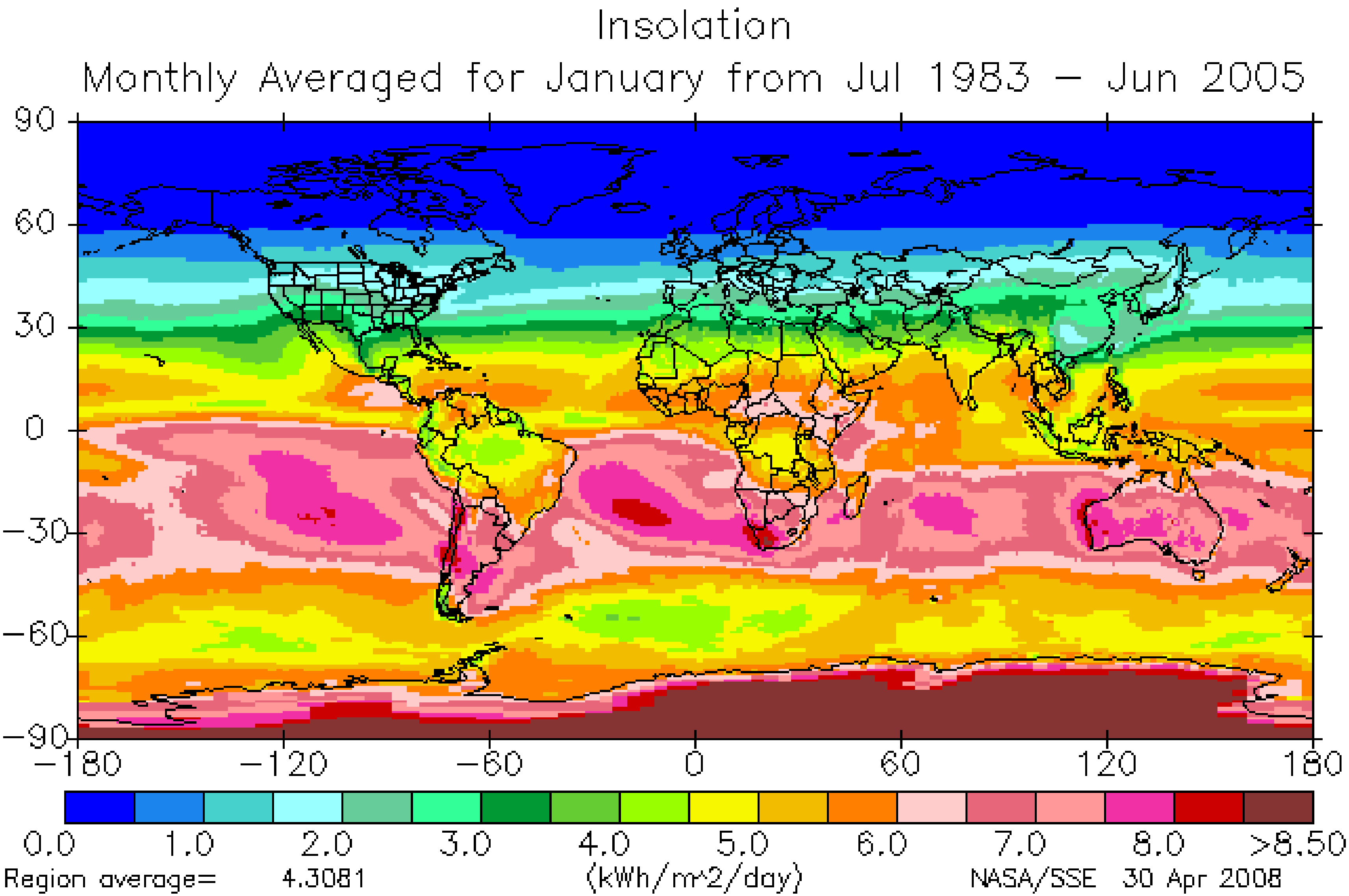
Solar Insolation (kWh/m^2/day)

0 >8.5

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

Image courtesy NASA Earth Observatory.

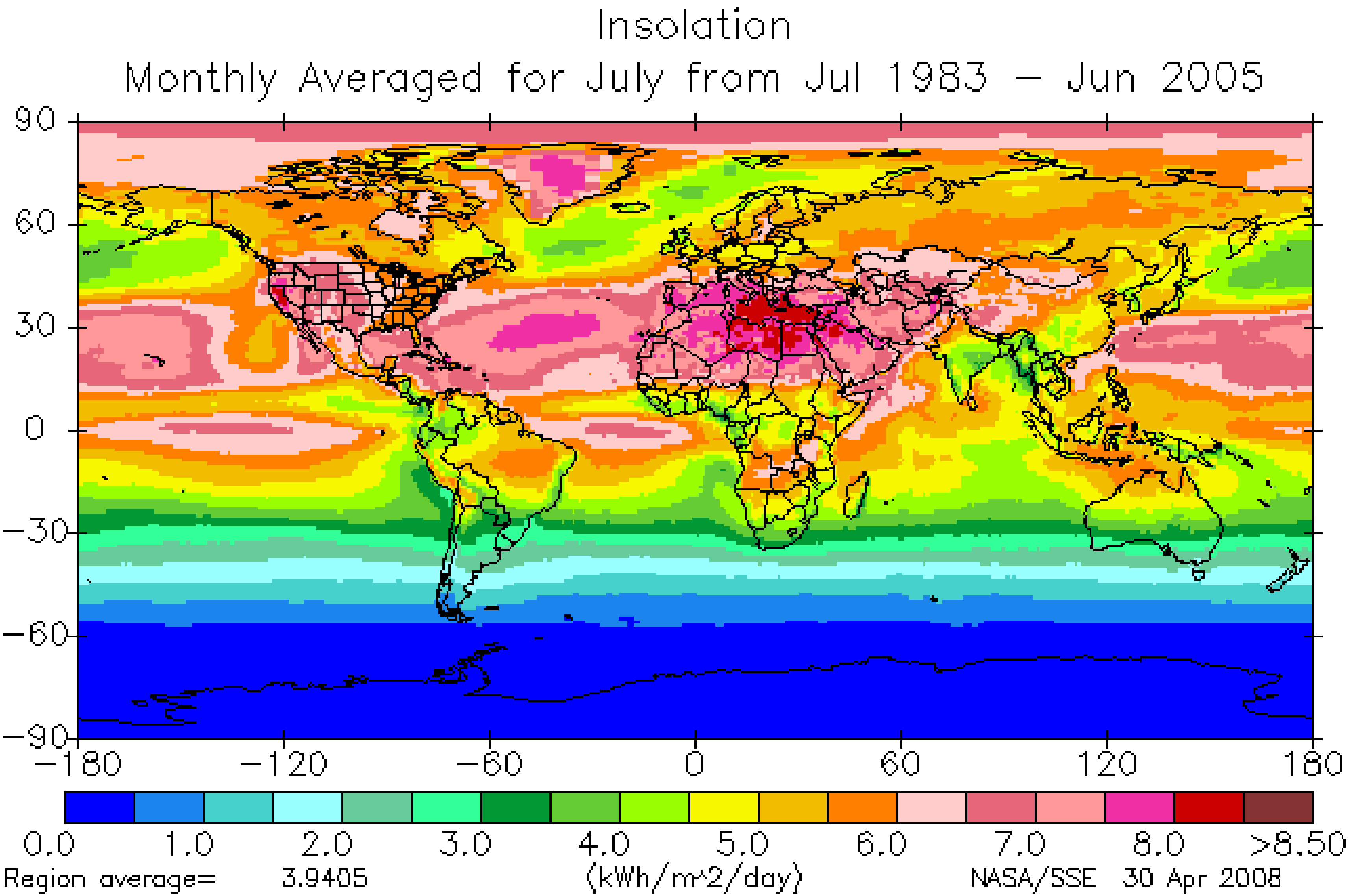
Global Insolation Data



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

Image courtesy NASA Earth Observatory.

Global Insolation Data



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

Image courtesy NASA Earth Observatory.

Global Insolation

Insolation at AM0: Resource determined by latitude (~cos theta).

Image removed due to copyright restrictions. Please see
http://en.wikipedia.org/wiki/File:Insolation.png

Average Surface Insolation: Determined by atmospheric absorption, local weather patterns…

http://www.answers.com/topic/solar-power-1

Estimating Solar System Outputs

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:

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

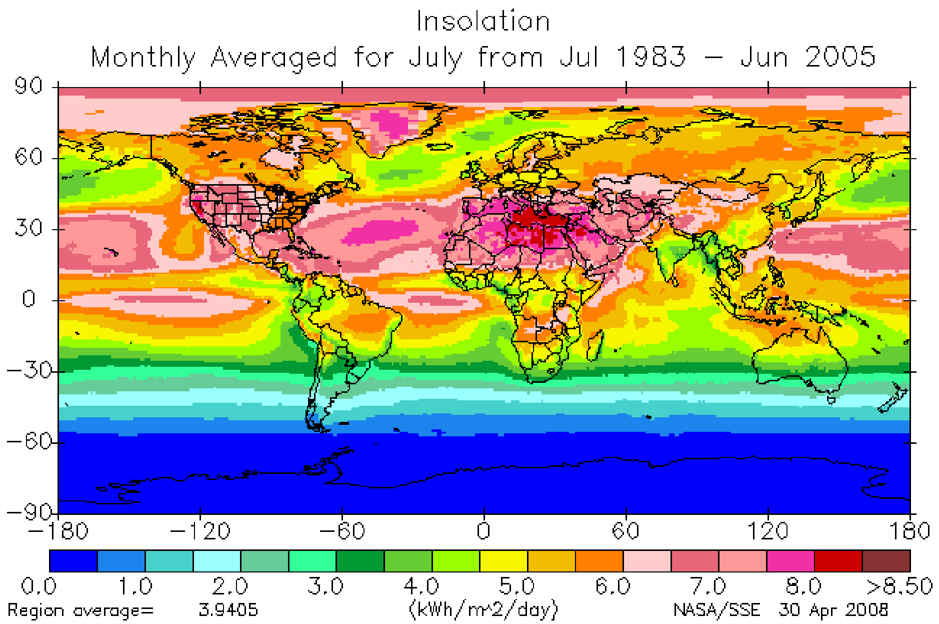


Image courtesy NASA Earth Observatory.

Estimating System Output from Insolation Maps

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System size

Insolation at site of installation

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

AM 1.5G

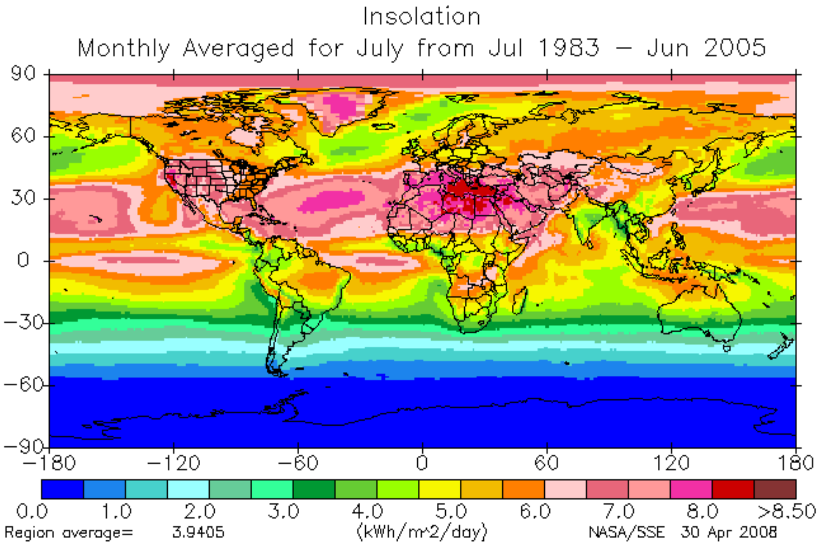

Image courtesy NASA Earth Observatory.

Actual System Outputs

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

See, e.g., http://soltrex.masstech.org/systems.cfm

Image removed due to copyright restrictions.
Please see any site listed at
http://soltrex.masstech.org/systems.cfm

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.

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

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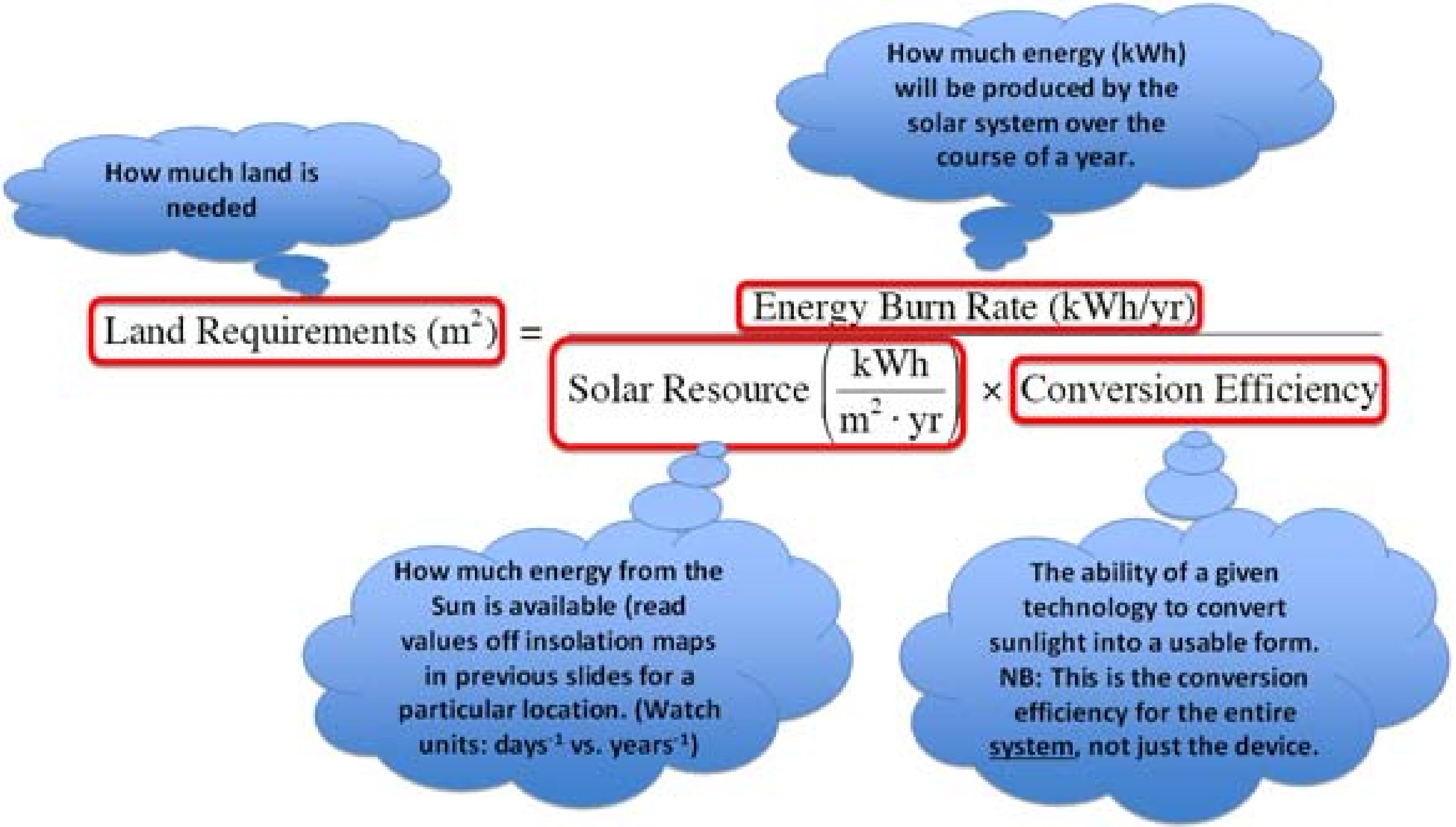

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How much land is needed

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

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} (3.5×10^{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:

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

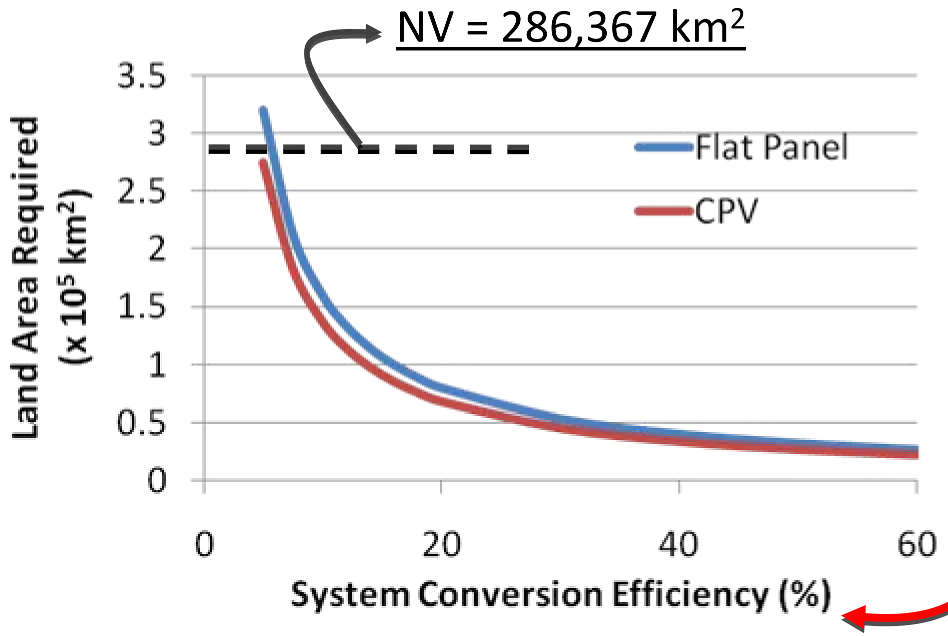
$$= \frac{\left(3.5 \times 10^{13} \text{ kWh/yr}\right)}{\left(2192 \dfrac{\text{kWh}}{\text{m}^2 \cdot \text{yr}}\right) \times (0.12)} \approx 1.3 \times 10^{5} \text{ km}^2$$

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.

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



NV = 286,367 km^2

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http://commons.wikimedia.org/wiki/File:Solar_land_area.png

6 Circles at 3 TW_e Each = 18 TW_e

http://www.answers.com/topic/solar-power-1