Solar Resource

Lecture 1 – 2.626

Tonio Buonassisi
Solar Resource Base

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

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

Human Energy Use (mid- to late-century)
4x10^{14} \text{ kWh/} \text{year}
50 \text{ } TW_{\text{ave}}

References:
Solar Resource Base

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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}

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References:
The Sun

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

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

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

Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.
Quantifying Solar Power

\[ P_0 = \frac{\sigma \cdot T^4}{4\pi R_{\text{Sun}}^2} \]
Quantifying Solar Power

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

Surface Area of Sun

Power radiated per unit area
5.961x10^7 W/m^2

\[ P_o = \frac{\sigma \cdot T^4}{4 \pi R_{Sun}^2} \]
Quantifying Solar Power

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

\[ P_{Earth} = \frac{R_{sun}^2}{D^2} P_o \]
Quantifying Solar Power

not to scale!

\[ P_\text{Earth} = \frac{R_{\text{Sun}}^2}{D^2} P_o \]

Average \( P_{\text{Earth}} \approx 1366 \text{ W/m}^2 \)

Ratio of Surface Areas of Spheres: \( 4\pi R^2 \).
Orbit Ellipticity

The Earth’s orbit around the Sun is slightly elliptical...

\[ e = 0.017 \]

Perihelion (Jan 4±2)
\[ D = 147.5 \text{M km} \]

Aphelion (July 4±2)
\[ D = 152.6 \text{M km} \]

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

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

\[ P_{\text{Earth}} \approx 1366 \text{ W/m}^2 \]

Orbit Ellipticity

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

TABLE 2 Solar Irradiance at the Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Solar Irradiance, W*m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Mercury</td>
<td>9116.4</td>
</tr>
<tr>
<td>Venus</td>
<td>2611.0</td>
</tr>
<tr>
<td>Earth</td>
<td>1366.1</td>
</tr>
<tr>
<td>Mars</td>
<td>588.6</td>
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<tr>
<td>Jupiter</td>
<td>50.5</td>
</tr>
<tr>
<td>Saturn</td>
<td>15.04</td>
</tr>
<tr>
<td>Uranus</td>
<td>3.72</td>
</tr>
<tr>
<td>Neptune</td>
<td>1.510</td>
</tr>
<tr>
<td>Pluto</td>
<td>0.878</td>
</tr>
</tbody>
</table>

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.

Angles Matter!

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

Building orientation with the long axis facing south

Figure by MIT OpenCourseWare.
Atmospheric Absorption

• Causes.
• Estimating the effects.
• The solar spectrum on Earth.
Atmospheric Absorption

Courtesy NASA.

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.

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.

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* $\theta$

AM1: Sun directly overhead

AM1.5G: “Conventional”

G (Global): Scattered and direct sunlight

D (Direct): Direct sunlight only

AM0: Just above atmosphere (space applications)

Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.
SOLAR SPECTRUM

![Graph showing the solar spectrum with labels for 6000K Black Body and Visible Spectrum.](image)
SOLAR SPECTRUM
SOLAR SPECTRUM
SOLAR SPECTRUM

AM1.5 Global: Used for testing of Flat Panels (Integrated power intensity: 1000 W/m²)
AM1.5 Direct: Used for testing of concentrators (900 W/m²)
AM0: Outer space (1366 W/m²)

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

Source of data:
http://www.nrel.gov/rrredc/smarts/
INSOLATION

Insolation: Incoming Solar Radiation

Typically given in units of:

Energy per Unit Area per Unit Time
(kWh/m²/day)

Helpful when designing or projecting PV systems: Expected yield

Affected by: latitude, local weather patterns, etc.
Measuring Global/Direct Insolation

Equipment for solar irradiance measurements [http://www.nrel.gov/data/pix/searchpix_visual.html]
Solar Insolation Maps

• United States
• Europe
• Africa
• World
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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 Direct Normal Solar Radiation (Two-Axis Tracking Concentrator), July, NREL.
Germany & U.S. : A quick comparison

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

Image removed due to copyright restrictions. Please see http://citysustainable.com/images/SEIA_compare_germany_us.jpg
(annual average of daily sums, GJ)
Global Insolation Data

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

Image courtesy NASA Earth Observatory.
Global Insolation Data

Insolation
Monthly Averaged for January from Jul 1983 – Jun 2005

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

Image courtesy NASA Earth Observatory.
Global Insolation Data

Insolation
Monthly Averaged for July from Jul 1983 – Jun 2005

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

Image courtesy NASA Earth Observatory.
**Global Insolation**

**Insolation at AM0:** Resource determined by latitude ($\sim\cos \theta$).

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

Estimating Solar System Outputs
Q: Let’s say I have a 2.2 kWp photovoltaic array. How much energy will it produce in a year?

A: Let’s say our location receives, on average, 4 kWh/m²/day from the Sun. The calculation is then straightforward:

\[
\text{Energy Output} = \frac{2200 \text{ W}_p}{1000 \text{ W}_p/\text{m}^2} \times \left(4.0 \text{ kWh/m}^2/\text{day}\right) = 8.8 \text{ kWh/day} \approx 3200 \text{ kWh/year}
\]
Estimating System Output from Insolation Maps

Q: Let’s say I have a 2.2 kW\textsubscript{p} photovoltaic array. How much energy will it produce in a year?

A: Let’s say our location receives, on average, 4 kWh/m\textsuperscript{2}/day from the Sun. The calculation is then straightforward:

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

- **How much land is needed**
- **Energy Burn Rate (kWh/yr)**
- **Solar Resource (kWh/m}^2\cdot\text{yr})**
- **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$_{ave}$ ($3.5 \times 10^{13}$ 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 (m}^2\) = \frac{\text{Energy Burn Rate (kWh/yr)}}{\text{Solar Resource \(\frac{\text{kWh}}{\text{m}^2 \cdot \text{yr}}\)} \times \text{Conversion Efficiency}}
\]

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

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.

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

\[NV = 286,367 \text{ km}^2\]
Estimating Solar Land Area Requirements

6 Circles at 3 TW_e Each = 18 TW_e