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
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The Solar Resource

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Learning Objectives: Solar Resource

- Quantify available solar resource relative to human energy needs and other fuel sources.
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- Describe how solar insolation maps are made, and use them to estimate local solar resource.
- List the causes of variation and intermittency of solar resource and quantify their time constant and magnitude.
- Estimate land area needed to provide sufficient solar resource for a project (house, car, village, country, world).
Before we begin... Review of Readings

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

Courtesy of [PVCDROM](http://pveducation.org/pvcdrom/properties-of-sunlight/declination-angle). Used with permission.
Before we begin... Review of Readings

LSTM (Local Standard Time Meridian) used in a local time zone. Shown here is the LSTM for the time zone incorporating parts of Brazil and Greenland.

Prime Meridian (longitude = 0°) used for Greenwich Mean Time

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

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Person</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>9th-8th Centuries BCE</td>
<td>Yajnavalkya</td>
<td>Solar calendar, relative sizes of Earth, Sun, and Moon, possibly first heliocentric model.</td>
</tr>
<tr>
<td>3rd Century BCE</td>
<td>Aristarchus of Samos</td>
<td>Confirms Yajnavalkya’s principles, estimates interstellar distances via heliocentric model.</td>
</tr>
<tr>
<td>10th-11th Century BCE</td>
<td>Abu Rayhan al-Biruni</td>
<td>Applies cartographic methods to aid astronomical observation, <em>Indica</em>.</td>
</tr>
<tr>
<td>16th-17th Century</td>
<td>Johannes Kepler</td>
<td>Refines predictive astronomy with elliptical orbital model, <em>Astronomia Nova</em>.</td>
</tr>
</tbody>
</table>

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!

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:
Solar Resource is VAST!

- **Solar Energy Resource Base**
  - $1.5 \times 10^{18}$ kWh/year
  - $1.7 \times 10^5$ TW$_{ave}$

- **Solar Resource on Earth’s Surface**
  - $5.5 \times 10^{17}$ kWh/year
  - $3.6 \times 10^4$ TW$_{ave}$

- **Wind Energy Resource Base**
  - $6 \times 10^{14}$ kWh/year
  - $72$ TW$_{ave}$

- **Human Energy Use** (mid- to late-century)
  - $4 \times 10^{14}$ kWh/year
  - $50$ TW$_{ave}$

References:
Solar Resource is VAST!

Solar Energy Resource Base
3400 HEC

Solar Resource on Earth’s Surface
720 HEC

In units of HEC
(human energy consumption)

Wind Energy Resource Base
1.4 HEC

Human Energy Use
(mid- to late-century)
1 HEC

References:
Quantifying Solar Power

$$P_0 = \sigma \cdot T^4$$

Sun
Quantifying Solar Power

Power radiated per unit area: $6.250 \times 10^7$ W/m$^2$

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

$P_0 = \sigma \cdot T^4$

Assumes Sun is a “black body.”
Quantifying Solar Power

\[ P_\text{Earth} = \frac{R_{\text{Sun}}^2}{D^2} P_0 \]

\[ P_0 = \sigma \cdot T^4 \]

D (distance to Sun)
Quantifying Solar Power

$P_o = \sigma \cdot T^4$

$D \approx 1.496 \times 10^{11} \text{ m}$

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

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

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

$R_{sun} \approx 6.955 \times 10^8 \text{ m}$

Not to scale!
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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.

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)

Source: [http://www.pveducation.org/pvcdrom](http://www.pveducation.org/pvcdrom)

Courtesy of [PVCDROM](http://www.pveducation.org/pvcdrom). Used with permission.
SOLAR SPECTRUM

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

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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.pveducation.org/pvcdrom/appendicies/standard-solar-spectra

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

Courtesy of PVCDROM. Used with permission.
SOLAR SPECTRUM

From: [http://www.pveducation.org/pvcdrom](http://www.pveducation.org/pvcdrom)

Courtesy of [PVCDROM](http://rredc.nrel.gov/solar/spectra/am1.5/). Used with permission.
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Insolation: Incomming 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.
Global/Direct Insolation: Ground Measurements

pyranometer

Insolation: Satellite Measurements

Global Insolation Data

Insolation
Monthly Averaged for January from Jul 1983 – Jun 2005

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

Buonassisi (MIT) 2011
Global Insolation Data

Insolation

Monthly Averaged for July from Jul 1983 – Jun 2005

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

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Seasonal Variation of Insolation

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

Courtesy of PVCDROM. Used with permission.
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!

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...

From PVWatts for Boston
Direct vs. Diffuse Sunlight

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Local Weather Patterns: Long Time Constant


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

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.

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
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.

Please see lecture video for comparative insolation between Germany and the US.
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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)
Units 101

• Basic Units Check: Assign Appropriate Units

• Energy
• Power
• Current
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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} ~ 1 kWh/day

1.88 kW_{peak} ~ 0.5 kWh/day

Photo courtesy of Niels van Eck on Flickr.
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<sub>p</sub> photovoltaic array. How much energy will it produce in a year?

A: Let’s say our location receives, on average, 4 kWh/m<sup>2</sup>/day from the Sun. The calculation is then straightforward:

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

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\]
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):
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.

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

- **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} \text{ 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 $4 \text{TW}_{\text{ave}} \ (3.5 \times 10^{13} \text{kWh/yr})$
   \textit{(forward-projected U.S. energy consumption, including waste heat)}
2. An insolation value of $6 \text{kWh/m}^2/\text{day}$
   \textit{(typical year-average value for flat panel in Nevada; CPV \sim 7 \text{kWh/m}^2/\text{day})}
3. System conversion efficiency of 12%
   \textit{(including all system losses)}

Using:

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

= \frac{(3.5 \times 10^{13} \text{kWh/yr})}{(2192 \frac{\text{kWh}}{\text{m}^2 \cdot \text{yr}} \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.

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

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

6 Circles at 3 TW_e Each = 18 TW_e

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

Image by Miino76 on Wikipedia. License: CC-BY.