Learning Objectives

• Describe the typical spectra that are used when testing solar cell performance. What is meant by “air mass”?
• Familiarize ourselves with “insolation”. How is insolation measured?
• Given proper insolation data, be able to estimate solar array outputs at a particular location on earth
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Quick Aside: Units

• energy:
  - 1 BTU = energy required to raise the temperature of 1 lb of water by 1 degree F (think about the energy released by a burning wooden match)
  - 1 Joule = 1 N m (tennis ball at 14 mph)
  - 1 BTU = 1055 Joules

• power = energy used per unit time
  – 1 Watt = 1 J/sec
  – kW, MW, GW

• if we use a kW of power for 1 hour, we have used 1 kWh of energy
  – 1 kWh ~ 3400 BTU
Example

- The US in 2017 consumed 97.5 Quadrillion BTUs of energy
- 97.5 Quadrillion = 97.5 \times 10^{15}
- How much energy per person?
  - Population of US in 2009: 325,000,000
  - \sim 300 million BTUs per person per year
- On average how many “100 Watt light bulbs” is one person in the US burning at any given time?
Effects of Atmospheric Absorption on Solar Radiation Received at Earth’s Surface

• Reduction in the power of solar radiation due to absorption, scattering, and reflection in the atmosphere
• Change in the spectral content due to greater absorption/scattering of some wavelengths
• Introduction of a diffuse (indirect) component
• Local variations (due to water, clouds, pollution)

For example, of the 342 W/m² incident on the earth just outside of the earth’s atmosphere:
  - around 70 W/m² is absorbed by the atmosphere
  - around 80 W/m² is reflected by the atmosphere
  - leaving behind around 190 W/m² to strike the surface of the earth
Diffuse vs. Direct Sunlight
Atmospheric Effects

energy balance

http://lasp.colorado.edu/sorce/instruments/tim/tim_science.htm
**AIR MASS**

the path length light takes through the atmosphere, relative to the shortest possible length (which is when the sun is directly overhead)

“air mass” serves as a way to quantify the attenuation of the power of light as it passes through the atmosphere.

\[
AM = \frac{y}{x} \approx \frac{1}{\cos(\theta)}
\]
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)

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

Courtesy: Tonio Buonassisi, MIT
**AM0 spectrum** = represents the solar spectrum just above the earth’s atmosphere. Total integrated power density is 1368 W/m². Relevant for PV on spacecraft, satellites, etc.

**AM1 spectrum** = represents incident spectrum when the sun is directly overhead. By convention, it is normalized so that the total integrated power density is 1000 W/m².

**AM1.5 spectrum** = standard spectrum used in the solar industry for testing terrestrial cells (unless otherwise specified, you can assume that the cell has been tested under AM1.5D or AM1.5G)

**AM1.5D (direct)** – includes only the direct part of the solar spectrum, normalized by convention to 900 W/m²; relevant for concentrator systems

**AM1.5G (global)** – includes the direct and scattered part of the solar spectrum, normalized by convention to 1000 W/m² (relevant for fixed flat panel systems).
SOLAR SPECTRUM

Sunlight Intensity (kW/m²/µm) vs. Wavelength (µm)

6000K Black Body

Visible Spectrum

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

Courtesy: Tonio Buonassisi, MIT
SOLAR SPECTRUM

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

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SOLAR SPECTRUM

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

Courtesy: Tonio Buonassisi, MIT
Air Mass Spectra

Download the spectra: http://www.nrel.gov/rredc/smarts/
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INSOLATION

Incoming Solar Radiation

• How we describe what actually hits the earth’s surface at a particular location
• Includes effects of latitude, local weather, etc.
• Helpful when designing PV systems for a given location
• Empirically measured (e.g. NREL database online)
• Units: kWh/m²/day
The following insolation maps are available for download at http://www.nrel.gov/gis/solar.html.
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude

March

Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005. The data for Alaska is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy, December 2008.
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude

April

Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005. The data for Alaska is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy, December 2008.
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude

July

Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005. The data for Alaska is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy, December 2006.
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude

August

Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005. The data for Alaska is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy, December 2008.
Photovoltaic Solar Resource: Flat Plate Tilted South at Latitude

October

Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.

The data for Alaska is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy, December 2006.
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude

November

Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005. The data for Alaska is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by
the National Renewable Energy Laboratory
for the U.S. Department of Energy
December, 2008
Photovoltaic Solar Resource: Flat Plate Tilted South at Latitude

December

Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005. The data for Alaska is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy. December, 2008.
The following insolation maps are available for download at http://eosweb.larc.nasa.gov/
Insolation
Monthly Averaged for June from Jul 1983 – Jun 2005

Region average = 4.0286 (kWh/m^2/day)

NASA/SSE 29 Aug 2011
Insolation

Monthly Averaged for December from Jul 1983 – Jun 2005

Region average = 4.4088 (kWh/m²/day)

NASA/SSE 29 Aug 2011
How is insolation measured?

Pyranometer: equipment for ground measurement of solar irradiance

http://www.nrel.gov/data/pix/searchpix_visual.html
How is insolation measured?

Satellite Based measurements:
- CERES – Clouds and Earth’s Radiant Energy System – instrument on board NASA’s Terra and Aqua satellites
Seasonal Variation of Insolation

• The trajectory of the sun relative to a fixed ground position is important when mounting a fixed solar array
• At the most basic level, the motions of the sun are (1) the E->W movement over the course of a single day, and (2) the height of the sun in the sky over the course of one year
• For a fixed solar array in the northern hemisphere, to maximize insolation solar panels are tilted southwards at an angle equal to the latitude of the location
• Competing factor: available real estate (surface to mount the panels, considering shading)
Fixed vs. Tracking Systems

• Panels that constantly move and follow the sun can increase their output per day
• Can incorporate single or double axis tracking system – (often with concentrator systems)
• Of course, added cost of building a tracking system may or may not make this a good idea
• Also: array now involves moveable parts
To Track or Not To Track?

PV Solar Radiation
(Flat Plate, Facing South, Latitude Tilt)

Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/solar_pv.html documentation for more details.

http://www.nrel.gov/gis/solar.html

Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004
To Track or Not To Track?

Direct Normal Solar Radiation (Two-Axis Tracking Concentrator)

Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/fi_csp.html documentation for more details.

Better for non-concentrating solar

Better for concentrating solar

http://www.nrel.gov/gis/solar.html

Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004
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Watts Peak vs. Watts Average

Example: Fridge vs. Hairdryer

- Which one is more likely to blow a fuse?
- Which one is more likely to blow your budget?

Courtesy: Tonio Buonassisi, MIT
Watts Peak vs. Watts Average

Example: Fridge vs. Hairdryer

- Which one is more likely to blow a fuse?
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0.044 kW_{avg} vs. 1.88 kW_{p}

Courtesy: Tonio Buonassisi, MIT
Watts Peak vs. Watts Average

Example: Fridge vs. Hairdryer

- Which one is more likely to blow a fuse?
- Which one is more likely to blow your budget?

0.044 kW_{avg}  
\sim 1 \text{ kWh/day}

1.88 kW_{p}  
\sim 0.5 \text{ kWh/day}

Courtesy: Tonio Buonassisi, MIT
Solar Cell Ratings: “Peak Power”

- When tested for performance, solar modules are given a “peak power” rating ($kW_p$)
- The peak power refers to the power generated under the standard testing spectrum (AM1.5D, AM1.5G)
- “Peak power” is a useful concept, because it is a location neutral rating of output power
  - i.e. a PV module will have the same $kW_p$ in Arizona or Alaska, although its $kW_{ave}$ will be very different
Estimating Array Output from Insolation Maps

Example: Let’s say I have a 2.2 kWp photovoltaic array that I deploy here in Illinois. How much energy will it produce in a year?
Estimating Array Output from Insolation Maps

For more accurate predictions:

**PVWatts: Tapping into the NREL database**
http://www.pvwatts.org/

**SAM (Solar Advisor Model)**
https://www.nrel.gov/analysis/sam
Estimating solar land area requirements

Example: How much land area is needed to meet the entire US energy needs on today’s solar technology?

Assume the following:

(1) Average burn rate of 4 TW\textsubscript{ave} \((3.5 \times 10^{13} \text{ kWh/year})\). This is a forward-projected estimate, including waste heat.

(2) We’ll put the solar farm in Nevada. Insolation = 6 kWh/m\textsuperscript{2}/day

(3) An overall array conversion efficiency of 15%
• Placing PV farms that operate at 8% efficiency at the sites of the black spots shown here will generate enough energy to power the whole world’s needs.
Mechanical Engineering Building Renovation Example
Estimating Solar Array Outputs

- Example: Will a solar array on the roof of the expanded Mechanical Engineering Building at UIUC be sufficient to meet the building’s current energy needs?

Figure 1. Mechanical Engineering Building Expansion (proposed)
It appears that roughly $3 \times 10^6$ kWh per year need to be produced by the solar array.
Crunching The Numbers ...

- The proposed expansion of the building will have 5000 m² roof space available for the solar array
- We will go as state-of-the-art as possible with our array, using the highest efficiency modules that are commercially available (SunPower E20 series), and we’ll estimate an overall energy conversion efficiency for the whole array to be 18% (in line with best systems today)
- Insolation in Urbana is around 4.2 kWh/m²/day

\[
\text{power generated} = (\text{solar resource}) \times (\text{conversion efficiency}) \times (\text{array area})
\]

\[
= \left( \frac{4.2 \text{ kWh}}{\text{m}^2 \text{ day}} \right) \times (0.18) \times (5000 \text{ m}^2)
\]

\[
= 3780 \text{ kWh/day}
\]

\[
= 1.38 \times 10^6 \text{ kWh/year}
\]

In other words, the array can produce around 46% of MEB’s current energy needs.
Can we get to Net Zero? …

- The answer is *stay tuned* …
- The current MEB is a huge energy consumer, due to the fact that it is overwindowed, poorly insulated, and heating efficiency is only around 50%. Additionally, the clean room in the building produces a huge energy demand
  - Based on Energy Intensity Usage (EIU), MEB is in the 90\(^{th}\) percentile for energy consumption amongst buildings in the US (i.e. 90% of buildings are better)
- As part of the renovation, we will also make improvements to the building insulation and climate control efficiency. For example, we are also considering installing
  - mini-split ductless heat pumps, or a ground based heat pump system
  - low “e” gas-filled thermal windows with low loss frames
  - insulation on exterior/interior walls and roof
  - Installing heat pump water heaters, LED lighting, smart controls with sensors, and a rain water collection system
- If these technologies are implemented, estimated EIU will improve to the 20\(^{th}\) percentile and heating costs will be virtually negligible