2.626 Fundamentals of Photovoltaics
Fall 2008

Solar Resource – Interactive Slides

Lecture 2 – 2.626

Tonio Buonassisi

Foreword

- These were presented in class as “interactive slides”. As such, reading them online might not give you the “full experience”. We expect to have full video of the class posted online by January.

A few intro items

1. Course material posted to MIT class Web site . If you do not have access, pls. email Sarah.

2. OCW: Privacy concerns w/ project postings.

3. PV listserv signup

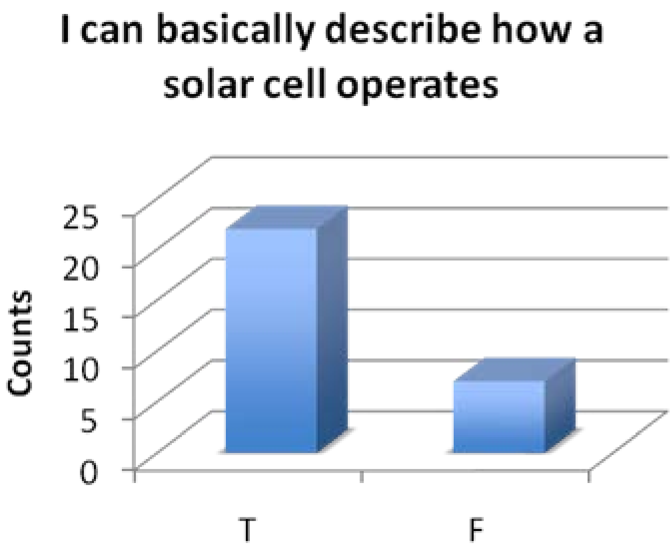
4. UNSW book order – next week, be prepared!

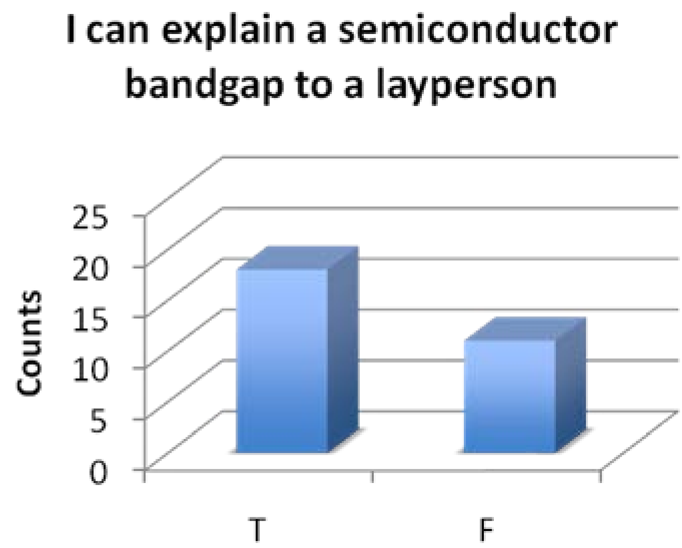
5. Community resources: photovoltaics.mit.edu listserv.

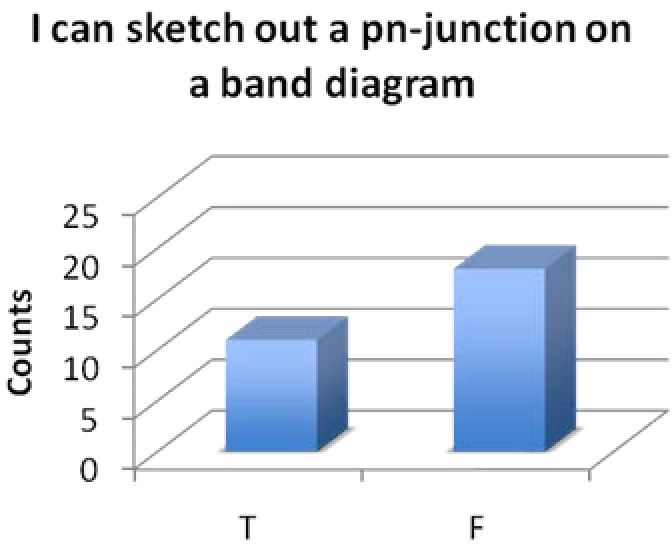
6. Upcoming events:
    - Monday, Sept. 15: Swiss Solar Taxi makes Round-the-World Trip, stops at MIT
    - Tuesday, Sept. 16: PV Social @ Muddy Charles Pub, 5:30-7:30pm.

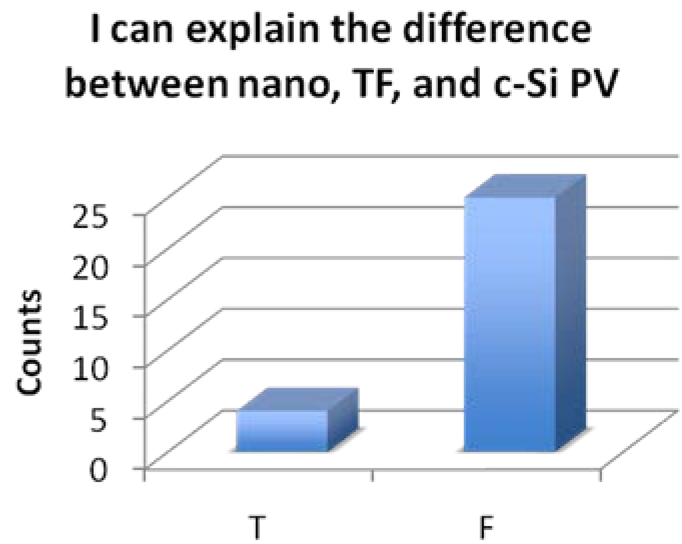
7. Who checked out the PVCDROM at www.pveducation.org?

Who's sitting next to you? (bkgnd survey results)

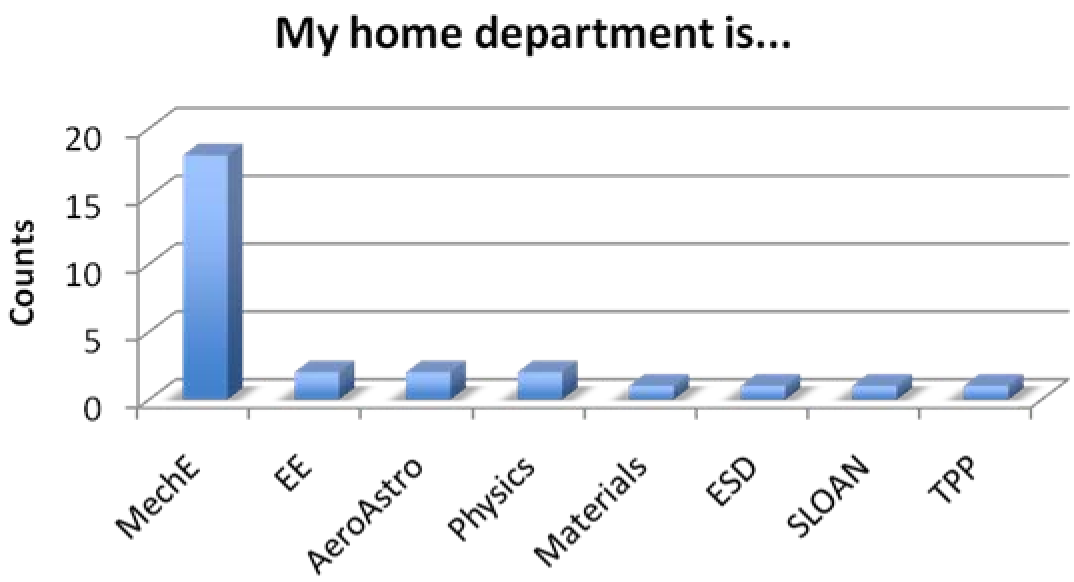


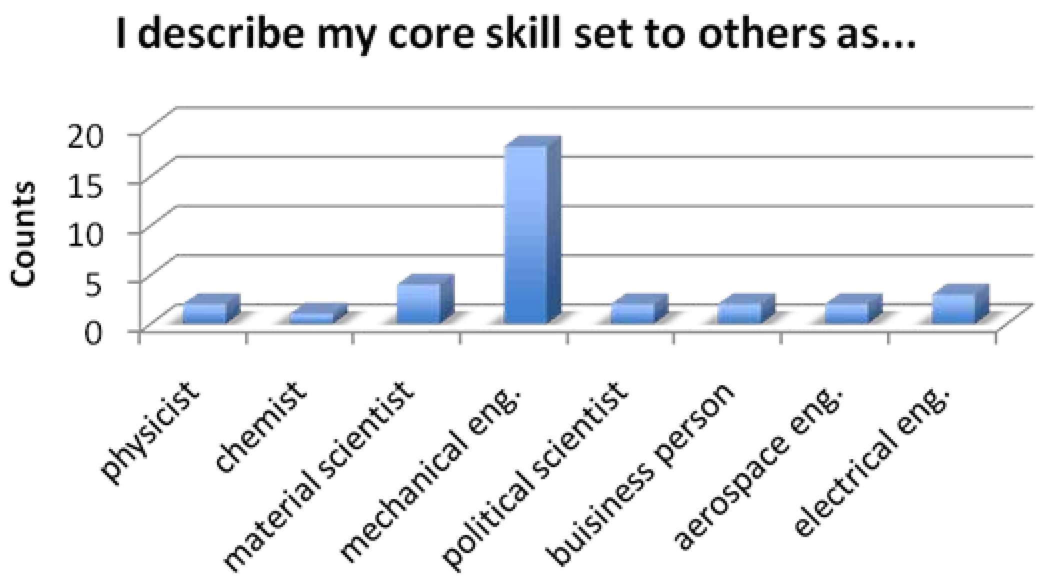




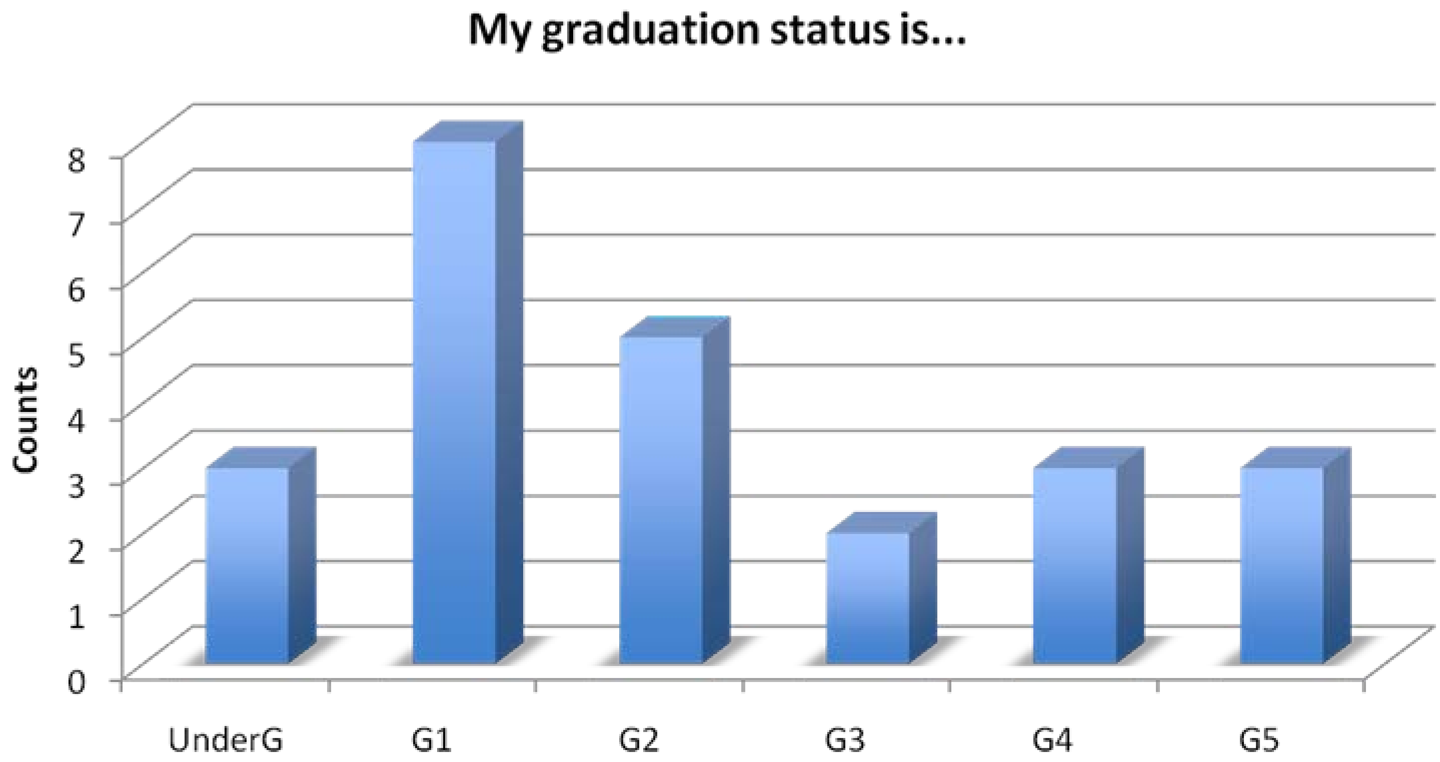


Who's sitting next to you? (bkgnd survey results)

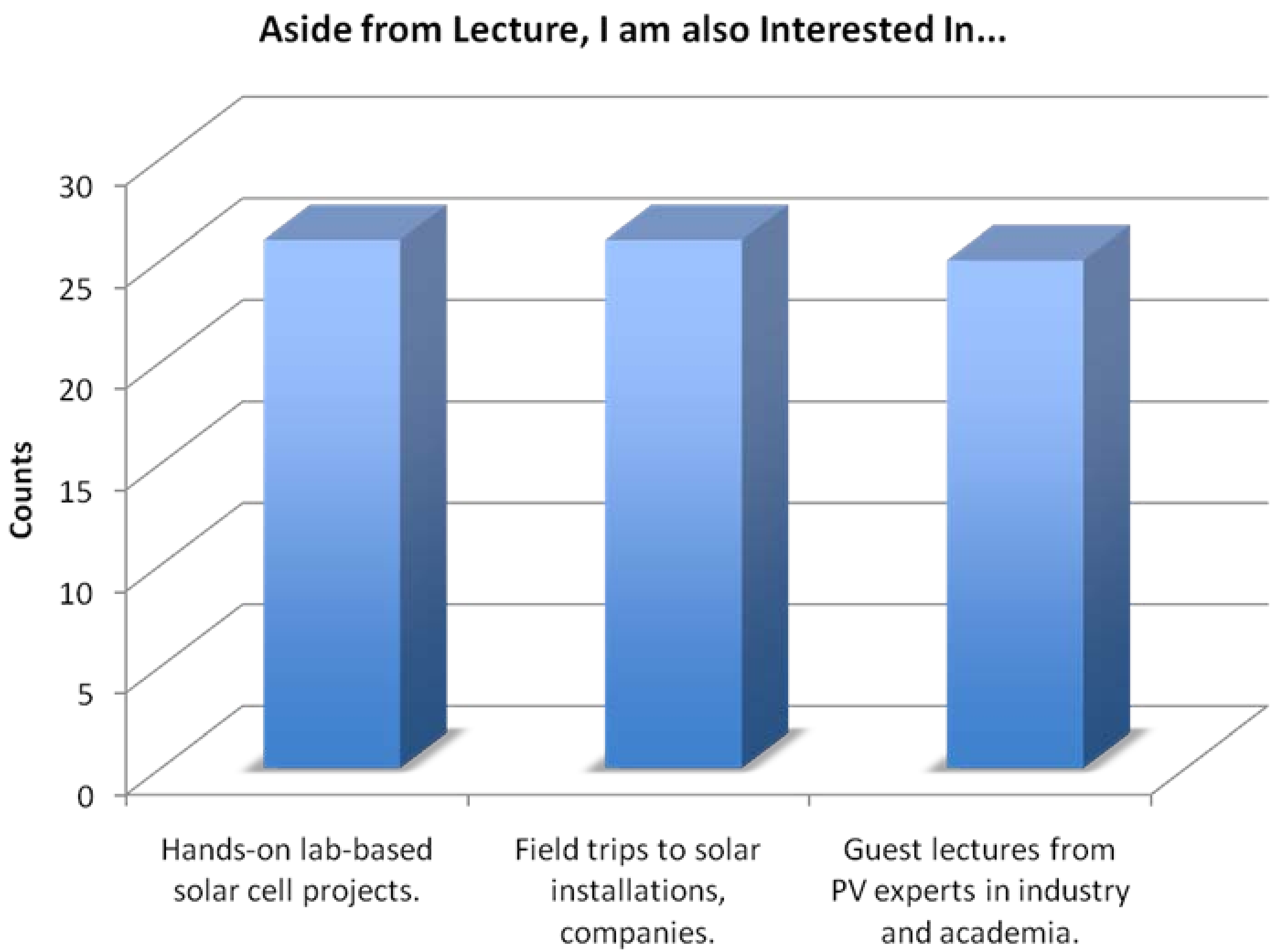




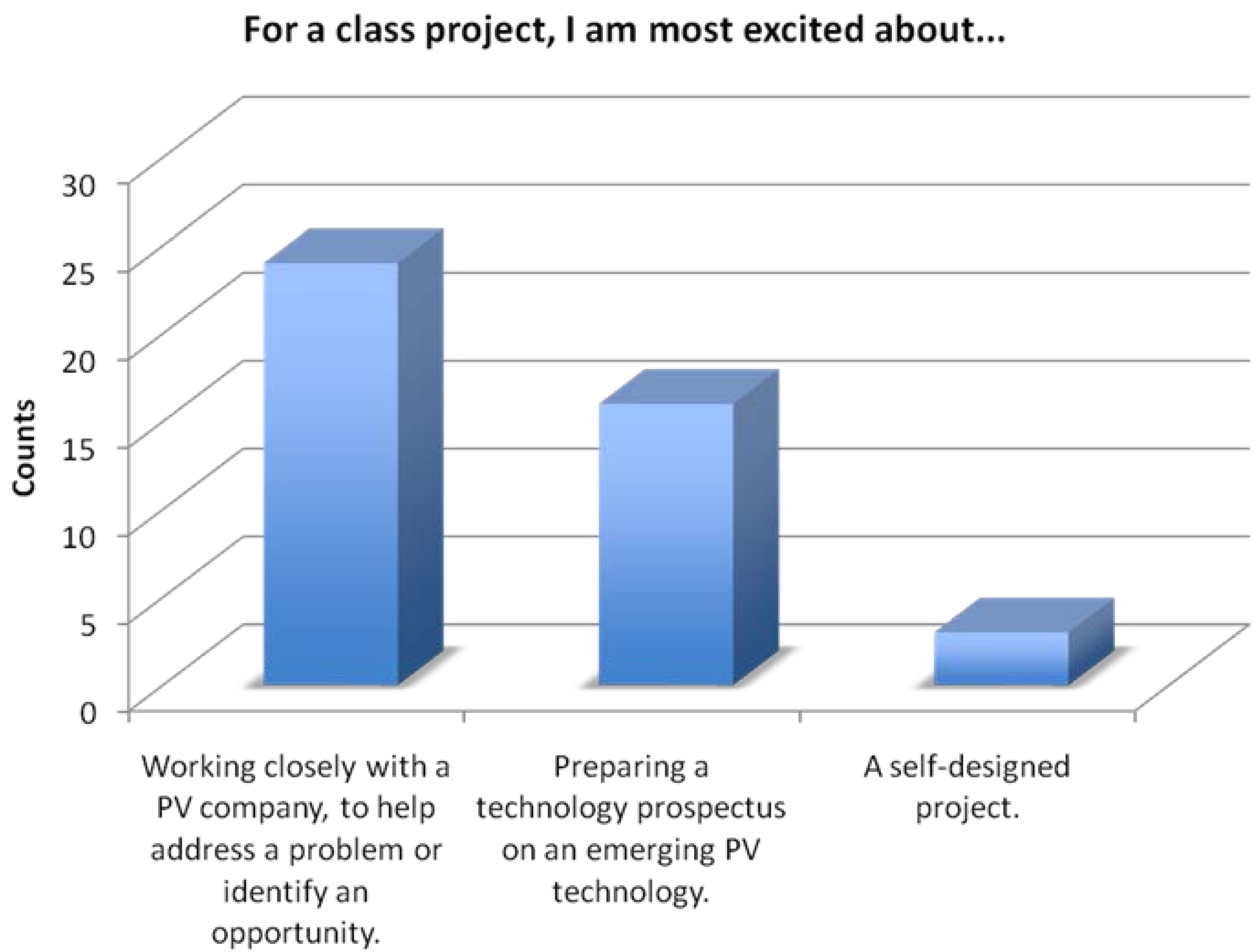
Who's sitting next to you? (bkgnd survey results)



Who's sitting next to you? (bkgnd survey results)



Who's sitting next to you? (bkgnd survey results)



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
- Voltage

- 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?

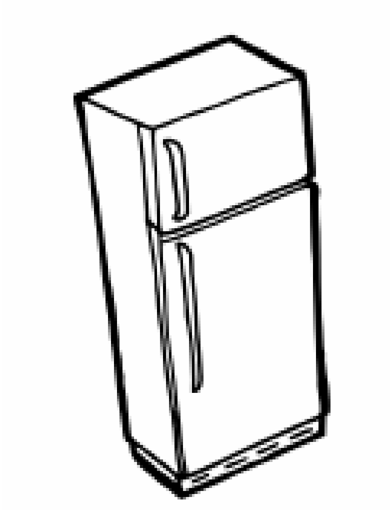


Image from the Open Clip Art Library, http://openclipart.org/

Image from flickr user Niels van Eck.

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}

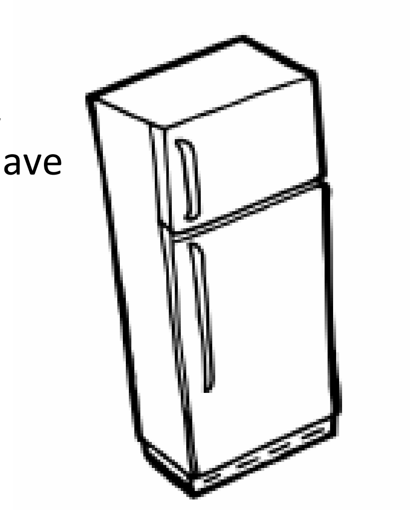


Image from the Open Clip Art Library, http://openclipart.org/

1.88 kW_{peak}

Image from flickr user Niels van Eck.

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

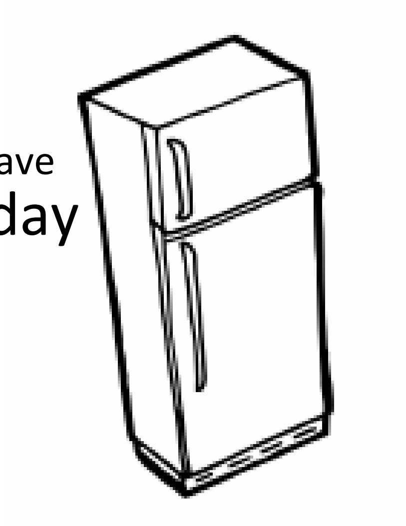
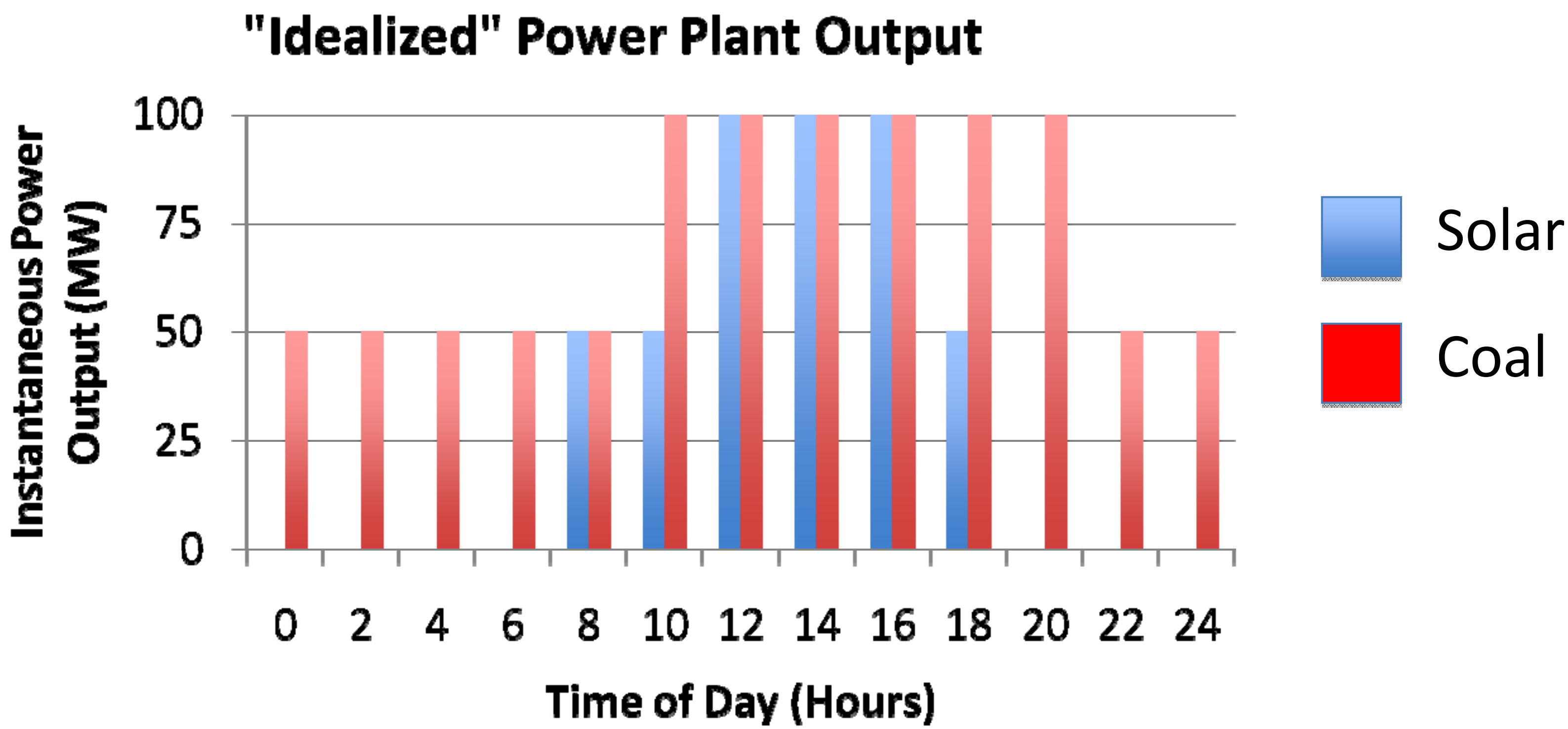


Image from the Open Clip Art Library, http://openclipart.org/

Image from flickr user Niels van Eck.

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

Units 101



- What is the *peak* power produced by each?
- What is the *average* power produced by each?

Why "Peak Power"?

- Why is "peak power" (kW_p) useful?

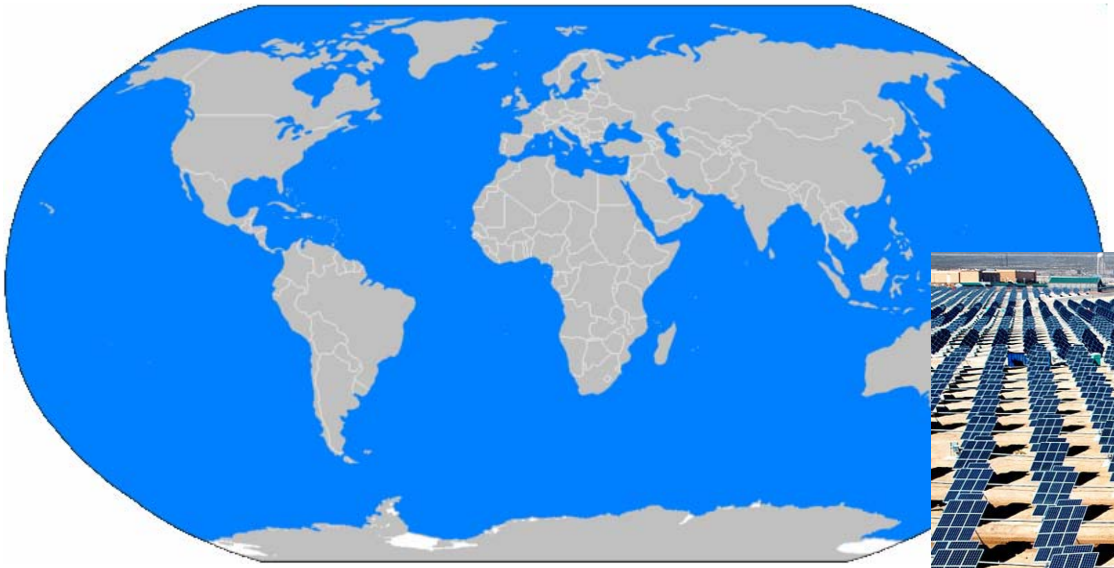


Image from Wikimedia Commons, http://commons.wikimedia.org

Courtesy USAF.

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.*

Courtesy USAF.

Solar Resource Questions

- For a fixed (non-tracking) PV system somewhere in the U.S., what tilt angle should the modules be facing, to maximize yearly electricity output?
- Does your answer hold true, if above the Arctic Circle?

Influence of Weather on Irradiance

Images removed due to copyright restrictions. Please see
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?

http://www.newport.com/Introduction-to-Solar-Radiation/411919/1033/catalog.aspx

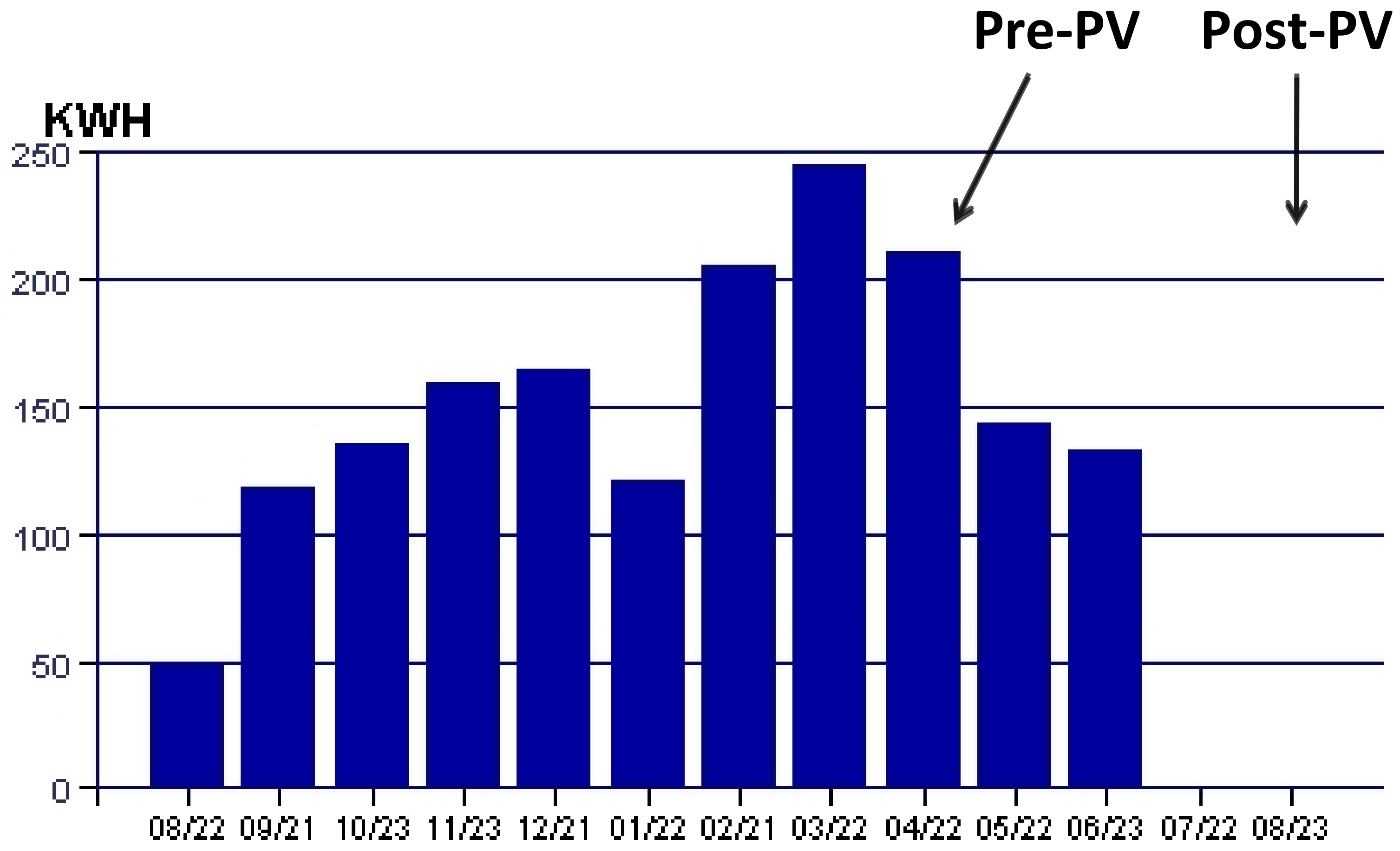
Estimation of Land Area

- Let’s spec out a solar system…

Buonassisi Residence

Boston latitude: 42° 19’ North

Electricity Consumption of Buonassisi Residence

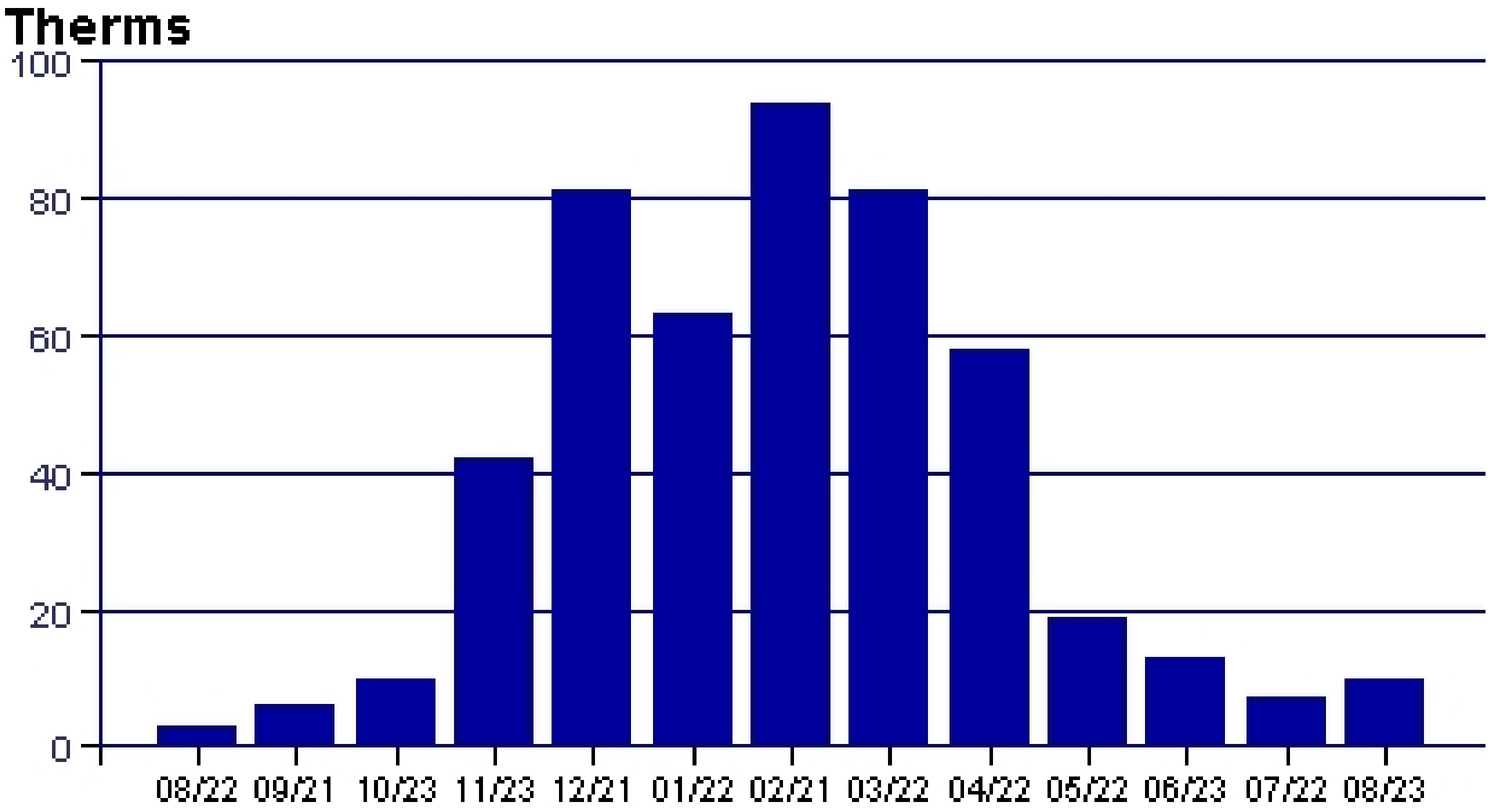


Questions…

- What is the average monthly electricity (pre-PV) use of the Buonassisi household?
- Assuming a certain insolation for the Boston area, calculate the suggested PV system size to match all electricity use.
- Does this fit on the roof?

Natural Gas Consumption of Buonassisi Residence

What uses more energy – electricity or natural gas?
What are the implications for energy neutrality?



1 therm of natural gas = 29.3 kWh

Predicted vs. Actual System Outputs

Predicted: PVWatts:

http://rredc.nrel.gov/solar/codes_algs/PVWATTS/version1/

1 therm of natural gas = 29.3 kWh

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

Difference between tracking concentrator and non-tracking flat panel?

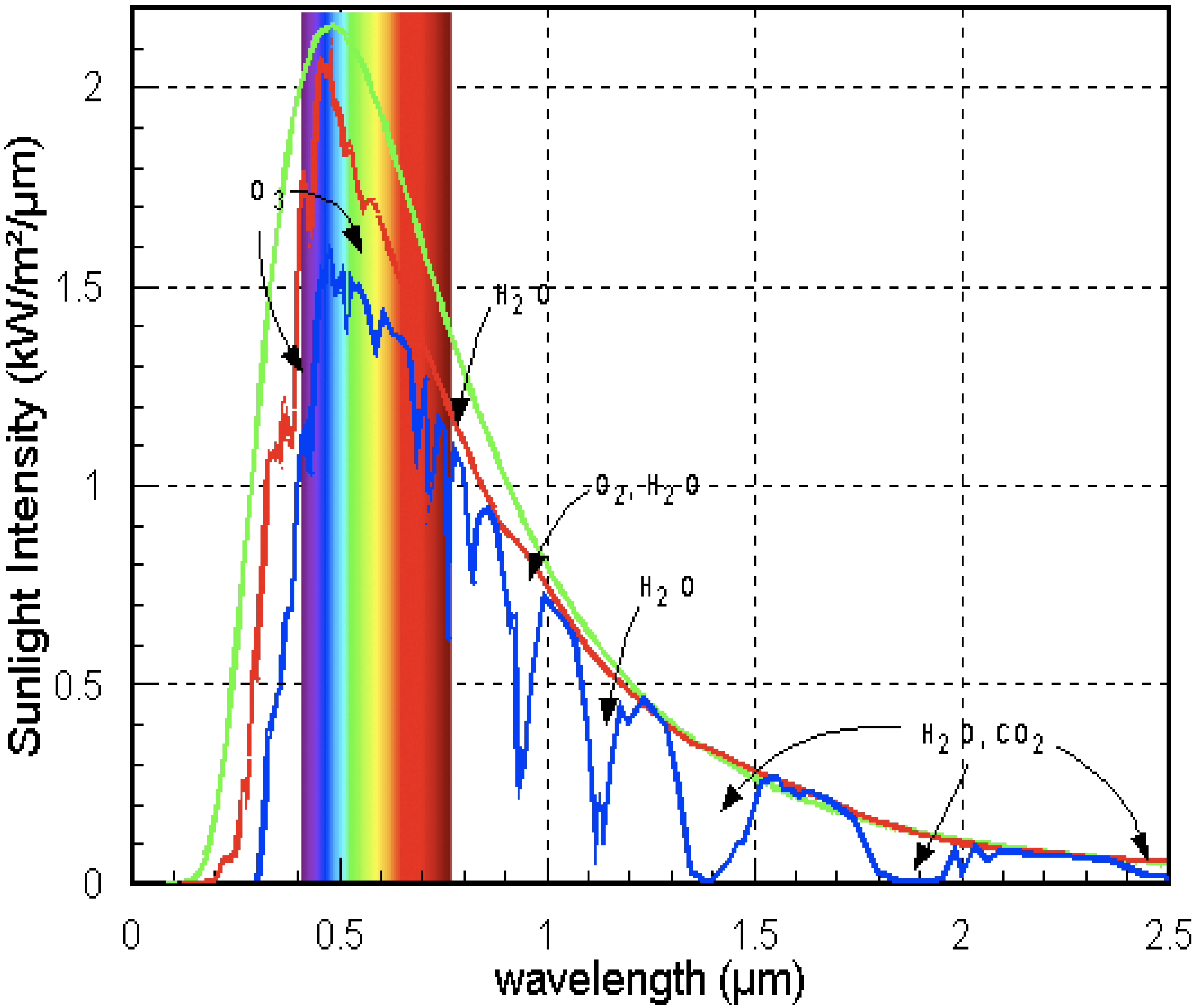
Map removed due to copyright restrictions. Please see [PV Solar Radiation (Flat Plate, Facing South, Latitude Tilt), Annual], NREL.

Map removed due to copyright restrictions. Please see [Direct Normal Solar Radiation (Two-Axis Tracking Concentrator), Annual]. NREL.

Map removed due to copyright restrictions. Please see [Direct Normal Solar Radiation (Two-Axis Tracking Concentrator), Annual]. NREL.

What other types of PV systems are there?

SOLAR SPECTRUM



Solar Spectra

- What are the standards?
- How is the solar spectrum simulated in the lab?

Where to find it?

Solar Spectra

http://rredc.nrel.gov/solar/spectra/

Solar Spectra

http://rredc.nrel.gov/solar/spectra/

NREL's Electric Systems Center provides the following solar spectra in HTML, text and/or MS Excel® spreadsheet format:

- Air Mass Zero: Extraterrestrial Solar Irradiance Spectra
  - Standard Spectra
    - 2000 ASTM Standard Extraterrestrial Spectrum Reference E-490-00
    - 1985 Wehrli Standard Solar Irradiance Spectrum
  - Nonstandard Spectra
- Air Mass 1.5: ASTM E-891 and ASTM E-892, both combined into ASTM G-159

  (Note: Previous versions of reference spectra, ASTM E-891, E-892, and G-159 have been superceded by ASTM G-173.)

SMARTS: Simple Model of the Radiative Transfer of Sunshine

SMARTS2 version 2.9.2 is the model used to generate the American Society for Testing and Materials (ASTM) terrestrial reference spectra for ASTM Standard G-173-03 "Standard Tables for Reference Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37 Tilted Surface".

Where to find it?

Solar Spectra

http://rredc.nrel.gov/solar/spectra/

Solar Spectra

http://rredc.nrel.gov/solar/spectra/

NREL's Electric Systems Center provides the following solar spectra in HTML, text and/or MS Excel® spreadsheet format:

- Air Mass Zero: Extraterrestrial Solar Irradiance Spectra
  - Standard Spectra
    - 2000 ASTM Standard Extraterrestrial Spectrum Reference E-490-00
    - 1985 Wehrli Standard Solar Irradiance Spectrum
  - Nonstandard Spectra

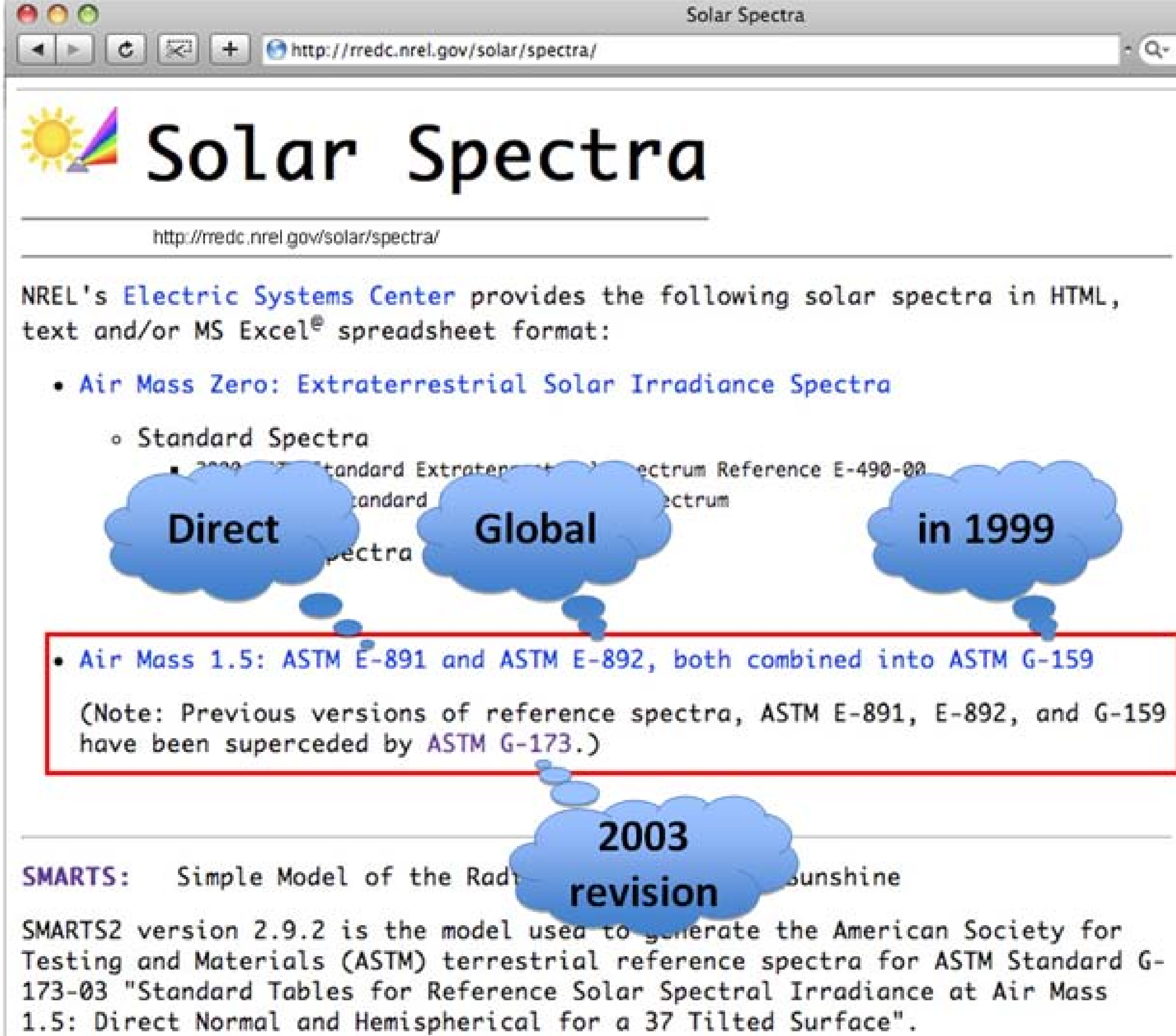
- Air Mass 1.5: ASTM E-891 and ASTM E-892, both combined into ASTM G-159

  (Note: Previous versions of reference spectra, ASTM E-891, E-892, and G-159 have been superceded by ASTM G-173.)

SMARTS: Simple Model of the Radiative Transfer of Sunshine

SMARTS2 version 2.9.2 is the model used to generate the American Society for Testing and Materials (ASTM) terrestrial reference spectra for ASTM Standard G-173-03 "Standard Tables for Reference Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37 Tilted Surface".

Where to find it?



Where to find it?

Solar Spectra

http://rredc.nrel.gov/solar/spectra/

Solar Spectra

http://rredc.nrel.gov/solar/spectra/

NREL's Electric Systems Center provides the following solar spectra in HTML, text and/or MS Excel® spreadsheet format:

- Air Mass Zero: Extraterrestrial Solar Irradiance Spectra
  - Standard Spectra
    - 2000 ASTM Standard Extraterrestrial Spectrum Reference E-490-00
    - 1985 Wehrli Standard Solar Irradiance Spectrum
  - Nonstandard Spectra
- Air Mass 1.5: ASTM E-891 and ASTM E-892, both combined into ASTM G-159

  (Note: Previous versions of reference spectra, ASTM E-891, E-892, and G-159 have been superceded by ASTM G-173.)

SMARTS: Simple Model of the Radiative Transfer of Sunshine

SMARTS2 version 2.9.2 is the model used to generate the American Society for Testing and Materials (ASTM) terrestrial reference spectra for ASTM Standard G-173-03 "Standard Tables for Reference Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37 Tilted Surface".

ASTM G173-03

The receiving surface is defined in the standards as an inclined plane at 37° tilt toward the equator, facing the sun (i.e., the surface normal points to the sun, at an elevation of 41.81° above the horizon)

The specified atmospheric conditions are:

a) the 1976 U.S. Standard Atmosphere b with temperature, pressure, aerosol density (rural aerosol loading), air density, molecular species density specified in 33 layers
b) an absolute air mass of 1.5 (solar zenith angle 48.19°s)
c) Angstrom turbidity (base e) at 500 nm of 0.084 c
d) total column water vapor equivalent of 1.42 cm
e) total column ozone equivalent of 0.34 cm
f) surface spectral albedo (reflectivity) of Light Soil as documented in the Jet Propulsion Laboratory ASTER Spectral Reflectance Database (http://speclib.jpl.nasa.gov.)

Experts: Keith Emery, Daryl Myers.

Source: http://rredc.nrel.gov/solar/spectra/am1.5/

Attempts to Simulate Solar Spectra

Non-ideal matches: QTH, Hg, M-Halide…

http://www.newport.com/Simulation-of-Solar-Irradiation/411986/1033/catalog.aspx

Attempts to Simulate Solar Spectra

Better matches: Xe lamps with air mass filters

http://www.newport.com/Simulation-of-Solar-Irradiation/411986/1033/catalog.aspx

Spectral response of different PV materials

Warning: Different PV materials are sensitive to different parts of the solar spectrum. You may be over/under estimating your performance, if the solar simulator calibration cell is made of a different material to the cells you are testing.

http://www.newport.com/Energy%E2%80%90Conversion/412147/1033/catalog.aspx

Solar Simulator Qualities

Uniformity

Spectral Fidelity

Temporal Stability

Image removed due to copyright restrictions. Please see http://www.newport.com/images/web150w-EN/images/806.gif

http://www.newport.com/Simulation-of-Solar-Irradiation/411986/1033/catalog.aspx

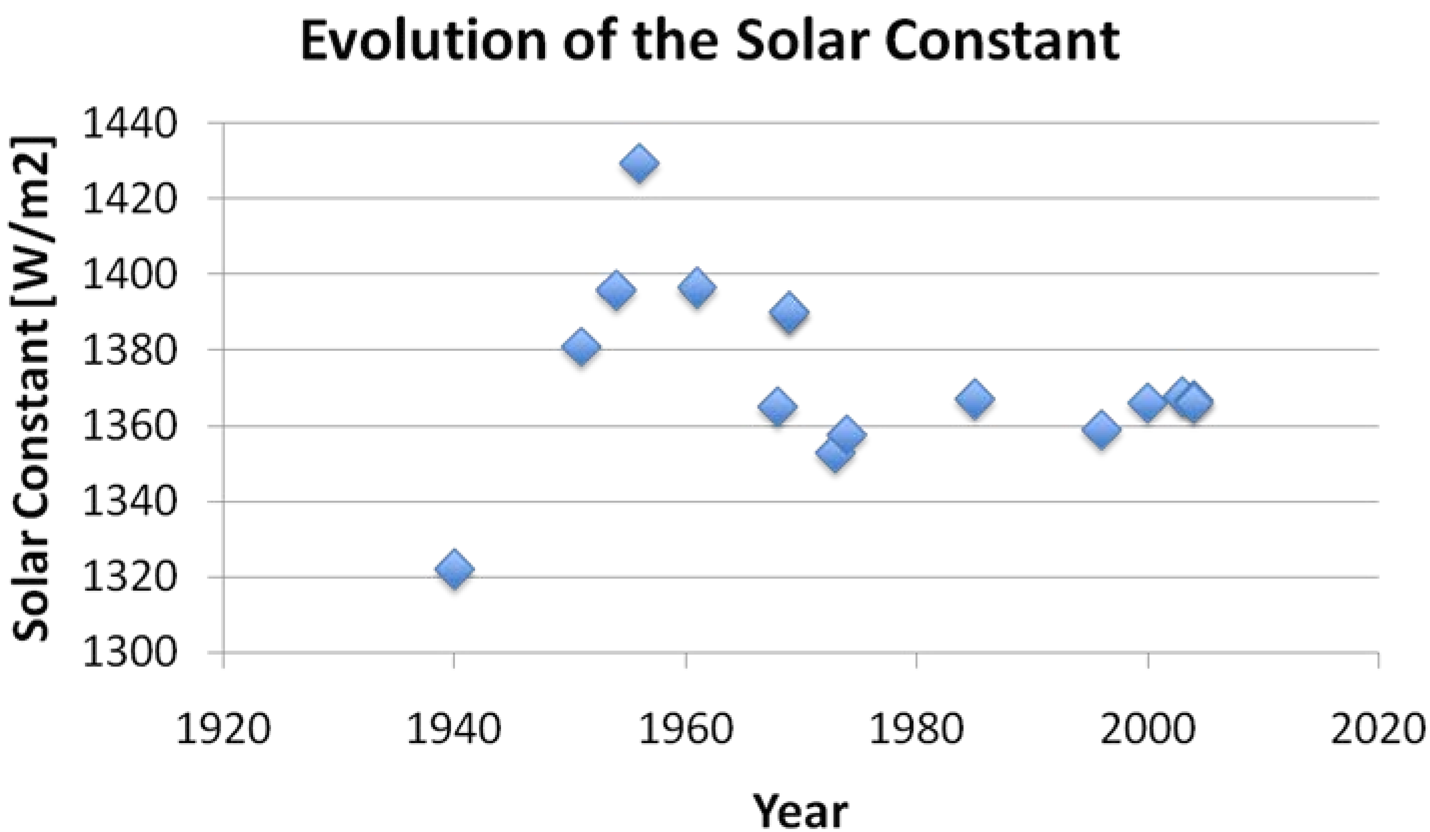
Solar Simulator Standards

Standard IEC 904-9: Requirements for solar simulators for crystalline Si single-junction devices

	Class A	**Class B**	**Class C**
Spectral match (ratio of the actual percentage of total irradiance to the required percentage specified for each wavelength range)	0.75-1.25	0.6-1.4	0.4-2.0
Non-uniformity of irradiance	< ±2%	< ±5%	< ±10%
Temporal Instability	< ±2%	< ±5%	< ±10%

For more info on PV testing standards, see:
http://photovoltaics.sandia.gov/docs/pvstndrds.htm

Change is the Only Constant…



From data included in C.A. Gueymard / Advances in Space Research 37 (2006) 323–340

Change is the Only Constant…

Text removed due to copyright restrictions. Please see
http://www.livescience.com/environment/060119_dark_china.html