EE80J/180J

Spring 2015,
Lecture #4
Personal Energy Audit

The goal of this project is for students to get a full picture of the supply and demand of energy used in their daily life. While working on this report, students will identify all energy services and their energy sources, obtain records of their energy usage, determine the energy consumption for each service, analyze the information, compare, draw conclusions and make recommendations.

Two parts:
  report (due in class)
  on-line questionnaire (completed on campus)
Report Format

- Abstract
- Introduction (should include information about the student)
- Calculations
  - List of energy services and sources
  - Transportation
  - Hot water consumption
  - Electricity usage (Wh/week)
    - Calculated from labels
    - Measured with “Kill a Watt” meter
      - When appliances are on
      - When appliances are off
- Analysis
  - If student has access to their PG&E bill and Smart Meter
    - Look for peaks of energy consumption, what do they consist of? What appliances were on during those particular hours.
    - How does your home compare to others
    - How does your energy consumption vary with weather
  - If student does not have access to their PG&E bill
    - Make a plot of energy consumed throughout the week
    - Make a plot of peak outside temperatures throughout the week
    - Compare the two plots for similarities
- Conclusion (should include qualitative and quantitative analysis summary from previous section). It has to answer specific list of questions.
Calculations and Analysis
List of energy services and sources

<table>
<thead>
<tr>
<th>Services</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>
Calculations and Analysis
List of energy services and sources

<table>
<thead>
<tr>
<th>Services</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Heating</td>
<td>Natural gas</td>
</tr>
<tr>
<td>Space Heating</td>
<td>Natural gas</td>
</tr>
<tr>
<td>Lighting</td>
<td>Electricity</td>
</tr>
<tr>
<td>....</td>
<td>....</td>
</tr>
</tbody>
</table>
Calculations and Analysis
Transportation

Driving
5 mi daily Scotts Valley to Santa Cruz
10 mi * 4 days/week = 40 mi / week
Car: 30 miles / gallon
1.33 gallons = 5 L of gas / week
35 MJ/L energy content 86 Octane gas
35 MJ/L * 5 L = 175 MJ
Carpool: 175 MJ / 2 = 87.5 MJ

Busses, Trains
1.6 MJ / km for each passenger
Hot Water Consumption

Heat Energy

- \[ Q = m \times c_p \times (T_1 - T_2) \]
  - \( c_p \) : specific heat constant, 4190 J / kg C
  - \( T_1 \) : temperature of the hot water
  - \( T_2 \) : temperature of the cold water

Example
James uses 50 L of hot water per day from an electric hot water system. The water is heated from 18\( ^\circ \)C to 60\( ^\circ \)C.
The heat energy contained in the water,
\[ Q = m \times c_p \times (T_1 - T_2) \]

Efficiency of Electric Water Heater is 0.7 to 0.8

Efficiency of Gas Water Heater is 0.6 to 0.75
Hot Water Consumption

Heat Energy

- $Q = m \times c_p \times (T_1 - T_2)$
  - $c_p$ : specific heat constant, 4190 J / kg C
  - $T_1$ : temperature of the hot water
  - $T_2$ : temperature of the cold water

Example

James uses 50 L of hot water per day from an electric hot water system. The water is heated from 18C to 60C.

The heat energy contained in the water,

- $Q = m \times c_p \times (T_1 - T_2)$
- $Q = 50 \text{ kg} \times 4190 \times (60 \text{ C} - 18\text{ C})$
- $Q = 8.8 \text{ MJ / day}$
- $Q = 61.6 \text{ MJ/ week}$

Efficiency of Electric Water Heater is 0.7 to 0.8

- $61.6 \text{ MJ} / 0.8 = 77 \text{ MJ}$

Efficiency of Gas Water Heater is 0.6 to 0.75
# Electricity Usage

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer</td>
<td>1</td>
<td>120</td>
<td>3</td>
<td>360</td>
<td>2520</td>
<td>9.07 M</td>
</tr>
<tr>
<td>Vacuum Cleaner</td>
<td>1</td>
<td>1000</td>
<td>0.14</td>
<td>140</td>
<td>140</td>
<td>0.5 M</td>
</tr>
<tr>
<td>Electric Drill</td>
<td>1</td>
<td>600</td>
<td>0.07</td>
<td>42</td>
<td>42</td>
<td>0.15 M</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>542 W*h</td>
<td></td>
<td></td>
<td>9.72 MJ</td>
</tr>
</tbody>
</table>
Electricity Usage

Confirmed with “Kill a Watt” meter
- When appliances are on
- When appliances are off
Electricity Usage
As seen on PG&E Web-site

- Compare to homes in your area
- Compare to weather patterns
Conclusion

Should include qualitative and quantitative analysis summary from previous sections

Should answer the following set of questions:

- Which energy services are the biggest energy users?
- How would you expect energy use for each service to change throughout the year?
- Any surprises or noteworthy points?
- From working on this project, would you now consider alternative energy sources for particular services?
- From the calculations above, suggest a replacement for one of the high energy appliances? How much would it offset your energy consumption by?
- Would you now consider a habit or lifestyle change?
- Compare your results to the data collected by David MacKay.
Conclusion

- Compare your results to the data shown below.

Average Power Consumption (UK)

125 kWh/day (Europe)
250 kWh/day (USA)

(Not including embodied energy in imports nor solar energy used by agriculture)

For CO₂ pollution, divide by 10:
100 kWh/day ~ 10 tonnes CO₂/y
Part II

Complete an online questionnaire on campus (~45 questions).

http://classes.soe.ucsc.edu/e e080j/Spring11/Labs/Question naire/forms.html
• Due Dates:

• April 27, in class
Photovoltaics:

Direct conversion of solar radiation to electricity
Average Daily Solar Radiation Per Month

APRIL

Horizontal Flat Plate

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

NREL
National Renewable Energy Laboratory
Resource Assessment Program

kWh/m²/day

- 10 to 14
- 8 to 10
- 7 to 8
- 6 to 7
- 5 to 6
- 4 to 5
- 3 to 4
- 2 to 3
- 0 to 2
- none

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

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Maps are not drawn to scale.

National Renewable Energy Laboratory
Resource Assessment Program
Figure 3.10

(a)

conduction band

valence band

(b)

conduction band

valence band
Figure 3.11

Pure silicon

N type silicon
(Phosphorus doping)

P type silicon
(Boron doping)
light energy

- sunlight as a form of "radiation"
- radiation comes in packets of energy, photons (massless "particles")
  \[ E = \frac{hc}{\lambda} \]
  \( h = \) Planck's constant
  \( c = \) velocity of light
  \( \lambda = \) wavelength

- rule of thumb
  \[ E(eV) \cong \frac{12345}{\lambda(\text{Å})} \]
  \( \text{Å} = 10^{-10} \text{m} \)

  if \( E > E_{\text{gap}} \), excess energy \( \rightarrow \) heat

  if \( E = E_{\text{gap}} \), absorption (max efficiency)

  if \( E < E_{\text{gap}} \), photons pass right through
Solar Spectrum

The Sun emits visible light and radiation characteristic of its surface temperature of 6000 °C. The Earth reflects away 30% of this radiation. The average atmospheric temperature is −20 °C, and the average surface temperature is approximately 15 °C. The Earth radiates away the rest of the radiation as long-wave infrared radiation to deep space at −270 °C.

1 nm = 10 Angstroms
Figure 3.13

Diagram illustrating the process of converting sand (SiO₂) to metallurgical grade silicon and subsequently to silicon wafers, which are used to form photovoltaic modules.

1. **Sand (SiO₂)** is processed in an arc furnace to produce coke reduction.
2. Coke reduction results in polycrystalline silicon.
3. Polycrystalline silicon is then subjected to a Czochralski process at 1500°C.
4. The process yields high purity trichlorosilane.
5. Trichlorosilane is distilled and dissolved in HCl to form chlorosilanes.
6. Chlorosilanes are converted into silicon wafers through diamond sawing.
7. Silicon wafers are then chemically polished to produce polished wafers.
8. Polished wafers are formed into front contact for interconnection, testing, encapsulation, and assembly into modules.
9. Interconnected modules are assembled into arrays.
10. Testing is performed to validate the photovoltaic modules.

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Solar Cell

- Light absorption
- Electron/hole separation
- Charge transport

Ken Pedrotti, UCSC

A. Shakouri, Purdue Univ. 4/17/2012; p.3
Solar Photovoltaic

- Front metal contacts
- Antireflection coating
- Antireflection coating
- N-type crystal
- P-type crystal
- Rear metal contact
- Electron-hole pairs formed
- Holes drift to p-region (back contact)
- Electrons drift to n-region (front contacts)
- Current flows in external circuit
- Current collector
- Ammeter
\[ AM = \frac{1}{\cos \theta} = \frac{SO}{ZO} \quad \text{air mass} \]
Solar Cell Current-Voltage Characteristics

- Short circuit current ($I_C$)
- Open circuit voltage ($V_{OC}$)
- Maximum power point
## Silicon Solar cells

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Commercial Production:</strong></td>
<td></td>
</tr>
<tr>
<td>Mono-crystalline</td>
<td>12 - 16 %</td>
</tr>
<tr>
<td>Poly-crystalline</td>
<td>10 - 12 %</td>
</tr>
<tr>
<td>Amorphous</td>
<td>6 - 7 %</td>
</tr>
<tr>
<td>Triple Junction Amorphous</td>
<td>9 %</td>
</tr>
<tr>
<td><strong>Laboratory cells:</strong></td>
<td></td>
</tr>
<tr>
<td>Mono-crystalline</td>
<td>&gt; 23 %</td>
</tr>
<tr>
<td>Poly-crystalline</td>
<td>18 %</td>
</tr>
<tr>
<td>Multi layer Amorphous</td>
<td>Up to 16 %</td>
</tr>
</tbody>
</table>
Revolutionary Photovoltaics: goal of 50% Efficient Solar Cell

Present technology: 32% limit for
- single junction
- one exciton per photon
- relaxation to band edge

Multiple junctions, multiple gaps, multiple excitons per photon, hot carriers

Rich variety of new physical phenomena challenge: to understand and implement

Millie Dresselhaus, MIT
Multijunction Solar Cells

Zhores Alferov, “Global Sustainability: A Nobel Cause”
Potsdam, Germany, 8-10 Oct 2007

A. Shakouri, Purdue Univ. 4/17/2012; p.12
Nanorod/Nanowire Solar Cells

Fig. 3. Arrays of nanorods, illustrating an approach to orthogonalization of the directions of light absorption (down the length of the rods) and charge carrier collection (radially outward to the surface of the rods). (Adapted from (2))
Why Nanowire Solar Cells?

- Traditional device design requires expensive, long diffusion length materials.
- Nanowire device decouples light absorption and carrier extraction into orthogonal spatial directions.
- Radial geometry allows for high quantum efficiency with short minority carrier diffusion lengths (i.e. inexpensive materials and processes).
- Radial or axial pn junction geometries envisioned.
- Hetero- and multi-junction devices possible.

H. Atwater, Caltech
Large Area Au-Catalyzed Si Arrays

3 μm array, 500 nm Au, $T_{\text{growth}} = 1060^\circ\text{C}$, $P_{\text{growth}} = 760$ Torr, 30 min growth, 2 mole % SiCl$_4$ in H$_2$

Nearly 100% vertically aligned, 75 μm length microwire arrays over areas $> 1 \text{ cm}^2$.

H. Atwater, Caltech
Dye-sensitized solar cell, in which a nanoparticulate network provides collection of charge carriers injected into it as a result of absorption of sunlight by the adsorbed dye molecule. The oppositely charged carrier moves through the contacting liquid or polymeric phase to the counterelectrode, completing the electrical circuit in the solar cell. [Adapted from (2)]

From N. Lewis, 2007
Printing of Plastic Electronics

“inks” ---- with electronic functionality!

The Dream

Plastic Substrate
Solar Cells
Functional Ink

Alan Heeger, “Global Sustainability: A Nobel Cause”
Potsdam, Germany, 8-10 Oct 2007
“Plastic” Solar Cells

Ultrafast charge separation with quantum efficiency approaching Unity!

1992

50 femtoseconds!!

Open circuit voltage doubled; Efficiency 6.5%
The tendency in concentrator PV:
from large to small concentrators at high concentration ratio!

Zhores Alferov
"Global Sustainability: A Nobel Cause"
in Potsdam, Germany,
8-10 Oct 2007
Semiprius’ micro PV cells

Microcell:
600 µm diameter GaAs multi junction cell
+ High-power optics

- 1000x concentration
- No cooling
Semprius’ micro printing technology

No dicing (material waste)

→ Use chemical etching and sacrificial layer

Use only a thin surface layer

→ Wafer back to the foundry to be reused.
Cost/Efficiency of Photovoltaic Technology

Costs are modules per peak W; installed is $5-10/W; $0.35-$1.5/kW-hr

A. Shakouri, Purdue Univ. 4/17/2012; p.20
Among Conventional Thin Films (CuIn$_x$Ga$_{1-x}$Se$_2$, CdTe, Si) Only Si Abundant Enough

![Graph of relative abundance of chemical elements](image)

Silicon solar cell and module manufacturing
Solar Energy - Photovoltaics

- Captures the energy in the solar radiation that reaches the Earth
- Electricity production
  - Photovoltaic (PV) cells are semiconductors that convert sunlight directly into electricity
- R&D Focus
  - Fundamental science of materials, advanced solar cells and processes, scale-up, lower cost

- Generating Capacity
  - Grid-connected PV generating capacity in the U.S. ~ 25 MW (fraction of off-grid PV capacity)
- Power System Size Range
  - 1 W (single cell) – 400 kW (PV array)
- Electricity Generation Costs
  - 25¢ – $1/kWh


Keith Wipke, NREL 2008
### Table 3: TOP TEN STATES
#### Ranked by Grid-Connected PV Cumulative Installed Capacity through 2009

<table>
<thead>
<tr>
<th>Rank</th>
<th>State</th>
<th>MW_{dc}</th>
<th>Market Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>California</td>
<td>768</td>
<td>61%</td>
</tr>
<tr>
<td>2</td>
<td>New Jersey</td>
<td>128</td>
<td>10%</td>
</tr>
<tr>
<td>3</td>
<td>Colorado</td>
<td>59</td>
<td>5%</td>
</tr>
<tr>
<td>4</td>
<td>Arizona</td>
<td>46</td>
<td>4%</td>
</tr>
<tr>
<td>5</td>
<td>Florida</td>
<td>39</td>
<td>3%</td>
</tr>
<tr>
<td>6</td>
<td>Nevada</td>
<td>36</td>
<td>3%</td>
</tr>
<tr>
<td>7</td>
<td>New York</td>
<td>34</td>
<td>3%</td>
</tr>
<tr>
<td>8</td>
<td>Hawaii</td>
<td>26</td>
<td>2%</td>
</tr>
<tr>
<td>9</td>
<td>Connecticut</td>
<td>20</td>
<td>2%</td>
</tr>
<tr>
<td>10</td>
<td>Massachusetts</td>
<td>18</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>All Other States</td>
<td>83</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1,256</strong></td>
<td>--</td>
</tr>
</tbody>
</table>

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### Table 4: TOP TEN STATES
#### Ranked by Cumulative Installed PV Capacity per Capita (W_{dc}/person) through 2009

<table>
<thead>
<tr>
<th>Rank</th>
<th>State</th>
<th>Cumulative through 2009 (W_{dc}/person)</th>
<th>2009 Installations (W_{dc}/person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>California</td>
<td>20.8</td>
<td>5.7</td>
</tr>
<tr>
<td>2</td>
<td>Hawaii</td>
<td>20.2</td>
<td>9.8</td>
</tr>
<tr>
<td>3</td>
<td>New Jersey</td>
<td>14.6</td>
<td>6.6</td>
</tr>
<tr>
<td>4</td>
<td>Nevada</td>
<td>13.8</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>Colorado</td>
<td>11.8</td>
<td>4.7</td>
</tr>
<tr>
<td>6</td>
<td>Arizona</td>
<td>7.0</td>
<td>3.2</td>
</tr>
<tr>
<td>7</td>
<td>Connecticut</td>
<td>5.6</td>
<td>2.5</td>
</tr>
<tr>
<td>8</td>
<td>Delaware</td>
<td>3.7</td>
<td>1.6</td>
</tr>
<tr>
<td>9</td>
<td>Oregon</td>
<td>3.7</td>
<td>1.7</td>
</tr>
<tr>
<td>10</td>
<td>Vermont</td>
<td>2.7</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td><strong>National Average</strong></td>
<td><strong>4.2</strong></td>
<td><strong>1.4</strong></td>
</tr>
</tbody>
</table>

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**IREC’s 2009 edition of U.S. Solar Market Trends**
## Table 2: TOP TEN STATES
Ranked by Grid-Connected PV Capacity Installed in 2009

<table>
<thead>
<tr>
<th>2009 Rank by State</th>
<th>2009 (MW_{dc})</th>
<th>2008 (MW_{dc})</th>
<th>08-09 % change</th>
<th>2009 Market Share</th>
<th>2008 Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. California</td>
<td>212.1</td>
<td>197.6</td>
<td>7%</td>
<td>49%</td>
<td>1</td>
</tr>
<tr>
<td>2. New Jersey</td>
<td>57.3</td>
<td>22.5</td>
<td>155%</td>
<td>13%</td>
<td>2</td>
</tr>
<tr>
<td>3. Florida</td>
<td>35.7</td>
<td>0.9</td>
<td>3668%</td>
<td>8%</td>
<td>16</td>
</tr>
<tr>
<td>4. Colorado</td>
<td>23.4</td>
<td>21.7</td>
<td>8%</td>
<td>5%</td>
<td>4</td>
</tr>
<tr>
<td>5. Arizona</td>
<td>21.1</td>
<td>6.2</td>
<td>243%</td>
<td>5%</td>
<td>8</td>
</tr>
<tr>
<td>6. Hawaii</td>
<td>12.7</td>
<td>8.6</td>
<td>48%</td>
<td>3%</td>
<td>5</td>
</tr>
<tr>
<td>7. New York</td>
<td>12.1</td>
<td>7.0</td>
<td>72%</td>
<td>3%</td>
<td>7</td>
</tr>
<tr>
<td>8. Massachusetts</td>
<td>9.5</td>
<td>3.5</td>
<td>174%</td>
<td>2%</td>
<td>11</td>
</tr>
<tr>
<td>9. Connecticut</td>
<td>8.7</td>
<td>7.5</td>
<td>16%</td>
<td>2%</td>
<td>6</td>
</tr>
<tr>
<td>10. North Carolina</td>
<td>7.8</td>
<td>4.0</td>
<td>96%</td>
<td>2%</td>
<td>10</td>
</tr>
<tr>
<td>All Other States</td>
<td>34.2</td>
<td>24.6</td>
<td>41%</td>
<td>7%</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>434.6</strong></td>
<td><strong>311.3</strong></td>
<td><strong>40%</strong></td>
<td><strong>--</strong></td>
<td><strong>--</strong></td>
</tr>
</tbody>
</table>

2008 and 2009 columns include installations completed in those years.


California Solar Initiative

- The program is funded at $3.35 billion over 11 years.
- 10 percent of the program is set aside for low income homes.
- Expands the net metering cap to 2.5 percent, allowing approximately 500,000 new solar systems into the net metering program.
- Mandates that solar systems are a standard option for all new homeowners.
- Requires the state's municipal utilities to create their own solar rebate programs, totaling $800 million in rebates.
- Directs the California State Licensing Board to review current licensing requirements for solar installers.
Germany leads world
In Solar Power Generation

Solar Generation (GWh)

Spain: 234
U.S.: 1871
Japan: 2978
Germany: 4450

Source: IEA PVPS; La Generacion del Sol
* Numbers calculated using capacity factors of 20% for PV and 25% for CSP

Keith Wipke, NREL 2008 (2006 Data)
Solar Powered Satellites
Photonic design principles for ultrahigh-efficiency photovoltaics

Albert Polman and Harry A. Atwater

For decades, solar-cell efficiencies have remained below the thermodynamic limits. However, new approaches to light management that systematically minimize thermodynamic losses will enable ultrahigh efficiencies previously considered impossible.
Figure 2 | Light-management architectures for reaching ultrahigh efficiency. a, Three-dimensional parabolic light reflectors direct spontaneous emission back to the disk of the Sun. b, Planar metamaterial light-director structures. c, Mie-scattering surface nanostructure for light trapping. d, Metal-dielectric-metal waveguide or semiconductor-dielectric-semiconductor slot waveguide with enhanced optical density of states to increase the spontaneous emission rate.
Figure 3 | Multi-junction solar cells. 

(a) Multi-junction energy diagram. Semiconductors with different bandgaps convert different portions of the solar spectrum to reduce thermalization losses. The quasi-Fermi levels defining the open-circuit voltage are indicated by the horizontal blue dashed lines. The yellow dots represent the electrons. 

(b) Parallel-connected architecture that can be realized using epitaxial lift-off and printing techniques of the semiconductor layers, followed by printing of a micro- or nanophotonic spectrum splitting layer. Each semiconductor layer can be combined with one of the structures in Fig. 2 to reduce entropy losses and these structures can be separately optimized for each semiconductor.
Problem:
- Energy loss in Carnot cycle
- Entropy loss in absorption or emission
- Entropy loss due to non-reciprocity
- Energy loss due to thermalization or lack of absorption
- Entropy loss due to lack of angle restriction
- Entropy loss to incomplete light trapping and reduced QE
- Conventional single-junction solar cell

Solution:
- Intrinsic loss
- Multi-junction solar cell
- Surface light directors
- Light-trapping structures, density of states engineering