Solar Technologies
Ways to extract useful energy from the sun

Notable quotes

• I’d put my money on the sun and solar energy. What a source of power! I hope we don’t have to wait until oil and coal run out before we tackle that.
  – Thomas Edison, 1910
• My father rode a camel. I drive a car. My son flies a jet airplane. His son will ride a camel.
  – Saudi proverb

Four Basic Schemes

1. Photovoltaics (Lecture 12)
2. Thermal electric power generation
3. Flat-Plate direct heating (hot water, usually)
4. Passive solar heating

Photovoltaic Reminder

• Sunlight impinges on silicon crystal
• Photon liberates electron
• Electron drifts aimlessly in p-region
• If it encounters junction, electron is swept across, constituting current
• Electron collected at grid, flows through circuit (opposite current lines)
Photovoltaic power scheme

- Sunlight is turned into DC voltage/current by PV
- Can charge battery (optional)
- Inverted into AC
- Optionally connect to existing utility grid
- AC powers household appliances

Putting photovoltaics on your roof

- The greater the efficiency, the less area needed
- Must be in full-sun location: no shadows
  - south-facing slopes best, east or west okay

<table>
<thead>
<tr>
<th>PV Efficiency (%)</th>
<th>PV capacity rating (watts)</th>
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<tbody>
<tr>
<td></td>
<td>100</td>
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<tr>
<td>4</td>
<td>30</td>
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<td>8</td>
<td>15</td>
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<td>12</td>
<td>10</td>
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<td>15</td>
<td>8</td>
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- Above table uses about 900 W/m² as solar flux

When the sun doesn’t shine...

- Can either run from batteries (bank of 12 gives roughly one day’s worth) or stay on grid
  - usually design off-grid system for ~3 days no-sun
- In CA (and 37 other states), they do “net metering,” which lets you run your meter backwards when you are producing more than you are consuming
  - this means that the utility effectively buys power from you at the same rate they sell it to you: a sweet deal
- but very few U.S. utilities cut a check for excess production
- Backup generator also possible
Photovoltaic Transportation

- A 10 m² car using 15% efficiency photovoltaics under 850 W/m² solar flux would generate at most 1250 W
  - 1.7 horsepower max
  - in full sun when sun is high in the sky
- Could only take a 5% grade at 20 mph
  - this neglects any and all other inefficiencies
- Would do better if panels charged batteries
  - no more shady parking spots!

Photovoltaic transportation

- Quote about solar car pictured above:
  - “With sunlight as its only fuel, the U of Toronto solar car, named Faust, consumes no more energy than a hairdryer but can reach speeds of up to 120 kilometers per hour.”
    - Is this downhill?? Note the mistake in the above quote…
- The real point is that it can be done
  - but most of the engineering effort is in reducing drag, weight, friction, etc.
  - even without air resistance, it would take two minutes to get up to freeway speed if the car and driver together had a mass of 250 kg (very light)
    - just \( \text{v} = \sqrt{\text{a} \cdot \text{t}} \) divided by 1000 W of power

Future Projections

- As fossil fuels run out, the price of FF energy will climb relative to PV prices
- Break-even time will drop from 15 to 10 to 5 years
  - now at 8 years for California home (considering rebates)
- Meanwhile PV is sure to become a more visible/prevalent part of our lives!
  - In Japan, it is so in to have photovoltaics, they make fake PV panels for rooftops so it’ll look like you’ve gone solar!

But not all is rosy in PV-land…

- Photovoltaics don’t last forever
  - useful life is about 30 years (though maybe more?)
  - manufacturers often guarantee < 20% degradation in 25 years
  - damage from radiation, cosmic rays create crystal imperfections
- Some toxic chemicals used during production
  - therefore not entirely environmentally friendly
- Much land area would have to be covered, with corresponding loss of habitat
  - not clear that this is worse than mining/processing and power plant land use (plus thermal pollution of rivers)
Solar Thermal Generation

- By concentrating sunlight, one can boil water and make steam
- From there, a standard turbine/generator arrangement can make electrical power
- Concentration of the light is the difficult part: the rest is standard power plant stuff
- Called Solar Thermal, or CSP: Concentrated Solar Power

Concentration Schemes

- Most common approach is parabolic reflector:
  - A parabola brings parallel rays to a common focus
    - better than a simple spherical surface
    - the image of the sun would be about 120 times smaller than the focal length
    - Concentration $\sim 13,000 \times (D/f)^2$, where $D$ is the diameter of the device, and $f$ is its focal length

The steering problem

- A parabolic imager has to be steered to point at the sun
  - requires two axes of actuation: complicated
- Especially complicated to route the water and steam to and from the focus (which is moving)
- Simpler to employ a trough: steer only in one axis
  - concentration reduced to $114 \times (D/f)$, where $D$ is the distance across the reflector and $f$ is the focal length

Power Towers

Power Tower in Barstow, CA
Who needs a parabola!

- You can cheat on the parabola somewhat by adopting a steerable-segment approach
  - each flat segment reflects (but does not itself focus) sunlight onto some target
  - makes mirrors cheap (flat, low-quality)
- Many coordinated reflectors putting light on the same target can yield very high concentrations
  - concentration ratios in the thousands
  - Barstow installation has 1900 20x20-ft$^2$ reflectors, and generates 10 MW of electrical power
    - calculate an efficiency of 17%, though this assumes each panel is perpendicular to sun

Solar thermal economics

- Becoming cost-competitive with fossil fuel alternatives
- Cost Evolution: solar thermal plants
  - 1983 13.8 MW plant cost $6 per peak Watt
    - 25% efficient
    - about 25 cents per kWh
  - 1991 plant cost $3 per peak Watt
    - 8 cents per kWh
  - Solar One in Nevada cost $266 million, produces 75 MW in full sun, and produces 134 million kWh/year
    - so about $3.50 per peak Watt, 10 cents/kWh over 20 years
- California dominated world for CSP (354 MW)
  - now U.S. has 1000 MW capacity; 500 MW in Spain

Barstow Scheme

Flat-Plate Collector Systems

- A common type of solar “panel” is one that is used strictly for heat production, usually for heating water
- Consists of a black (or dark) surface behind glass that gets super-hot in the sun
- Upper limit on temperature achieved is set by the power density from the sun
  - dry air may yield 1000 W/m$^2$ in direct sun
  - using off, this equates to a temperature of 364 °K for a perfect absorber in radiative equilibrium (boiling is 373 °K)
- Trick is to minimize paths for thermal losses
Flat-Plate Collector

Controlling the heat flow

- You want to channel as much of the solar energy into the water as you can
  - this means suppressing other channels of heat flow
- Double-pane glass
  - cuts conduction of heat (from hot air behind) in half
  - provides a buffer against radiative losses (the pane heats up by absorbing IR radiation from the collector)
  - If space between is thin, inhibits convection of air between the panes (making air a good insulator)
- Insulate behind absorber so heat doesn’t escape
- Heat has few options but to go into circulating fluid

What does the glass do, exactly?

- Glass is transparent to visible radiation (aside from 8% reflection loss), but opaque to infrared radiation from 8–24 microns in wavelength
  - collector at 350 °K has peak emission at about 8.3 microns
  - inner glass absorbs collector emission, and heats up
  - glass re-radiates thermal radiation: half inward and half outward: cuts thermal radiation in half
  - actually does more than this, because outer pane also sends back some radiation: so 2/3 ends up being returned to collector

An example water-heater system

Figure 4.6: A circulating liquid solar collector system that provides hot water for space heating and domestic use. In a typical installation the collector will be on the roof of a building with the other components in an indoor utility area.
Flat plate efficiencies

- Two-pane design only transmits about 85% of incident light, due to surface reflections
- Collector is not a perfect absorber, and maybe bags 95% of incident light (guess)
- Radiative losses total maybe 1/3 of incident power
- Convective/Conductive losses are another 5–10%
- Bottom line is approximately 50% efficiency at converting incident solar energy into stored heat
  - \(0.85 \times 0.95 \times 0.67 \times 0.90 = 0.49\)

How much would a household need?

- Typical showers are about 10 minutes at 2 gallons per minute, or 20 gallons.
- Assume four showers, and increase by 50% for other uses (dishes, laundry) and storage inefficiencies:
  - 20 x 4 x 1.5 = 120 gallons = 450 liters
- To heat 450 l from 15 °C to 50 °C requires:
  - \(4184 \text{ J/kg}^\circ\text{C} \times (450 \text{ kg}) \times (35 - 15) \text{ °C} = 66 \text{ MJ of energy}\)
- Over 24-hour day, this averages to 762 W
- At average insolation of 200 W/m² at 50% efficiency, this requires 7.6 m² of collection area
  - about 9-feet by 9-feet, costing perhaps $6000

Interesting societal facts

- In the early 1980’s, the fossil fuel scare led the U.S. government to offer tax credits for installation of solar panels, so that they were in essence free
- Many units were installed until the program was dropped in 1985
  - most units were applied to heating swimming pools!
- In other parts of the world, solar water heaters are far more important
  - 90% of homes in Cyprus use them
  - 65% of homes in Israel use them (required by law for all buildings shorter than 9 stories)

Passive Solar Heating

- Let the sun do the work of providing space heat
  - already happens, but it is hard to quantify its impact
- Careful design can boost the importance of sunlight in maintaining temperature
- Three key design elements:
  - insulation
  - collection
  - storage
South-Facing Window

- Simple scheme: window collects energy, insulation doesn’t let it go, thermal mass stabilizes against large fluctuations
- overhang defeats mechanism for summer months

The Trombe Wall

- Absorbing wall collects and stores heat energy
- Natural convection circulates heat
- Radiation from wall augments heat transfer

How much heat is available?

- Take a 1600 ft² house (40x40 footprint), with a 40x10 foot = 400 ft² south-facing wall
- Using numbers from Table 4.2 in book, a south-facing wall at 40° latitude receives about 1700 Btu per square foot per clear day
- comes out to about 700,000 Btu for our sample house
- Account for losses:
  - 70% efficiency at trapping available heat (guess)
  - 50% of days have sun (highly location-dependent)
- Net result: 250,000 Btu per day available for heat
  - typical home (shoddy insulation) requires 1,000,000 Btu/day
  - can bring into range with proper insulation techniques

Announcements and Assignments

- Stay in School
- No HW this week, but Quiz Friday, by midnight
- Read Chapter 5 (5.1, 5.2, 5.3, 5.5, 5.7) for next lecture
- Optional Reading from Do the Math
  - 23. A Solar-Powered Car
  - 25. Wind Fights Solar: Triangle Wins
  - 31. Basking in the Sun