Solar Technologies

Ways to extract useful energy from the sun

Notable quotes

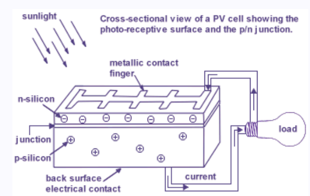
- I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that.
  - Thomas Edison, 1910
- My father rode a camel. I drive a car. My son flies a jet airplane. His son will ride a camel.
  - Saudi proverb

Four Basic Schemes

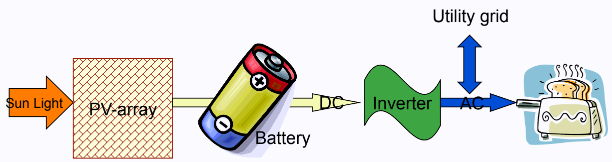
1. Photovoltaics (Lecture 12)
2. Thermal electric power generation
3. Flat-Plate direct heating (hot water, usually)
4. Passive solar heating

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)

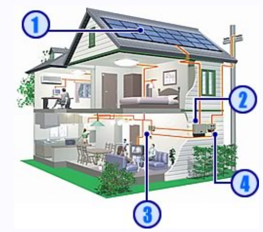


Photovoltaic power scheme



- 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

Typical Installation



1. PV array
2. Inverter/power-conditioner
3. Indoor distribution panel
4. Energy meter (kWh, connected to grid)

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

PV Efficiency (%)	PV capacity rating (watts)							
	100	250	500	1K	2K	4K	10K	100K
	Roof area needed (sq. ft.)							
4	30	75	150	300	600	1200	3000	30000
8	15	38	75	150	300	600	1500	15000
12	10	25	50	100	200	400	1000	10000
16	8	20	40	80	160	320	800	8000

- Above table uses about 900 W/m^2 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 m^2 car using 15% efficiency photovoltaics under 850 W/m^2 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 $\frac{1}{2}mv^2$ 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)

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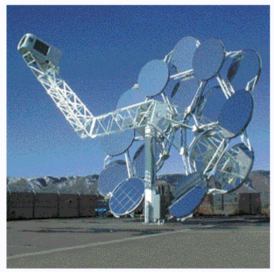
Solar Thermal Generation

- 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



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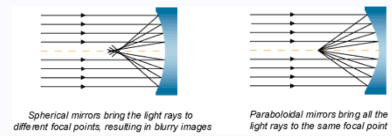
Concentration Schemes

- 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 ≈ 13,000×$(D/f)^2$, where D is the diameter of the device, and f is its focal length

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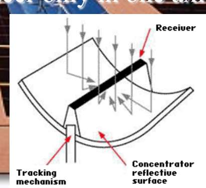
The steering problem

- 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×(D/f), where D is the distance across the reflector and f is the focal length



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Power Towers

Power Tower in Barstow, CA

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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 20×20-ft^2 reflectors, and generates 10 MW of electrical power
    - calculate an efficiency of 17%, though this assumes each panel is perpendicular to sun

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Barstow Scheme

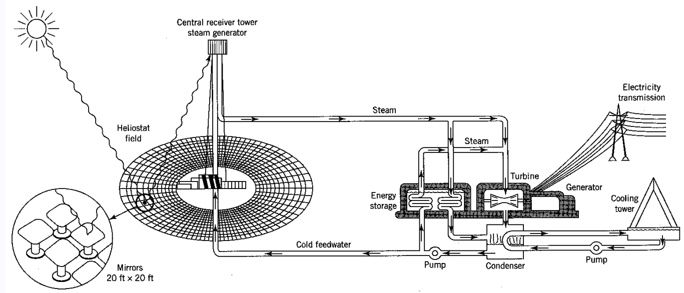

Figure 4.11 A schematic view of a 10 MW_e solar-thermal power plant near Barstow, California. The receiver and boiler that absorb the sunlight reflected from 1900 heliostats are at the top of a 90 meter tower. The heliostats are each steered by computer control to reflect the sunlight onto the receiver. The steam from the boiler can be either delivered directly to the turbine and generator or to storage. The storage system can provide steam for 4 hours of generation at a level of 7 MW_e without sunlight. (Figure supplied by the Solar Energy Research Institute.)

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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

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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 σT^4, 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

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Flat-Plate Collector

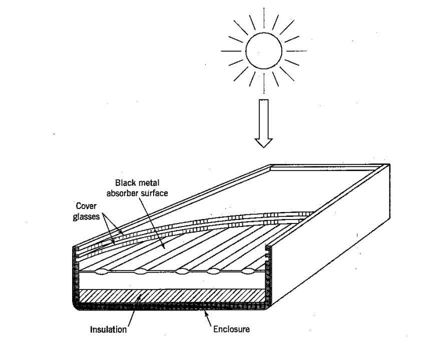

Figure 4.5 A cutaway view of a flat-plate solar collector with two cover glasses. A heat-transfer fluid is circulated through the tubular passages integrally formed into the metal absorber surface. (Not drawn to scale.)

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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

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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

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An example water-heater system

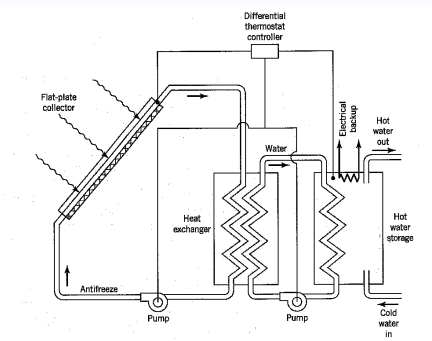

Figure 4.6 A circulating-liquid solar collector system that provides hot water for space heating and domestic use. In a typical installation the collector will be on the roof of a building with the other components in an inside utility area.

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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
  - $0.85\times0.95\times0.67\times0.90 = 0.49$

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:
  - $20\times4\times1.5 = 120$ gallons ≈ 450 liters
- To heat 450 *l* from 15 ºC to 50 ºC requires:
  (4184 J/kg/ºC)×(450 kg)×(35 ºC) = 66 MJ of energy
- Over 24-hour day, this *averages* to 762 W
- At average insolation of 200 W/m^2 at 50% efficiency, this requires 7.6 m^2 of collection area
  - about 9-feet by 9-feet, costing perhaps $6–8,000

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

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South-Facing Window

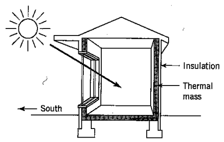

Figure 4.8 A home heated by the direct gain passive solar method. South-facing windows act as solar collectors. Sunlight enters the living space, is converted to heat at absorbing surfaces, and the heat is dispersed throughout the space and to the various enclosing surfaces and room contents. The windows can be covered at night with movable insulation to reduce heat loss. A massive masonry floor and back wall serve for heat storage and prevent overheating. The exterior overhang helps to prevent overheating in the summer. (Adapted from: J. Douglas Balcomb, *Passive Solar Space Heating*, Los Alamos National Laboratory, LA-UR-80-2555.)

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

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The Trombe Wall

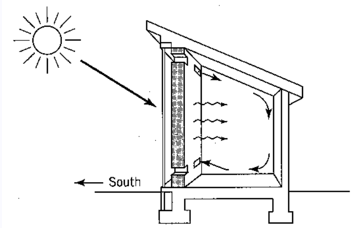

Figure 4.7 A typical Trombe wall installation. The massive concrete wall inside a glass window acts both as a collector and a heat storage medium. The room air circulates by natural convection as shown. Heat is also radiated by the wall into the living space. (Adapted from: J. Douglas Balcomb, *Passive Solar Space Heating*, Los Alamos National Laboratory, LA-UR-80-2555.)

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

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How much heat is available?

- Take a 1600 ft^2 house (40×40 footprint), with a 40×10 foot = 400 ft^2 south-facing wall
- Using numbers from Table 4.2 in book, a south-facing wall at 40º 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

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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

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