Solar Energy II

Chapter 4 Summary
- Energy from the Sun
  - Spoke way too much about this in our last meeting
- Today’s focus
  - Photovoltaic systems
    - Making electricity directly
  - Solar Thermal Systems
    - Electric power generation indirectly
  - Passive solar systems

iClicker Question
- The release of energy from the Sun is accompanied by a very slight
  A increase in the Sun’s gravitational attraction on the planets
  B increase in the Sun’s rotation rate
  C decrease in the mass of the Sun
  D all of the above are true
  E none of the above are true

iClicker Question
- Most of the Sun’s energy is produced in
  A supergranules
  B the convection zone
  C the photosphere
  D the chromosphere
  E the core

iClicker Question
- Energy generation in the Sun results from
  A fission of uranium
  B fission of hydrogen
  C gravitational contraction
  D the Sun isn’t generating energy; it’s just cooling
  E fusion of hydrogen

iClicker Question
- The highest temperatures found in the Sun’s atmosphere is located in the
  A chromosphere
  B corona
  C photosphere
  D core
  E cytosphere
iClicker Question

Sunspot cycles are, on the average, what length?
- A 22 years
- B 11 years
- C 5.5 years
- D 1 year
- E 3 years

Renewable Energy Consumption

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<td>Wind</td>
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<td>0.040</td>
<td>0.108</td>
<td>0.11</td>
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<td>Total</td>
<td>6.351</td>
<td>7.18</td>
<td>6.15</td>
<td>6.3</td>
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How much energy is available?
- Above the atmosphere, we get 1368 W/m² of radiated power from the sun, across all wavelengths
  - This number varies by ±3% as our distance to the sun increases or decreases (elliptical orbit)
  - The book uses 2 calories per minute per cm² (weird unit!!!)
- At the ground, this number is smaller due to scattering and absorption in the atmosphere
  - about 63%, or ~850 W/m² with no clouds, perpendicular surface
  - probably higher in dry desert air

Making sense of the data
- Derived from the previous figure
  - 52% of the incoming light hits clouds, 48% does not
    - 25% + 10% + 17%
  - in cloudless conditions, half (24/48) is direct, 63% (30/48) reaches the ground
  - in cloudy conditions, 17/52 = 33% reaches the ground
  - about half of the light of a cloudless day averaging all conditions, about half of the sunlight incident on the earth reaches the ground
- the analysis is simplified
  - assumes atmospheric scattering/absorption is not relevant when cloudy

The Solar Spectrum

The wavelength distribution of solar radiation above the atmosphere consists of four major components: ultraviolet, visible, near-infrared, and far-infrared. The distribution changes due to absorption and scattering in the atmosphere, which depends on factors such as altitude, atmospheric composition, and weather conditions. Understanding this distribution is crucial for designing solar energy systems and assessing their efficiency.

Input flux (average properties)

Absorption and scattering of solar radiation in the atmosphere. The values shown are for average weather, and are averaged over all seasons and latitudes.
Another View of EARTH'S ENERGY BUDGET

Comparable numbers
- Both versions indicate about half the light reaching (being absorbed by) the ground
  - 47% vs. 51%
- Both versions have about 1/3 reflected back to space
  - 34% vs. 30%
- Both versions have about 1/5 absorbed in the atmosphere/clouds
  - 19% vs. 19%

iClicker Question
- Roughly what percentage of light from the Sun reaches the ground?
  - A 10%
  - B 20%
  - C 30%
  - D 40%
  - E 50%

Energy Balance
- Note that every bit of the energy received by the sun is reflected or radiated back to space
- If this were not true, earth's temperature would change until the radiation out balanced the radiation in
- In this way, we can compute surface temperatures of other planets (and they compare well with measurements)

Average Insolation
- The amount of light received by a horizontal surface (in W/m²) averaged over the year (day & night) is called the insolation
- We can make a guess based on the facts that on average:
  - half the incident light reaches the ground
  - half the time it is day
  - the sun isn't always overhead, so that the effective area of a horizontal surface is half its actual area
    - half the sphere (2πR²) projects into just πR² for the sun
    - twice as much area as the Sun "sees"
  - So 1/8 of the incident sunlight is typically available at the ground
  - 171 W/m² on average

Insolation variation
- While the average insolation is 171 W/m², variations in cloud cover and latitude can produce a large variation in this number
  - A spot in the Sahara (always sunny, near the equator) may have 270 W/m² on average
  - Alaska, often covered in clouds and at high latitude may get only 75 W/m² on average
  - Is it any wonder that one is cold while one is hot?
iClicker Question

- What is the definition of insolation?
  - A The effective solar insulation factor.
  - B The amount of light received by a horizontal surface averaged over the year.
  - C The amount of light received by a unit area of the atmosphere averaged over the year.
  - D There is none, it is a mis-spelling of insulation.
  - E The amount of insulation that is received from the Sun.

Average daily radiation received

divide by 24 hr to get average kW/m²

Higher Resolution Insolation Map

Tilted Surfaces

- Can effectively remove the latitude effect by tilting panels
  - raises incident power on the panel, but doesn’t let you get more power per unit area of (flat) real estate

Which is best?

- To tilt, or not to tilt?
  - If the materials for solar panels were cheap, then it would make little difference (on flat land)
  - If you have a limited number of panels (rather than limited flat space) then tilting is better
  - If you have a slope (hillside or roof), then you have a built-in gain
  - Best solution of all (though complex) is to steer and track the sun

Orientation Comparison

Figure 6.4: Solar power incident on three types of collectors for a typical winter day at 40° N latitude. The energy collected each day is given by the area under each curve.
Numerical Comparison: winter at 40º latitude

<table>
<thead>
<tr>
<th>Date</th>
<th>Perpendicular (sheared, W/m²)</th>
<th>Horizontal (W/m²)</th>
<th>Vertical S (W/m²)</th>
<th>60º South (W/m²)</th>
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<td>322</td>
<td>177</td>
<td>217</td>
<td>272</td>
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<td>Dec 21</td>
<td>260</td>
<td>103</td>
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<td>Jan 21</td>
<td>287</td>
<td>125</td>
<td>227</td>
<td>256</td>
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<td>Feb 21</td>
<td>347</td>
<td>186</td>
<td>227</td>
<td>286</td>
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<tr>
<td>Mar 21</td>
<td>383</td>
<td>243</td>
<td>195</td>
<td>286</td>
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So why don’t we go solar?

- What would it take?
  - To convert 1/500th of available energy to useful forms, would need 1/500th of land at 100% efficiency
  - about the size of New Jersey
  - But 100% efficiency is unrealistic: try 15%
  - now need 1/75th of land
  - Pennsylvania-sized (100% covered)
  - Can reduce area somewhat by placing in S.W.

Making sense of the big numbers

- How much area is this per person?
  - U.S. is 9.36 \times 10^{12} \text{ m}^2
  - 1/75th of this is 1.25 \times 10^{11} \text{ m}^2
  - 300 million people in the U.S.
  - 416 m² per person = 4,500 square feet
  - this is a square 20.4 meters (67 ft) on a side
  - one football field serves only about 10 people!
  - much larger than a typical person’s house area
  - rooftops can’t be the whole answer, especially in cities

Alternatives for using solar energy

- Direct heating of flat panel (fluids, space heating)
- Passive heating of well-designed buildings
- Thermal power generation (heat engine) via concentration of sunlight
- Direct conversion to electrical energy (photovoltaics)

Total available solar energy

- Looking at average insolation map (which includes day/night, weather, etc.)
  - estimated average of 4.25 kWh/day = 177 W/m²
  - The area of the U.S. is 3.615 \times 10^6 square miles
    - this is 9.36 \times 10^{12} \text{ m}^2
  - Multiplying gives 1.66 \times 10^{25} \text{ Watts average available power}
  - Multiply by 3.1557 \times 10^7 seconds/year gives 5.23 \times 10^{22} \text{ Joules every year}
  - This is 50 \times 10^8 Btu, or 50,000 Q\text{8tu}
  - Compare to annual budget of about 100 Q\text{8tu}
    - 500 times more sun than current energy budget

Methods of Harvesting Sunlight

- Passive: cheap, efficient design; block summer rays; allow winter sunlight
- Solar Thermal: ~30% efficient; cost-competitive; requires direct sun; heats fluid in pipes that then boils water to drive steam turbine
- Solar hot water: up to 50% efficient; several $k to install; usually keep conventional backup; freeze protection vital
- Photovoltaic (PV): direct electricity; 15% efficient; $8 per Watt to install without rebates/incentives; small fraction of roof covers demand of typ. home
- Biofuels, algae, etc. also harvest solar energy, at few % eff.
Photovoltaic (PV) Scheme
- Highly purified silicon (Si) from sand, quartz, etc. is “doped” with intentional impurities at controlled concentrations to produce a p-n junction
- p-n junctions are common and useful: diodes, CCDs, photodiodes
- A photon incident on the p-n junction liberates an electron
- Electron disappears, any excess energy goes into kinetic energy of electron (heat)
- Electron wanders around drunkenly, and might stumble into “depletion region” where electric field exists
- Electric field sweeps electron across the junction, constituting a current
- More photons → More electrons → More current → More power

Provide a circuit for the electron flow
- Without a path for the electrons to flow out, charge would build up and end up canceling electric field
- Must provide a way out
- Direct through external load
- PV cell becomes a battery

iClicker Question
- Which of the following is NOT a viable application of solar energy?
  - A. Direct heating of flat panels
  - B. Passive heating of well-designed buildings
  - C. Thermal power generation via concentration of sunlight
  - D. Direct conversion to electrical energy
  - E. Concentration of heat energy to develop nuclear energy

PV types
- Single-crystal silicon
  - 15-18% efficient, typically
  - Expensive to make (grown as big crystal)
- Poly-crystalline silicon
  - 12-16% efficient
  - Cheaper to make (cast in ingots)
- Amorphous silicon (non-crystalline)
  - 4-8% efficient
  - Cheapest per Watt
  - Called “thin film”
  - Easily deposited on a wide range of surface types

How good can it get?
- Silicon is transparent at wavelengths longer than 1.1 microns (1100 nm)
  - 23% of sunlight passes right through with no effect
- Excess photon energy is wasted as heat
  - Near-infrared light (1100 nm) typically delivers only 51% of its photon energy into electrical current energy
  - Red light (700 nm) only delivers 33%
  - Blue light (400 nm) only delivers 19%
- All together, the maximum efficiency for a silicon PV in sunlight is about 23%
  - But some estimates in the low 30’s also

Silicon Photovoltaic Budget
- Only 77% of solar spectrum is absorbed by silicon
- Of this, ~30% is used as electrical energy
- Net effect is 23% maximum efficiency
PV Cells as "Batteries"

- A single PV cell (junction) in the sun acts like a battery
  - characteristic voltage is 0.58 V
  - power delivered is current times voltage
  - current is determined by the rate of incoming solar photons
- Stack cells in series to get usefully high voltages
  - voltage ≠ power, but higher voltage means you can deliver power with less current, meaning smaller wiring, greater transmission efficiency
- A typical panel has 36 cells for about 21 V open-circuit (no current delivered)
  - but actually drops to ~16 V at max power
  - well suited to charging a nominal 12 V battery

![Typical I-V curves](image)

- Typical single panel (this one: 130 W at peak power)
  - Power is current times voltage, so area of rectangle
  - max power is 7.6 amps times 17.5 V = 133 W
  - Less efficient at higher temperatures

iClicker Question

- What is roughly the maximum efficiency for a photovoltaic cell?
  - A 10%
  - B 15%
  - C 30%
  - D 40%
  - E 50%

![Solar Economics](image)

- Consider electricity cost at $0.13 per kWh
- PV model: assume 5 hours peak-sun equivalent per day
  - in one year, get 1800 hours full-sun equivalent
  - installed cost is $8 per peak Watt capability, no rebates
  - one Watt installed delivers 1.8 kWh in a year
  - panel lasts at least 25 years, so 45 kWh for each Watt of capacity
  - paid $8.00 for 45 kWh, so $0.178/kWh
  - rebates pull price to ~ $5/kWh → ~ $0.11/kWh
- Assuming energy rates increase at a few % per year, payback is < 15 years
- therefore: "free" electricity
- but sinking $$ up front means loss of investment capability
- net effect: cost today is what matters to most people
- Solar PV is on the verge of "breakout," but demand may keep prices stable throughout the breakout process

How much does it cost?

- Solar PV is usually priced in dollars per peak Watt
  - or full-sun max capacity: how fast can it produce energy
  - panels cost $4.50 per Watt, installed cost $8/W
  - so a 3kW residential system is $24,000 to install
  - CA rebate plus federal tax incentive puts this lower than $5 per peak W
  - so 3kW system < $15,000 to install
- To get price per kWh, need to figure in exposure
  - rule of thumb: 4-6 hours per day full sun equiv: 3kW system produces ~15 kWh per day
- Mythbusting: the energy it takes to manufacture a PV panel is recouped in 3-4 years of sunlight
  - contrary to myth that they never achieve energy payback

![Solar's Dirty Secret](image)

- It may come as a surprise, but the Sun is not always up
- A consumer base that expects energy availability at all times is not fully compatible with direct solar power
- Therefore, large-scale solar implementation must confront energy storage techniques to be useful
  - at small scale, can easily feed into grid, and other power plants take up slack by varying their output
- Methods of storage (all present challenges):
  - conventional batteries (lead-acid)
  - exotic batteries (need development)
  - hydrogen fuel (could power fleet of cars)
  - global electricity grid (always sunny somewhere)
  - pumped water storage (not much capacity)
The Powell Solar Array at UCSD

grid-tie system delivering up to 11 kW
Typ. home system less than 1/4 this size

Powell PV Project Display

2007-Apr-01 through 2007-Apr-30

iClicker Question
- What may cause the 'spikes' in the previous plot?
  - A clouds
  - B precipitation
  - C both A and B
  - D sunrise/sunset
  - E failure in system

Numbers indicate kWh produced for flat, tilted arrays, respectively
Similar yields on cloudy days
Powell Array Particulars

- Each array is composed of 32 panels, each containing a 6 x 9 pattern of PV cells 0.15 m (6 inches) on a side
  - 95% fill-factor, given leads across front
  - estimated 1.15 m² per panel; 37 m² total per array
- Peak rate is 5,500 W
  - delivers 149 W/m²
- At 15% efficiency, this is 991 W/m² incident power
- Flat array sees 162, 210, 230 W/m² on average for February, March, April
  - includes night and cloudy weather
- Cloudy days deliver 25% the energy of a sunny day
  - 1 kW rate translates to 180 W/m² incident during cloudy day

UCSD 1 MW initiative: Gilman = 200 kW

At present, UCSD has been "authorized" to install 1 MW solar, online since Dec. 2008.
UCSD uses 30 MW, 25 MW generated on campus (gas turbines, mostly)

The Biggest of the Big

- PG&E recently signed an agreement to build 800 MW of solar PV in two plants in Northern California
  - 550 MW of thin-film, 250 MW of silicon
- This is the size of a nuclear power plant (but only generates the equivalent of 23-25% full-time 800 MW)
- Compare to largest current systems: 60 MW in Spain, 35 MW in Germany, 15 MW in U.S.
- Global totals:
  - Solar hot water: 154,000 MW (~12,000 MW in U.S.)
  - PV: 10,600 MW (4,150 MW in Germany, < 1,000 MW U.S.)
  - 62% growth in the industry from 2007 to 2008
  - Solar thermal: 431 MW (354 MW in CA), U.S. and Spain pushing for 7 GW by 2012
- Added together: 165 GW → ~0.3% of global demand

Solar Economics, revisited

- In remote locations, routing grid power is prohibitively expensive, so stand-alone PV is a clear choice
- For an experimental system at home, the cost is not competitive with retail electricity
  - small does not scale favorably: a system monitor can cost as much for a small system as for a large system
- But dollars and cents should not be the only considerations
  - consider: CO₂ contributed by burning fossil fuels, and climate change
  - consider: environmental damage in mining coal
  - consider: environmental damage in drilling/transporting oil
  - consider: depletion of finite resources: robbing future generations
  - consider: concentrated control of energy in a few wealthy hands

iClicker Question

- What must be done to overcome the setting of the Sun in a solar energy system?
  - A Store energy in batteries.
  - B Get electrical power from elsewhere.
  - C Don't use electrical power at night.
  - D All of the above are alternative approaches for energy after sunset.

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
iClicker Question

- How much energy does the largest photovoltaic system produce?
  - A 10 MW
  - B 20 MW
  - C 60 MW
  - D 100 MW
  - E 200 MW

Review Four Basic Solar Energy Schemes

1. Photovoltaics
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
  - 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!

Future Projections

- As fossil fuels are depleted, their prices will climb relative to photovoltaics
  - Break-even time will drop from 15 to 10 to 5 years
    - now at 8 years for a California home (considering rebates/tax incentives)
  - Meanwhile PV is sure to become a more visible/prevalent part of our lives
    - In Japan, it is a fad to have photovoltaics
      - they make fake PV panels for rooftops so it looks like you have solar power

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
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 $\approx 13,000 \times (D/f)^2$, 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 in one axis
- concentration reduced to
  - concentration $\approx 114 \times (D/f)$, where $D$ is the distance across the reflector and $f$ is the focal length

Power Towers

- 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-ft² reflectors, and generates 10 MW of electrical power
  - calculate an efficiency of 17%, though this assumes each panel is perpendicular to sun

Barstow Scheme

Who needs a parabola

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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
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 850 W/m² in direct Sun
  - using $\sigma T^4$, this equates to a temperature of 350 °K for a perfect absorber in radiative equilibrium (boiling is 373 °K).
- Trick is to minimize paths for thermal losses.

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.

iClicker Question

- Based upon the discussion of the glass in a flat-plate collector, how would you define the greenhouse gas effect?
  - A An effect caused by a gas that is transparent to visible light and opaque to infrared radiation.
  - B An effect caused by a gas that is transparent to infrared radiation and opaque to ultraviolet radiation.
  - C An effect caused by a gas that is transparent to ultraviolet radiation and opaque to infrared radiation.
  - D An effect caused by a gas that is transparent to infrared radiation and opaque to visible light.
  - E An effect caused by the sun emitting more infrared radiation than ultraviolet radiation.
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 (laundry) and storage inefficiencies:
  \[ 20 \times 4 \times 1.5 = 120 \text{ gallons} = 450 \text{ liters} \]
- To heat 450 l from 15 °C to 50 °C requires:
  \[ (4184 \text{ J/kg}^\circ\text{C})(450 \text{ kg})(35 \circ\text{C}) = 66 \text{ MJ of energy} \]
- 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 $6–8,000

Some Amusing 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 (40×40 footprint), with a 40×10 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