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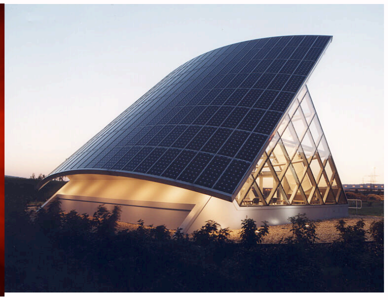

## Solar Energy

Introduction to renewable energy

Energy from the sun

Many slides courtesy of Prof. Tom Murphy

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## World Energy Budget (annual: 2001)

| Energy Source | QBtu/year | Percent of total |
|---|---|---|
| Petroleum | 150 | 40.0 |
| Coal | 87 | 23.2 |
| Natural Gas | 84 | 22.5 |
| Hydroelectric | 27 | 7.2 |
| Nuclear | 25 | 6.6 |
| Biomass (burning) | 1.5 | 0.4 |
| Geothermal | 0.5 | 0.13 |
| Wind | 0.12 | 0.03 |
| Solar Direct | 0.03 | 0.008 |
| Sun Abs. By Earth | 2,000,000 | Then radiated away |

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## Renewable Energy Consumption

| Energy Source | QBtu (1994) | Percent (1994) | QBtu (2003) | Percent (2003) |
|---|---|---|---|---|
| Hydroelectric | 3.037 | 3.43 | 2.779 | 2.83 |
| Geothermal | 0.357 | 0.40 | 0.314 | 0.32 |
| Biomass | 2.852 | 3.22 | 2.884 | 2.94 |
| Solar Energy | 0.069 | 0.077 | 0.063 | 0.06 |
| Wind | 0.036 | 0.040 | 0.108 | 0.11 |
| **Total** | **6.351** | **7.18** | **6.15** | **6.3** |

much room for improvement/growth, but **going backwards**!

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## The Solar Spectrum

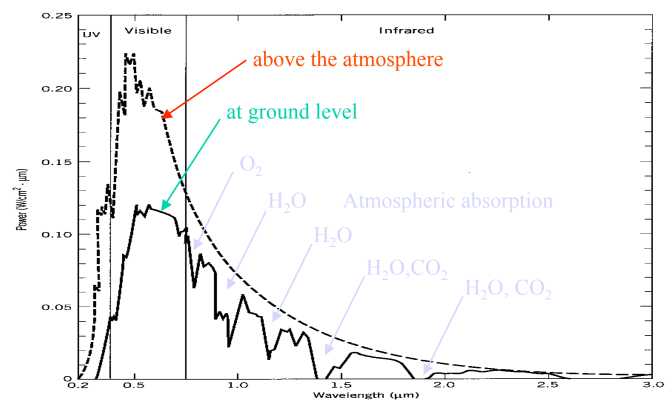


**Figure 4.1** The wavelength distribution of solar radiation above the atmosphere (dashed line) and at the earth's surface (solid line). The Solar Constant is given by the area under the dashed curve. The sharp dips in the solid line are due to absorption of certain wavelengths by various atmospheric gases, including water vapor and carbon dioxide. (Adapted from *On the Nature and Distribution of Solar Radiation*, Watt Engineering, Washington, D.C.: U.S. Government Printing Office, Department of Energy HCP/T2552-01, 1978).

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## How much energy is available?

- Above the atmosphere, we get 1368 W/m$^2$ 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)
  - Some books uses 2 calories per minute per cm$^2$ (weird units!!)
- At the ground, this number is smaller due to scattering and absorption in the atmosphere
  - about 63%, or ~850 W/m$^2$ with no clouds, perpendicular surface
  - probably higher in dry desert air
- Note: you should learn all material highlighted in RED

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## Input flux (average properties)

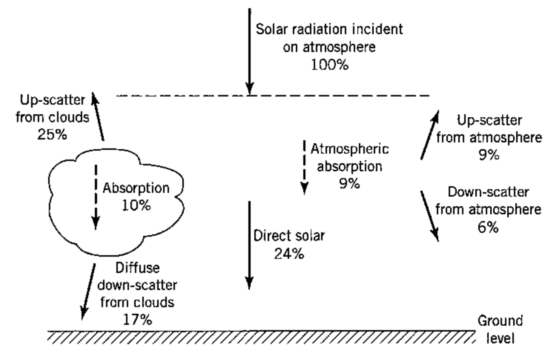


**Figure 4.2** Absorption and scattering of solar radiation in the atmosphere. The values shown are for average weather, and are averaged over all seasons and latitudes.

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## Making sense of the data

- We can infer a number of things from the previous figure:
  - 52% of the incoming light hits clouds, 48% does not
  - 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 above analysis is simplified: assumes atmospheric scattering/absorption is not relevant when cloudy

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## 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)

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## Average Insolation

- The amount of light received by a horizontal surface (in $W/m^2$) 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 it's actual area
    - half the sphere ($2\pi R^2$) projects into just $\pi R^2$ 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 $W/m^2$ on average
  - Can also be written 1300 Btu/(day $ft^2$) (less in winter of course)

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## Insolation variation

- While the average insolation is 171 W/m$^2$, 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/m$^2$ on average
  - Alaska, often covered in clouds and at high latitude may get only 75 W/m$^2$ on average
  - Is it any wonder that one is cold while one is hot?

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## Average daily radiation received

ranges in W/m$^2$:

- < 138
- 138–162
- 162–185
- 185–208
- 208–231
- > 231

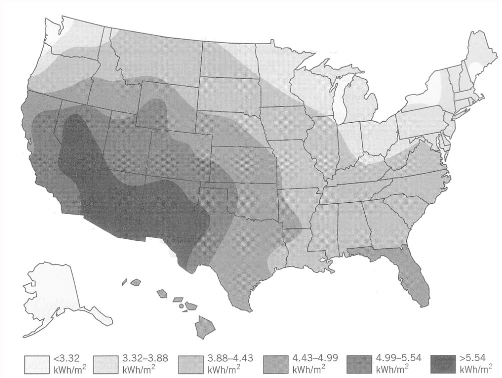


**Figure 4.3** The mean daily solar radiation received on a horizontal surface, averaged over the year, for the United States. This figure includes both the direct and diffuse components of the solar radiation. (*Source:* National Renewable Energy Laboratory.)

divide by 24 hr to get average kW/m$^2$

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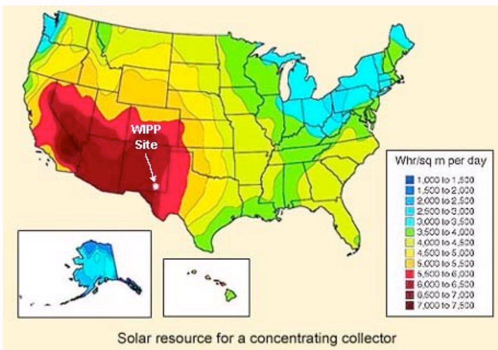
## Higher Resolution Insolation Map

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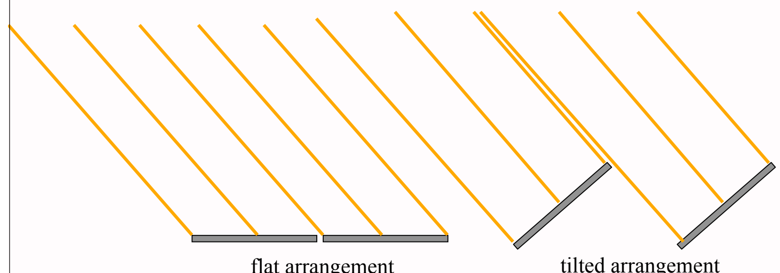
## Tilted Surfaces

- 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

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## Total available solar energy

- Looking at average insolation map (which includes day/night, weather, etc.), estimate average of 4.25 kWh/day/m$^2$ = 177 W/m$^2$
- The area of the U.S. is $3.615\times10^6$ square miles
  - this is $9.36\times10^{12}$ m$^2$
- Multiplying gives $1.66\times10^{15}$ Watts average available power
- Multiply by $3.1557\times10^7$ seconds/year gives $5.23\times10^{22}$ Joules every year
- This is $50\times10^{18}$ Btu, or 50,000 QBtu
- Compare to annual budget of about 100 QBtu
  - 500 times more sun than current energy budget

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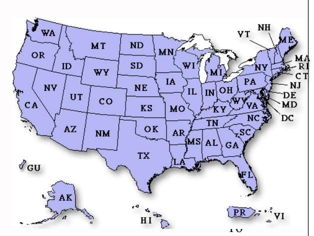
## So why don't we go solar?

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



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## Solar Land Area Requirements


6 Boxes at 3.3 TW Each

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## Making sense of these big numbers

- How much area is this per person?
  - U.S. is $9.36\times10^{12}$ $m^2$
  - 1/75th of this is $1.25\times10^{11}$ $m^2$
  - 300 million people in the U.S.
  - 416 $m^2$ 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 for total U.S energy

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## But how about for an individual's energy?

- Prof. Tom Murphy found his family used
  - 10.3 kWh/day average electricity
  - 26 kWh/day average nat gas for heating
  - 26 kWh/day gasoline for driving (think electric cars in future)
  - Total then is 62 kWh/day
- Say had 1000 square foot roof, all solar PV, 15% eff.
  - Using same average daily insolation of 4.25 kWh/day/$m^2$ and 1000 sq ft = 93 $m^2$, we find house could give total 60 kWh/day. (actually in San Diego, we get more like 5 kWh/day/$m^2$ => 70 kWh/day..
  - Compare to per capita energy use needing 4164 square feet
- So rooftop solar PV could easily supply individual electric energy, and even all energy including charging electric cars (but didn't consider cities or northern climates)

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## Problems with solar energy

- Only available during the day when Sun is shining
- No easy way to store it, or to store electricity made from it
- But, peak demand of electricity is during hot summer days when solar is at its best
- Estimates are that more than 20% solar might not work; at very least would require changes to grid management
- Possible solutions include ways of storing electricity: pumped water, batteries, hydrogen, etc. But these currently are not ready for prime time.

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Solar Technologies

Ways to extract useful energy from the sun

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## Question

- How was the midterm?

A. About right
B. Too hard
C. Too long
D. Too short or too easy
E. I won't know until I get my score!

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## Question

- Green houses get hotter than the outside air because

A. Glass is transparent to IR allowing the heat energy in

B. Glass is transparent to visible light but opaque to IR

C. The glass prevents wind from carrying away the heated air

D. Glass amplifies the solar energy

E. Both B. and C.

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## Question

- The energy from the Sun is 100% used in which of the following?

A. Silicon photovoltaic solar cells

B. Photosynthesis

C. Passive solar space heating

D. Flat plate solar thermal water heating

E. Non of the above

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## Question

- In planning a rooftop solar system, how many watts per square meter should you use?

A. About 1386 $W/m^2$

B. About 1/2 of 1386 $W/m^2$

C. About 500 $W/m^2$

D. About 171 $W/m^2$

E. None of the above

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## Question

- Does the Sun provide enough energy to meet all current human needs?

A. Yes

B. Eventually yes, but current technology is not available

C. Maybe yes, if humans can reduce their need for energy

D. No, current human use is more than the Sun provides

E. It is not clear at the present time

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## Four Basic Schemes

1. Passive solar heating
2. Flat-Plate direct heating
3. Thermal electric power generation
4. Photovoltaics (direct conversion to electricity)

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## 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

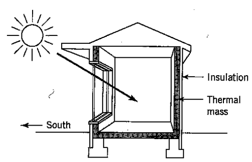


**Figure 4.8** A home heated by the direct gain passive solar method. South-facing windows act as solar collectors. Sunlight enters the living space, is converted to heat at absorbing surfaces, and the heat is dispersed throughout the space and to the various enclosing surfaces and room contents. The 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

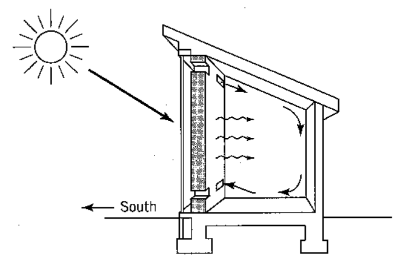


**Figure 4.7** A typical Trombe wall installation. The massive concrete wall inside a glass window acts both as a collector and a heat storage medium. The room air circulates by natural convection as shown. Heat is also radiated by the wall into the living space. (Adapted from: J. Douglas Balcomb, *Passive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





## 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/$m^2$ 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

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## Flat-Plate Collector

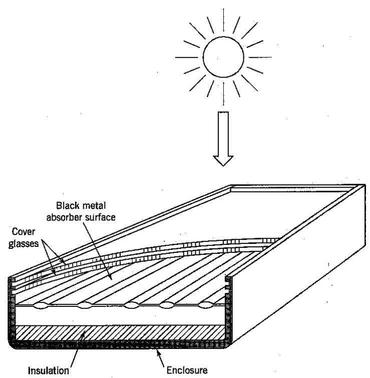


**Figure 4.5** A cutaway view of a flat-plate solar collector with two cover glasses. A heat-transfer fluid is circulated through the tubular passages integrally formed into the metal absorber surface. (Not drawn to scale.)

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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
  - This is also principle of $CO_2$ greenhouse effect (named after greenhouses!)

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## An example water-heater system

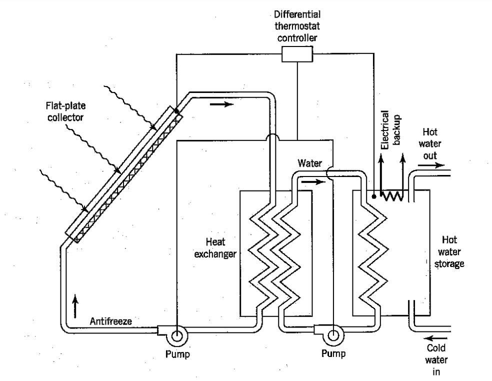


**Figure 4.6** A circulating-liquid solar collector system that provides hot water for space heating and domestic use. In a typical installation the collector will be on the roof of a building with the other components in an inside utility area.

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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
  - $0.85 \times 0.95 \times 0.67 \times 0.90 = 0.49$

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## What area solar thermal collector needed for a household?

- Want to find area (in square ft)
- Given: Solar insolation: 1000 Btu/(sqft day)
  - 4 showers a day plus 50% more for laundry, etc.
  - Heat water by 60 F
  - 40% efficiency
  - Water weighs 8lb/gal
  - Energy = cp m Delta T
  - Cp of water is 1 Btu/(lb F)
- Typical showers are about 10 minutes at 2 gallons per minute, or 20 gallons. Four showers, and increase by 50% for other uses (laundry) and storage inefficiencies:
  - $20 \times 4 \times 1.5 = 120$ gallons. So water weighs 120*8 = 960lb of water
- Formula gives energy needed = 1 Btu/(lb F) (960 lb) (60F) = 57600 Btu
- But efficiency is only 40% => must divide this number by .4 => 144,000Btu/day
- Area = Energy needed/(solar insolation) = (144000Btu/day)/(1000 Btu/sqft day) = 144 sqft or about 12 by 12 feet. (or 10ft by 14.4 ft)

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## 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)

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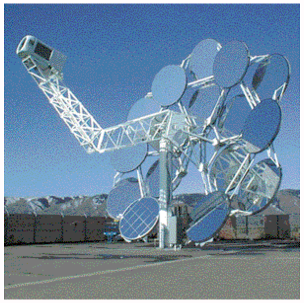
## Solar Thermal Generation

- 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



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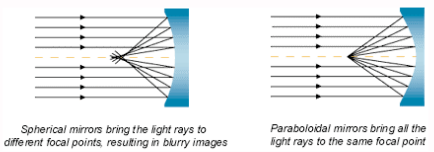
## Concentration Schemes

- 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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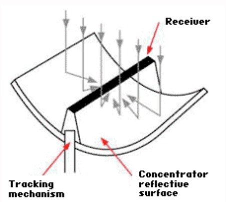
## The steering problem

- 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 $20 \times 20$-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

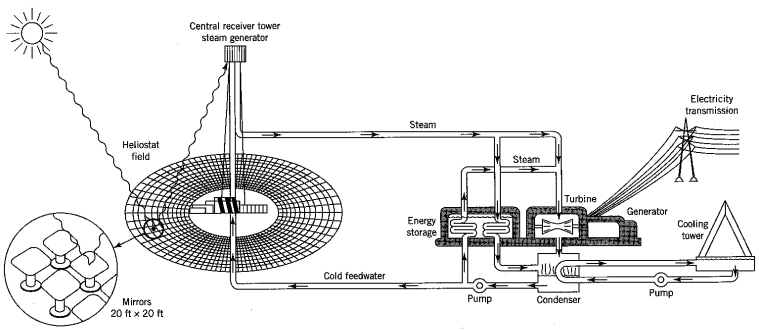


**Figure 4.11** A schematic view of a 10 $MW_e$ solar-thermal power plant near Barstow, California. The receiver and boiler that absorb the sunlight reflected from 1900 heliostats are at the top of a 90 meter tower. The heliostats are each steered by computer control to reflect the sunlight onto the 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

- Not cost-competitive at this time: 3–4 times as expensive as fossil fuel alternatives
- Example: Luz International's solar troughs
  - 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
  - total of 354 MW put on grid until bankruptcy hit

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## Photovoltaics: direct solar to electrical energy

- What could be better: eliminate the middle-man
- The process relies on properties of semiconductors (between metals and insulators) such as silicon
- Silicon is cheap and abundant
  - sand (and earth's crust in general) is full of it
  - until you want it in high-quality crystalline form…

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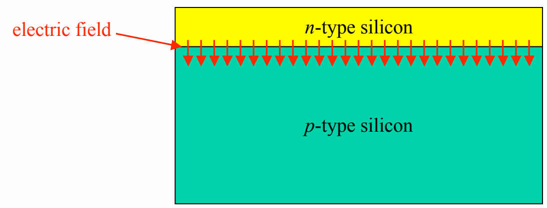
## The basic idea

- Create a *p-n* junction in silicon
  - called a diode, a central component of transistors
- Contact potential sets up an electric field
  - not too dissimilar to funny buzz you get when you put some kinds of metals in your mouth

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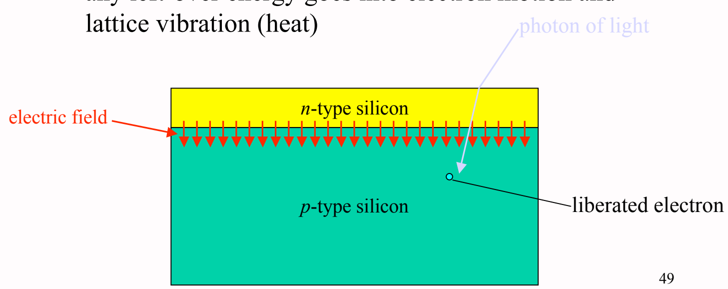
## Light energy liberates electrons

- A photon of light striking the silicon penetrates a little way, but eventually knocks an electron out of a silicon atom, ceasing to exist in the process
  - the energy in the photon pulls the electron out of its potential well (doing work to liberate the electron)
  - any left-over energy goes into electron motion and lattice vibration (heat)

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## Then what happens??

- The electron wanders aimlessly (like a drunkard), constantly changing directions
- If at some point the electron gets close to the junction (and electric field), it is swept rapidly to the other side
  - electrons feel a force opposite to the electric field direction
- This flow of an electron represents a *current*—a flow of charge
- Enough electrons doing this can constitute a macroscopic current flow (and can do external work)

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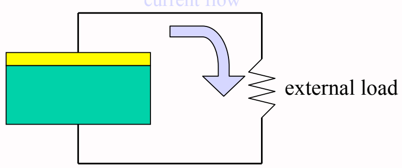
## Provide a circuit for the electron flow

- 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

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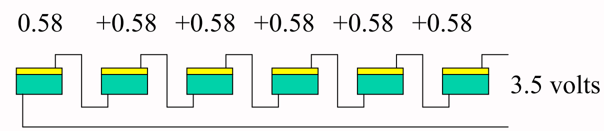
## Getting higher voltages

- If you want 120 V AC power, you need to start with something better than 0.58 volts
- Daisy-chain cells in series to stack up voltages

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## 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) only delivers 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 theoretical efficiency for a silicon PV in sunlight is about 23%

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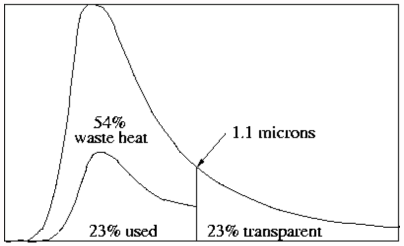
## Silicon Photovoltaic Budget




- Only 77% of solar spectrum is absorbed by silicon
- Of what remains, 30% is used as electrical energy
- Net effect is 23% maximum theoretical efficiency

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## PV Characteristics

- A photovoltaic cell in sunlight is like a battery
  - characteristic voltage for silicon is 0.58 volts *independent of area, thickness, etc.*
- Typical efficiencies are around 10–12%, though expensive space architectures achieve 20% or even up to 40% with more layers and elements
- Typical residential units cost about $6 per peak Watt ($25,000 for a 4kW system)

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## When will PV take over?

- Confusing numbers out there. Some say new coal fired plant produces wholesale electricity at $0.08 - $0.20/kWh; we pay about $0.10/kWh but that includes cheap hydro, nat gas and old power plants. Some says new PV is $0.5-$1.00/kWh => need PV to get 5 times cheaper to compete on purely economic grounds
- Currently there are numbers for PV of $4-$8/Peak Watt, => factor of 5 would be about $1/Peak Watt.
- Should include environmental effects, e.g. if there was a proper Carbon tax, then Coal would greatly increase in price making PV more attractive
- In any case, if PV comes down by a factor of 2 or 3 it should start taking over. Note PV has come down in price by that much in the past 15 years, and there are no reasons why price should not continue to drop as demand increases

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## Should I install PV on my roof?

- Suppose 1kW system, hooked to grid with net metering. When do I save money?
- Numbers:
  - Panels $5/W, plus inverters, meters, wires, etc. (say $8/W total)
  - Murphy says get on average 5kWh/day, or 1825kWh/year => save $220/year at $0.12/kWh
  - Panels would cost $5000, but get rebate of $2.5/W or $2500. If inverter costs $1/W add $1000, and $1500 for installation, wiring, grid connection for total of about $5000.
  - Then it would take $5000/$220/year = 23 years to pay off your investment. Since systems are suppose to last 20-30 years, it just breaks even.
  - But one should consider other things: could have invested money instead; price of energy will go up (If energy inflation rate is same as investment return, then calculation above is ok; if energy goes up more then payoff time is quicker than 23 years). What if move out after 5 years (lose money or does PV make house more valuable?).
  - Berkeley is allowing cost to go onto property taxes!
- Conclude: if price of PV drops by factor of 2-3, everyone will do it!

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## Example Solar Panel from Prof. Murphy

- Standard rating scheme applies to 1000 W/m$^2$ of incident light at 1.5 *airmasses*, and at 25ºC
  - a condition that never really happens
- Example cell rated at 30 W
  - open circuit voltage = 21 V (36 cells in series)
  - short-circuit current = 1.94 amps
  - max power $V$, $I$ = 16.8 V, 1.78 amps (power = $I \cdot V$)
- More realistic 800 W/m$^2$, 1.5 AM, 47 ºC:
  - power = 21.3 W, 14.7 V, 1.45 A
  - total area = 0.228 m$^2$ → 182 W incident
  - 21.3/182 = 11.7% efficient, as compared to 16% rating! (remind you of rated mpg in cars vs. what you actually get?)

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## 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

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## Orientation Comparison

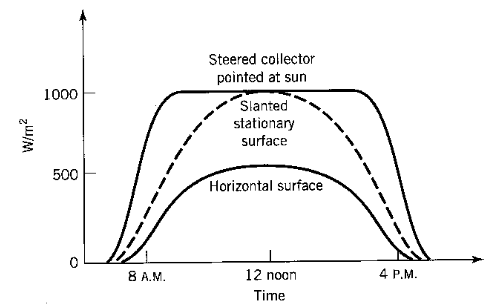


**Figure 4.4** Solar power incident on three types of collectors for a typical winter day at 40° N latitude. The *energy* collected each day is given by the area under each curve.

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## Numerical Comparison: winter at 40º latitude

based on clear, sunny days

| Date | Perpendicular (steered, W/m²) | Horizontal (W/m²) | Vertical S (W/m²) | 60º South (W/m²) |
|---|---|---|---|---|
| Oct 21 | 322 | 177 | 217 | 272 |
| Nov 21 | 280 | 124 | 222 | 251 |
| Dec 21 | 260 | 103 | 216 | 236 |
| Jan 21 | 287 | 125 | 227 | 256 |
| Feb 21 | 347 | 186 | 227 | 286 |
| Mar 21 | 383 | 243 | 195 | 286 |
| | overall winner | better in summer | good in winter | 2nd place |

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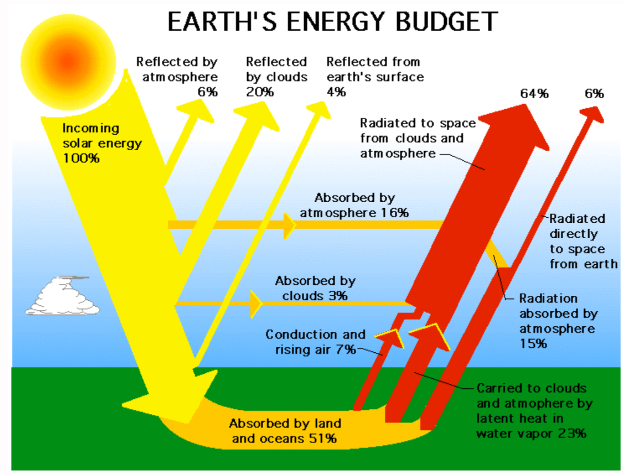
## A naturally balanced budget

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## 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%

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