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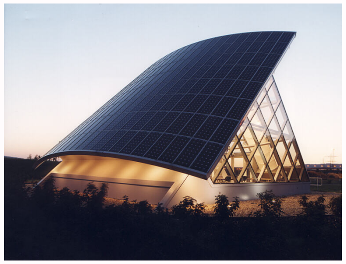

Solar Energy

Introduction to renewable energy

Energy from the sun

2×Q

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Renewable Energy Consumption

Energy Source	**QBtu / % (1994)**	**QBtu / % (2003)**	**QBtu / % (2011)**
Hydroelectric	3.037 / 3.43	2.779 / 2.83	3.171 / 3.26
Geothermal	0.357 / 0.40	0.314 / 0.32	0.226 / 0.23
Biomass	2.852 / 3.22	2.884 / 2.94	4.511 / 4.64
Solar Energy	0.069 / 0.077	0.063 / 0.06	0.158 / 0.16
Wind	0.036 / 0.040	0.108 / 0.11	1.168 / 1.20
Total	**6.351 /7.18**	**6.15 / 6.3**	**9.135 / 9.39**

much room for improvement/growth, but **went backwards** from 1994 to 2003!

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The Solar Spectrum

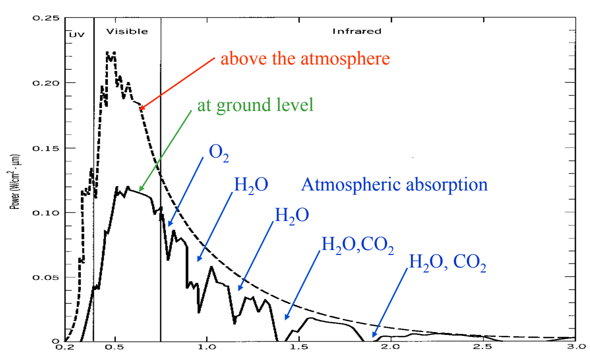

Figure 4.1 The wavelength distribution of solar radiation above the atmosphere (dashed line) and at the earth's surface (solid line). The Solar Constant is given by the area under the dashed curve. The sharp dips in the solid line are due to absorption of certain wavelengths by various atmospheric gases, 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)
  - The book 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

Input flux (average properties)

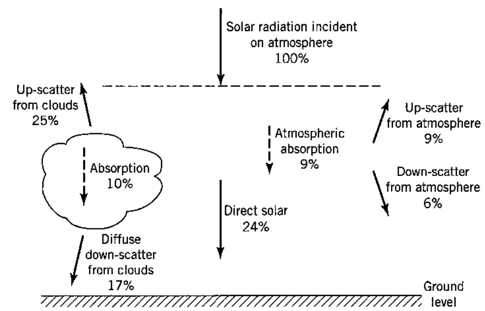
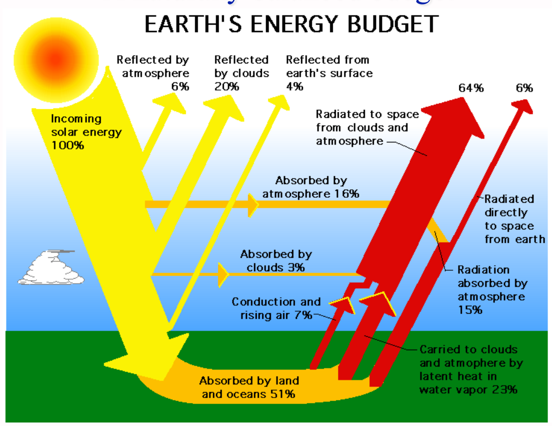


Figure 4.2 Absorption and scattering of solar radiation in the atmosphere. The values shown are for average weather, and are averaged over all seasons and latitudes.

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
    - 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 above analysis is simplified: assumes atmospheric scattering/absorption is not relevant when cloudy

A naturally balanced 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%

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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 πR^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

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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

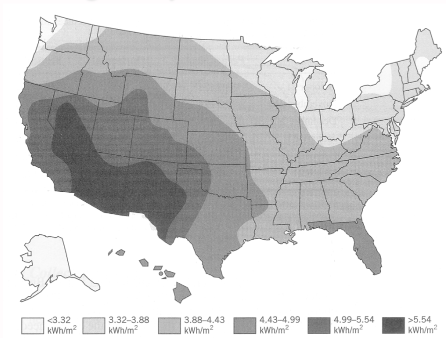

Figure 4.3 The mean daily solar radiation received on a horizontal surface, averaged over the year, for the United States. This figure includes both the direct and diffuse components of the solar radiation. (*Source:* National Renewable Energy Laboratory.)

ranges in W/m^2:
- < 138
- 138–162
- 162–185
- 185–208
- 208–231
- > 231

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

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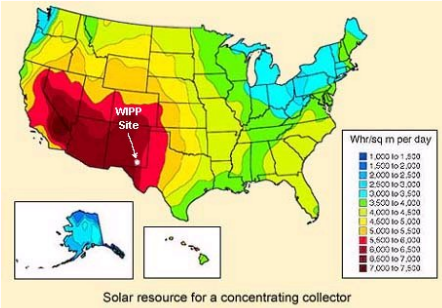
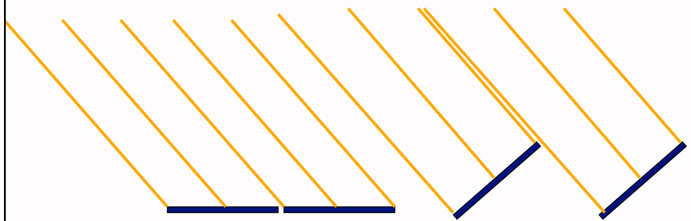
Map for Concentrating Solar Potential



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



flat arrangement tilted arrangement

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

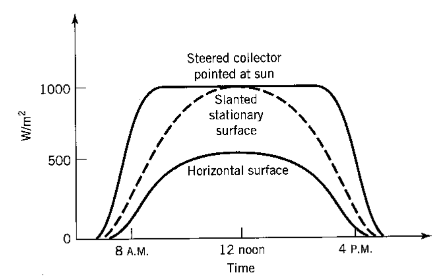


Figure 4.4 Solar power incident on three types of collectors for a typical winter day at 40° N latitude. The *energy* collected each day is given by the area under each curve.

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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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Total available solar energy

- Looking at average insolation map (which includes day/night, weather, etc.), I estimate average of 4.25 kWh/day/m^2 = 177 W/m^2
- The area of the U.S. is 3.615×10^6 square miles
  - this is 9.36×10^{12} m^2
- Multiplying gives 1.66×10^{15} Watts average available power
- Multiply by 3.1557×10^7 seconds/year gives 5.23×10^{22} Joules every year
- This is 50×10^{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 1/500th 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.

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Making sense of these big numbers

- How much area is this per person?
  - U.S. is 9.36×10^{12} m^2
  - 1/75th of this is 1.25×10^{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, especially in cities

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Ways of using solar energy

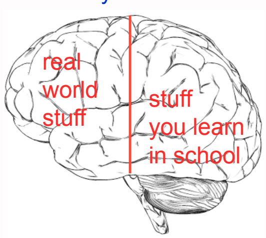
- Direct heating of flat panel (fluids, space heating)
- Passive heating of well-designed buildings
- Thermal power generation (heat engine) via concentration of sunlight
- Direct conversion to electrical energy

Assignments / Announcements19

- Read Chapter 4 if you haven't already
- Optional Reading from DtM:
  - http://physics.ucsd.edu/do-the-math/2012/08/solar-data-treasure-trove/
- HW4 available on web
- Midterm will be Monday, May 6, York 2622
  - will need red half-sheet scan-tron with place for Student ID (Form No. X-101864-PAR-L)
  - study guide posted on web site
    - problems com *from this study guide*!
  - will plan review session, at a time TBD

My Plans for Your Brain

this is your brain…



…this is your brain after physics 12