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

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 units!)
- 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

### Renewable Energy Consumption

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydroelectric</td>
<td>3.037 / 3.43</td>
<td>2.779 / 2.83</td>
<td>3.171 / 3.26</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0.357 / 0.40</td>
<td>0.314 / 0.32</td>
<td>0.226 / 0.23</td>
</tr>
<tr>
<td>Biomass</td>
<td>2.852 / 3.22</td>
<td>2.884 / 2.94</td>
<td>4.511 / 4.64</td>
</tr>
<tr>
<td>Solar Energy</td>
<td>0.069 / 0.077</td>
<td>0.063 / 0.06</td>
<td>0.158 / 0.16</td>
</tr>
<tr>
<td>Wind</td>
<td>0.036 / 0.040</td>
<td>0.108 / 0.11</td>
<td>1.168 / 1.20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6.351 / 7.18</strong></td>
<td><strong>6.15 / 6.3</strong></td>
<td><strong>9.135 / 9.39</strong></td>
</tr>
</tbody>
</table>
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

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%
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/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 (2πr^2) projects onto 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

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?

Average daily radiation received

- Divide by 24 hr to get average kW/m^2

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

Figure 6.3: The annual 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.)
Map for Concentrating Solar Potential

Solar resource for a concentrating collector

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 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.
Numerical Comparison: winter at 40° latitude
based on clear, sunny days

<table>
<thead>
<tr>
<th>Date</th>
<th>Perpendicular (steered, W/m²)</th>
<th>Horizontal (W/m²)</th>
<th>Vertical S (W/m²)</th>
<th>60° South (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 21</td>
<td>322</td>
<td>177</td>
<td>217</td>
<td>272</td>
</tr>
<tr>
<td>Nov 21</td>
<td>280</td>
<td>124</td>
<td>222</td>
<td>251</td>
</tr>
<tr>
<td>Dec 21</td>
<td>260</td>
<td>103</td>
<td>216</td>
<td>236</td>
</tr>
<tr>
<td>Jan 21</td>
<td>287</td>
<td>125</td>
<td>227</td>
<td>256</td>
</tr>
<tr>
<td>Feb 21</td>
<td>347</td>
<td>186</td>
<td>227</td>
<td>286</td>
</tr>
<tr>
<td>Mar 21</td>
<td>383</td>
<td>243</td>
<td>195</td>
<td>286</td>
</tr>
</tbody>
</table>

overall winner: better in summer, good in winter, 2nd place

Total available solar energy

- Looking at average insolation map (which includes day/night, weather, etc.), I estimate average of 4.25 kWh/day/m² = 177 W/m²
- The area of the U.S. is \(3.615 \times 10^6\) square miles
  - this is \(9.36 \times 10^{12}\) m²
- Multiplying gives \(1.66 \times 10^{13}\) Watts average available power
- Multiply by \(3.1557 \times 10^7\) seconds/year gives \(5.23 \times 10^{22}\) Joules every year
- This is \(50 \times 10^{13}\) Btu, or \(50,000\) QBtu
- Compare to annual budget of about 100 QBtu
  - 500 times more sun than current energy budget

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 these big numbers

- How much area is this per person?
  - U.S. is \(9.36 \times 10^{12}\) m²
  - 1/75th of this is \(1.25 \times 10^{11}\) m²
  - 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
**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

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**Assignments / Announcements**

- Read Chapter 4 if you haven’t already
- Optional Reading from DtM:
- 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

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**My Plans for Your Brain**

- this is your brain…
- …this is your brain after physics 12