Renewable Energy I

Hydroelectricity
Wind Energy

Renewable Energy Consumption

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Q\text{Btu} / % (1994)</th>
<th>Q\text{Btu} / % (2003)</th>
<th>Q\text{Btu} / % (2011)</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>Total</td>
<td>6.351 / 7.18</td>
<td>6.15 / 6.3</td>
<td>9.135 / 9.39</td>
</tr>
</tbody>
</table>

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

Renewable Resources

- Renewable means anything that won’t be depleted by using it
  - sunlight (the sun will rise again tomorrow)
  - biomass (grows again)
  - hydrological cycle (will rain again)
  - wind (sunlight on earth makes more)
  - ocean currents (driven by sun)
  - tidal motion (moon keeps on producing it)
  - geothermal (heat sources inside earth not used up fast)

Another look at available energy flow

- The flow of radiation (solar and thermal) was covered in Lecture 11
  - earth is in an energy balance: energy in = energy out
  - 30% reflected, 70% thermally re-radiated
- Some of the incident energy is absorbed, but what exactly does this do?
  - much goes into heating the air/land
  - much goes into driving weather (rain, wind)
  - some goes into ocean currents
  - some goes into photosynthesis
Lots of energy associated with evaporation:
both $mgh$ (4% for 10 km lift) and latent heat (96%) of water
Energetics of the hydrologic cycle

- It takes energy to evaporate water: 2,250 J per gram
  - this is why “swamp coolers” work: evaporation pulls heat out of environment, making it feel cooler
  - 23% of sun’s incident energy goes into evaporation
- By contrast, raising one gram of water to the top of the troposphere (10,000 m, or 33,000 ft) takes
  \[ mgh = (0.001 \text{ kg}) \times (10 \text{ m/s}^2) \times (10,000 \text{ m}) = 100 \text{ J} \]
- So > 96% of the energy associated with forming clouds is the evaporation; < 4% in lifting against gravity

Let it Rain

- When water condenses in clouds, it re-releases this “latent heat”
  - but this is re-radiated and is of no consequence to hydro-power
- When it rains, the gravitational potential energy is released, mostly as kinetic energy and ultimately heat
- Some tiny bit of gravitational potential energy remains, IF the rain falls on terrain (e.g., higher than sea level where it originated)
  - hydroelectric plants use this tiny left over energy: it’s the energy that drives the flow of streams and rivers
  - damming up a river concentrates the potential energy in one location for easy exploitation

How much of the process do we get to keep?

- According to Figure 5.1, 40×10^{15} W of solar power goes into evaporation
  - this corresponds to 1.6×10^{15} kg per second of evaporated water!
  - this is 3.5 mm per day off the ocean surface (replenished by rain)
- The gravitational potential energy given to water vapor (mostly in clouds) in the atmosphere (per second) is then:
  \[ mgh = (1.6 \times 10^{15} \text{ kg}) \times (10 \text{ m/s}^2) \times (2000 \text{ m}) = 3.2 \times 10^{24} \text{ J} \]
- One can calculate that we gain access to only 2.5% of the total amount (and use only 1.25%)
  - based on the 1.8% land area of the U.S. and the maximum potential of 147.7 GW as presented in Table 5.2

Power of a hydroelectric dam

- Most impressive is Grand Coulee, in Washington, on Columbia River
  - 350 feet = 107 m of “head”
  - > 6,000 m³/s flow rate! (Pacific Northwest gets rain!)
  - each cubic meter of water (1000 kg) has potential energy: \[ mgh = (1000 \text{ kg}) \times (10 \text{ m/s}^2) \times (110 \text{ m}) = 1.1 \text{ MJ} \]
  - At 6,000 m³/s, get over 6 GW of power
- Large nuclear plants are usually 1–2 GW
- 11 other dams in U.S. in 1–2 GW range
- 74 GW total hydroelectric capacity, presently
Hydro and Wind

Importance of Hydroelectricity

Hydroelectric potential by region, in GW

<table>
<thead>
<tr>
<th>Region</th>
<th>Potential</th>
<th>Developed</th>
<th>Undeveloped</th>
<th>% Developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>New England</td>
<td>6.3</td>
<td>1.9</td>
<td>4.4</td>
<td>30.1</td>
</tr>
<tr>
<td>Middle Atlantic</td>
<td>9.8</td>
<td>4.9</td>
<td>4.9</td>
<td>50.0</td>
</tr>
<tr>
<td>East North Central</td>
<td>2.9</td>
<td>1.2</td>
<td>1.7</td>
<td>41.3</td>
</tr>
<tr>
<td>West North Central</td>
<td>6.2</td>
<td>3.1</td>
<td>3.1</td>
<td>50.0</td>
</tr>
<tr>
<td>South Atlantic</td>
<td>13.9</td>
<td>6.7</td>
<td>7.2</td>
<td>48.2</td>
</tr>
<tr>
<td>East South Central</td>
<td>8.3</td>
<td>5.9</td>
<td>2.4</td>
<td>71.1</td>
</tr>
<tr>
<td>West South Central</td>
<td>7.3</td>
<td>2.7</td>
<td>4.6</td>
<td>36.9</td>
</tr>
<tr>
<td>Mountain</td>
<td>28.6</td>
<td>9.5</td>
<td>19.1</td>
<td>33.2</td>
</tr>
<tr>
<td>Pacific</td>
<td>64.4</td>
<td>38.2</td>
<td>26.2</td>
<td>59.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>147.7</strong></td>
<td><strong>74.1</strong></td>
<td><strong>73.6</strong></td>
<td><strong>58.2</strong></td>
</tr>
</tbody>
</table>

Hydroelectricity in the future?

- We’re almost tapped-out:
  - 50% of potential is developed
  - remaining potential in large number of small-scale units
- Problems with dams:
  - silt limits lifetime to 50–200 years, after which dam is useless and in fact a potential disaster and nagging maintenance site
  - habitat loss for fish (salmon!), etc.; wrecks otherwise stunning landscapes (Glenn Canyon in UT)
  - Disasters waiting to happen: 1680 deaths in U.S. alone from 1918–1958; often upstream from major population centers

Sorry: try again…

- So hydroelectricity is a nice “freebee” handed to us by nature, but it’s not enough to cover our appetite for energy
- Though very efficient and seemingly environmentally friendly, dams do have their problems
- This isn’t the answer to all our energy problems, though it is likely to maintain a role well into our future
Wind Energy

- We’ve talked about the kinetic energy in wind before:
  - a wind traveling at speed \( v \) covers \( v \) meters every second (if \( v \) is expressed in m/s)
  - the kinetic energy hitting a square meter is then the kinetic energy the mass of air defined by a rectangular tube
  - tube is one square meter by \( v \) meters, or \( v \) m\(^3\)
  - density of air is \( \rho = 1.3 \text{ kg/m}^3 \) at sea level (and 0°C)
  - mass is \( \rho v \) kg
  - K.E. = \( \frac{1}{2} \rho v^2 \) = \( \frac{1}{2} \rho v^3 \) (per square meter)
    - \( 0.65v^3 \) at sea level

Wind Energy proportional to cube of velocity

- The book (p. 134) says power per square meter is 0.61\( v^3 \), which is a more-or-less identical result
  - accounts for above sea level and more typical temps.
- If the wind speed doubles, the power available in the wind increases by \( 2^3 = 2 \times 2 \times 2 = 8 \) times
- A wind of 10 m/s (22 mph) has a power density of 610 W/m\(^2\)
- A wind of 20 m/s (44 mph) has a power density of 4,880 W/m\(^2\)

Can’t get it all

- A windmill can’t extract all of the kinetic energy available in the wind, because this would mean stopping the wind entirely
- Stopped wind would divert oncoming wind around it, and the windmill would stop spinning
- On the other hand, if you don’t slow the wind down much at all, you won’t get much energy
- Theoretical maximum performance is 59% of energy extracted
  - corresponds to reducing velocity by 36%
Practical Efficiencies

- Modern windmills attain maybe 50–70% of the theoretical maximum
  - 0.5–0.7 times 0.59 is 0.30–0.41, or about 30–40%
  - this figure is the mechanical energy extracted from the wind
- Conversion from mechanical to electrical is 90% efficient
  - 0.9 times 0.30–0.41 is 27–37%

Typical Windmills

- A typical windmill might be 15 m in diameter
  - 176 m²
- At 10 m/s wind, 40% efficiency, this delivers about 40 kW of power
  - this would be 320 kW at 20 m/s
  - typical windmills are rated at 50 to 600 kW
- How much energy per year?
  - 10 m/s → 610 W/m² × 40% → 240 W/m² × 8760 hours per year → 2,000 kWh per year per square meter
  - but wind is intermittent: real range from 100–500 kWh/m²
  - corresponds to 11–37 W/m² average available power density
- Note the really high tip speeds: bird killers
  - but nowhere near as threatening as cars and domestic cats!

Average available wind power

recall that average solar insolation is about 150–250 W/m²
Comparable to solar?

- These numbers are similar to solar, if not a little bigger!
  - Let’s go to wind!
- **BUT**: the "per square meter" is not land area—it’s rotor area.
- Doesn’t pay to space windmills too closely—one robs the other.
- Typical arrangements have rotors 10 diameters apart in direction of prevailing wind, 5 diameters apart in the cross-wind direction.
  - Works out to 1.6% "fill factor"

Current implementations

- Rapidly developing resource
  - 1.4 GW in 1989; 6.4 GW in 2003; 60 GW by end of 2012
  - Fast-growing (about 25% per year)
  - Cost (at 5–7¢ per kWh) is competitive
  - Expect to triple over next ten years
- Current capacity: ~60 GW
  - But should only count as 15 GW of continuous

Flies in the Ointment

- Find that only 25% of rated capacity is achieved
  - Design for high wind, but seldom get it
- 3% of electrical supply in U.S. is now wind
  - Total electrical capacity in U.S. is 1051 GW; average supply 451 GW
  - Limited tolerance on grid for intermittent sources
    - Nora says 20%, but could be substantially higher in nationwide grid
- If fully developed, *we could* generate an average power almost equal to our current electrical capacity (764 GW)
  - But estimates vary widely
  - Some compute < 2000 GW practically available worldwide
  - And struggle to deal with intermittency hits at some point

Texas overtook California in 2007; Iowa coming up fast

http://www.windpoweringamerica.gov/wind_installed_capacity.asp
### An Aside: Capacity vs. Delivered (2011)

<table>
<thead>
<tr>
<th>Electricity Source</th>
<th>Capacity (GW)</th>
<th>Delivered (TWh)</th>
<th>Capacity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>415</td>
<td>1016.6</td>
<td>28%</td>
</tr>
<tr>
<td>Coal</td>
<td>318</td>
<td>1734</td>
<td>62%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>101</td>
<td>790.2</td>
<td>89%</td>
</tr>
<tr>
<td>Hydro</td>
<td>79</td>
<td>325.1</td>
<td>47%</td>
</tr>
<tr>
<td>Wind + Solar</td>
<td>62</td>
<td>121.5</td>
<td>22%</td>
</tr>
<tr>
<td>Petroleum</td>
<td>51</td>
<td>28.2</td>
<td>6%</td>
</tr>
<tr>
<td>Other (biomas, geo)</td>
<td>25</td>
<td>73.4</td>
<td>38%</td>
</tr>
</tbody>
</table>

- N.G. plants often used as “peaker” plants when demand is high
- Nuclear plants basically just ON
- Use oil for electricity only when necessary
- Wind and solar effectively 5 hours/day

---

### Announcements/Assignments

- Read Chapter 5, sections 1, 2, 3, 5, 7
- Optional reading at Do the Math:
  - 27. [How Much Dam Energy Can We Get?](#)
  - 25. [Wind Fights Solar; Triangle Win](#)
- HW 5 & Quiz due Friday