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Renewable Energy I

Hydroelectricity

Wind Energy

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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)

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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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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

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The Renewable Budget

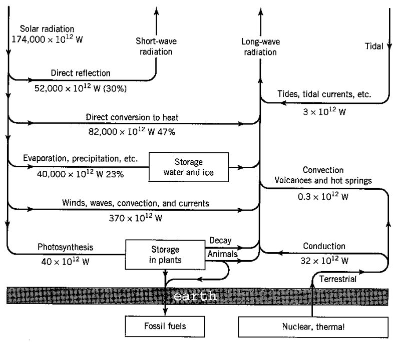

Figure 5.1 Natural energy flow (in units of power) to and from the earth. (*Source:* M. K. Hubbert, "Man's Conquest of Energy: Its Ecological and Human Consequences," in The Environmental and Ecological Forum 1971–1972. Washington D.C.: U.S. Atomic Energy Commission Publication TID—25857, 1972.)

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Outstanding Points from Fig. 5.1

- Incident radiation is 174×10^{15} W
  - this is 1370 W/m^2 times area facing sun (πR^2)
- 30% directly reflected back to space
  - off clouds, air, land
- 47% goes into heating air, land, water
- 23% goes into evaporating water, precipitation, etc. (part of weather)
- Adds to 100%, so we're done
  - but wait! there's more…

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Energy Flow, continued

- 0.21% goes into wind, waves, convection, currents
  - note this is 100 times less than driving the water cycle
  - but this is the "other" aspect of weather
- 0.023% is stored as chemical energy in plants via photosynthesis
  - total is 40×10^{12} W; half in ocean (plankton)
  - humans are 7 billion times 100 W = 0.7×10^{12} W
  - this is 1.7% of bio-energy; 0.0004% of incident power
- **All of this** (bio-activity, wind, weather, etc.) ends up creating heat and re-radiating to space
  - except some small amount of storage in fossil fuels

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The Hydrologic Cycle

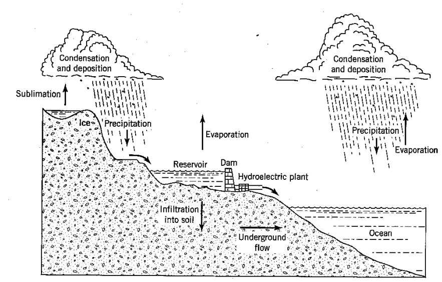

Figure 5.2 The hydrologic cycle. Electricity is produced in the hydroelectric plant by the action of water against a turbine connected to a generator. In this way the stored potential energy of the water in the reservoir becomes electrical energy.

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^{10} 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:

  $mgh = (1.6\times10^{10} \text{ kg})\times(10 \text{ m/s}^2)\times(2000 \text{ m}) = 3.2\times10^{14} \text{ J}$
- 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 m^3/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 m^3/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

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Importance of Hydroelectricity

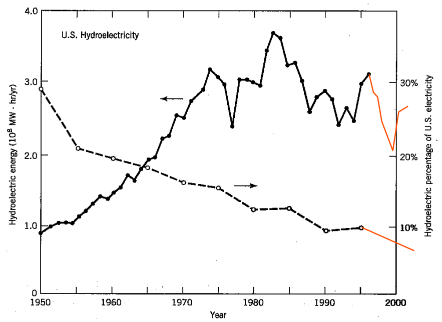

Figure 5.4 Electric energy from hydroelectric installations in the United States (solid line). The percentage of the United States electricity is shown as the dashed line. (*Source:* Data from *Annual Energy Review 1990* for 1950 to 1990; 1991 to 1996 from U. S. Energy Information Administration.

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Hydroelectric potential by region, in GW

Region	Potential	Developed	Undeveloped	% Developed
New England	6.3	1.9	4.4	30.1
Middle Atlantic	9.8	4.9	4.9	50.0
East North Central	2.9	1.2	1.7	41.3
West North Central	6.2	3.1	3.1	50.0
South Atlantic	13.9	6.7	7.2	48.2
East South Central	8.3	5.9	2.4	71.1
West South Central	7.3	2.7	4.6	36.9
Mountain	28.6	9.5	19.1	33.2
Pacific	64.4	38.2	26.2	59.3
Total	**147.7**	**74.1**	**73.6**	**50.2**

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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

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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

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Wind Energy

The Power of Wind

- 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 $\rho = 1.3$ kg/m^3 at sea level (and 0°C)
  - mass is ρv kg
  - K.E. = $\frac{1}{2}(\rho v)\cdot v^2 = \frac{1}{2}\rho v^3$ (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 $0.61v^3$, 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 $2^3 = 2\times2\times2 = 8$ 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%

Achievable efficiencies

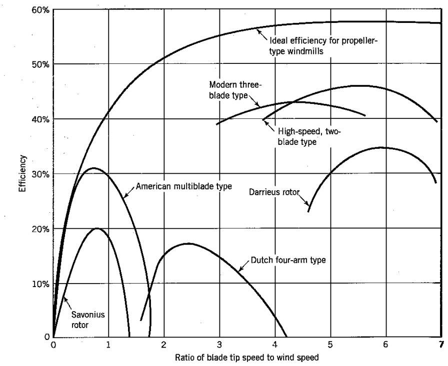

Figure 5.6 Typical efficiencies of several types of windmills plotted against their tip-speed ratio. The maximum efficiencies are seen to vary from about 16 to 46%. The ideal efficiency shown is a mathematical ideal, never to be achieved in practice. (Basic data from R. Wilson and P. Lissaman, *Applied Aerodynamics of Wind Power Machines*, Oregon State University.)

Typical Windmills

- A typical windmill might be 15 m in diameter
  - 176 m^2
- 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/m^2 × 40% → 240 W/m^2 × 8760 hours per year → 2,000 kWh per year per square meter
  - but wind is intermittent: real range from 100–500 kWh/m^2
  - corresponds to 11–57 W/m^2 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/m^2

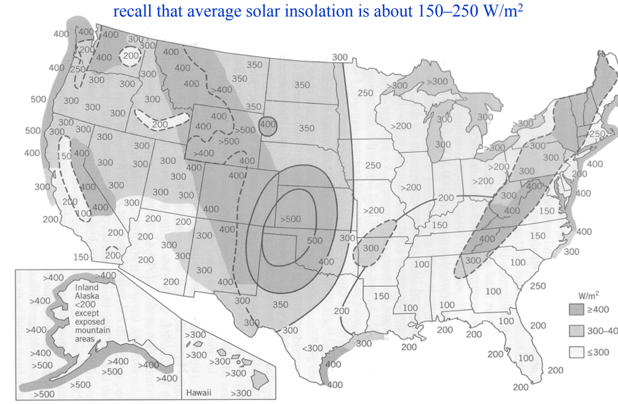

Figure 5.7 Annual average wind power density (watts per square meter) at 50 meters altitude. (Figure supplied by the National Renewable Energy Laboratory.)

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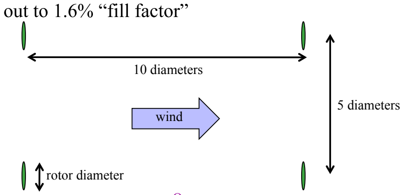
Comparable to solar?

- 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"



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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

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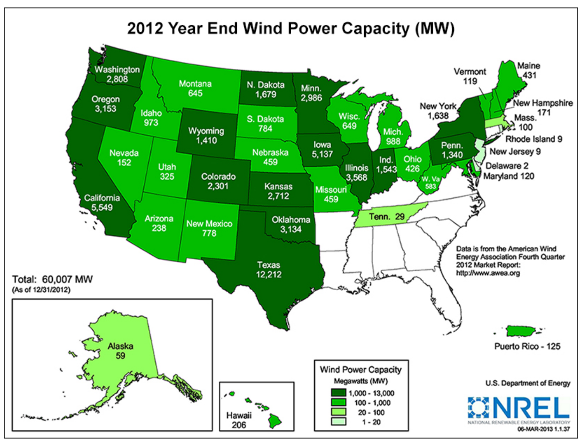
http://www.windpoweringamerica.gov/wind_installed_capacity.asp



Texas overtook California in 2007; Iowa coming up fast

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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
    - lore 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

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An Aside: Capacity vs. Delivered (2011)

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

- 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 Wins
- HW 5 & Quiz due Friday