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Hydroelectricity

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The Renewable Budget

NOTE:
100 Qbtu/year
= 3.35 TW

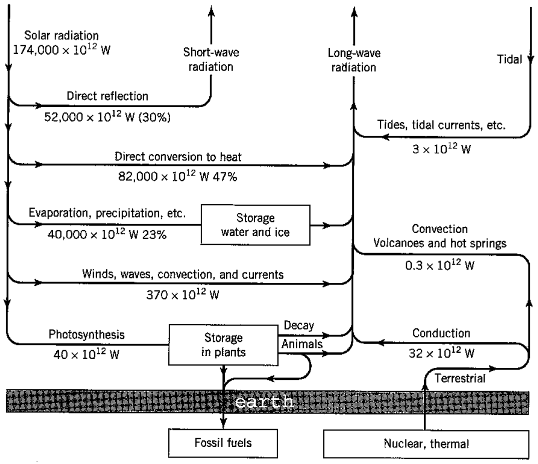

Figure 5.1 Natural energy flow (in units of power) to and from the earth. (*Source:* M. K. Hubbert, "Man's Conquest of Energy: Its Ecological and Human Consequences," in The Environmental and Ecological Forum 1971–1972. Washington D.C.: U.S. Atomic Energy Commission Publication TID—25857, 1972.)

The Hydrologic Cycle

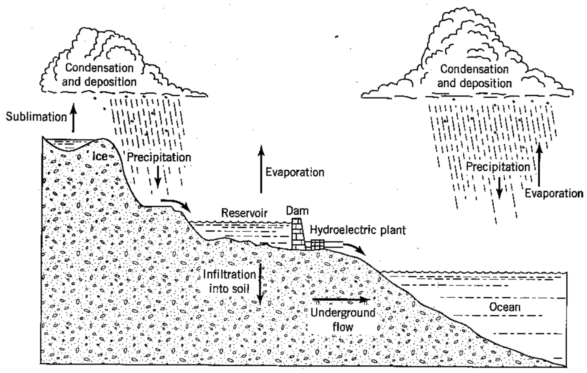

Figure 5.2 The hydrologic cycle. Electricity is produced in the hydroelectric plant by the action of water against a turbine connected to a generator. In this way the stored potential energy of the water in the reservoir becomes electrical energy.

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: 2,444 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: $mgh = (1000\ kg)\times(10\ m/s^2)\times(110\ m) = 1.1\ MJ$
  - 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

Importance of Hydroelectricity

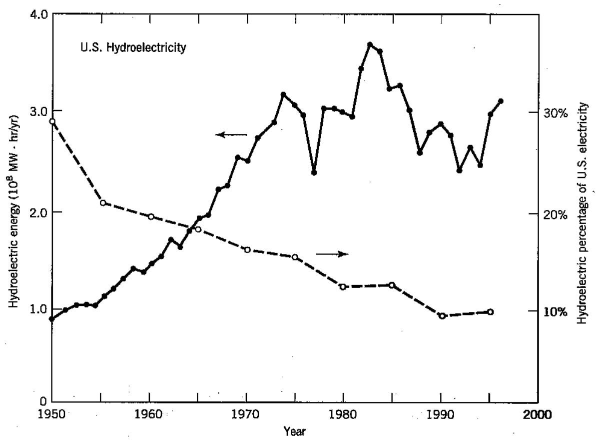

Figure 5.4 Electric energy from hydroelectric installations in the United States (solid line). The percentage of the United States electricity is shown as the dashed line. (*Source:* Data from *Annual Energy Review 1990* for 1950 to 1990; 1991 to 1996 from U. S. Energy Information Administration.

Pros and cons of hydroelectric

- Pros
  - No CO_2 (great for climate change)
  - Renewable
  - Cheapest electricity on the market
  - Reservoir water is used for many purposes (recreation/irrigation/etc)
- Cons
  - Don't last forever; slit up in 50-150 years, no more electricity, but Dam has to be maintained anyway
  - Loss of river and land; salmon die, eco-systems destroyed
  - Dam bursts happen and kill thousands down stream
    - 1918-1958 33 major dam failures in U.S. killed 1680
    - 1959-1965 nine large dam failures
    - Hundreds of thousands live downstream from current dams
  - Not many more can be built in industrialized countries, so can't be big part of solution for future energy demands

Question

◆ A PV cell is:

🟪 A. Like a battery that is charged by the Sun

🟩 B. Uses silicon, one of the most common elements on Earth

🟨 C. Typically converts up to around 15% of the Sun's energy into electricity

🟦 D. Takes more energy to make that it can produce over its lifetime

⬜ E. All of the above except D

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Question

- Hydroelectricity is:

🟥 A. A renewable energy source with few drawbacks except that there is not enough of it
🟩 B. Has great potential to fill much of future U.S. energy needs
🟨 C. Typically converts up to around 15% of the potential energy into electricity
🟦 D. Is currently the cheapest source of electricity for California
⬜ E. Both A and C

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Participation Question (Write on paper and turn in, for class participation credit)

1. Name the one or two most interesting things you've learned in the class so far.

2. Name the least interesting topic we've covered (if you can remember it!)

Other Renewable Energy Sources

Wind Power
Biomass
OTEC, Tides,

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 meters cubed
  - density of air is $\rho = 1.3$ kg/m^3
  - mass is ρv kg
  - K.E. = $\frac{1}{2}(\rho v)\cdot v^2 = \frac{1}{2}\rho v^3$ (per square meter)

Coast Guard Eagle

Several Megawatt wind power machine

Wind Energy proportional to *cube* of velocity

- Formulas in texts say power per square meter is $0.61v^3$, which is a more-or-less identical result
- So 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

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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%

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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

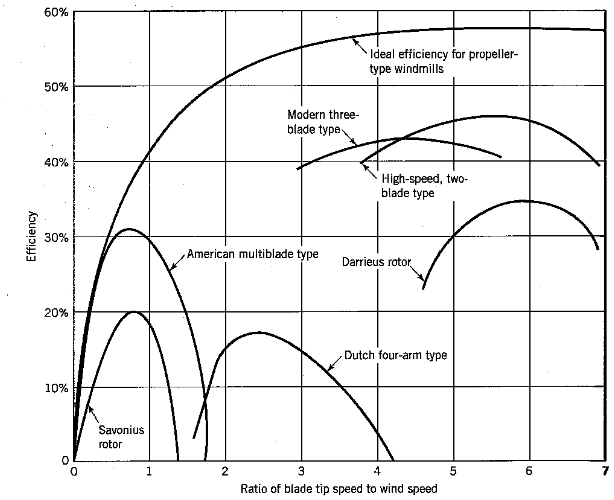


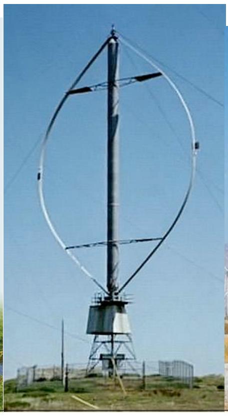
Figure 5.6 Typical efficiencies of several types of windmills plotted against their tip-speed ratio. The maximum efficiencies are seen to vary from about 16 to 46%. The ideal efficiency shown is a mathematical ideal, never to be achieved in practice. (Basic data from R. Wilson and P. Lissaman, *Applied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

High speed 2 blade

Dutch 4-arm

American multiblade

Darrieus rotor



Modern 3 blade (palm springs)

Typical Windmills

- A typical windmill might be 15 m in diameter
  - 176 m^2
- At 10 m/s wind, 40% efficiency, this delivers about 100 kW of power
  - this would be 800 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
  - 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

Average available wind power

note that average solar insolation is about 150–250 W/m^2

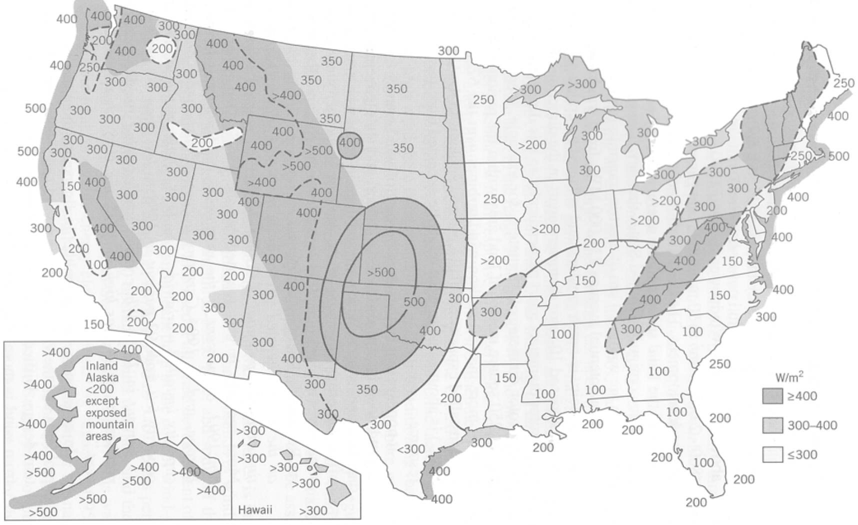


Figure 5.7 Annual average wind power density (watts per square meter) at 50 meters altitude. (Figure supplied by the National Renewable Energy Laboratory.)

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

- California is biggest participant, with 1,745 MW capacity
  - cost is 5–7¢ per kWh (1993) getting to be competitive
  - but still insignificant total (one large hydro plant)
- Find that only 20% of rated capacity is achieved
  - design for high wind, but seldom get it
- If fully developed, we *could* generate an average power comparable to our current electricity demands (764 GW)
  - but highly variable resource, and problematic if more than 20% comes from the intermittent wind

Biomass

- Biomass is any living organism, plant, animal, etc.
- 40×10^{12} W out of the $174{,}000\times10^{12}$ W incident on the earth from the sun goes into photosynthesis
  - 0.023%
  - this is the fuel for virtually all biological activity
  - half occurs in oceans
- Compare this to global human power generation of 13×10^{12} W, or to 0.6×10^{12} W of human biological activity
- Fossil fuels represent *stored* biomass energy

Photosynthesis

- Typical carbohydrate (sugar) has molecular structure like: $[CH_2O]_x$, where x is some integer
  - refer to this as “unit block”: $C_6H_{12}O_6$ (glucose) has x=6
- Photosynthetic reaction:

$$\begin{array}{ccccccccc} xCO_2 & + & xH_2O & + & \text{light} & \rightarrow & [CH_2O]_x & + & xO_2 \\ 1.47\text{ g} & & 0.6\text{ g} & & 16\text{ kJ} & & 1\text{ g} & & 1.07\text{ g} \end{array}$$

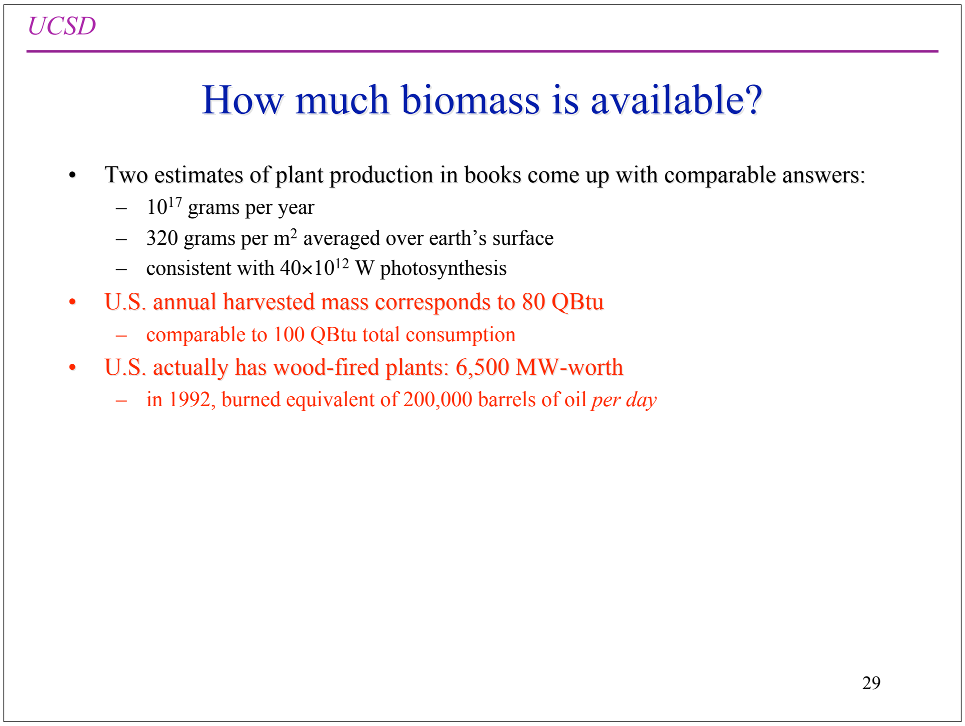
- Carbohydrate reaction (food consumption) is photosynthesis run backwards
  - 16 kJ per gram is about 4 Calories per gram
- Basically a “battery” for storing solar energy

Photosynthetic efficiency

- Only 25% of the solar spectrum is useful to the photosynthetic process
  - uses both red and blue light (reflects green), doesn’t use IR or UV
- 70% of this light is actually absorbed by leaf
- Only 35% of the absorbed light energy (in the useful wavelength bands) is stored as chemical energy
  - the rest is heat
  - akin to photovoltaic incomplete usage of photon energy
- Net result is about 6%

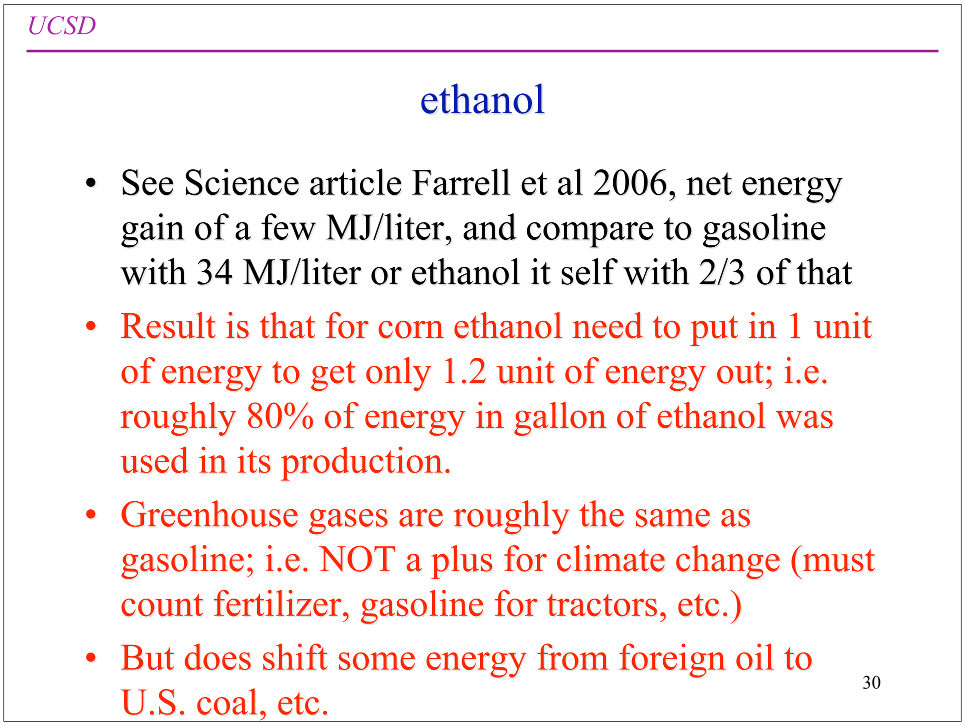
Realistic photosynthetic efficiency

Location	**Plant Production (g/m^2 per day)**	**Solar Energy Conversion Efficiency**
Potential Maximum	71	5%
Polluted stream (?!)	55	4%
Iowa cornfield	20	1.5%
Pine Forest	6	0.5%
Wyoming Prairie	0.3	0.02%
Nevada Desert	0.2	0.015%



How much biomass is available?

- Two estimates of plant production in books come up with comparable answers:
  - 10^{17} grams per year
  - 320 grams per m^2 averaged over earth's surface
  - consistent with 40×10^{12} W photosynthesis
- U.S. annual harvested mass corresponds to 80 QBtu
  - comparable to 100 QBtu total consumption
- U.S. actually has wood-fired plants: 6,500 MW-worth
  - in 1992, burned equivalent of 200,000 barrels of oil *per day*



ethanol

- See Science article Farrell et al 2006, net energy gain of a few MJ/liter, and compare to gasoline with 34 MJ/liter or ethanol it self with 2/3 of that
- Result is that for corn ethanol need to put in 1 unit of energy to get only 1.2 unit of energy out; i.e. roughly 80% of energy in gallon of ethanol was used in its production.
- Greenhouse gases are roughly the same as gasoline; i.e. NOT a plus for climate change (must count fertilizer, gasoline for tractors, etc.)
- But does shift some energy from foreign oil to U.S. coal, etc.

Quantitative Ethanol

- Let's calculate how much land we need to replace oil
  - an Iowa cornfield is 1.5% efficient at turning incident sunlight into stored chemical energy
  - the conversion to ethanol is 17% efficient
    - assuming 1.2:1 ratio, and using corn ethanol to power farm equipment and ethanol production itself
  - growing season is only part of year (say 50%)
  - net is 0.13% efficient (1.5% × 17% × 50%)
  - need 40% of 10^{20} J per year = 4×10^{19} J/yr to replace petroleum
  - this is 1.3×10^{12} W: thus need 10^{15} W input (at 0.13%)
  - at 200 W/m^2 insolation, need 5×10^{12} m^2, or (2,200 km)^2 of land
  - that's a square 2,200 km on a side

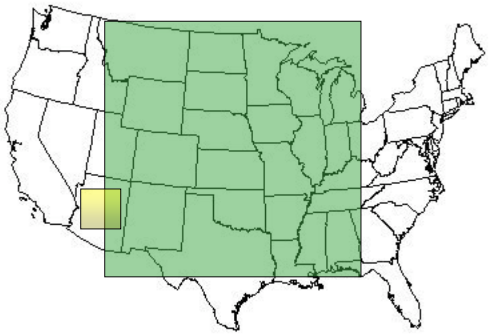
Thanks to T. Murphy

What does this amount of land look like?

Land needed to replace
Current U.S. oil energy

Green: corn ethanol

Yellow: Solar photo-voltaics:
(all US energy, not just oil!)



We don't *have* this much arable land!
And where do we grow our food?

Thanks to T. Murphy

The lesson here

- Hopefully this illustrates the power of quantitative analysis
  - lots of ideas are floated/touted, but many don't pass the quantitative test
  - a plan has to do a heck of a lot more than sound good!!!
  - by being quantitative in this course, I am hoping to instill some of this discriminatory capability in you

Other renewables

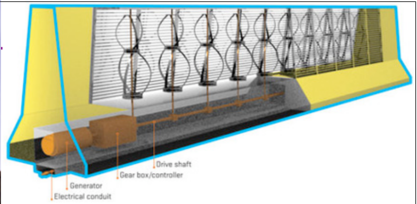
- We won't spend time talking about every conceivable option for renewable energy (consult text and other books for more on these)
- Lots of imagination, few likely major players
- As a way of listing renewable alternatives, we will proceed by most abundant
  - for each, I'll put the approximate value of QBtu available annually
  - compare to our consumption of 100 QBtu per year

Renewables list

- Solar (photovoltaic, solar thermal)
  - get 100 QBtu/yr with < 2% coverage of U.S. land area
- Wind
  - maybe 180 QBtu/yr *worldwide*, maybe 25 QBtu in U.S.
- Hydroelectric
  - 70 QBtu/yr feasible *worldwide*: twice current development
  - 5 QBtu/yr max potential in U.S.
- Biomass: complicated since depends upon how much food crops/forests are displaced. Could be substantial. May come back to this if time.
  - Corn ethanol in U.S. not a good idea
  - Sugar cane ethanol in Brazil is major part of their energy equation; running many of their cars on it (much more efficient than corn)
  - Celluosic ethanol (e.g. switch grass) may be good if possible
  - Other ideas e.g. bio-diesel, algae have pros and cons (mostly cons!)

Renewables, continued

- Geothermal: run heat engines off earth's internal heat
  - could be as much as 1.5 QBtu/yr *worldwide* in 50 years
  - limited to a few rare sites
- Tidal: oscillating hydroelectric "dams"
  - a few rare sites are conducive to this (Bay of Fundy, for example)
  - up to 1 QBtu/yr practical *worldwide*
- Ocean Thermal Energy Conversion (OTEC)
  - use thermal gradient to drive heat engine
  - complex, at sea, small power outputs, very low efficiency
  - Not likely to be important
- Waves
  - World total about 70 QBtu/year, but usable much less
  - U.K. estimate is 1.5 Qbtu/year from their (very favorable) coastlines



Good idea?

a. Yes
b. No
c. Not clear

Clogged highways and frustratingly waiting while your gas needle plummets to empty usually doesn't conjure up thoughts of green, but it seems like these very roads could become the source of a lot more energy. Several recent student designs have proposed that major roadways be retrofitted with various forms of wind energy collection devices, ranging from overhead turbines that collect energy from quickly-moving cars below to barrier panels (pictured after the jump) that harness the wind from closely passing vehicles moving in opposite directions. Ideally, the wind energy could then be sent back out to the grid to power nearby communities, light-rail transportation systems, or even intelligent billboards. Of course, most of these ideas are still in the research phase, and even if proven feasible, we can't imagine the up-front costs (or inconveniences of installing these things) to be minor, but we're sure that government subsidies should be able to to lend a helping hand.

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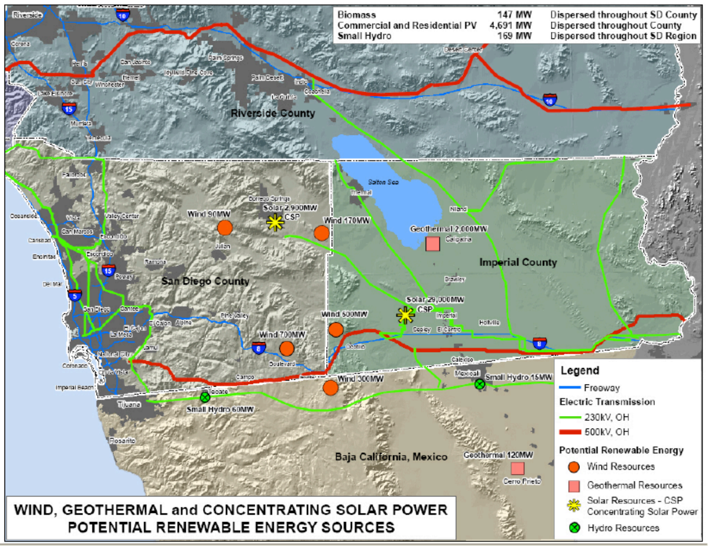
Potential for Renewable Energy in the San Diego Region
August 2005

Figure 1.1: Approximate Locations for Major Renewable Resources in the Region



Biomass	147 MW	Dispersed throughout SD County
Commercial and Residential PV	4,691 MW	Dispersed throughout County
Small Hydro	169 MW	Dispersed throughout SD Region

WIND, GEOTHERMAL and CONCENTRATING SOLAR POWER POTENTIAL RENEWABLE ENERGY SOURCES

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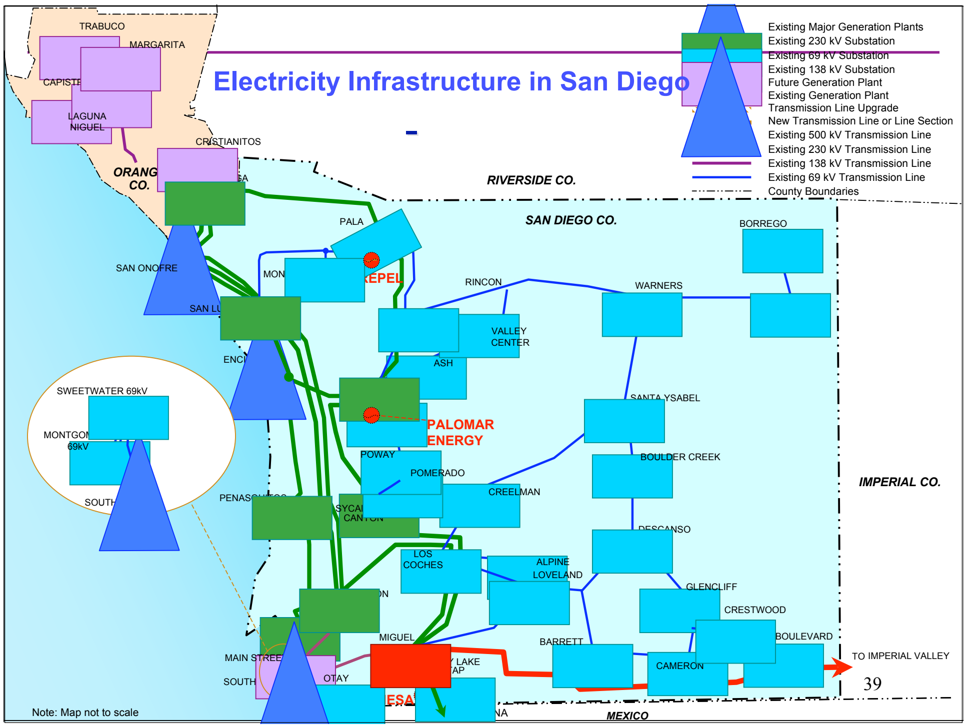


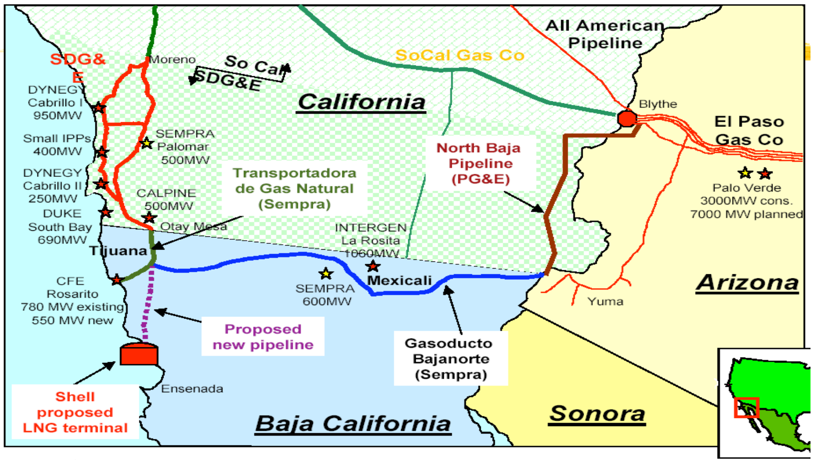
Electricity Infrastructure in San Diego

- Existing Major Generation Plants
- Existing 230 kV Substation
- Existing 69 kV Substation
- Existing 138 kV Substation
- Future Generation Plant
- Existing Generation Plant
- Transmission Line Upgrade
- New Transmission Line or Line Section
- Existing 500 kV Transmission Line
- Existing 230 kV Transmission Line
- Existing 138 kV Transmission Line
- Existing 69 kV Transmission Line
- County Boundaries

Note: Map not to scale

Existing Gas Pipeline Infrastructure

Coral Energy (Shell) Testimony, CPUC, Sept. 5, 2003



- ★ Power plant existing or under construction
- ☆ Power plant planned