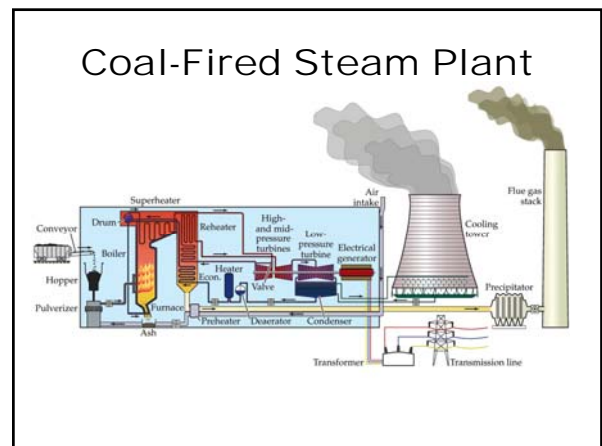
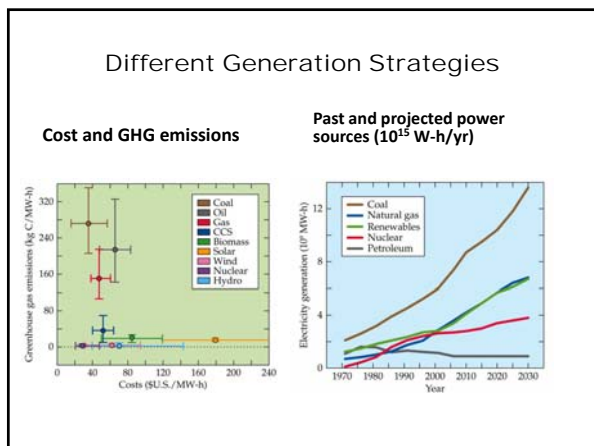
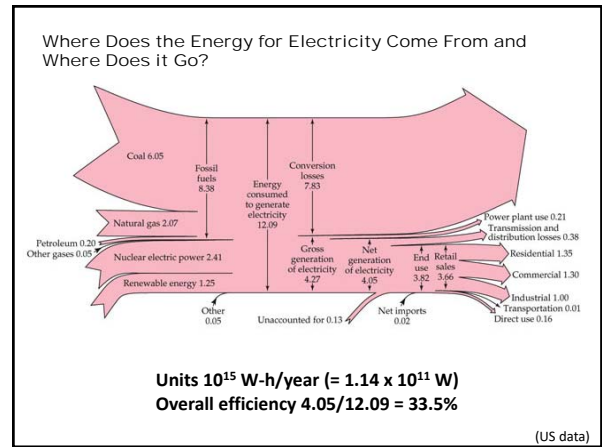
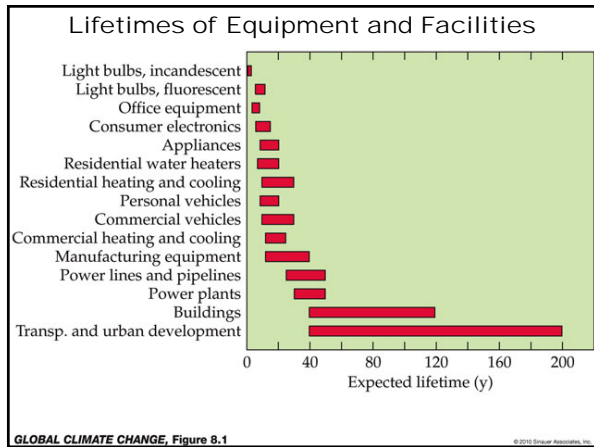


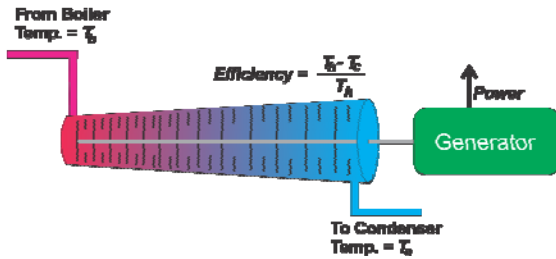


Just the Facts

- Automobiles account for 10% of GHG emissions worldwide
 - 19% in US
- Transportation in general accounts for 21% (33% US)
- Car fuel efficiencies (per unit weight) improve 2% /yr
- GHG emissions from power generation improve 0.4%/yr
- And from manufacturing 1.3%/yr
- Cars are less sensitive to energy costs
- Generation and industrial facilities last a long time, imposing legacy costs on the future.
- Remember that, per Joule, Coal produces twice as much GHG as natural gas and 50% more than fuel oil or gasoline



Thermodynamic Efficiency



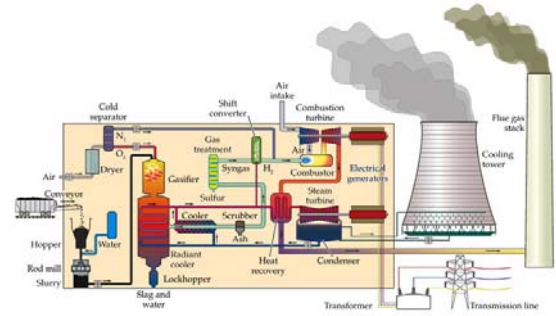
If $T_h = 450\text{K}$ and $T_c = 300\text{K}$, Efficiency = $150\text{K}/450\text{K} = 33.3\%$

If $T_h = 600\text{K}$ and $T_c = 300\text{K}$, Efficiency = $300\text{K}/600\text{K} = 50\%$

Integrated Gas Combined Cycle

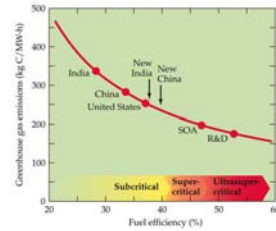
- Converts Coal to "syngas," CO and H₂ before burning it:
 - $2\text{C} + \text{O}_2 \rightarrow \text{CO} + \text{heat}$
 - $\text{C} + \text{H}_2\text{O} + \text{heat} \rightarrow \text{CO} + \text{H}_2$
 - $\text{CO} + \text{H}_2\text{O} + \text{heat} \rightarrow \text{CO}_2 + \text{H}_2$
 - $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{heat}$
- Last reaction is burning in a gas turbine
- Heat also runs steam turbine
- Advantages:
 - Releases less oxides of sulfur and nitrogen because it's cleaned from fuel
 - High fuel efficiencies, 38-56%
 - Can capture CO₂ from flue gas using cryogenic separation of N₂ from intake gas
- Disadvantage: High capital costs

IGCC Plumbing Diagram



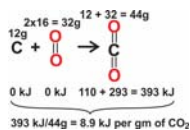
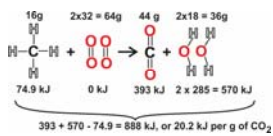
Subcritical & Supercritical Steam Plants

- In a Subcritical plant water condenses to a liquid
- In a supercritical plant ($T > 374^\circ\text{C}$; $p > 22\text{ Mpa}$) there is no distinction between vapor & liquid
- Requires better materials and higher capital costs
- But can reach much higher efficiencies

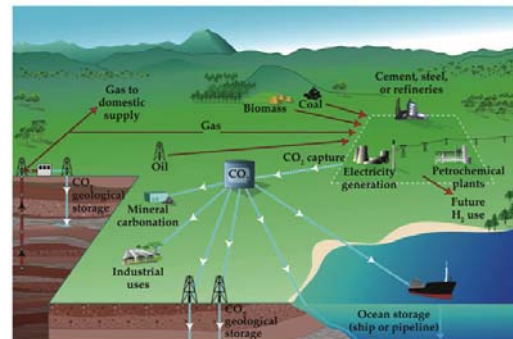


- Work like Coal fired IGCC, but with no gasifier or filters
- Low capital costs
- Because of fracking, CH₄ is becoming much cheaper in the US
- Gas turbine power plants can start and stop quickly to meet changes in demand
- Can also be more efficient (up to 60%) if they have combined-cycle steam generation
- In principle, conversion to natural gas could reduce GHG emission by > 50% relative to coal
- Currently about 20% of capacity, increasing 2% yr⁻¹

Natural Gas

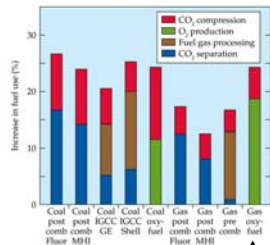


Carbon Capture and Storage



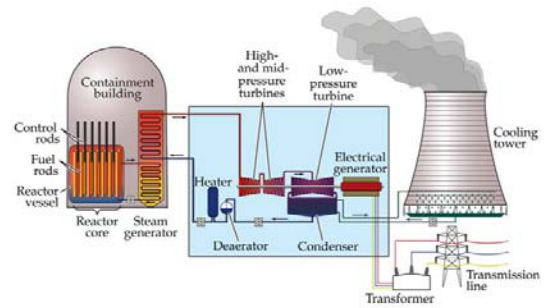
CCS Technologies

- Capture CO₂ from flue gasses and sequester it.
- Problem: Flue gas is mostly N₂ unless N₂ is removed pre-combustion
- Technologies:
 - Chemical absorption
 - Cryogenic
 - Membrane separation
- Technologies are unpromising and not yet used on a large scale
 - Double capital cost and increases generation costs by 50%
- Exception: Extraction of pure O₂ from intake air so that flue gas is nearly pure CO₂
 - If it's done cryogenically, cold intake gas increase thermodynamic efficiency



HEW: Costs as much to put it back in the ground as it did to get it out

Nuclear

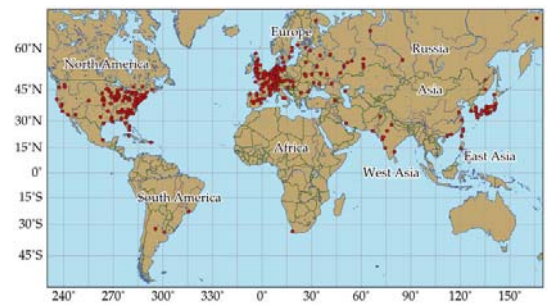


- Positive:
 - No GHG Emissions
 - Potentially large (centuries of supply) Uranium reserves
- Negative
 - Low thermodynamic efficiency because reactors are not as hot a boilers
 - Nuclear waste
 - Decommissioned plants
 - Meltdowns

Issues

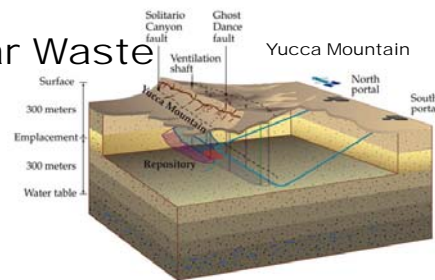


Where Are the Reactors?



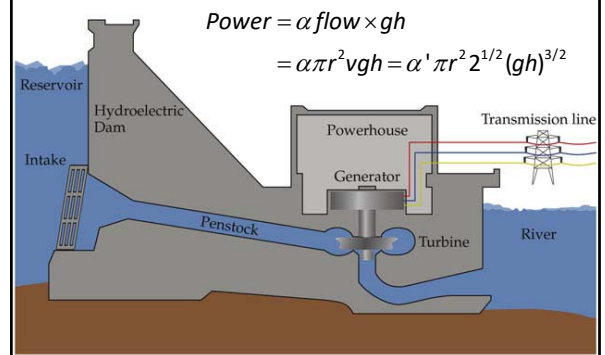
US (19%), France (~ 77%), Japan (~28%), S. Korea, and former Soviet are the big users.

Nuclear Waste



- Reprocessing of fuel reduces both radioactivity and volume
- Waste stays both thermally hot and very radioactive for about 40 years
- Much more stable after that
- But must be isolated from human contact for > 1000 yr
- Hazard in transportation to site
- NIMBY syndrome and lack of political will

Hydroelectric Power




$$Power = \alpha \text{flow} \times gh$$

$$= \alpha \pi r^2 vgh = \alpha' \pi r^2 2^{1/2} (gh)^{3/2}$$


Issues

- Positive:
 - No GHG emissions
 - Recreational opportunities
 - Can improve navigation
 - Water for irrigation
- Negative:
 - Flooding of archaeological and cultural sites
 - Reduction of downstream flows that flush pollution
 - General disruption of riparian ecosystems
 - Silting of reservoirs
 - Lack of silt downstream to maintain land fertility and elevation

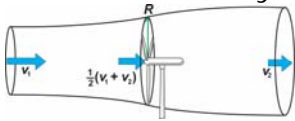


Wind Power

- Second only to hydroelectric power
- Thousands of turbines in California
- Denmark gets 20% of its electricity from them
- Available power depends upon the cube of the wind speed
- Need windy sites



Wind Turbine Dynamics




$$Power = \alpha \rho \pi R^2 \frac{1}{2} (v_1 + v_2) \left(\frac{1}{2} v_1^2 - \frac{1}{2} v_2^2 \right) = \frac{1}{4} \alpha \rho \pi R^2 v_1^3 \left(1 + \frac{v_2}{v_1} \right) \left(1 - \frac{v_2^2}{v_1^2} \right)$$

- Generates power by slowing the wind
- Most efficient when $v_2 = \frac{1}{3} v_1$ Results in slow-moving wake downwind of the turbine
- Efficiency = $16/27 = 59.3\%$. Betz's Law
- Actual efficiencies are typically less, $\alpha = 0.75-0.8$
- If the turbine were to stop the wind, $Power = 0$

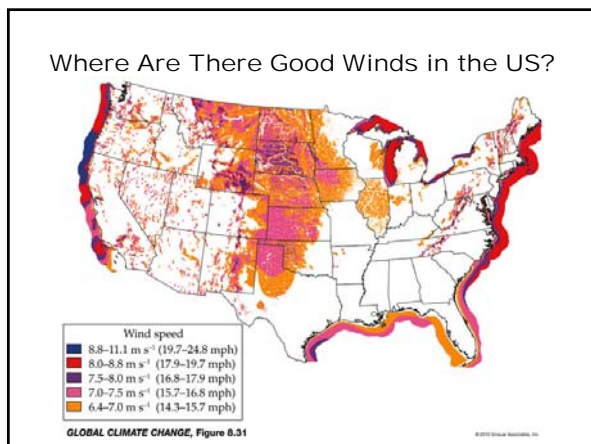
Other Designs

Classic American Multi-blade

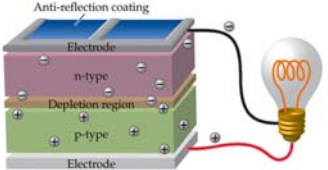


Darrieus Vertical "Eggbeater"



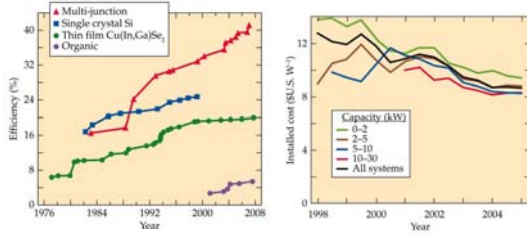


Photovoltaic Cell



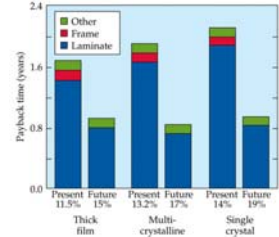
- Composed of two layers of silicon (or other semiconductor):
 - n-type (doped with P, As or Sb,) where electrons like to be
 - and p-type (doped with B or Al) where holes "unelectrons" like to be
 - Sunlight excites electrons in the "Depletion Region" so that they migrate to the n-type layer causing current to flow

Efficiency and Cost



Assessment

- No GHG emissions from operation
- Works only when sun is shining
- Cells have ~20yr lifecycle
- Expensive
- Takes energy to produce cells.
- Payback time is 1-2 yr and improving



Where is There Good Sunshine?

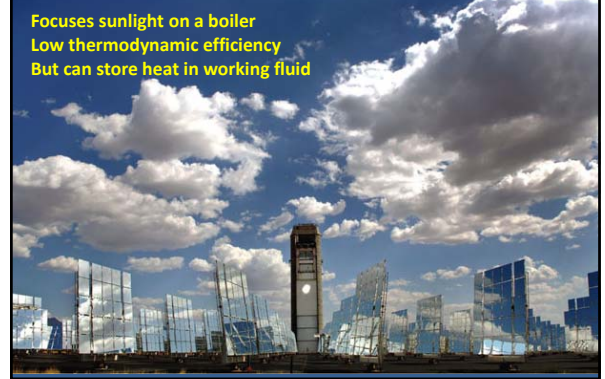


GLOBAL CLIMATE CHANGE, Figure 8.35

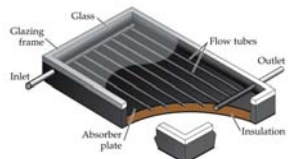
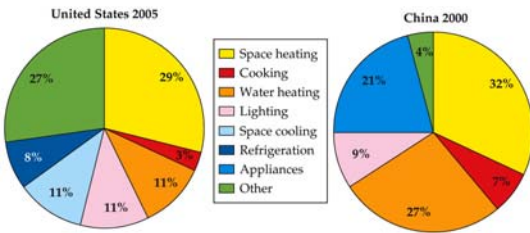
25-60 W over 24-h cycle

Solar Thermal Generation

Focuses sunlight on a boiler
 Low thermodynamic efficiency
 But can store heat in working fluid

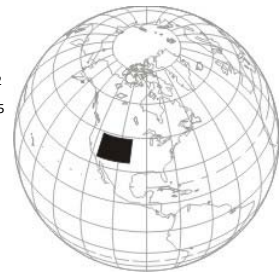


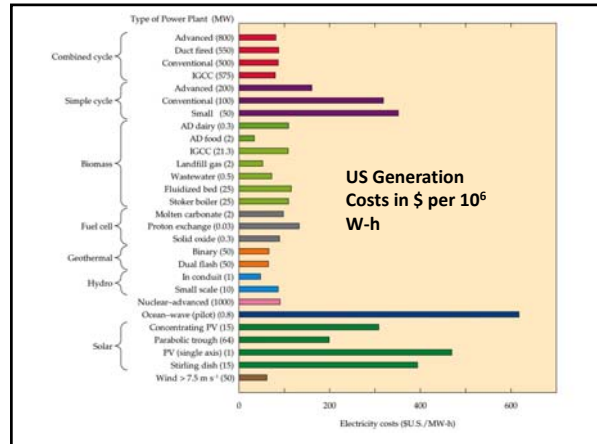
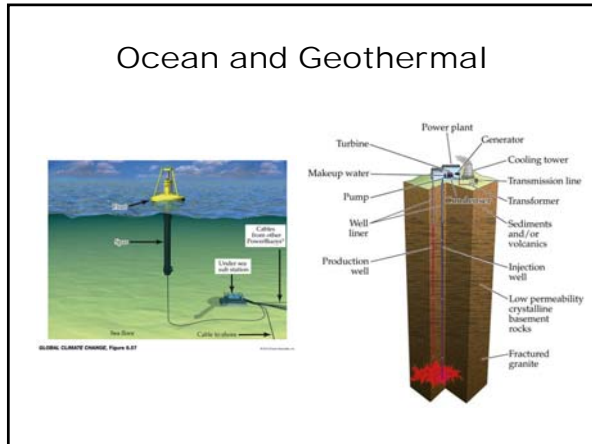
Solar Water Heating



A Speculation

- Imagine the world of 2114 with ten billion (10¹⁰) people
- Each uses 10 kW (10⁴ W)
- Generated with 20% efficient solar cells that produce 50 W m⁻²
- That works out to 2x10¹² m²
- Or ~7 Arizonas (area = 3x10⁵ m²) covered with solar cells to provide the whole world with as much energy as North Americans, or Icelanders, or Saudis use now





- ### Summary
- Power generation accounts for 30% of GHG emissions
 - Coal fired plants predominate because they are cheap
 - Can be efficient with newer engineering
 - Natural gas produces much less CO₂ (½ as much) and is becoming cheaper
 - Book likes CCS, but I think it's hogwash
 - Nuclear power produces no GHGs, but it's expensive and has a bad image
 - Hydroelectric produces no CO₂, but has other environmental problems
 - Wind and solar show promise, but are expensive and intermittent
 - Geothermal and wave are niche sources