GEOS 24705 / ENST 24705
Lecture 19: End-use and summary
We covered in most of class:
We covered yesterday and will review:
We’ll cover quickly today:

U.S. energy use, 2005

from LLNL, in quads/yr: 1 Q/yr \( \sim 10^{18} \) J/yr \( \sim 30 \text{ GW} \)
**Solar thermal:** focuses uses heat from sun

*Advantage:* you can build a better heat engine than the atmosphere

*Thermal energy is readily stored*

**Efficiency:** ~ 19%

*Effective efficiency:* ~ 10% ?

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**Solar PV:** direct conversion of solar radiation to electricity

*Advantage:* better efficiency than a plant, and bypass the heat engine

**Efficiency:** ~ 15%

*Effective efficiency:* ~ 10% ?
Solar is the first renewable that meets our criterion:

Sufficient areal energy density to power the modern world

Box = 200 km$^2$

All U.S. power needs (5000 W)
But population is growing at ~ 1%/yr
What is it doubles? Increase areal needs by x 2
And we are growing richer...
Energy demands growing by 2%/yr... Increase areal needs by x 4
Wind has much lower areal energy density: Solar in good terrain was 33 W/m². Wind more like 1 W/m². Need 33x more area.

Wind belt is skinny though so one dimension shouldn’t be more than 600 km. The other dimension is then 2200 km.
Wind has much lower areal energy density: Solar in good terrain was 33 W/m². Wind more like 1 W/m². Need 33x more area

Oops, too much area needed for U.S. wind belt - already go to non-optimal sites.
U.S. energy use, 2005

from LLNL, in quads/yr: $1 \text{ Q/yr} \sim 10^{18} \text{ J/yr} \sim 30 \text{ GW}$

Non-transportation use: buildings
Buildings: what is all that energy used for?

Sources of energy use, in order, for residential & commercial:

**Residential energy end usage**

In 2006 the residential sector consumed 21.8 quads of primary energy. This chart shows the relative amounts going to various residential end uses.

Source: Energy Data Book (2007); EERE, U.S. Department of Energy

**Commercial energy end usage**

In 2006 the commercial sector consumed 17.9 quads of primary energy. This chart shows the relative amounts going to various end uses. The category “Other” includes non-building commercial use such as street lighting, lighting in garages, etc.

Source: Energy Data Book (2007); EERE, U.S. Department of Energy

U. Chicago heating energy use was 6 kW per person, more than half average American per capita total energy usage.
Conservation: **Building energy efficiency strategies**

Heat and cooling:
- better insulation
- better thermostat control
- heat exchangers in ventilated buildings
- passive solar heating
- heat pumps instead of combustion heating

• Lighting:
- more efficient lighting
  - LEDs/CFLs/incandescent are 100 / 50 / 15 lumen/W
  - “efficiency” ~ 10% / 30% / 60% - reduce usage by ~85%
- daylighting (use less artificial light)
Building conservation potential estimates consistent at 1/3

Source: EAI
Annual Energy Outlook 2011
Building conservation potential estimates consistent at 1/3

For large residential, main savings come from heating /cooling

Empire State estimated 38% potential savings

Energy and CO2 savings in the optimal package result from 8 key projects.

Annual Energy Savings by Measure

Source: Empire State Building Sustainability

DDC = “Direct Digital Control”, VAV AHUs = “Variable Air Volume Air Handling Units”
Building conservation potential estimates consistent at 1/3

McKinsey estimate ~ 3 GtCO2e /yr savings from building efficiency, i.e. 0.8 GtC/yr
...or 10% of current emissions
... means about 10% savings on U.S. energy use

Since buildings are ~30% of current emissions, then 10% savings from building energy use means
....reduce building energy use by 1/3, or 30%

...Note that Rocky Mountain Institute estimates much more...
  RMI is the optimistic outlier
U.S. energy use, 2005

from LLNL, in quads/yr: 1 Q/yr ~ 10^{18} J/yr ~ 30 GW

Non-transportation use: industry
Industry: what is all that energy used for?

- Very little is for endothermic chemical reactions
- 54% goes to electric motors
- 22% goes to building energy use (heating + lighting)
- 11% is heat of any kind, little of which goes to chemical energy

* = Motor-driven equipment.

Energy use by industrial sector:

- Refining: 30%
- Chemicals: 27%
- Paper: 10%
- Metals: 9%
- Food: 5%

Total: 81% from just 5 industries

Industry: what are opportunities for savings?

Potential industrial energy savings suggested by studies: high for specific industries, and motor savings high globally

- motor and pumping systems: 15-30%
- paper manufacture in total: 35%
- steel, cement, paper with easy improvements: 16-18%
- steel with current technology: 24%
- steel long-term: 35%
- papermaking long-term: 75-90% (!)

Citations compiled by InterAcademy Council, Netherlands
http://www.interacademycouncil.net/CMS/Reports/11840/11914/11920.aspx

Also perhaps 30% for industry...
Embedded energy: rule of thumb for estimating (MJ/$)

Take U.S. annual energy per cap energy use
(10,000 W/cap * 3*10^7 s/yr = 3*10^5 J/cap*yr )
Divide by U.S. annual per cap GDP
($15T/300 M people -> $50,000/cap*yr)
\[ \rightarrow (30/5) \text{ MJ/} $ \]
\[ \rightarrow 7 \text{ MJ/} $ \]

Then decide that infrastructure probably takes more than average energy
x2 estimate for infrastructure energy cost: 14 MJ/$

- Paper: 15 MJ/$
- Metals: 14
- Chemicals: 8.5
- Machinery: 0.7

### Table 8  Typical Energy Costs of Common Materials (MJ/kg)

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy cost</th>
<th>Made or extracted from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>227–342</td>
<td>Bauxite</td>
</tr>
<tr>
<td>Bricks</td>
<td>2–5</td>
<td>Clay</td>
</tr>
<tr>
<td>Cement</td>
<td>5–9</td>
<td>Clay and limestone</td>
</tr>
<tr>
<td>Copper</td>
<td>60–125</td>
<td>Sulfide ore</td>
</tr>
<tr>
<td>Glass</td>
<td>18–35</td>
<td>Sand, etc.</td>
</tr>
<tr>
<td>Iron</td>
<td>20–25</td>
<td>Iron ore</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.07–0.1</td>
<td>Sedimentary rock</td>
</tr>
<tr>
<td>Nickel</td>
<td>230–70</td>
<td>Ore concentrate</td>
</tr>
<tr>
<td>Paper</td>
<td>25–50</td>
<td>Standing timber</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>87–115</td>
<td>Crude oil</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>62–108</td>
<td>Crude oil</td>
</tr>
<tr>
<td>Polyvinylchloride</td>
<td>85–107</td>
<td>Crude oil</td>
</tr>
<tr>
<td>Sand</td>
<td>0.08–0.1</td>
<td>Riverbed</td>
</tr>
<tr>
<td>Silicon</td>
<td>230–235</td>
<td>Silica</td>
</tr>
<tr>
<td>Steel</td>
<td>20–50</td>
<td>Iron</td>
</tr>
<tr>
<td>Sulfuric acid</td>
<td>2–3</td>
<td>Sulfur</td>
</tr>
<tr>
<td>Titanium</td>
<td>900–940</td>
<td>Ore concentrate</td>
</tr>
<tr>
<td>Water</td>
<td>0.001–0.01</td>
<td>Streams, reservoirs</td>
</tr>
<tr>
<td>Wood</td>
<td>3–7</td>
<td>Standing timber</td>
</tr>
</tbody>
</table>

### Table 6  Ranges of Energy Densities of Common Fuels and Foodstuffs

<table>
<thead>
<tr>
<th>Energy density</th>
<th>(MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>114.0</td>
</tr>
<tr>
<td>Gasolines</td>
<td>46.0–47.0</td>
</tr>
<tr>
<td>Crude oils</td>
<td>42.0–44.0</td>
</tr>
<tr>
<td>Pure plant oils</td>
<td>38.0–37.0</td>
</tr>
<tr>
<td>Natural gases</td>
<td>33.0–37.0</td>
</tr>
<tr>
<td>Butter</td>
<td>29.0–30.0</td>
</tr>
<tr>
<td>Ethanol</td>
<td>29.6</td>
</tr>
<tr>
<td>Best bituminous coals</td>
<td>27.0–29.0</td>
</tr>
<tr>
<td>Pure protein</td>
<td>23.0</td>
</tr>
<tr>
<td>Common steam coals</td>
<td>22.0–24.0</td>
</tr>
<tr>
<td>Good lignites</td>
<td>18.0–20.0</td>
</tr>
<tr>
<td>Pure carbohydrates</td>
<td>17.0</td>
</tr>
<tr>
<td>Cereal grains</td>
<td>15.2–15.4</td>
</tr>
<tr>
<td>Air-dried wood</td>
<td>14.0–15.0</td>
</tr>
<tr>
<td>Cereal straws</td>
<td>12.0–15.0</td>
</tr>
<tr>
<td>Lean meats</td>
<td>5.0–10.0</td>
</tr>
<tr>
<td>Fish</td>
<td>2.9–9.3</td>
</tr>
<tr>
<td>Potatoes</td>
<td>3.2–4.8</td>
</tr>
<tr>
<td>Fruits</td>
<td>1.5–4.0</td>
</tr>
<tr>
<td>Human feces</td>
<td>1.8–3.0</td>
</tr>
<tr>
<td>Vegetables</td>
<td>0.6–1.8</td>
</tr>
<tr>
<td>Urine</td>
<td>0.1–0.2</td>
</tr>
</tbody>
</table>

*From: Vaclav Smil, "Energies"*
Most metals extracted from ore by **smelting**

Extractive metallurgy, to separate a pure metal from its ore
Always involves a change in oxidation state (from oxide or sulfide)
Typically uses high heat and a reducing agent (iron: T to 2300 C, 4200 F)

- Iron: \( \text{Fe}_2\text{O}_3 \rightarrow \text{Fe} \)
- Copper: \( \text{CuCO}_3 \rightarrow \text{Cu} \)
- Lead: \( \text{PbS} \rightarrow \text{Pb} \)

*Left: Blast furnace “pour”. Photo from Brock Solutions*
*Right: Blast furnace schematic. Figure from Wealden Iron*
Aluminum has highest manufacturing energy cost

Highly desirable: light, good electrical conductor, good thermal conductor

Abundant (3rd most in Earth’s crust)

“Young” metal, only in production for ~150 years

Why?

Extremely difficult to extract from its ore. Tight bonds = high energy cost of extraction. Can’t be extracted by smelting.

Modern methods: 100 x more energy cost of production than iron.

Now most economical metal to recycle since new production is so costly.

Al production in Washington state and Iceland (2-> 3) *(hydropower, geothermal power)*
Aluminum – formerly luxury good, now mainstay

Identified and named 1807 (by Humphrey Davy). Isolated 1825 (Hans Christian Oersted) and more purely 1827 (Wohler)

Luxury good: displayed at 1855 Paris Exposition next to Crown Jewels: “silver from clay” Napoleon III, who ruled France between 1848-1870, had a flatware service made of aluminum for state dinners – it was more precious than silver or even gold.

Low production: in 1884, 125 lb (60 kg) of aluminum was produced in the United States, sold for about the same unit price as silver.

...1886, Hall-Heroult process invented; 1888, Bayer process ...

Aluminum is now the 2nd most used metal in the world (after iron).

2006: 34 Mt primary production (16 Mt recycled). Price: 1.3% silver.

World Al energy: 300 MJ/kg * 34 Mt/yr * 1 yr/3e7 s
-> 3e8 * 3.4e10 / 3e7 ~ 340 GW
.... 2% of world energy use!
Aluminum: Hall-Heroult + Bayer processes

1886: two 22-year-old scientists, one American (Hall), one French (Heroult), independently developed electrochemical smelting to convert alumina to aluminum: electrolysis of alumina dissolved in cryolite.

1888: Austrian chemist (Bayer) develops process for refining bauxite, aluminum ore, separating the alumina from all contaminants. Quickly adopted – first plant in 1893.

Aluminum: Chemical processing of alumina ore (Bayer process)

1. **Mechanical crushing** of bauxite
2. **Dissolution** in caustic soda (sodium hydroxide, NaOH, a base)
   \[ \text{Al(OH)}_3 + \text{Na}^+ + \text{OH}^- \rightarrow \text{Al(OH)}_4^- + \text{Na}^+ \]
3. **Clarification** to remove impurities (esp. iron oxides)
4. **Crystallization** of alumina hydrate in precipitator (gibbsite)
   \[ \text{Al(OH)}_4^- + \text{Na}^+ \rightarrow \text{Al(OH)}_3 + \text{Na}^+ + \text{OH}^- \]
5. **Calcination** drives off water to form alumina:
   \[ 2\text{Al(OH)}_3 \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O} \]

Above: Bauxite mine, Northern Territory, Australia

Photo: J. Clover, Webshots:travel

Right: Figure from Aluminiumville.co.uk
Aluminum: Electrolytic separation (Hall-Heroult process)

Alumina crystals dissolved in molten cryolite (sodium, aluminium, fluorine) at 1760 F (960 C)

Electric current (> 100,000 A at ~5V) is passed directly through molten cryolite – no indirect heating.

Pure molten aluminum is collected at bottom of vessel

*Manam, Bahrein, world’s 3rd largest Al smelter*

*Photo from: Manufactured Landscapes*
Nitrogen is critical limiting nutrient
Needed for life but most is locked up as N2

**Nitrogen is fundamental to life but difficult to get**
Nitrogen required in all amino acids (proteins).
Hard to get “fixed” nitrogen because N≡N triple bond means nitrogen “wants” strongly to be in N₂
Most ecosystems on Earth are nitrogen-limited, so important for fertilizer

N is “fixed” from N₂ by some bacteria
\[ N₂ + 6 \text{H}^+ + 6 \text{e}^- \rightarrow 2 \text{NH}_3 \]
Symbiotes in root nodules of some plants:
• Soybeans, peanuts, peas,
• Clover, lupines

**Fixed nitrogen is explosive**
Nitrogen “wants” strongly to be in N₂, so get violent reactions. Most explosives are N-based
e.g. nitroglycerin (dynamite), TNT (trinitrotoluene), gunpowder (potassium nitrate), ammonium nitrate (both fertilizer and explosive).
In 1913, Chile is the world’s largest producer of fixed nitrogen ... from guano. Nitrogen seem as critical national priority.

Lead-up to WWI increased pressure on industrial chemists to avoid dependence on foreign nitrogen: *nitrogen independence*. Wanted for both food & as explosive.

Synthetic nitrogen fixation invented 1909 by German chemist Haber, commercialized by Bosch just before WWI. Contributed to war effort (explosives). Nobel prizes for both.
Haber-Bosch process:
Making ammonia from natl. gas (CH₄) and air (N₂)
Currently 1% of world & U.S. energy use – in U.S., same as food energy.

Half the N in your body came from a factory like this.
Climate change mitigation policies: suggested emissions reductions to 80% of 1990 levels (this still won’t stabilize CO2, but is a commonly discussed target)

If target was 80% drop from current levels, U.S. use would drop from:

• **current**: 10 kW/person
• **to**: 2 kW/person

In fact we have more people now than 1990 & are richer, so need to drop even more

• **target would be**: 1.6 kW/person
Likely can’t conserve our way out of energy / emissions crisis

Green dots: major energy producers, dashed line = emissions target if fossil fueled

Data: EIA, U.N
And can’t ask developing world to stay poor....

Green dots: major energy producers, dashed line = emissions target if fossil fueled
Growth outweighs any efforts at conservation

U.S. per capita energy use is
10,000 W

World average per capita energy use is
2000 W

Means even if U.S. stops growing altogether, and
no population growth, if developing world rises to
U.S. level ..... 

..... world energy would rise by x 5
Growth outweighs any efforts at conservation

Global 2 % growth in energy use / yr

\[ E_{\text{use}} = E_{\text{use}_0} * e^{rt} \]

Means e-folding (x e or x 2.7 increase) in
\[ \tau = 1/r = 50 \text{ yrs} \]

Doubles in less time
\[ \tau_2 = \ln(2)/r = 34 \text{ yrs} \quad \ln(2) \sim 0.7 \]

30% growth in \( t = \ln(1.3)/r = 13 \text{ yrs} \)

All the conservation that we can imagine just buys us a bit over a decade....
We can’t conserve our way out of an energy crisis

EIA, see http://www.eia.gov/todayinenergy/detail.cfm?id=4390 for animation
We’re not going to tolerate using less energy
Meeting emissions target requires ca. 1875 per capita emissions
Energy sector is resistant to innovation

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Also: phonograph (1877), telephone (1876), movies (1877,1895), photographic film (1884), radar (1887)
## Energy sector is resistant to innovation

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<td><em>Semiconductors, transistors, diodes, and all their offspring:</em></td>
</tr>
<tr>
<td>AC generator and transformer (1888)</td>
<td>Light-emitting diodes (LEDs)</td>
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<tr>
<td>3-phase power transmission (1895 demo)</td>
<td>Solar photovoltaics</td>
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<tr>
<td>Induction motor (1885-1888)</td>
<td>Computers &amp; electronics</td>
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<td>Incandescent bulb (1880 commercialized)</td>
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Also: phonograph (1877), telephone (1876), movies (1877, 1895), photographic film (1884), radar (1887)
Conclusions from our energy studies

• If we want to keep CO2 emissions to what scientists believe is relatively safe, we will have to make deep cuts in emissions.

• We won’t get those from conservation – world energy use will go up rather than down.

• In fact, world energy use will go up so much that an equal worry may be running out of fossil fuels too quickly to adjust.

• The only renewable energy source that can alone power the world is direct use of solar energy, either solar PV or solar thermal. The rest are marginal.

• Biomass – no, no way, no how. Plants are too inefficient, and we need to eat. Niche applications only (e.g. liquid fuel for aircraft).

• Wind works for whole-world power only if you put it offshore, and then there’s a cost issue.
Final thoughts on economics and motivations

• Electricity offers many alternative sources at relatively close costs (wind nearly cost-competitive, solar or carbon sequestration painful but tolerable at ~$40-$130/MWh)

• Oil for transportation has no cost-competitive alternative. Oil also ~10x more expensive per C atom than are coal or natural gas. Therefore you can’t affect oil supply much with a carbon price.

• U.S. has coal and gas but not enough oil.

• If your only motivation is to stop climate change, you accept that all the oil will be burnt and focus on electricity to keep some coal in the ground.

• If your only motivation is national security, you dig the coal and do coal-to-liquids to avoid oil imports, and suffer the climate consequences.

• Or you just pray for a miracle breakthrough in technology.

• No option is good – how to split the difference, or avoid this conflict?