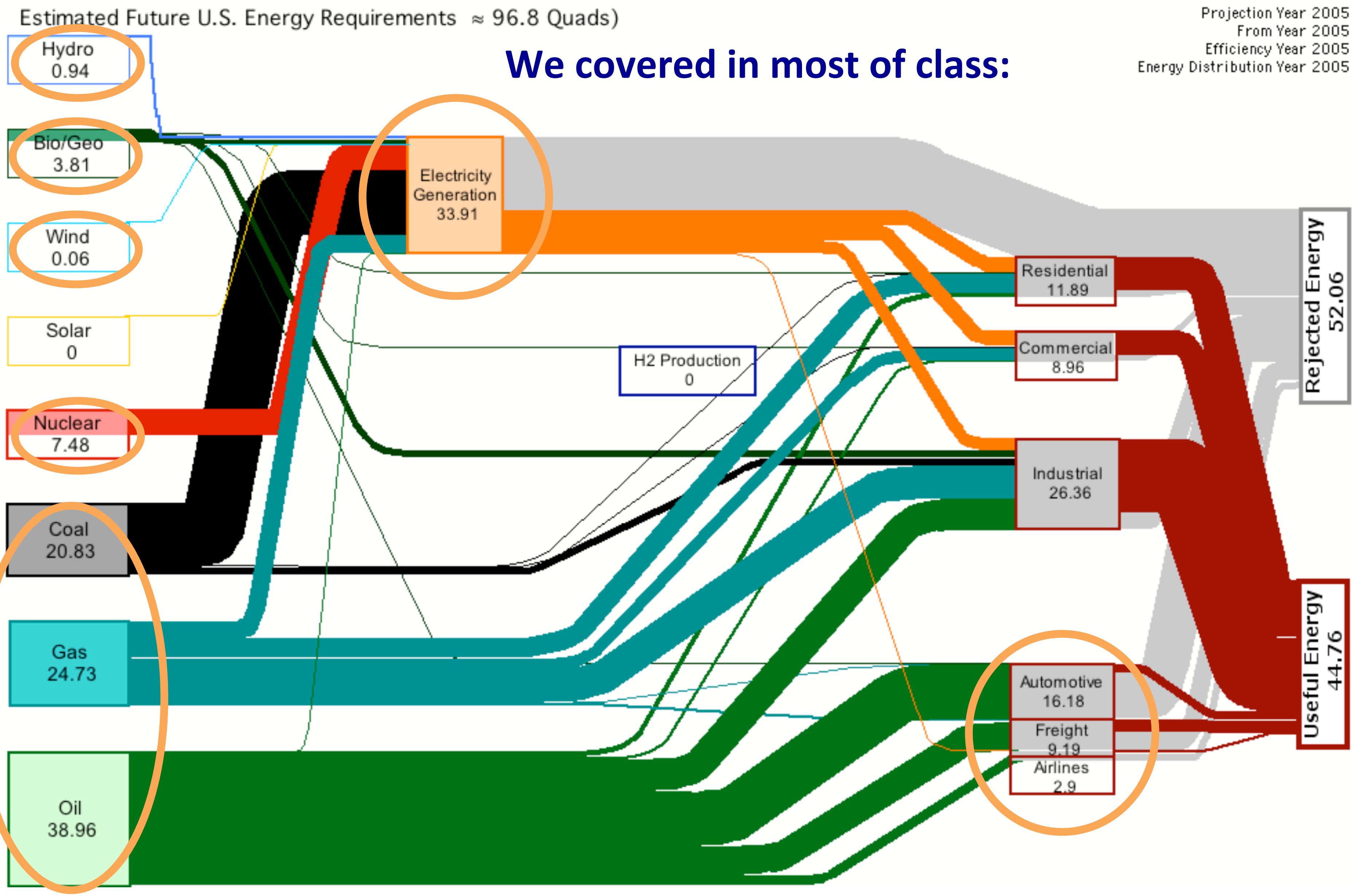
GEOS 24705 / ENST 24705
Lecture 19: End-use and summary

U.S. energy use, 2005

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

We covered in most of class:



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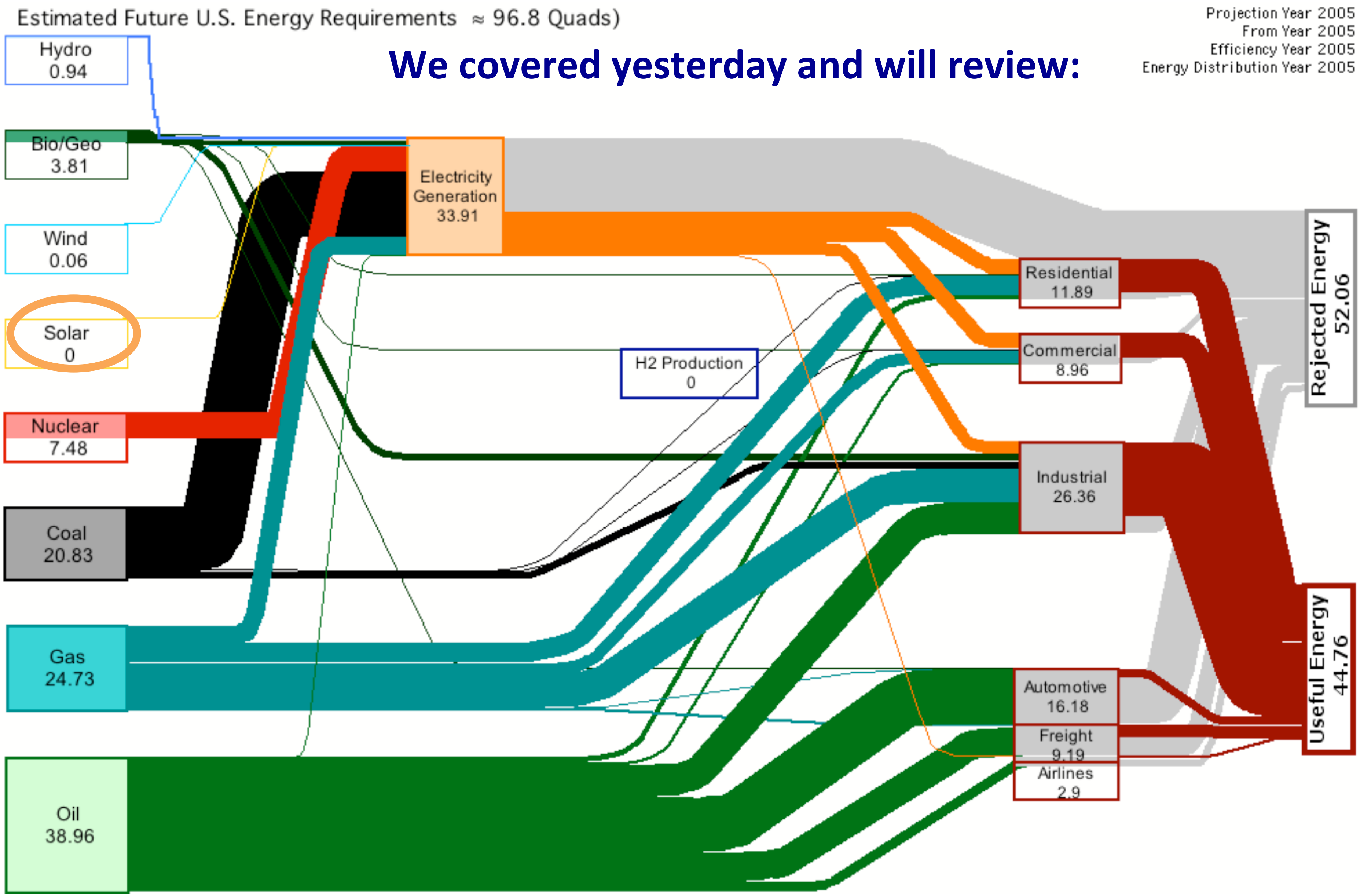
We covered yesterday and will review:



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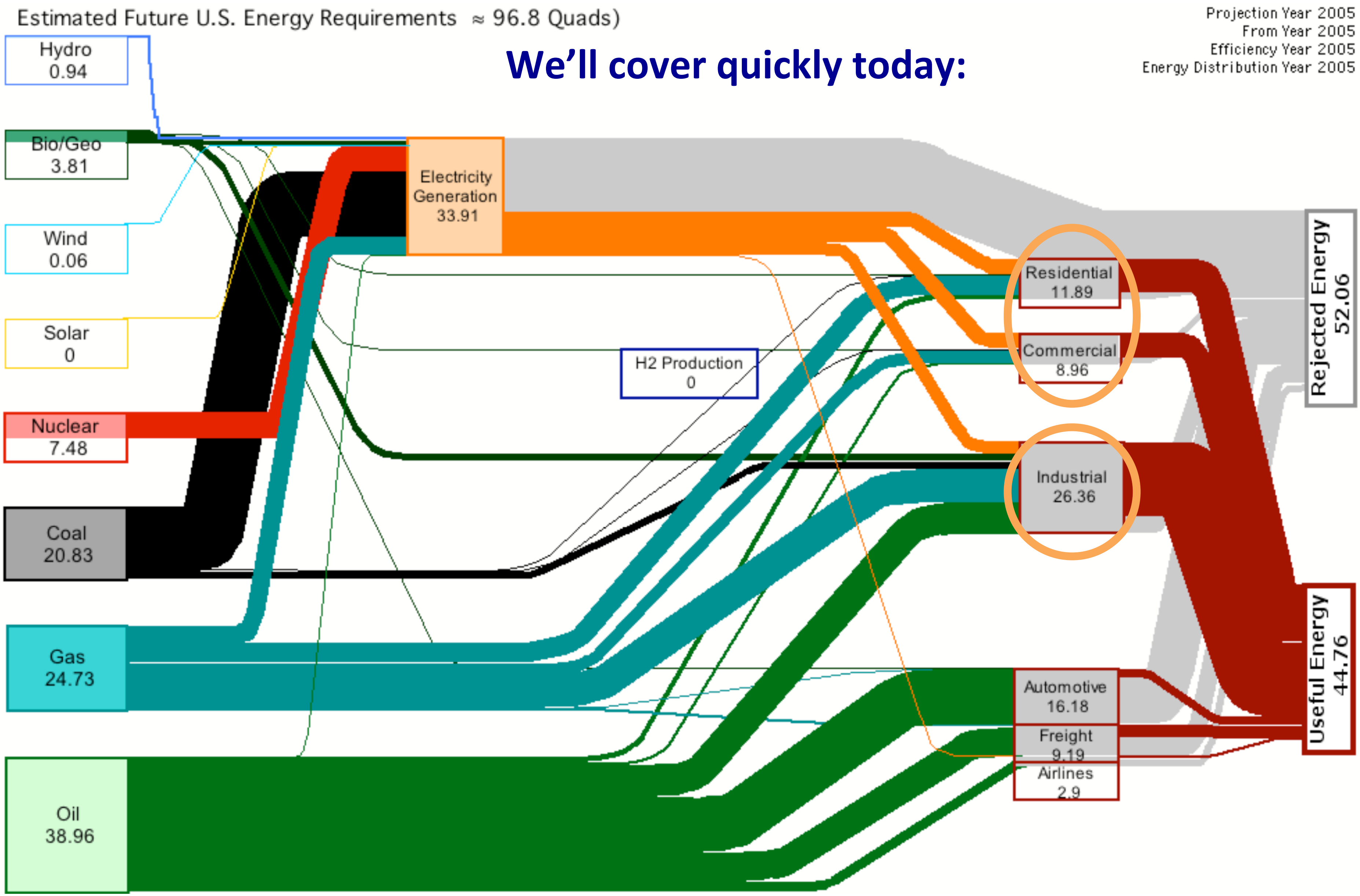


We'll cover quickly today:

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% ?

Solar PV: direct conversion of solar radiation to electricity

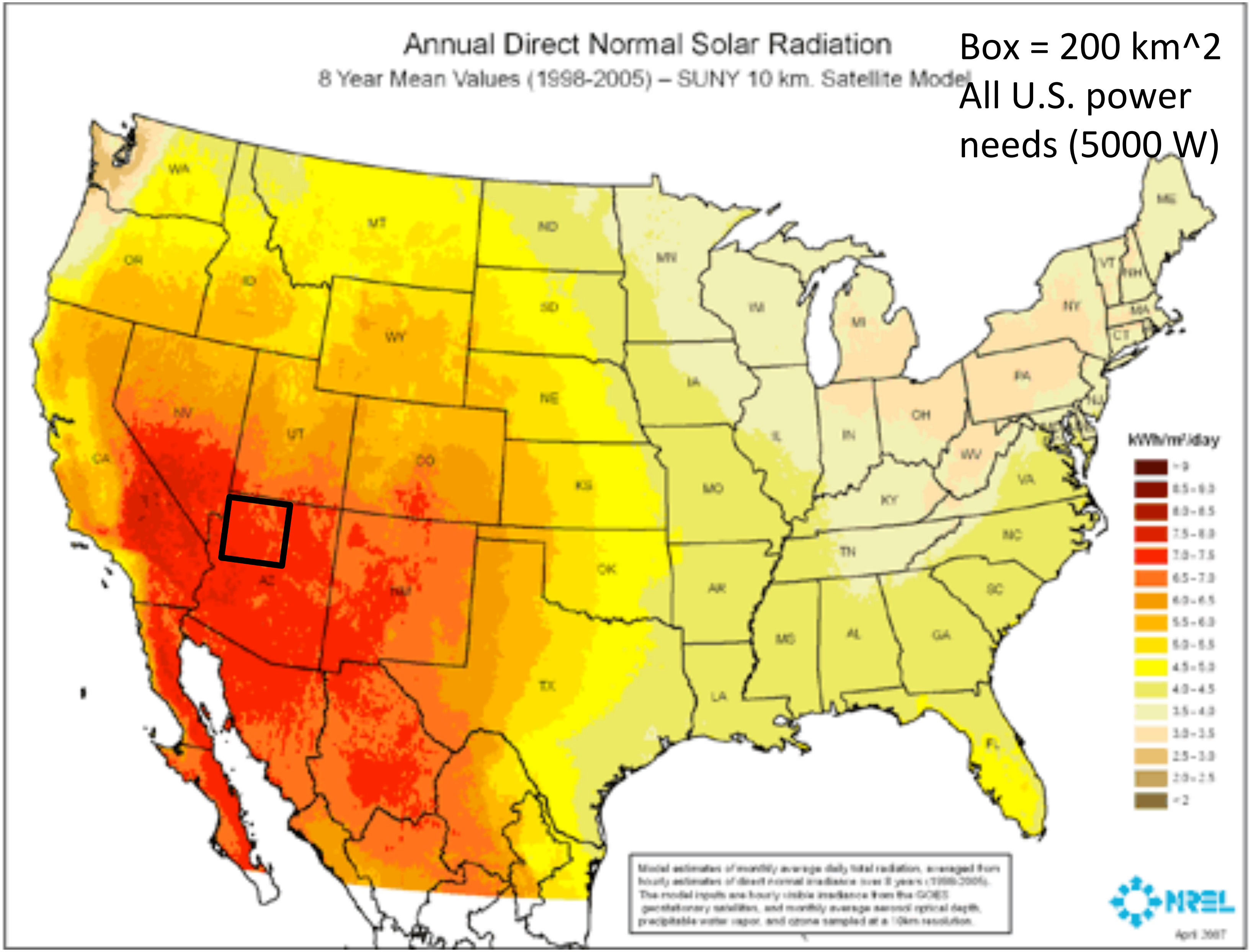
Advantage: better efficiency than a plant, and bypass the heat engine

Efficiency: ~ 15%

Effective efficiency: ~ 10% ?

Solar is the first renewable that meets our criterion:

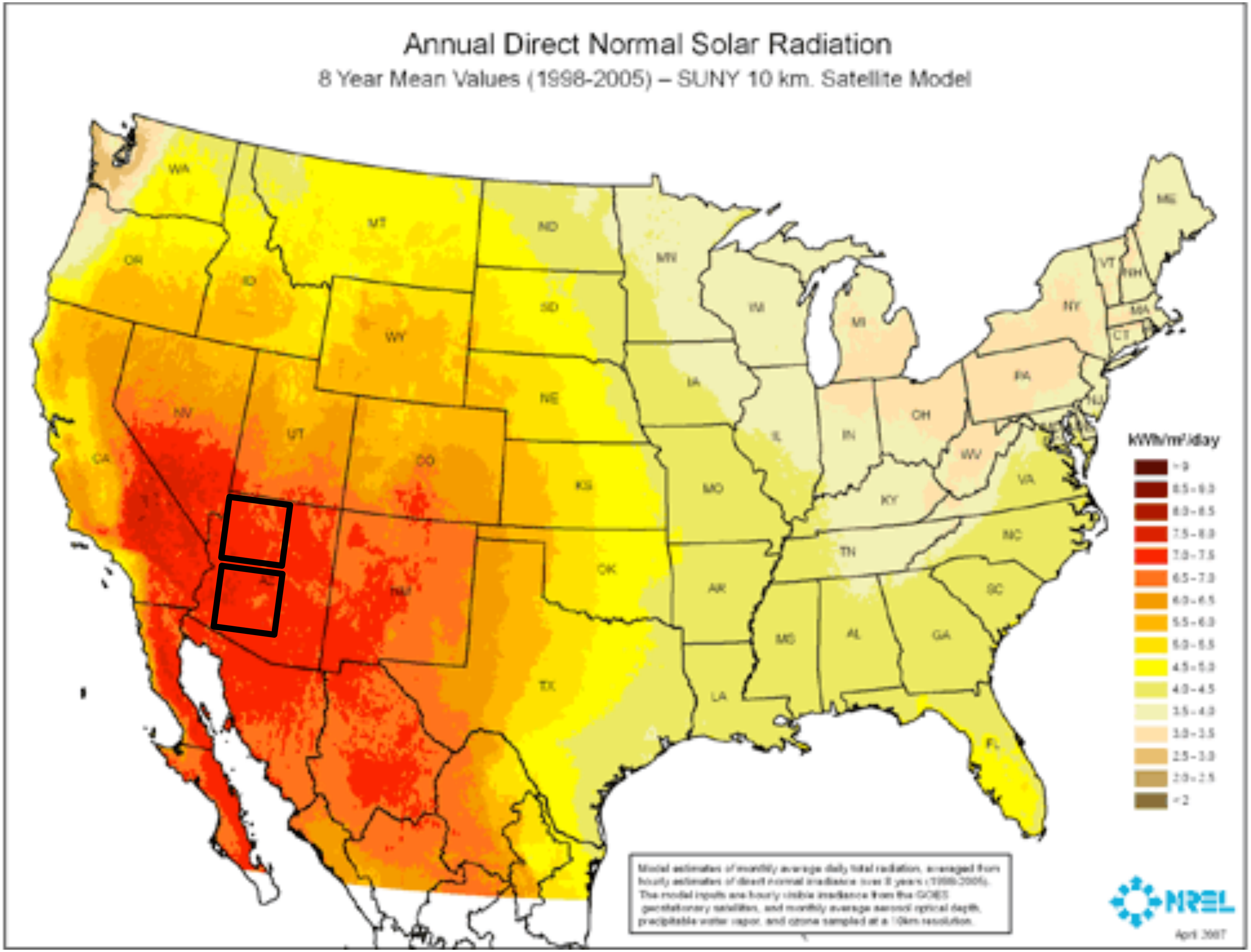
Sufficient areal energy density to power the modern world



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



Annual Direct Normal Solar Radiation

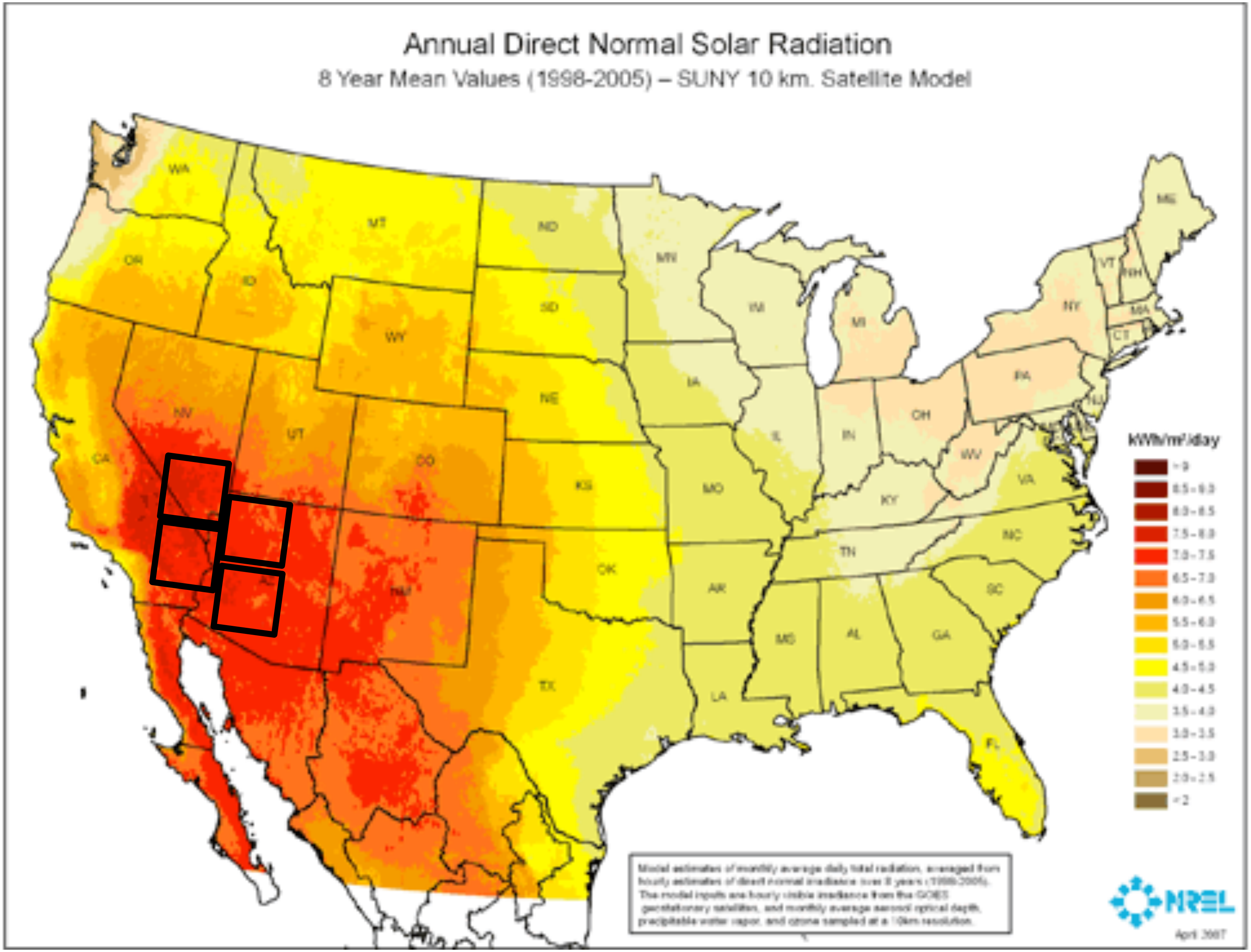
8 Year Mean Values (1998-2005) – SUNY 10 km. Satellite Model

Model estimates of monthly average daily total radiation, averaged from hourly estimates of direct normal irradiance over 8 years (1998-2005). The model inputs are hourly visible irradiance from the GOES geostationary satellites, and monthly average aerosol optical depth, precipitable water vapor, and ozone sampled at a 10km resolution.

April 2007

And we are growing richer…

Energy demands growing by 2%/yr… Increase areal needs by x 4



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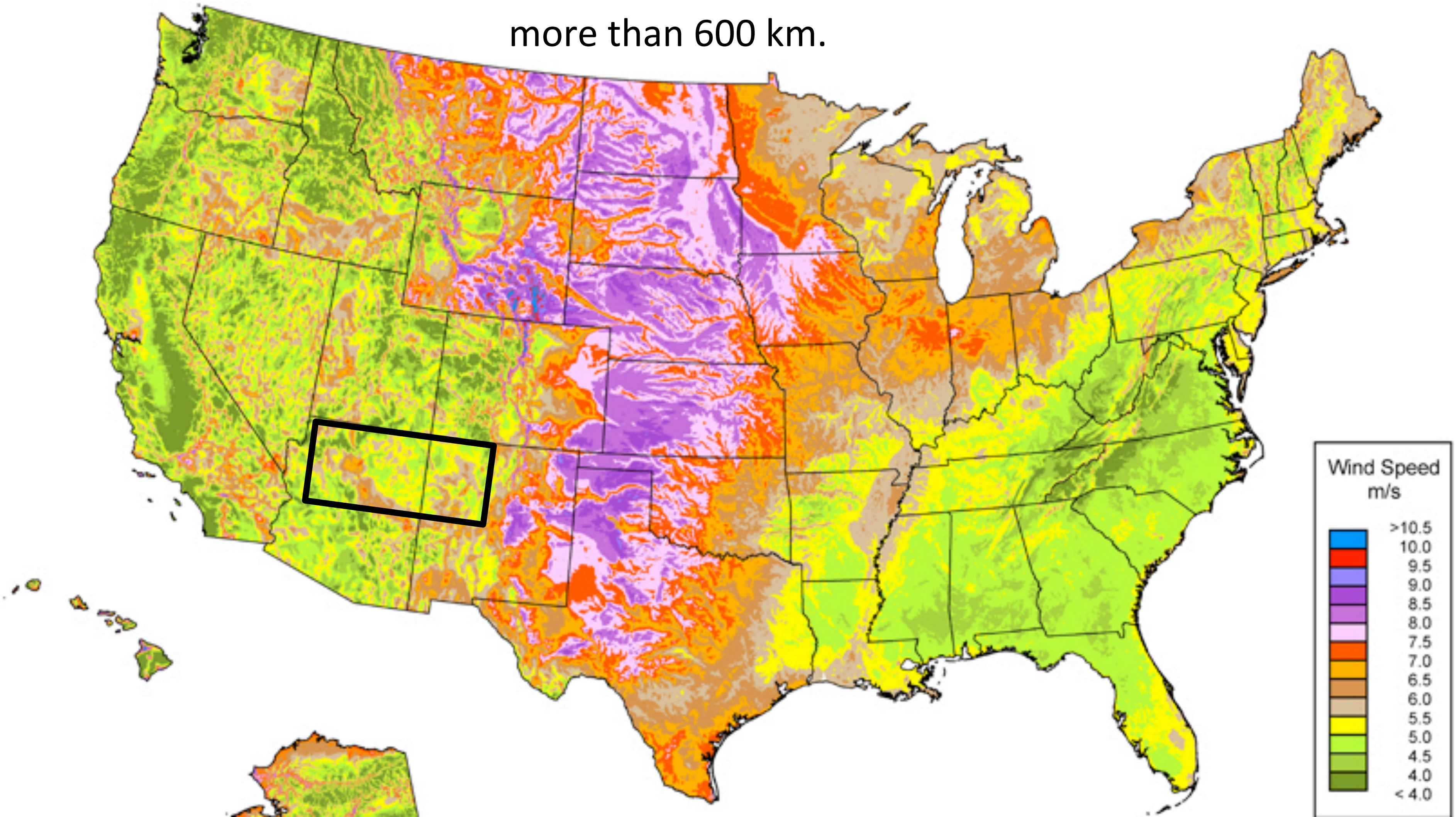
April 2007

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



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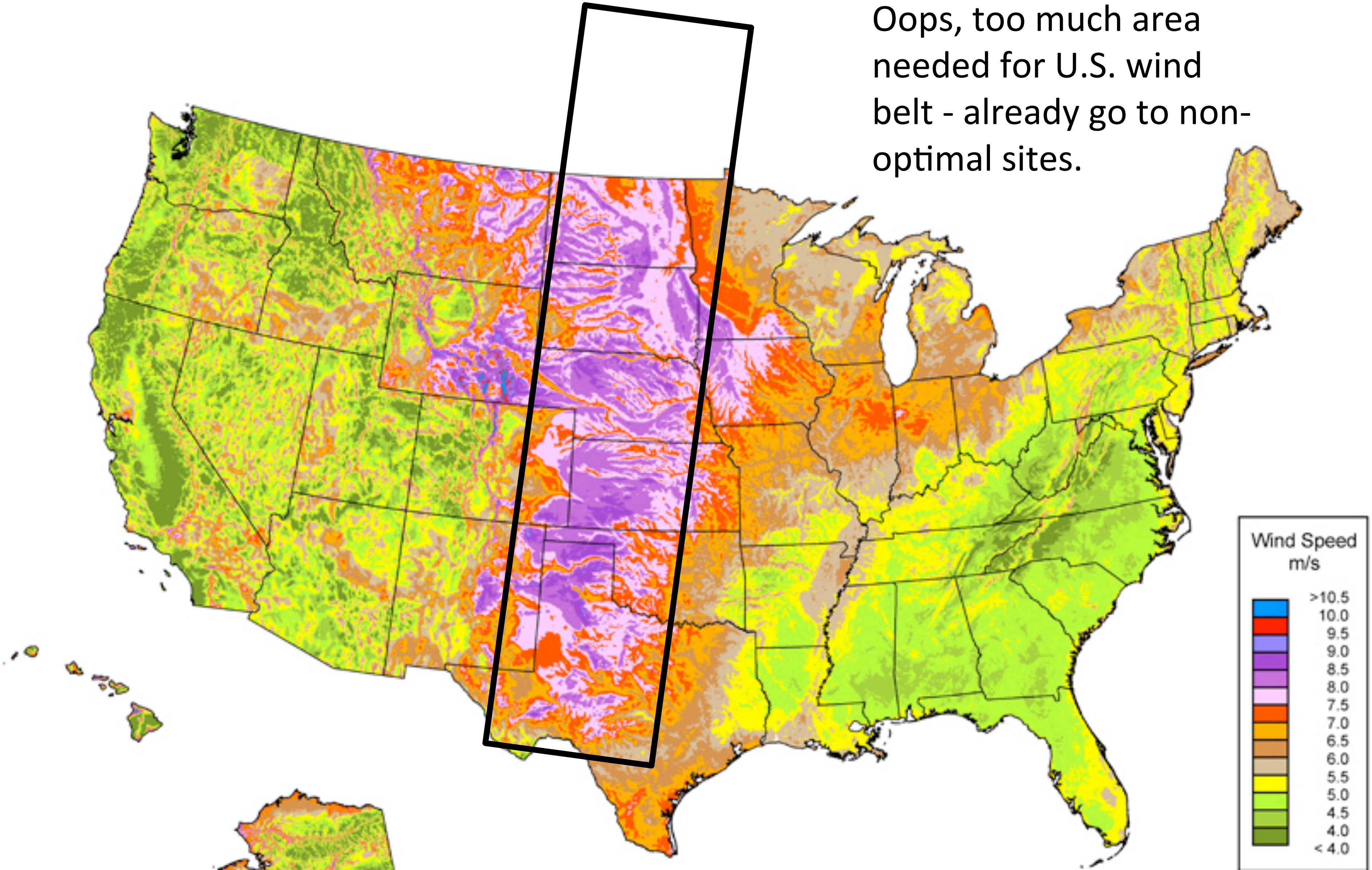

Oops, too much area needed for U.S. wind belt - already go to non-optimal sites.

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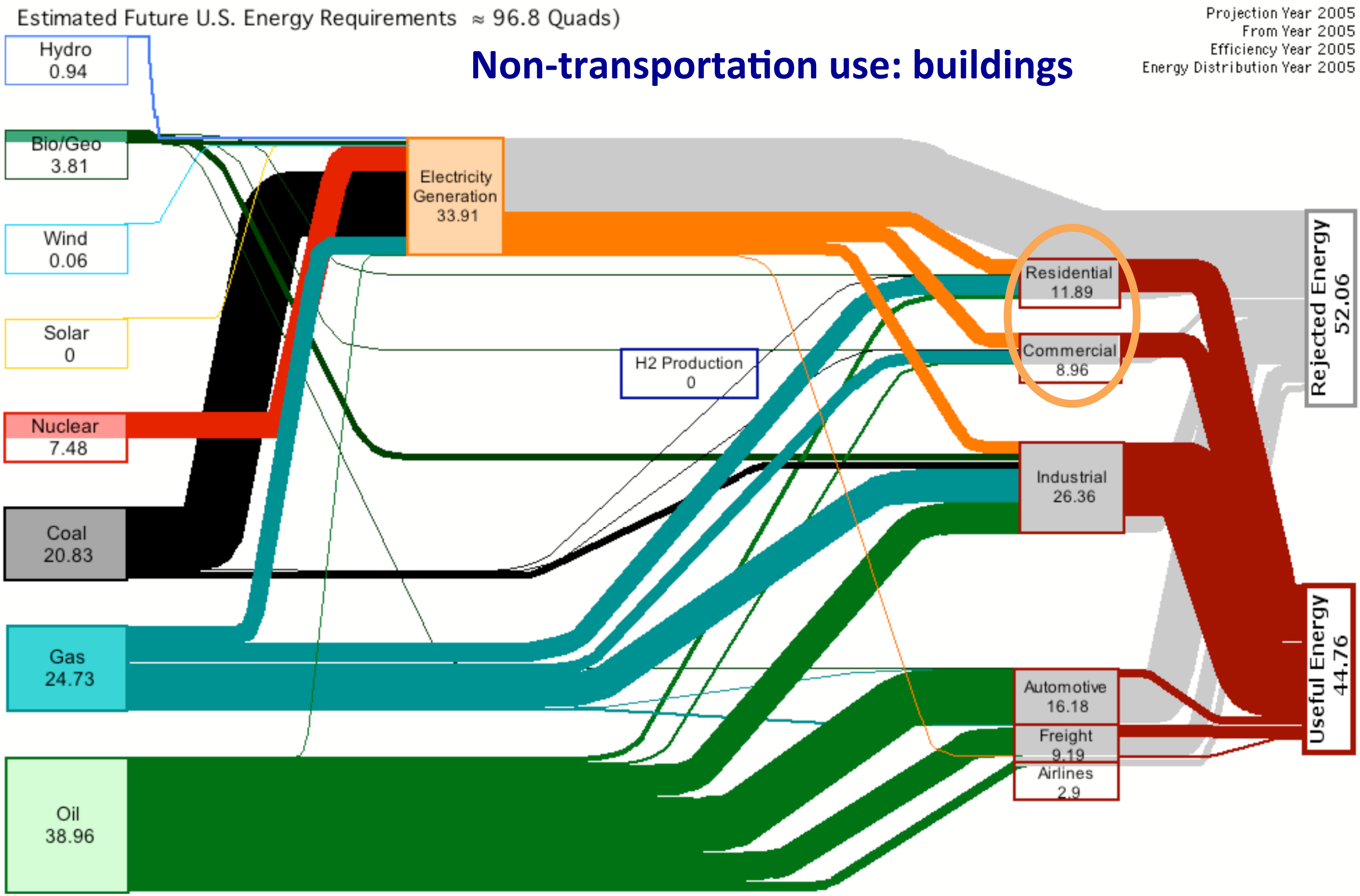


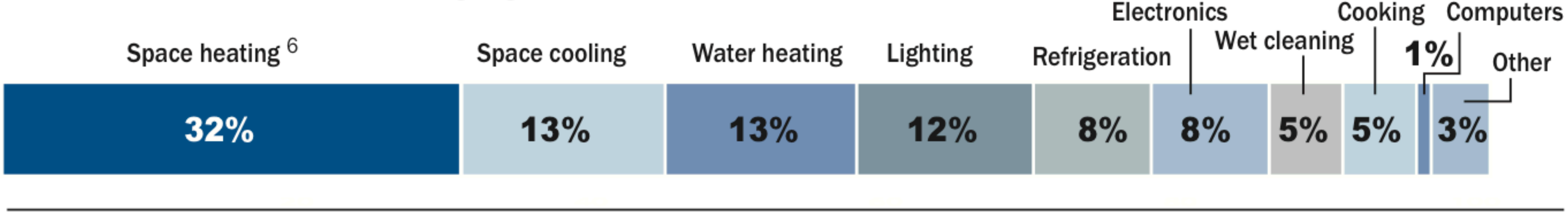
Non-transportation use: buildings

Buildings: what is all that energy used for?

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

Residential energy end usage

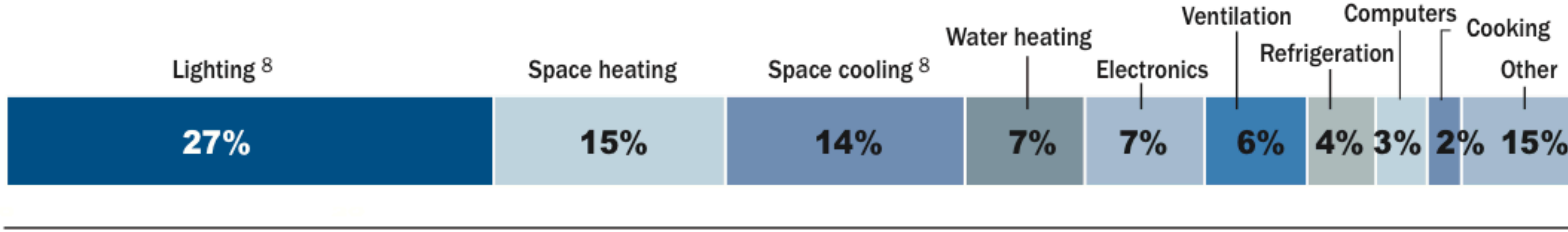
In 2006 the residential sector consumed 21.8 quads[4] of primary energy.
This chart shows the relative amounts going to various residential end uses.[5]



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.[7]
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

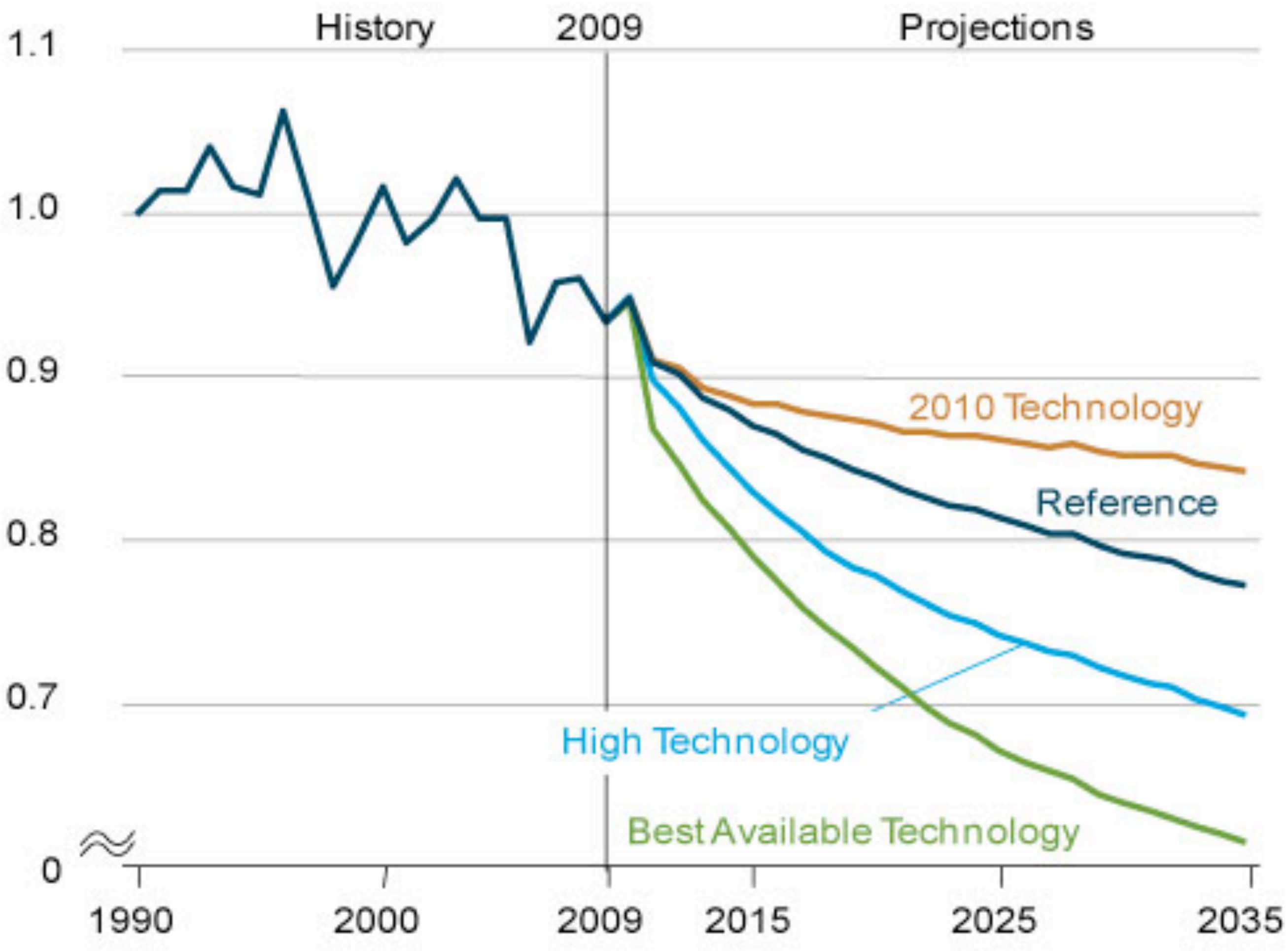
Heat and cooling:

- 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

Figure 58. Residential delivered energy consumption per capita in four cases, 1990-2035 (index, 1990 = 1)



Source: EAI Annual Energy Outlook 2011

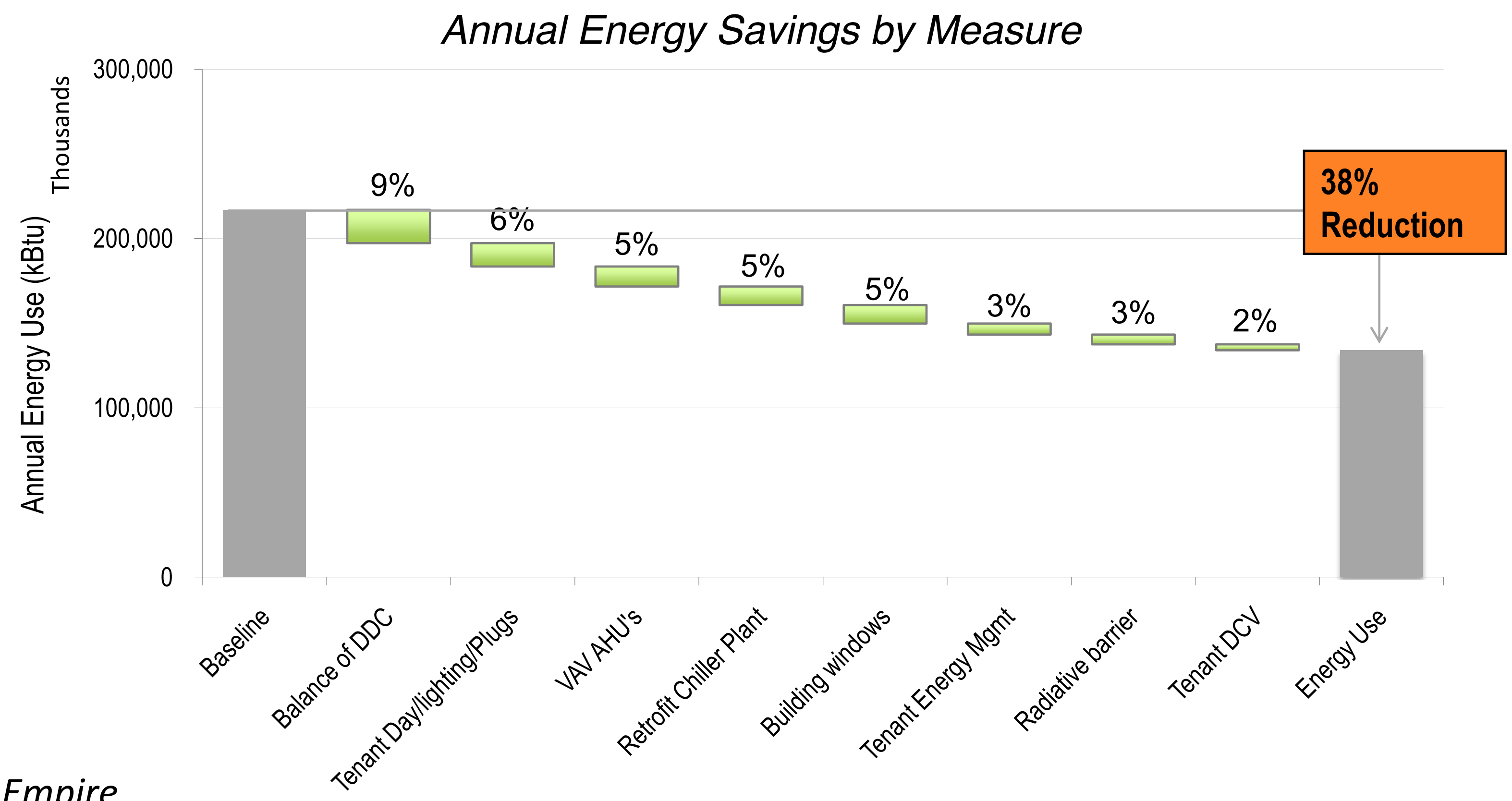
Building conservation potential estimates consistent at 1/3

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

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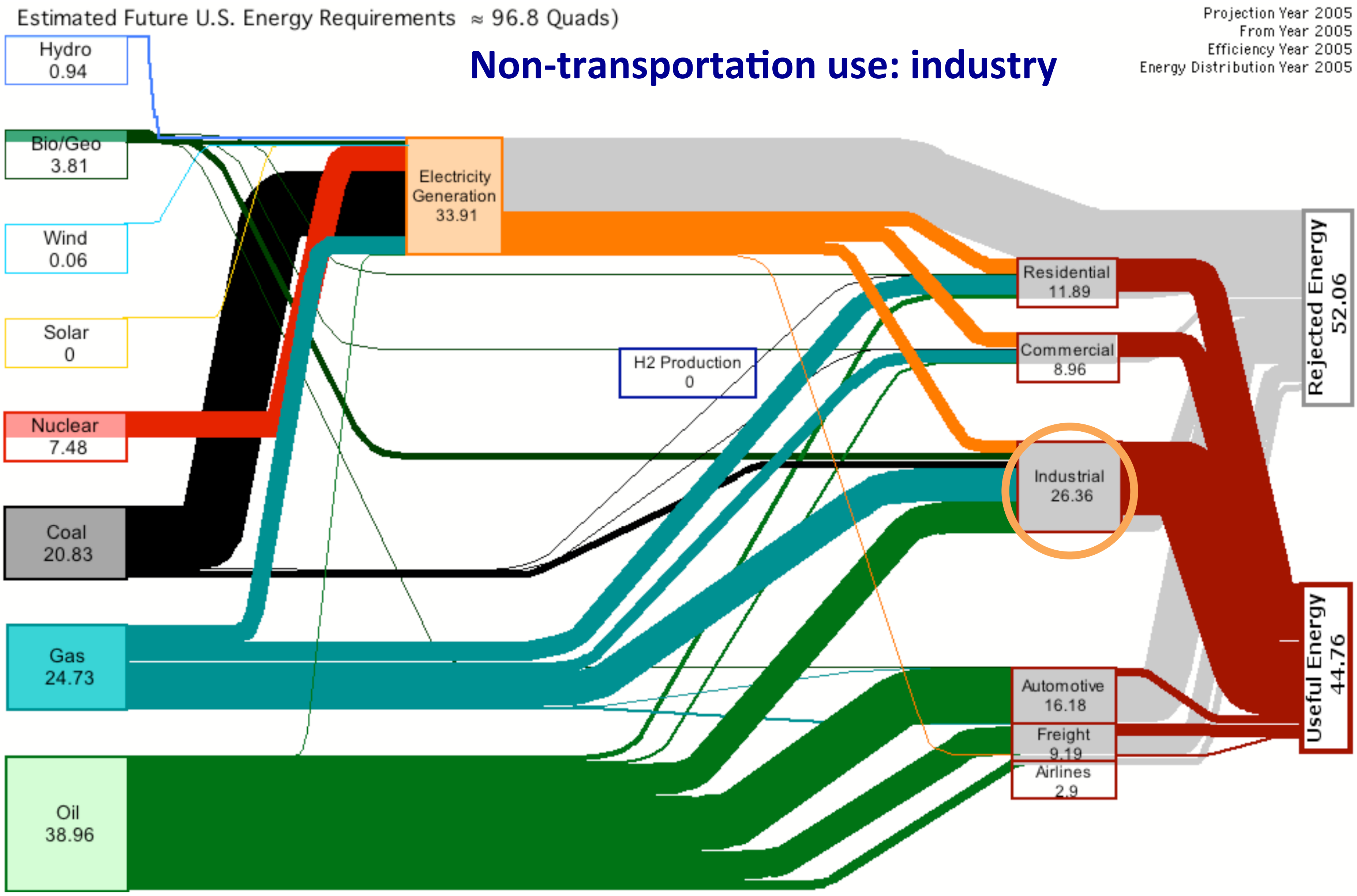
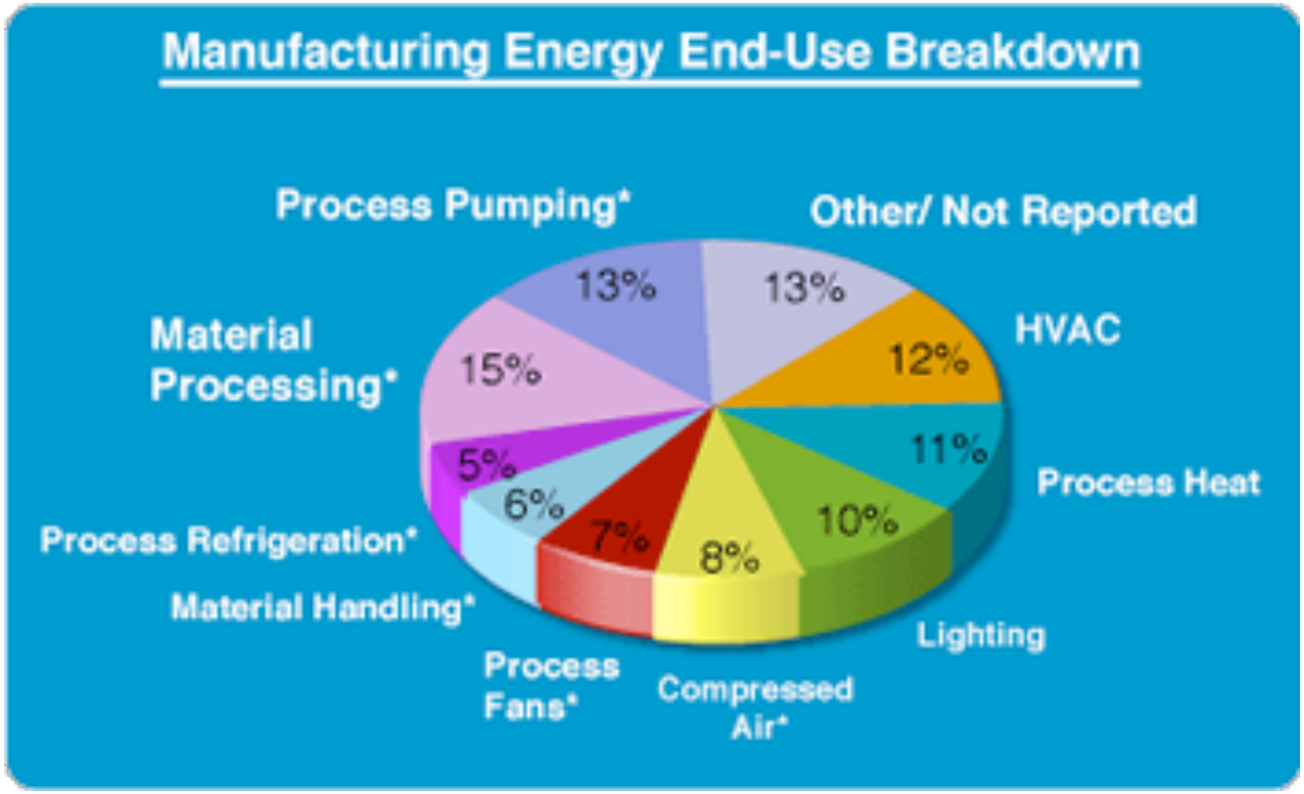
Non-transportation use: industry



Industry: what is all that energy used for?



** = Motor-driven equipment.*

California Energy Commission, "California Energy Demand 2003-2013 Forecast," February 11, 2003, #100-03-002SD and Xenergy analysis.

- 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

Industry: who uses the energy?

Energy use by industrial sector:

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

Total: 81% from just 5 industries

U.S. Energy Information Agency, 2002

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 -> $50,000/cap*yr)
→(30/5) MJ/$
→7 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

U.S. Energy Information Agency, 2002

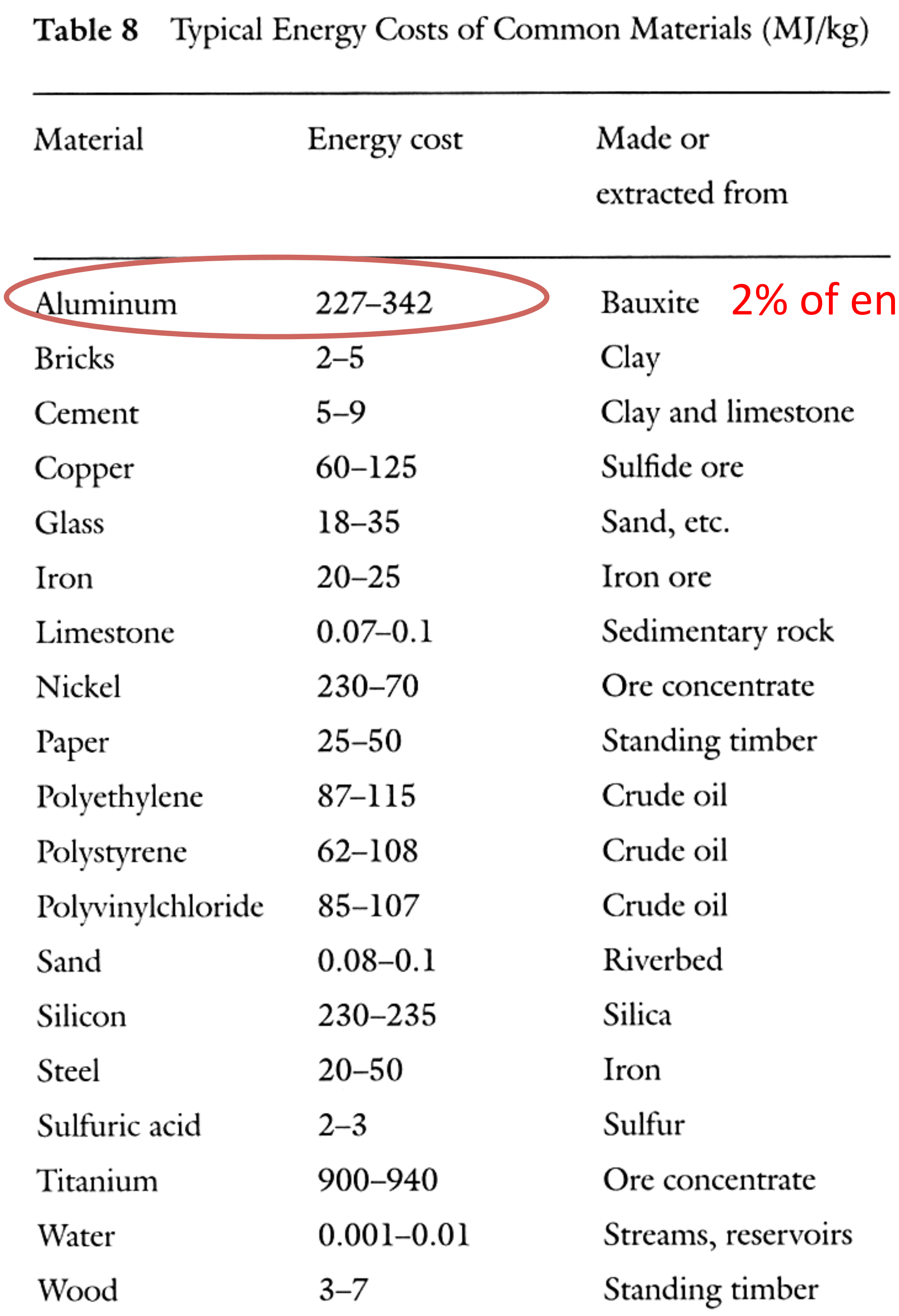


Table 8 Typical Energy Costs of Common Materials (MJ/kg)

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

2% of energy use

1% of energy use

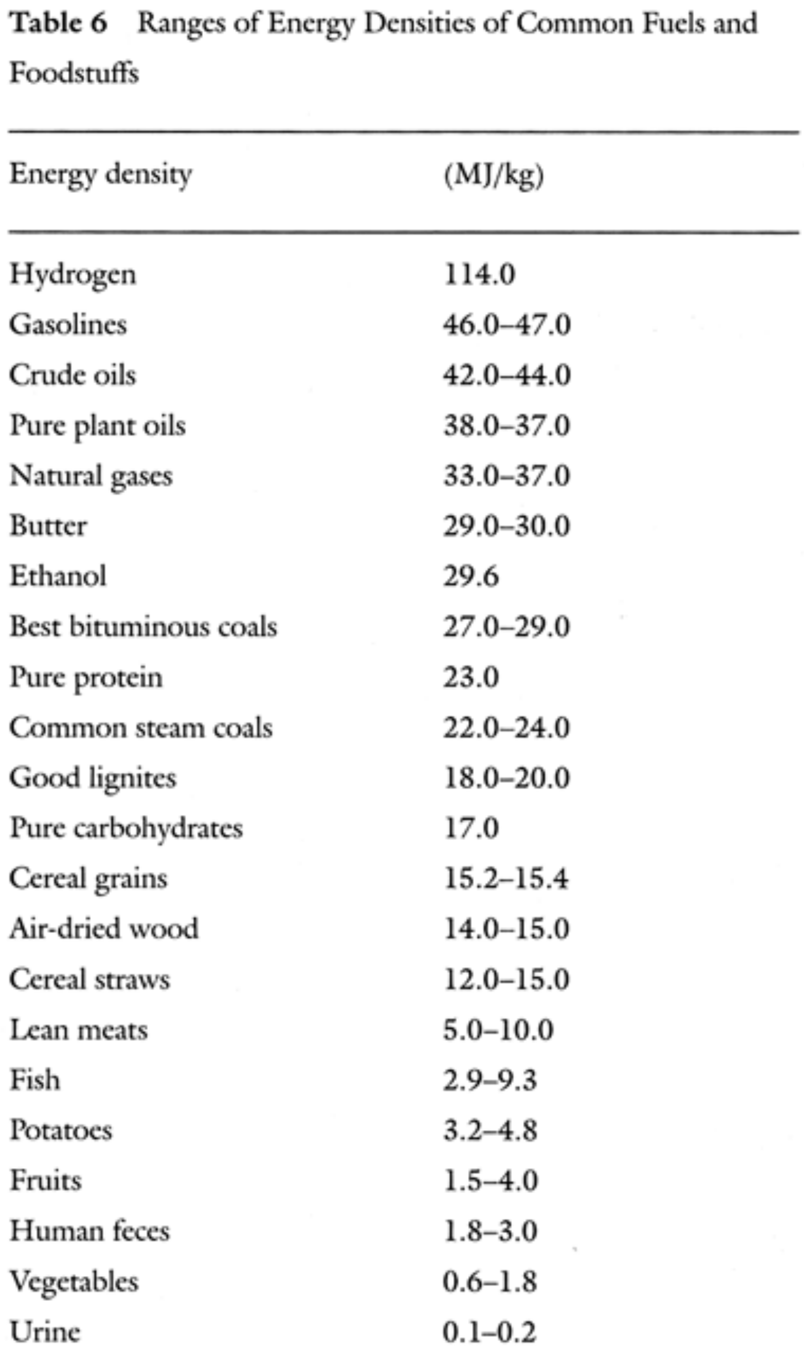


Table 6 Ranges of Energy Densities of Common Fuels and Foodstuffs

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

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)

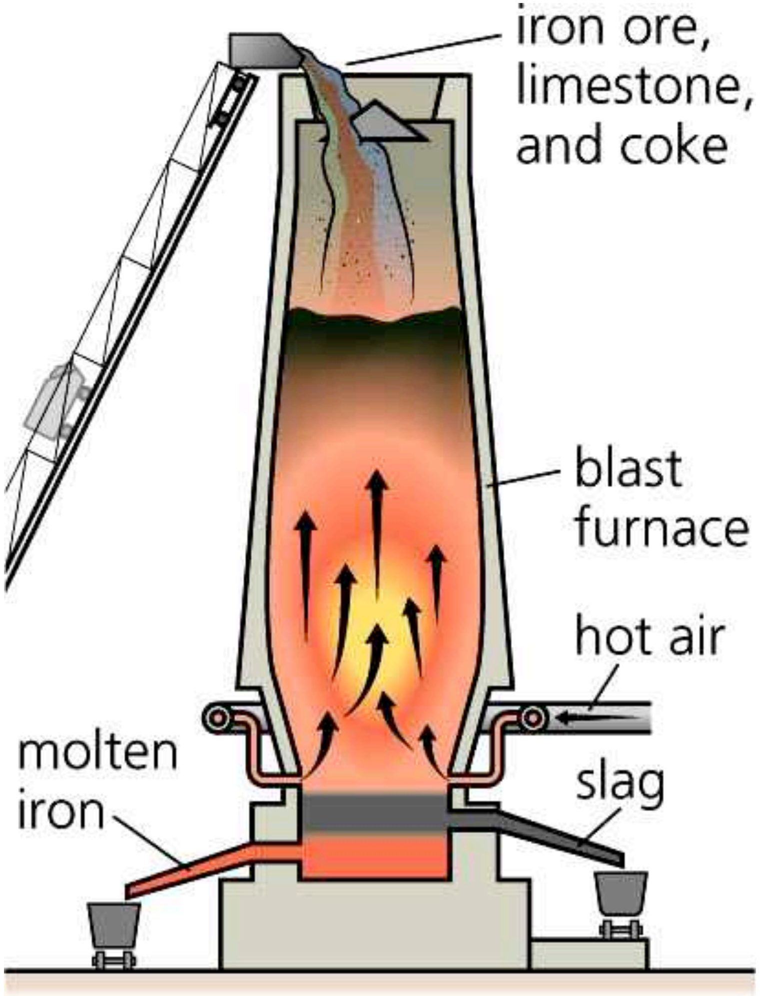
Iron: Fe_2O_3 -> Fe

Copper: $CuCO_3$ -> Cu

Lead: PbS -> 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.

Bayer process plant, W. Australia. From: CSIRO Minerals Div.

C.M. Hall at graduation from Oberlin College, 1885.

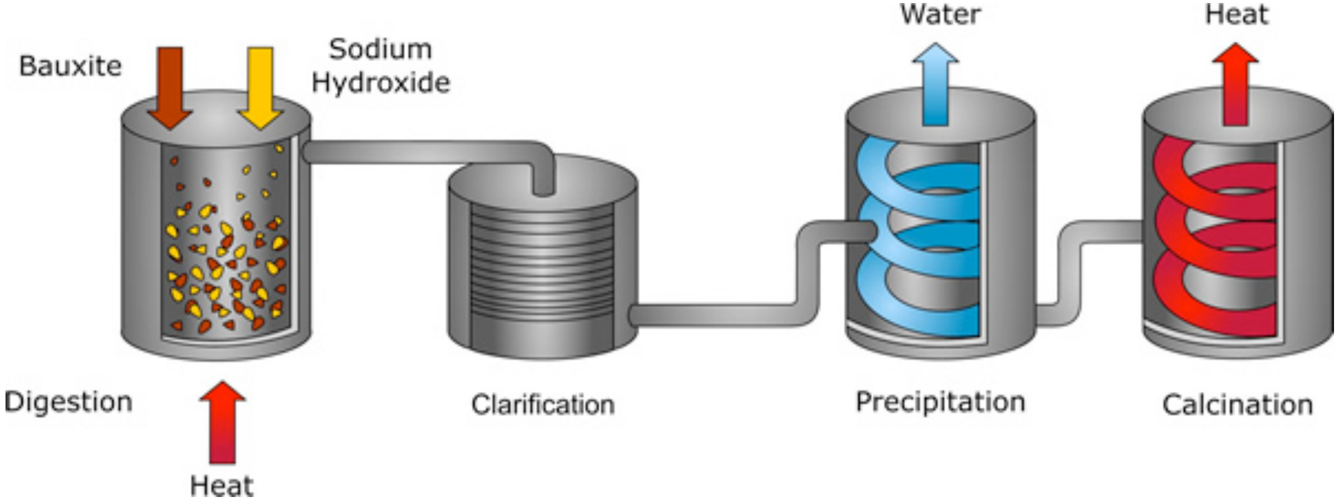
Poor U.S. research infrastructure. Hall entered Oberlin age 16, no chemistry courses til junior year. Electricity for experiments only through homemade batteries. Worked in woodshed behind his parents' house.

Aluminum: Chemical processing of alumina ore (Bayer process)

1. **Mechanical crushing** of bauxite
2. **Dissolution** in caustic soda (sodium hydroxide, NaOH, a base)
   $Al(OH)_3 + Na^+ + OH^- \dashrightarrow Al(OH)_4^- + Na^+$
3. **Clarification** to remove impurities (esp. iron oxides)
4. **Crystallization** of alumina hydrate in precipitator (gibbsite)
   $Al(OH)_4^- + Na^+ \dashrightarrow Al(OH)_3 + Na^+ + OH^-$
5. **Calcination** drives off water to form alumina: $2Al(OH)_3 \dashrightarrow Al_2O_3 + 3H_2O$

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 N_2
Most ecosystems on Earth are nitrogen-limited, so important for fertilizer

N is "fixed" from N2 by some bacteria

$N_2 + 6\,H^+ + 6\,e^- \rightarrow 2\,NH_3$

Symbiotes in root nodules of some plants:

- Soybeans, peanuts, peas,
- Clover, lupines

Photo: W. Eberhart, Getty Images

Fixed nitrogen is explosive

Nitrogen "wants" strongly to be in N_2 , so get violent reactions.
Most explosives are N-based

e.g. nitroglycerin (dynamite), TNT (trinitrotoluene), gunpowder (potassium nitrate), ammonium nitrate (both fertilizer and explosive).

History of nitrogen use by industry

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.

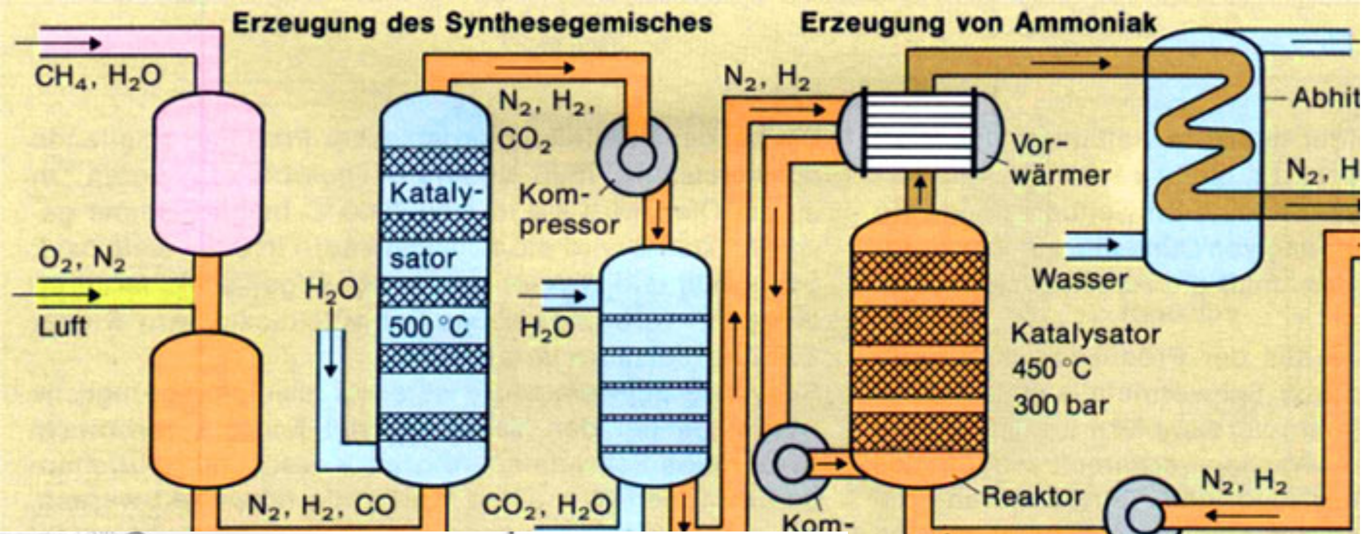
Synthetic nitrogen fixation invented 1909 by German chemist Haber, commercialized by Bosch just before WWI. Contributed to war effort (explosives). Nobel prizes for both.

Haber-Bosch process:

Making ammonia from natl. gas (CH_4) and air (N_2)

Currently 1% of world & U.S. energy use – in U.S., same as food energy..

Fritz Haber
Nobel Prize, 1918



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)

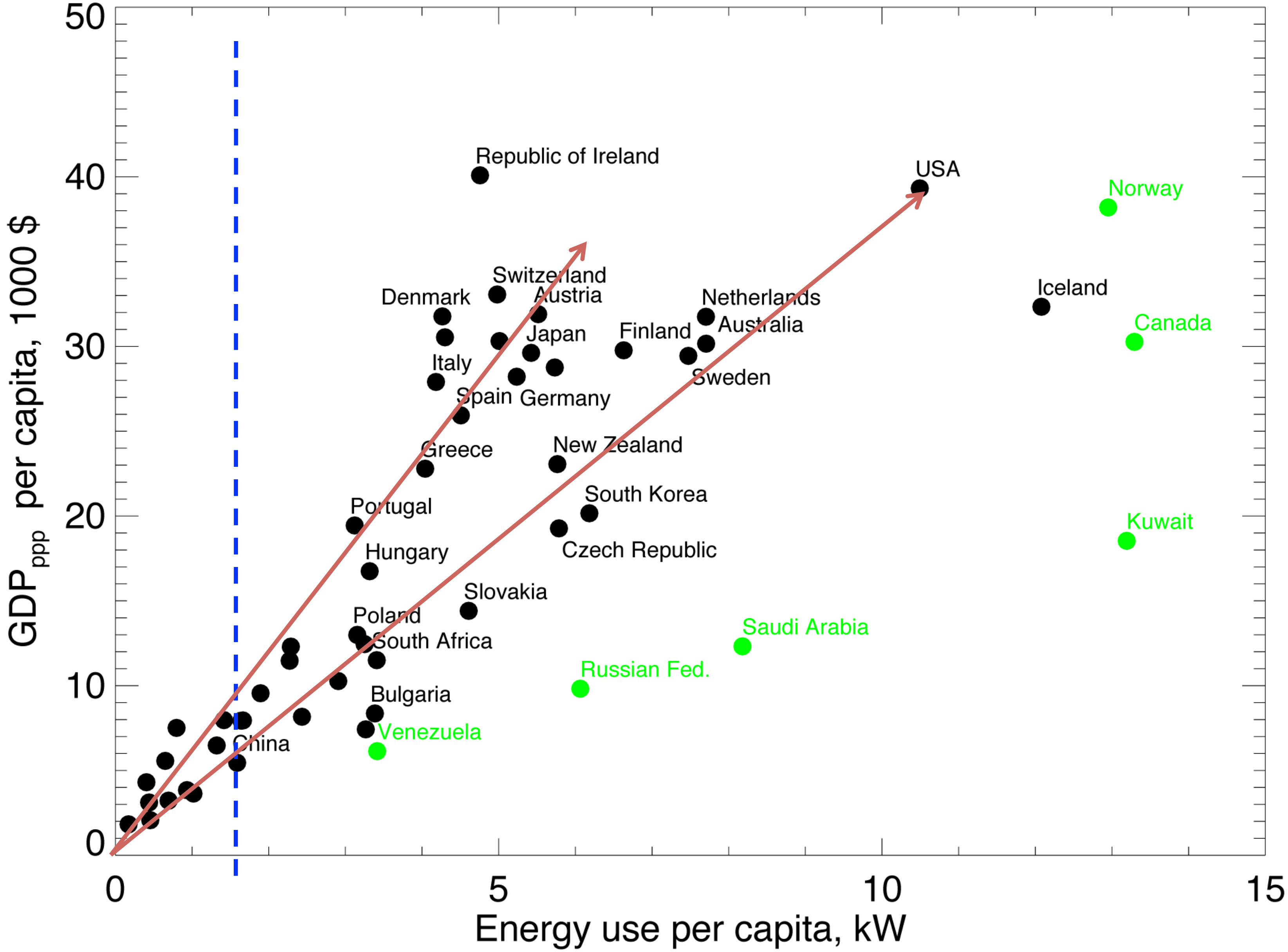
If target was 80% drop from current levels,
U.S. use would drop from:

- 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

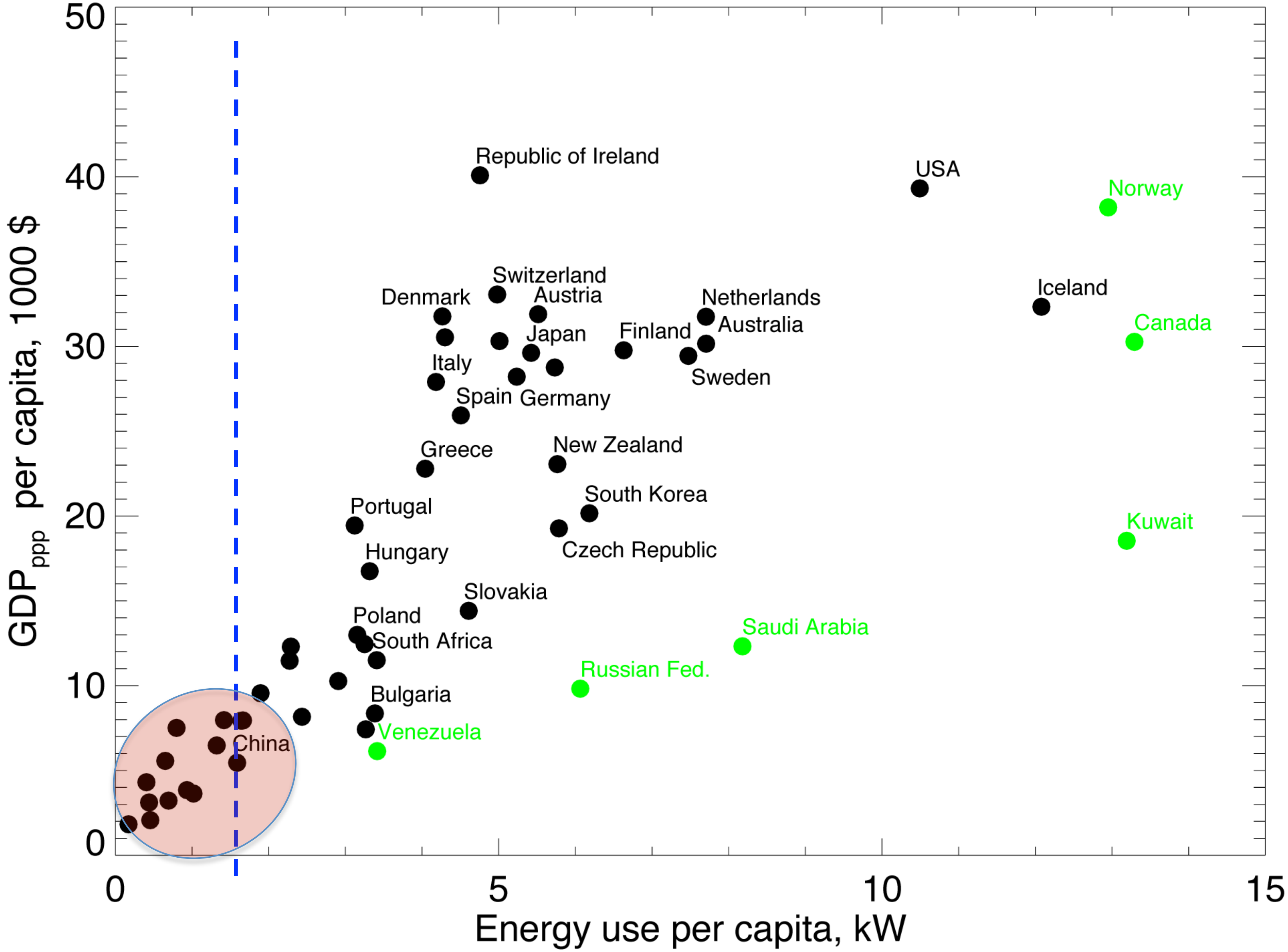
Likely can't conserve our way out of energy / emissions crisis



Data: EIA, U.N

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

And can't ask developing world to stay poor….



Data: EIA, U.N

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

$E_{use} = E_{use\_0} * e^{rt}$

Means e-folding (x e or x 2.7 increase) in

$\tau = 1/r = 50$ yrs

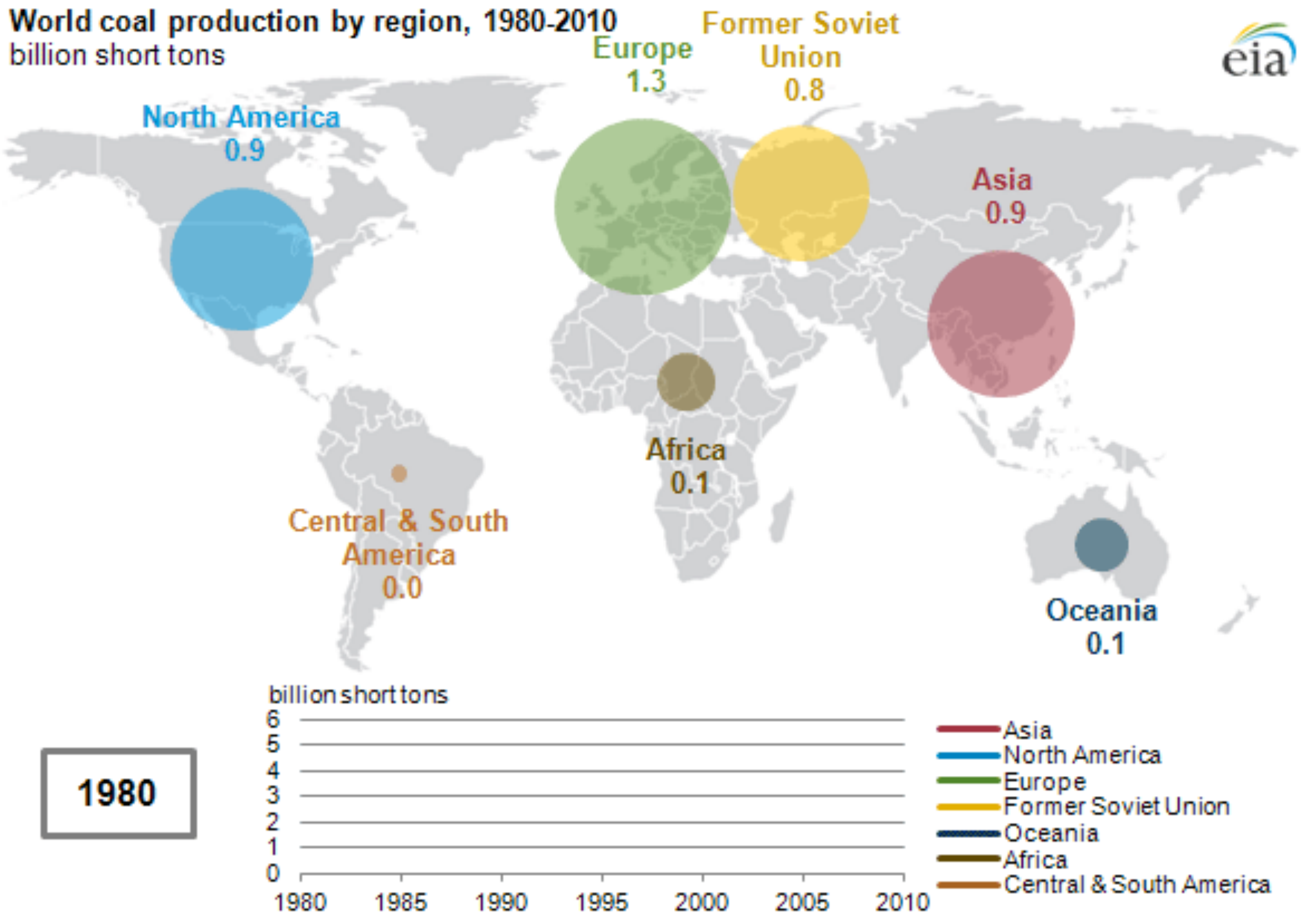
Doubles in less time

$\tau_2 = \ln(2)/r = 34$ yrs $\quad\quad \ln(2) \sim 0.7$

30% growth in $t = \ln(1.3)/r = 13$ yrs

All the conservation that we can imagine just buys us a bit over a decade….

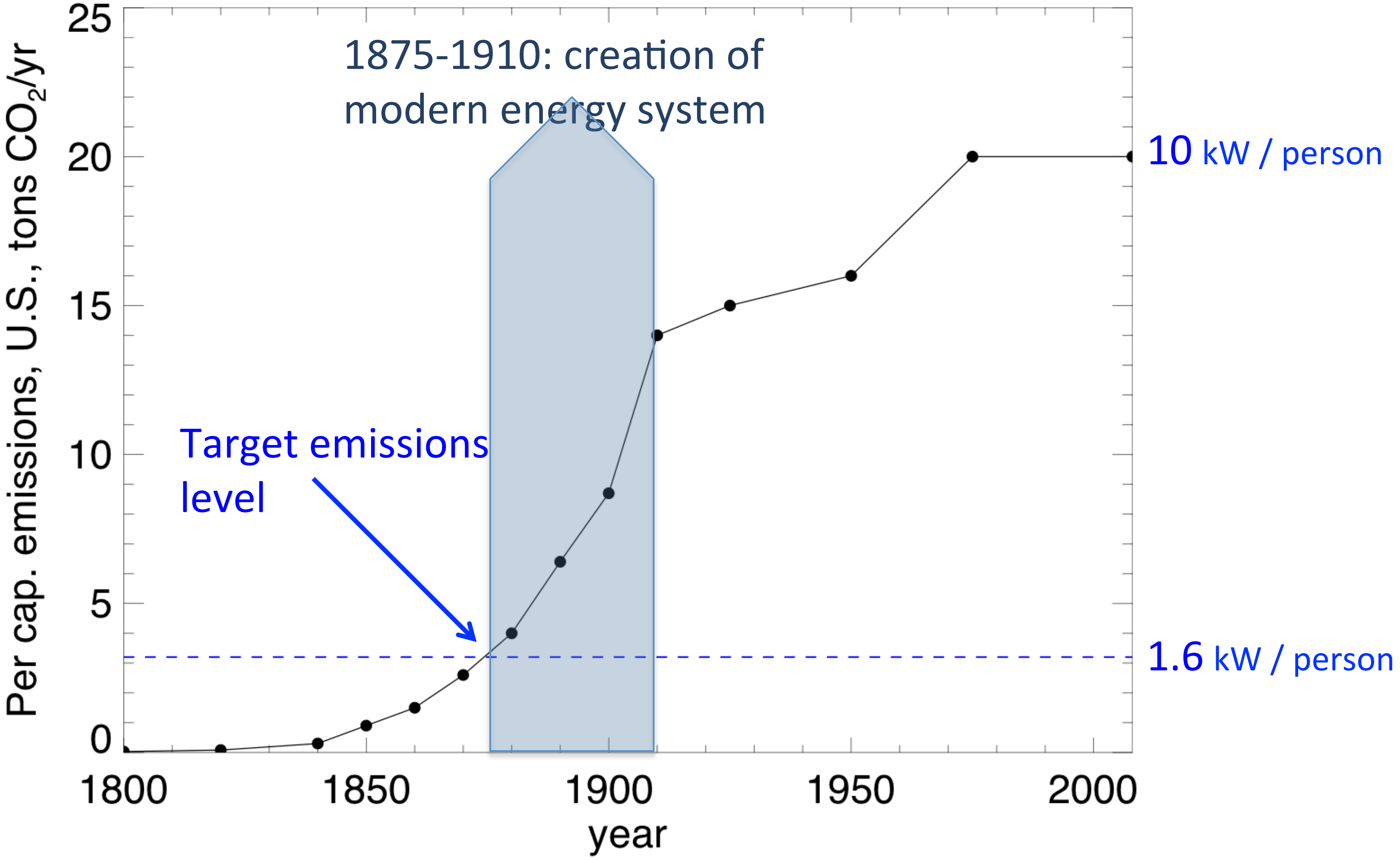
We can’t conserve our way out of an energy crisis



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

1870's-1910	Newer

Energy sector is resistant to innovation

1870's-1910	Newer
Hydro turbine (1848) *(a bit earlier)* Steam turbine (1884)	
AC generator and transformer (1888)	
3-phase power transmission (1895 demo)	
Induction motor (1885-1888)	
Incandescent bulb (1880 commercialized)	
Internal combust. engine: Otto cycle (1876)	
Internal combust. engine: Diesel cycle (1892)	
Automobile (1885)	
Air conditioner (1902)	
Airplane (1903)	
Hall–Héroult: aluminum (1888)	
Haber-Bosch: N fixation (1908)	

Also: phonograph (1877), telephone (18 76), movies (1877,1895), photographic film (1884), radar (1887)

Energy sector is resistant to innovation

1870's-1910	**Newer**
Hydro turbine (1848) *(a bit earlier)* Steam turbine (1884)	*Semiconductors, transistors, diodes, and all their offspring:*
AC generator and transformer (1888)	Light-emitting diodes (LEDs)
3-phase power transmission (1895 demo)	Solar photovoltaics
Induction motor (1885-1888)	Computers & electronics
Incandescent bulb (1880 commercialized)	Brushless DC motors
Internal combust. engine: Otto cycle (1876)	FACTS grid control
Internal combust. engine: Diesel cycle (1892)	DC transformers, HVDC transmiss.
Automobile (1885)	*also*
Air conditioner (1902)	Nuclear power generation
Airplane (1903)	
Hall–Héroult: aluminum (1888)	
Haber-Bosch: N fixation (1908)	

Also: phonograph (1877), telephone (18 76), 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?