A brief overview of our energy challenge(s) …

Robert Rosner
Dept. of Physics & Harris School of Public Policy
The Univ. of Chicago

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R.E. Smalley's view of Humanity's Top Ten Problems for the next 50 years …

1. **ENERGY**
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

… that was the view in 2005

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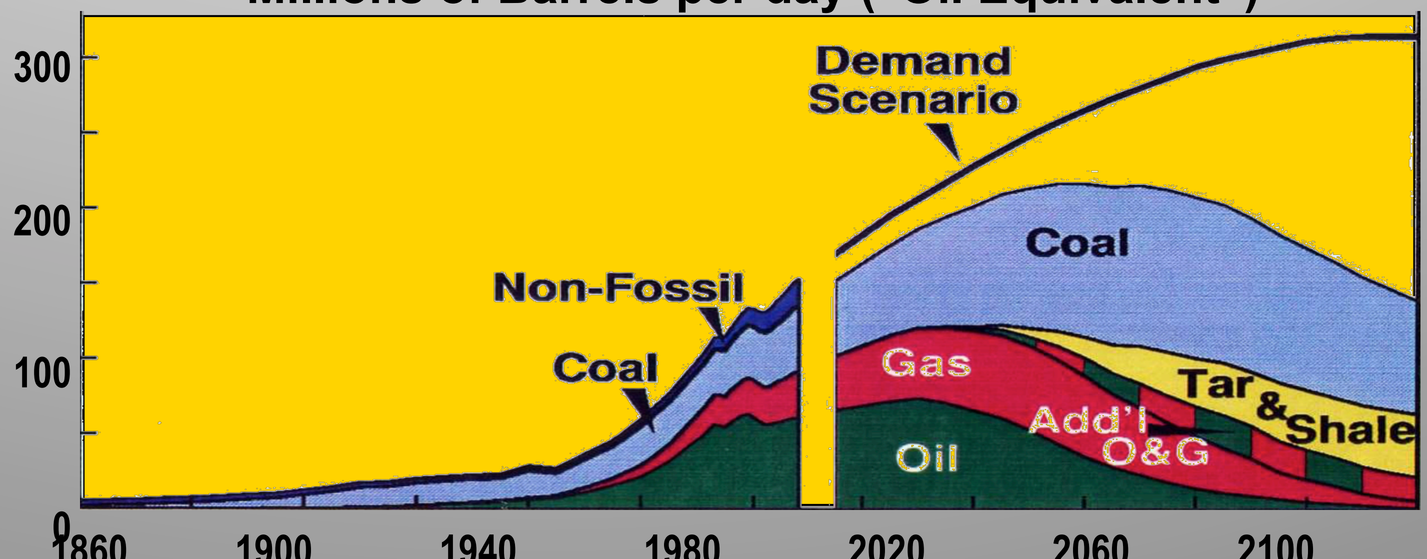
Here's how things looked like back in ~2005 …

- Population growth projections
  - 2004: ~ 6.5 billion people
  - 2050: ~ 10 billion people
- Energy demand growth
  - Population increase
  - **Increased expectations**

Source: John F. Bookout (President, Shell USA) ,"Two Centuries of Fossil Fuel Energy" International Geological Congress, Washington DC; July 10,1985.
Episodes, vol. 12, 257-262 (1989).

Millions of Barrels per day ("Oil Equivalent")



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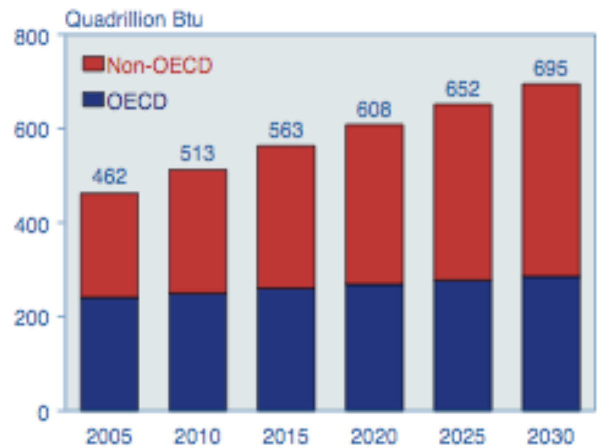
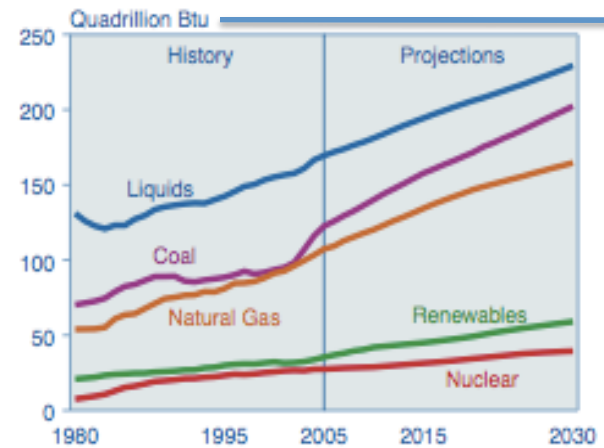
1 BTU (British Thermal Unit) = energy required to raise the temperature of 1 lbs of water by 1° F

World Marketed Energy Consumption, 2005-2030



Sources: **2005:** Energy Information Administration (EIA), *International Energy Annual 2005* (June-October 2007), web site www.eia.doe.gov/iea. **Projections:** EIA, World Energy Projections Plus (2008).

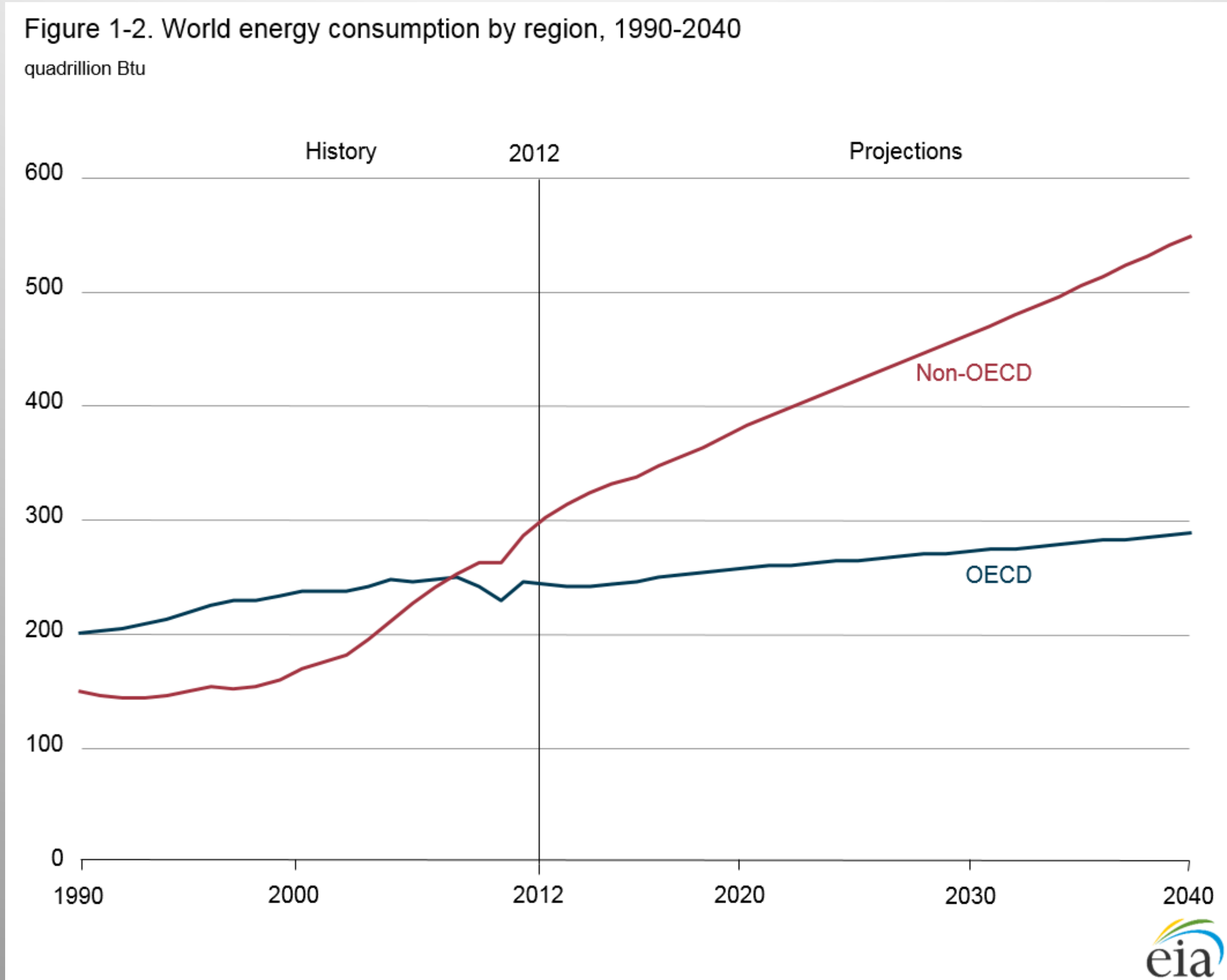
Figure 2. World Marketed Energy Use by Fuel Type, 1980-2030



Sources: **2005:** Energy Information Administration (EIA), *International Energy Annual 2005* (June-October 2007), web site www.eia.doe.gov/iea. **Projections:** EIA, World Energy Projections Plus (2008).

Source: DOE Energy Information Service, June 25 2008

… and 11 years later, things don't look any different …



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http://www.eia.gov/forecasts/ieo/world.cfm | Updated May 11, 2016

… and here are some things to keep in mind

There are two main drivers of governing today's world energy systems:

Energy security – Making sure that society has the energy available to sustain our standard of living

- For the U.S., this reduces to the question: Do we have secure access to what we need, and for how long do we have this sort of access?
- Note that 'energy independence' (which is NOT a synonym for 'energy security') is not a realistic goal for the U.S., given the global market for most fuels …
  - Natural gas is a recent, and important, exception …

Climate change – Making sure that the production and use of energy does not impinge on the quality of life …

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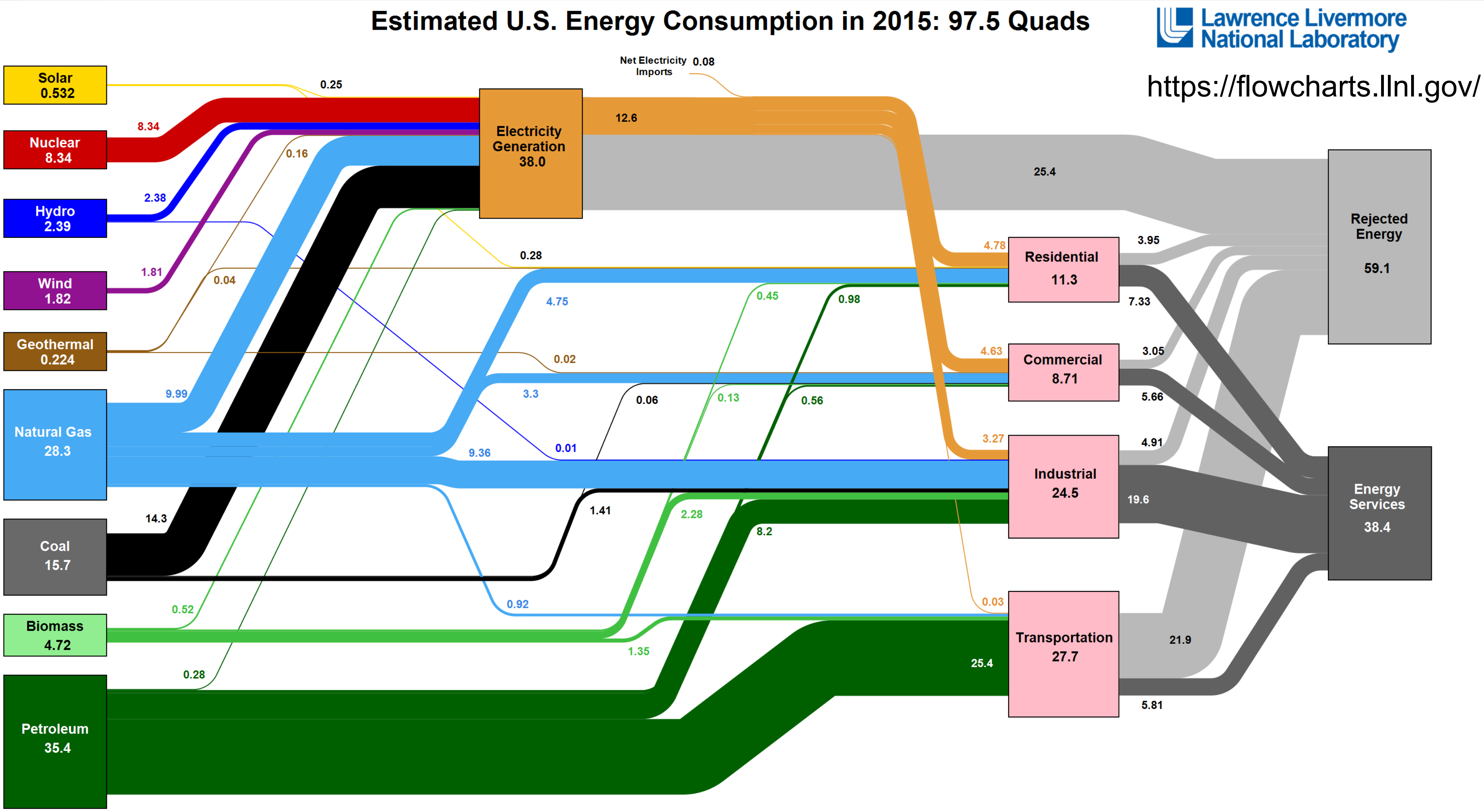
… and here are a few more things to to keep in mind

- Our energy problems of today are NOT the same as those of the 1970s
  - It was all international politics in the '70s, driven by OPEC's need to assert itself
  - Today the dominant driver is the need to respond to ongoing climate change …
- The sustainability problem with the 'business-as-usual' (BAU) energy path is not that we are running out of energy supplies …
  - It's that we are running out of cheap and easily recovered liquid fuels
  - It's that we are running out of environment …
  - It's that readily available supplies are increasingly precariously balanced against sharply increased demands …
    - … and the emerging nations are seriously focused on locking in access to key raw materials – consider China's approach in Africa & Australia …
- Solutions for the industrialized nations may not be relevant for the developing (and undeveloped) nations …

Let's now turn to …

- Some numbers, to put things into context …
- An overview of
  - Climate constraint(s)
  - Energy use options (and costs) in a climate-constrained energy future
- An overview of energy alternatives … and a very abbreviated version of evaluation …

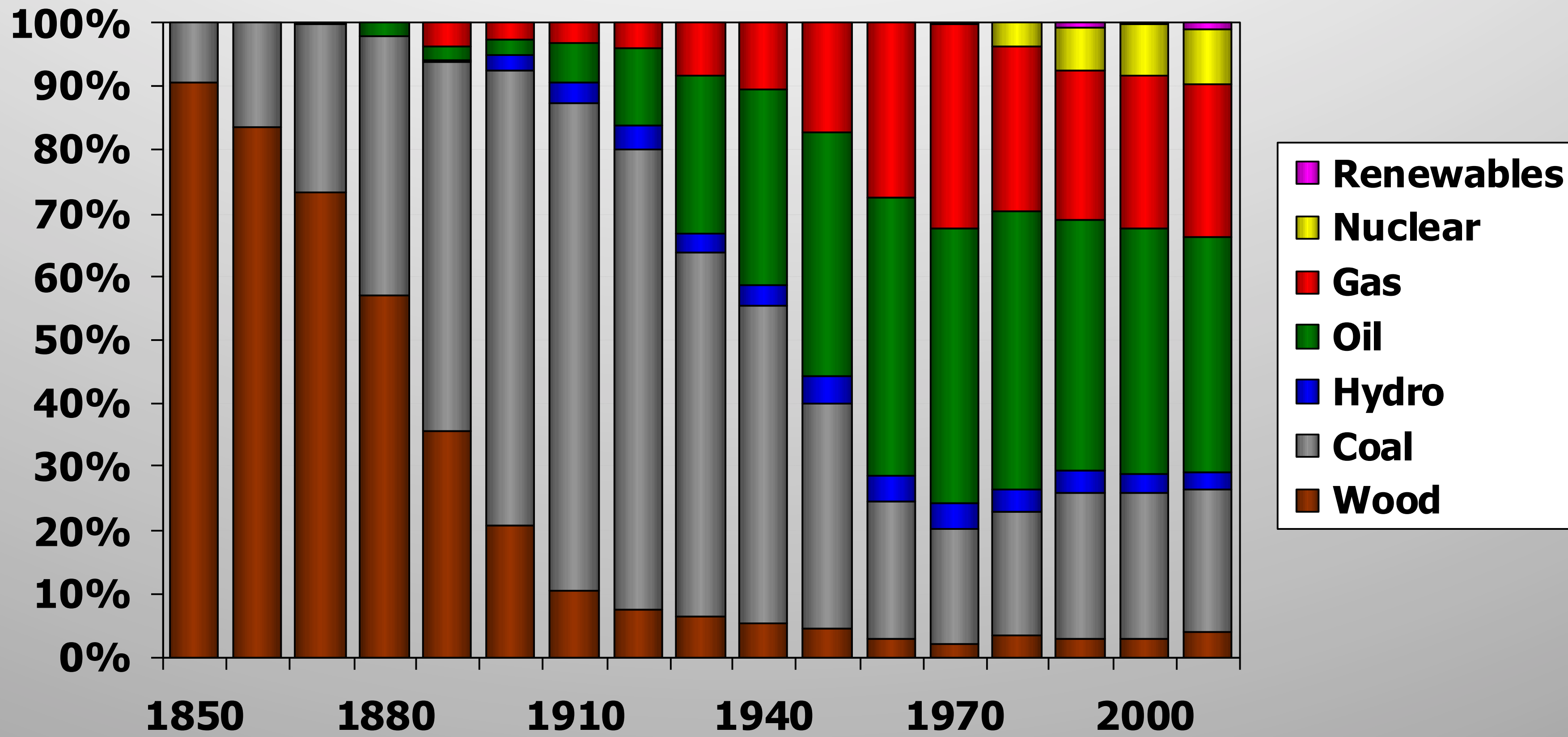
So: where does our energy come from, and how is it used?



This is a "Sankey" diagram …

- #s all in 'quads'; 1 quad ~ 10^{15} BTU ~ 1.055 x 10^{18} joules (~ 1 exajoule)

How easy is it to change from one energy technology to another?



- Historically, U.S. energy systems have changed on a time scale of 3-4 decades (!)
- The reasons boil down to the very high cost of change: infrastructure, social and other resistance, …

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How easy is it to change from one energy technology to another?

- A central issue you will hear about, over and over again, at this workshop is that in many cases, it is not technological readiness that determines how energy technologies are deployed …
- Instead, what often matters most is a mix of
  - Economics ...
  - Regulations …
  - Politics …
- The Obama Administration's attempts to reign in the coal industry is a case study – illustrating the challenges faced when trying to implement well-understood technological changes that carry with them considerable economic and political consequences …

So: let's start by talking numbers … first, electricity

- US energy needs break down into:
  - Electricity generation: ~ 40%
  - Transport (cars, …): ~ 30%
  - Heat: ~ 30%
  - In an 'average' home: Heating/cooling ~ 42%; lighting/appliances ~ 36%; water heating ~ 14%; refrigeration ~ 9%

- Let's say a 'typical' person in the US (World Bank/IEA 2014) consumes ~ 13,246 kWh per year (including transmission losses, …), or – on average – ~ 1.5 kW
  - A city of 1,000,000 requires ~1.5 GW of power
  - Large stationary power plants typically produce 1-2 GW: so 1,000,000 people need ~ 1-2 large power plants
  - "Perfect" solar: ~1.3 kW/m^2, 8 hrs/day, 0.43 kW average over 24 hours -> ~3.5 sq. km area
  - Wind: 1 MW/turbine -> 1,400 turbines (if wind blows steadily)

So: let's start by talking numbers … second, transport

- Average American uses 500 gallons of gasoline/year
- The energy contents of 500 gallons of gasoline is equivalent to
  - ~ 3 short tons of coal
  - ~ 60,000 cubic feet of natural gas
  - ~ 450 gallons of diesel fuel
  - ~ 991 gallons of methanol
  - ~ 1925 gallons of liquid hydrogen gas
    - H_2 provides 33.33 kW-hr/kg; liquid H_2 at -253 C has an energy density of 2.36 kW-hr/liter
  - ~ 6060 gallons of 30 Mpa high-pressure hydrogen gas
    - H_2 energy density ~ 0.75 kW-hr/liter

500 gallons of gasoline ~ 62 million BTU
~ 18,171 kW-hr

Costs*:
Gas: $2150 @ $4.30/gallon
Electricity: $1817 @ $0.10/kW-hr

- If one wishes to replace fossil fuels, one needs to account for the infrastructure and operating costs of alternatives:
  - Production of the alternative energy source
  - Distribution of the alternative energy source
  - "Consumption": Viz., electric drive via batteries or fuel cells, …

*N.b.: To compute costs, one needs to also take into account the efficiency of delivering motive power (e.g., 'mileage' & engine cost).

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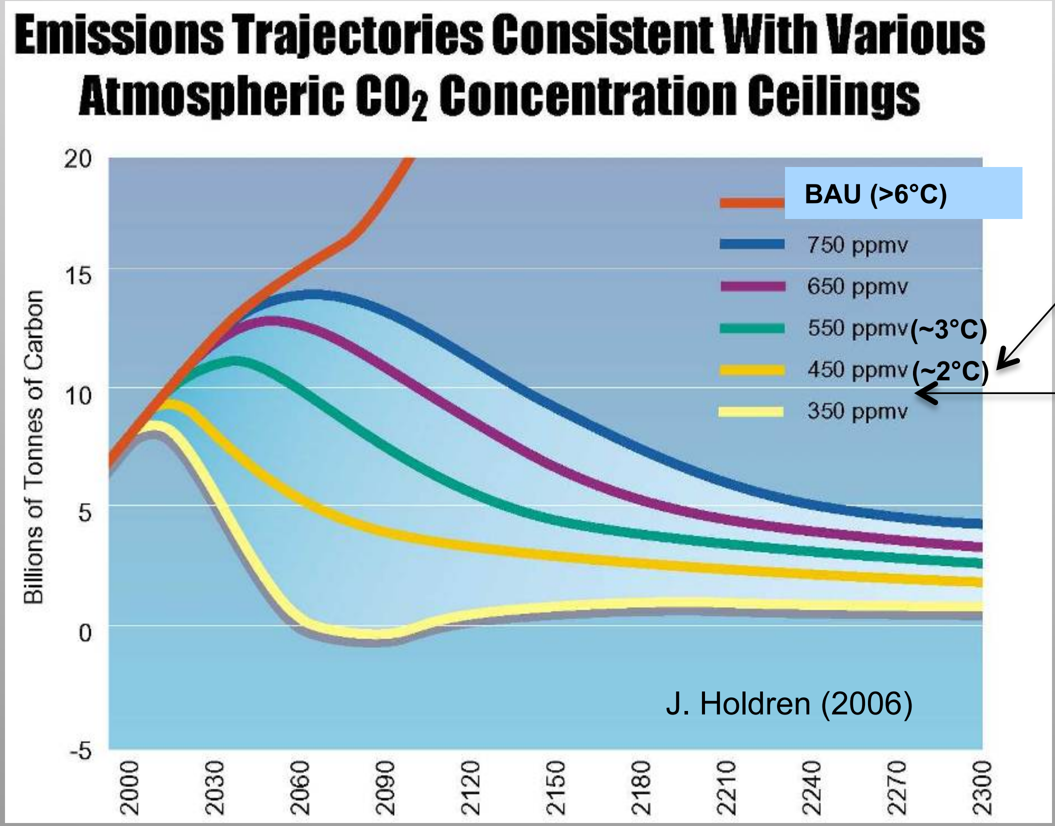
… and then there is the climate constraint

- We do not know for sure where the 'tipping point' for the atmospheric CO_2 load is – but let's assume for the moment that 600 ppm CO_2 equivalent is a hard target.
- The US is no longer the largest contributor of CO_2 – China is, over 4 years ago (!)



This is the target agreed upon at the Paris climate conference …

400 ppm was reached in May 2013, a Measured at Mauna Loa Observatory in Hawaii. See: *http://climate.nasa.gov/400ppmquotes/*

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How should we think about all this?

- Rob Socolow (Princeton Univ.) has suggested that we think in terms of 'wedges'
  - 1 'wedge' = 10^9 tons of carbon equivalent/year
  - Each 'wedge' corresponds to a particular carbon source/sink …
- Stabilization at 600 ppm will require 7-8 wedges

NOTE: This graphic is blown up on the next page for better viewing

R. Socolow (2006)

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The Rob Socolow 'wedges', blown up

R. Socolow (2006)

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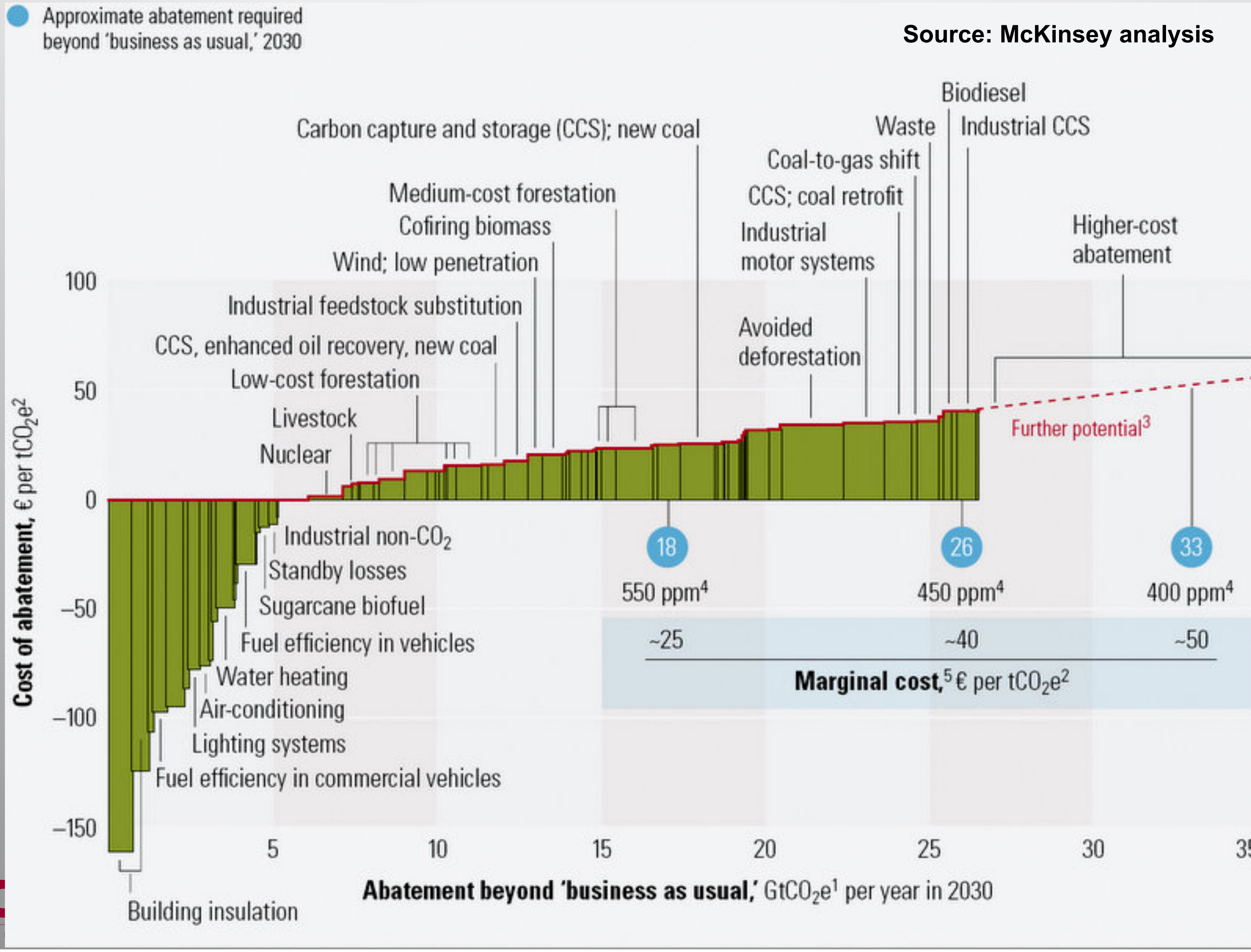
How much do ‘wedges’ cost?



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The point is …

- Gasoline, and fossil fuel products in general, are today amazingly efficient in packaging energy in an
  - easily obtained (= technically simple and cheap), and
  - easily transportable way – and the infrastructure is in place and paid for …
- **All** of the alternatives - except for one, namely increased efficiency of energy use - are burdened with one or more relative disadvantages *<u>at present</u>*, which come in many flavors …
  - Environmentally not benign, or [~ coal-based synfuels; 'clean' coal; tight gas]
  - Relatively costly, or [~ solar*/fission/wind*]
  - Inefficient, or [~ corn-based ethanol]
  - Ineffective (despite the hype …), or [~ hydrogen]
  - Does not really/yet exist, or [~ nuclear fusion/CCS/'clean' coal]
- These disadvantages are the fundamental reason that oil still dominates …

* Wind is cheap if one does not account for energy storage required because it is an intermittent energy source … this is also the case for (solar) photovoltaics, less so for solar thermal (because heat can be stored in, viz., molten salt heat transfer fluid)

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From the policy perspective, what <u>should be</u> some of the strategic considerations for future energy options?

- **The Environment**
  - **Global warming**: We have no choice but to implement primary energy sources that do not continue to impact the Earth's atmosphere in the long run
    - If carbon-based fuels, then sequestration or renewables, or
    - Non-carbon based energy sources
  - **Minimization of toxic waste streams**
  - **Land use** and **water use** policies
    - Food vs power?
    - Competition for water use/reuse
  - **Population distribution/planning**: Urban vs. suburban vs. exurban
    - Centralized power production vs. distributed power production
    - Housing energy efficiency & Mass transit vs. 'personalized' transport

November 3, 2006-10

Exploding U.S. Grain Demand for Automotive Fuel Threatens World Food Security and Political Stability

Lester R. Brown

- **Risk minimization**
  - Technology promises are not the same as technology delivery … cast a wide net!
  - Life cycle analysis is essential …
- **Costs:** *True costs include environmental costs and life cycle costs …*
  - Who pays for cleaning up our atmosphere? Decommissioning power plants? Taking long-term care of the waste? What are the hidden and not-so-hidden subsidies?

Here's an illustration of the water-energy nexus problem …

Four Corners coal-fired power plant

Cooling towers at Palo Verde nuclear plant near Phoenix, AZ

- **The physics:** All thermal power plants require cooling, which is usually done by either evaporating water (= cooling towers) or circulating water through heat exchangers and returning the hot water to its source …
- **The impact:** Significant water loss in arid regions ...

… and – to end – here are my own pros and cons for the various alternatives …

Type	Main Pros	Main Cons	Time frame
Conservation	Non-polluting; no global warming impacts; incremental	Does not solve base power problem	Now
Wind/solar/tidal/ geothermal	Low or no pollution; no global warming impacts	Intermittent (need storage/R&D); highly location-dependent; solar relatively inefficient/expensive (R&D needed)	Now
Water ('hydro')	No pollution; no global warming impacts	Highly location-dependent/limited; possible environmental damage	Now
High-value bio synfuels	No global warming impact; positive for waste recycling; useful for transport	Non-carbon pollutants (NOx, particulates); possible agriculture impacts; R&D needed for increased efficiency/lowered cost	Now
Ethanol	Can have little global warming impact; useful for transport	Agricultural impacts; current production methods energy-inefficient	Now
Coal/oil shale/tar sands/tight gas	Very abundant; useful for transport	Possible ground water impact; climate impacts (w/o C capture & sequestration)	Now
Nuclear fission	Minimal global warming impact; potential long-term energy solution	Permanent waste storage in absence of closed fuel cycle; public perception concerns (safety, proliferation, …)	Now
Nuclear fusion	Minimal global warming impact	We don't know how to do this at present	?
Hydrogen	Depending on production mechanism, no global warming impact; transport fuel	Requires substantial primary energy source; production presently inefficient; storage & distribution major R&D issues	? for U.S.; now for Iceland (!), w/ geothermal

… which brings us to

DISCUSSION AND QUESTIONS