

Nuclear Power in the World's Energy Future

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Outline of Talk

Nuclear power is still a miracle of nature, science, and technology.

Where we are. Where we might be to make a difference in the world.

The world's energy future.

Energy use, where. Energy use, how.

Current production not easy to maintain—production vs. resource.

Current production is not enough—Population; development and increasing living standards are even more important.

Energy field highly noncompetitive—e.g., OPEC, ENRON.

**Not running out of energy. To quote John Holdren, Running out of:
cheap energy; environment; societal will; time.**



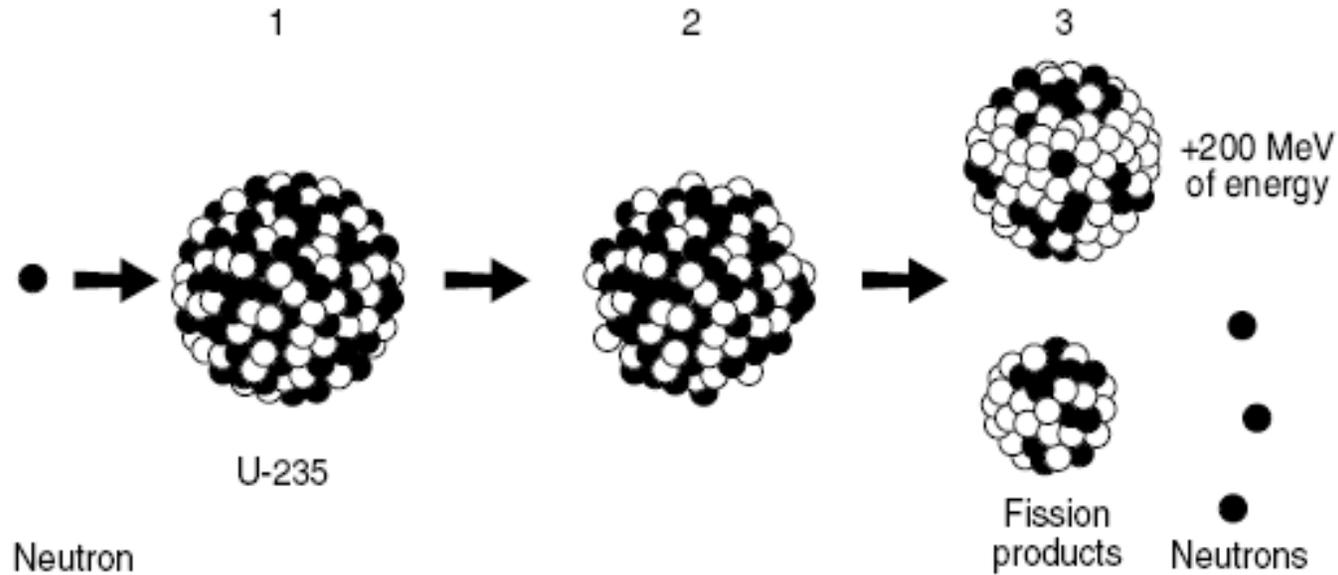
Four nuclear reactors at the Cattenom nuclear power plant in France



Three-reactor NPP at Itaka, Japan

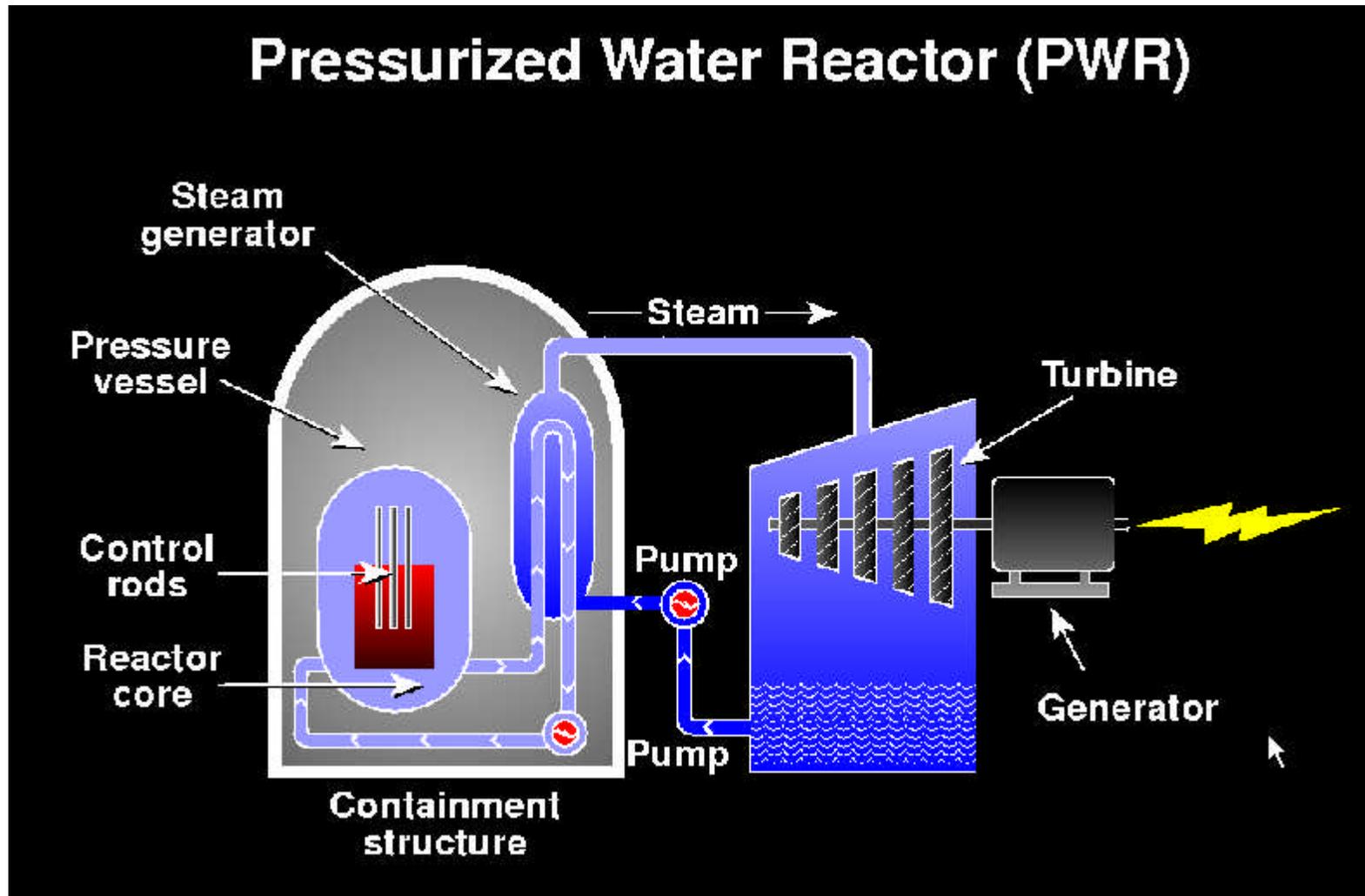
**NUCLEAR POWER IS A MIRACLE,
ANALOGOUS TO FIRE**

The fission chain reaction, with the neutron as carrier:

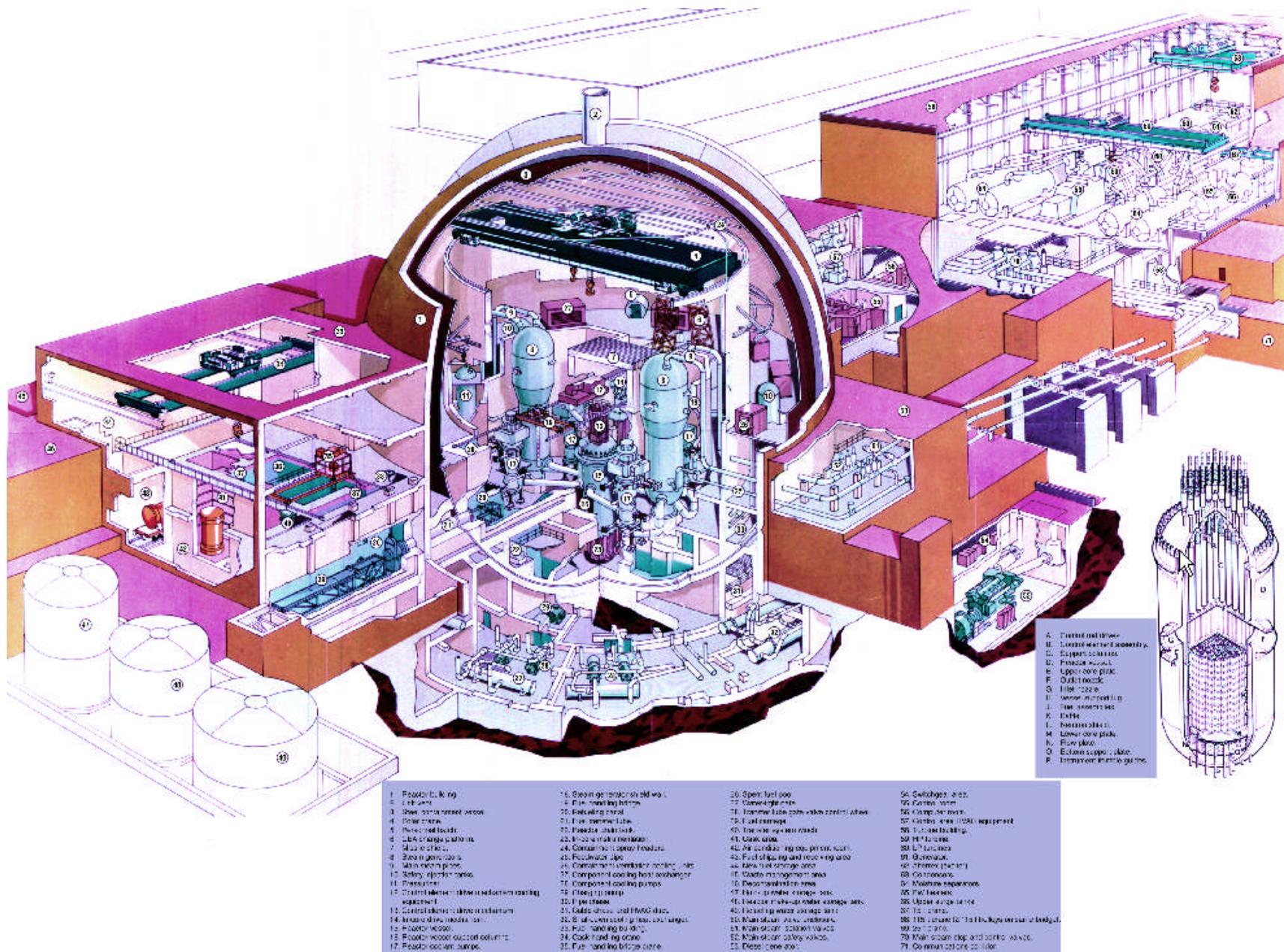


and with enough U-235, the fission neutrons provoke more fissions, and so on. With the help of a lot of science and engineering, one has a useful power reactor: neutronics, heat transfer, structure, and “balance of plant.”

Pressurized Water Reactor (PWR)



Schematic of the PWR, the most common power reactor



A PWR in the context of the nuclear power plant

One approach to the treatment of spent fuel before disposition in a mined geological repository



Figure 9. Dry cask storage of spent fuel. Two casks typically contain the equivalent of a year's spent fuel discharges from a 1000 MWe nuclear power plant. Comparison of the simplicity of interim spent fuel storage with the complexity of the huge reprocessing complex shown in Figure 6 makes it easier to understand the relatively low cost of interim storage.⁸⁷

Dry-cask storage of spent fuel (Yankee site)

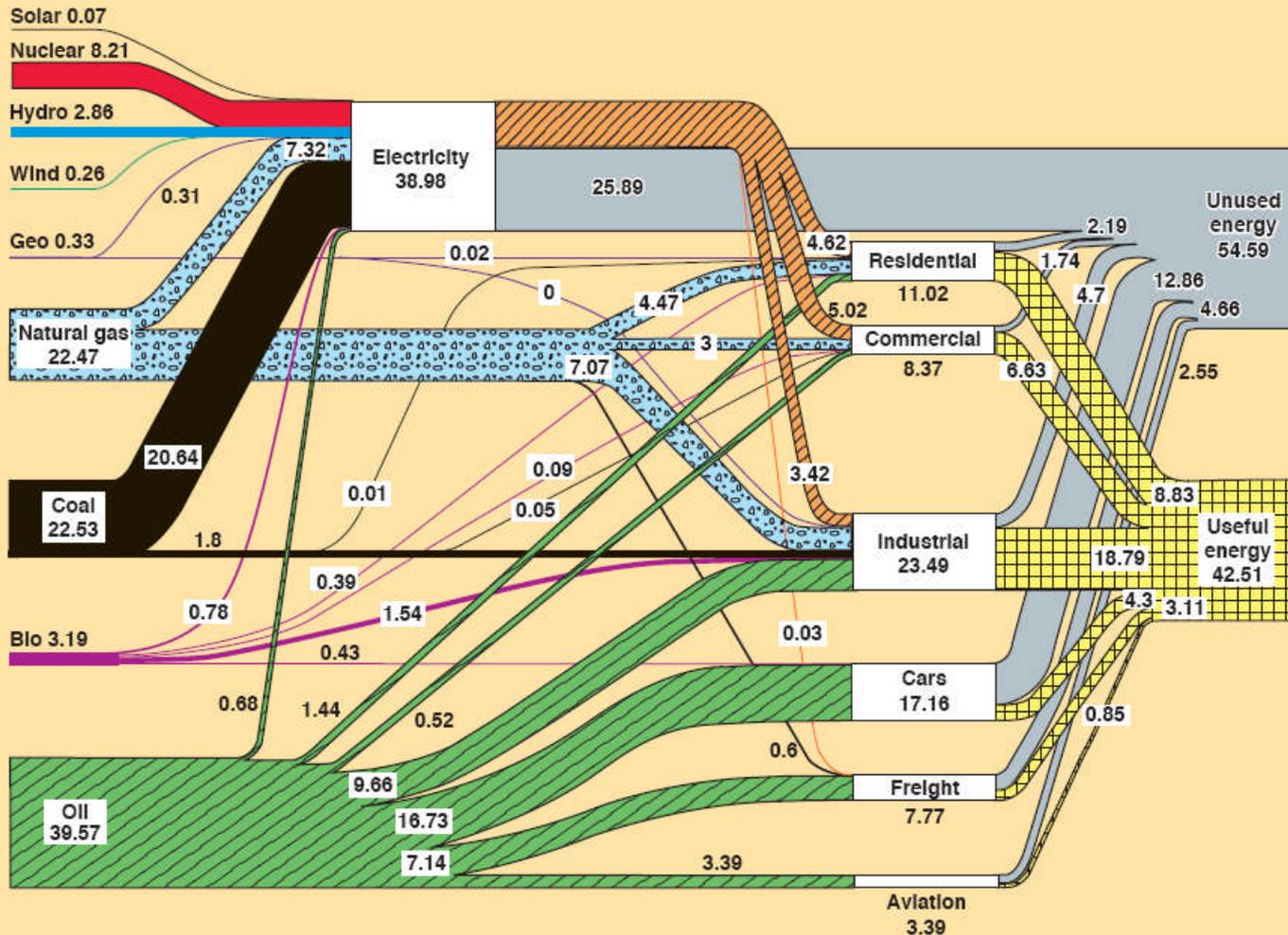
Another approach to the treatment of spent fuel before disposition in a mined geological repository



Figure 6. France's spent-fuel reprocessing complex on La Hague in northern France. Its plutonium fuel fabrication facility is in southern France, requiring regular long-distance truck shipments of separated plutonium.⁴⁹

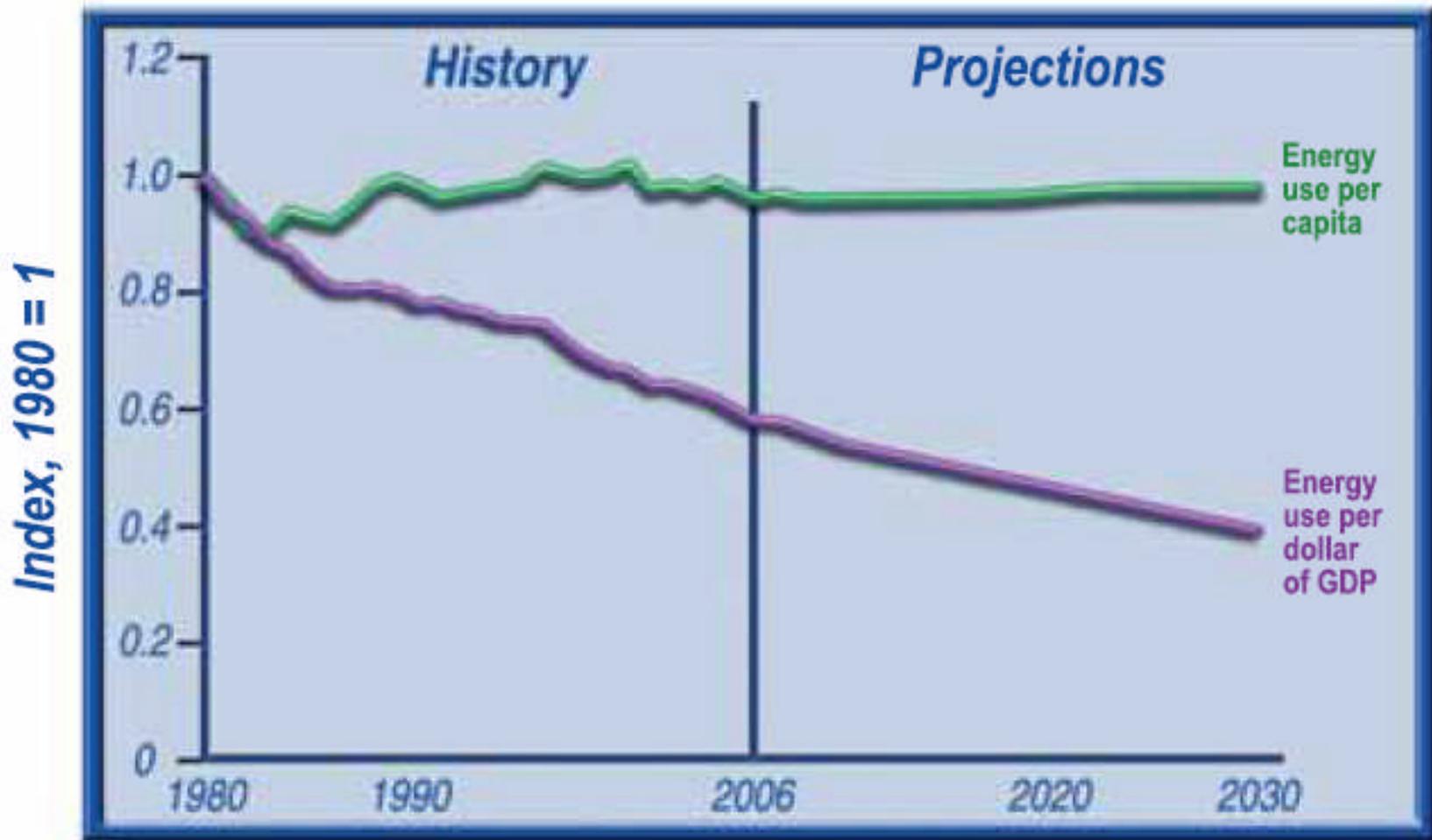
France's spent-fuel reprocessing complex at La Hague

Estimated Energy Usage in 2006 ~97.1 Quads



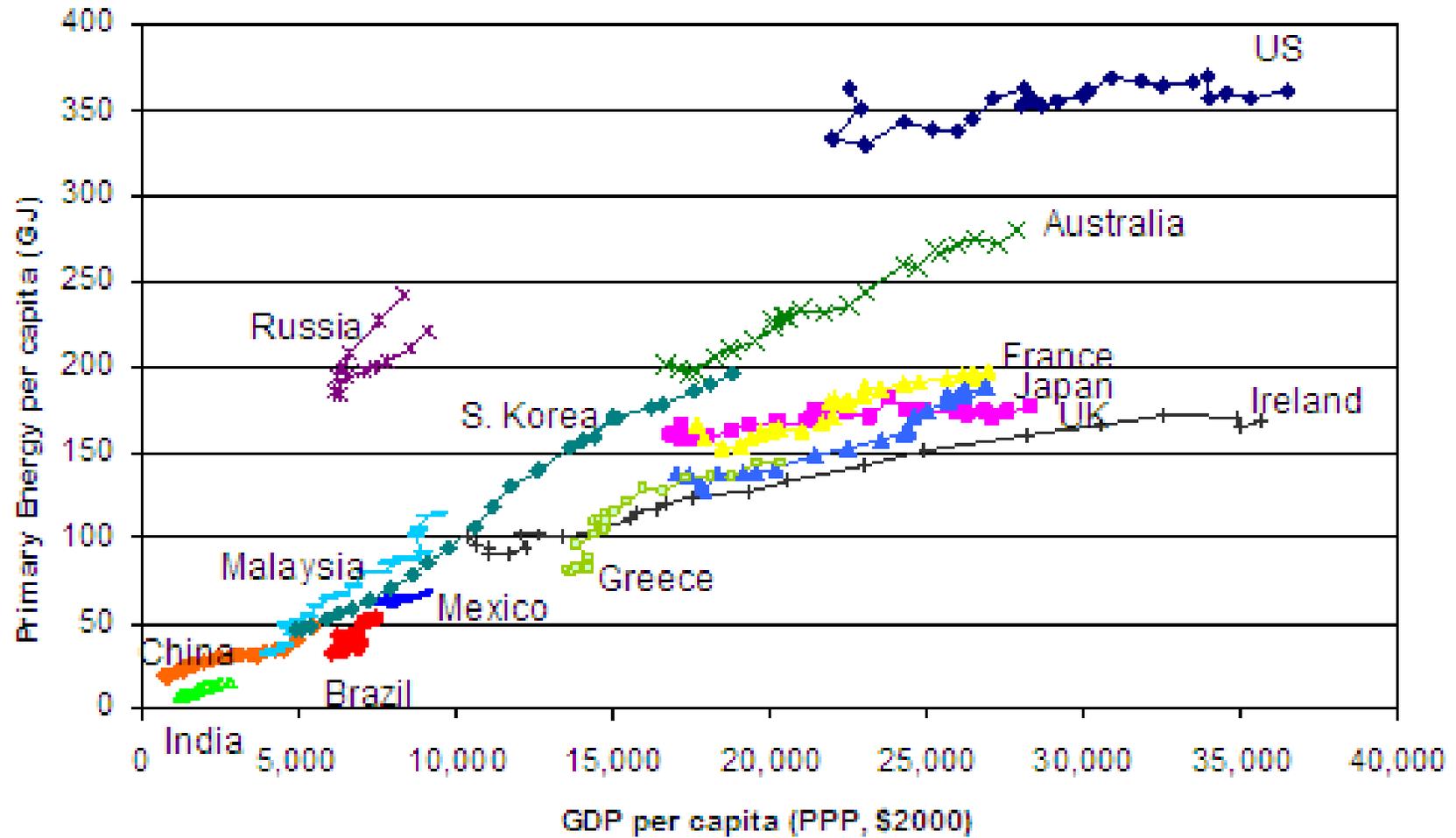
Source: LLNL 2008; data is based on DOE/EIA-0384(2006), June 2007. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include small amounts of electricity imports or self-generation. Energy flows for non-thermal sources (i.e., hydro, wind, and solar) represent electricity generated from those sources. Electricity generation, transmission, and distribution losses include fuel and thermal energy inputs for electric generation and an estimated 9% transmission and distribution loss, as well as electricity consumed at power plants. Total lost energy includes these losses as well as losses based on estimates of end-use efficiency, including 80% efficiency for residential, commercial, and industrial sectors, 20% efficiency for light-duty vehicles, and 25% efficiency for aircraft.

U.S. energy usage in 2006 (1 quad = 1.055 exajoule)



U.S. energy use per capita and per dollar of GDP from 1980 to 2030

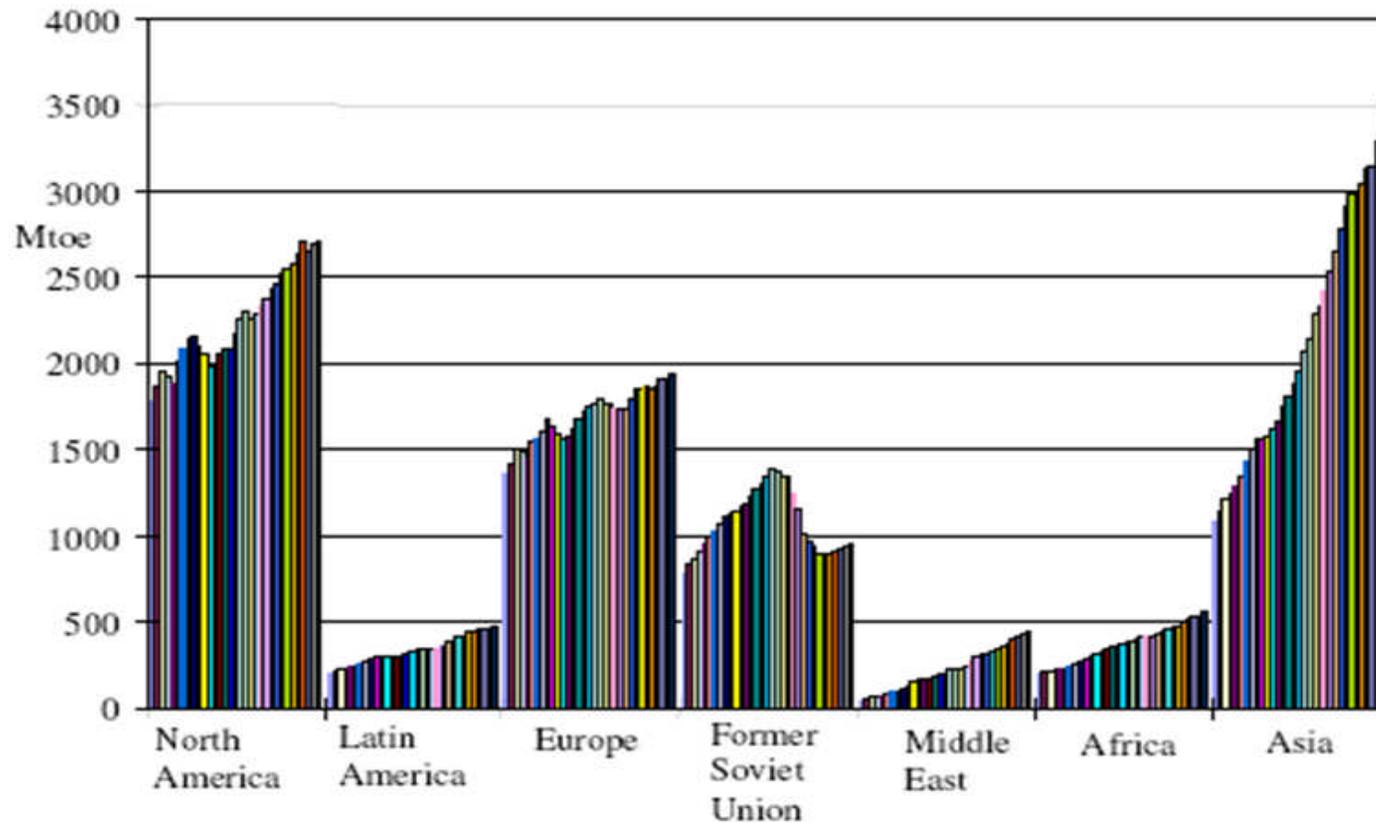
energy demand and GDP per capita (1980-2004)



Source: UN and DOE EIA
 Russia data 1992-2004 only

(Courtesy of Dr. Steve Koonin, BP)

annual primary energy demand 1971-2003



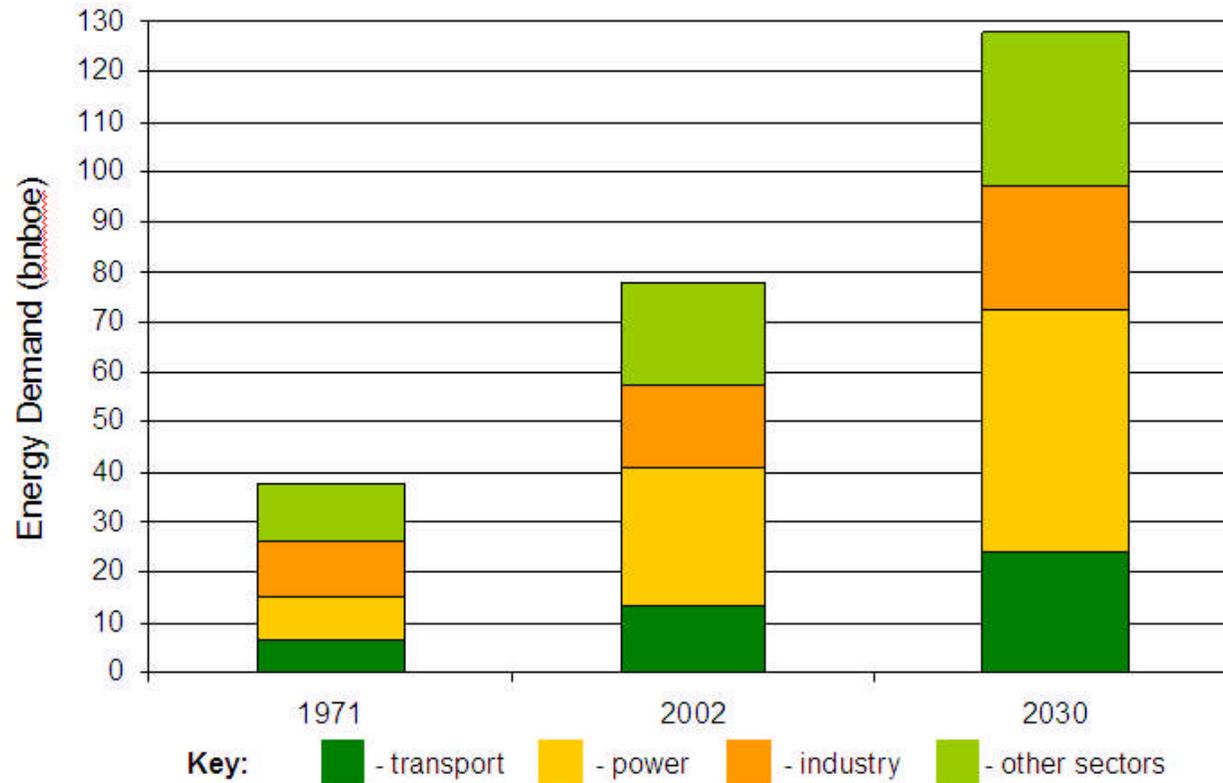
Source IEA, 2004 (Excludes biomass)

Units of energy! 1 Mtoe (million tonnes of oil equivalent) = 0.042 EJ (exajoule = 10^{18} J); 1 quad = 1 quadrillion BTU = 10^{15} BTU = 1.055 EJ; 1 boe (barrel of oil equivalent) = 6.12 GJ; 1 Mbpd (million barrels of oil per day) x 365 days = 2.24 EJ/year

growing energy demand is projected



Global Energy Demand Growth by Sector (1971-2030)

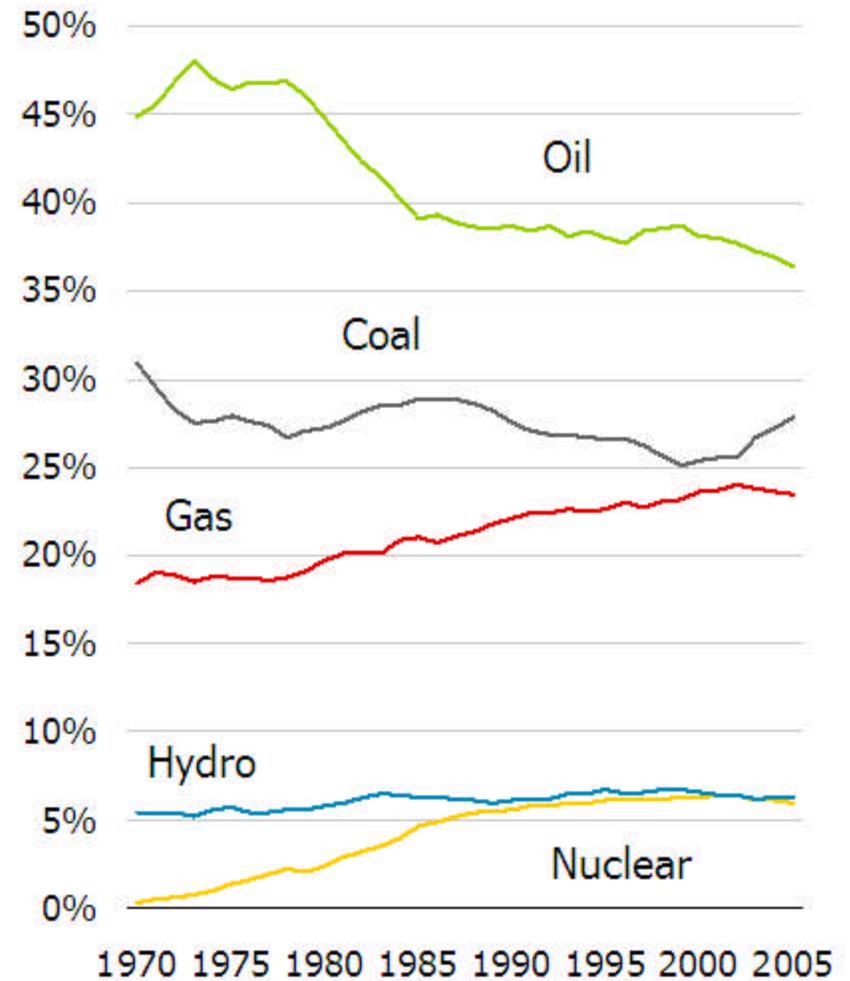
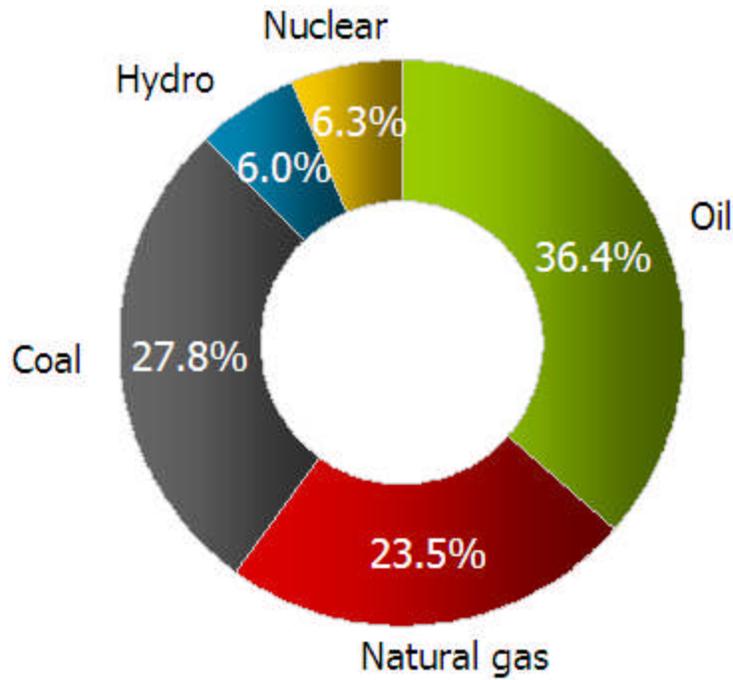


Notes: 1. Power includes heat generated at power plants
 2. Other sectors includes residential, agricultural and service

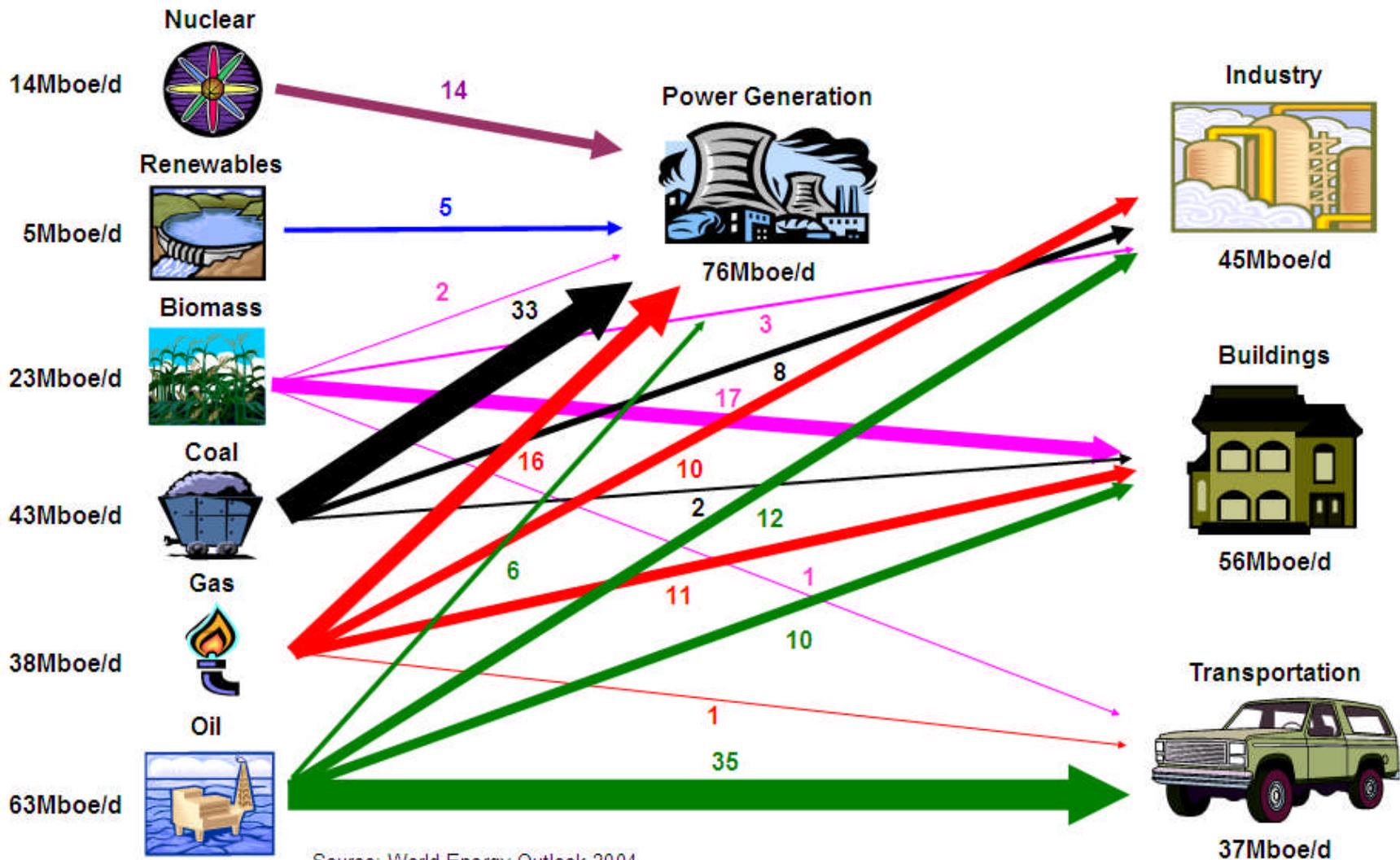
Source: IEA WEO 2004

1 bnboe = 1Gboe = 6.12 GJ x 10⁹ = 6.12 EJ; 2002 total about 477 EJ, of which U.S. is 102 EJ.

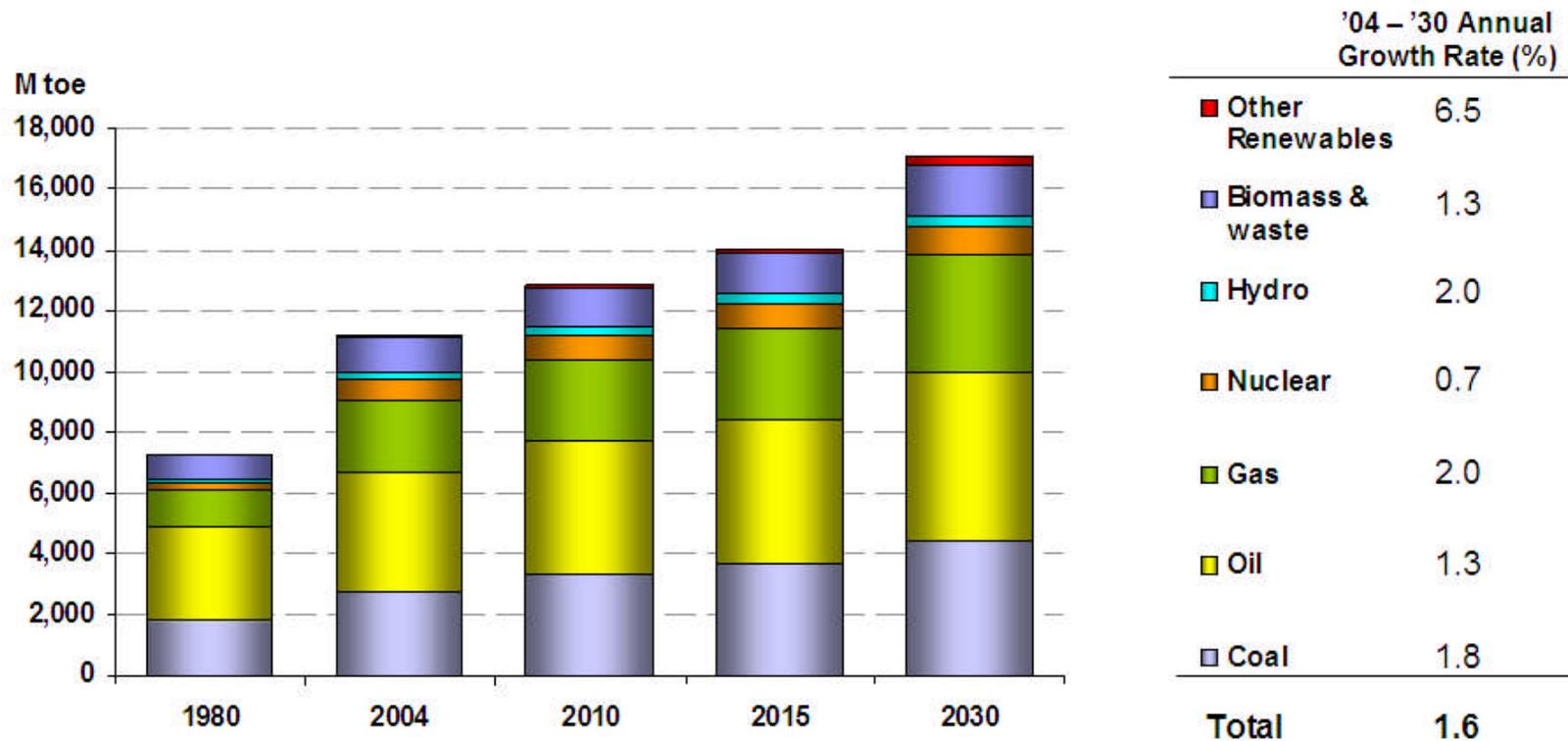
global primary energy sources



global energy supply & demand (total = 186 Mboe/d)



BAU projection of primary energy sources



Note: 'Other renewables' include geothermal, solar, wind, tide and wave energy for electricity generation

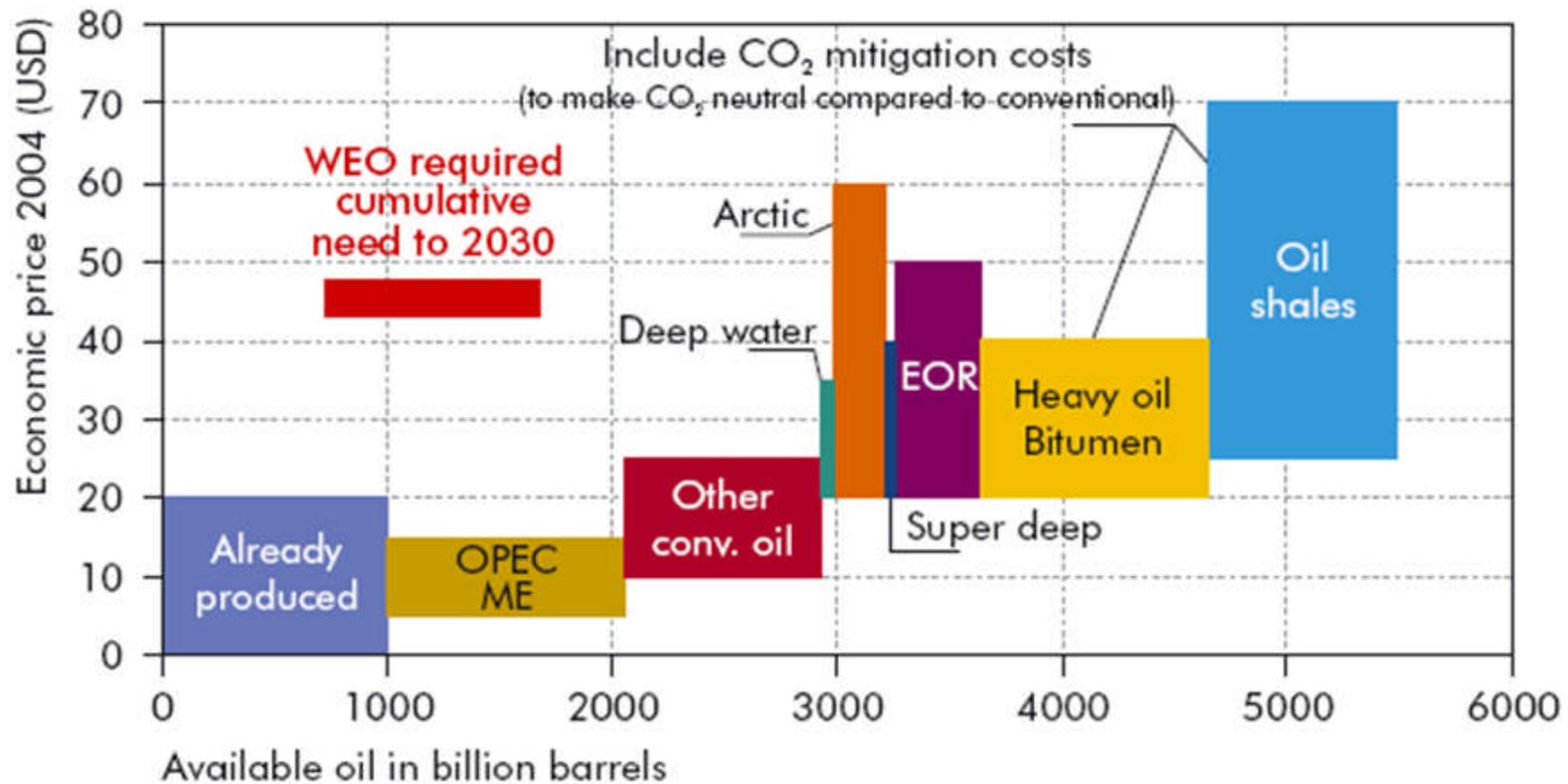
Source: IEA World Energy Outlook 2006 (Reference Case)

“BAU” is “business as usual”

oil supply and cost curve



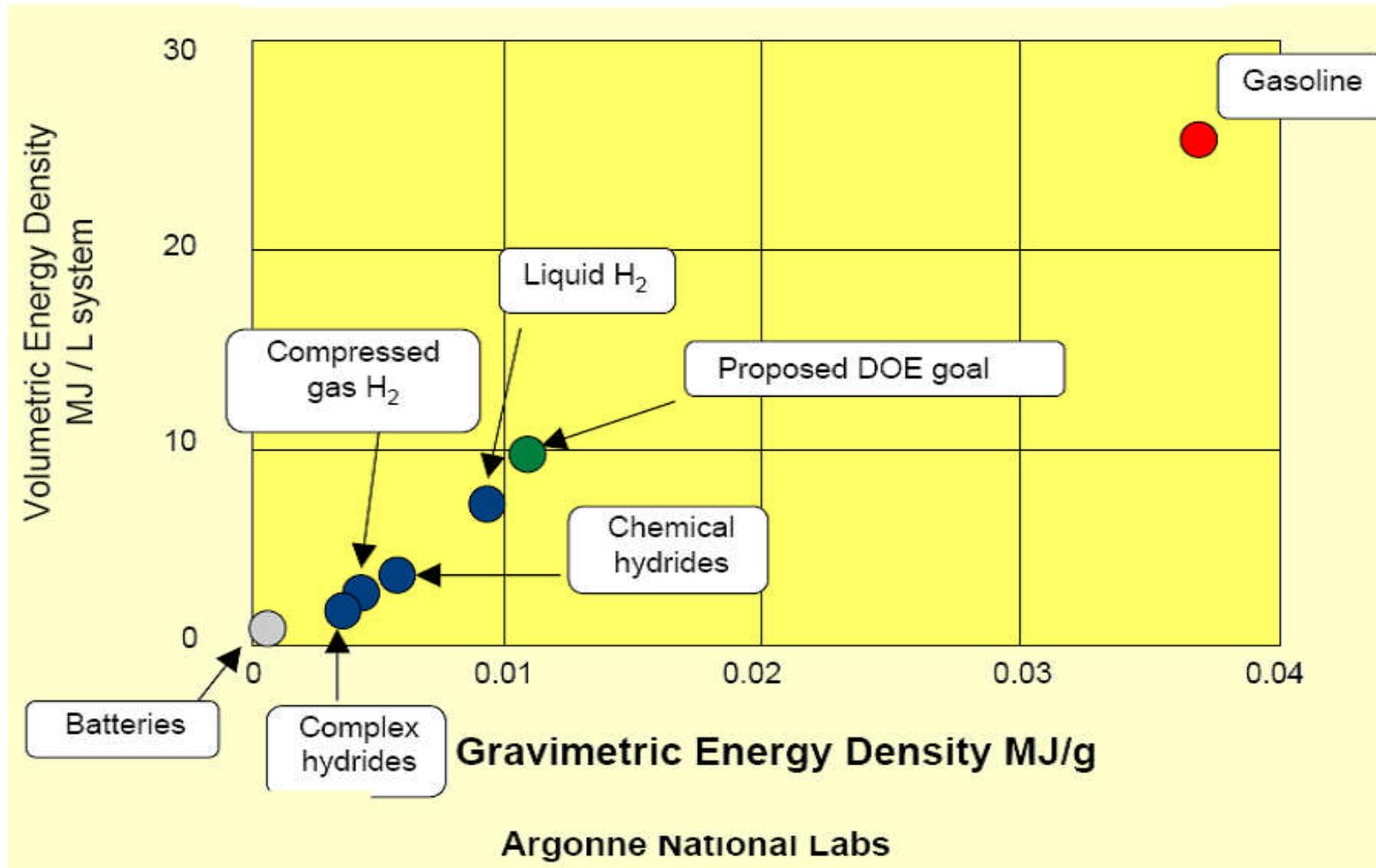
Availability of oil resources as a function of economic price



Source: IEA (2005)

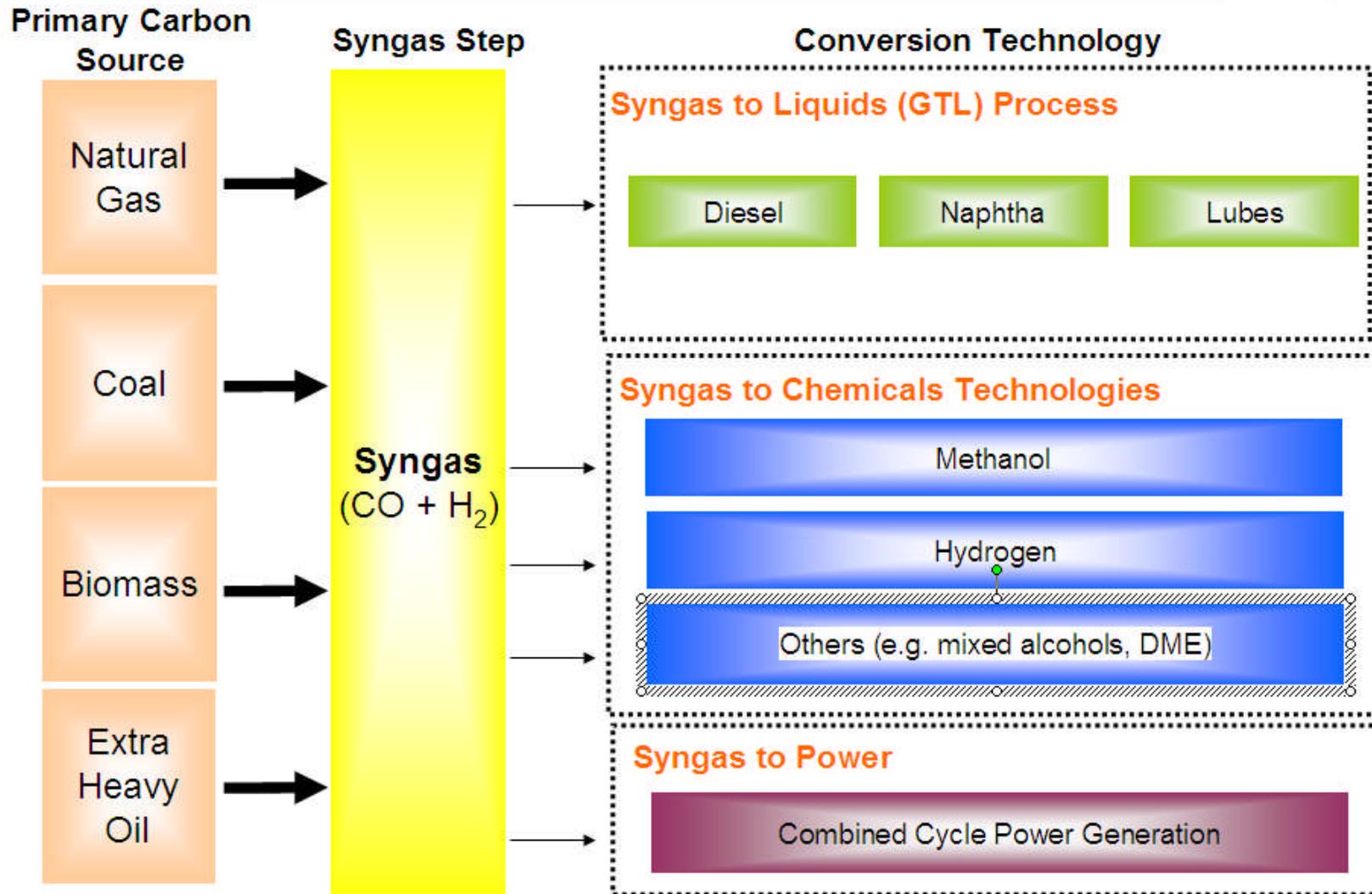
Compare 2008 \$130/barrel price with max \$25/bbl cost.

it's really hard to beat liquid hydrocarbons



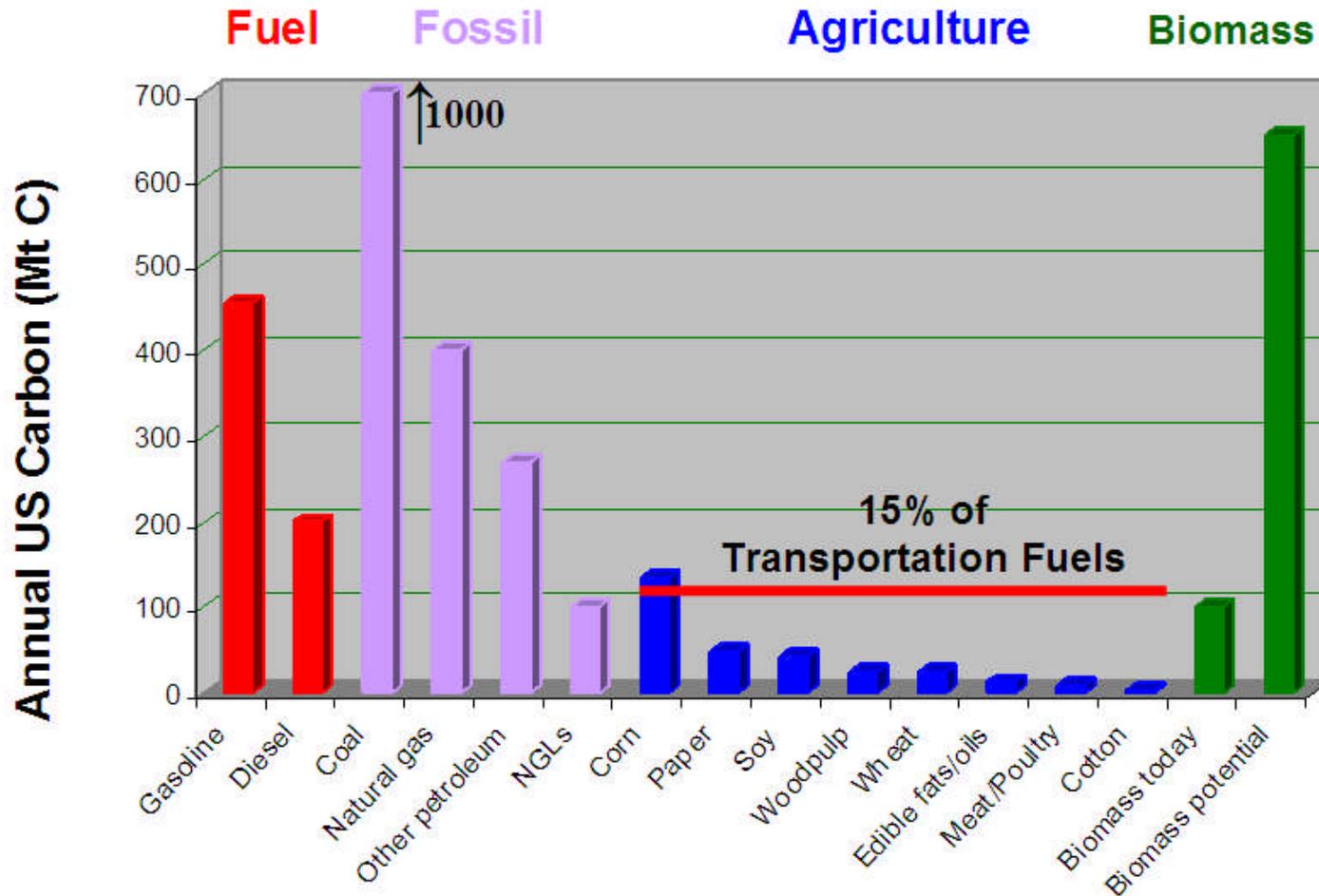
Gasoline or diesel fuel is an efficient energy carrier

the fungibility of carbon



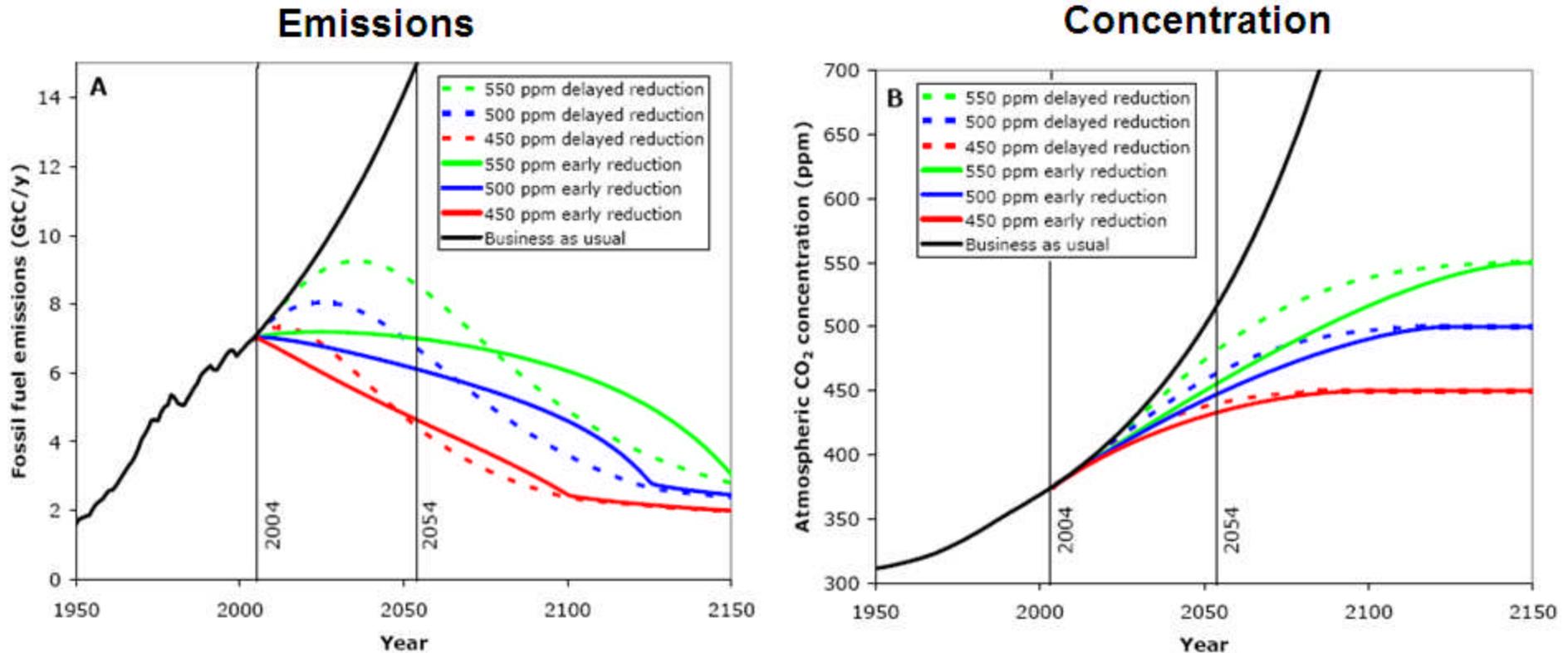
Can supply major amounts of transport fuel, but even more CO₂ emission

what carbon “beyond petroleum”?

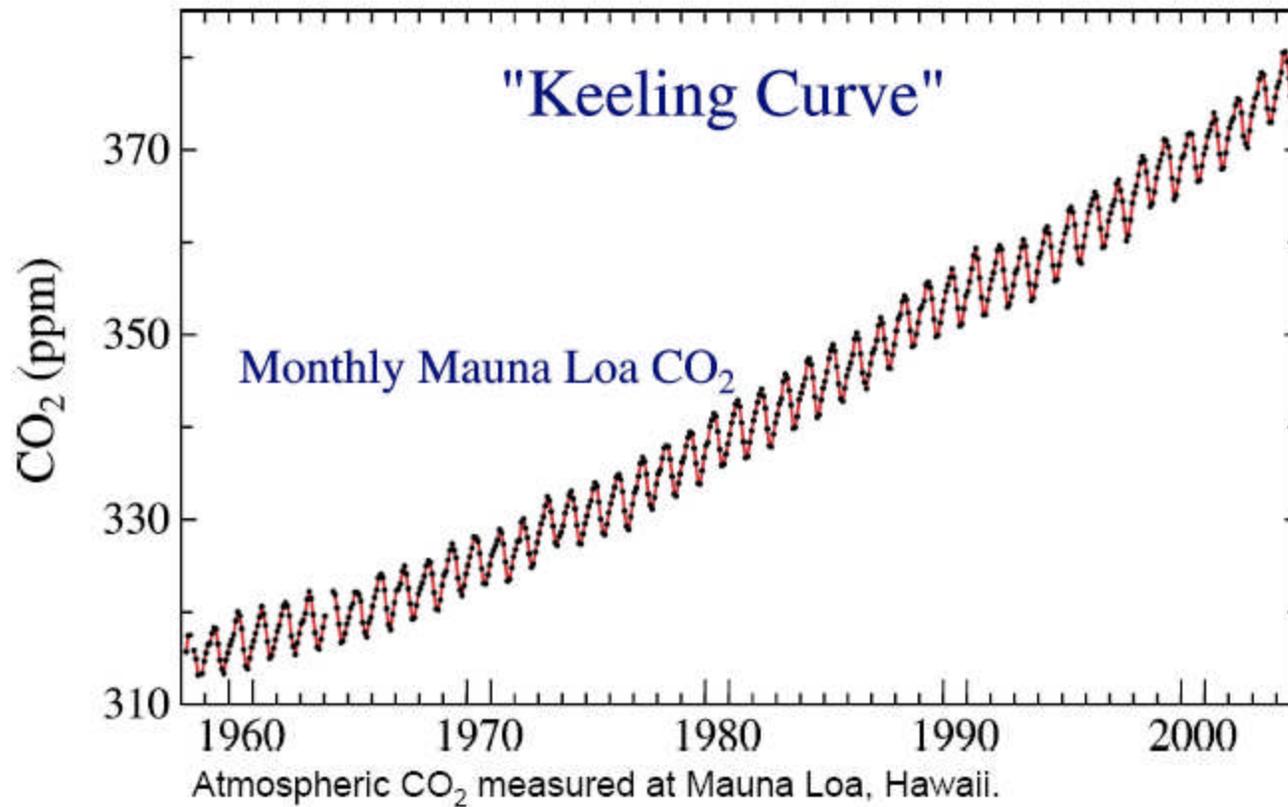


Biomass for transport fuel can provide energy without net CO₂ emission

crucial facts about CO₂ science



Strong measures are required to hold atmospheric CO₂ concentration to 450 or 550 ppm, compared with pre-industrial 280 ppm



NOAA Climate Monitoring and Diagnostic Laboratory

The “energy problem” would be severe without regard to CO₂; the “CO₂ problem” would be severe by itself. Together they may be the largest problem the world faces.

Emissions from energy are 65% of the problem, above all CO₂ from fossil-fuel combustion

The emissions arise from a 4-fold product...

$$C = P \times \text{GDP} / P \times E / \text{GDP} \times C / E$$

where C = carbon content of emitted CO₂ (kilograms),
and the four contributing factors are

P = population, persons

GDP / P = economic activity per person, \$/pers

E / GDP = energy intensity of economic activity, GJ/\$

C / E = carbon intensity of energy supply, kg/GJ

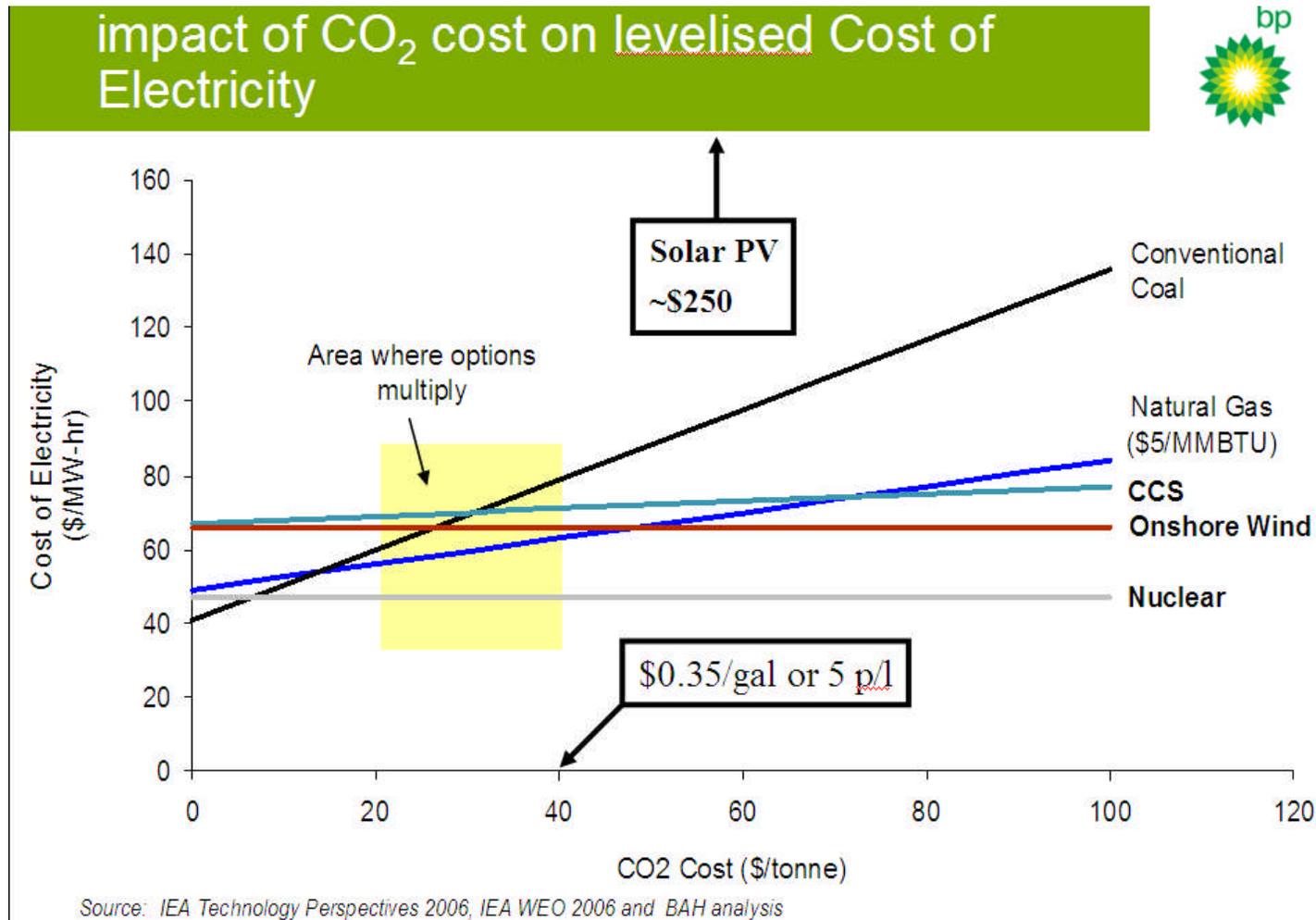
For example, in the year 2000, the world figures were...

$$\begin{aligned} &6.1 \times 10^9 \text{ pers} \times \$7400/\text{pers} \times 0.01 \text{ GJ}/\$ \times 14 \text{ kgC}/\text{GJ} \\ &= 6.4 \times 10^{12} \text{ kgC} = 6.4 \text{ billion tonnes C} \end{aligned}$$

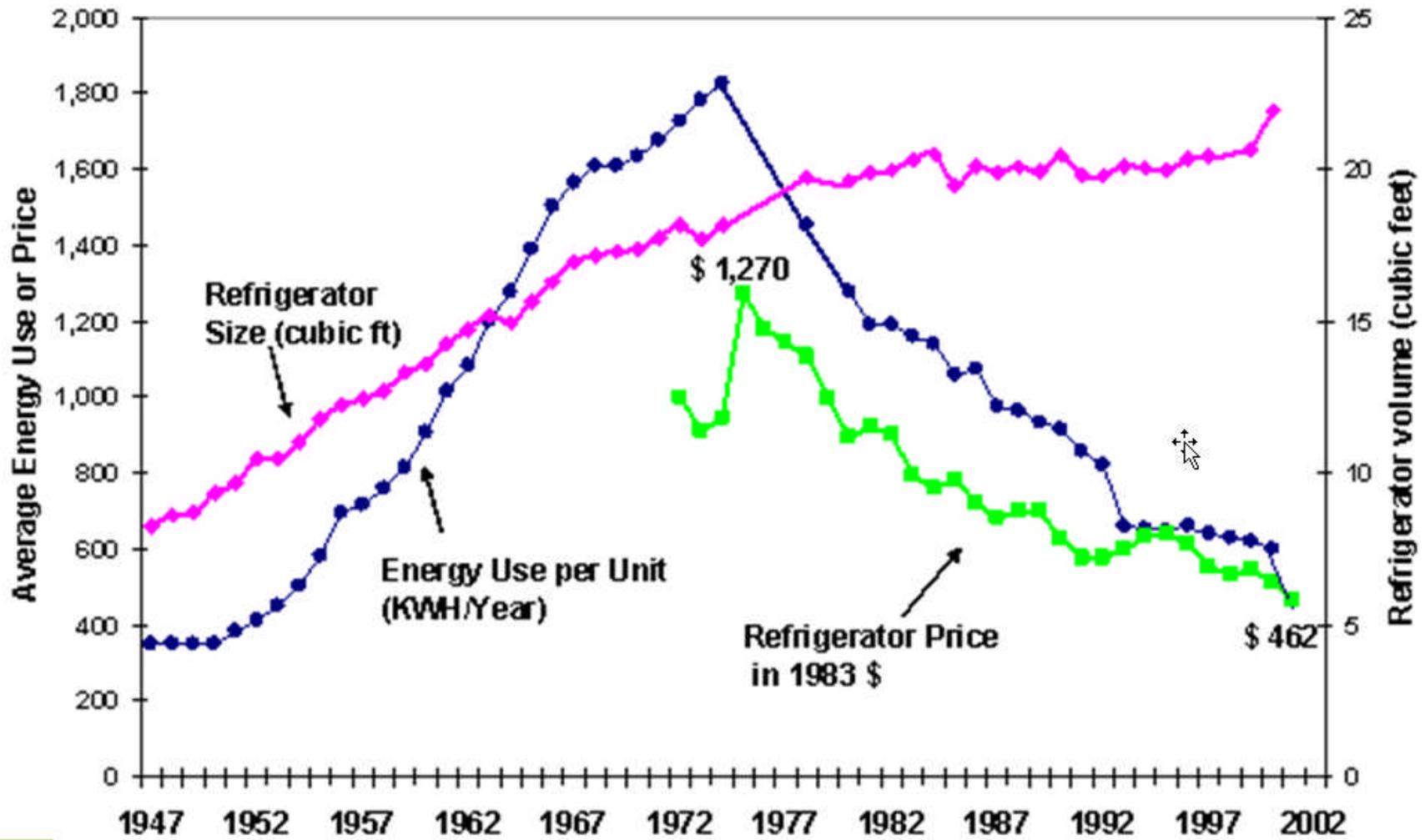
[From John Holdren]

Near-term tools

- A carbon tax to move toward low-carbon or no-carbon solutions



United States Refrigerator Use v. Time



Spectacular results in response to a government prize/incentive program

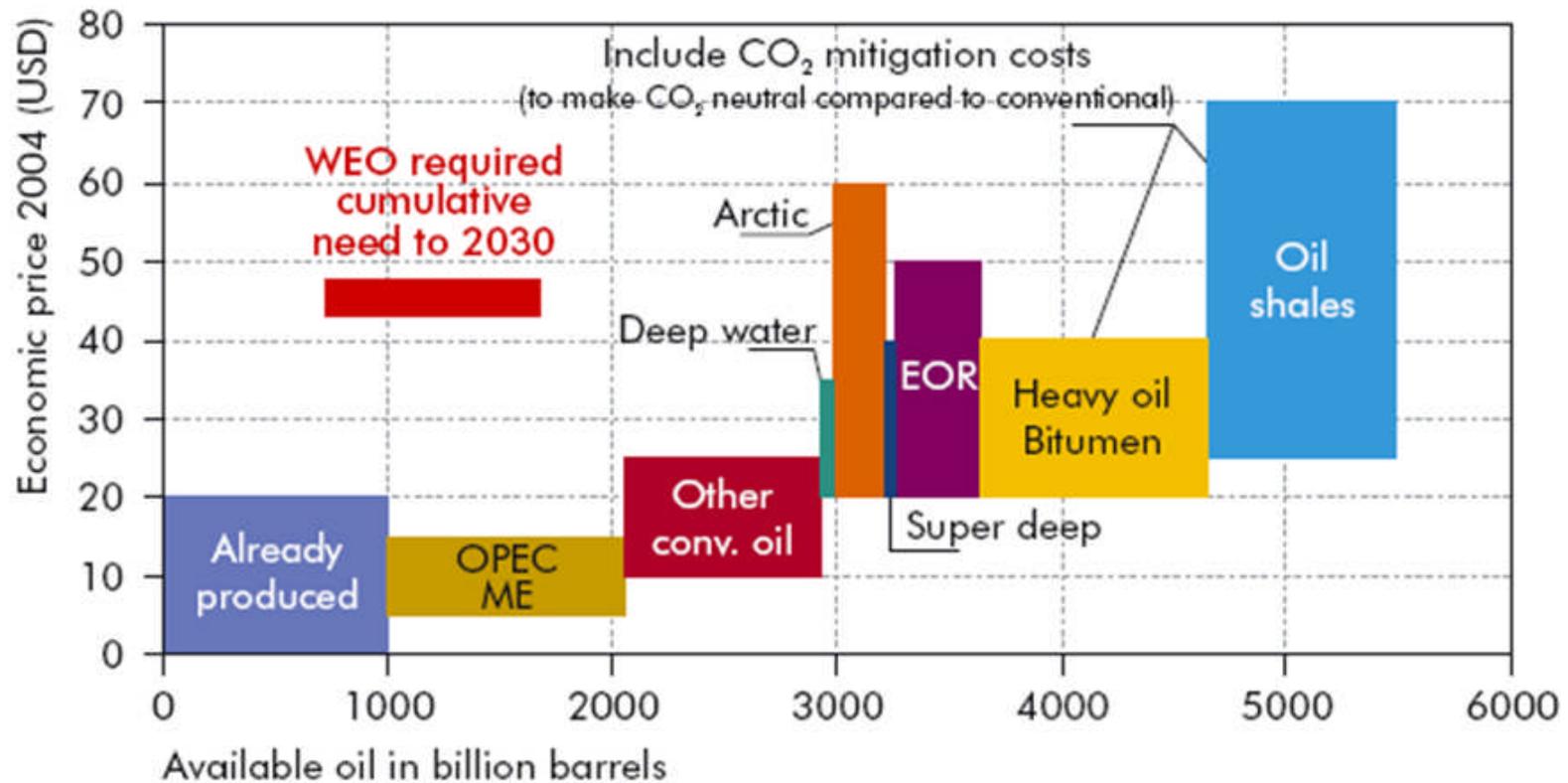
Near-term tools

- **More efficient use of energy, e.g., U.S. refrigerators.**
- **Major push for at-scale demonstration of “carbon capture and storage”. A single coal-fired 1000 MWe plant burns 2 million tonnes of carbon per year, generating $2 \times 44/12 = 7.3$ MT CO₂ per year. Dispose in aquifers, deep-sea pools, sea-bed sediment.**
- **Develop and deploy cellulose-to-ethanol plants for transport fuel, using waste plant material for zero-C fuel.**
- **Low-cost exploration to determine availability and cost of extraction of uranium for nuclear power—the “supply curve” of uranium.**
- **Explore the production of clathrate methane from ocean margins, and define the resource (perhaps 2000 Gt of carbon, but a dilute, non-flowing resource)**

oil supply and cost curve



Availability of oil resources as a function of economic price



Source: IEA (2005)

**Compare 2008 \$130/barrel price with max \$25/bbl cost.
What to do about the price?**

Getting serious

- **Create an Organization of Petroleum Importing States.**
- **Establish a virtual world energy laboratory—not necessarily centralized like CERN because no enormous machine would be involved. But perhaps a central nuclear-power laboratory.**
- **Support alternatives to conventional petroleum by contracting for their product at a fixed price, compensating for inflation, not by guaranteed profit.**
- **Since the effect of high petroleum prices is not increased production but reduced demand, the OPIS countries should impose taxes to produce comparable high prices—e.g. a tax of \$60/bbl equal to \$1.50 per gallon or Euro 0.35 per liter.**

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Steve Koonin and BP

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