# Nuclear Power in the World's Energy Future

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"Future of Energy" lecture
Harvard University
April 15, 2009

# Outline of Talk

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

**The world's energy future, and the need to reduce global warming.**

**Energy use, where.  Energy use, how.**

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

**Current production will not suffice—population growth, development and inproved living standards are 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.**

**Approaches to decarbonization of the energy supply.**

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

**Near-term tools.**

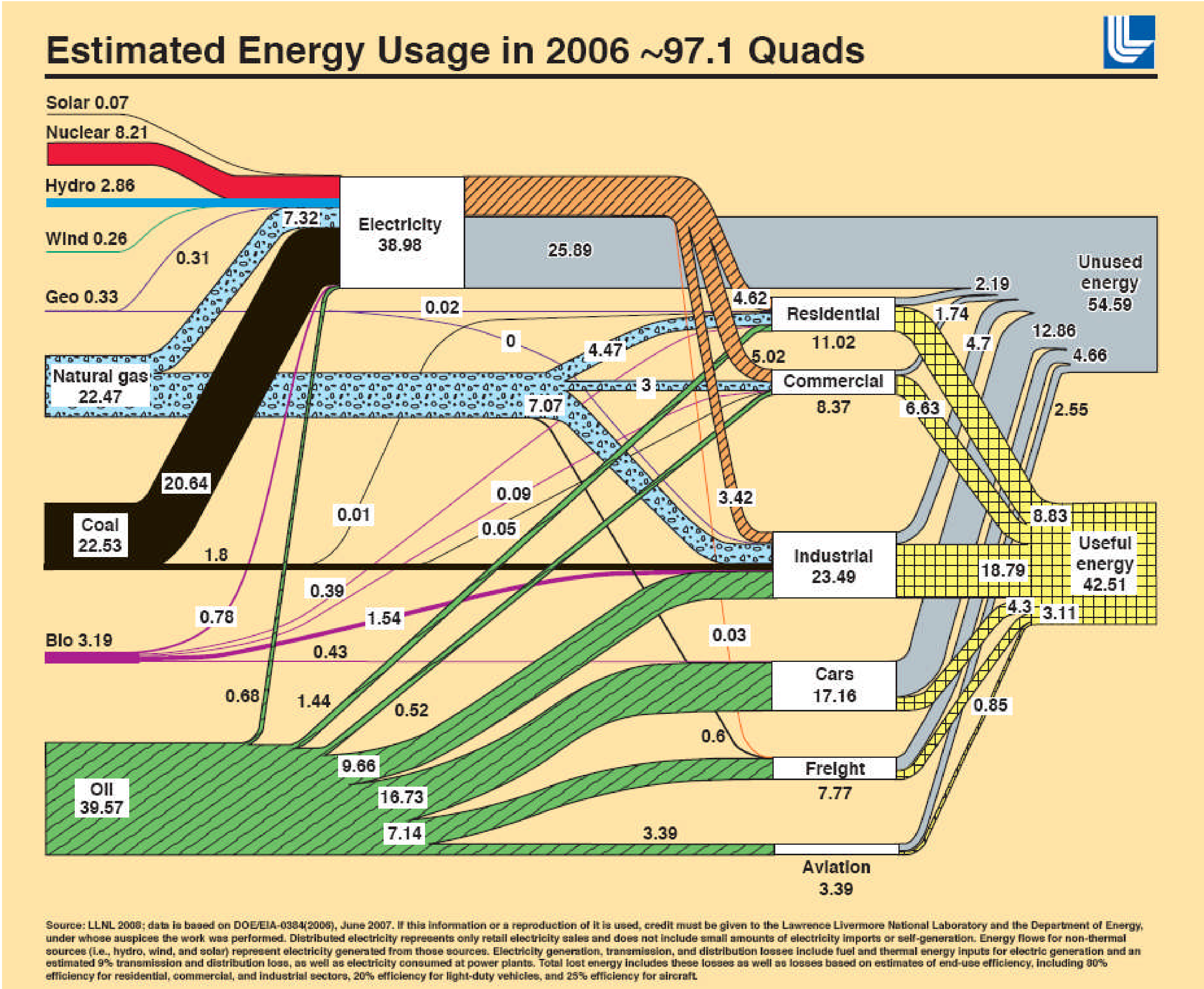
# Upfront: Recommendations on Nuclear Power

## Requirements and proposed solutions:

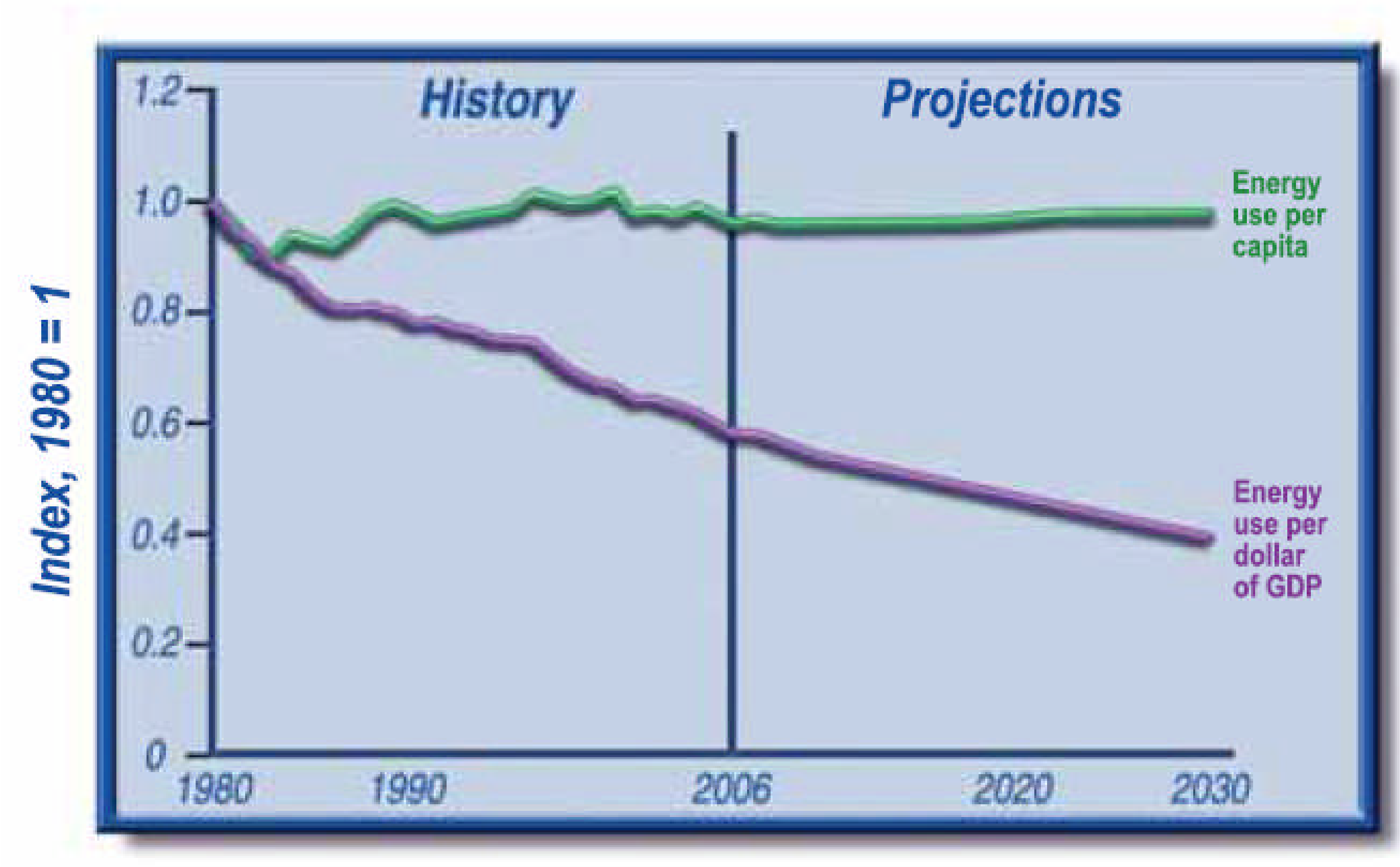
- **Economics including externalities—e.g., carbon tax**
  ***Small operating cost; large capital investment***
- **Safety against accidents**
  ***Superior to coal in expected deaths per gigawatt-year***
- **Reliable fuel supply at affordable cost**
  ***Buy fuel years ahead—safe and cheap to store, low cost and interest charges: ~$30 million per year investment of $350 million/yr sales. Governments should invest in determining the cost of uranium from seawater (3.3 ppb by weight)***

# Requirements and proposed solutions (2):

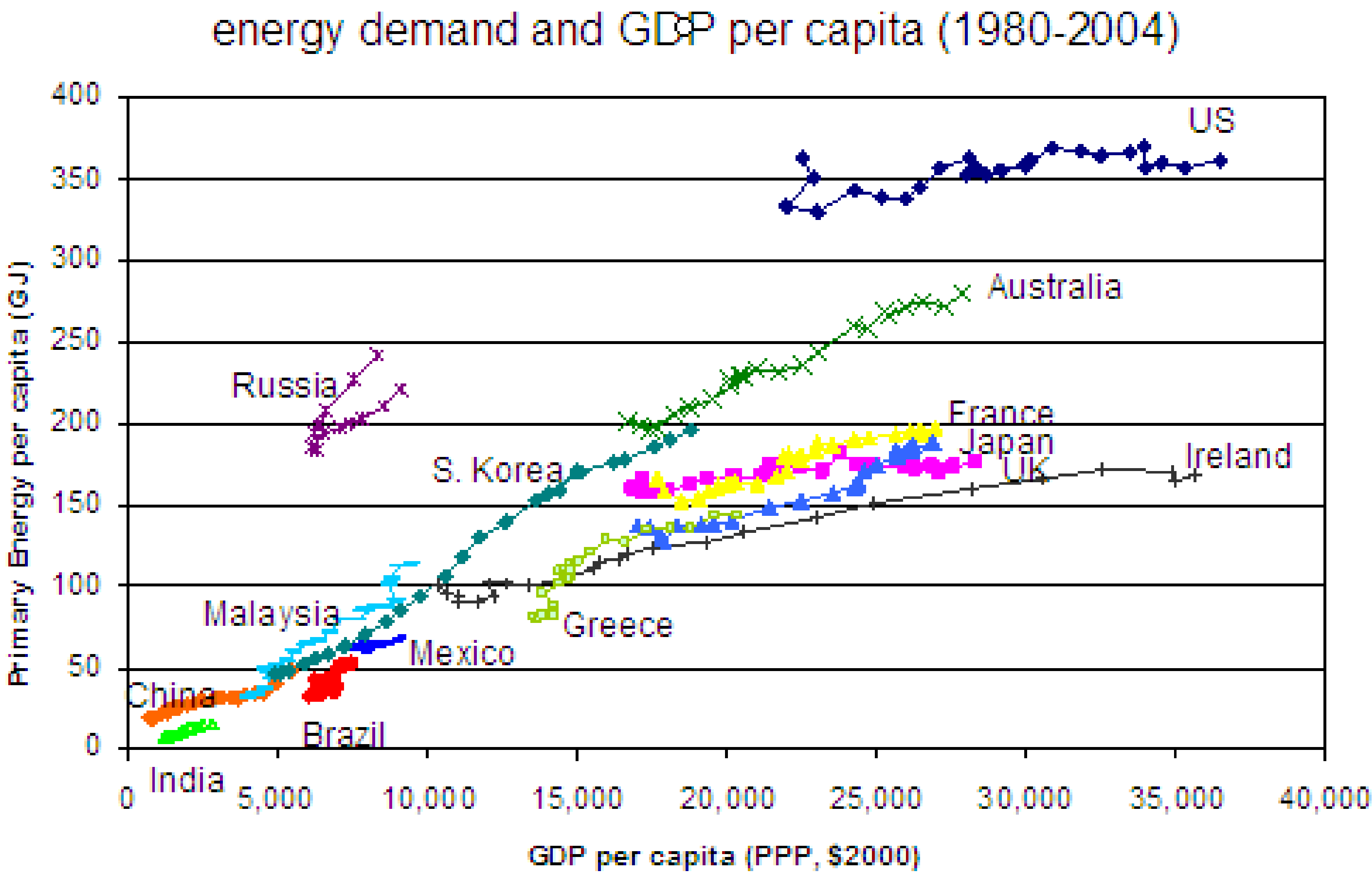
- **Safe, affordable disposal of spent fuel**
  ***Few years in-pool storage at the reactor; on-site dry cask storage until repositories are in operation—100-200 years***
- **Competitive, commercial mined geological repositories**
  ***Change law and custom to permit this, with spent fuel forms (reprocessed or intact fuel elements) approved by IAEA according to formal standards. Repositories, too, to meet IAEA regulatory requirement to avoid a "race to the bottom***
- **Major investments required to multiply nuclear power by factor 3 or 10**
- **World nuclear power lab to research (3) breeder reactor types, with specific fuel and reprocessing, and most advanced tools of digital simulation…**




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

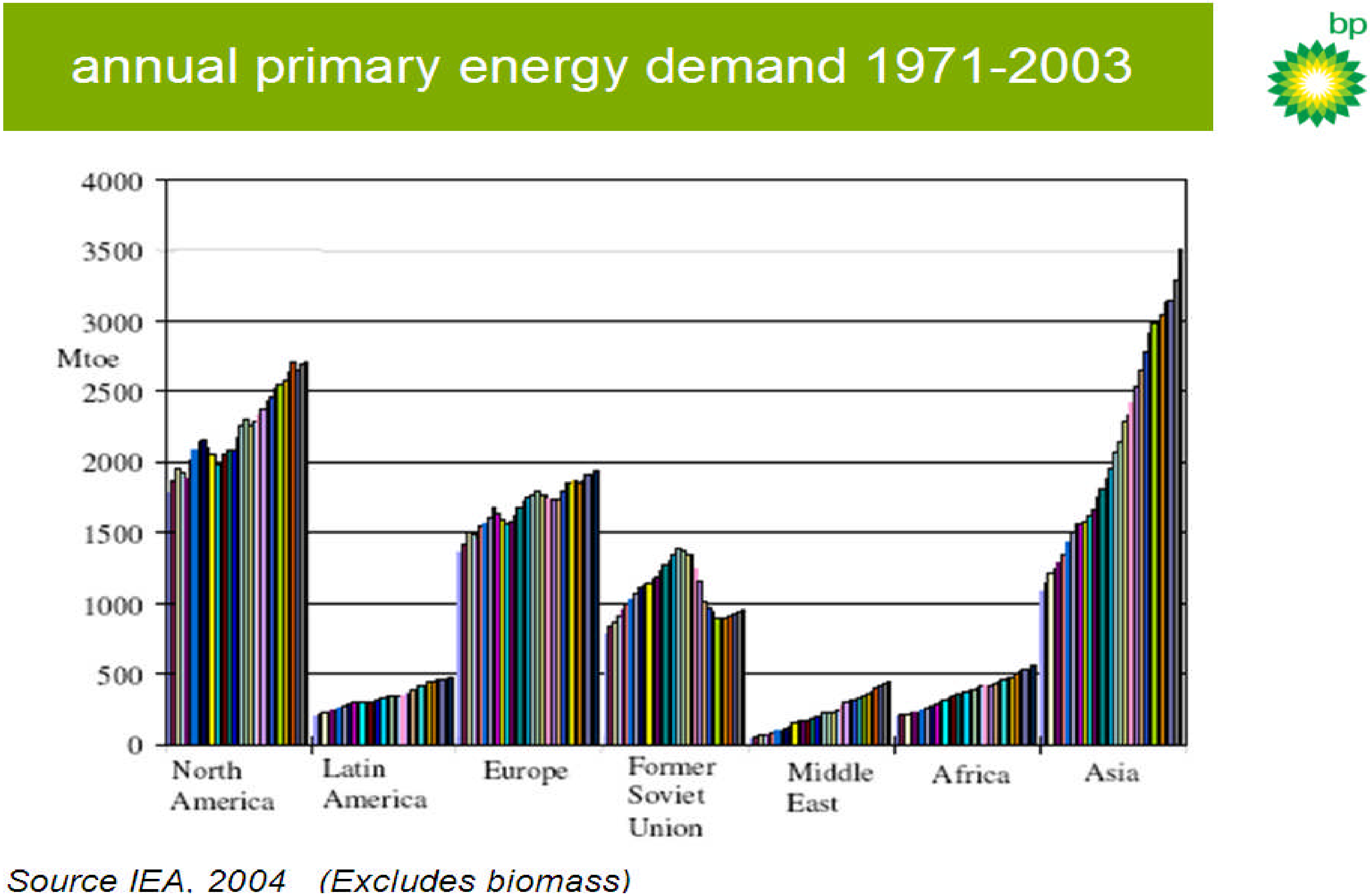



**U.S. energy use per capita and per dollar of GDP from 1980 to 2030**



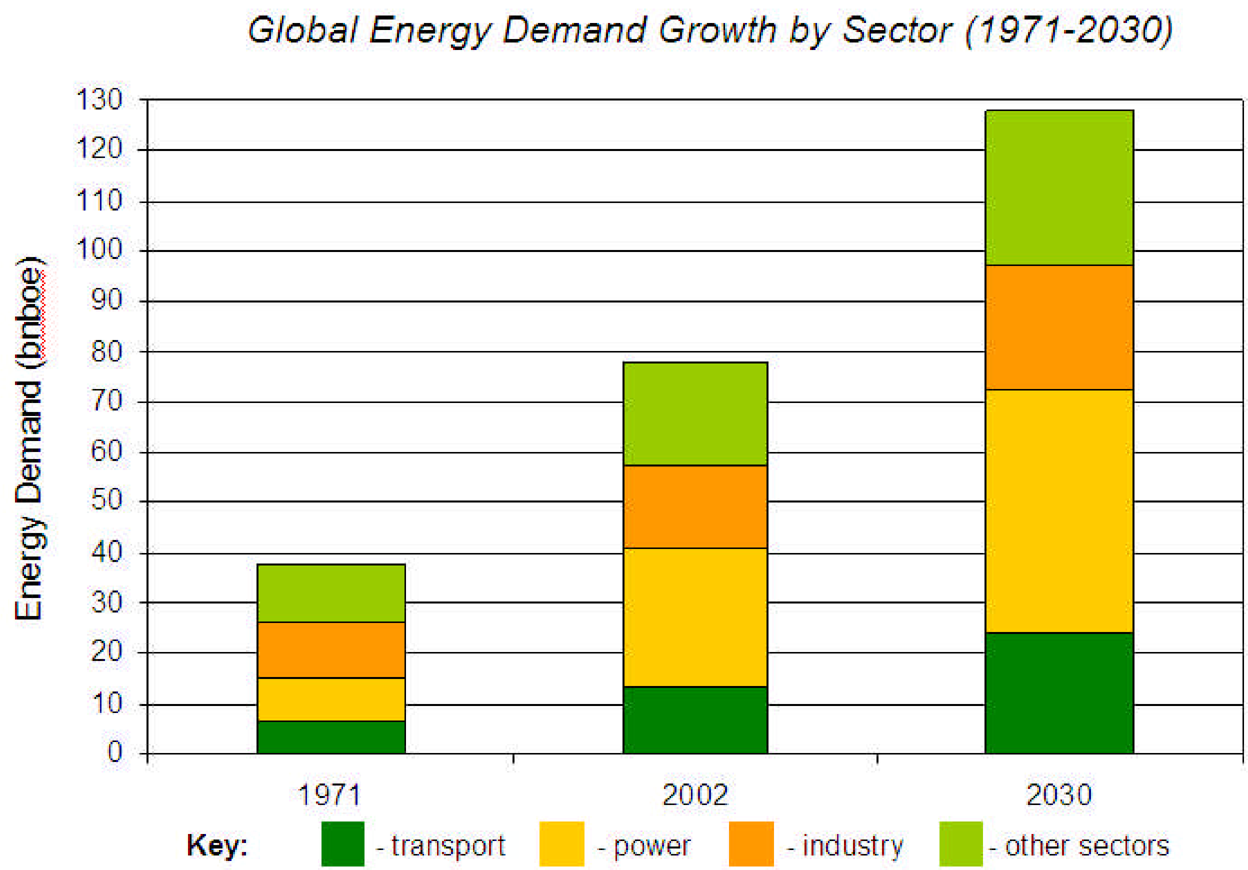

Source: UN and DOE EIA
Russia data 1992-2004 only

**(Courtesy of Dr. Steve Koonin, BP)**




**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. 1 trillion cubic feet methane (1 TCF) = 1 EJ.**

# growing energy demand is projected

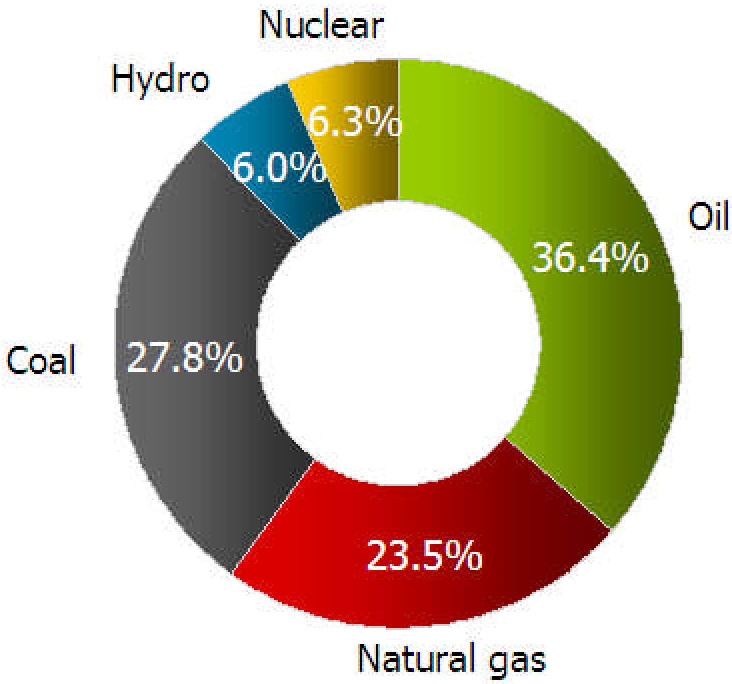


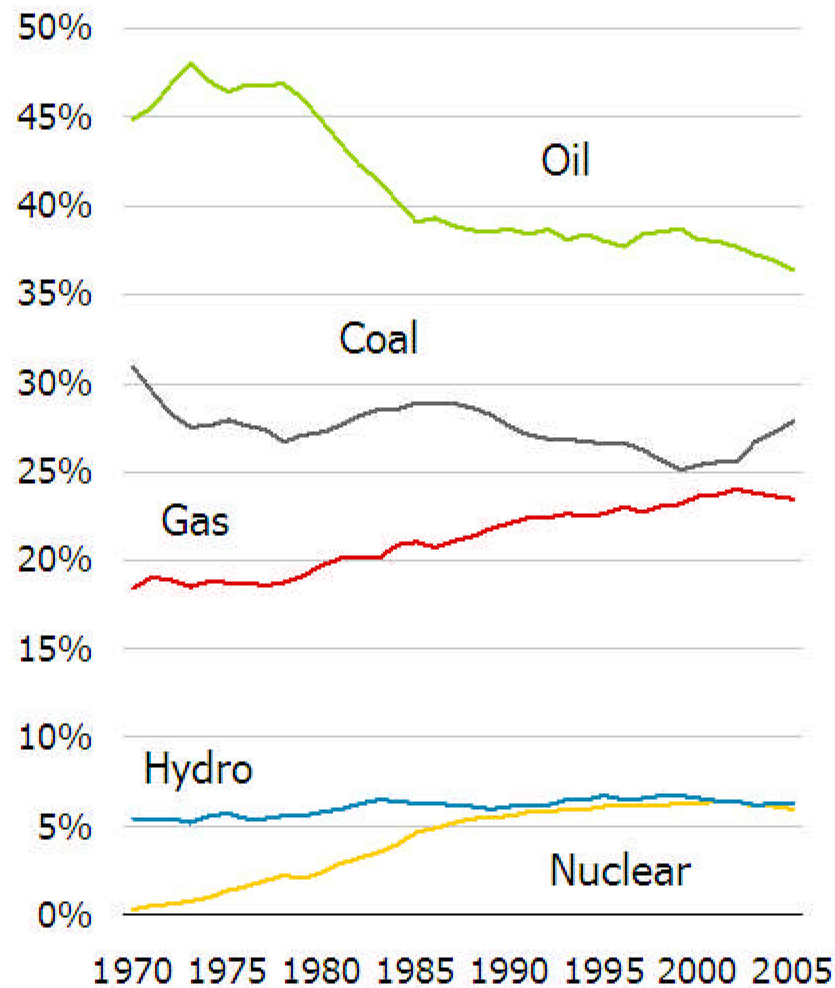

Notes: 1. Power includes heat generated at power plants
2. Other sectors includes residential, agricultural and service

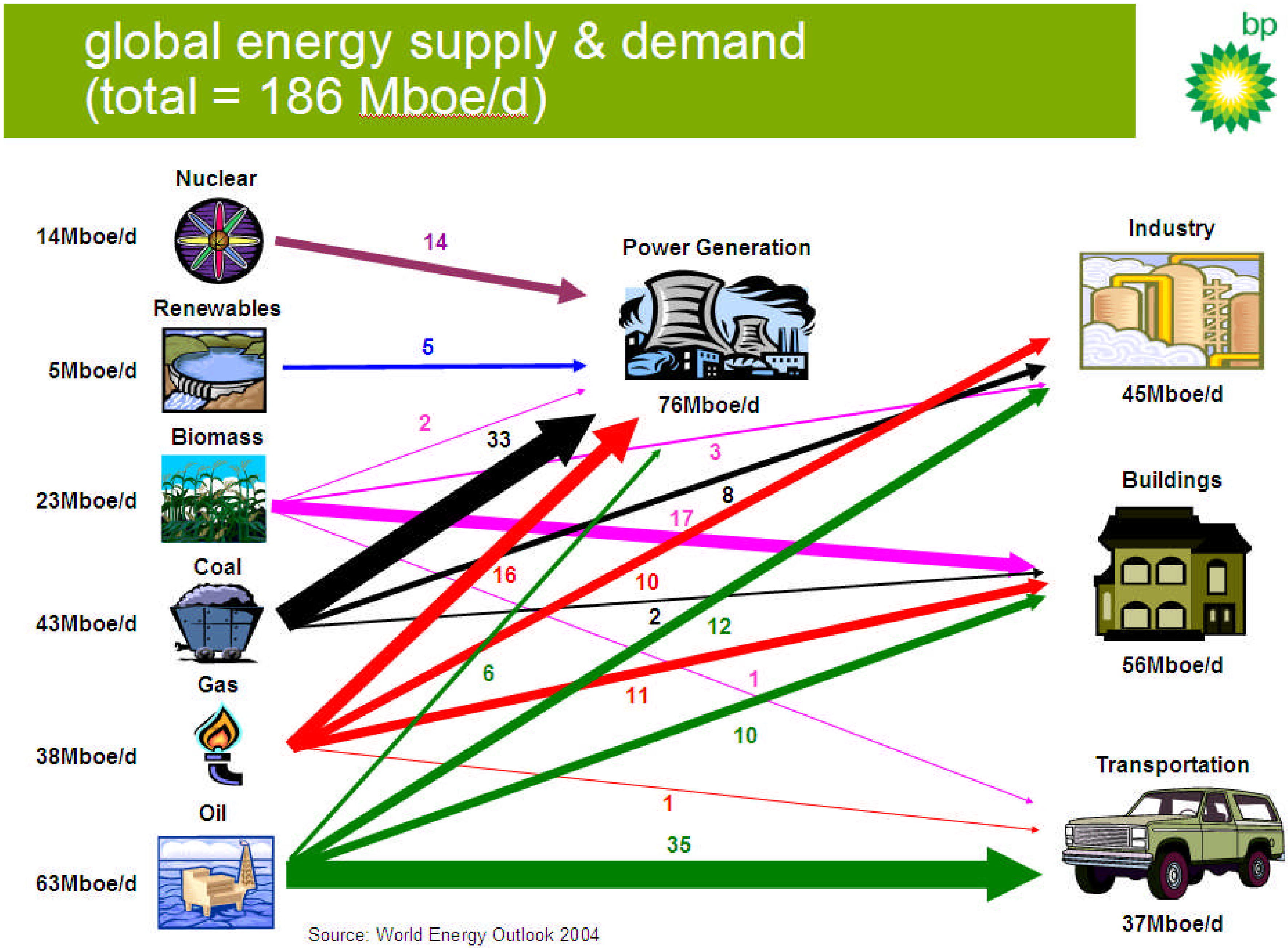
Source: IEA WEO 2004

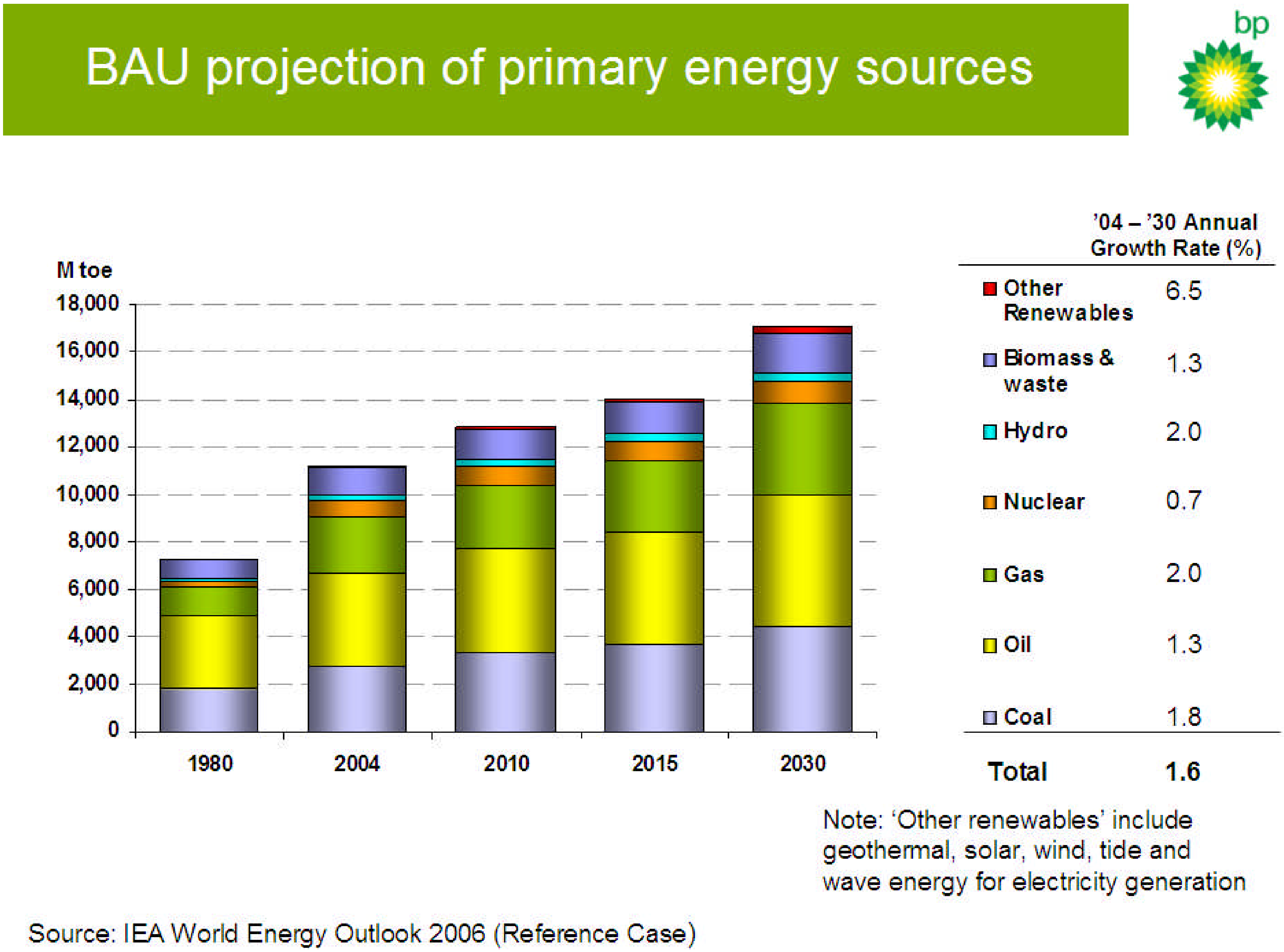
**1 bnboe = 1Gboe = 6.12 GJ x $10^9$ = 6.12 EJ; 2002 total about 477 EJ, of which U.S. is 102 EJ.**

# global primary energy sources



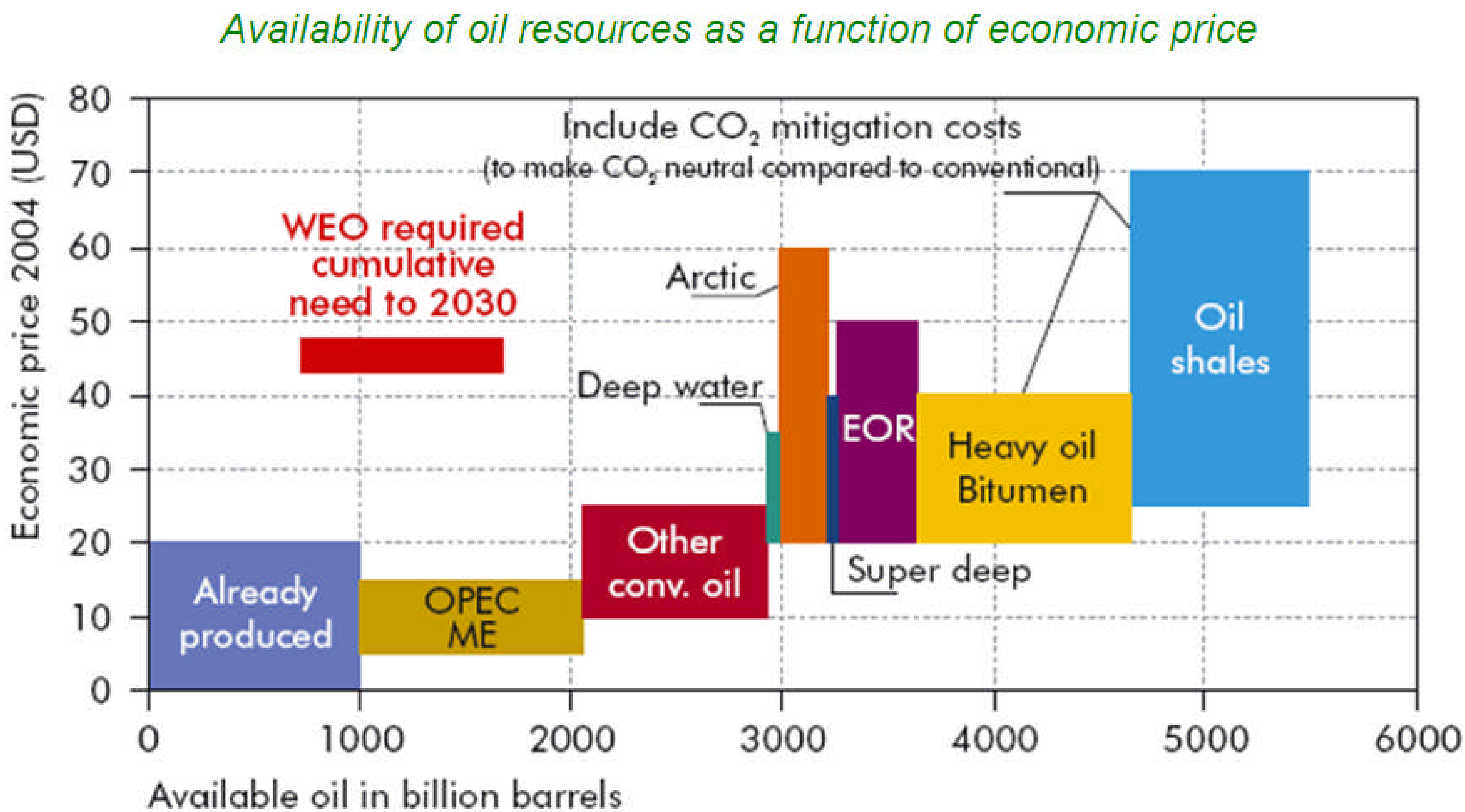




global energy supply & demand
(total = 186 Mboe/d)
bp
Nuclear
14Mboe/d
Renewables
5Mboe/d
Biomass
23Mboe/d
Coal
43Mboe/d
Gas
38Mboe/d
Oil
63Mboe/d
Power Generation
76Mboe/d
Industry
45Mboe/d
Buildings
56Mboe/d
Transportation
37Mboe/d
14
5
2
33
3
8
17
16
10
2
12
6
11
1
10
1
35
Source: World Energy Outlook 2004



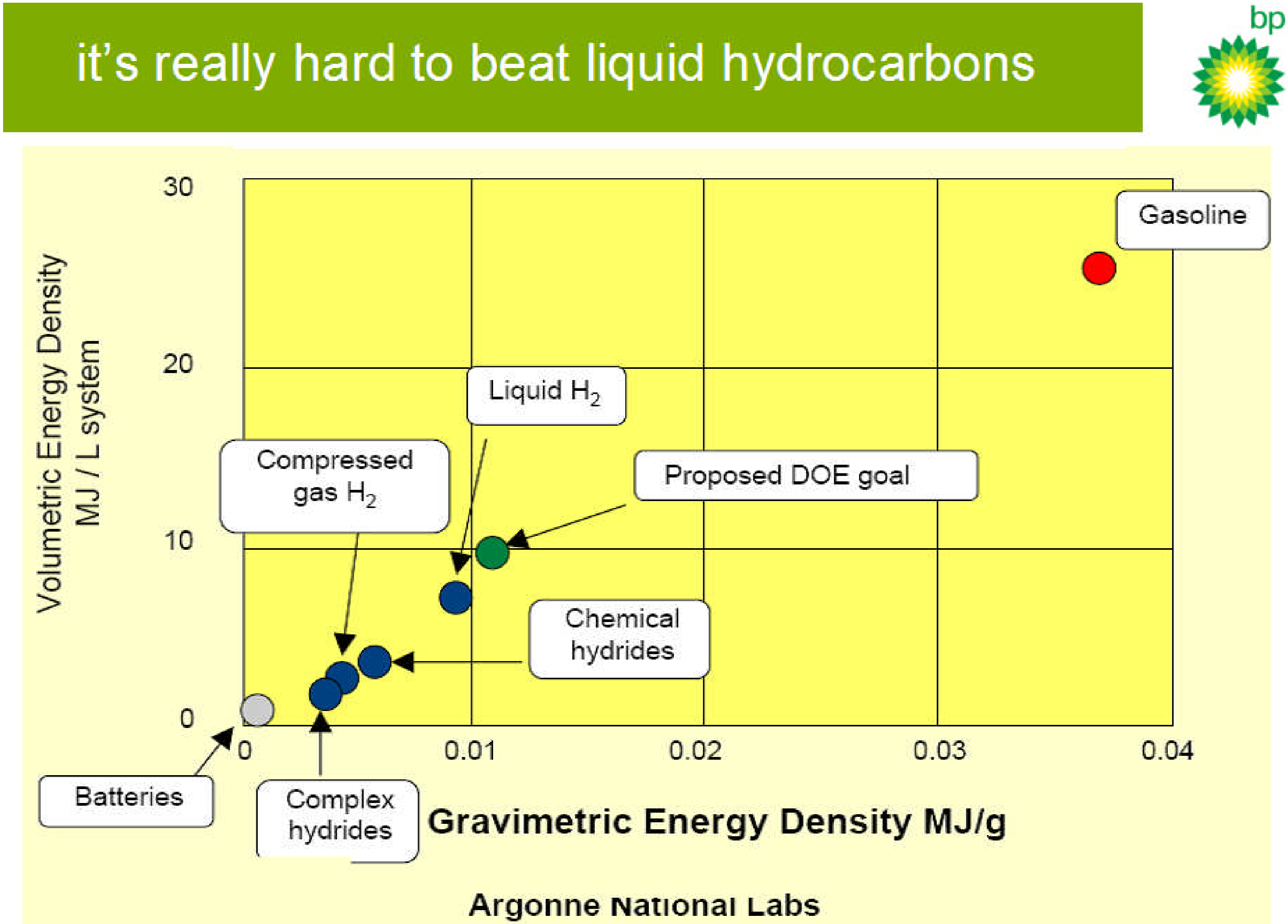

**"BAU" is "business as usual"**

# oil supply and cost curve

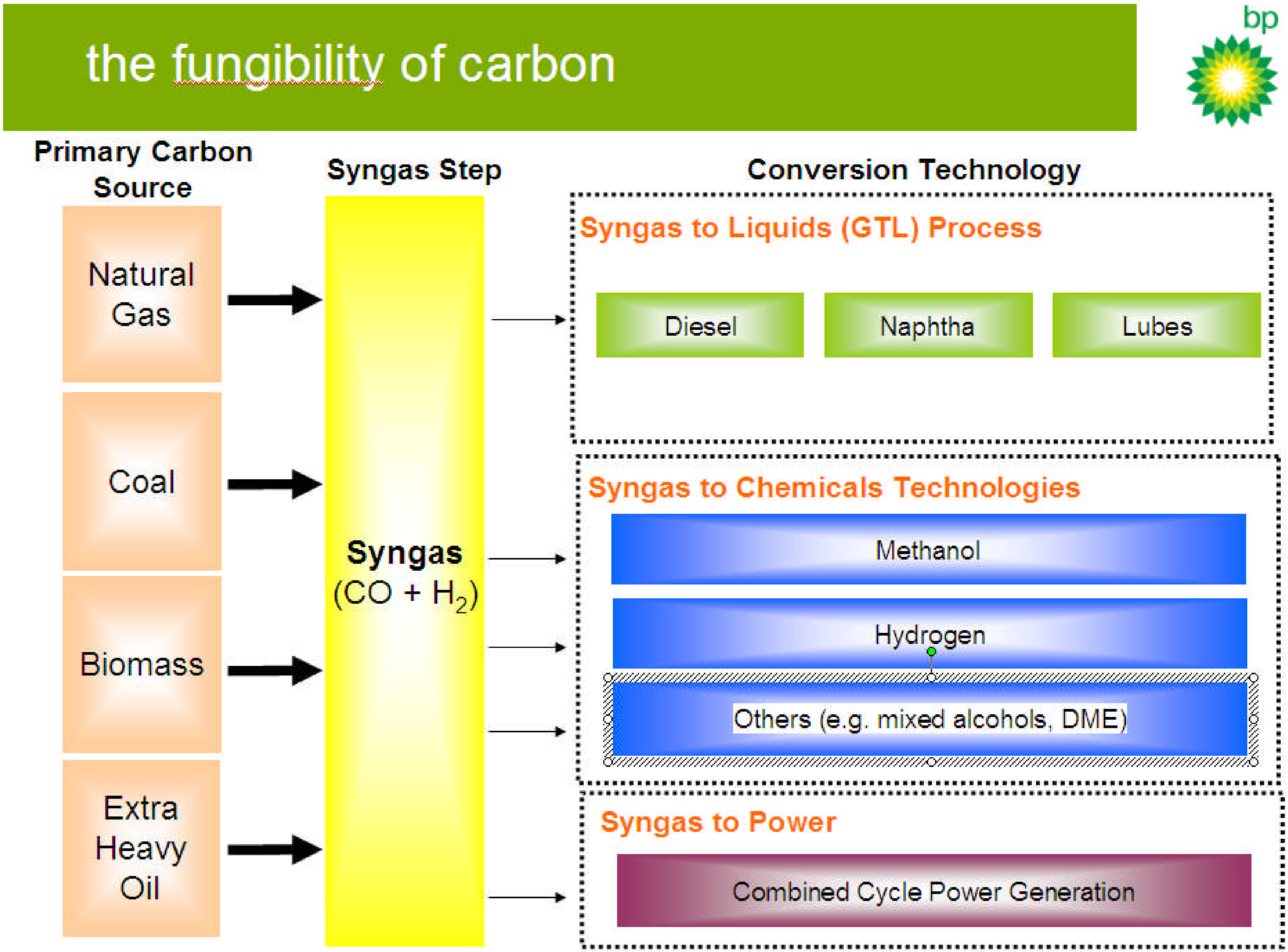



*Source: IEA (2005)*

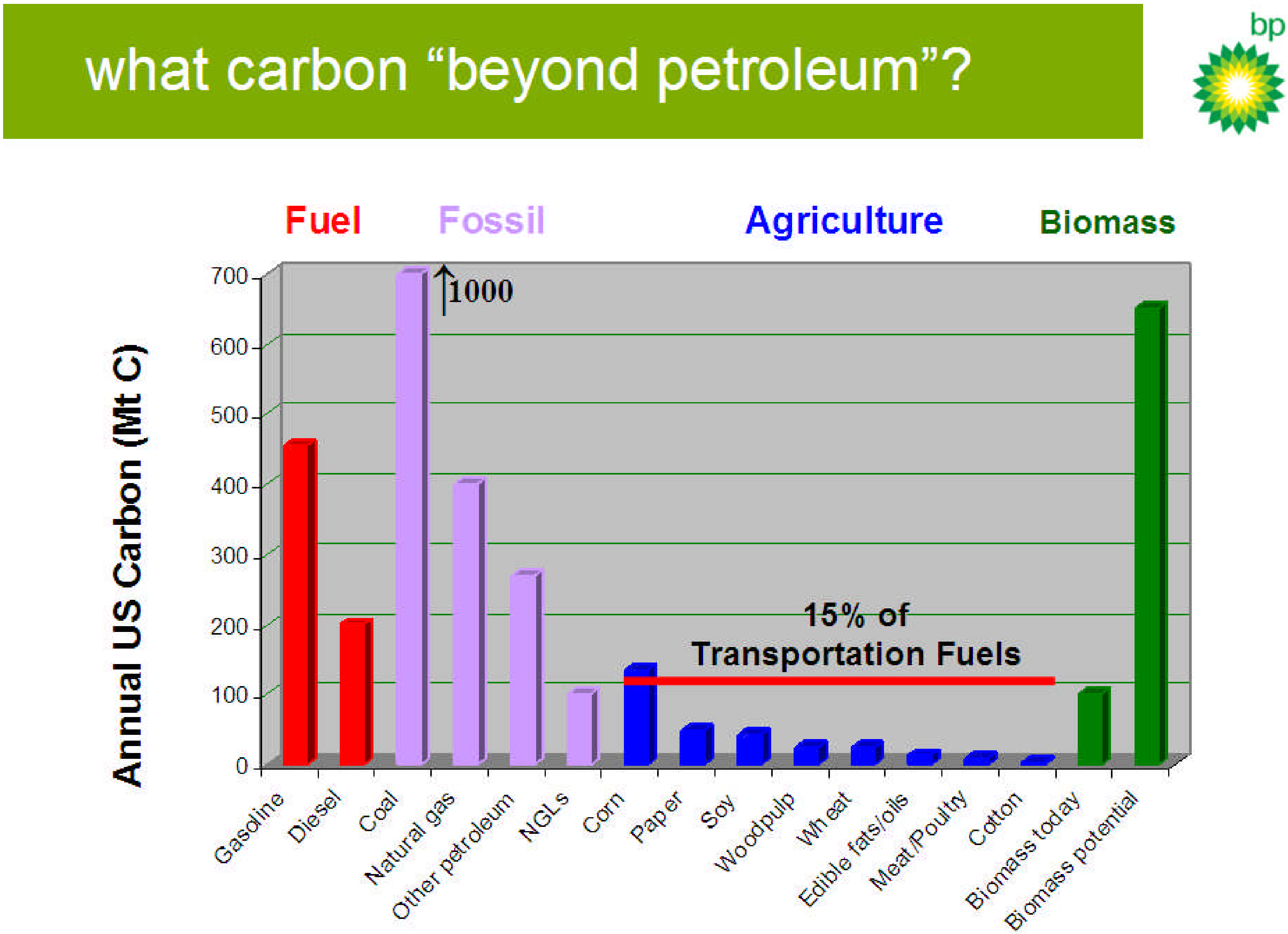
**Compare May 2008 $130/barrel price with max $25/bbl cost.**




**Gasoline and diesel fuel are efficient energy carriers**

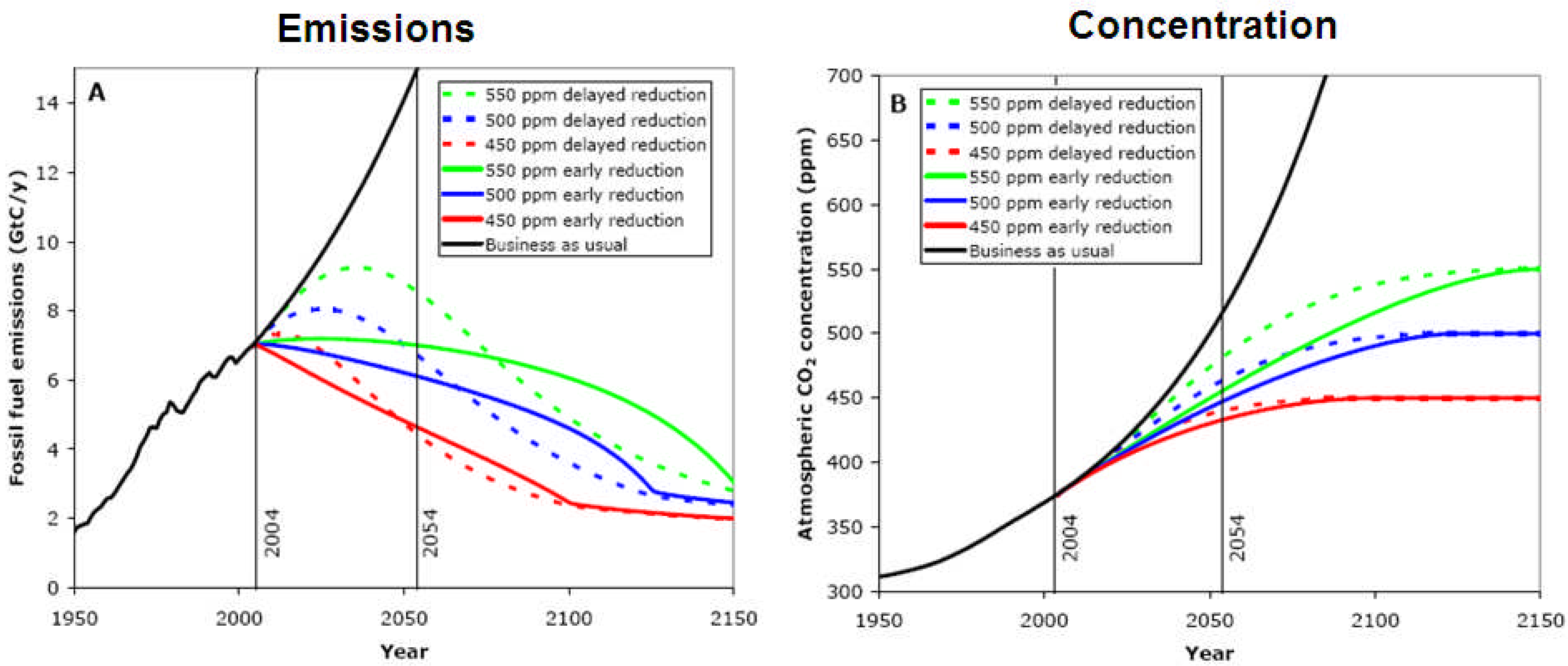



**Can supply major amounts of transport fuel, but even more $CO_2$ emission**

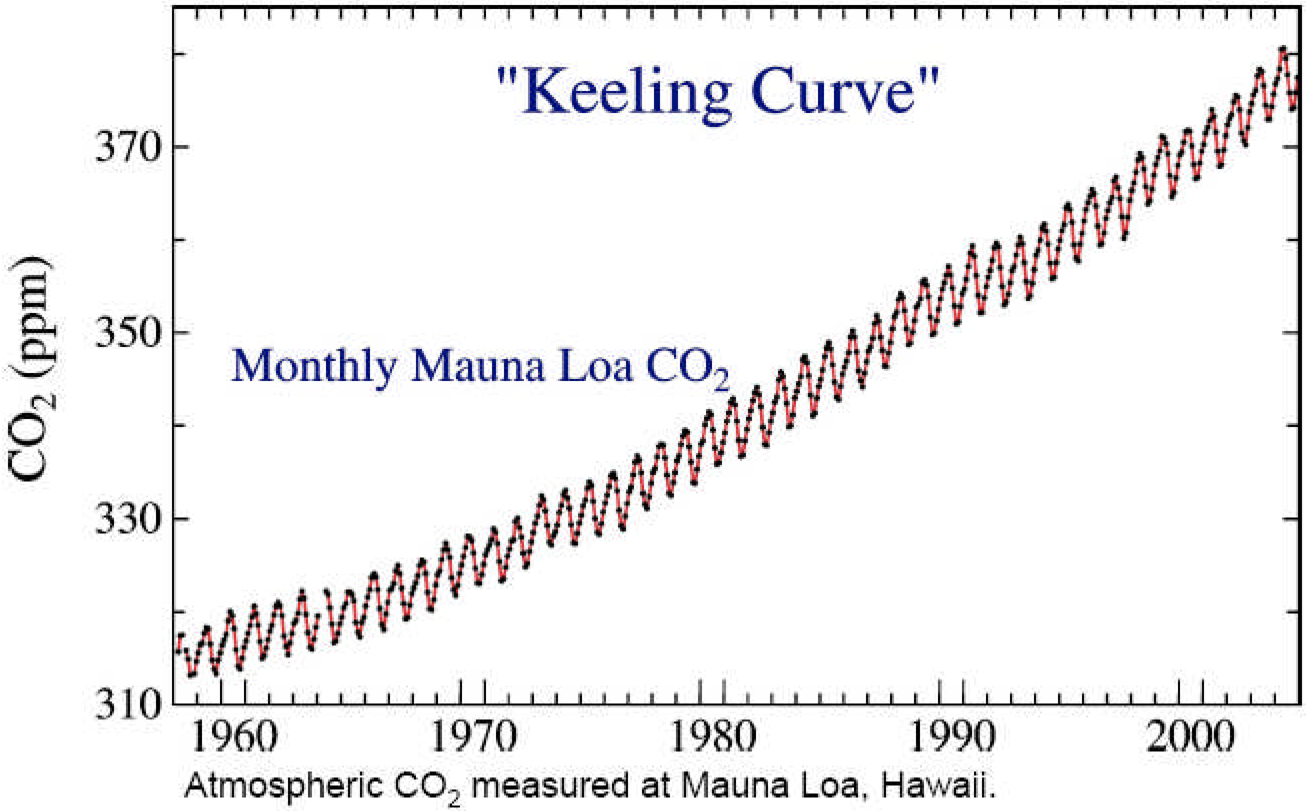



**Biomass for transport fuel can provide energy without net $CO_2$ emission**

# crucial facts about $CO_2$ science




**Strong measures are required to hold atmospheric $CO_2$ 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 $CO_2$; the "$CO_2$ 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 $CO_2$ from fossil-fuel combustion

The emissions arise from a 4-fold product…

$$C = P \times GDP / P \times E / GDP \times C / E$$

where C = carbon content of emitted $CO_2$ (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

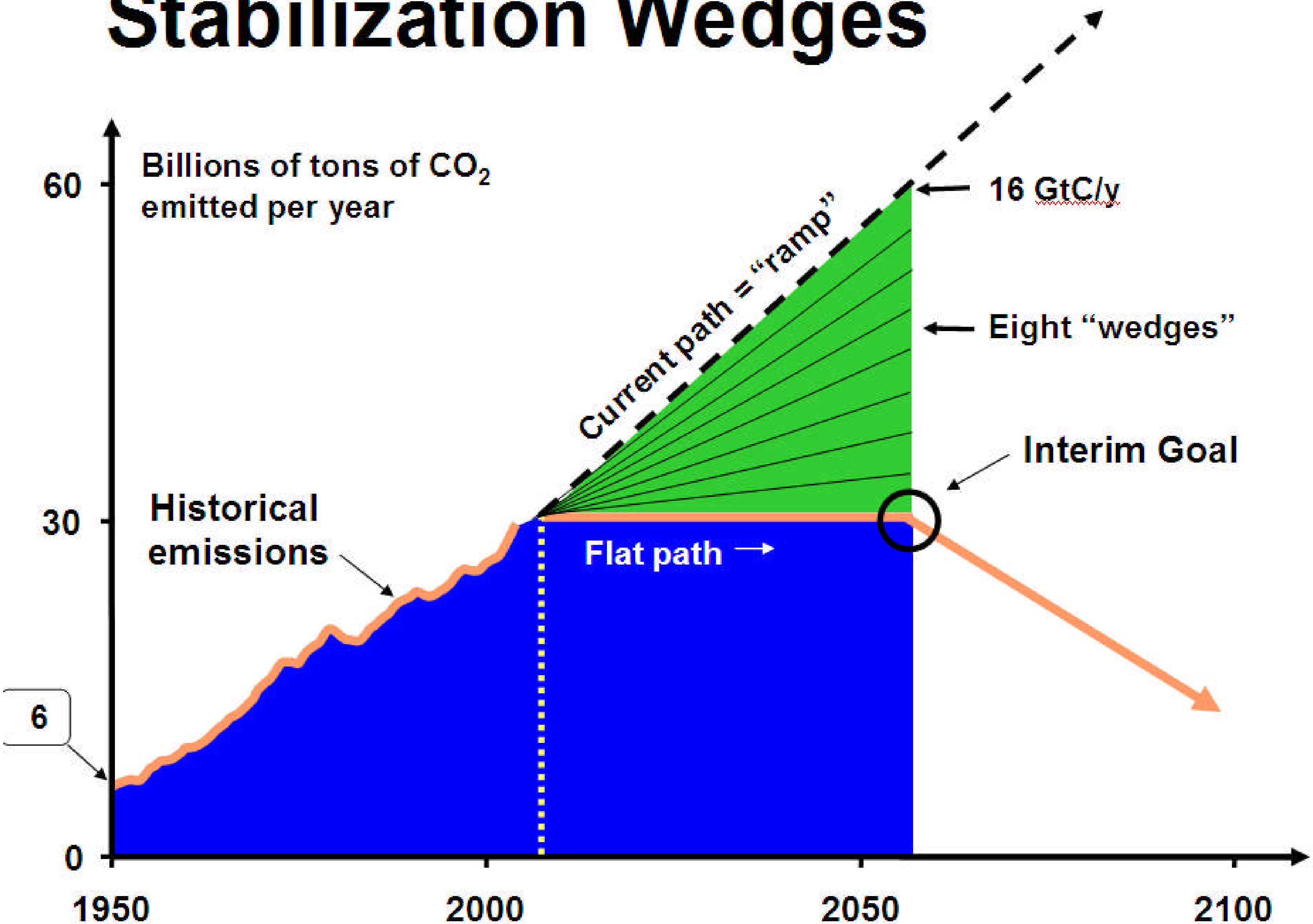
For example, in the year 2000, the world figures were…

$6.1 \times 10^9$ pers x \$7400/pers x 0.01 GJ/\$ x 14 kgC/GJ

= $6.4 \times 10^{12}$ kgC = 6.4 billion tonnes C

**[From John Holdren]**

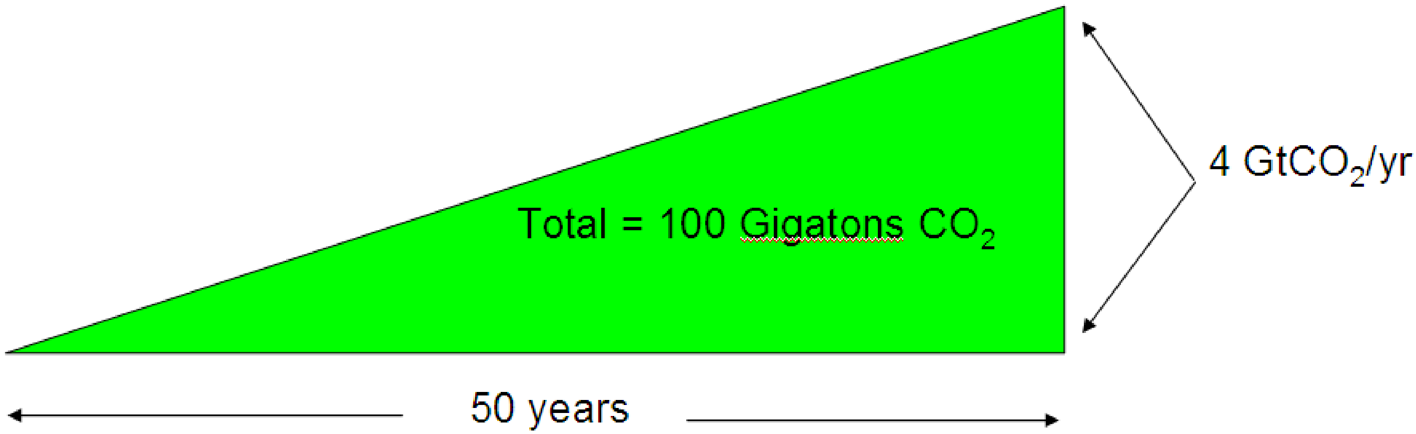
# Stabilization Wedges




**(Wedge charts from R. Socolow)**

# What is a "Wedge"?

A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to 4 $GtCO_2$/yr. The strategy has already been commercialized at scale somewhere.




Cumulatively, a wedge redirects the flow of 100 $GtCO_2$ in its first 50 years. This is **three trillion dollars** at \$30/$tCO_2$.

A "solution" to the $CO_2$ problem should provide at least one wedge.

# *Nuclear Electricity*

**Effort needed by 2055 for 1 wedge:** 700 GW (twice current capacity) displacing coal.

Phase out of nuclear power creates the need for another half wedge.

Dry cask storage, not for forever.

*Site*: Surry plants on James River, VA; 1625 MW since 1972-73,. *Credit*: Dominion.

# Wind Electricity

**Effort needed by 2055 for 1 wedge:**

One million 2-MW windmills displacing coal power.

2008: 100,000 MW (5%)

Wind turbines invisible from the shore.

*Source*: Hal Harvey, TPG talk, Aspen, CO, July 2007

# Photovoltaic Power

#1: Distributed, connected to smart grid

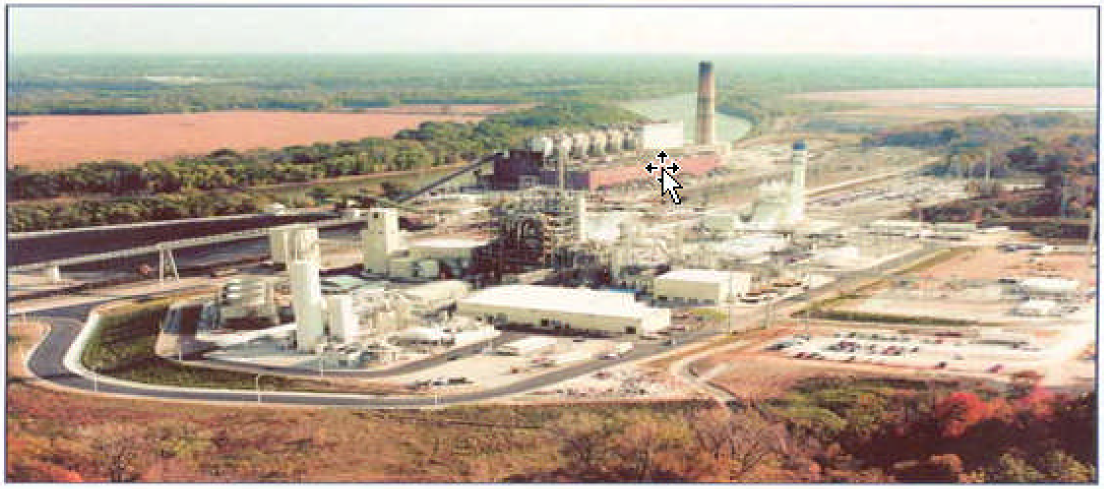
**Effort needed by 2055 for one wedge:**

2000 $GW_{peak}$ (250 x capacity in 2007)

200 million 100-$m^2$ rooftop units
(80 x 100 miles of desert collectors)

*Graphics courtesy of DOE Photovoltaics Program*

# Coal with Carbon Capture and Storage



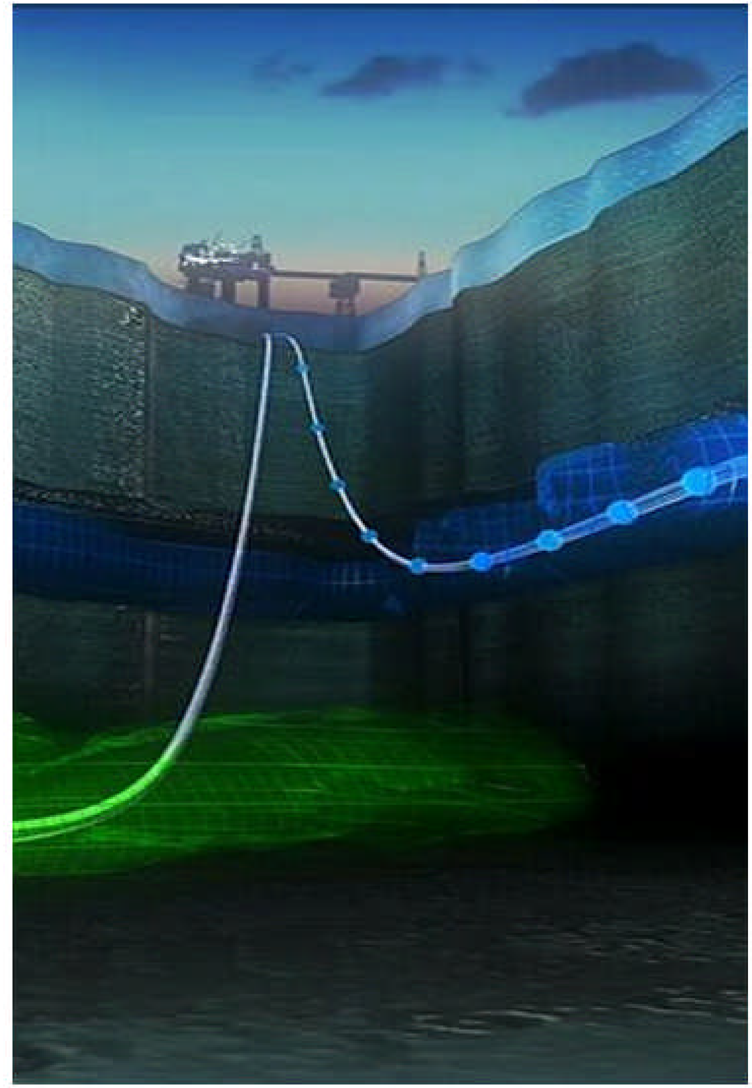
The Wabash River
Coal Gasification Repowering Project

**Effort needed by 2055 for 1 wedge:**

Carbon capture and storage (CCS) at 800 GW coal power plants.

CCS at "coal-to-liquids" plants producing 30 million barrels per day.

**Which will happen first?**



*Graphics courtesy of DOE Office of Fossil Energy* and *Statoil ASA*

# *Efficient Use of Electricity*

motors

lighting

cogeneration

**Effort needed by 2055 for 1 wedge:**

.

25% reduction in expected 2055 electricity use in commercial and residential buildings

**Target: Commercial and multifamily buildings as well as single-family homes.**

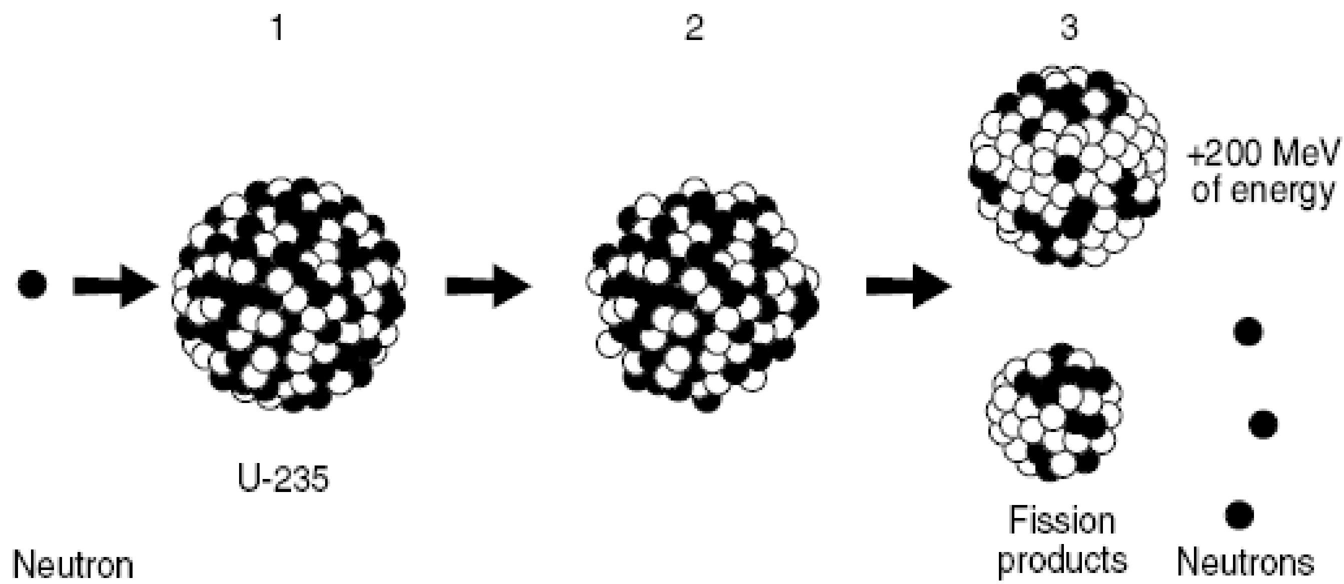
**Nuclear power is still a marvel of nature, science, and technology—devised in large part by physicists.**

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:

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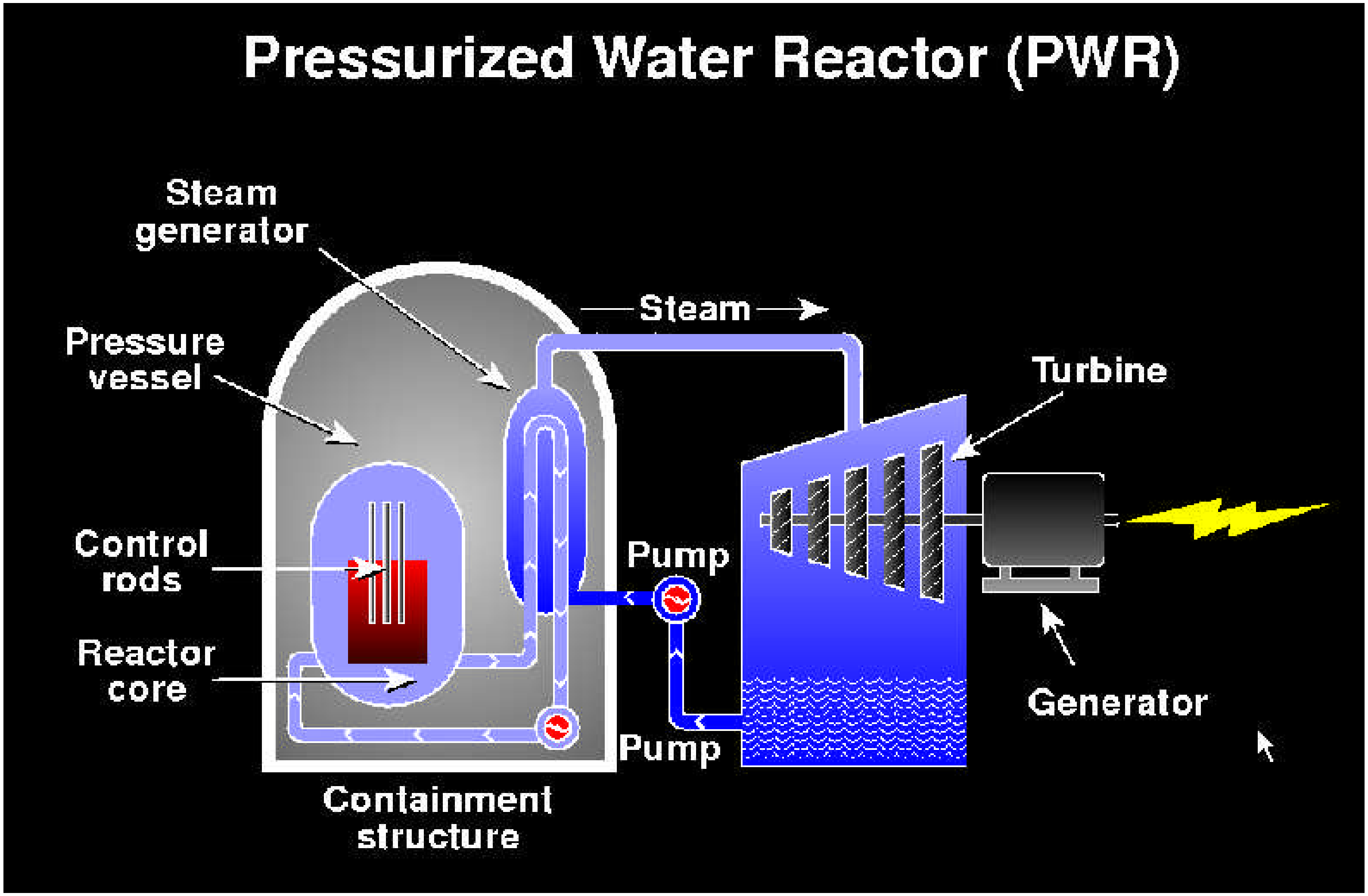
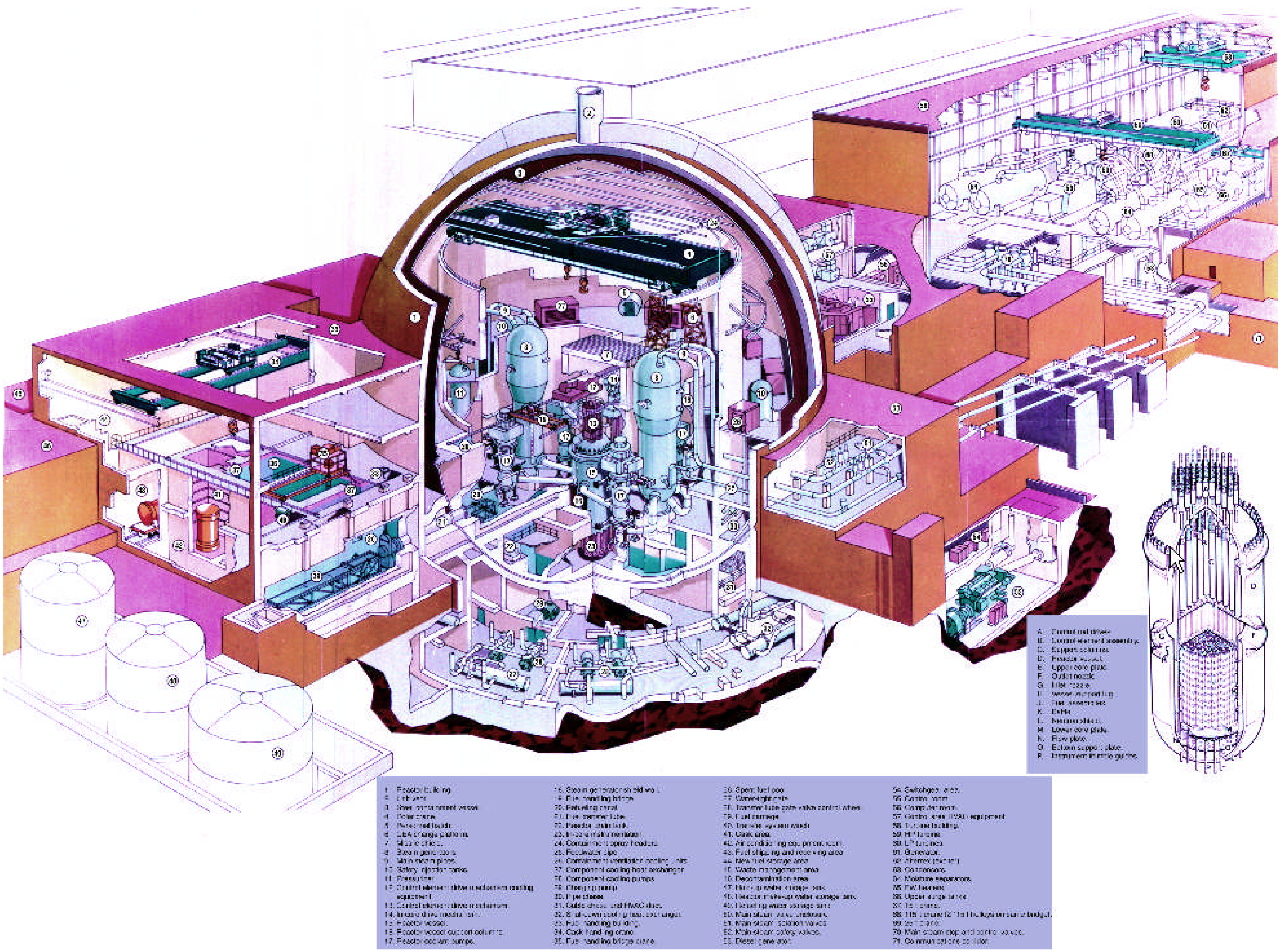
**and with enough U-235, the fission neutrons provoke more fissions, and so on. With the help of a lot of science and engineering, one has a useful power reactor: neutronics, heat transfer, structure, and "balance of plant."**




**Schematic of the PWR, the most common power reactor**



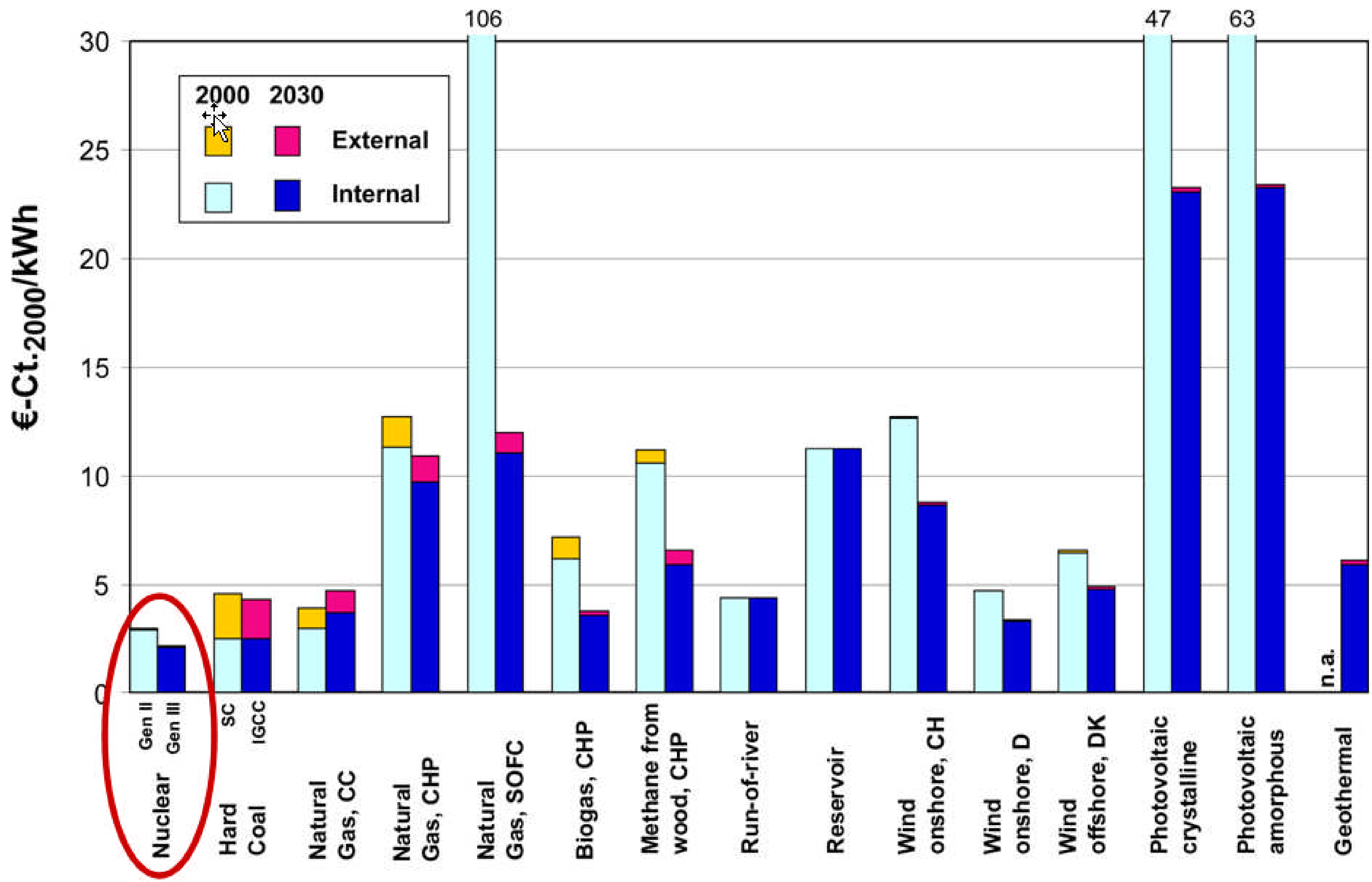
# A PWR in the context of the nuclear power plant

# 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)

# Full costs of electricity generation (Swiss study)




Source: Hirschberg et al., 2007

# 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

# Cost of MOX Fuel vs. UOX

(Two replacement slides of 04/16/09)

From 2003 KSG report, p. 15, UOX (M. Bunn, S.Fetter, J.P. Holdren, B. v.d. Zwaan),
*www.publicpolicy.umd.edu/**Fetter**/2005-NT-repro.pdf*

| | | |
|---|---|---|
| Uranium | 7 kg @ $50/kg | $350 |
| Conversion | 7 kg @ $5/kg | $35 |
| Enrichment | 6 SWU @ $100/SWU | $600 |
| Fabrication | 1 kg @ $200/kg | $250 |
| Total | | $1235 |

So cost of fresh UOX fuel element is $885/kg plus cost of 7 kg of natural uranium. MOX fuel fabrication cost estimate $1500/kg. Cost of 1 kg of MOX = fabrication cost plus reprocessing cost of 7 kg of UOX fuel. At 2003 estimate of $1000/kg UOX for reprocessing, cost of fresh MOX fuel element is $1500 + 7x$1000 = $8500/kg, but this is offset by the value of the uranium separated from the spent UOX—about 95% of the original uranium but not worth quite as much per kg because of U-236 buildup.

(It is a coincidence that 7 kg of NU is needed per kg of UOX, and 7kg of spent UOX per kg of MOX).

**Figure 2.1.** Breakeven uranium price as a function of the cost of reprocessing, for various sets of assumptions about the cost of other fuel-cycle services.

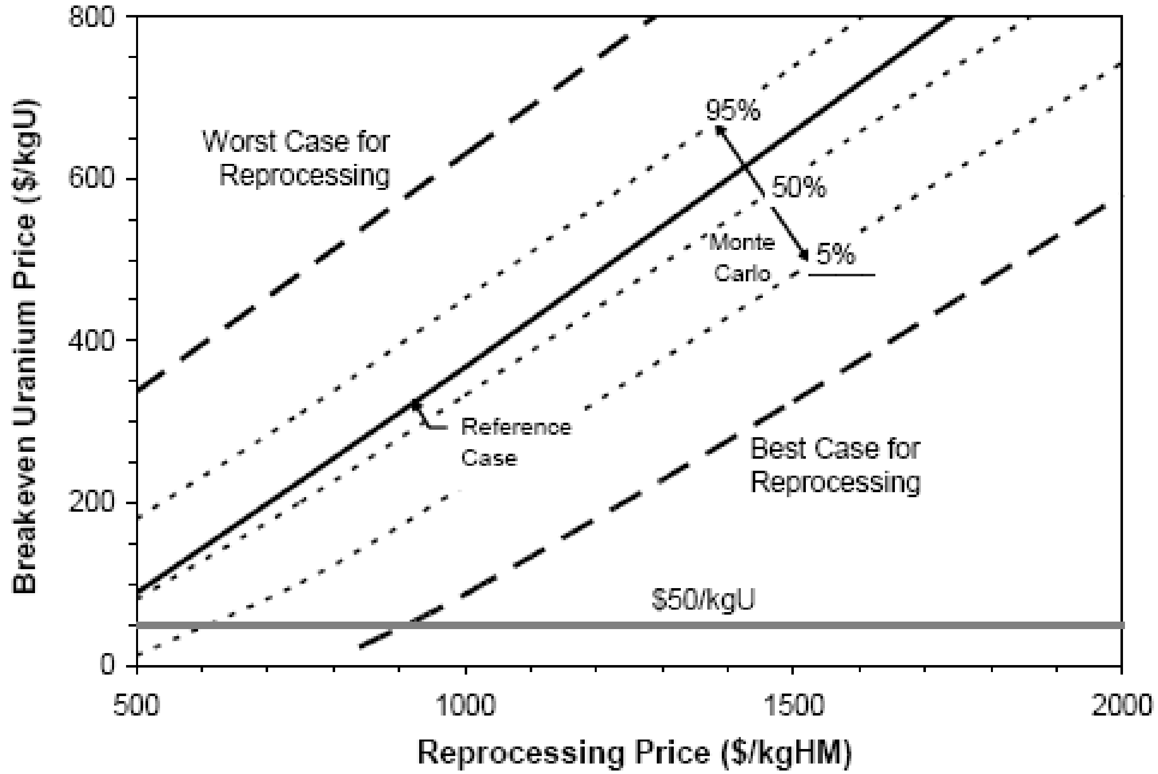



Figure 2.1 takes into account assumptions about interest rates, delay times, etc.

If Rokkasho-mura plant reprocesses at capacity of 800 MTIHM/yr and with annual cost of $2 billion, the Reprocessing Price is $2500/kgHM, and the corresponding "Reference Case" Breakeven Uranium Price is thus about $1300/kg, in contrast with recent (high) uranium price of $130/kg.

# Methane hydrates—a potential game-changer?

## WORLD ESTIMATES OF THE AMOUNT OF GAS WITHIN GAS HYDRATES

### In-Place Natural Gas in Marine Hydrates

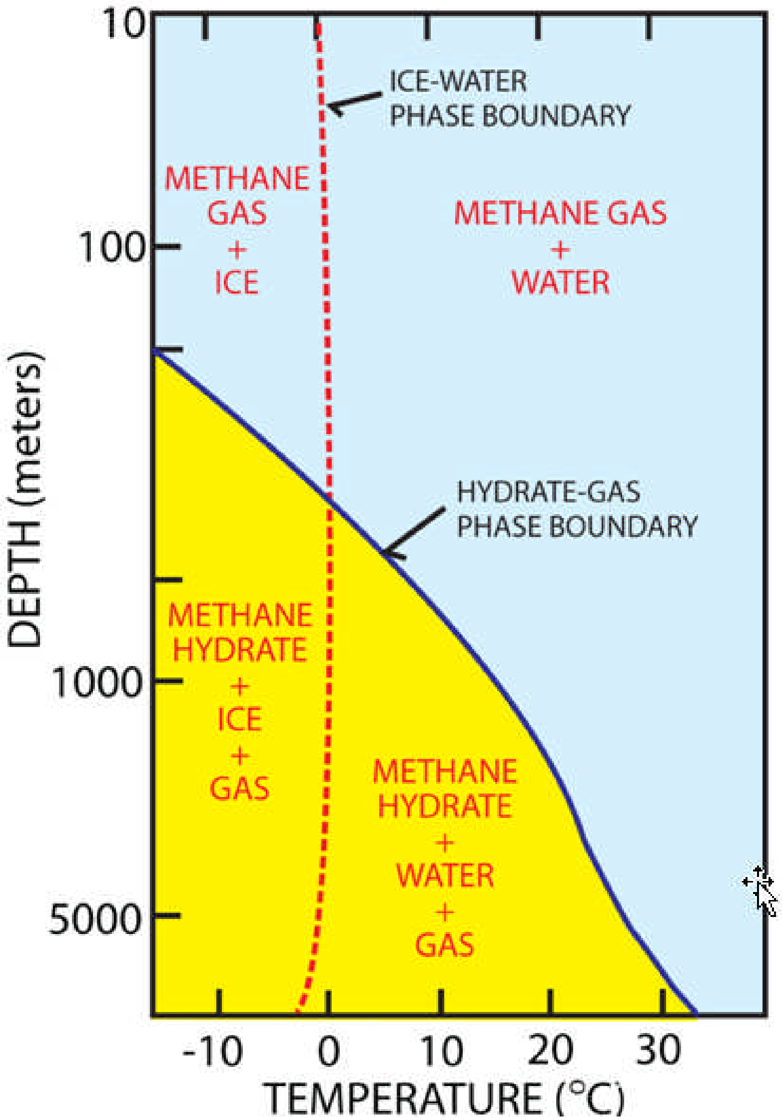
| Cubic meters | Reference |
|---|---|
| $3.1 \times 10^{15}$ | McIver, 1981 |
| $3\text{-}5 \times 10^{15}$ | Milkov et al., 2003 |
| $5\text{-}25 \times 10^{15}$ | Trofimuk et al., 1977 |
| $125 \times 10^{15}$ | Klauda and Sandler, 2005 |
| $2.0 \times 10^{16}$ | Kvenvolden, 1988 |
| $2.1 \times 10^{16}$ | MacDonald, 1990 |
| $4.0 \times 10^{16}$ | Kvenvolden and Claypool, 1988 |
| $7.6 \times 10^{18}$ | Dobrynin et al., 1981 |

### Remaining Recoverable Conventional Natural Gas

| Cubic meters | Reference |
|---|---|
| $4.4 \times 10^{14}$ | Ahlbrandt, 2002 |

**AT STP**

# Methane Hydrate Stability




## Temperatures and Moderate Pressures

- Temperatures above & below 0°C

## Stable

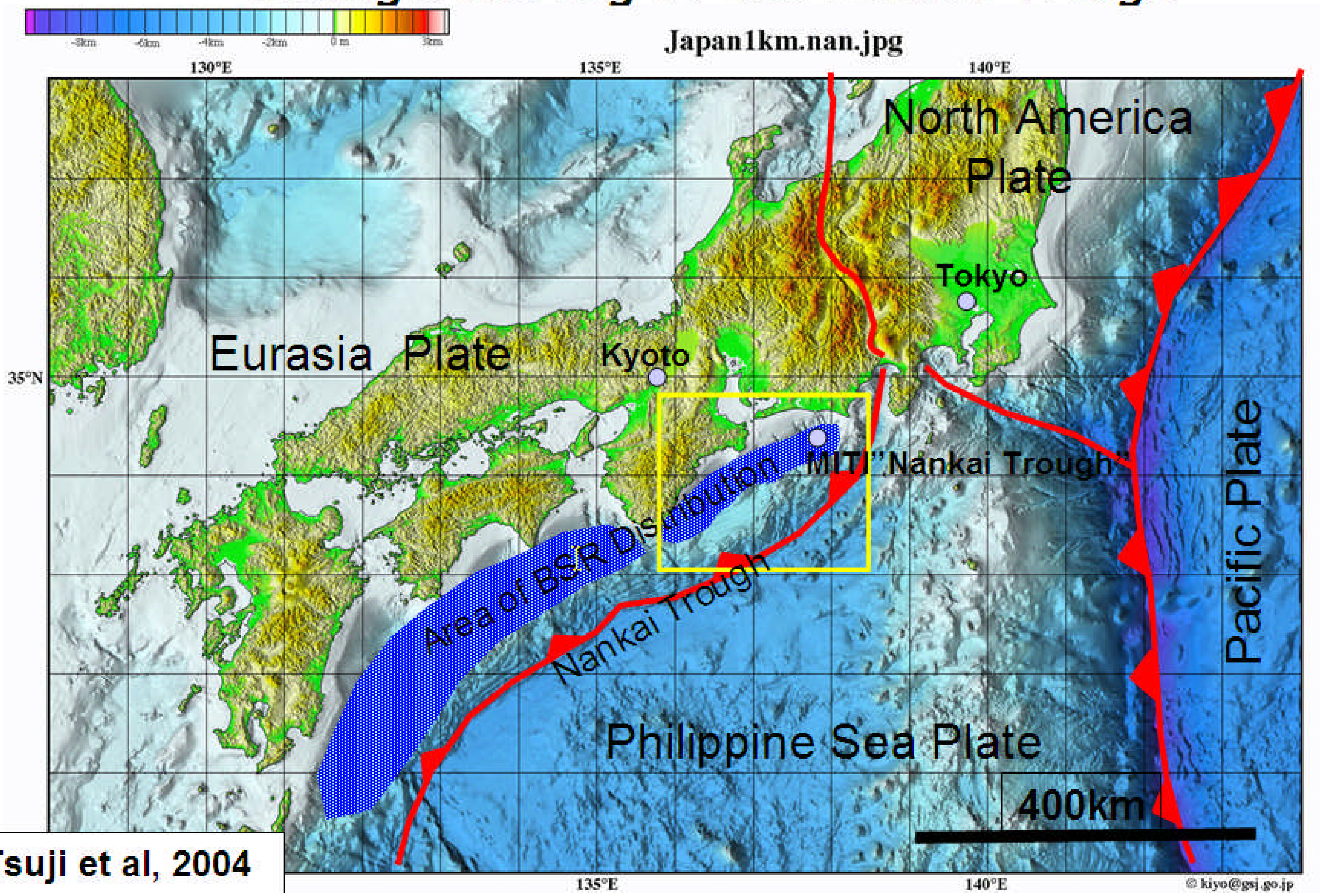
- Arctic associated with permafrost
- Marine sediments (> 500m deep)

## Requires Gas Source

- Biogenic
- Thermogenic

# National R&D Program for Methane Hydrate Resources in Japan

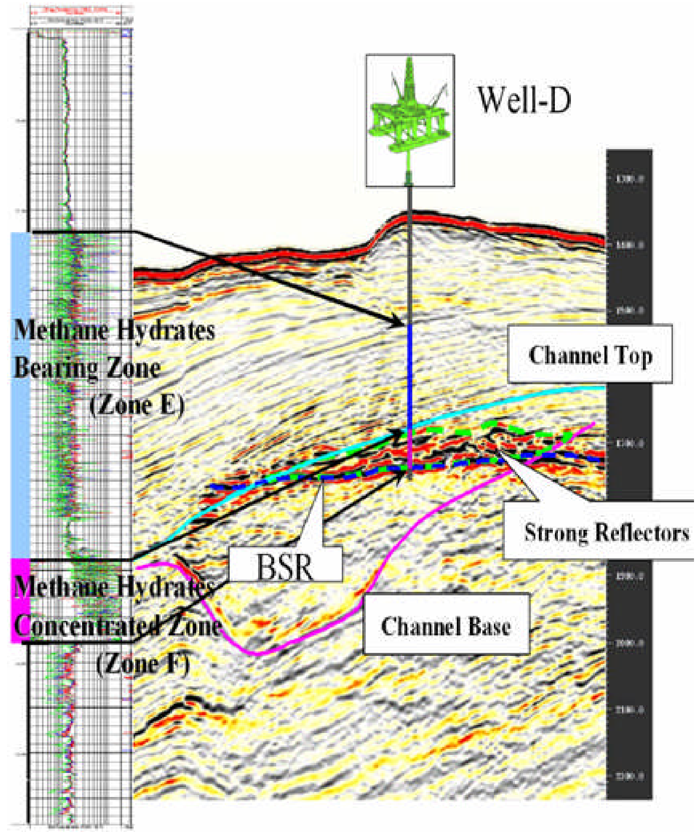
## -Geologic Setting of the Nankai Trough-




Tsuji et al, 2004

# Nankai Trough Hydrate Assessment

- **Geologic Resource Assessment**
- **Area = 5,000 km2 (10% of total Nankai BSR area)**
- **Volumetrics (probabilistic)**
  - Gross Rock Volume (wells-seismic)
  - Net-to-Gross (res > 3 ohm-m)
  - Porosity (density log)
  - Sgh (density/NMR cal to PTCS)
  - Conversion (1:173; 96% cage occ.)
- **20 Tcf (10-83) in 10 high-Sgh zones**
- **40 Tcf in full section**




*Saeki, et al., 2008*

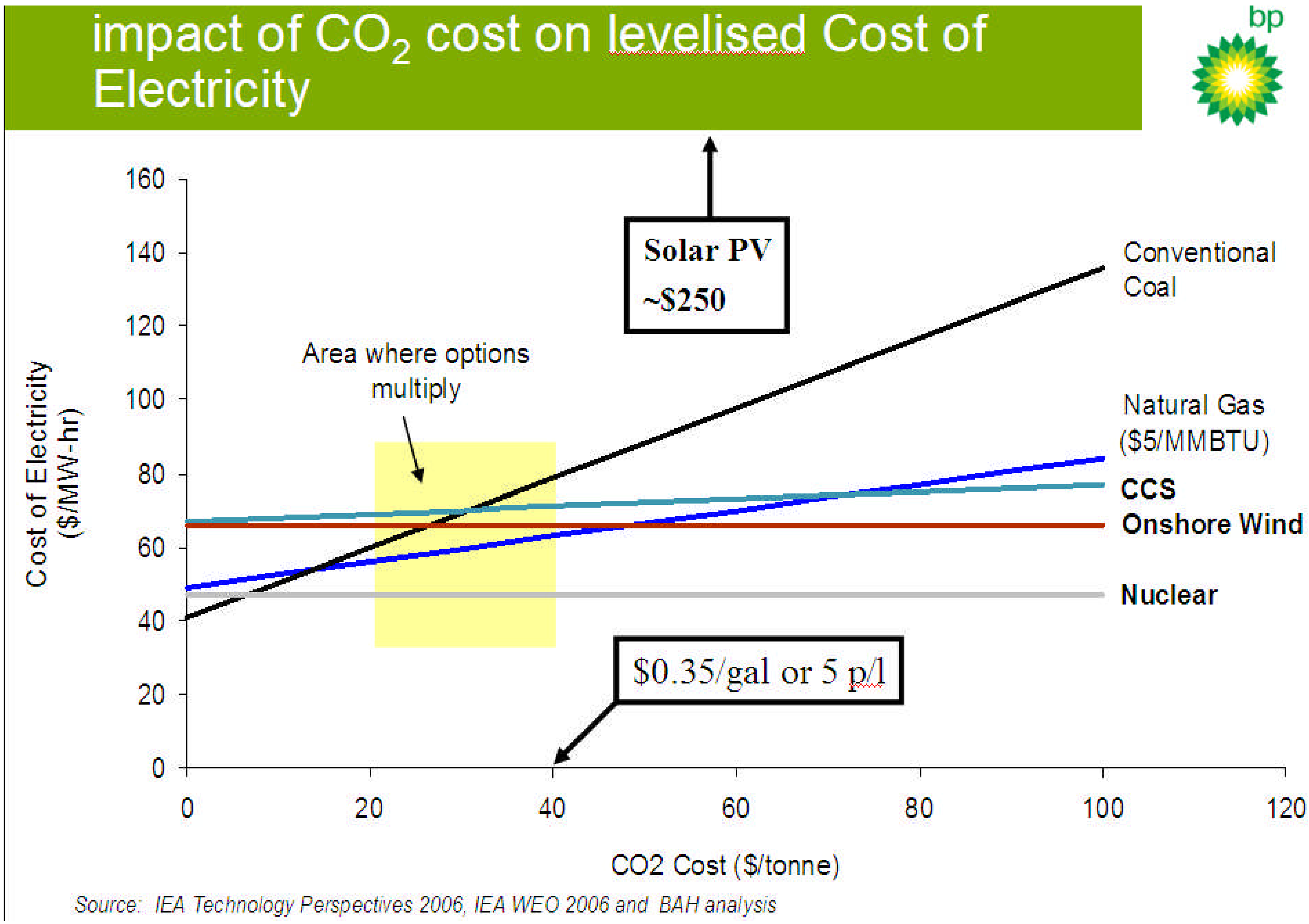
(1 Tcf = trillion cubic feet. At 1 MJ/cf this is $10^{18}$ J/Tcf. One GWe-yr of electrical energy is $3\text{x}10^{16}$ J of energy output. If full Nankai Trough is 400 Tcf, 10% recoverable and 50% efficient, equivalent to 7000 reactor-yrs worth of electrical output.)

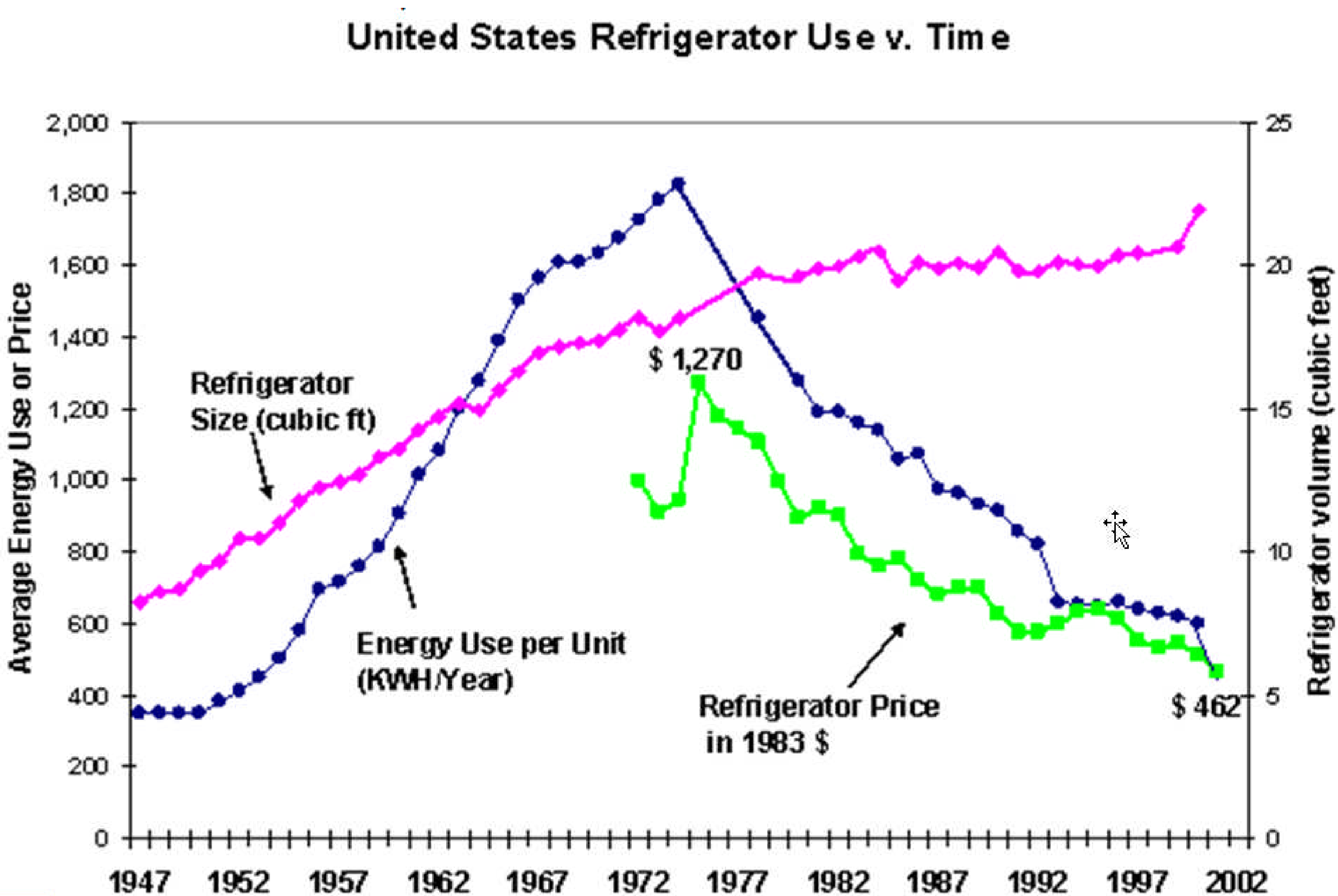
# Methane hydrates a challenging and fascinating resource

- Total resource greater than that of all other fossil carbon, but a very diffuse resource—much of it not producible.
- A competent solid not readily produced by oil technology.
- To liberate methane from hydrate requires heat to drive endothermic reaction.
- Carbon dioxide forms a more stable hydrate than methane, so carbon capture and storage in the methane hydrate formation might be used to liberate the methane without supplying heat as such.
- A potential route to low-carbon energy for marine states lacking conventional petroleum resources.

# Near-term tools

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



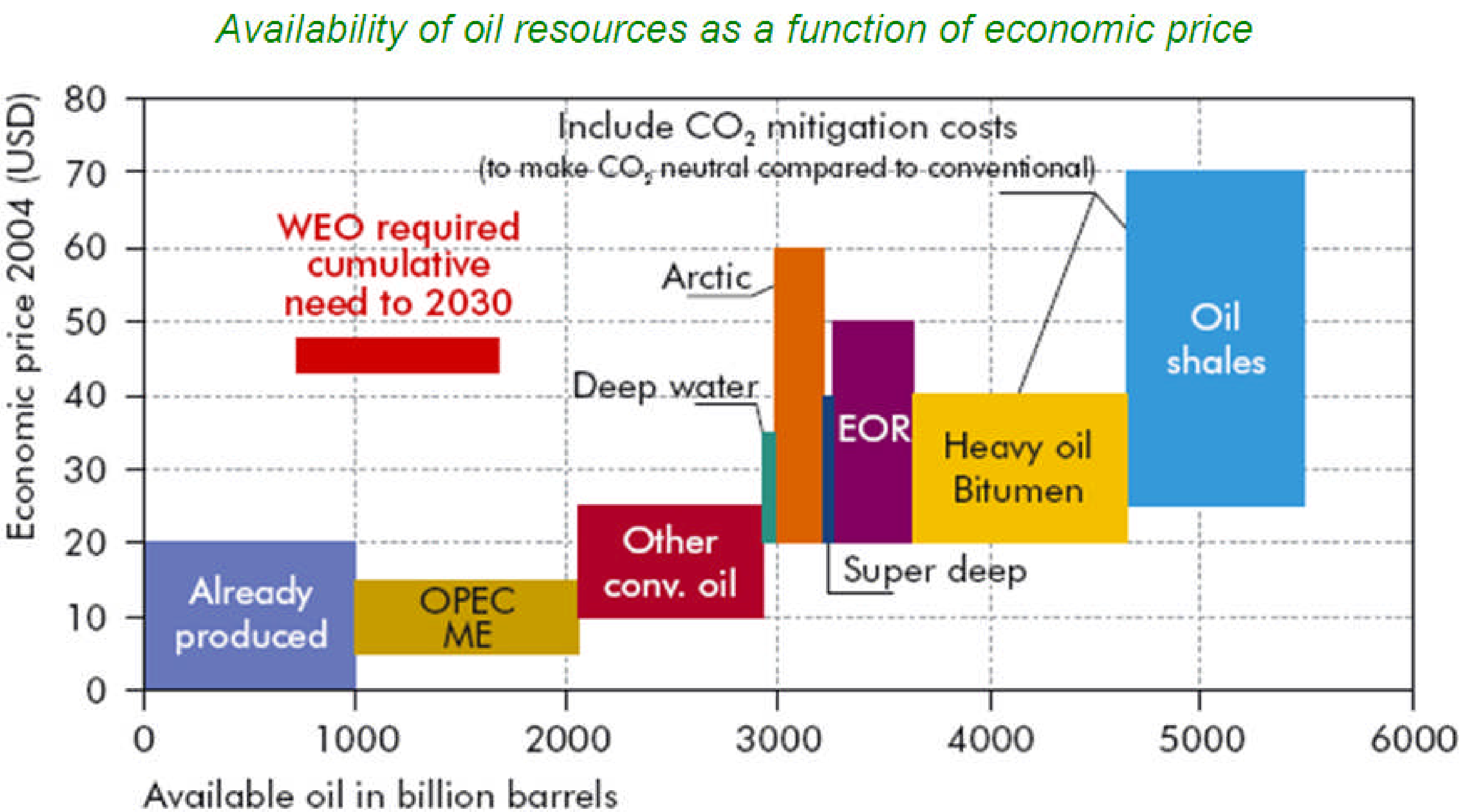



**Spectacular results in response to a government prize/incentive program**

# 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 x 44/12 = 7.3 MT $CO_2$ 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 methane hydrate from ocean margins, and define the resource (perhaps 2000 Gt of carbon, but a dilute, non-flowing resource)**

# oil supply and cost curve




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 €0.35 per liter.**

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**Robert Socolow**