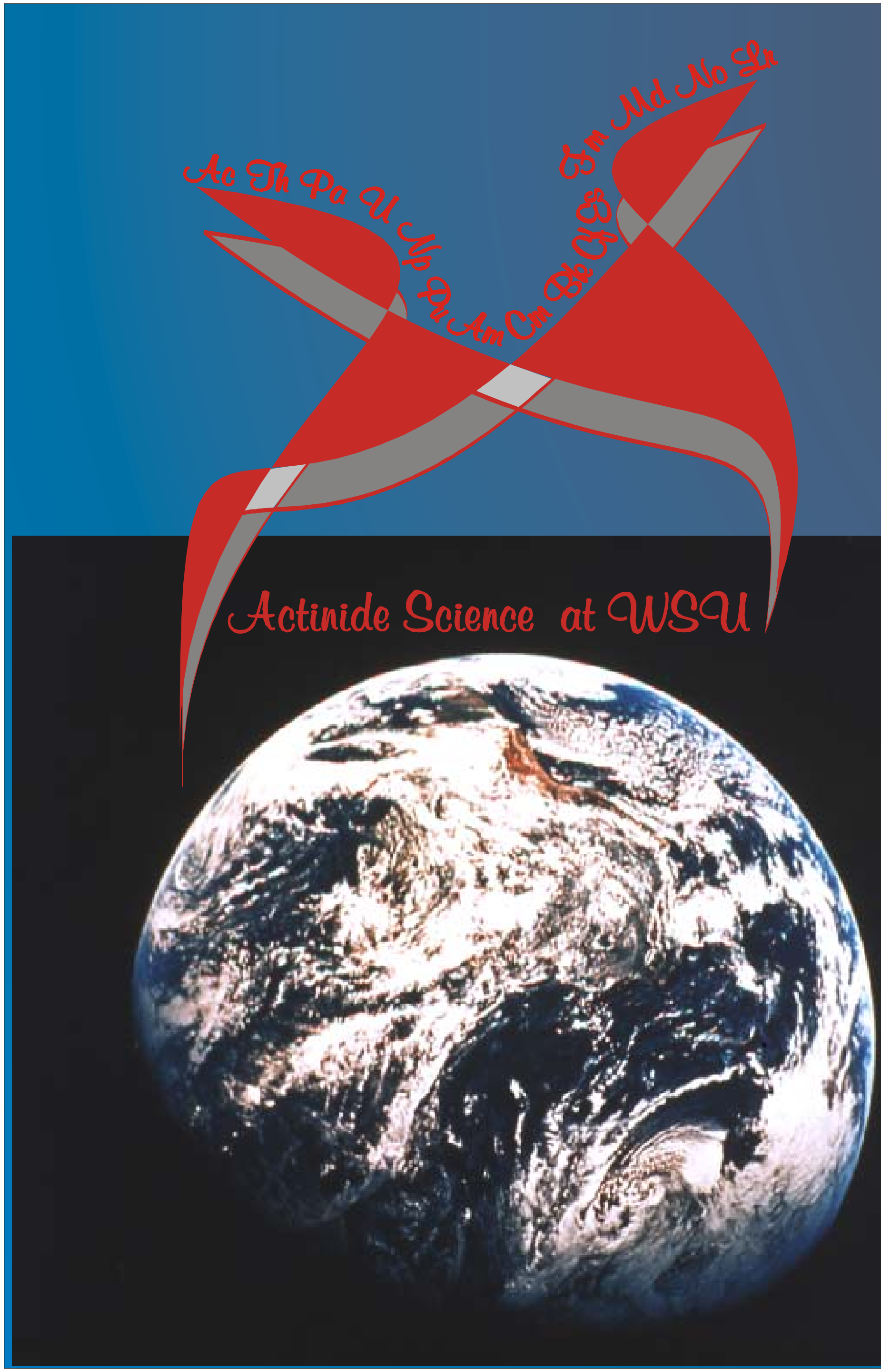

The Post Fukushima Era: Is Nuclear Power a Safe, Green Power Source?

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Washington State University
Pullman, WA 99163

Growing Cleantech Businesses
Bellvue, WA

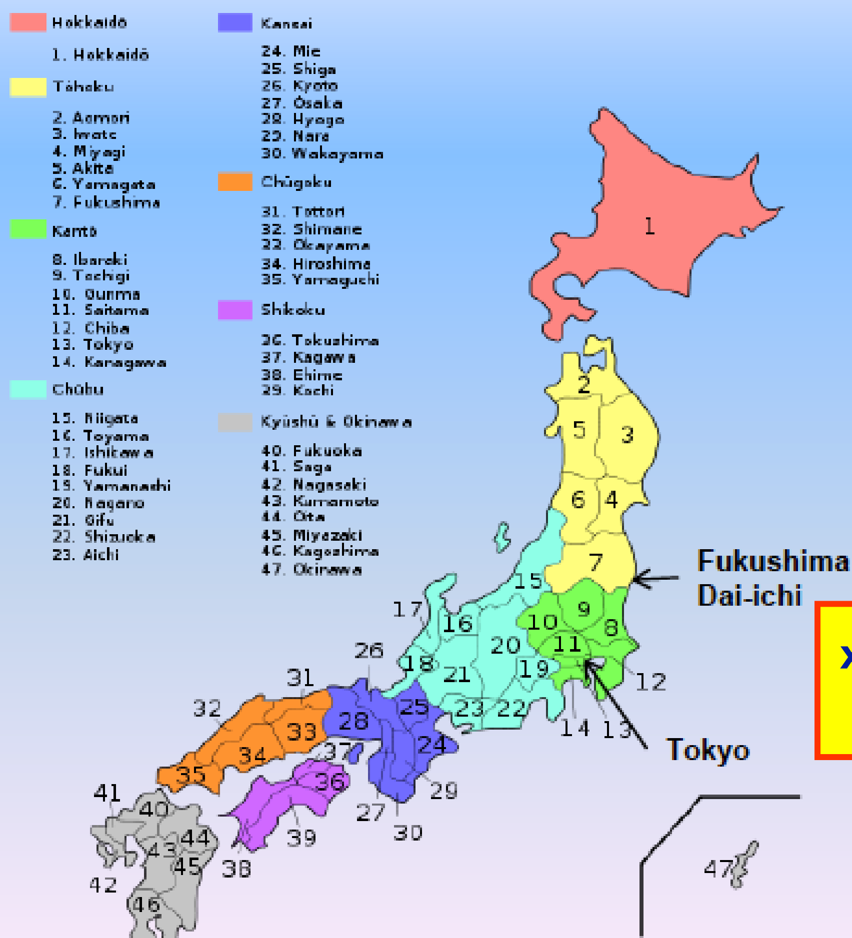
June 17, 2011

Reactors at Fukushima Daiichi

- Reactors performed as designed
- Automatically shut down at onset of 9.0 earthquake
- Withstood the tremendous force of the Tsunami
- Total loss of electrical power to the plant affected cooling systems of reactors and fuel storage pools
- Cold Shutdown will require another 3-6 months of rebuilding infrastructure

Dose Rates in Prefectures Near Fukushima plant as of 17 March at 18:00

Regions and Prefectures of Japan



Prefecture	Dose Rate 17 March At 18:00 (µSv/h)	Normal Natural Radiation Dose Rate (µSv/h)	Map Reference
Ibaraki	0.244	0.036 – 0.056	8
Tochigi	0.113	0.030 – 0.067	9
Gunma	0.109	0.017 – 0.045	10
Saitama	0.068	0.031 – 0.060	11
Chiba	0.041	0.022 – 0.044	12
Tokyo	0.053	0.028 – 0.079	13
Kanagawa	0.056	0.035 – 0.069	14
Niigata	0.048	0.031 – 0.153	15

x 24 h/d x 365 d/y = 2,137.4 µSv = 213 mrem/y

U.S. background average 360 mrem/y

Fundamental Relationships from Physical Science Needed for Energy Discussions

- Second law of thermodynamics:
  - $\Delta G = \Delta H - T\Delta S$
    - total available energy = heat content minus that lost to increasing disorder (in a spontaneous process entropy (S) always increases)
- Mass/Energy Equivalence (A. Einstein)
  - $E = mc^2$

Outline

- The Industrial Revolution/Fuel Energy - Power Density
- Fossil Fuels/Population/Global Climate
- U.S. Power Consumption
- Options for Power Generation and Distribution
- Potential Impact of Nuclear Power (Promise and Challenges)
- Energy as a National Priority - Where do We Go from Here?

The Industrial Revolution

Global energy consumption is 85-88% fossil carbon

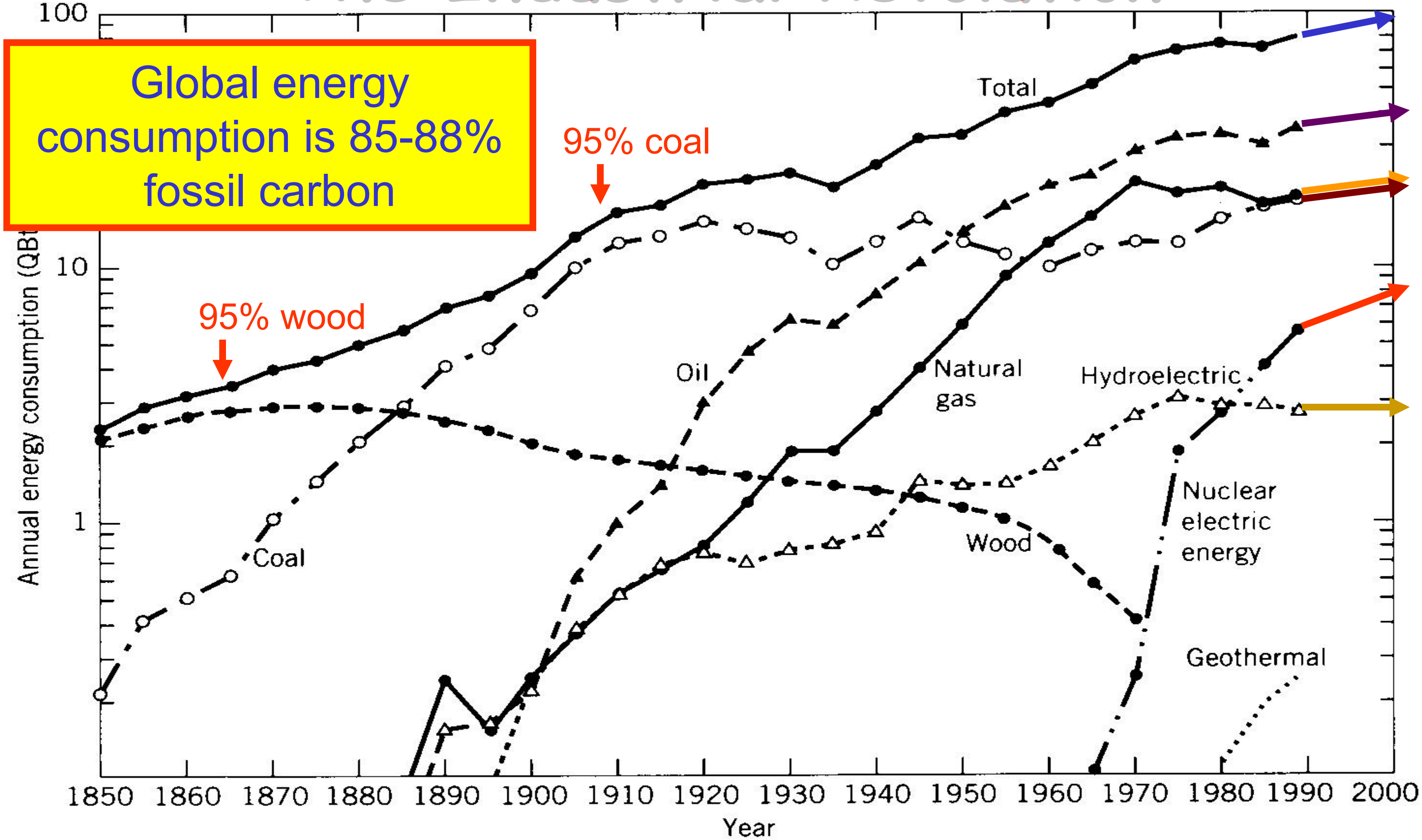
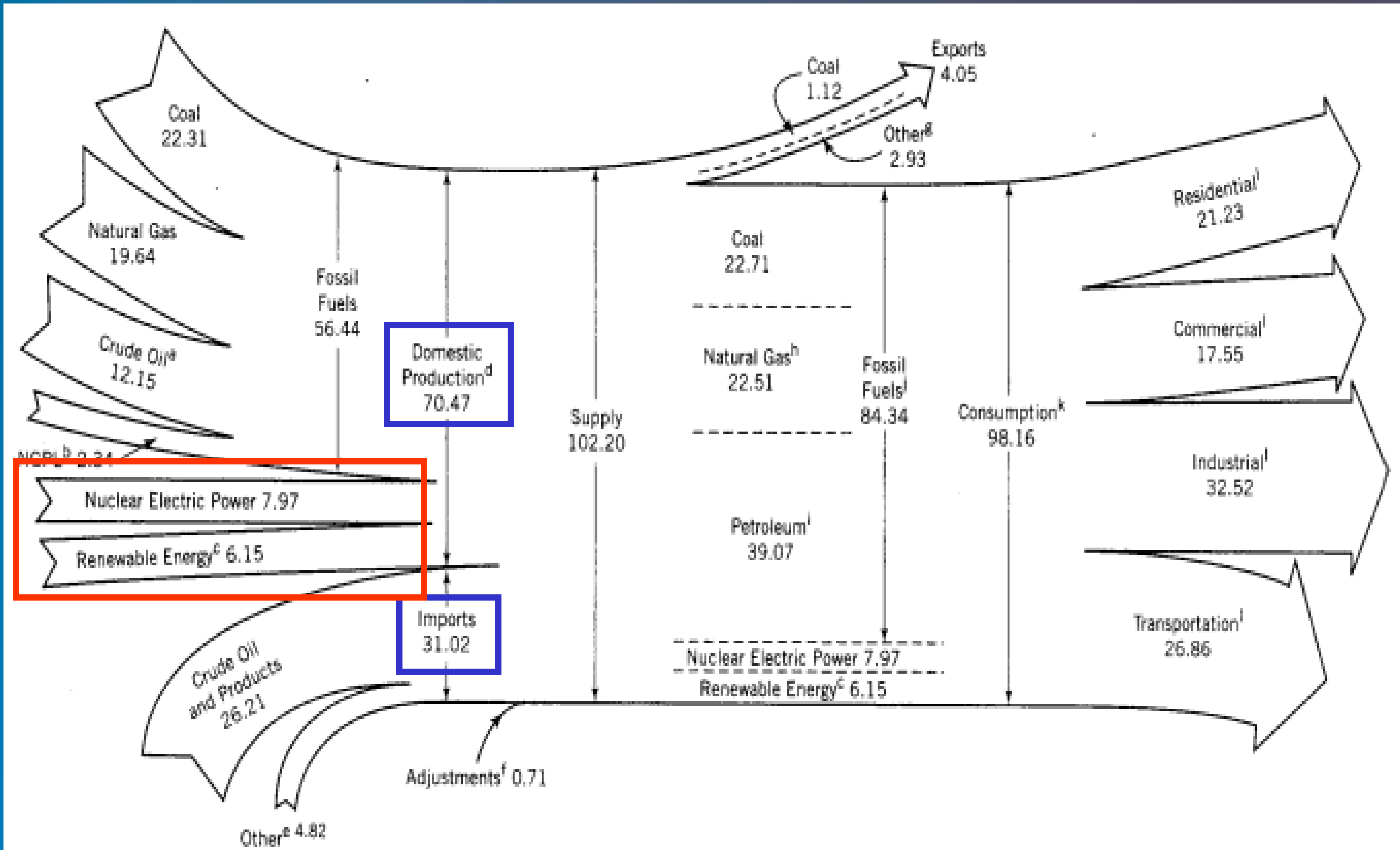


Figure 1.1 Various forms of energy consumed in the United States since 1850. This type of graph is called a semilogarithmic plot, and an explanation of the scales is given in the Appendix. *Sources*: *Historical Statistics of the United States, Colonial Times to 1970*. U.S.

Global population growth

1B (1804) 2B(1927) 3B 4B 5B 6B 7B

U.S. Total Energy Supply and Pattern of Use, 2003



Energy flow from source to use 2003 in units of QBtu (source, USDOE Energy Information Institute, Annual Energy Review 2003)

We have 6.9 billion neighbors in 2011

Currently, 2 billion people have no access to electricity

http://antwrp.gsfc.nasa.gov/apod/ap001127.html

Current global power consumption: 12 TW (1012), 85% fossil fueled

Atmospheric CO_2: 1900 - 270 ppm, 2000 - 377 ppm, 2100 - 550 ppm

To stabilize at 550 ppm, 15 TW of emission free power needed by 2050

"Advance Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet"
M. J. Hoffert et al. Science 298, 981 (2002)

By 2050 we may have 9 billion neighbors

Current global power consumption: 13 TW (2012), 85% fossil fueled

- Electricity promotes prosperity
- Prosperity lowers birthrates
- With increased availability of primary power, global population could stabilize after 2050

"Advance Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet"
M. J. Hoffert et al. Science 298, 981 (2002)

Global CO_2 Emissions

- Atmospheric CO_2 has increased 31% since 1750 to a higher level than any time in the last 420,000 years, and probably 20 million years.
- It contributes 60% of the warming effect.
- About three quarters of the human-induced CO_2 emission is due to fossil fuel combustion.
- Worldwide emissions of CO_2 from burning fossil fuels total 25 billion tonnes per year 2002, 29 in 2006.
- About 38% of this is from coal and about 43% from oil.
- Polar ice is melting.
- Every 1000 MWe power station running on black coal means CO_2 emissions of about 7 million tonnes per year. If brown coal is used, the amount is much greater (but coal is far and away the least expensive fuel for electricity production)

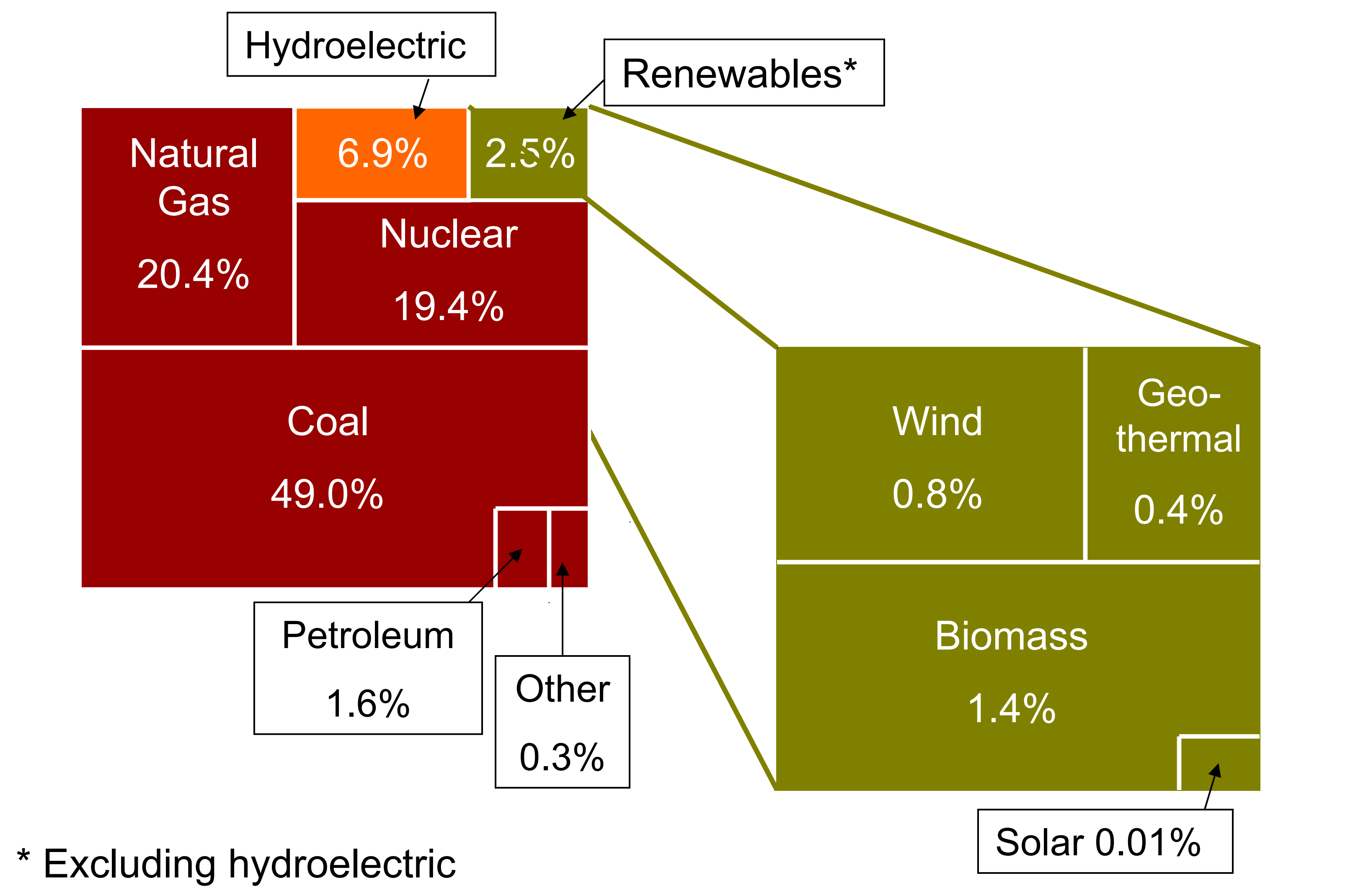
Table 10.4 Ten Large Per Capita Emitters of CO_2 from Fuel Combustion in 2002[a]

Country	Per Capital Emissions (tons/year)		Share of World Total Emissions (%)	
United States	19.66	5.9 x 10^9 total (2006)	23.5	19.9
Canada	16.93		2.2	
Russia	10.43		6.2	
Germany	10.15		3.5	
South Korea	9.48		1.9	
Japan	9.47		5.0	
United Kingdom	8.94		2.2	
Italy	7.47		1.8	
China	2.55	6.0 x 10^9 total (2006)	13.6	20.6
India	0.97		4.2	

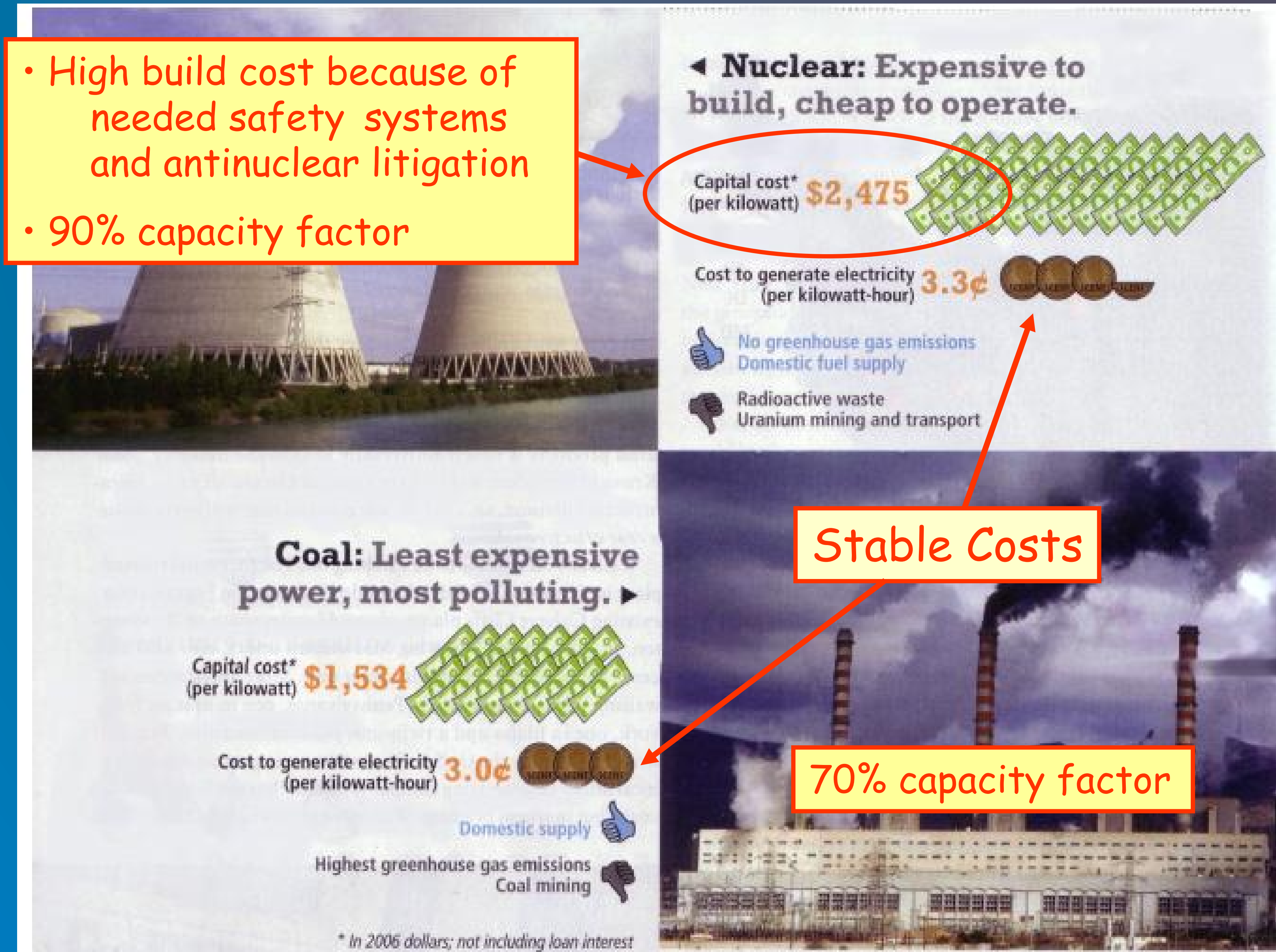
[a]Several less populous countries have higher per capita emissions of CO_2. For example, Qatar is reported to have emitted 59 tons per capita in 2002 (United Nations, 2005).

Source: CO_2 Emissions from Fuel Combustion, 1971–2002, International Energy Agency, 2004.

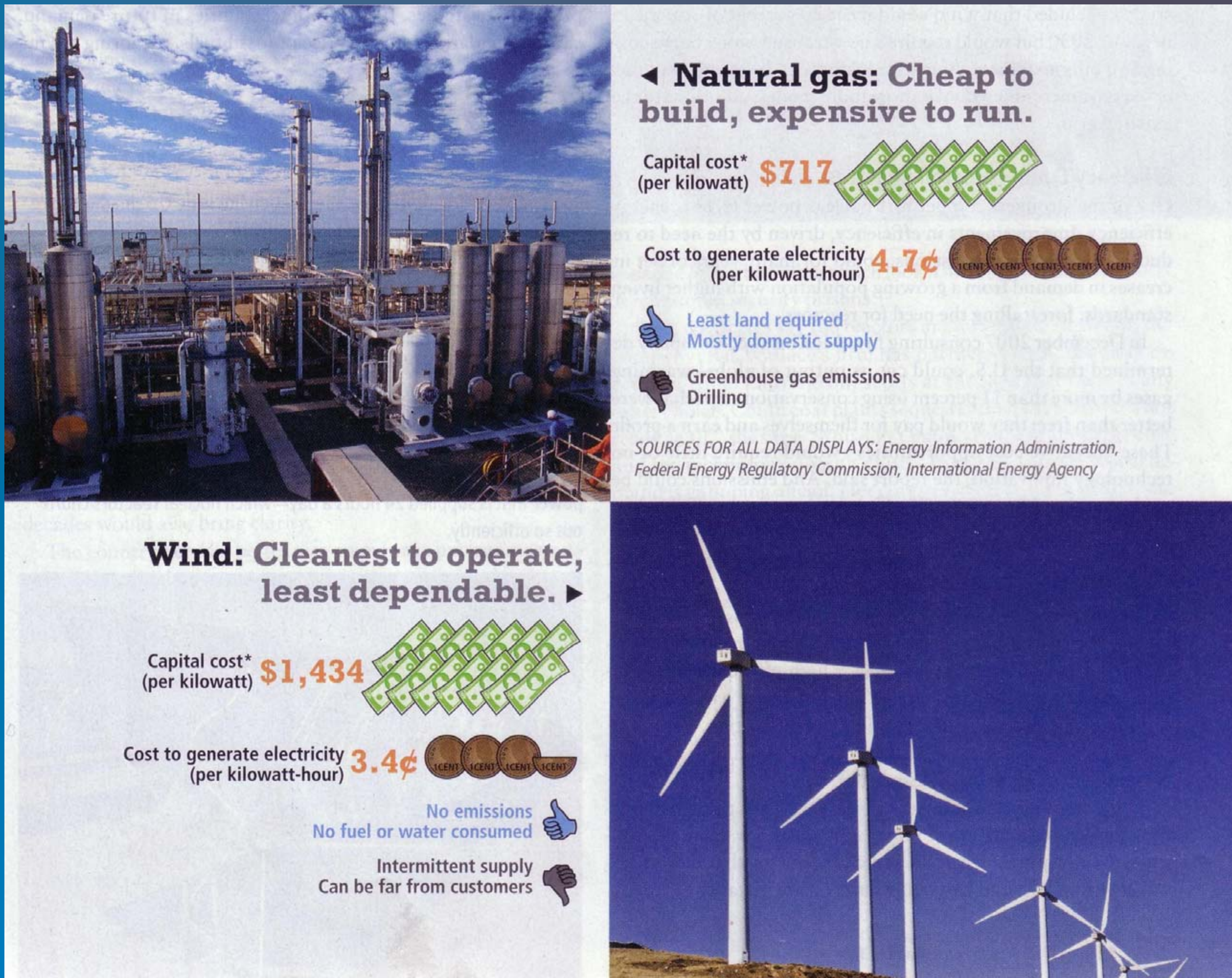
Sources of U.S. Electricity



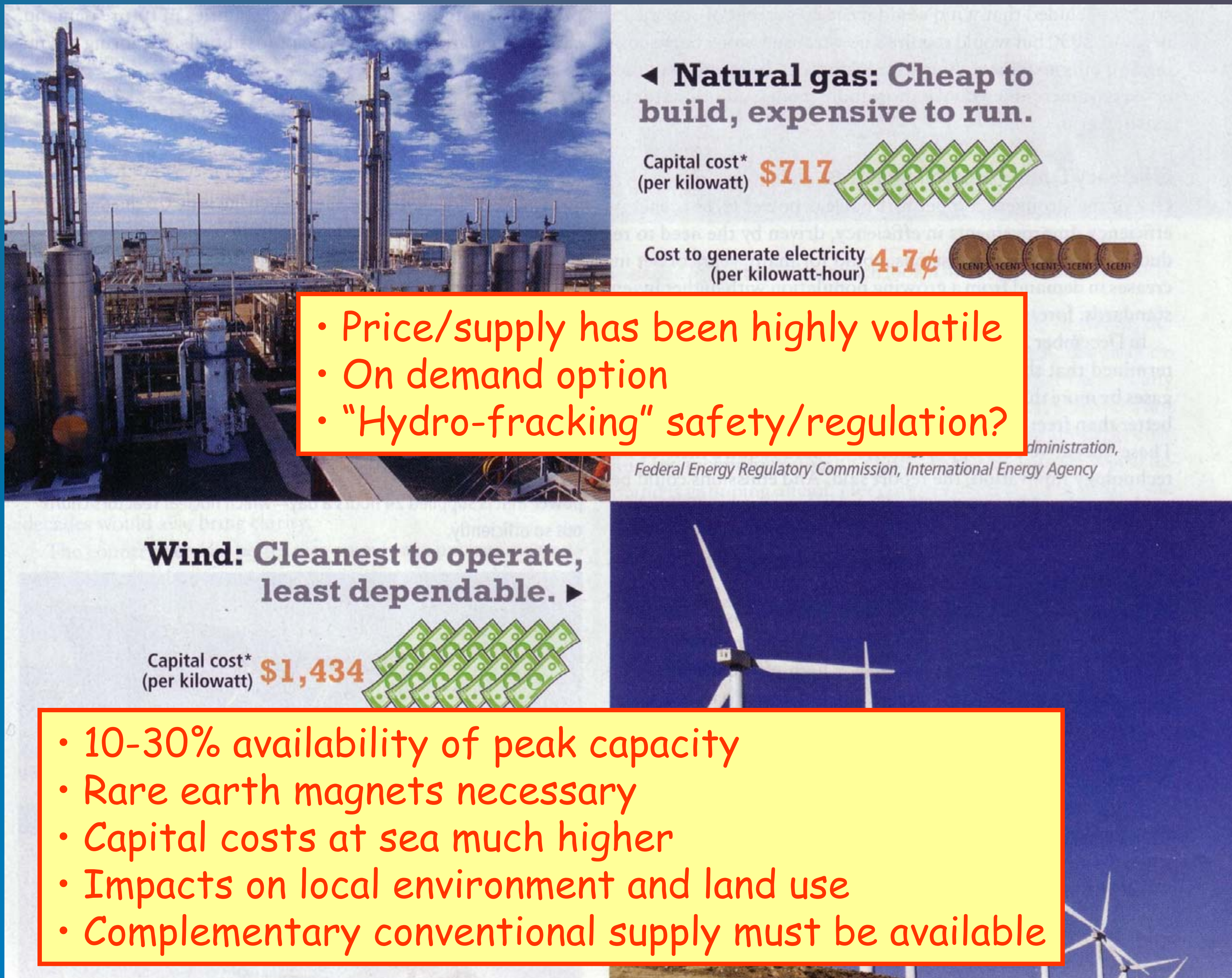
D. Talbot, Lifeline for Renewable Power, Technology Review, MIT, Jan/Feb 2009



Scientific American Earth 3.0 (2009)



Scientific American Earth 3.0 (2009)

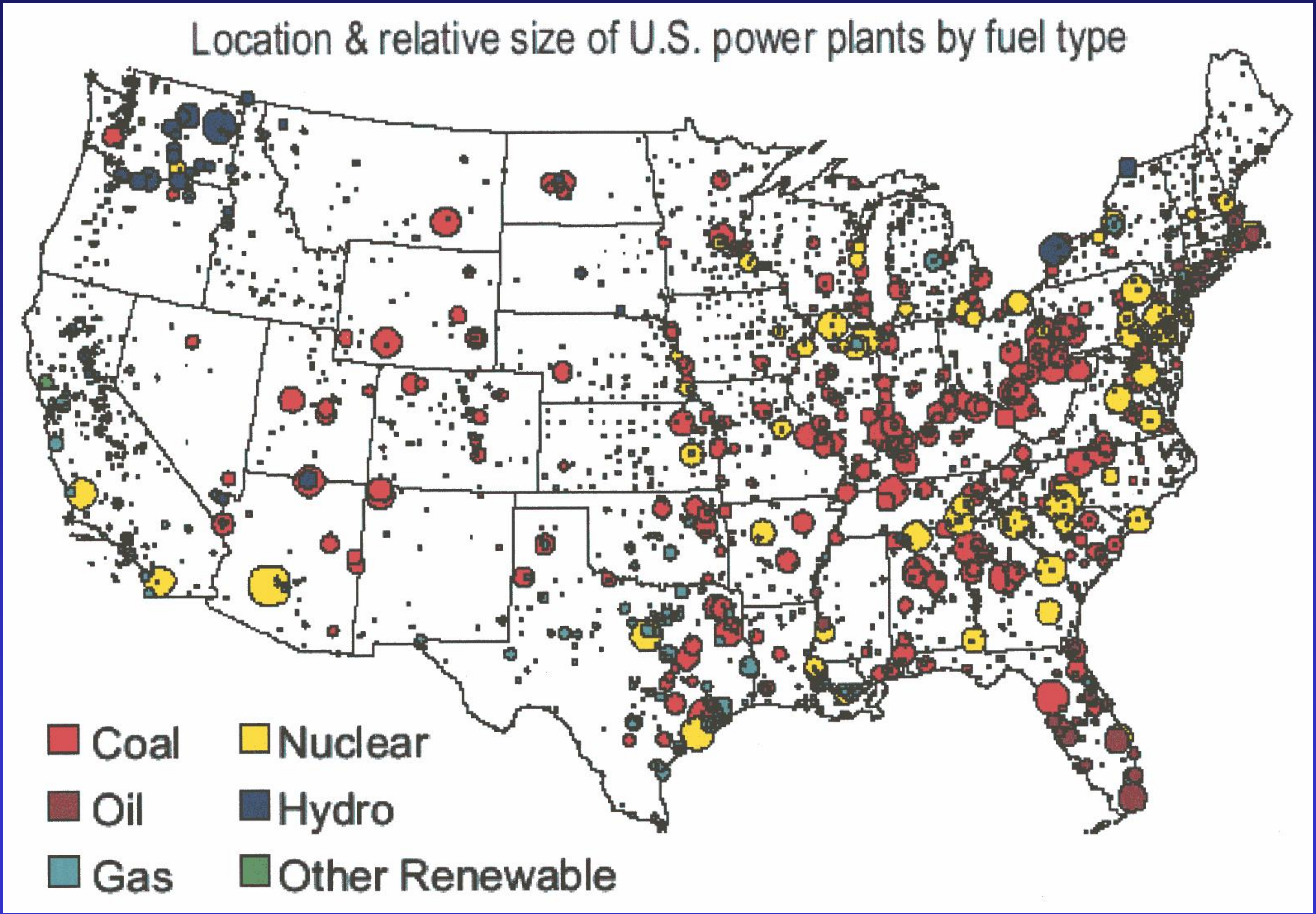


- Price/supply has been highly volatile
- On demand option
- "Hydro-fracking" safety/regulation?

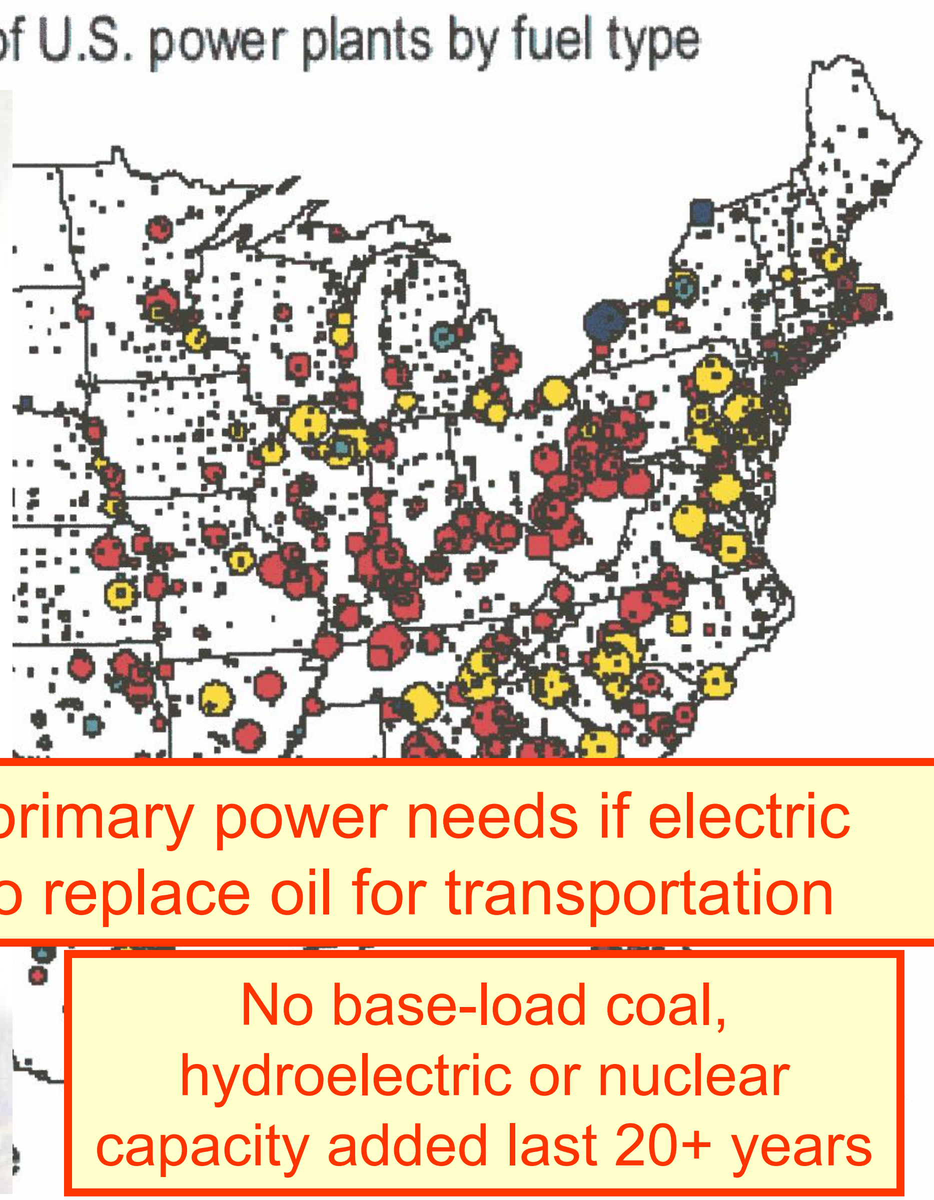
- 10-30% availability of peak capacity
- Rare earth magnets necessary
- Capital costs at sea much higher
- Impacts on local environment and land use
- Complementary conventional supply must be available

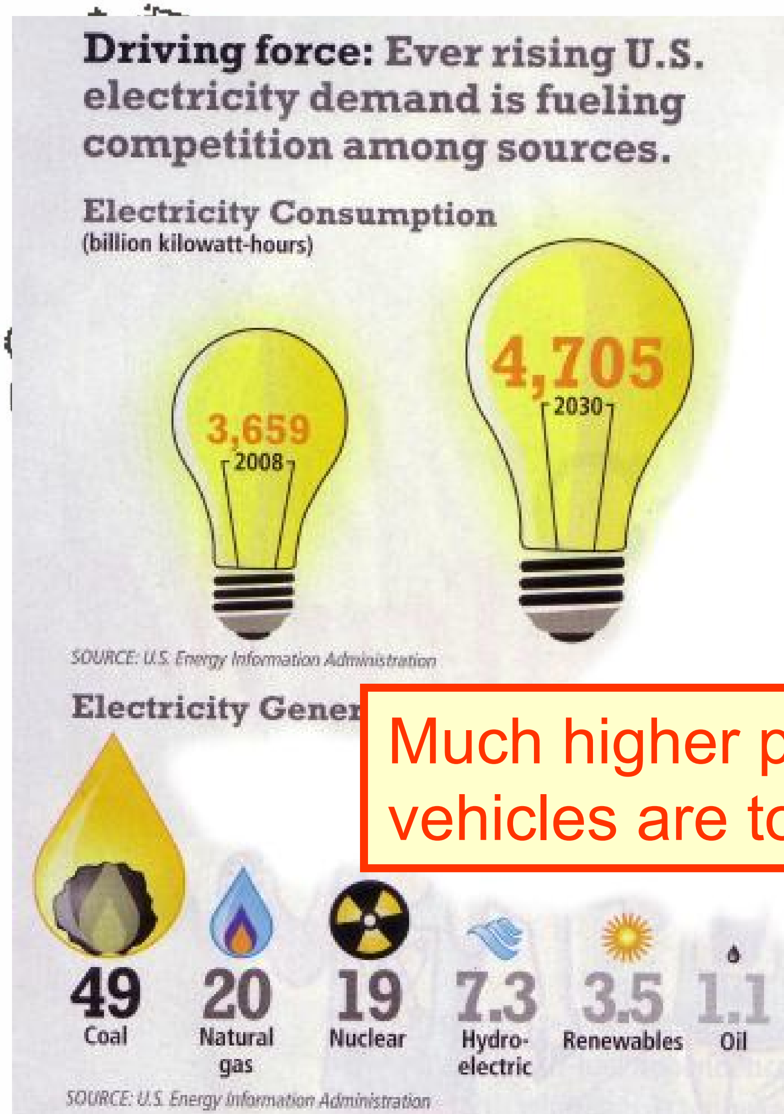
Scientific American Earth 3.0 (2009)

Power Production and Population in the U.S.



Power Production and Population in the U.S.





Much higher primary power needs if electric vehicles are to replace oil for transportation

No base-load coal, hydroelectric or nuclear capacity added last 20+ years

Renewable Component

Table 4.1 U.S. Renewable Energy Consumption in 2003 in QBtu[a]

Energy Source	QBtu	Percent[b]
Conventional hydroelectric power	2.779	2.83
Geothermal energy	0.314	0.32
Biomass	2.884	2.94
Solar energy	0.063	0.06
Wind	0.108	0.11
Total	**6.15**	**6.3**

[a]Hydroelectricity generated by pumped storage is not included in renewable energy.
[b]Based on total energy consumption of 98.156 QBtu in 2003.
(*Source*: U.S. Energy Information Administration, *Annual Energy Review*, 2003.)

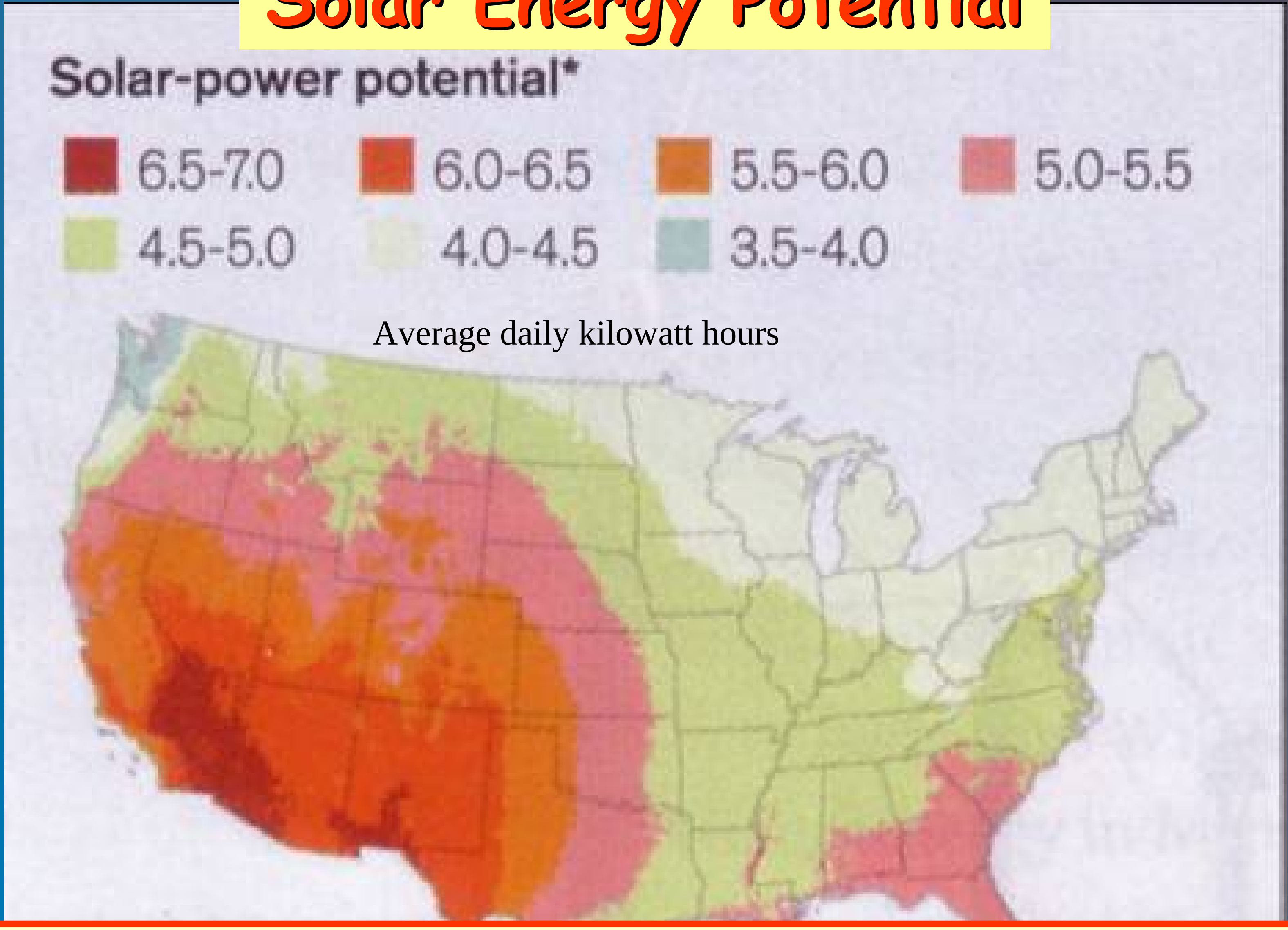
Table 5.1 Some Large Hydroelectric Projects in the United States

Project	River	First Year of Operation	Rated Capacity in 1991 (MW)	Rated Capacity Planned (MW)
Grand Coulee	Columbia	1942	6,480	10,230
John Day	Columbia	1969	2,160	2,700
Bath County, VA	Buck Creek	1985	2,100	2,100
Chief Joseph	Columbia	1955	2,069	2,069
Ludington	Lake Michigan	1973	1,979	1,979
Saunders/Moses —Niagara	St. Lawrence	1961	1,950	—
The Dalles	Columbia	1957	1,807	—
Raccoon Mtn.	Tennessee (Lake Nickajack)	1979	1,530	1,530
Hoover	Colorado	1936	1,345	2,451
Northfield, MA	Briggs	1972	1,000	1,000
McNary, OR	Columbia	1954	980	2,030
Glen Canyon	Colorado	1964	950	—

Source: U

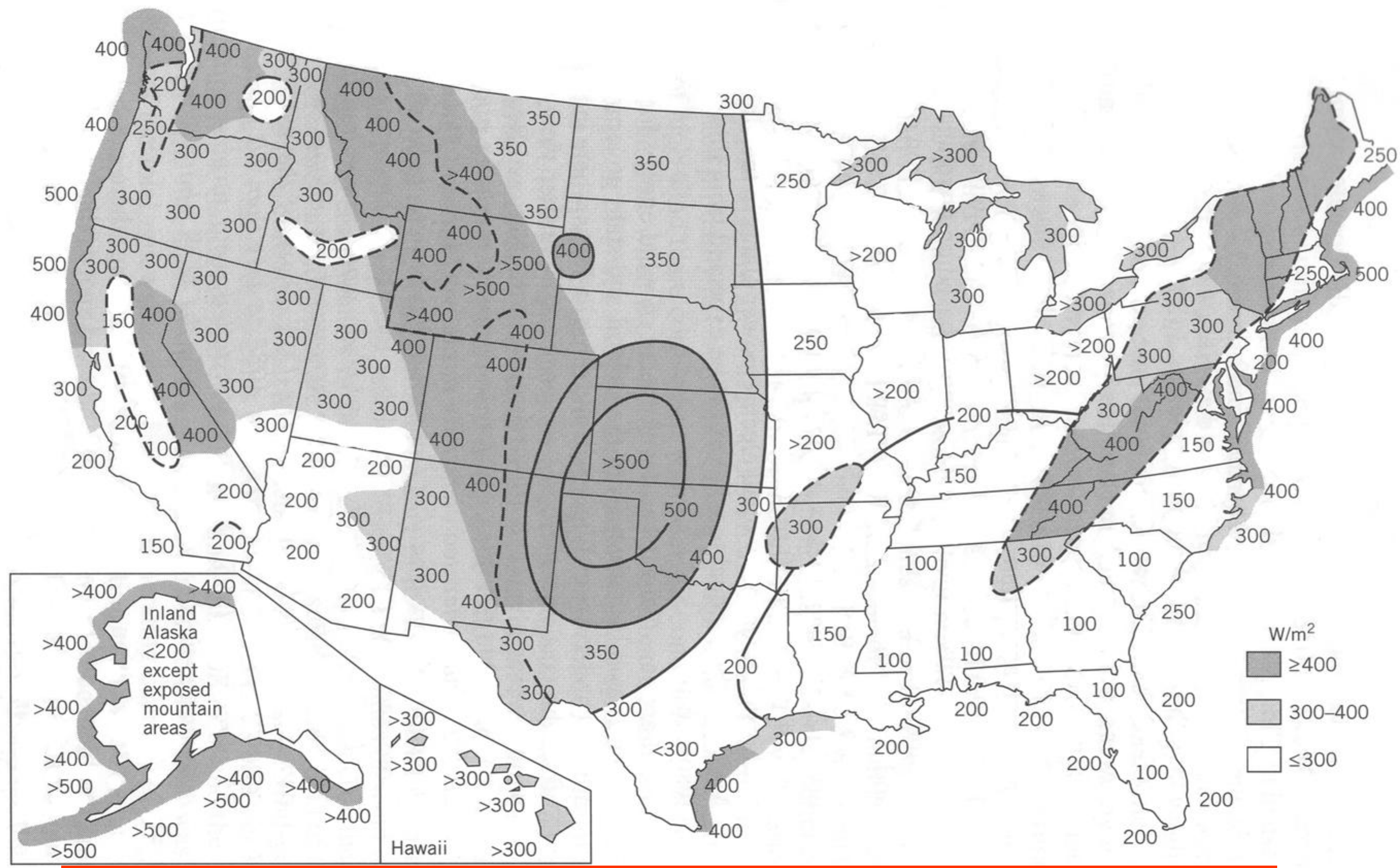
- Estimated additional potential for hydroelectric is about 2X this total, but there is opposition
- 200 dams have been dismantled in the US last 10 years

Solar Energy Potential



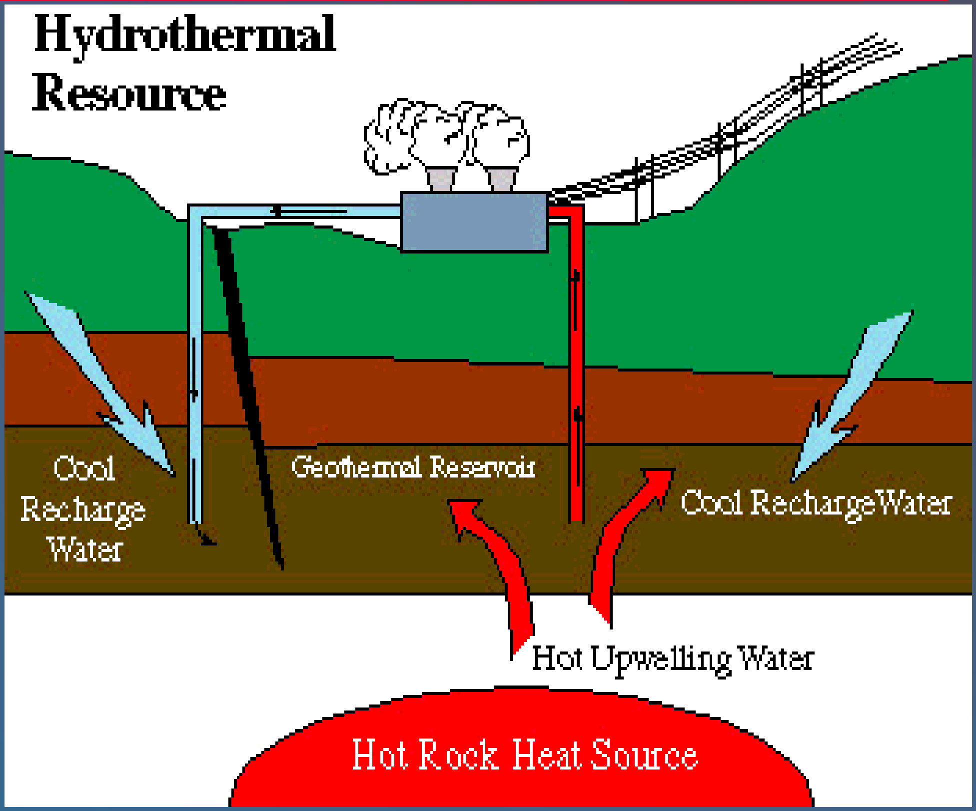
- Wholesale replacement of fossil by solar may be limited by materials availability (e.g., Ga, As, Te)
- Significant potential but a lot of research needed
- Intermittent supply requires backup power source

Wind Energy Potential



- Intermittent supply requires backup power source

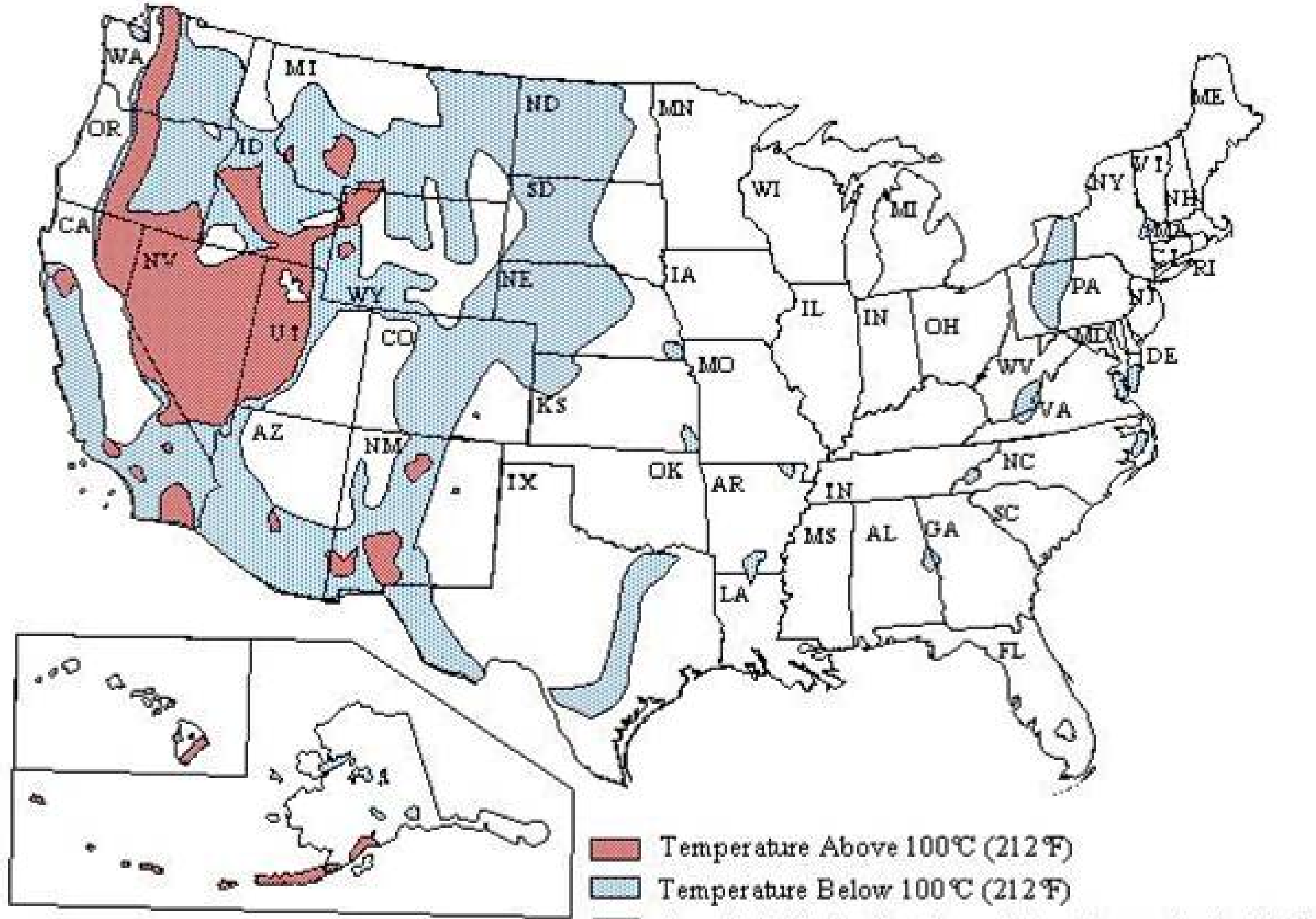
Geothermal Energy Potential



Hydrothermal systems
Hot dry rock (igneous systems)
Normal geothermal heat (200 ºC at 10 km depth)

G tial

- Wells "run out of steam" in 5 years
- Needs drilling technology breakthrough



Source: ESRI, 1995

Ocean Thermal Cycle

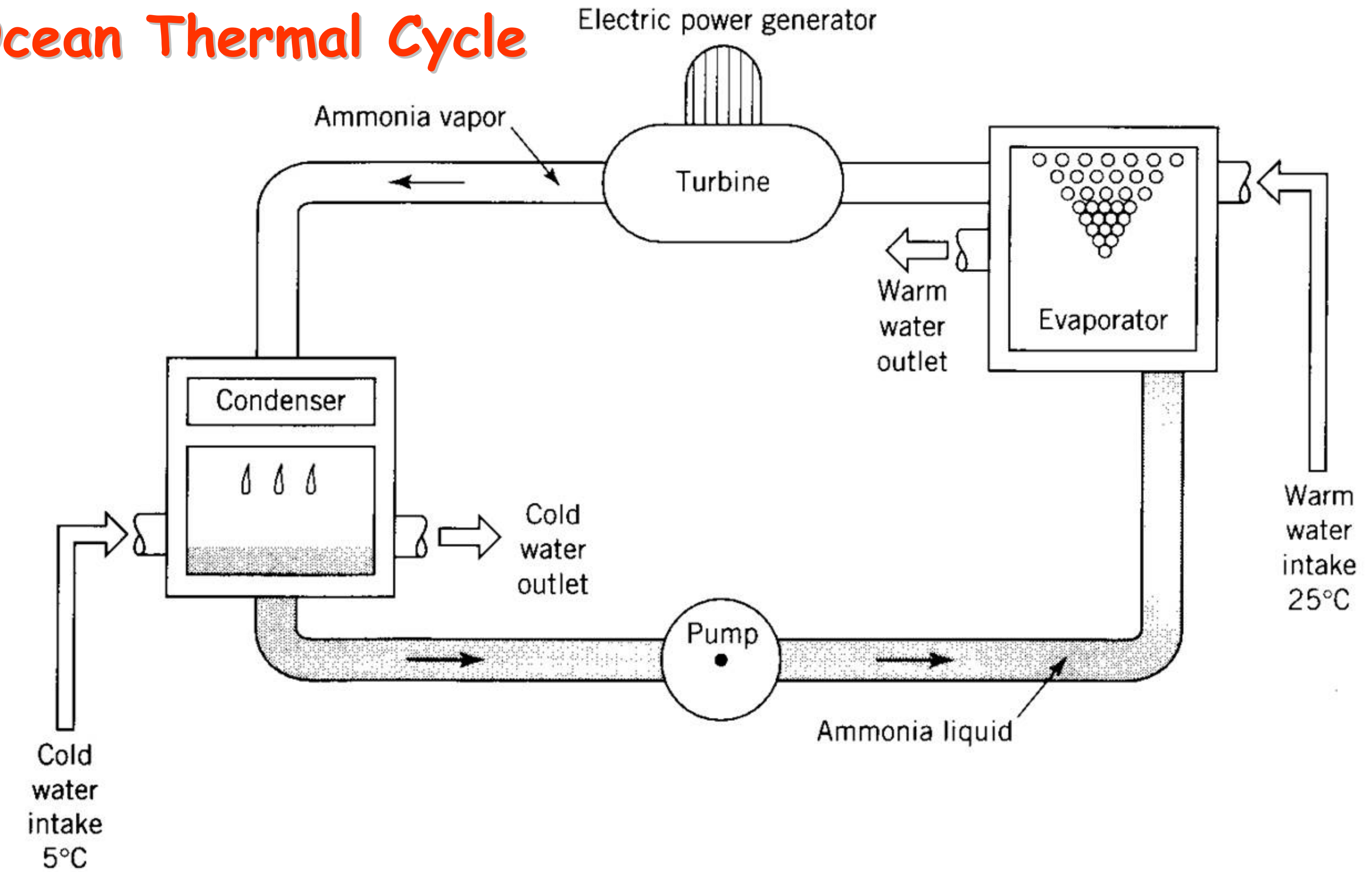


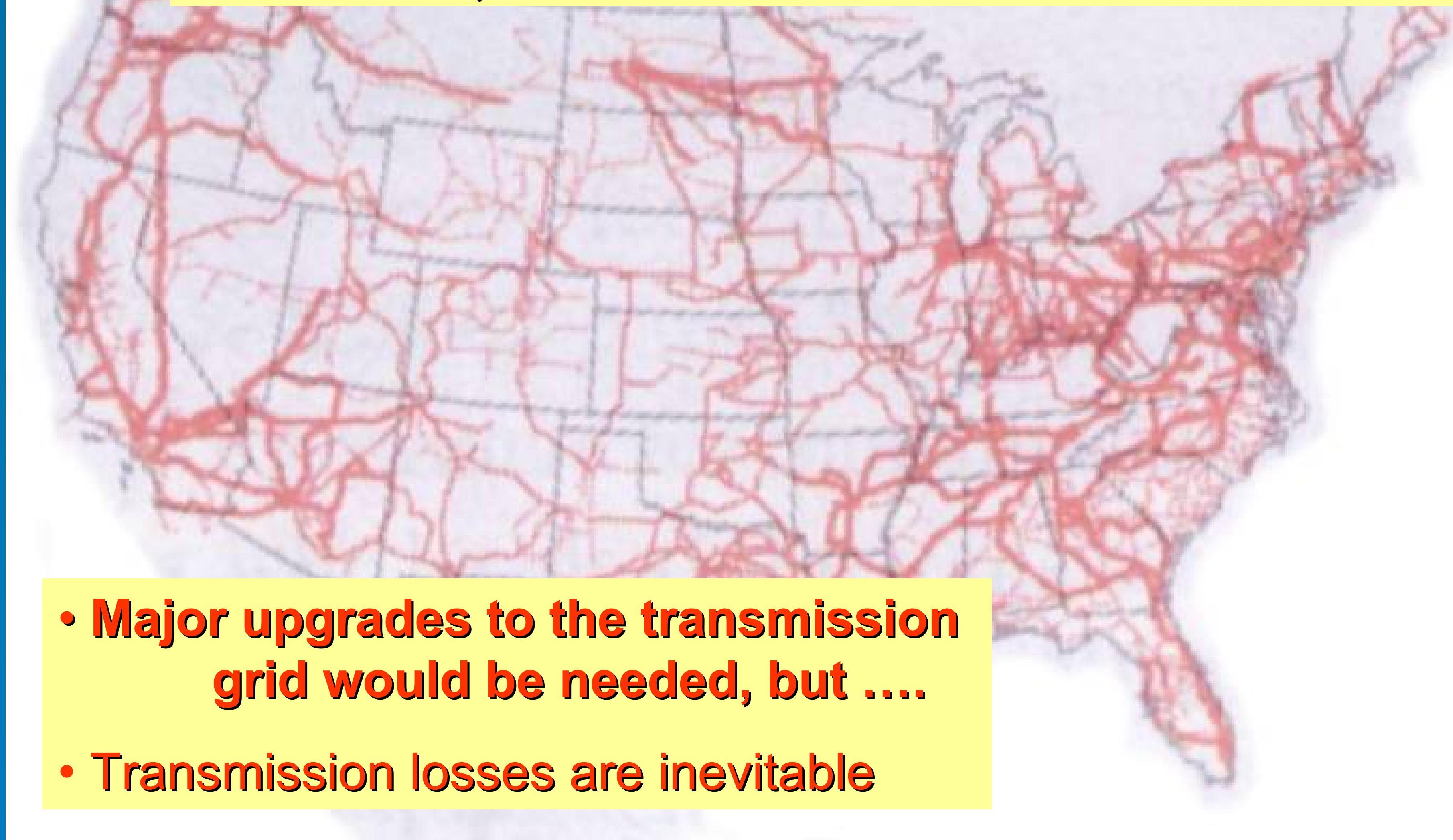
Figure 5.8 An OTEC heat engine using ammonia as a working fluid. The turbine is driven by the ammonia vapor and is connected to a generator to produce electricity. The warm water is drawn from the ocean surface; the cold water from a depth of 1000 meters. (Figure supplied by the National Renewable Energy Laboratory.)

Biomass Energy Potential

Global: Top Down

- Requires large land areas because of low efficiency (0.3%)
- 3 TW requires ≈ 600 million hectares = $6x10^{12}$ m^2
- 20 TW requires ≈ $4x10^{13}$ m^2
- Total land area of earth: $1.3x10^{14}$ m^2
- Hence requires 4/13 = 31% of total land area

• Unfortunately, the existing electrical grid does not adequately connect solar/wind fertile areas to existing the population centers (except in the Southwest).



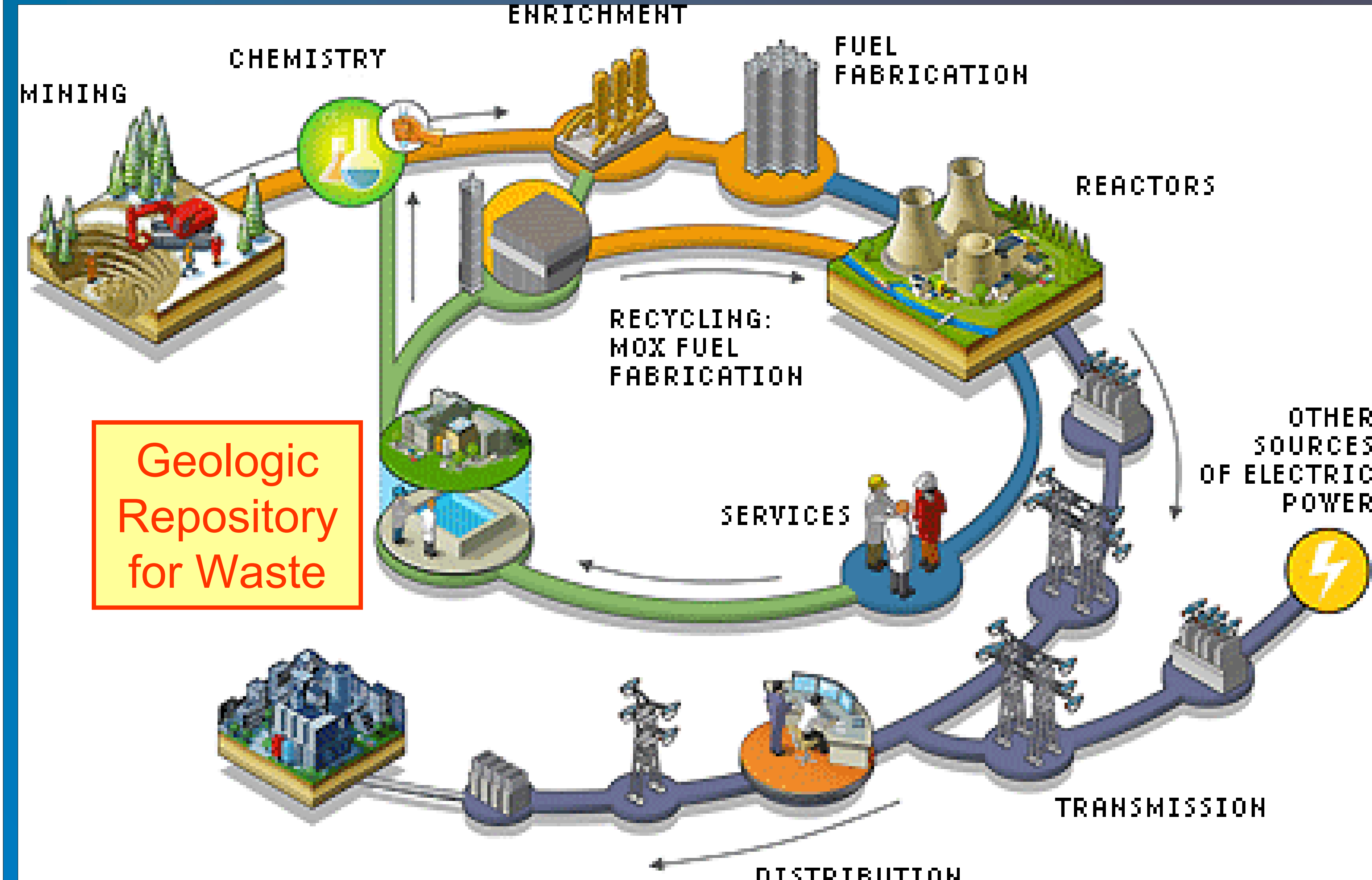
- **Major upgrades to the transmission grid would be needed, but ….**
- Transmission losses are inevitable

World-Wide Use of Nuclear Energy
15 % of Total Electricity Production

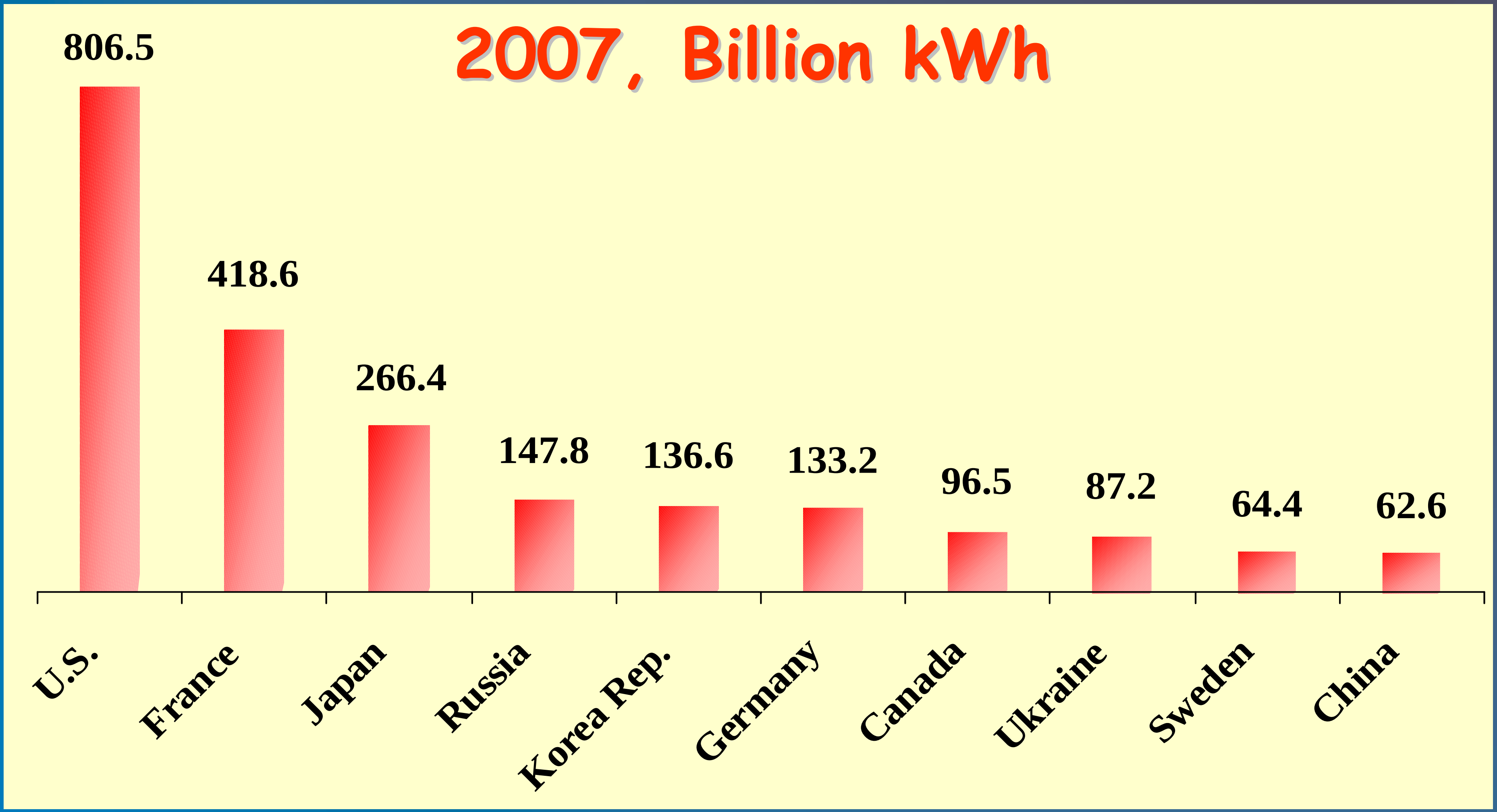
COUNTRY		REACTORS	% TOTAL ENERGY
USA	(open)	104	20
France	(closed)	59	75
Japan	(closed)	54	29
Great Britain	(closed)	31	18
Russia	(closed)	31	18
Germany	(open)	17	23
South Korea	(open)	20	35
India	(open)	18	2
Canada	(open)	18	15
Ukraine	(open)	15	49
Sweden	(open)	10	37
Finland	(open)	4	33
Switzerland	(open)	5	39
World		437	15

Deutsches Atomforum e.V., Kernenergie –Aktuell 2010; data until Dec. 31, 2009

A Closed Nuclear Fuel Cycle



Top 10 Nuclear Generating Countries



Source: International Atomic Energy Agency, U.S. is from Energy Information Administration

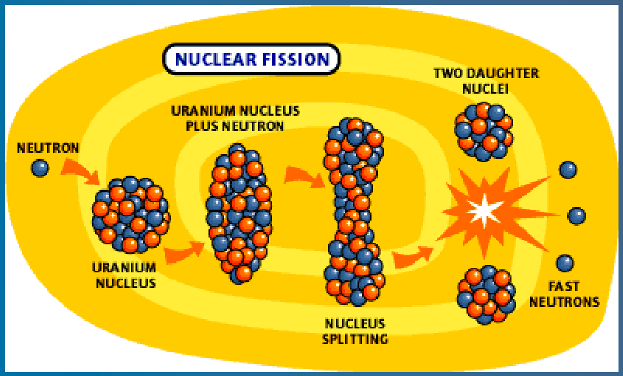
Updated: 5/08

Top 10 Nuclear Generating Countries

2008, Billion kWh

	USA	France	Germany	Japan
# LWR reactors	104	59	19	54
10^9 kWh nuclear	809.0	418.3	140.9	240.5
10^9 kWh/reactor	7.8	7.1	7.0	4.9
% Nuclear elec.	20	76	28	25
10^9 kWh total	4,107	550	498	966
Est. population	308M	65M	82M	127M
10^9 kWh /10^6 pop.	13.3	8.5	6.1	7.6
CO_2 emissions (ton/person)	19.0	6.2	10.4	9.8

Nuclear Power



Fission involves the direct conversion of mass to energy - ^{235}U and ^{239}Pu

Fission releases ~200 MeV/fission event or *8.1×10^{7} kJ/g (uranium)*

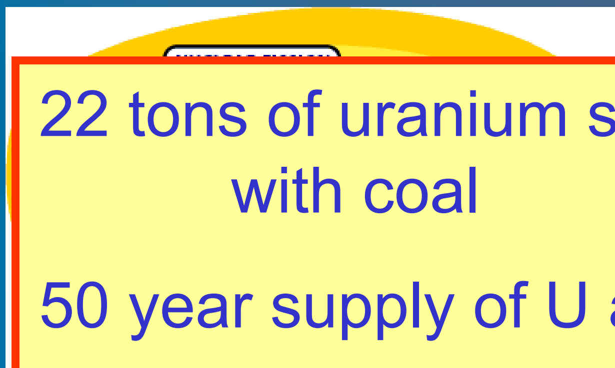
Fossil fuels involves breaking chemical bonds ~4 eV or *33 kJ/g (carbon)*

- Enormous amount of energy from a small volume of fuel
- Fuel has limited use to mankind other than for the production of electricity. In contrast, fossil fuels have a wide variety of applications from pharmaceuticals through transportation
- One ton of natural uranium produces electrical power equivalent to 20,000 tons of black coal or 30×10^{6} cubic meters of natural gas
- Nuclear power is the only energy industry that takes full responsibility for all of its wastes, and costs this into the product

D. Beller and R. Rhodes, "The Need for Nuclear Power" Foreign Affairs v79

Nuclear Power

Fission involves the direct conversion of mass to energy - ^{235}U and ^{239}Pu



22 tons of uranium saves 10^6 tons of CO_2 as compared with coal

50 year supply of U at current use rate in ready supply

250 years considering all known resources

Breeding and burning Pu and operating fast spectrum reactors extends the supply by a factor of up to 100

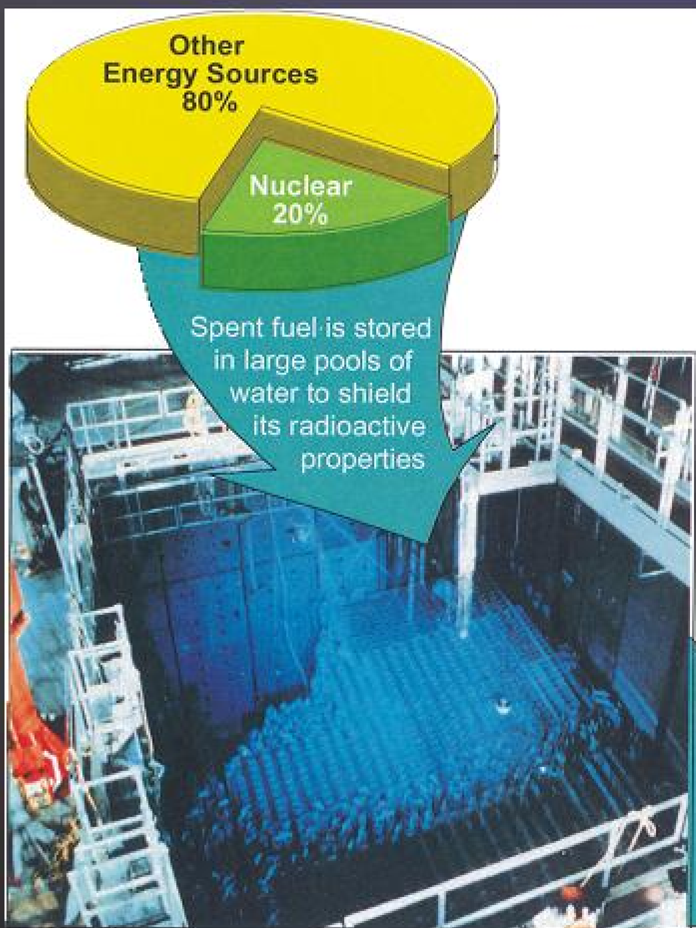
Keeping Pu in the fuel cycle reduces nuclear weapons proliferation concerns

Thorium-uranium breeder cycles broaden the possibilities by many orders of magnitude

D. Beller and R. Rhodes, “The Need for Nuclear Power” Foreign Affairs v79

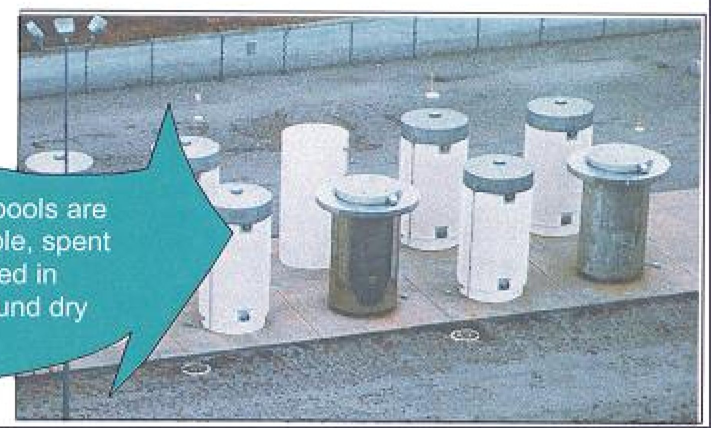
Background

Energy Sources for U.S. Electricity and Spent Fuel Statistics



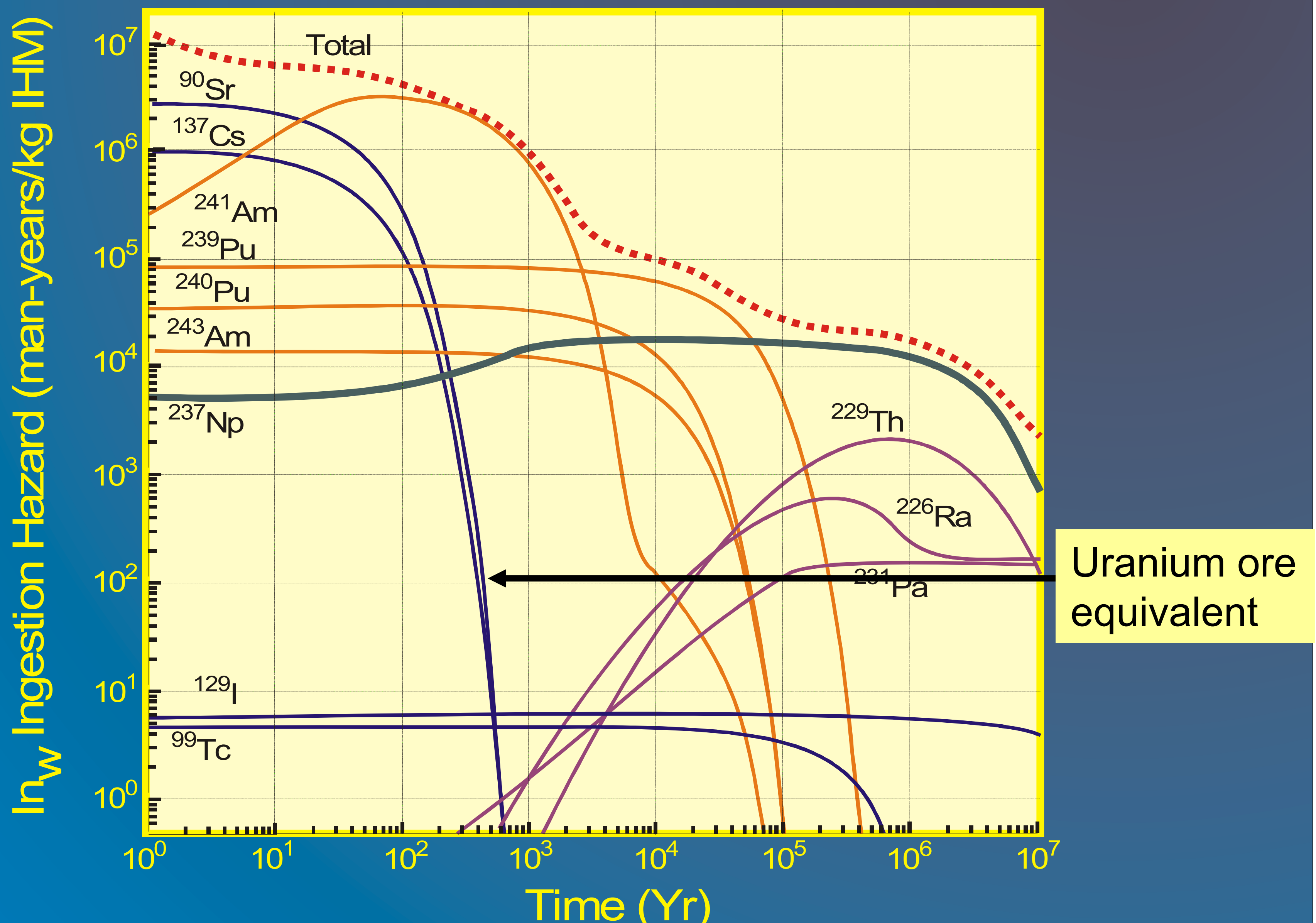
Nuclear power plants are producing about 20% of the electricity in the U.S.

- 104 operating reactors
- 14 decommissioned reactors
- 72 plant sites with spent fuel
- 5 DOE sites with spent fuel
- 36 states with spent fuel
- 40,000 metric tons of spent fuel exist in 2000
- 105,000 metric tons of high-level radioactive waste projected by 2035



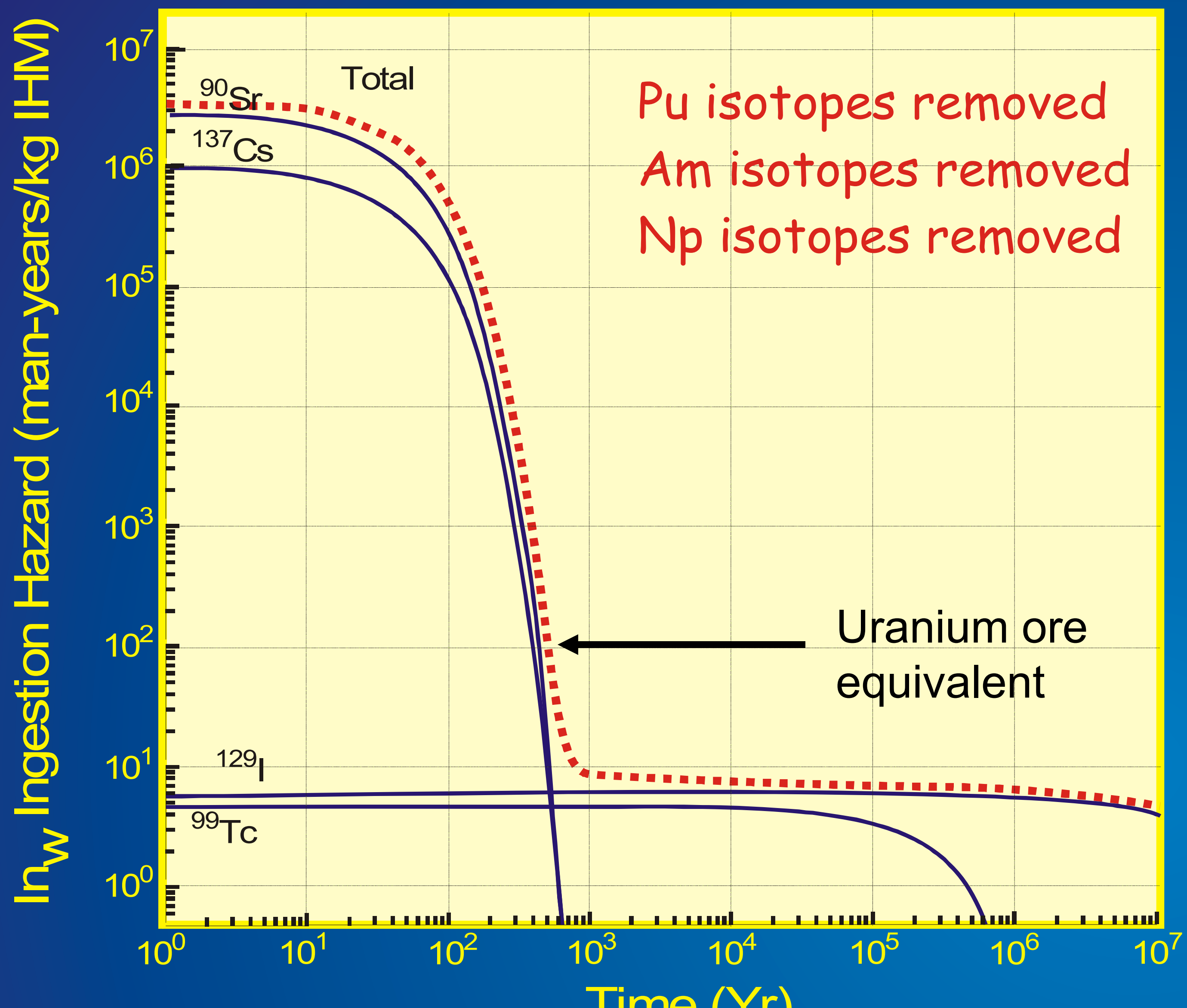
Or, when pools are not available, spent fuel is stored in above-ground dry casks

Radiotoxicity as Ingestion Hazard



In_w = A/ALI (man-years/kg spent fuel)
where A is activity in Bq and ALI is the Annual Limit for Ingestion)

Radiotoxicity as Ingestion Hazard



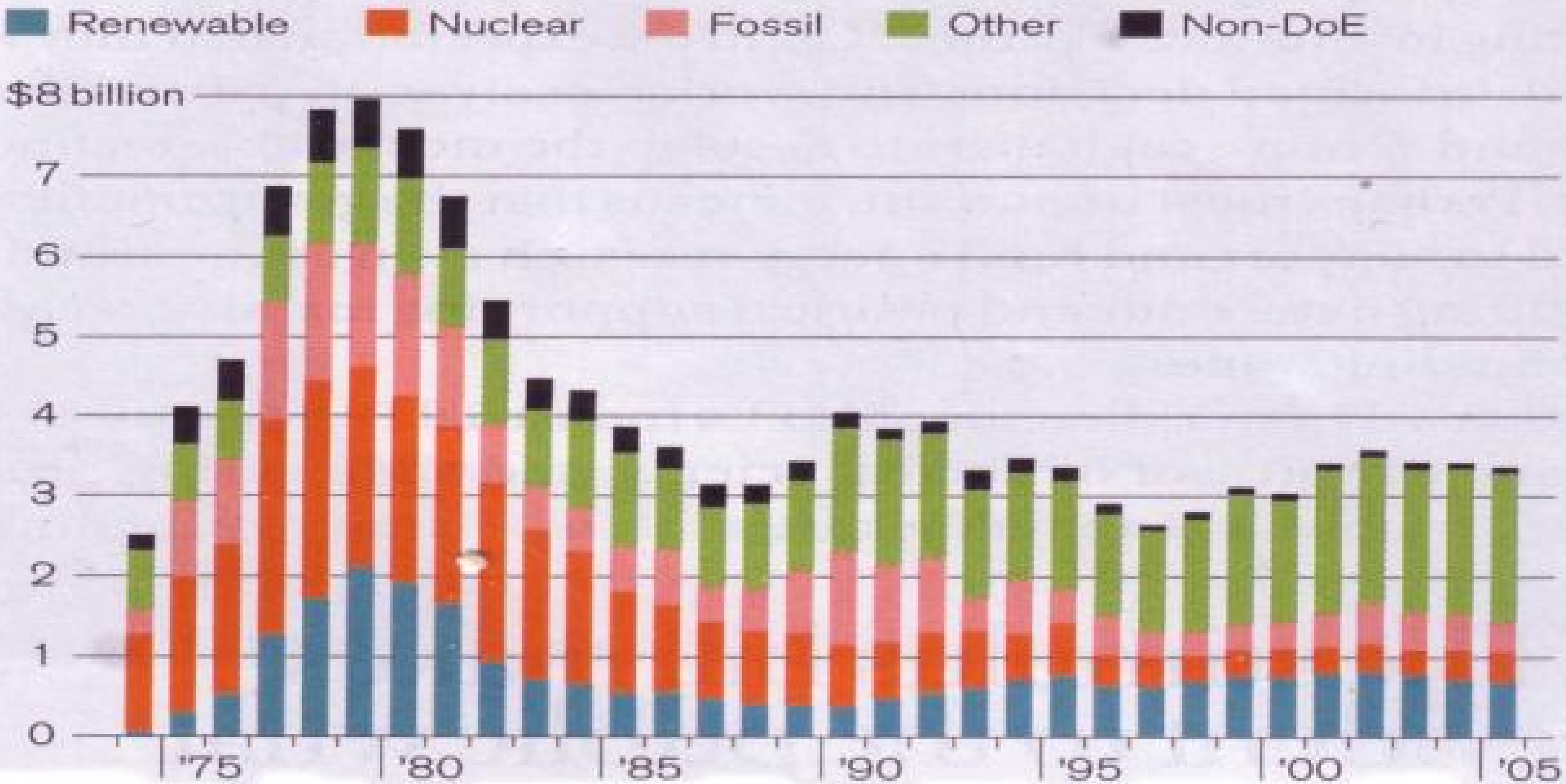
In_w =
wher

French estimate is that 6% increase in cost of nuclear power will support a closed nuclear fuel cycle with transmutation of wastes

ENERGY R&D SLOWDOWN

The stimulus bill will boost public-sector spending on energy research and development, which has been on the decline for decades.

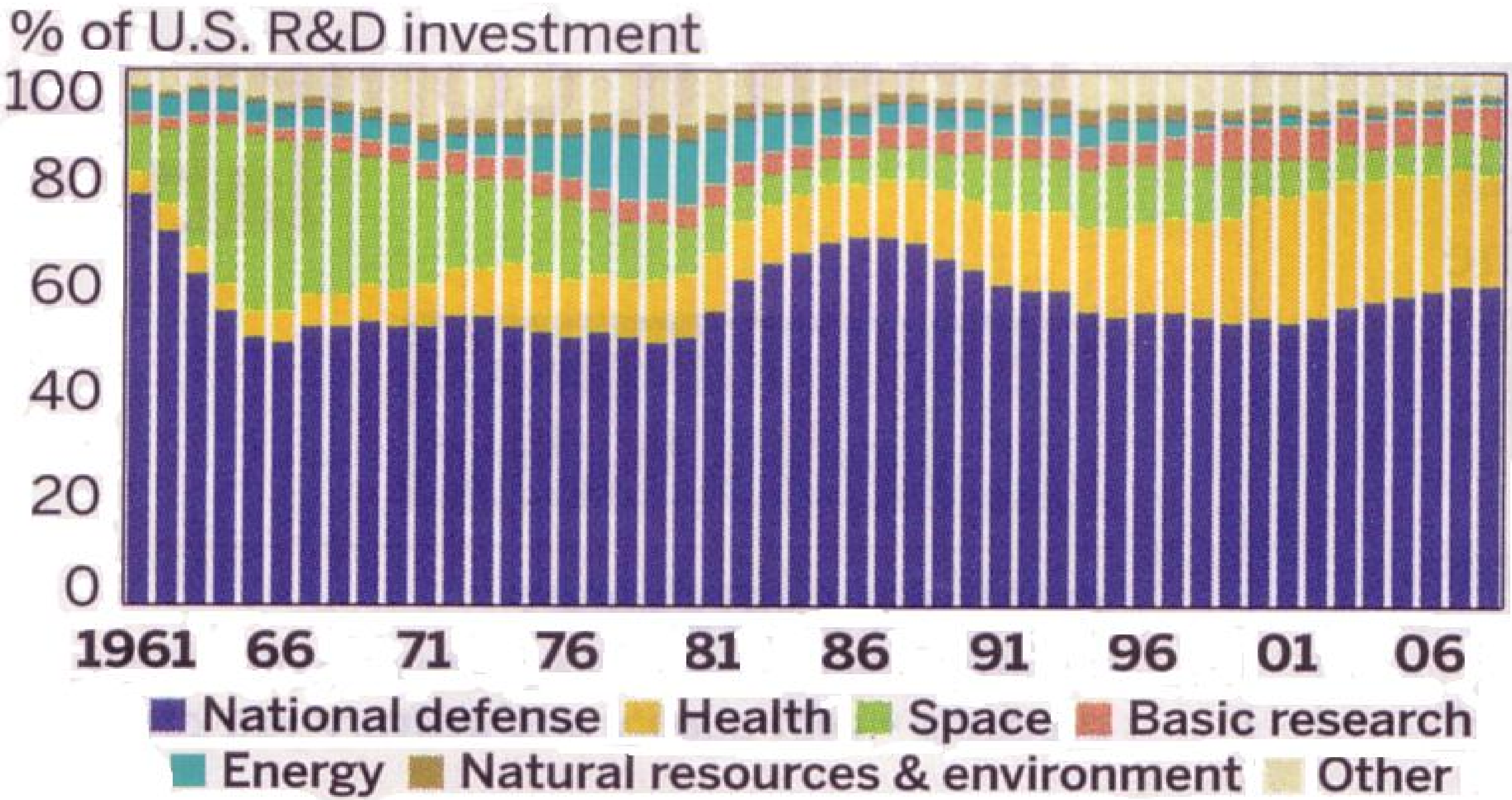
ENERGY R&D BY TECHNOLOGY
(in 2002 dollars)



Source: G.F. Nemet and D.M. Kammen (2007), "U.S. Energy Research and Development: Declining Investment, Increasing Need, and the Feasibility of Expansion."

U.S. R&D SPENDING

Historically, energy R&D has been but a sliver of overall federal R&D investment



SOURCE: J. J. Dooley/Joint Global Change Research Institute

Conclusion:

As the end of the age of fossil fuels approaches……

- Energy demand will grow faster than overall population
- More of the developing world will industrialize
- Global Climate will continue to be a matter of concern
- Pressure will increase for more efficient energy use
- Big breakthroughs in advanced energy technologies (fusion, solar, geothermal) may remain elusive
- Waste management, recycling and efficient use of energy and resources will be critical
- All forms of energy production have a role to play
- A well educated technological and scientific workforce will be needed and a better informed general population (including political leadership) will be desirable