Sustainability and Nuclear Energy: Perspectives on Alternate Futures

Ken Nash
Chemistry Department
Washington State University
Pullman, WA 99163

CRESP Nuclear Fuel Cycle Chemistry Course

Arlington, VA
August 4-6, 2009

Outline

- Fossil Fuels, the Industrial Revolution and Modern Problems
- Electricity in the U.S.
- The Nuclear Option
- Current Approaches to the Management of Used Nuclear Fuel
- Partitioning Strategies
- Where do we go from here?

Our Neighborhood Fusion Reactor

Sol (aka, the sun)
Hydrogen burning Yellow dwarf
Surface temperature: 6000 K
Core temperature: 1.5 x10^7 K

Principle energy producing reactions:

$^{1}H + {}^{1}H \rightarrow {}^{2}H + \beta^{+} + \nu$, Q = 1.44 Mev

$^{1}H + {}^{2}H \rightarrow {}^{3}He$, Q = 5.49 Mev

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H$, Q = 12.86 Mev

Net: $4\,{}^{1}H \rightarrow {}^{4}He + 2\,\beta^{+} + 2\,\nu$, Q = 26.7 Mev

During the past several billion years, some of this solar energy has been converted into a form that is more easily used for transportation and power production: coal, oil, natural gas.

The Industrial Revolution

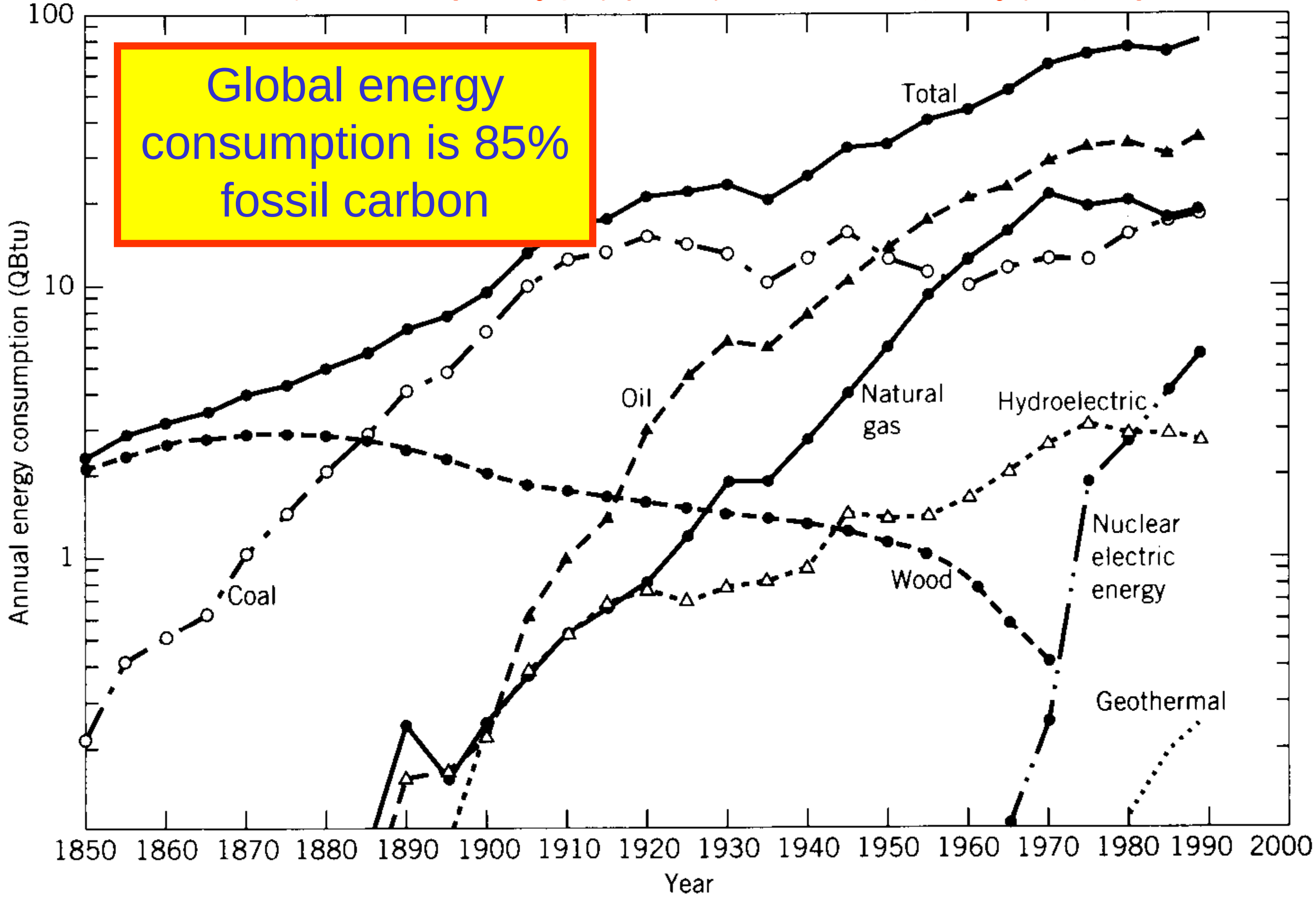


Figure 1.1 Various forms of energy consumed in the United States since 1850. This type of graph is called a semilogarithmic plot, and an explanation of the scales is given in the Appendix. *Sources*: *Historical Statistics of the United States, Colonial Times to 1970.* U.S. Department of Commerce, Bureau of the Census, 1975; U.S. Energy Information Administration. *Annual Energy Review* 1989.)

We are not alone - we have ~~six~~ 6.6 billion neighbors

Currently, 2 billion people have no access to electricity

Current global power consumption: 12 TW (10^{12}), 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 nine billion neighbors

Many global resources (and in fact the quality of the climate) could be seriously challenged by these numbers, but primary concerns will be the interconnected issues of adequate supplies of energy, water and food.

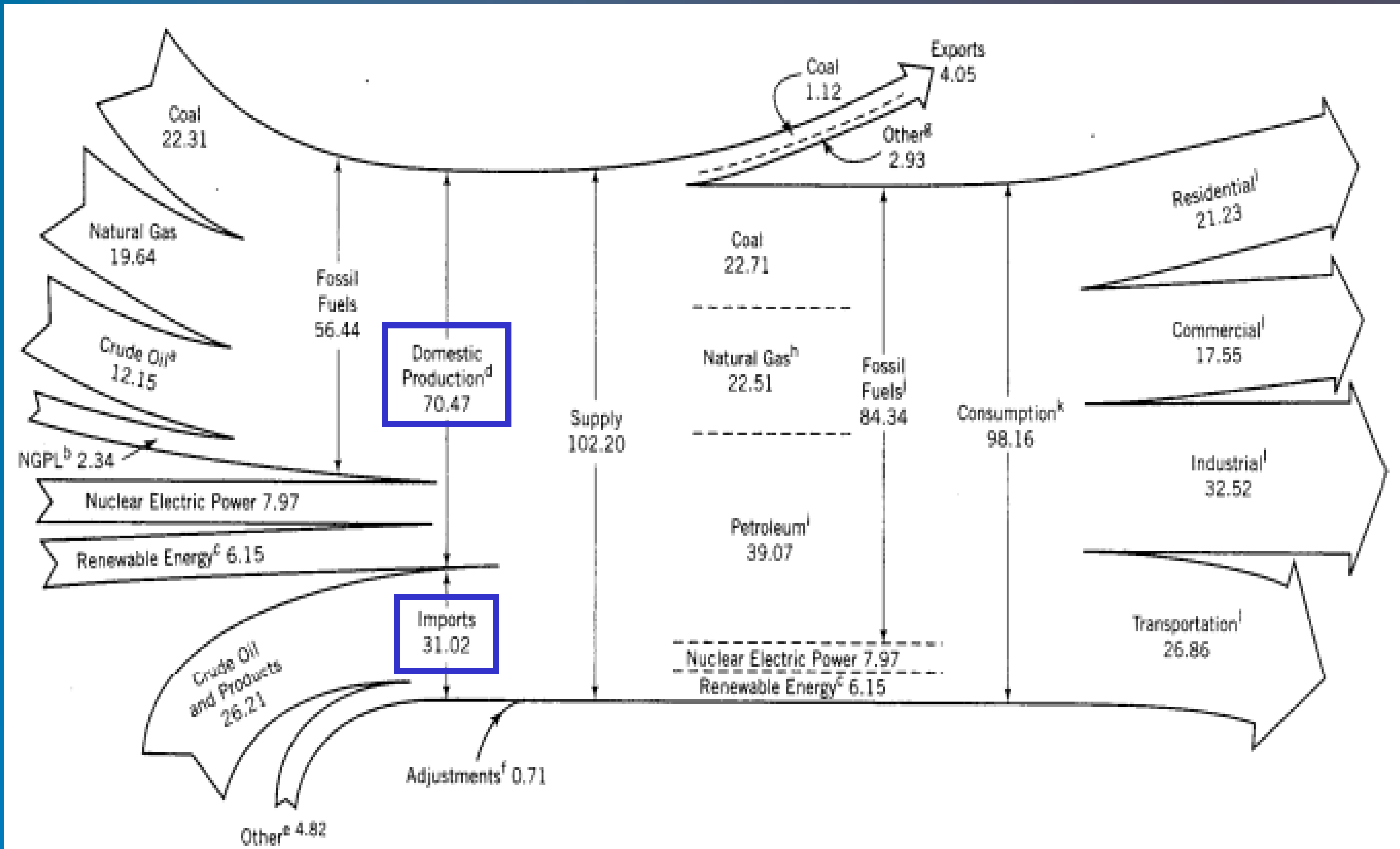
Table 10.4 Ten Large Per Capita Emitters of CO_2 from Fuel Combustion in 2002[a]

Country	Per Capital Emissions (tons/year)		Share of World Total Emissions (%)
United States	19.66	1.58×10^9 total (2007)	23.5
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	1.80×10^9 total (2007)	13.6
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.

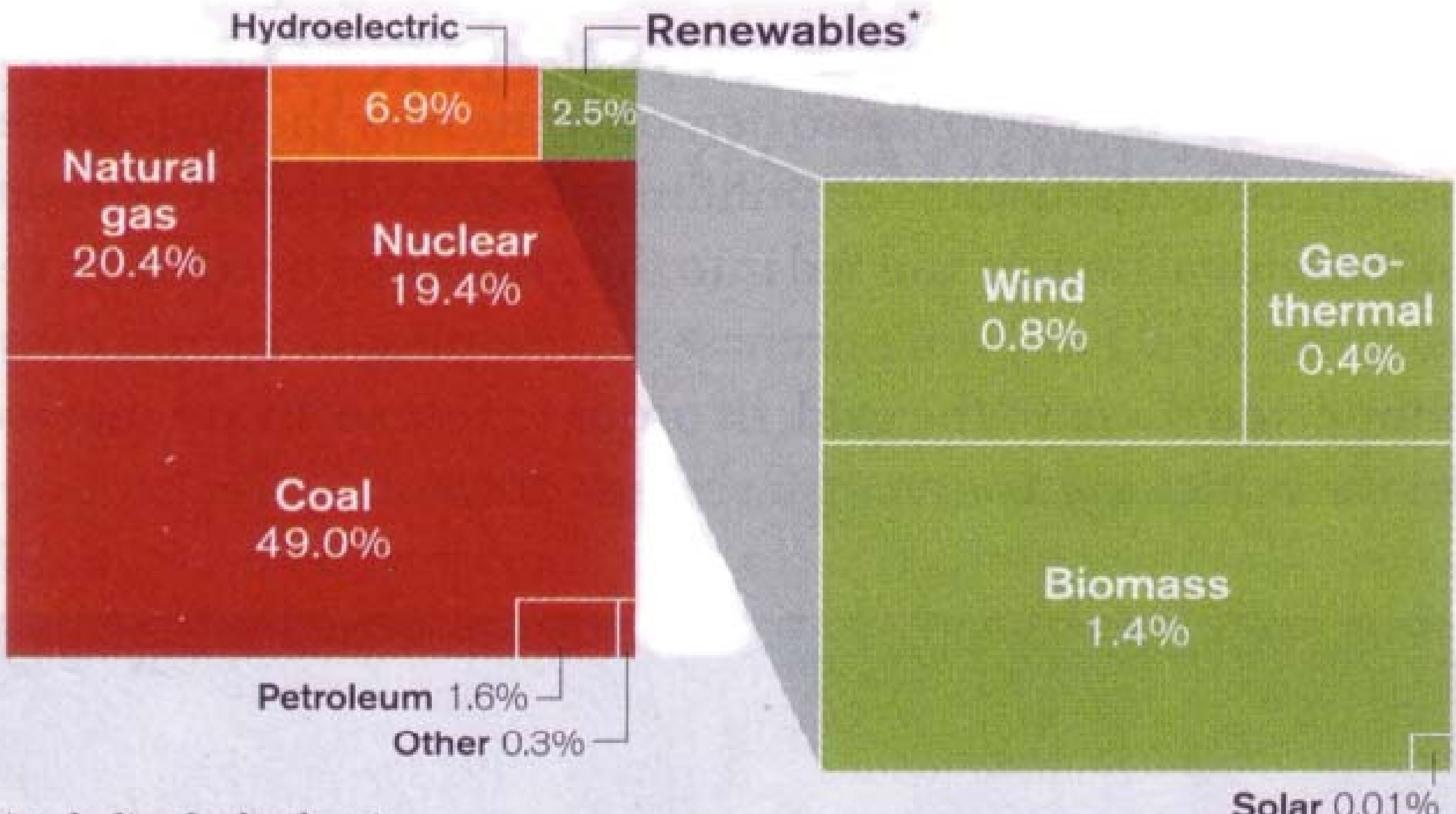
U.S. Total Energy Supply and Pattern of Use, 2003



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

Sources of U.S. electricity

Today, renewable sources provide little U.S. electricity. Wind and solar together furnish less than 1 percent ...



*excluding hydroelectric

◄ Nuclear: Expensive to build, cheap to operate.

Capital cost* (per kilowatt) **$2,475**

Cost to generate electricity (per kilowatt-hour) **3.3¢**

No greenhouse gas emissions
Domestic fuel supply

Radioactive waste
Uranium mining and transport

Coal: Least expensive power, most polluting. ►

Capital cost* (per kilowatt) **$1,534**

Cost to generate electricity (per kilowatt-hour) **3.0¢**

Domestic supply

Highest greenhouse gas emissions
Coal mining

** In 2006 dollars; not including loan interest*

◄ Natural gas: Cheap to build, expensive to run.

Capital cost* (per kilowatt) **$717**

Cost to generate electricity (per kilowatt-hour) **4.7¢**

Least land required
Mostly domestic supply

Greenhouse gas emissions
Drilling

SOURCES FOR ALL DATA DISPLAYS: Energy Information Administration, Federal Energy Regulatory Commission, International Energy Agency

Wind: Cleanest to operate, least dependable. ►

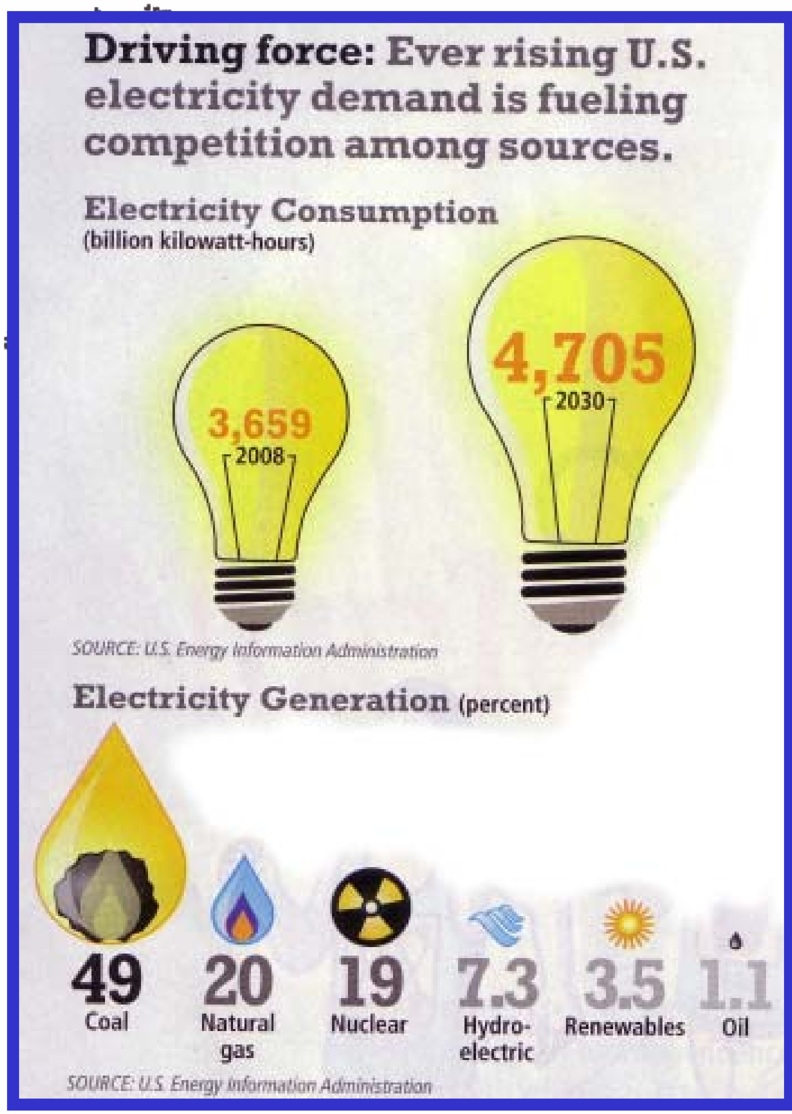
Capital cost* (per kilowatt) **$1,434**

Cost to generate electricity (per kilowatt-hour) **3.4¢**

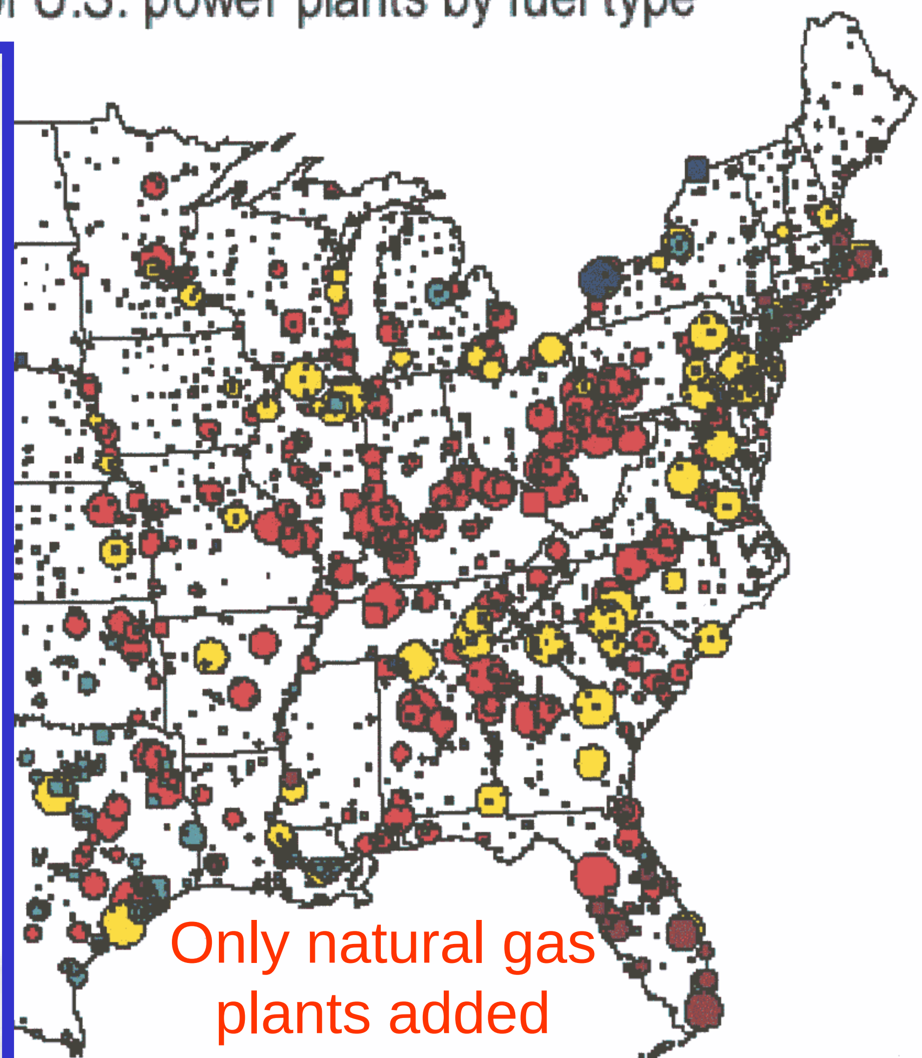
No emissions
No fuel or water consumed

Intermittent supply
Can be far from customers

Power Production and Population in the U.S.



Location & relative size of U.S. power plants by fuel type



Only natural gas plants added last 20+ years

Renewable Component

Table 4.1 U.S. Renewable Energy Consumption in 1994 in QBtu[a]

Energy Source	QBtu		Percent[b]
Conventional Hydroelectric Power	3.037		3.43
Geothermal Energy	0.357		0.40
Biomass	2.852		3.22
Solar Energy	0.069		0.077
Wind	0.036	Total 6.35	0.040

Source: Renewable Energy Annual. U.S. Energy Information Administration.

[a]Hydroelectricity generated by pumped storage is not included in renewable energy.

[b]Based on a total energy consumption of 88.5 QBtu in 1994.

Total 7.17

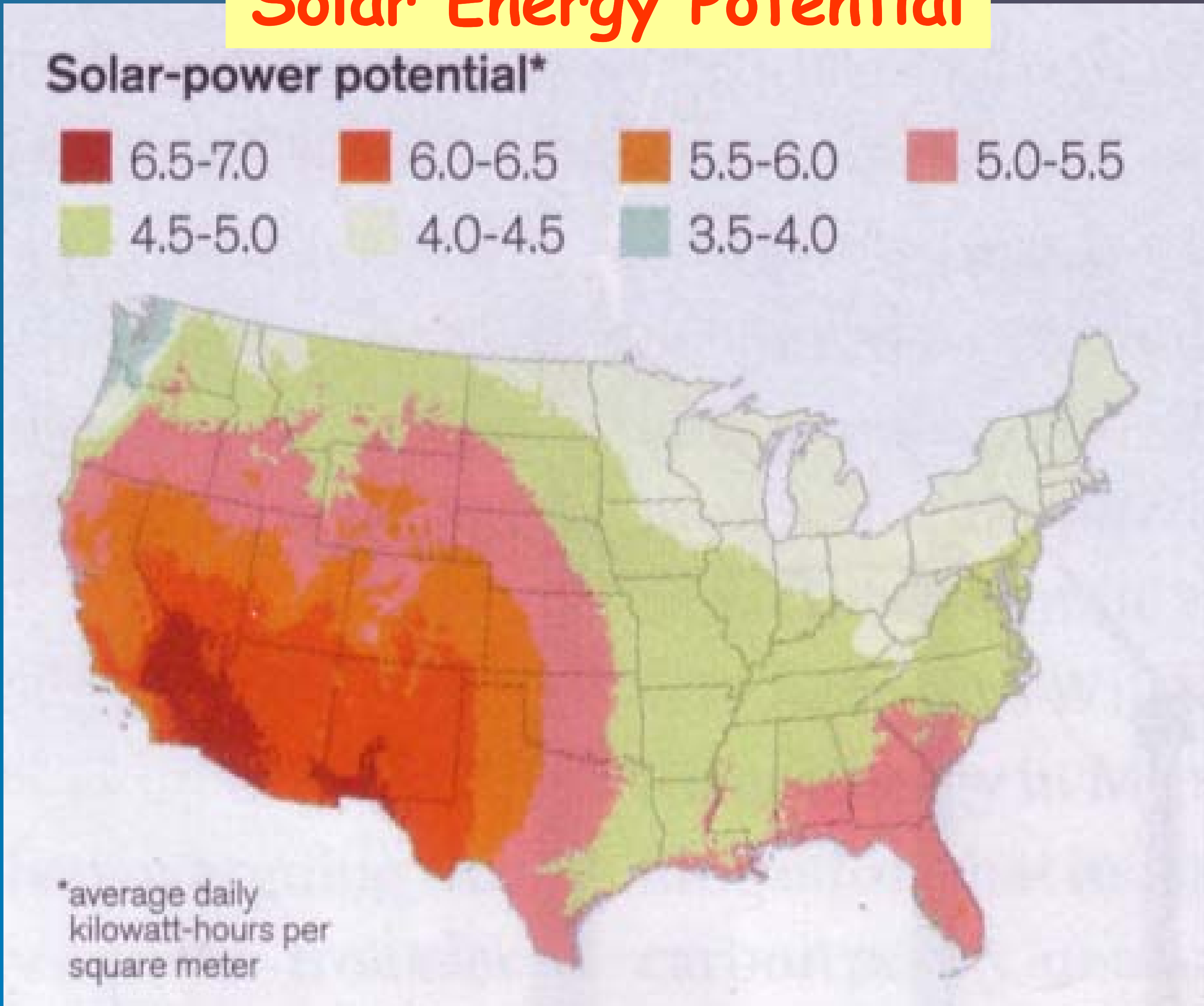
Renewable Component

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

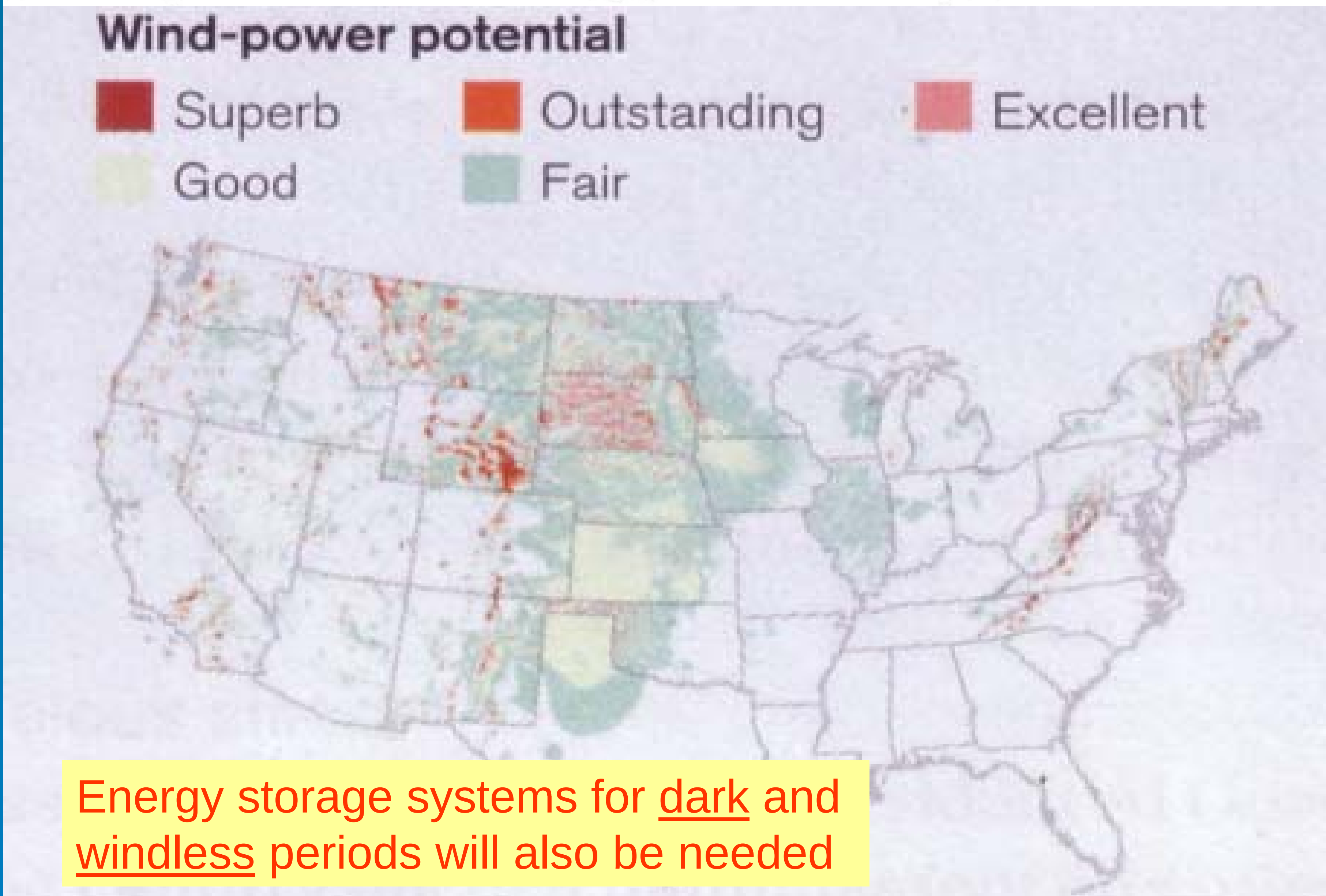
Energy Source	QBtu	Percent[b]
Conventional hydroelectric power	2.779	2.83
Geothermal energy	0.314	0.32
Biomass	2.884	2.94
Solar energy	0.063	0.06
Wind	0.108	0.11
Total	**6.15**	**6.3**

[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.)

Solar Energy Potential

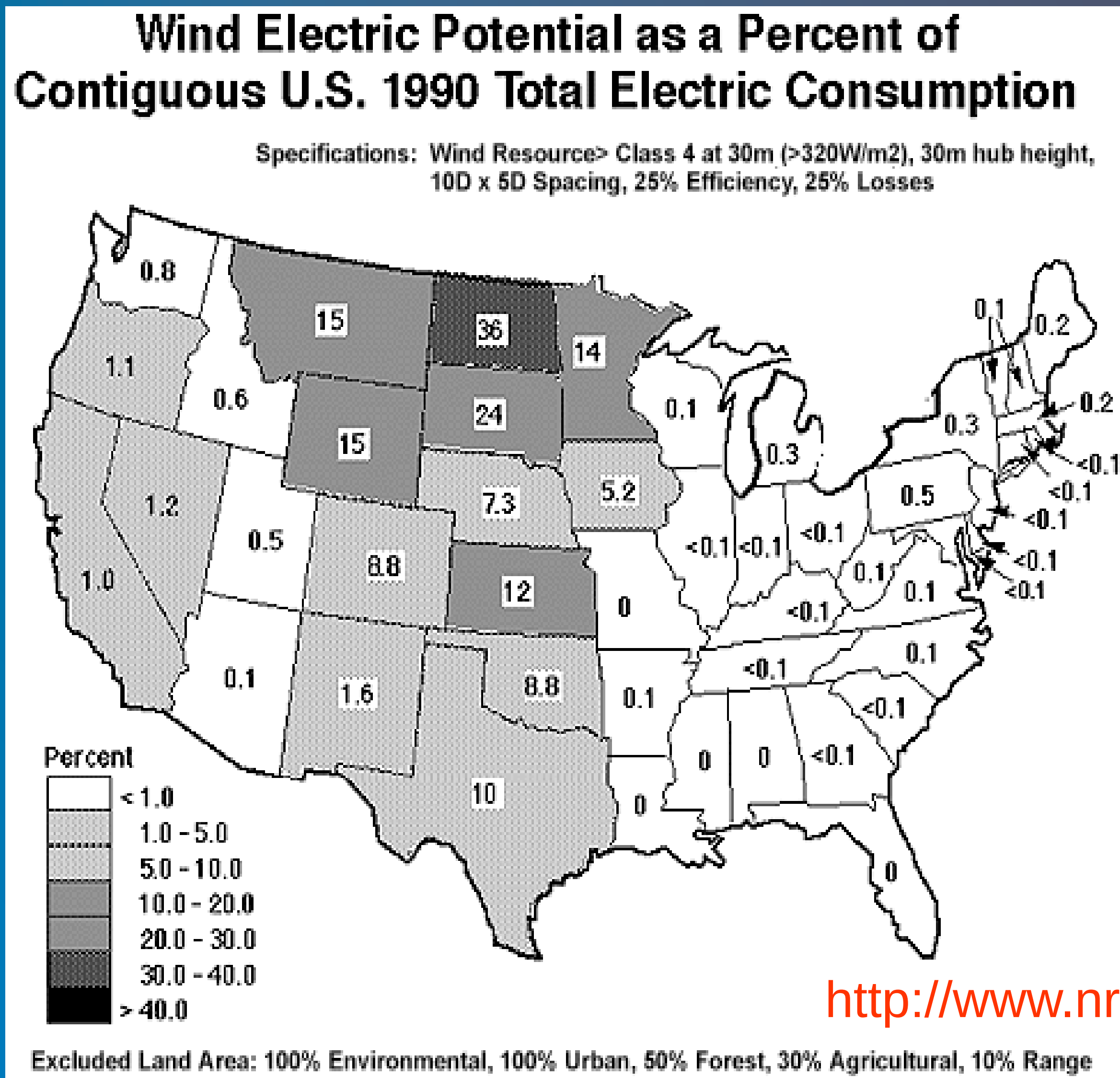


Wind Energy Potential



Energy storage systems for dark and windless periods will also be needed

Electric Potential of Wind



http://www.nrel.gov/wind/potential.html

Ocean Thermal Cycle

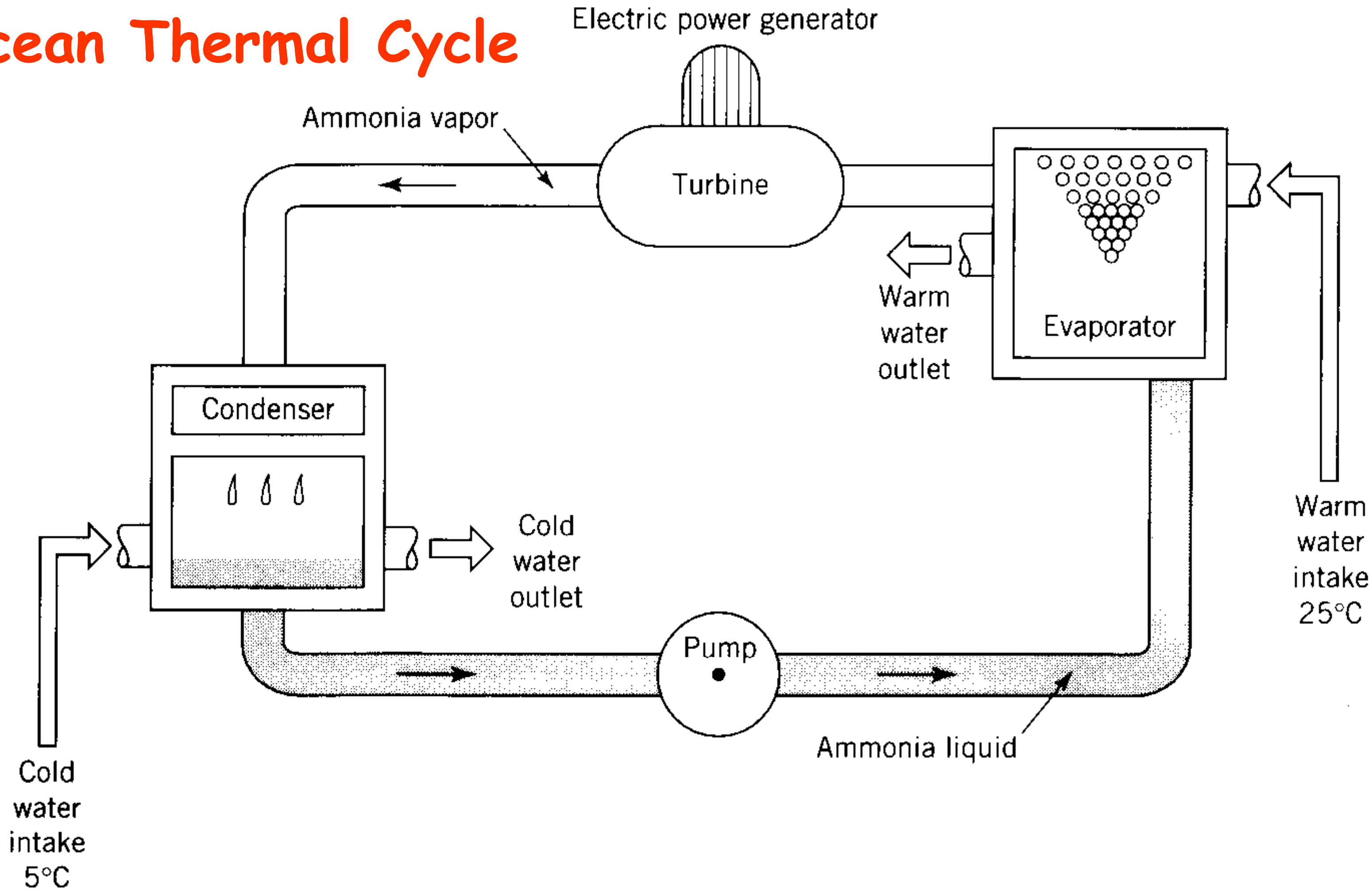
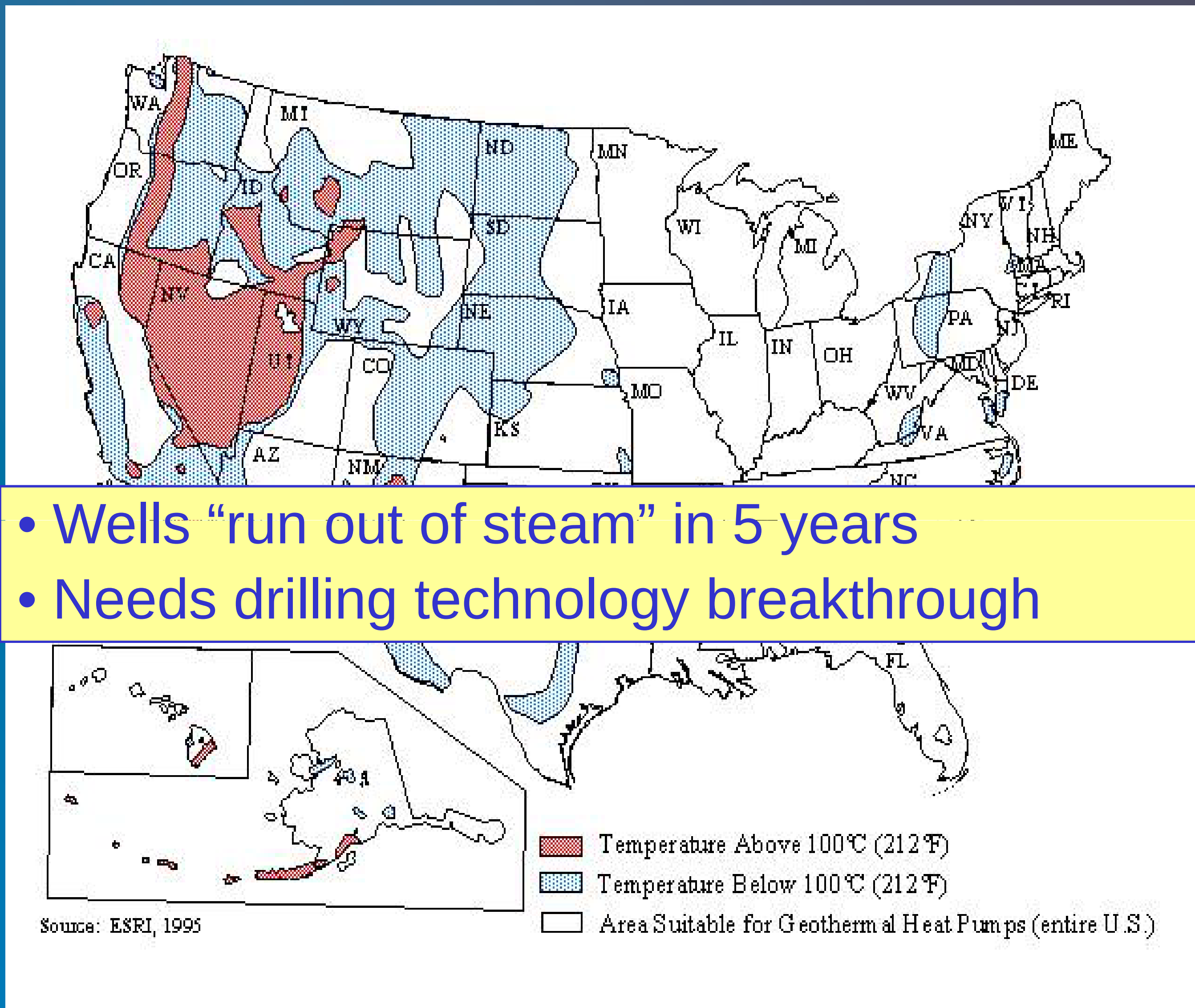


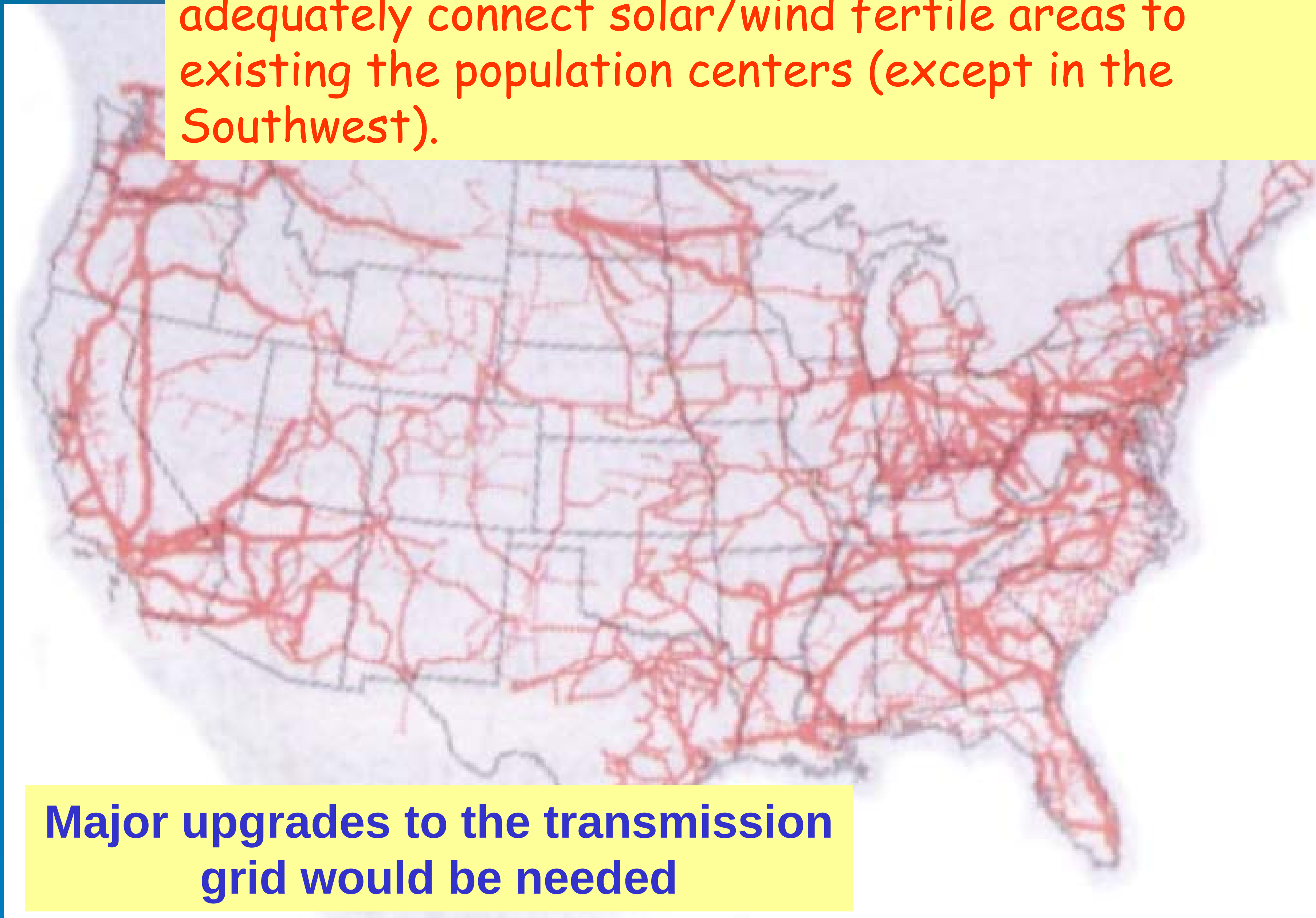
Figure 5.8 An OTEC heat engine using ammonia as a working fluid. The turbine is driven by the ammonia vapor and is connected to a generator to produce electricity. The warm water is drawn from the ocean surface; the cold water from a depth of 1000 meters. (Figure supplied by the National Renewable Energy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

Geothermal Energy Potential



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

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

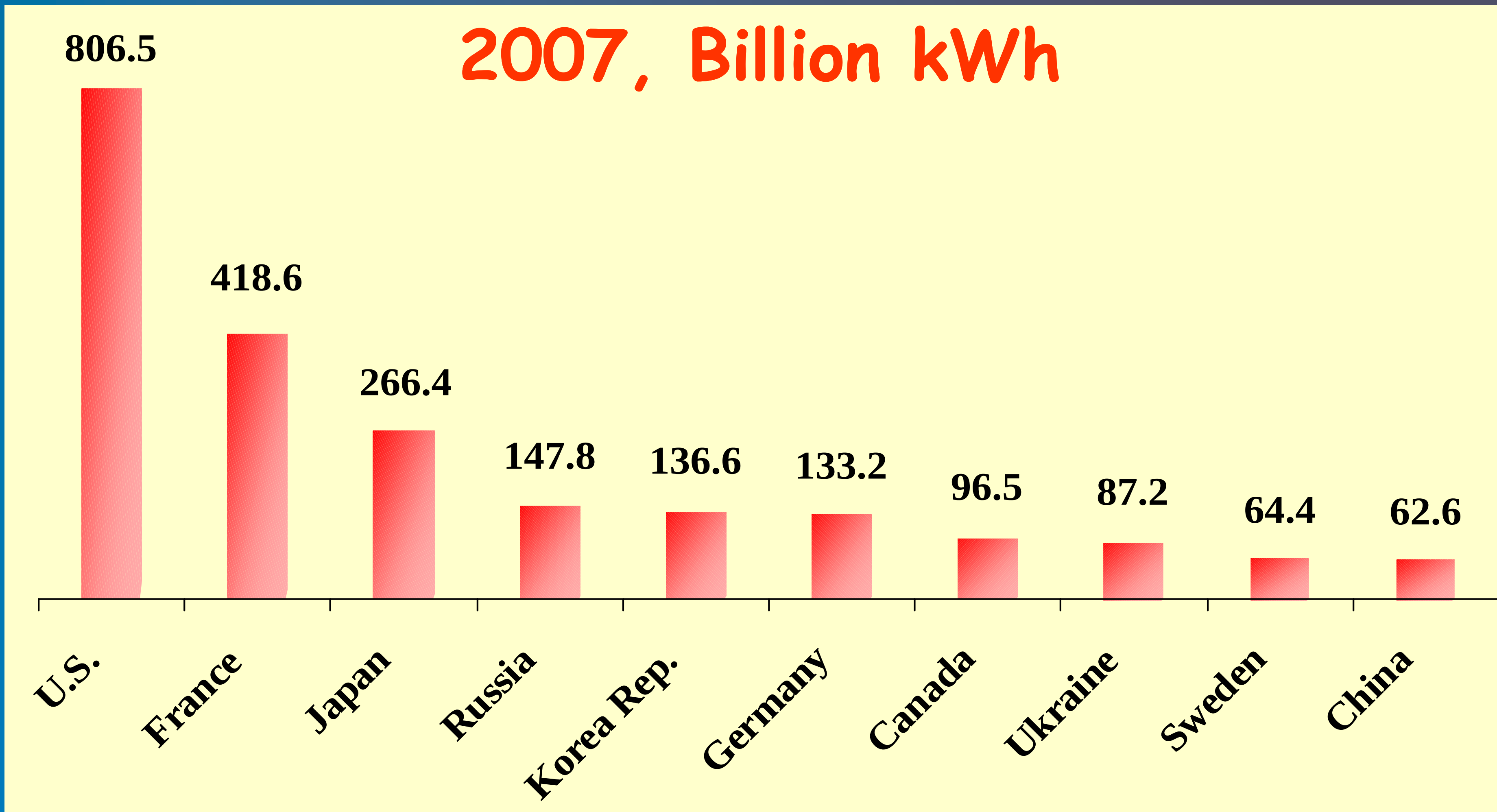


Major upgrades to the transmission grid would be needed

Use of Nuclear Energy World Wide
(16% of total electricity production)

USA	104 reactors produce	20% of total electrical energy
France	59	78%
Japan	54	39%
Great Britain	31	27%
Russia	30	16%
Germany	19	30%
South Korea	18	39%
India	14	4%
Canada	14	12%
Ukraine	13	46%
Sweden	11	47%
Switzerland	5	40%

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

2007, Billion kWh

	USA	France	Germany	Japan
# LWR reactors	104	59	19	54
10^9 kWh nuclear	806.5	418.5	133.2	266.4
10^9 kWh/reactor	7.8	7.1	7.0	4.9
% Nuclear elec.	20	78	30	39
10^9 kWh total	4,032	536	444	683
Est. population	300M	65M	65M	100M
10^9 kWh /10^6 pop.	13.4	8.2	6.8	6.8

To reach 78% nuclear electricity in the US at our present rate of consumption and efficiency would require 403 reactors. @ French rate of consumption, 246, @ German/Japanese rate of consumption, 205

New Nuclear Capacity Proposed to Address Anticipated Demand

"If the U.S. doesn't start building newly designed reactors soon, rolling blackouts could become the norm."

Michael J. Wallace

Chairman, Unistar Nuclear Energy

Scientific American Earth 3.0
March 2009

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

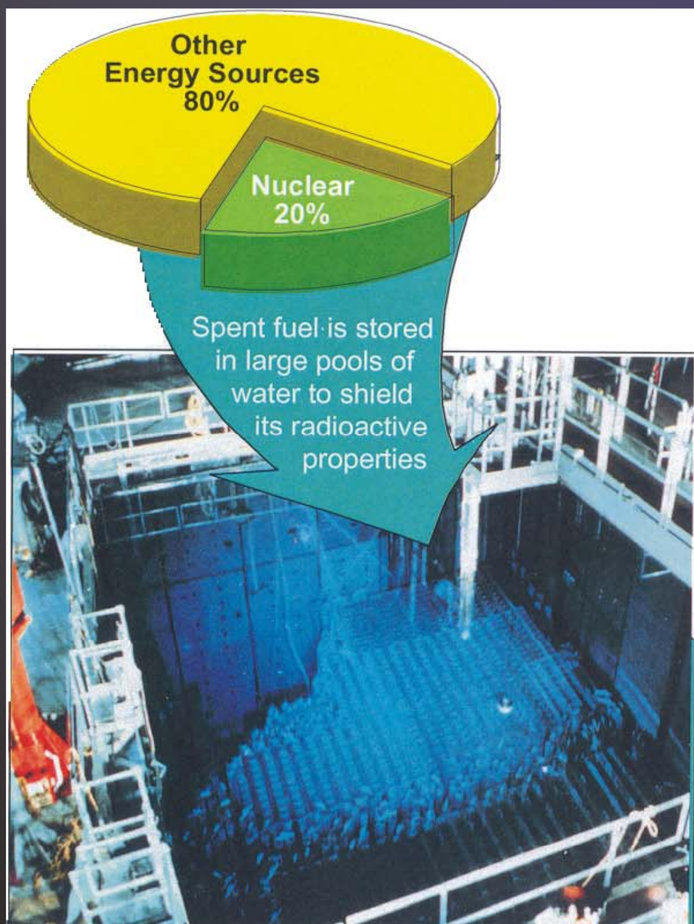
Keeping Pu in the fuel cycle reduces nuclear weapons proliferation concerns

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

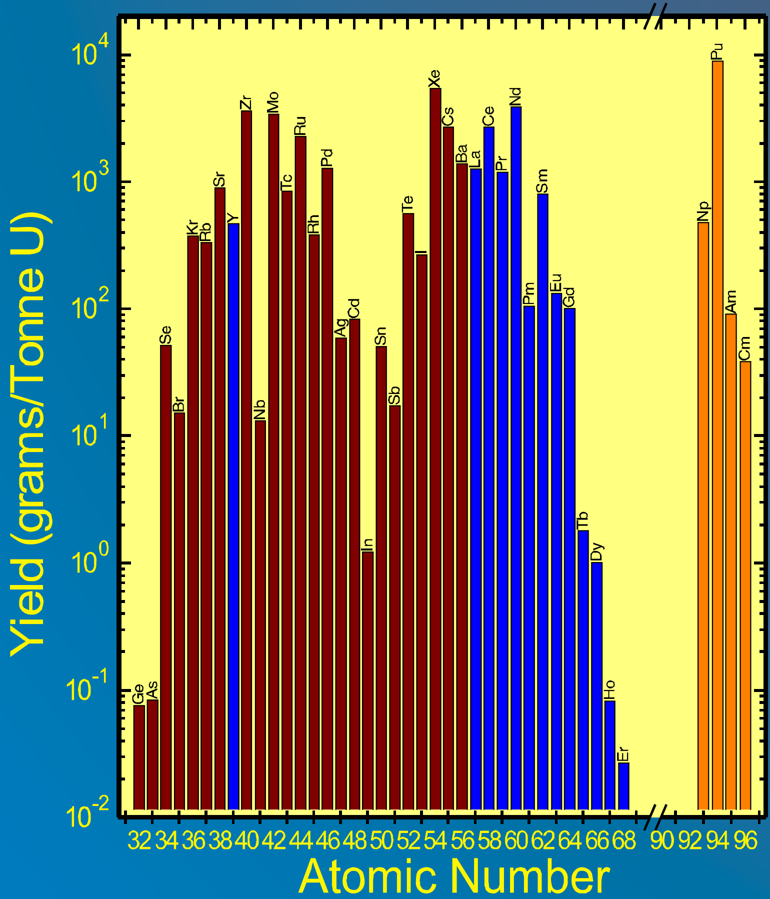


Nuclear power plants are producing about 20% of the electricity in the U.S.

- 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

Thermal Neutron Fission of Uranium

Reactor Charge:
967kg ^{238}U, **33kg** ^{235}U, **0.26kg** ^{234}U irradiated for 33,000 MWd/t U burnup at a power density of 30MW/t U and neutron flux of 2.92×10^{13} $Ncm^{-2}s^{-1}$
(Choppin & Rydberg, Nuclear Chemistry)



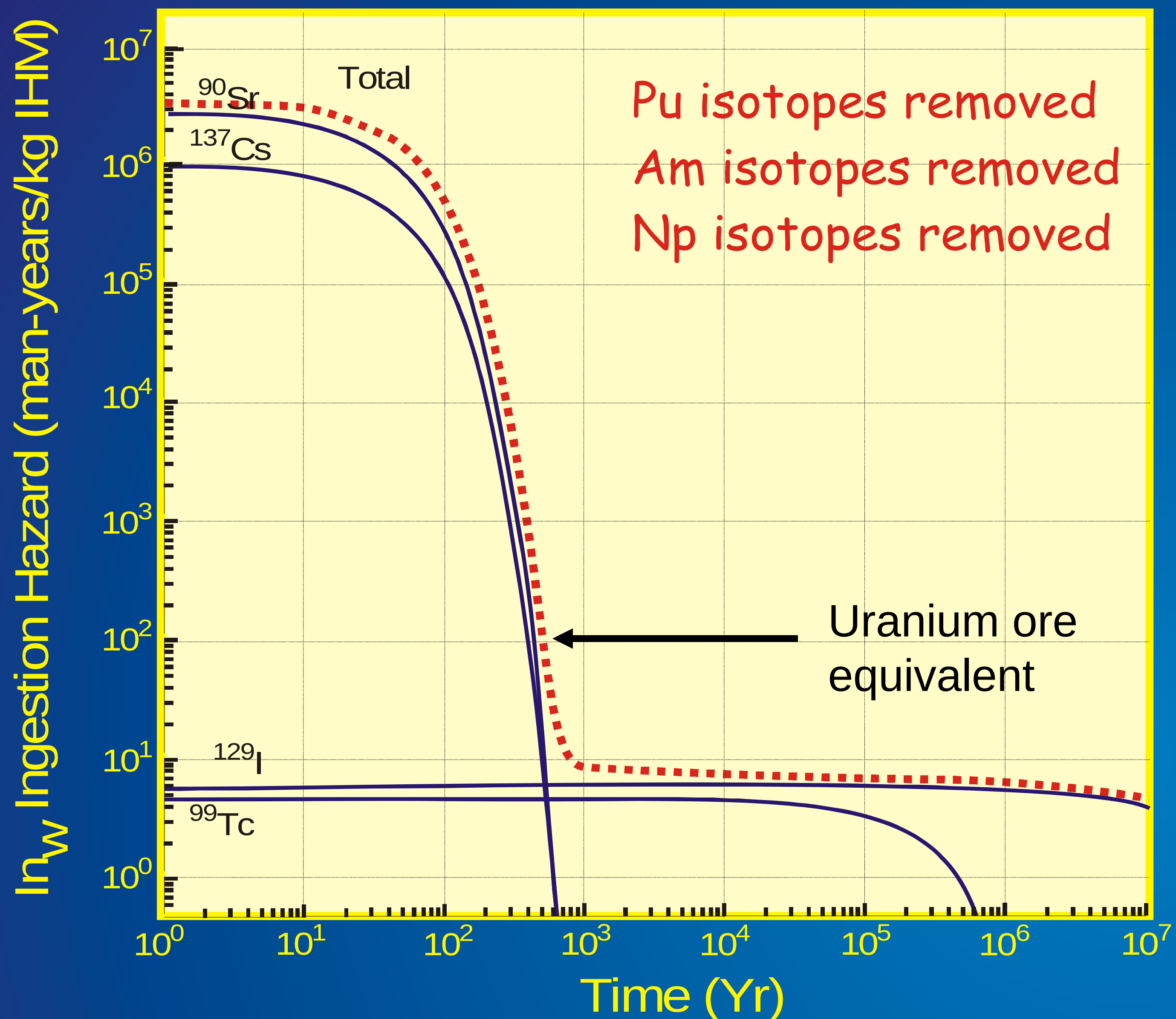
50 kg $^{235, 238}$U consumed (950 kg remain)
75 kg ^{235}U, 875 kg ^{238}U
14 kg ^{236}U and transuranics produced
36 kg of fission products (10 kg Ln)

- 50% of power production from fission of ^{239}Pu
- Discharged fuel contains 1% Pu isotopes, 0.8% ^{235}U, 87% ^{238}U
- Smaller amounts of Am, Np, Cm

Radiation Dose and Decay

14,410,000 Ci/tonne @ discharge
1,497,000 Ci @ 1 year
394,000 Ci @ 10 years
39,800 Ci @ 100 years
1590 Ci @ 1000 years
820 Ci @ 1000 years if U/Pu removed
18 Ci @ 1000 years if An transmuted
2 Ci in 1 tonne of uranium ore

Radiotoxicity as Ingestion Hazard



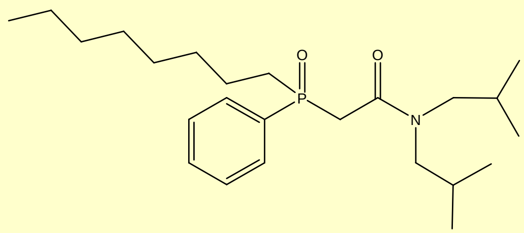
In_w = A/ALI (man-years/kg spent fuel)
where A is activity in Bq and ALI is the Annual Limit for Ingestion)

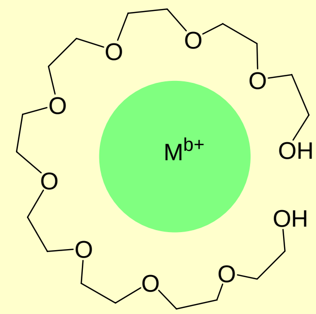
Advanced fuel cycles globally

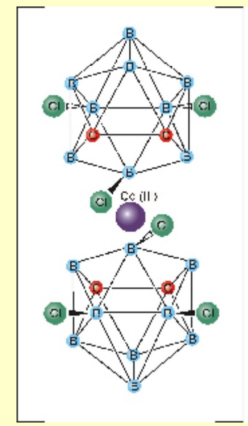
- France has assumed leadership in production and research
    - CHON philosophy
    - Actinide partitioning strategies
- Commercial fuel reprocessing in France, UK, Japan, Russia; Military activities in India, Pakistan, N Korea, Iran (?), ….?
- New nuclear power emphasis in developing economies of India and China
- Thorium-uranium breeder reactor seriously considered in India
- Management of wastes and repository qualification
    - Minor actinides (Np, Am, Cm) are the key component
- Plutonium for weapons production de-emphasized in general
- Transmutation and breeder reactor cycles being considered

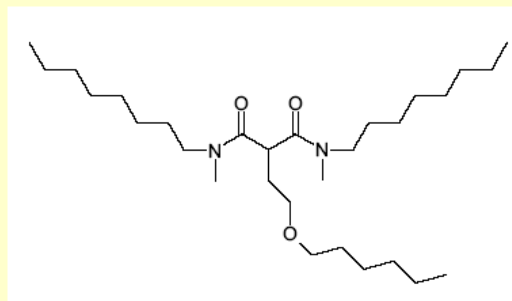
Other separation processes utilized for spent nuclear fuel and/or radioactive waste treatment

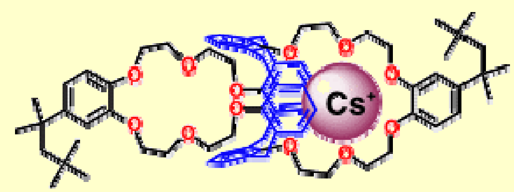
- TRUEX
- DIAMEX
- SREX
- CCD-PEG
- FPEX
- UNEX
- TALSPEAK
- SANEX
- Am(VI)/TBP
- CSSX
- Ion exchange

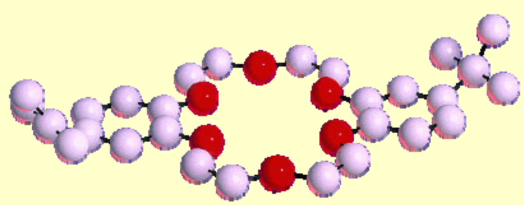


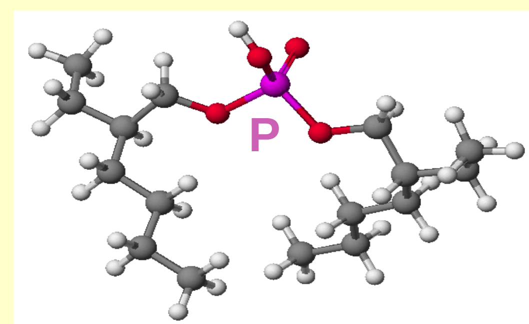




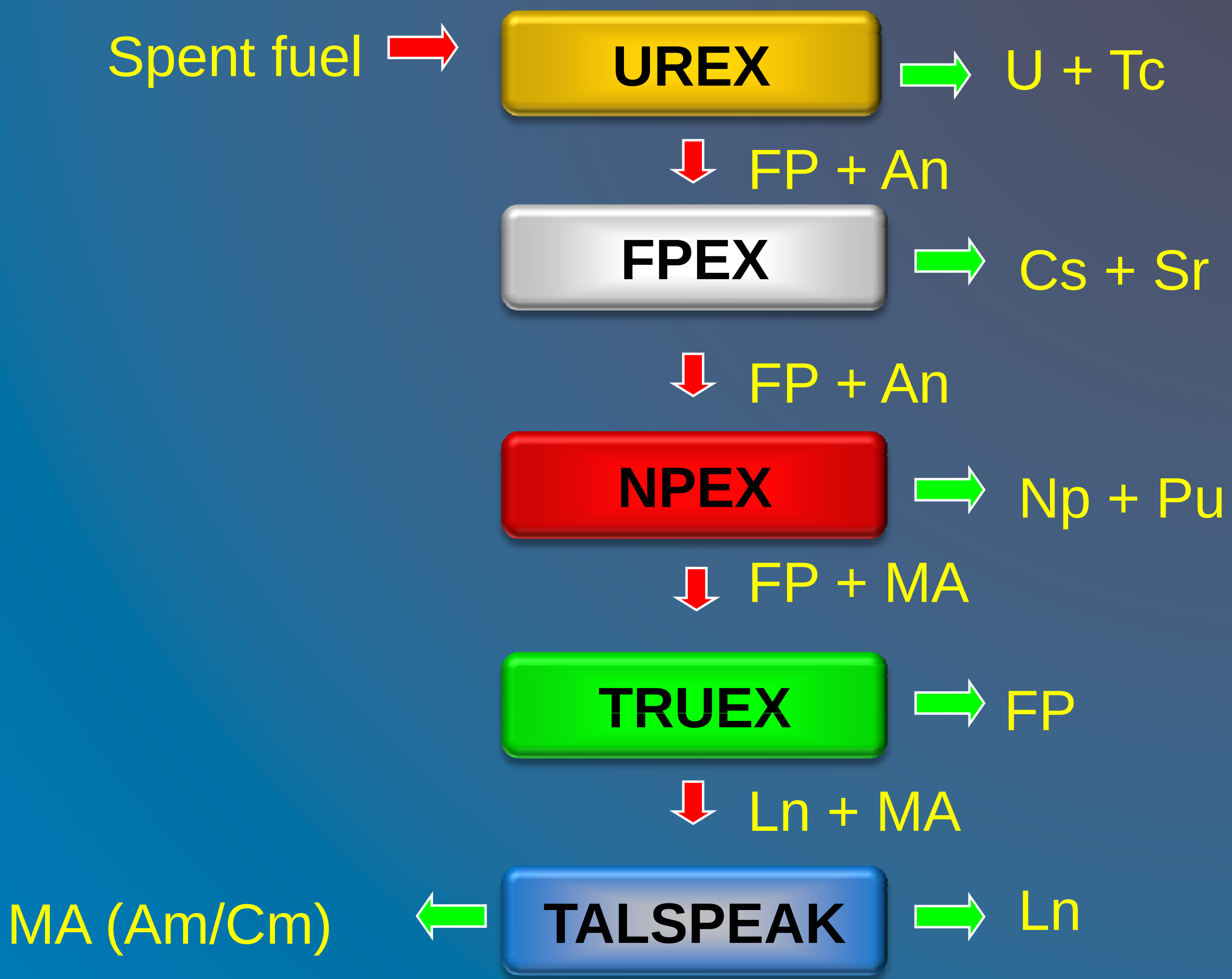






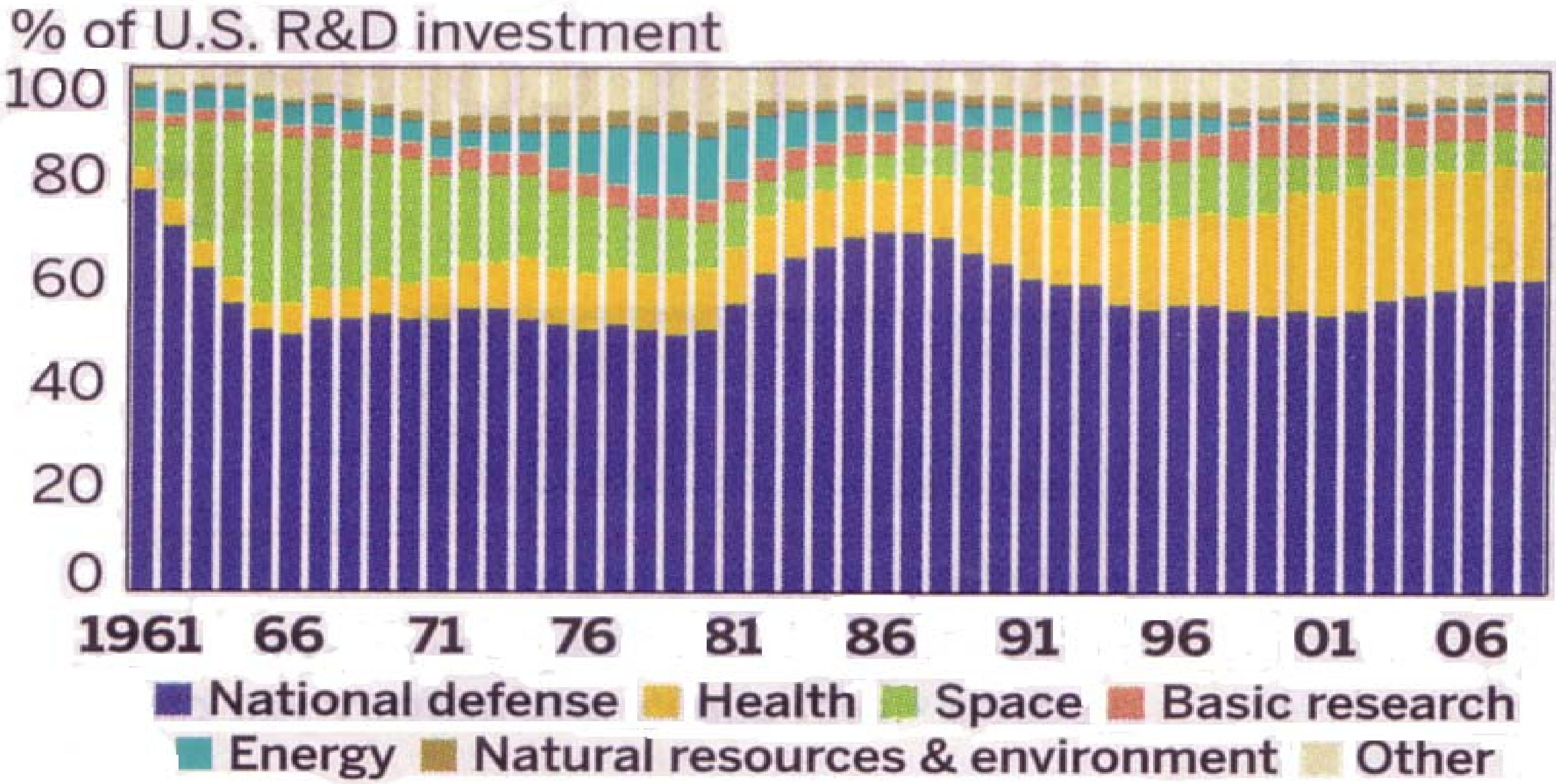


US model, UREX+



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

Conclusions

As the end of the age of Fossil Fuels approaches...

- Energy demand will grow with population
- Global climate will continue to be a matter of concern
- More of the developing world will industrialize
- Pressure on developed world will increase for more efficient energy use
- Big breakthroughs in advanced energy production methods (e.g., fusion, solar) may remain in "40-50 years away"
- Waste management, recycling, and energy/resouce use efficiency will be critical
- All forms of energy production have a role to play

Conclusions

Future Directions for the Nuclear Fuel Cycle

- Transmutation of transuranic actinides will enhance repository safety margins and reduce weapons proliferation concerns, but requires processing of used fuel
- Aqueous-based technologies will continue to dominate nuclear fuel recycling globally for at least the next 20 years - Non aqueous concepts (Pyro, volatility) more important for NGNP fuel cycles
- Breeding additional fissile material will probably be necessary if the nuclear contribution to the global energy balance is to grow
- Technological and scientific research must be fortified to provide a necessary base for a healthy program - research drives innovation
- Scientific studies must address more complex media and systems
- Rate of progress has been slowed during recent decades by inadequate funding and loss of capabilities to age and despair
- ***Support for education of a next generation of experts (and of the general public) - a global problem***

Hoffert et al.'s Conclusions

- "These results underscore the pitfalls of "wait and see"."
- Without policy incentives to overcome socioeconomic inertia, development of needed technologies will likely not occur soon enough to allow capitalization on a 10-30 TW scale by 2050
- "Researching, developing, and commercializing carbon-free primary power technologies capable of 10-30 TW by the mid-21st century could require efforts, perhaps international, pursued with the urgency of the Manhattan Project or the Apollo Space Program."