1.818J/2.65J/10.391J/11.371J/22.811J/ESD166J

SUSTAINABLE ENERGY

2.650J/10.291J/22.081J

INTRODUCTION TO SUSTAINABLE ENERGY

Prof. Michael W. Golay
Nuclear Engineering Dept.

NUCLEAR ENERGY BASICS AND STATUS

GOALS

- To Understand the Situation and Prospects of the Nuclear Power Enterprise Within the Overall Energy Context
  - Domestically
  - Internationally

NUCLEAR POWER TECHNOLOGIES

GOALS OF NUCLEAR POWER DISCUSSION: To Answer the Following Questions

- Who used nuclear power today?
  Answer: Most industrialized countries.
- Who is likely to use nuclear power in the future?
  Answer: East Asian and developing countries, countries wanting energy supply diversity.
- What are the important nuclear power technologies
  - Today? Answer: LWRs – pressurized and boiling water reactors.
  - Future? Answer: Maybe LWRs near term, gas-cooled reactors medium term, breeder reactors long term.
- How could nuclear power relieve global warming?
  Answer: Most likely with large-scale, high-temperature breeder reactors.
- What are the future prospects for nuclear power?
  Answer: That depends upon how concerned people are about the problems of other energy technologies and what nuclear power can produce in addition to electricity.

TYPES OF STEAM-ELECTRIC GENERATING PLANTS

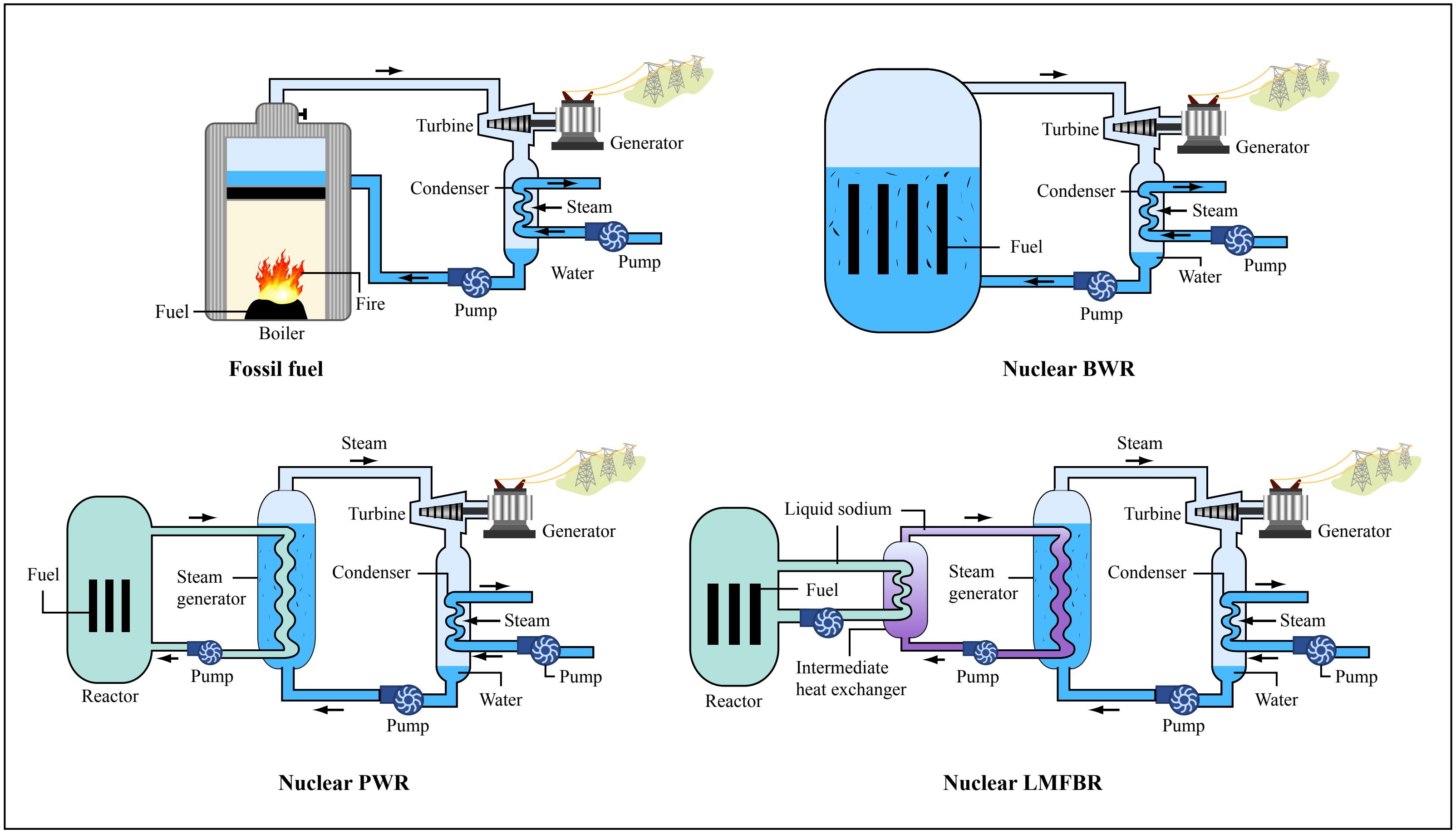
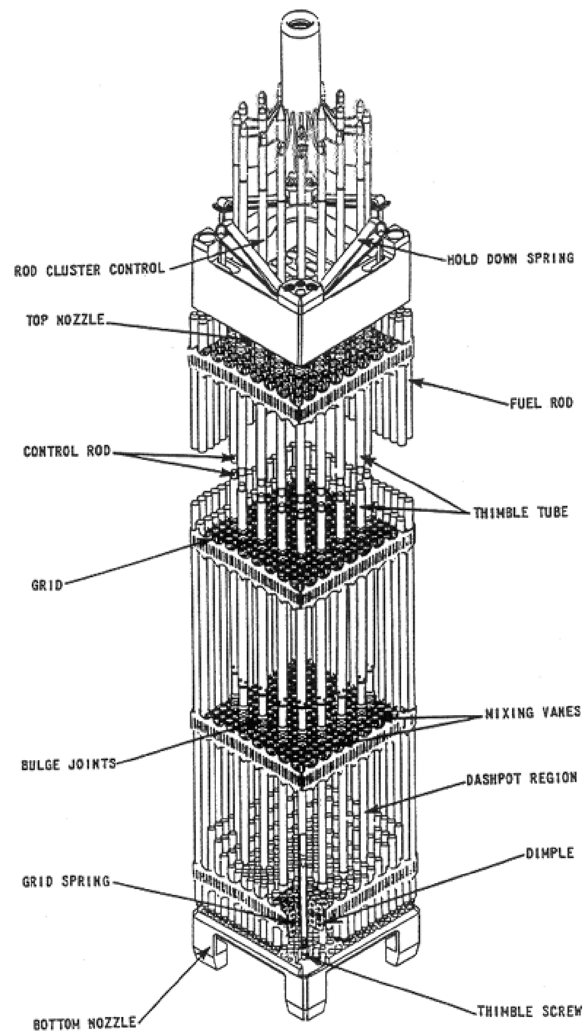


Image by MIT OpenCourseWare.

PWR FUEL ASSEMBLY AND CUTAWAY OF OXIDE FUEL FOR COMMERCIAL LWR POWER PLANTS



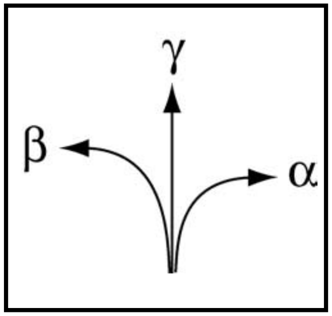
Reactor Fuel Assembly

A.V. Nero, Jr., *A Guidebook to Nuclear Reactors*, 1979.

Image by U.S. Nuclear Regulatory Committee.

RANGE OF RADIATION IN TISSUE

Particle Name	Range (m)	Particle Type and Charge
Fission Product	10^{-6}	Fragment of Nucleus
α	$10^{-4} – 10^{-5}$	Helium Nucleus^{++}, 2 protons, 2 neutrons
β	10^{-3}	Electron^{-}
γ	0.1 – 10	Photon^{0}
n	0.1 – 10	Neutron^{0}



TRANSMUTATION

Stable Isotope		Neutron		New Isotope
A^{m}	+	n	→	A^{m+1}

FISSION

$$n + {}^{235}U \rightarrow {}^{236}U \rightarrow 2\ \text{Fission Products}$$

$$+\ \nu\ (\approx 2.5)n$$

$$+\ 6\ \beta$$

$$+\ 10\ \gamma$$

$$+\ \text{neutrinos}$$

$$+\ \text{kinetic energy}\ (\approx 200\ \text{MeV})$$

TWO REPRESENTATIVE FISSION-PRODUCT DECAY CHAINS*

Flowchart of decay chains for Br-90 and Xe-143 removed due to copyright restrictions.

ENERGY BALANCE FOR AN AVERAGE FISSION

	MeV
Kinetic energy of fission fragments (2 nuclei: A Å95, A Å140)	165 ± 5
Prompt γ rays (5 γ rays)	6 ± 1
Beta decay of fragments (7 β rays)	8 ± 1.5
Neutrinos related to above	12 ± 2.5
Gamma rays related to above (7 γ rays)	6 ± 1
Kinetic energy of neutrons (2 to 3 neutrons)	5

NEUTRONIC PROPERTIES OF NUCLEAR FUELS

	NEUTRON ENERGIES					
	THERMAL			MeV		
Parameter	U^{233}	U^{235}	Pu^{239}	U^{233}	U^{235}	Pu^{239}
α	0.123	0.2509	0.38	0.1	0.15	0.1
η	2.226	1.943	2.085	2.45	2.3	2.7
ν	2.50	2.43	2.91	2.7	2.65	3.0

$$\eta = \frac{\nu}{1+\alpha}, \frac{\text{n's produced}}{\text{absorption}}; \quad \alpha = \frac{\text{captures}}{\text{fissions}}; \quad \nu = \frac{\text{n's produced}}{\text{fission}}$$

Conversion Reactions:

$$U^{238} + n \rightarrow U^{239} + \gamma \rightarrow Np^{239} + \beta^{-} \rightarrow Pu^{239} + \beta^{-}$$

$$Th^{232} + n \rightarrow Th^{233} + \gamma \rightarrow Pa^{233} + \beta^{-} \rightarrow U^{233} + \beta^{-}$$

SELF-SUSTAINED CHAIN REACTION

$$1 \text{ neutron } + U^{235} \rightarrow \eta \text{ neutrons} \Rightarrow \begin{cases} 1 \text{ neutron for subsequent fission, and} \\ (\eta - 1) \text{ neutrons for leakage, parasitic absorption, and conversion} \end{cases}$$

Necessary Condition for Breeding: for each fissile nucleus consumed another is produced via conversion of fertile material, e.g., a U^{235} nuclear is consumed and replaced by production of a new Pu^{239} nucleus, via the reaction –

$$n + U^{238} \rightarrow U^{239} + \gamma$$
$$\hookrightarrow Np^{239} + \beta^{-} + \gamma$$
$$\hookrightarrow Pu^{239} + \beta^{-} + \gamma$$

Conversion Ratio $\equiv$ Number of new fissile neuclei produced as a result of fission of a single nucleus

$$\text{Conversion Ratio}: \begin{cases} \geq 1 \text{ for breeding} \\ < \text{ for burning} \end{cases}$$

FUNDAMENTAL SOURCES OF ENERGY USED BY DIFFERENT ENERGY TECHNOLOGIES

Energy Source	Fundamental Nuclear Energy Source
Solar	Gravitationally confined solar fusion reactions transmitted via photons
Fossil Fuels	Gravitationally confined solar fusion reactions transmitted via photons and stored in biomass
Geothermal	Naturally-occurring radioactive decays of materials within the Earth and Gravitational Work
Tidal	Nuclear reactions following the Big Bang Sustaining Current Gravitational Work
Nuclear Fission	Neutron-induced fission reactions of heavy nuclei
Nuclear Fusion	Nuclear fusion reactions of light nuclei

ENVIRONMENTAL EFFECTS OF ENERGY SOURCES

FUEL / PHASE	Coal	Petroleum	Natural Gas	Nuclear	Hydro	Solar Terrestrial Photovoltaic	Solar Power Tower	Wind	Fusion	Geothermal
Extraction	Mining Accidents Lung Damage	Drilling-Spills (off-shore)	Drilling	Mining Accidents Lung Damage	Construction	Mining Accidents	- -	- -	He, H^2, Li Production	- -
Refining	Refuse Piles	Water Pollu- tion	- -	Milling Tails	- -	- -	- -	- -	- -	- -
Transportation	Collision	Spills	Pipeline Explosion	- -	- -	- -	- -	- -	- -	- -
<u>On-Site</u>										
Thermal	High Efficiency	High Efficiency	High Efficiency	Low Efficiency	- -	Low Efficiency Ecosystem Change	Ecosystem Change	- -	- -	Low Efficiency
Air	Particulates- SO_2, NO_x	SO_2, NO_x	NO_x	BWR Radia- tion Releases	- -	- -	- -	- -	- -	H_2S
Water	Water Treat- ment Chemi- cals	Water Treat- ment Chemi- cals	Water Treat- ment Chemi- cals	Water Treat- ment Chemi- cals	Destroys Prior Ecosystems	Water Treat- ment Chemi- cals	Water Treat- ment Chemi- cals	- -	Tritium in Cooling Water	Brine in Streams
Aesthetic	Large Plant Transmission Lines	Large Plant Transmission Lines	Large Plant Transmission Lines	Small Plant Transmission Lines	Small Plant Transmission Lines	Poor Large Area	Poor Large Area	Large Area Large Towers Noise?	Small Area	Poor Large Area
Wastes	Ash, Slag	Ash	- -	Spent Fuel Transportation Reprocessing Waste Storage	- -	Spent Cells	- -	- -	Irradiated Struc- tural Material	Cool Brine
Sprecial Problems	- -	- -	- -	- -	- -	Construction Accidents	- -	Bird, Human Injuries	Occupational Radiation Doses	- -
Major Accident	Mining	Oil Spill	Pipeline Explosion	Reactor Cooling	Dam Failure	Fire	- -	- -	Tritium Release	- -

PUBLIC MOOD MORE FAVORABLE TO NUCLEAR POWER

- Global Warming Concerns
  - Popular belief
  - IPCC reports and 2007 Nobel Peace Prize
- Fossil fuel costs/supply security
- Middle-East Wars
- Better Nuclear Power Technology – Mainly Concerning Safety
- Good Operational Record of Existing Nuclear Plants

WORLD ELECTRICITY GENERATION

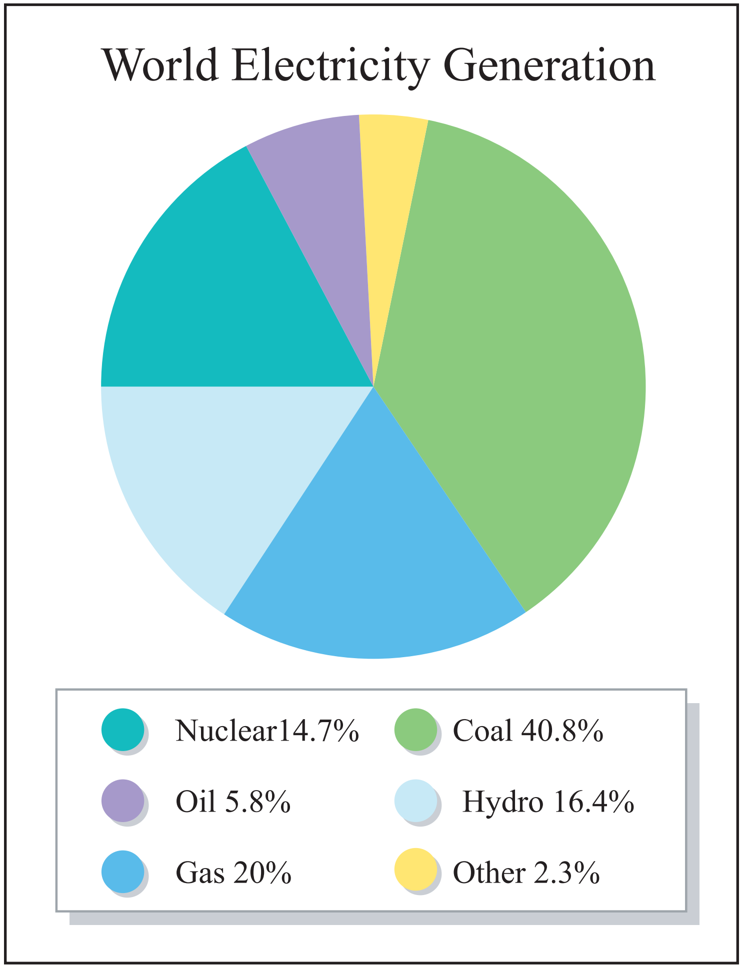


Image by MIT OpenCourseWare. Source: OECD/IEA 2006.

http://www.world-nuclear.org/info/inf01.html

INTERNATIONAL NUCLEAR POWER GROWTH – End of 2010

- 441 Units Operating in 30 Countries, with 376,000 MWe of total capacity
- 7 New Units Expected to Start Up in 2010
- 60 New Units Under Construction, 11 Started in 2009
- 150 New Units Planned
- 340 New Units Proposed
- China Plans 50 Units Over Next 10 Years
- UK "White Paper" Encourages New Nuclear Power Plants (1/08)
- New Units in South Korea, China, Finland, France, India, Japan, Russia—most growth is in Asia

FUEL FOR ELECTRICITY GENERATION 2006

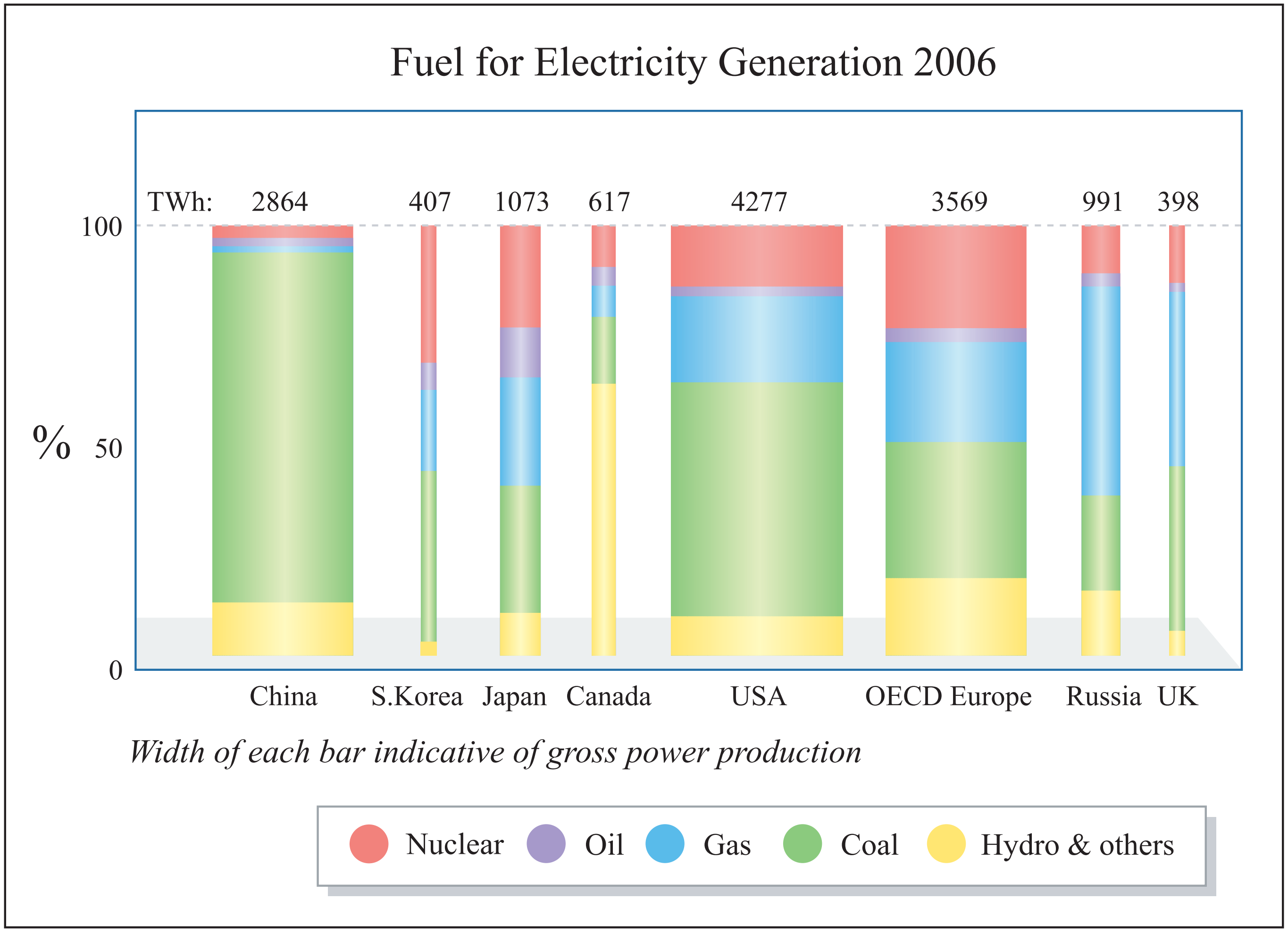


Image by MIT OpenCourseWare. Source: OECD/IEA Electricity Information 2007.

http://www.world-nuclear.org/info/inf01.html

NUCLEAR POWER STATUS AROUND THE WORLD

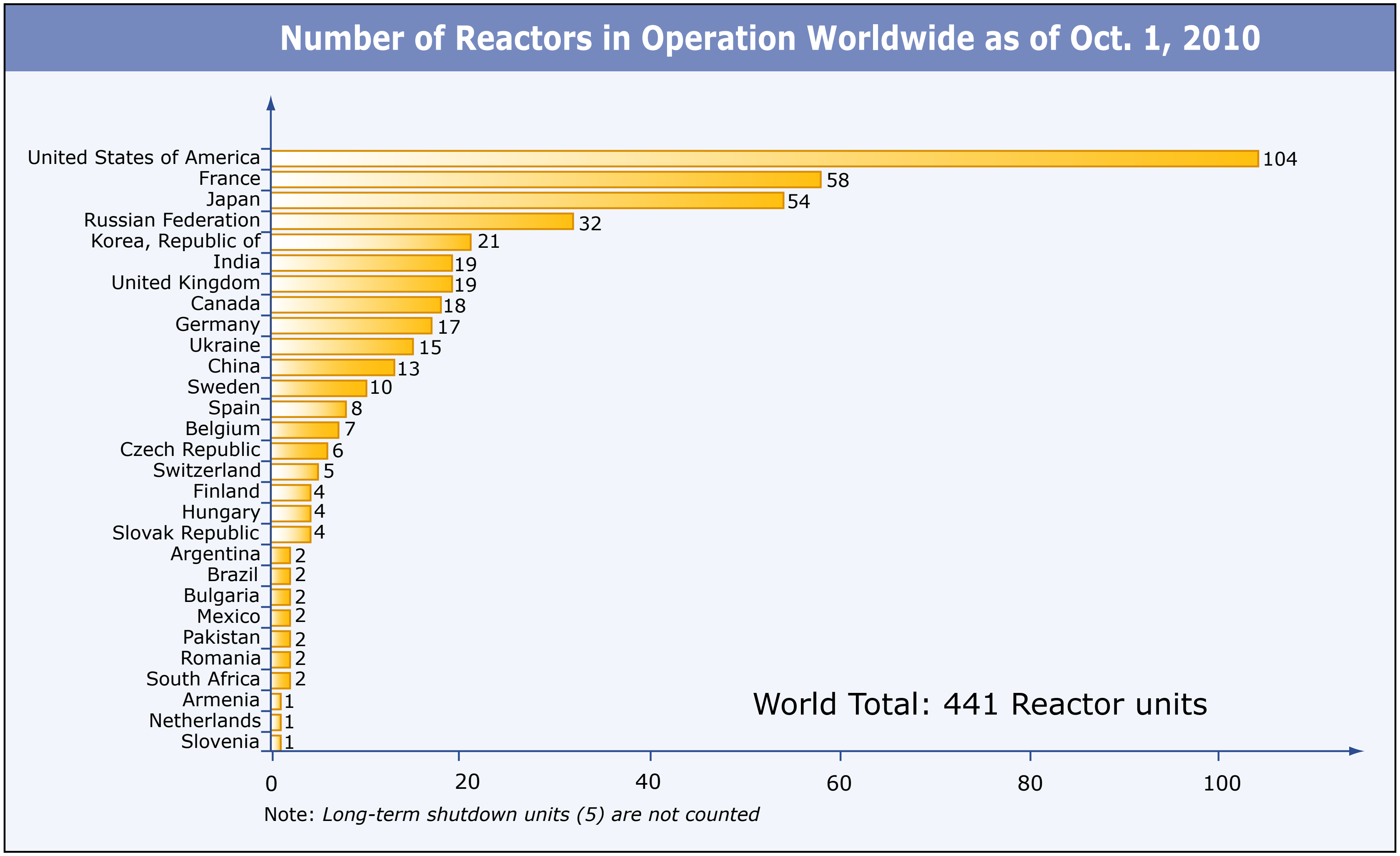


Image by MIT OpenCourseWare. Source: International Atomic Energy Agency.

http://www.iaea.org/cgi-bin/db.page.pl/pris.oprconst.htm

NUCLEAR ELECTRICITY PRODUCTION AND SHARE OF TOTAL ELECTRICITY PRODUCTION

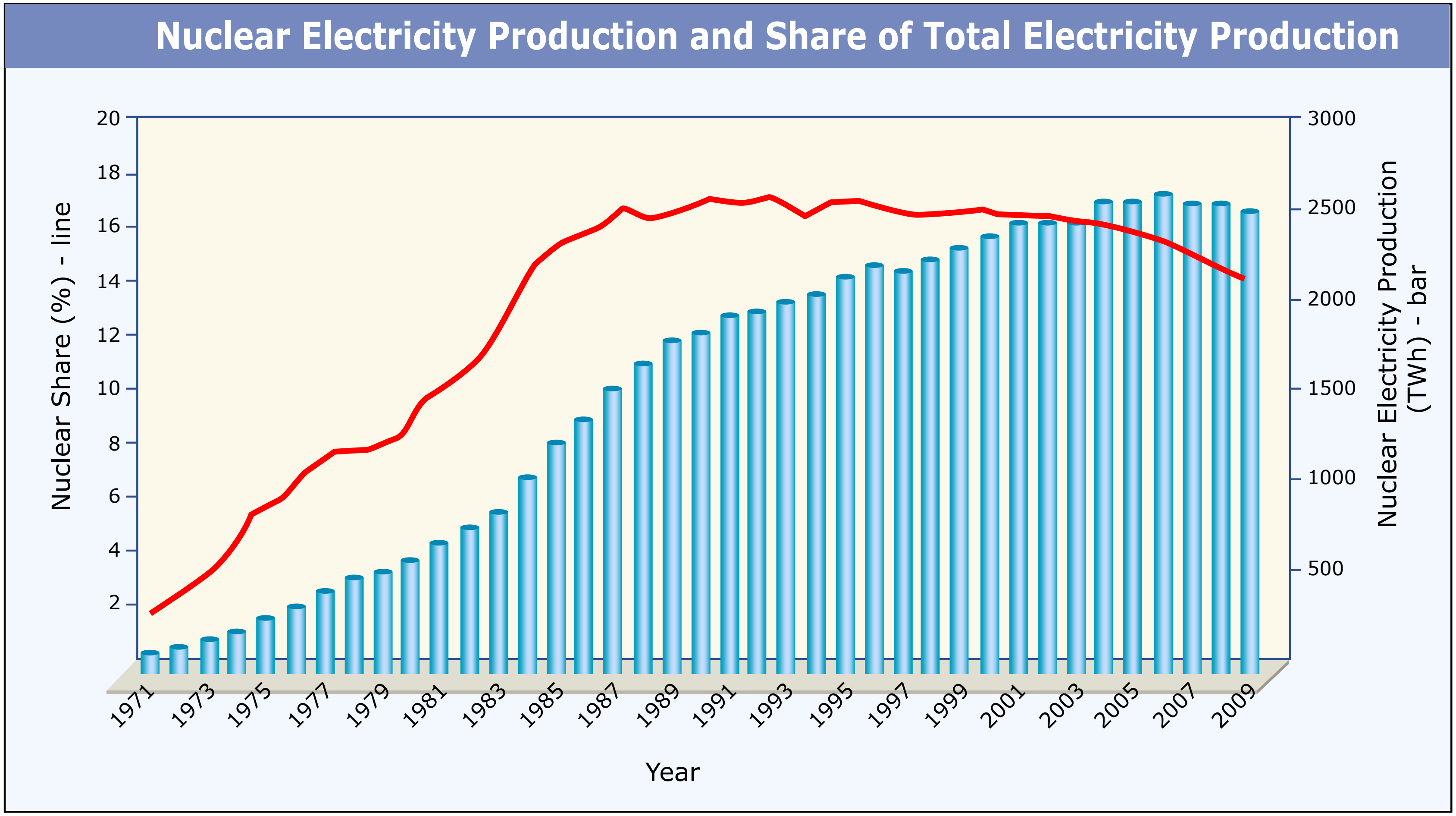


Image by MIT OpenCourseWare. Adapted from the World Nuclear Association.

http://www.world-nuclear.org/info/inf01.html

NUCLEAR ELECTRICITY GENERATION 2007

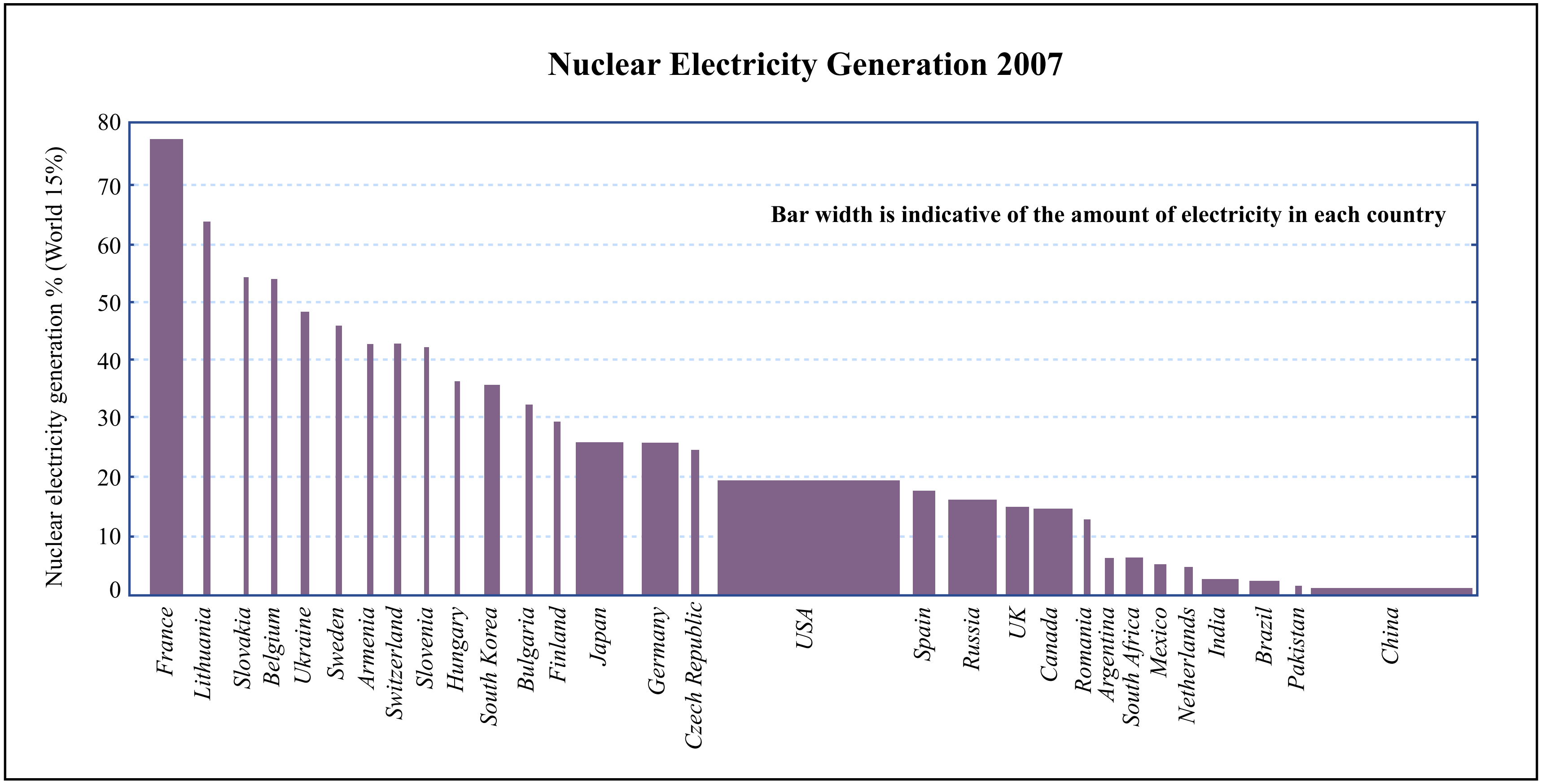


Image by MIT OpenCourseWare. Adapted from the World Nuclear Association.

http://www.world-nuclear.org/info/inf01.html

NUCLEAR ENERGY

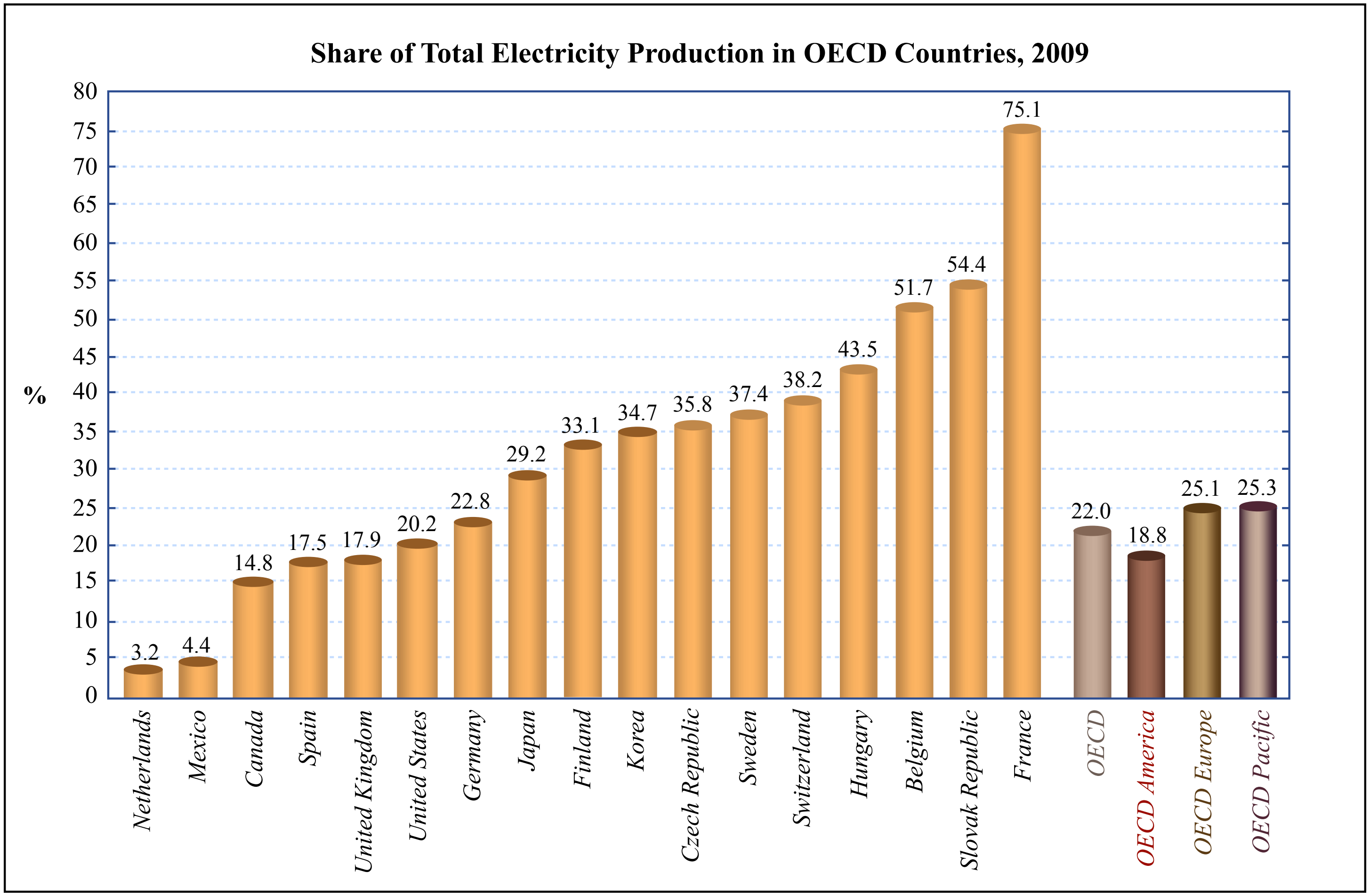


Image by MIT OpenCourseWare. Source: OECD.

Source: http://www.oecd.org, *Nuclear Energy Data*, 2010

EXISTING NUCLEAR POWER PLANTS (Approximately 441 Worldwide)

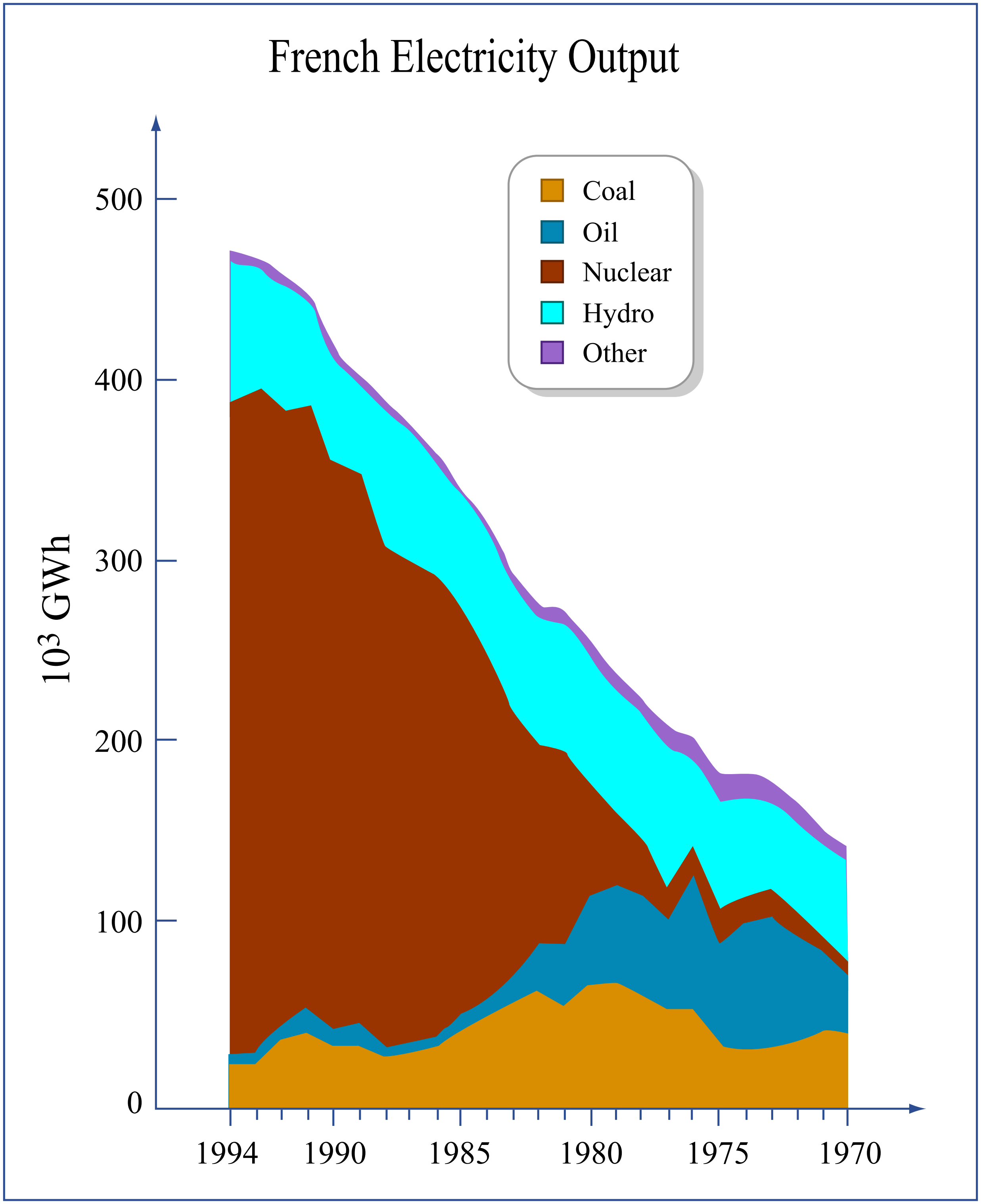
Country	Fraction of Electricity	Units Under Construction	Operating Units
France	75.2	1	59
Belgium	51.7	0	7
Bulgaria	35.9	0	2
S. Korea	34.8	6	21
Switzerland	39.5	0	5
Japan	28.9	2	55
UK	17.9	0	19
USA	20.2	1	104
Russia	17.8	10	32
S. Africa	4.8	0	2
Netherlands	3.7	0	1
China	1.9	23	13

Sources: world-nuclear.org & euronuclear.org, 10/10

SUMMARY OF TYPES OF POWER REACTORS USED WORLDWIDE

Type	Coolant	Moderator	Coolant Temperature (C)	Deployment	Current Population
Pressurized Water (PWR)	Light Water	Light Water	300	Most nuclear countries	265
Boiling Water (BWR)	Light Water	Light Water	300	Most nuclear countries	94
RBMK	Light Water	Graphite	300	Former USSR*	16
Pressurized Heavy Water (PHWR)	Heavy Water	Heavy Water	300	Canada, Korea, China, Argentina, India, Pakistan	44
Gas-Cooled (GCR)	Carbon Dioxide, Helium	Graphite	600	UK, Russia	18
Liquid Metal-Cooled (LMFBR)	Sodium, Lead, Lead-Bismuth	None	600	France, UK, Japan, Russia; former USSR, China and India	2

*Union of Soviet Socialists Republics


French Electricity Output
Coal
Oil
Nuclear
Hydro
Other
10^3 GWh
500
400
300
200
100
0
1994
1990
1985
1980
1975
1970

INTERNATIONAL TRENDS

- Deregulation originated in the United Kingdom, went well until natural gas prices fell (≈ 2002); British Energy was near bankruptcy and depended upon government loans
- Deregulation is also being tried in United States, Canada, Chile, Japan, South Korea, Australia, and European Community
- Consolidation among nuclear equipment vendors is occurring: Areva, Siemens, British Nuclear Fuels Ltd/Toshiba, General Electric, Hitachi, Mitsubishi Heavy Industries
- New reactor manufacturers from S. Korea, Russia, perhaps China next, entering international competition

REGIONAL FACTORS

EUROPE

- Electricité de France is a big exporter and owner
- Nuclear power shutdowns have been mandated in Sweden, Germany and Belgium; now being revoked or reconsidered
- Fifth Finnish nuclear unit (EPR) plant is proceeding

AFRICA

- South Africa was developing the pebble bed modular reactor (PBMR), has shut down the project

REGIONAL FACTORS, continued

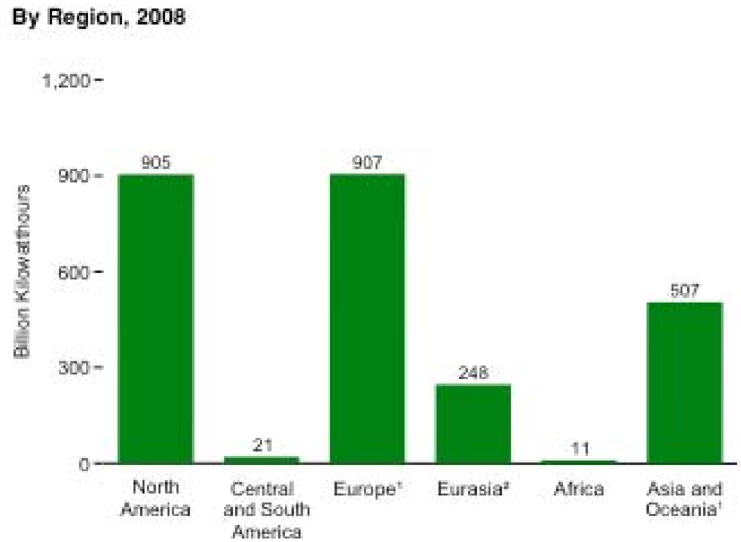
ASIA

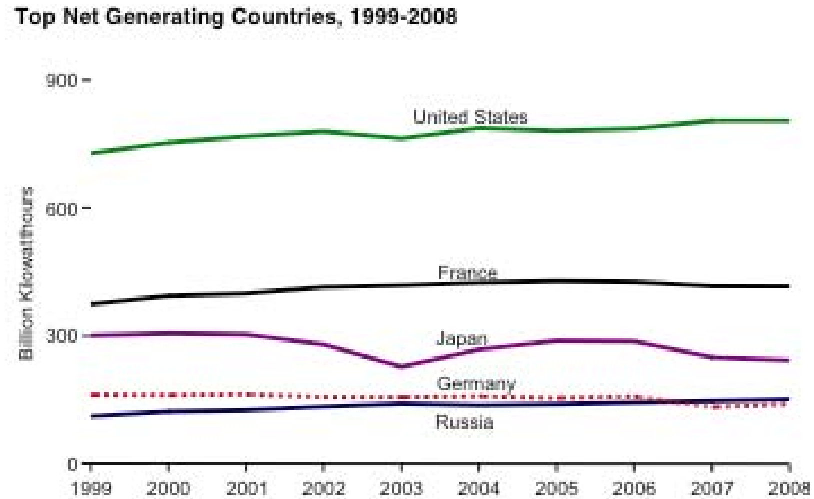
- China has 9 units under construction, 41 more planned
- Japan has 11 units planned and 2 units under construction; is in recovery from 7 units of TEPCO taken off-line following 2007 earthquake and are slowly returned to service
- South Korea has privatized KEPCO, is planning a new series of LWRs, has 6 units under construction and two planned
- Taiwan is completing 2 BWRs; nothing is planned beyond them

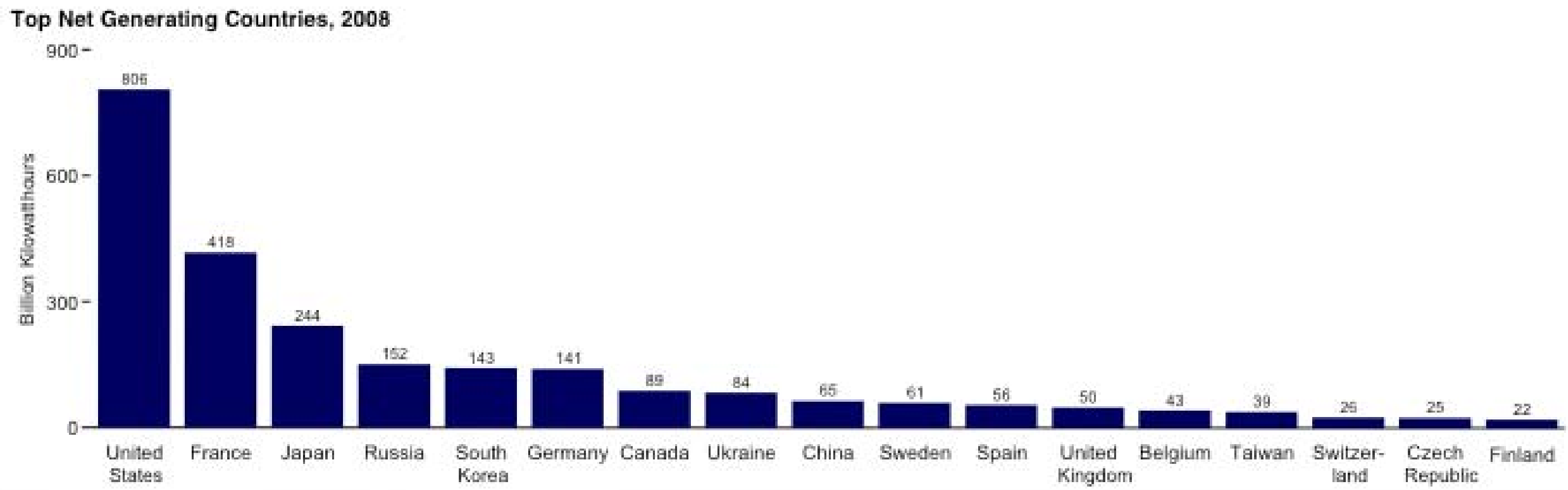
EMERGING NUCLEAR ENERGY COUNTRIES

- 45 Countries Considering New Nuclear Power Programs; some can be classified according to how far their plans have progressed
  - Iran: Power reactors under construction
  - UAE, Turkey: Contract signed, legal and regulatory infrastructure well-developed
  - Vietnam, Jordan, Italy: Committed plans, legal and regulatory infrastructure developing
  - Thailand, Indonesia, Egypt, Kazakhstan, Poland, Belarus, Lithuania: Well-developed plans but commitment pending
  - Saudi Arabia, Israel, Nigeria, Malaysia, Bangladesh, Morocco, Kuwait, Chile: Developing plans
  - Namibia, Kenya, Mongolia, Philippines, Singapore, Albania, Serbia, Estonia & Latvia, Libya, Algeria, Azerbaijan, Sri Lanka: Discussion as serious policy option
  - Australia, New Zealand, Portugal, Norway, Ireland: Officially not a policy option at present

WORLD NUCLEAR ELECTRICITY NET GENERATION







[1] Excludes countries that were part of the former U.S.S.R. See "Union of Soviet Socialist Republics (U.S.S.R.)" in Glossary.

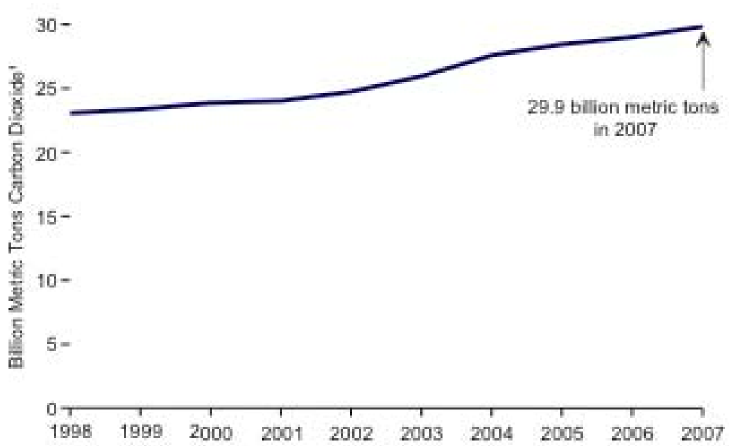
[2] Includes only countries that were part of the former U.S.S.R. See "Union of Soviet Socialist Republics (U.S.S.R.)" in Glossary.

Source: Table 11.18

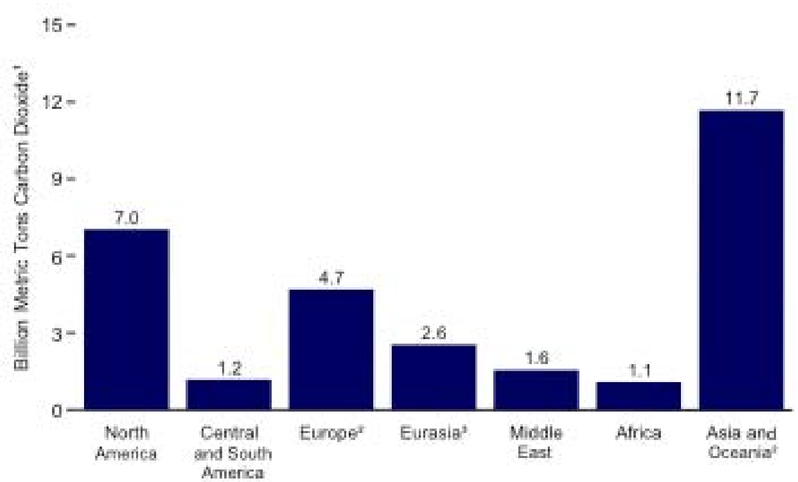
Energy Information Administration / Annual Energy Review 2009; http://www.eia.gov/emeu/aer/inter.html

WORLD CARBON DIOXIDE EMISSIONS FROM ENERGY CONSUMPTION

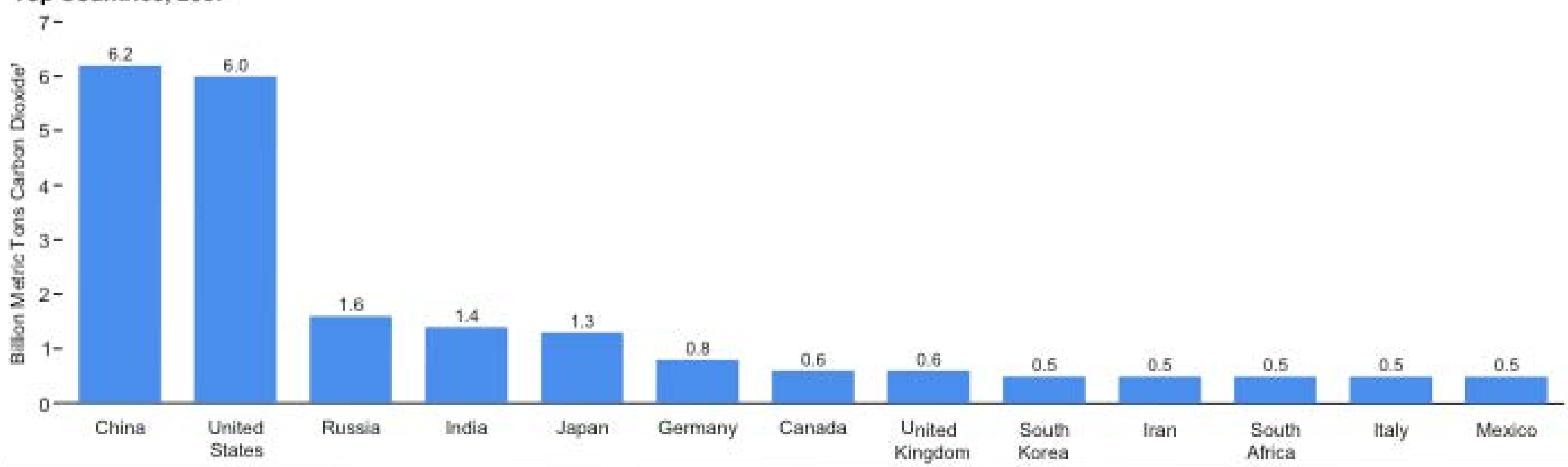
World, 1998-2007



World by Region, 2007



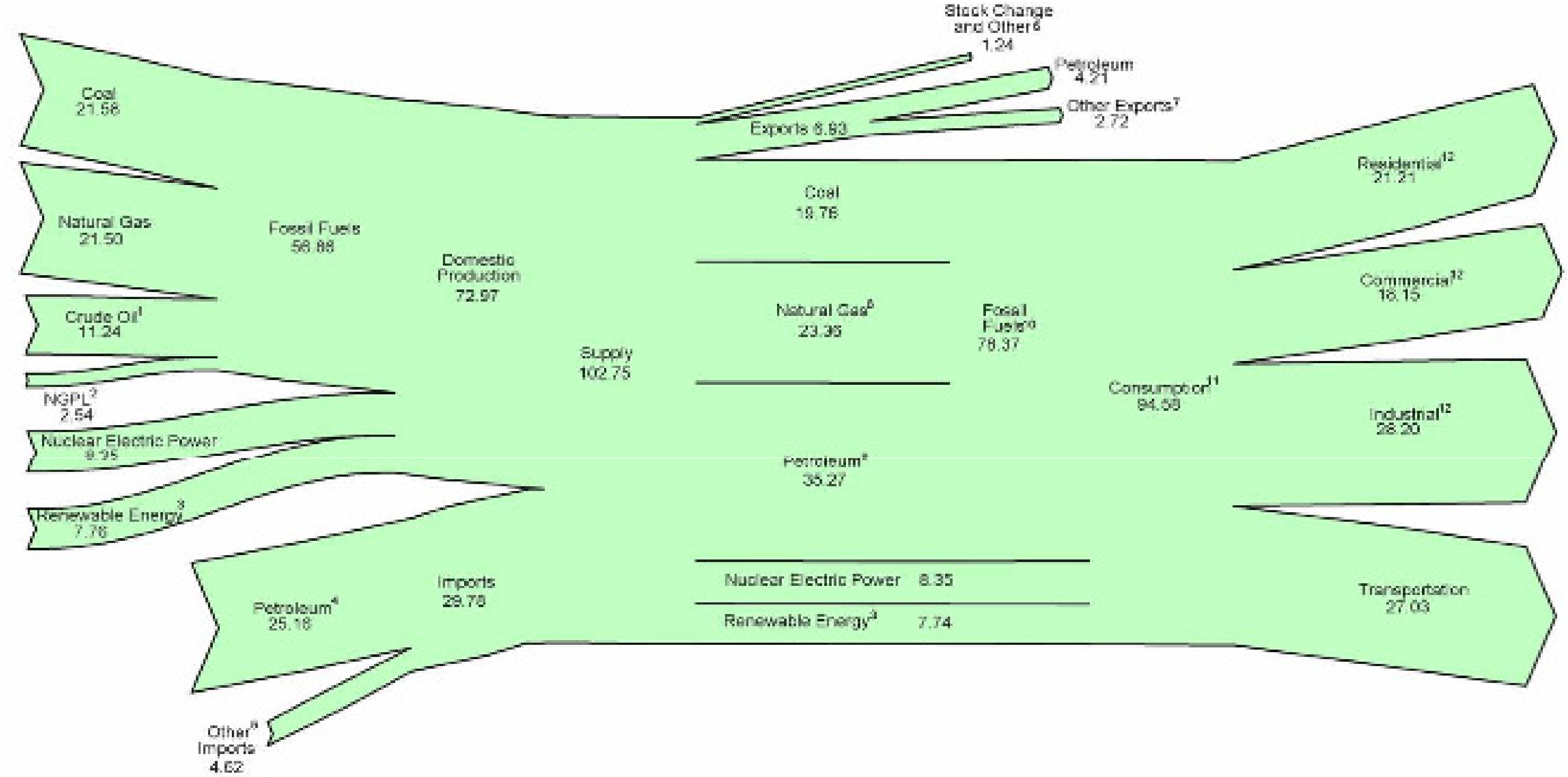
Top Countries, 2007



[1] Metric tons of carbon dioxide can be converted to metric tons of carbon equivalent by multiplying by 12/44.
[2] Excludes countries that were part of the former U.S.S.R. See "Union of Soviet Socialist Republics (U.S.S.R.)" in Glossary.
[3] Includes countries that were part of the former U.S.S.R. See "Union of Soviet Socialist Republics (U.S.S.R.)" in Glossary.
Note: Data include carbon dioxide emissions from fossil-fuel energy consumption and natural gas venting and flaring.
Source: Table 11.19.

Energy Information Administration / Annual Energy Review 2009;
http://www.eia.gov/emeu/aer/inter.html

ENERGY FLOW, 2009 (Quadrillion Btu)

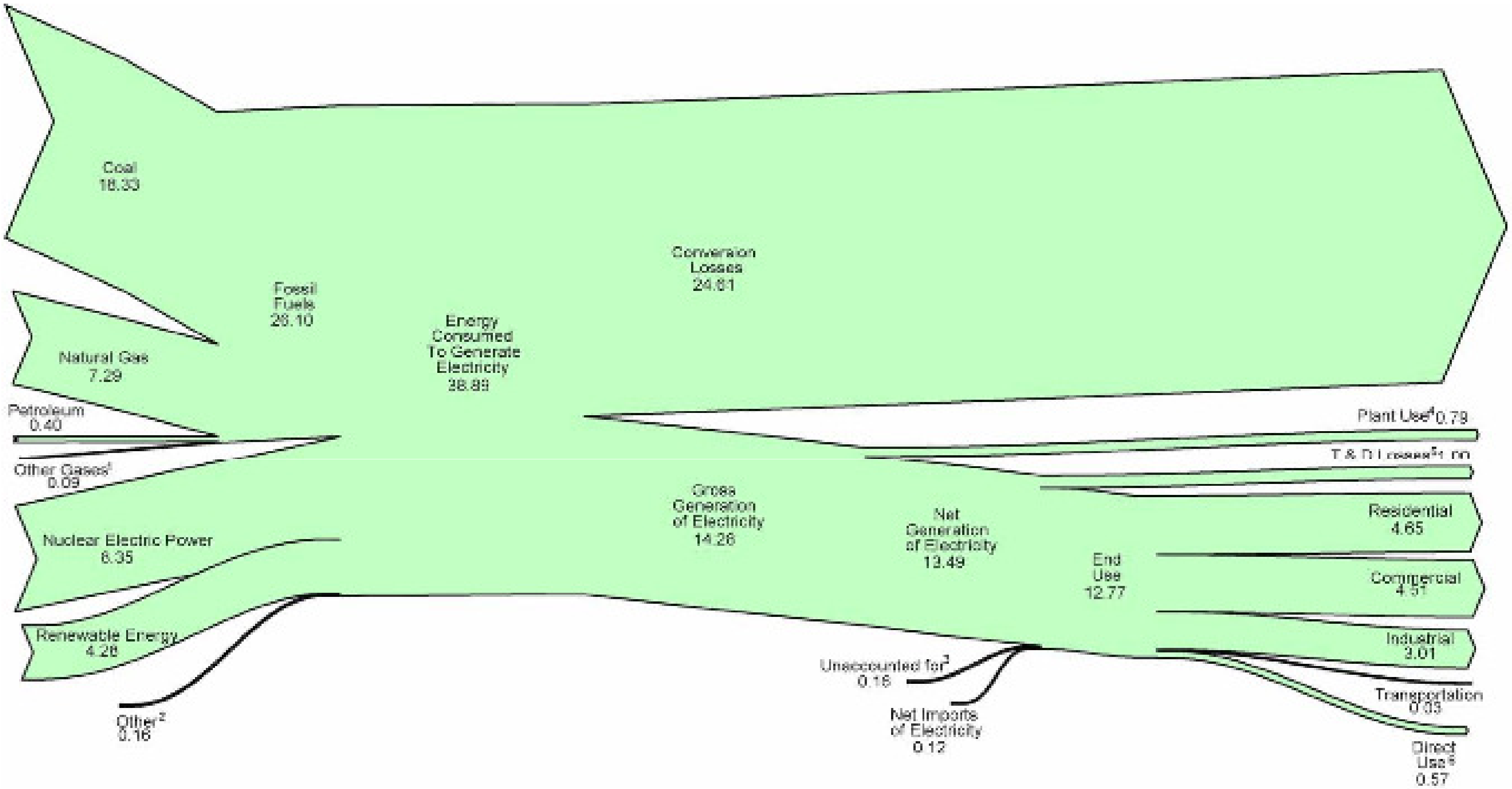


[1] Includes lease condensate.
[2] Natural gas plant liquids.
[3] Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.
[4] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[5] Natural gas, coal, coal coke, biofuels, and electricity.
[6] Adjustments, losses, and unaccounted for.
[7] Coal, natural gas, coal coke, electricity, and biofuels.
[8] Natural gas only; excludes supplemental gaseous fuels.
[9] Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.
[10] Includes 0.02 quadrillion Btu of coal coke net exports.
[11] Includes 0.12 quadrillion Btu of electricity net imports.
[12] Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.

ELECTRICITY FLOW, 2009 (Quadrillion Btu)



[1] Blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

[2] Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, miscellaneous technologies, and non-renewable waste (municipal solid waste from non-biogenic sources, and tire-derived fuels).

[3] Data collection frame differences and nonsampling error. Derived for the diagram by subtracting the "T & D Losses" estimate from "T & D Losses and Unaccounted for" derived from Table 8.1.

[4] Electric energy used in the operation of power plants.

[5] Transmission and distribution losses (electricity losses that occur between the point of generation and delivery to the customer) are estimated as 7 percent of gross generation.

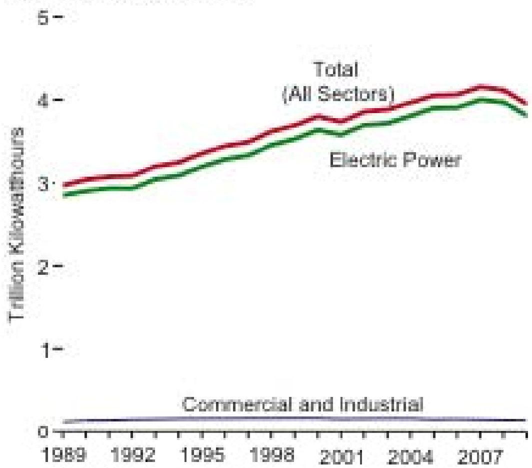
[6] Use of electricity that is 1) self-generated, 2) produced by either the same entity that consumes the power or an affiliate, and 3) used in direct support of a service or industrial process located within the same facility or group of facilities that house the generating equipment. Direct use is exclusive of station use.

Notes: • Data are preliminary. • See Note, "Electrical System Energy Losses," at the end of Section 2. • Net generation of electricity includes pumped storage facility production minus energy used for pumping. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

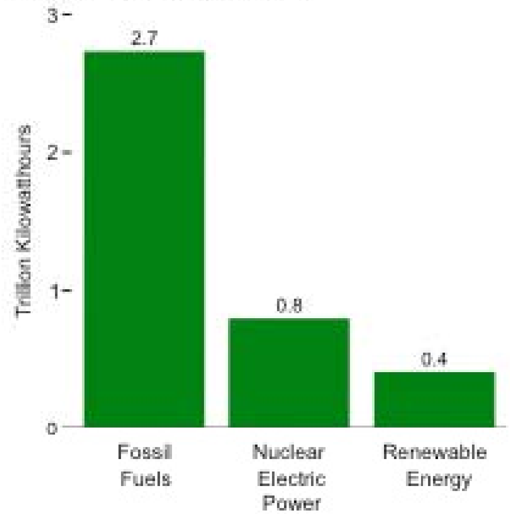
Sources: Tables 8.1, 8.4a, 8.9, A6 (column 4), and U.S. Energy Information Administration, Form EIA-923, "Power Plant Operations Report."

ELECTRICITY NET GENERATION, TOTAL (ALL SECTORS)

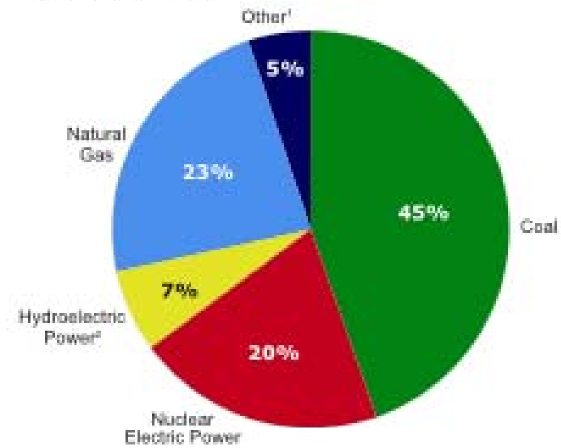
By Sector, 1989-2009



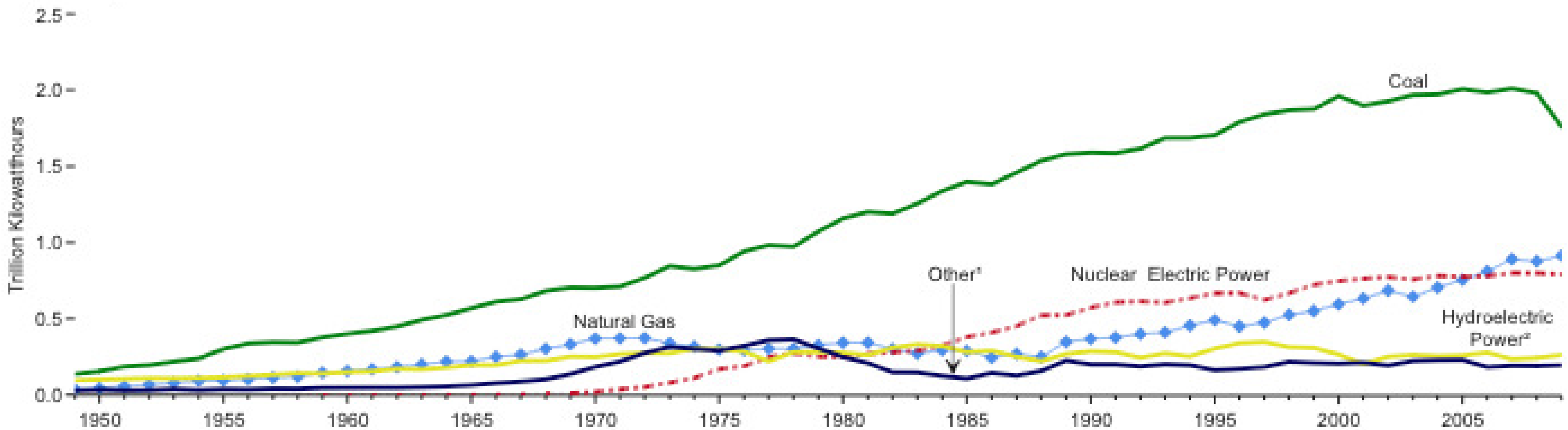
By Source Category, 2009



By Source, 2009



By Source, 1949-2009



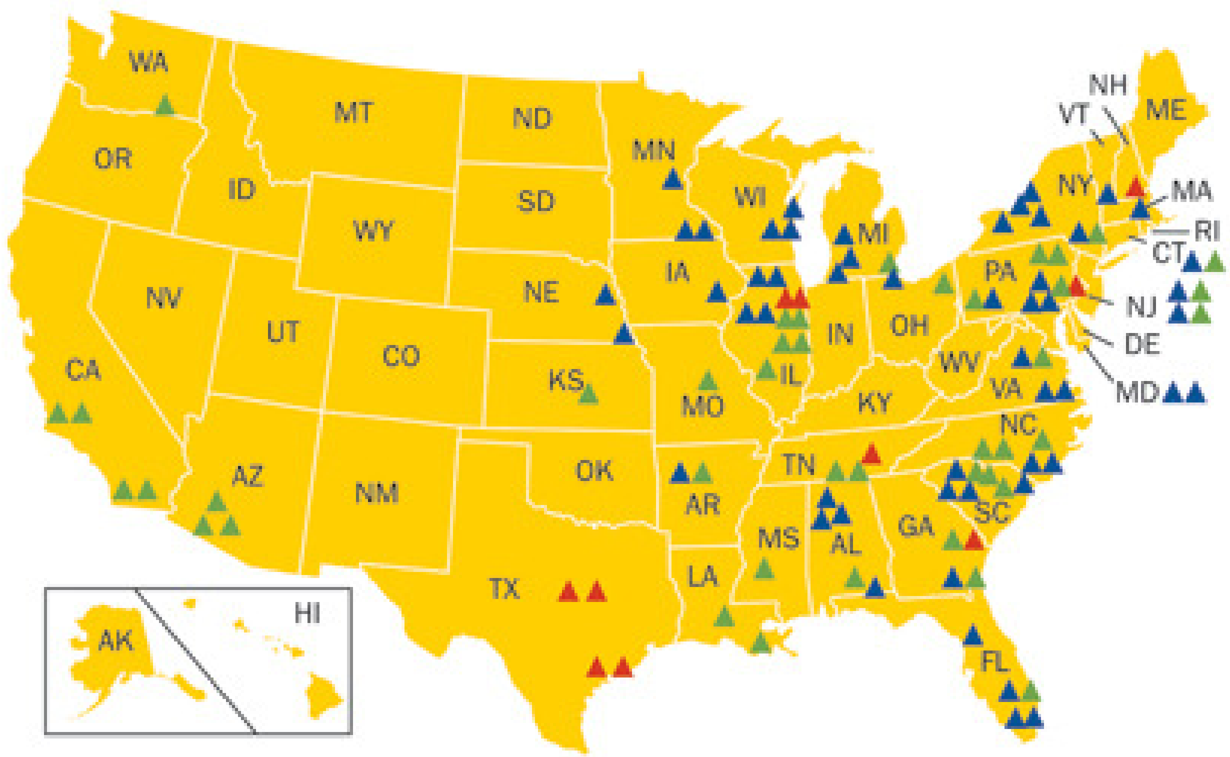
[1] Wind, petroleum, wood, waste, geothermal, other gases, solar thermal and photovoltaic, batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, miscellaneous technologies, and non-renewable waste (municipal solid waste from non-biogenic sources, and tire-derived fuels).

[2] Conventional hydroelectric power and pumped storage.
Sources: Tables 8.2a, 8.2b, and 8.2d.

Energy Information Administration / Annual Energy Review 2009: http://www.eia.doe.gov/emeu/aer/elect.html

NUCLEAR GENERATING UNITS

U.S. Commercial Nuclear Power Reactors—Years of Operation



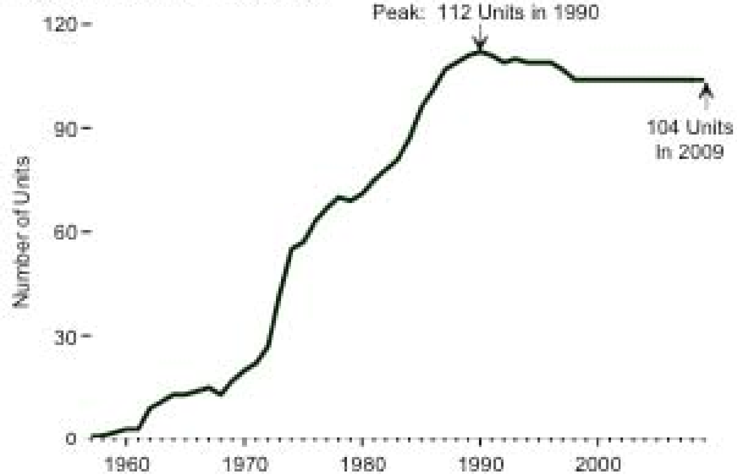
Years of Commercial Operation	Number of Reactors
△ 0-9	0
▲ 10-19	10
▲ 20-29	42
▲ 30-39	52

Source: U.S. Nuclear Regulatory Commission

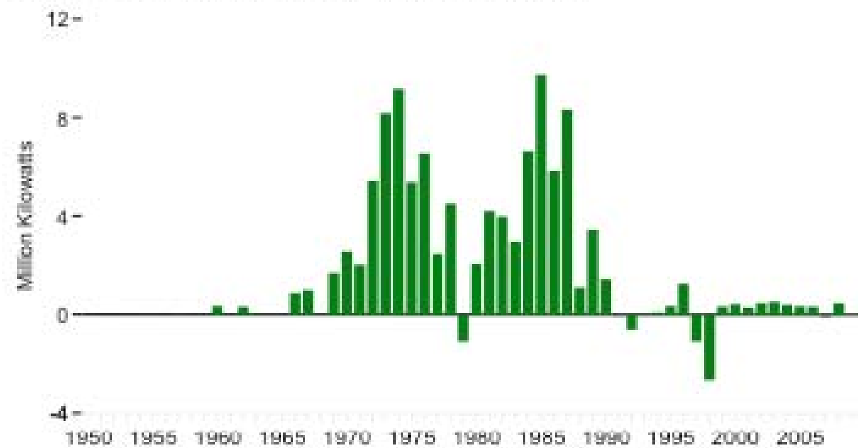
http://www.nrc.gov/reactors/operating/map-power-reactors.html

NUCLEAR GENERATING UNITS

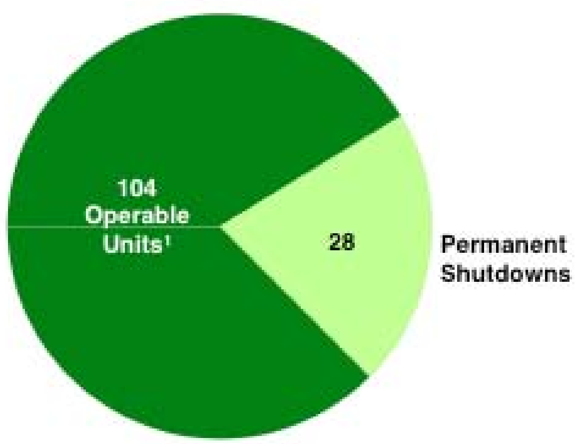
Operable Units,[1] 1957-2009



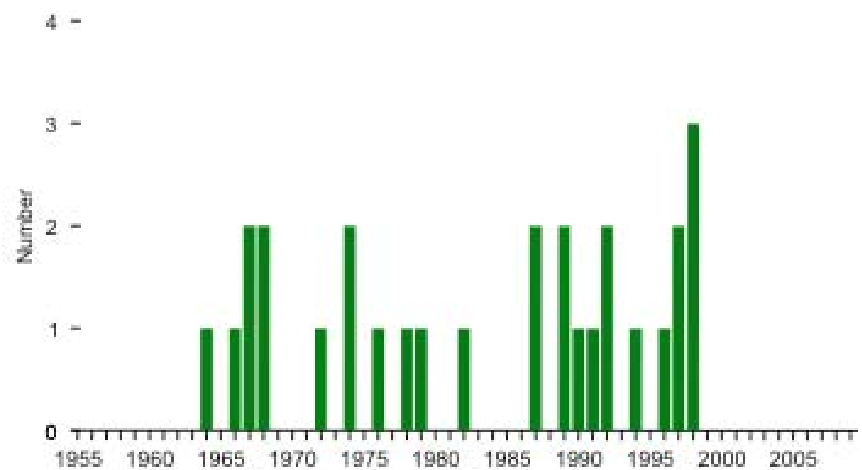
Nuclear Net Summer Capacity Change, 1950-2009



Status of All Nuclear Generating Units, 2009



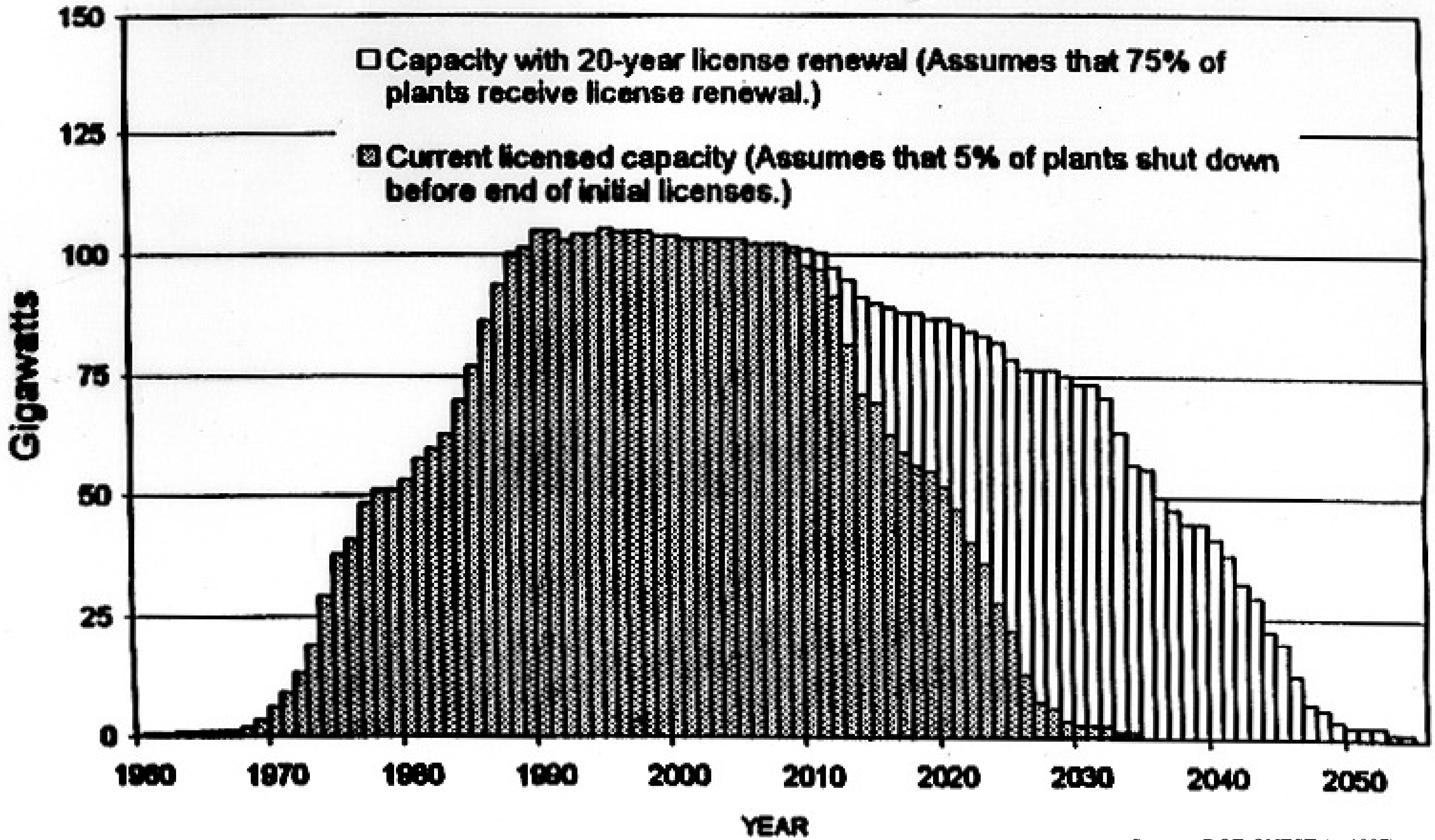
Permanent Shutdowns by Year, 1955-2009



[1] Units holding full-power operating licenses, or equivalent permission to operate, at the end of the year.

Note: Data are at end of year.
Sources: Tables 9.1 and 8.11a.

HISTORICAL AND PROJECTED US NUCLEAR ELECTRIC GENERATION CAPACITY, 1960-2055



Source: DOE-ONEST (c. 1997).

Fig. 5.3 in "Report to the President on Federal Energy Research and Development for the 21st Century."
President's Committee of Advisors on Science and Technology, Panel on Energy Research and Development, November 1997.

EXISTING USA NUCLEAR POWER INDUSTRY

Utilities

- Power capacity increases continuing
- Operating record is good but not improving
- Restructuring of economic regulation has stalled
- Consolidation has slowed
  - Exelon-PSEG merger failed
  - Constellation-FPL merger failed
- Plant purchases have stopped
- Restructuring of economic regulation has stalled

NRC Office of New Reactors

- Reactor oversight process continues in force
- Risk-informed regulation has stalled
- 17 new plant licenses under application for 28 reactors
- Three new plants being built

Vendors

- General Electric
  - In alliance with Hitachi
  - Nuclear operations are now in North Carolina
  - ESBWR cancelled
- Westinghouse purchased by Toshiba (who also make BWRs)
- Areva in alliance with Constellation Energy, EDF, Mitsubishi in UniStar
- Mitsubishi entering US market

OTHER PROJECTS

- Yucca Mountain HLW Repository (in Nevada)
  - License application submitted 2008, effectively withdrawn 2010
  - Earliest opening 2020
  - Will federal government take back spent fuel?
    - Several successful utility lawsuits
- Private Fuel Storage Interim Facility (in Utah) approved
  - Transportation access blocked
- Louisiana Enrichment Services (in New Mexico)
  - Urenco, Areva
- U.S. Enrichment Corp. (USEC) (in Ohio)
- Mixed Oxide (UO_2, PuO_2) Fuel Fabrication Plant (in Savannah River, South Carolina)

PLAUSIBLE TRENDS IN REACTOR TECHNOLOGY EVOLUTION

CURRENT/SHORT TERM

Light Water Reactors (LWRs)

- Pressurized Water Reactor (PWR)
- Boiling Water Reactor (BWR)

Heavy Water Reactor (PHWR)

- Pressurized Heavy Water Reactor (CANDU)

INTERMEDIATE TERM (>20 years)

Brayton Cycle Gas (He or CO_2) Cooled Reactor (GCR-GT)

LONG TERM (>50 years)

Fast Breeder ($^{238}U \Rightarrow {}^{239}Pu$-based)

Thermal Breeder ($^{232}Th \Rightarrow {}^{233}U$-based)

MHTGR SIDE-BY-SIDE ARRANGEMENT WITH PRISMATIC FUEL

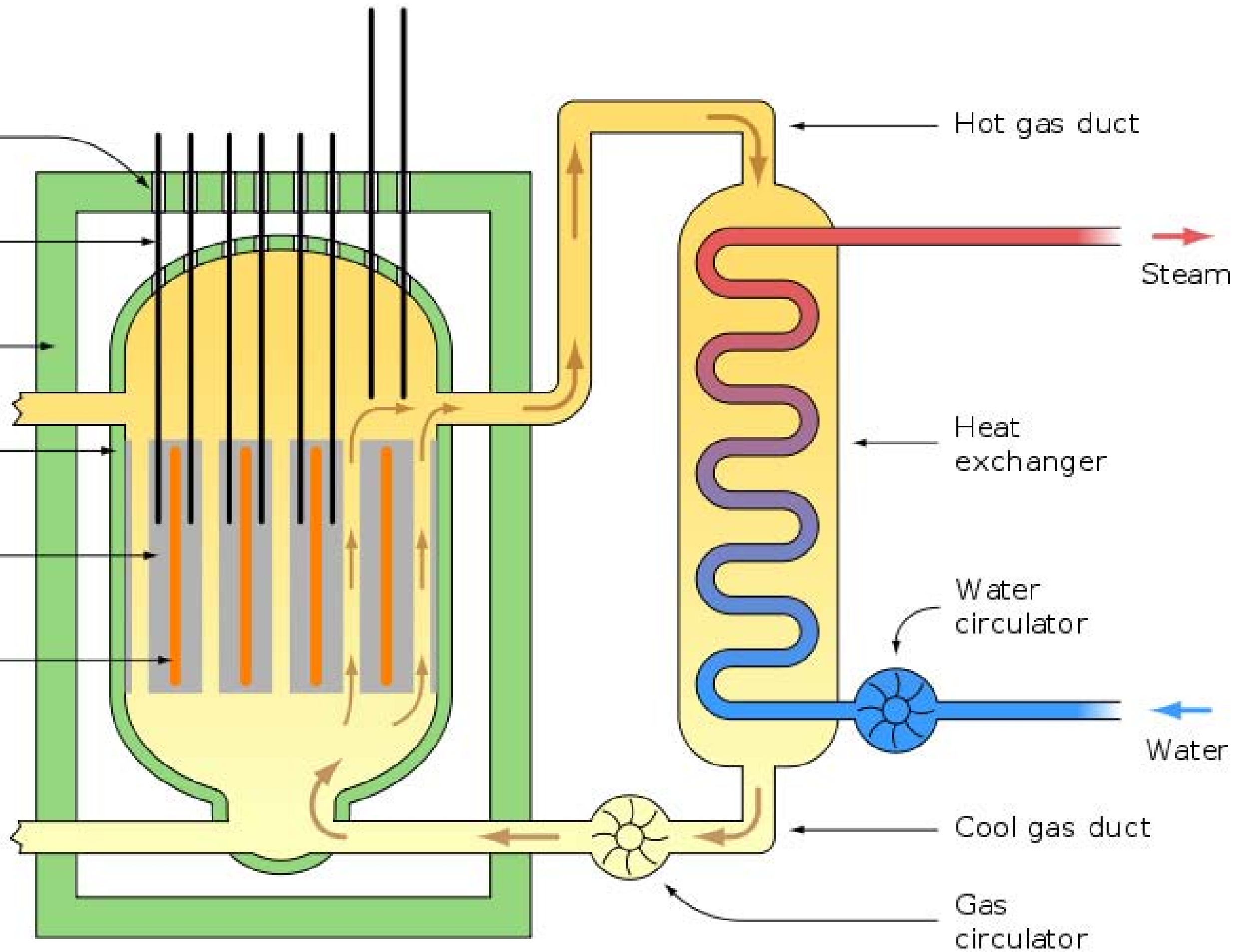


Image by Emoscopes on Wikimedia Commons.

FACTORS LIKELY TO AFFECT FUTURE USE OF NUCLEAR POWER

Operational Safety Record

Utility, Critical Elite, Public, Investor Attitudes

End of Cold War

Degree of Nuclear Weapons Proliferation

Nuclear Waste Disposal Success

Global Warming and Air Pollution Worries

Ability of Nuclear Power to Produce More than Electricity

22.081J / 2.650J / 10.291J / 1.818J / 2.65J / 10.391J / 11.371J / 22.811J / ESD.166J
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Fall 2010