EML 4930/EML 5930 Sustainable Energy Conversion Systems II

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Course Objectives

This course is aimed at providing the necessary knowledge to design power systems that use the direct conversion of sun light into electricity.

The emphasis will be on solar electric power systems for distributed applications. The use of photovoltaics, electrolytic hydrogen production and storage, fuel cells and power control systems in greenhouse gas emissions free energy production strategies are discussed. Strategies that promote greater efficiency of use will also be discussed.

Attention will be paid to systems engineering that include the economics of solar electric power systems installations.

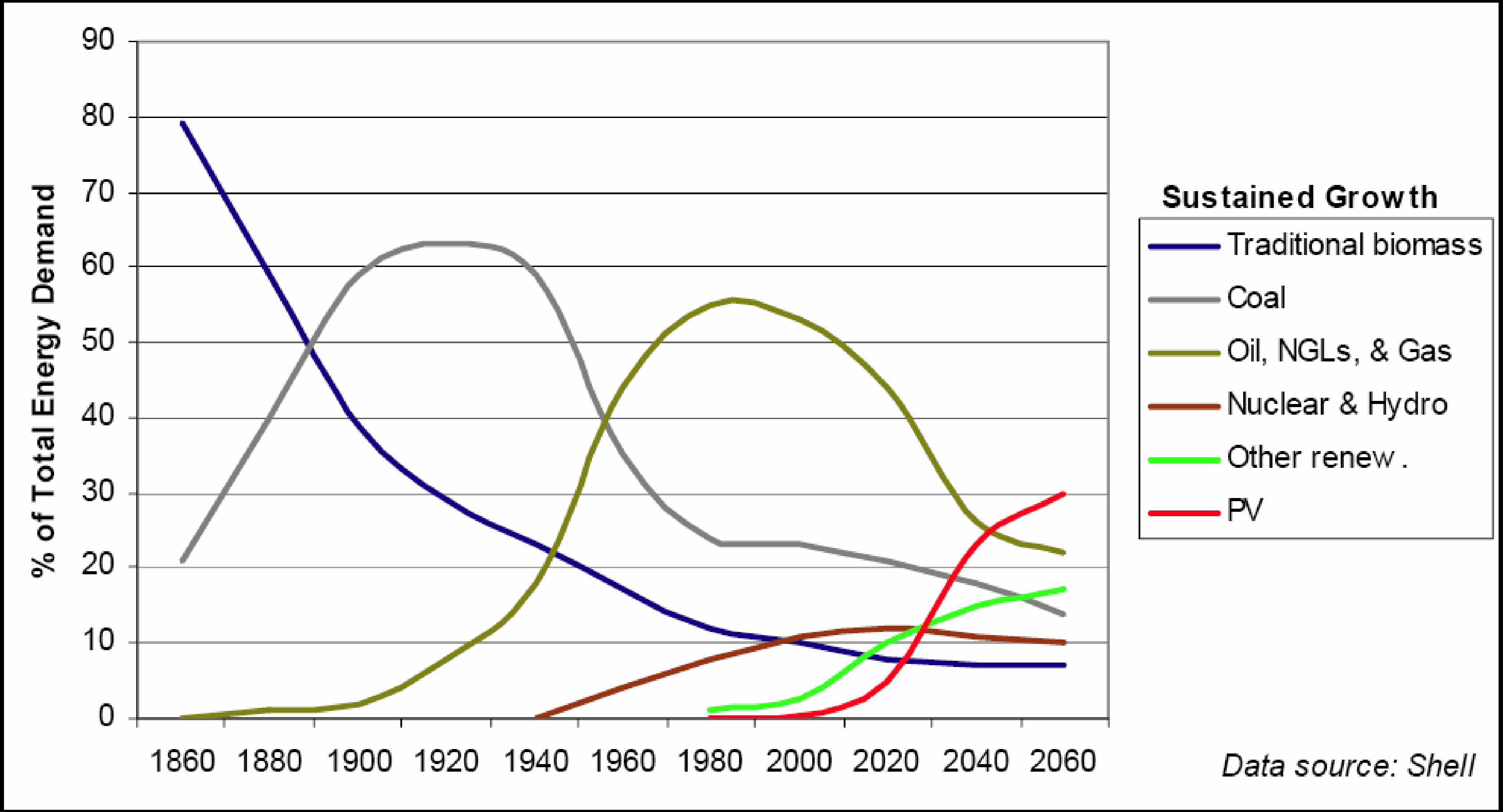
Laboratory experiments consisting of: solar cell characterization; photovoltaic system performance measurement and analysis; solar concentrator cogeneration system characterization and Proton Exchange Membranes (PEM) hydrogen fuel cell characterization.

A final project consisting of a design of 2.5 kW solar electricity generation system.

Topics

1. Electricity & sustainability
2. Solar radiation
3. Solar cells
4. Photovoltaic systems engineering
5. Concentrating solar collectors
6. Solar-thermal systems
7. Hydrogen production
8. Energy storage
9. Hydrogen handling & safety
10. Hydrogen use - fuel cells
11. Hydrogen based transportation
12. Socio-economic assessment of solar-hydrogen energy supply system

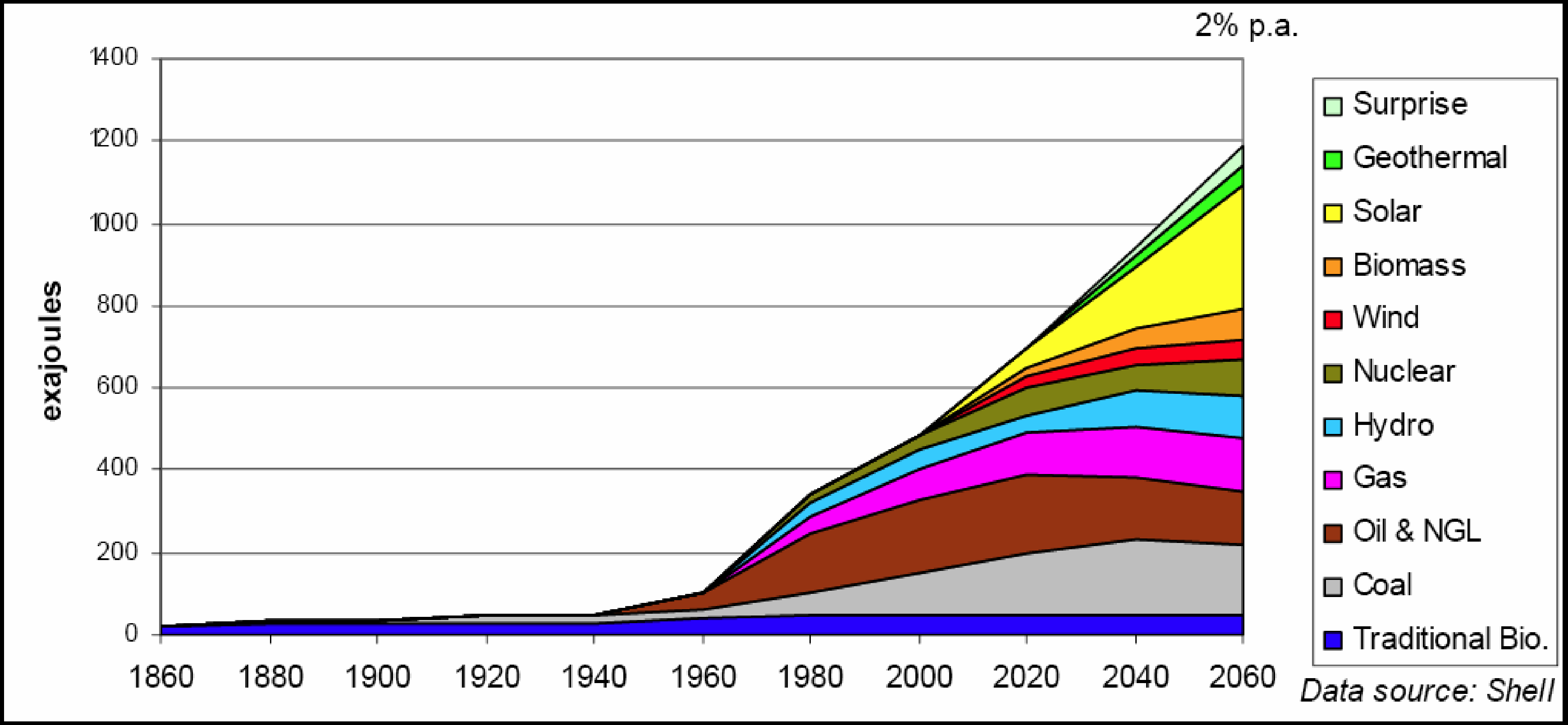
Energy Market Share



World use: 10 TW (US: 3 TW) -2004

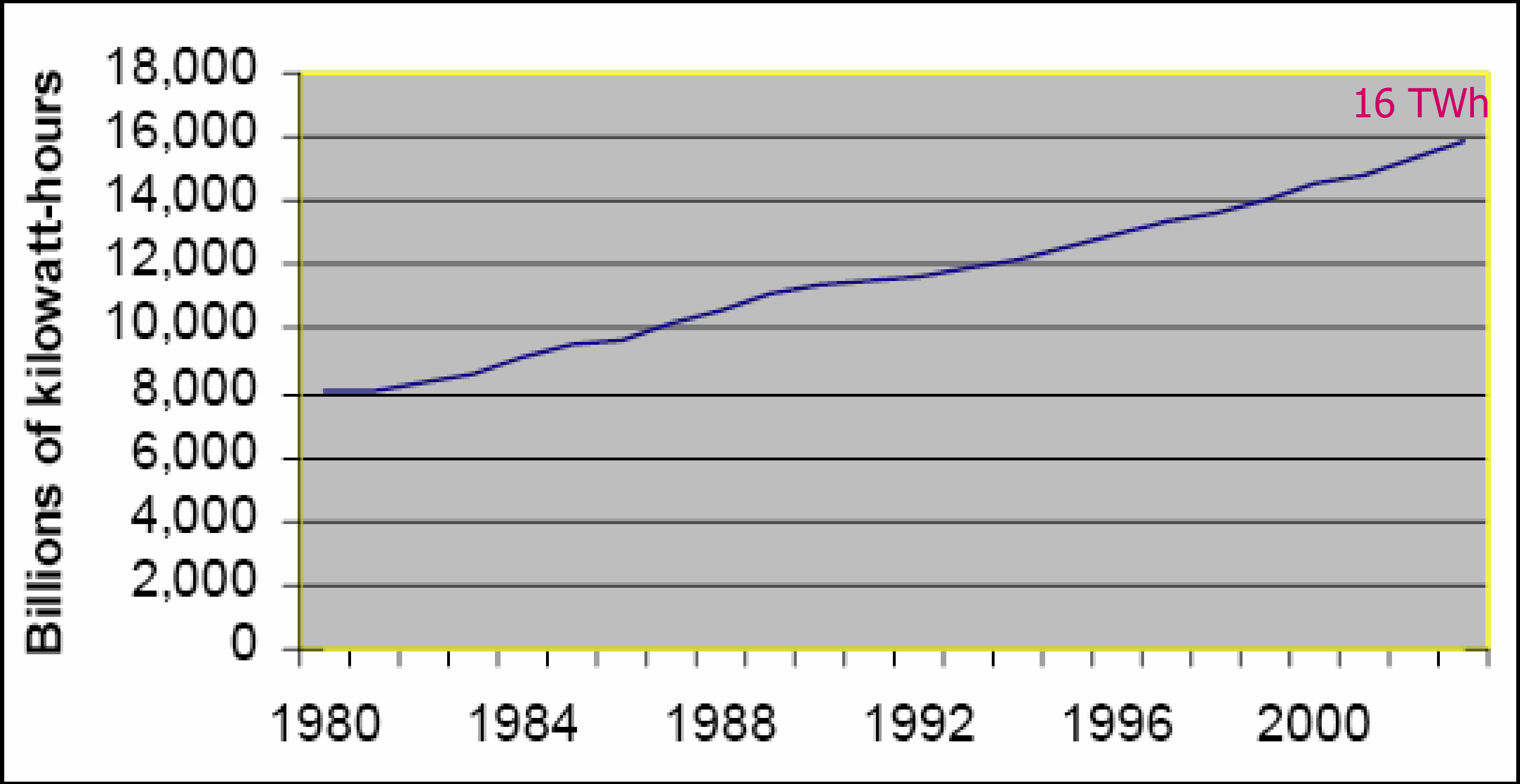
World use: 30 TW -2050 (projected ?)

Changing Energy Mix



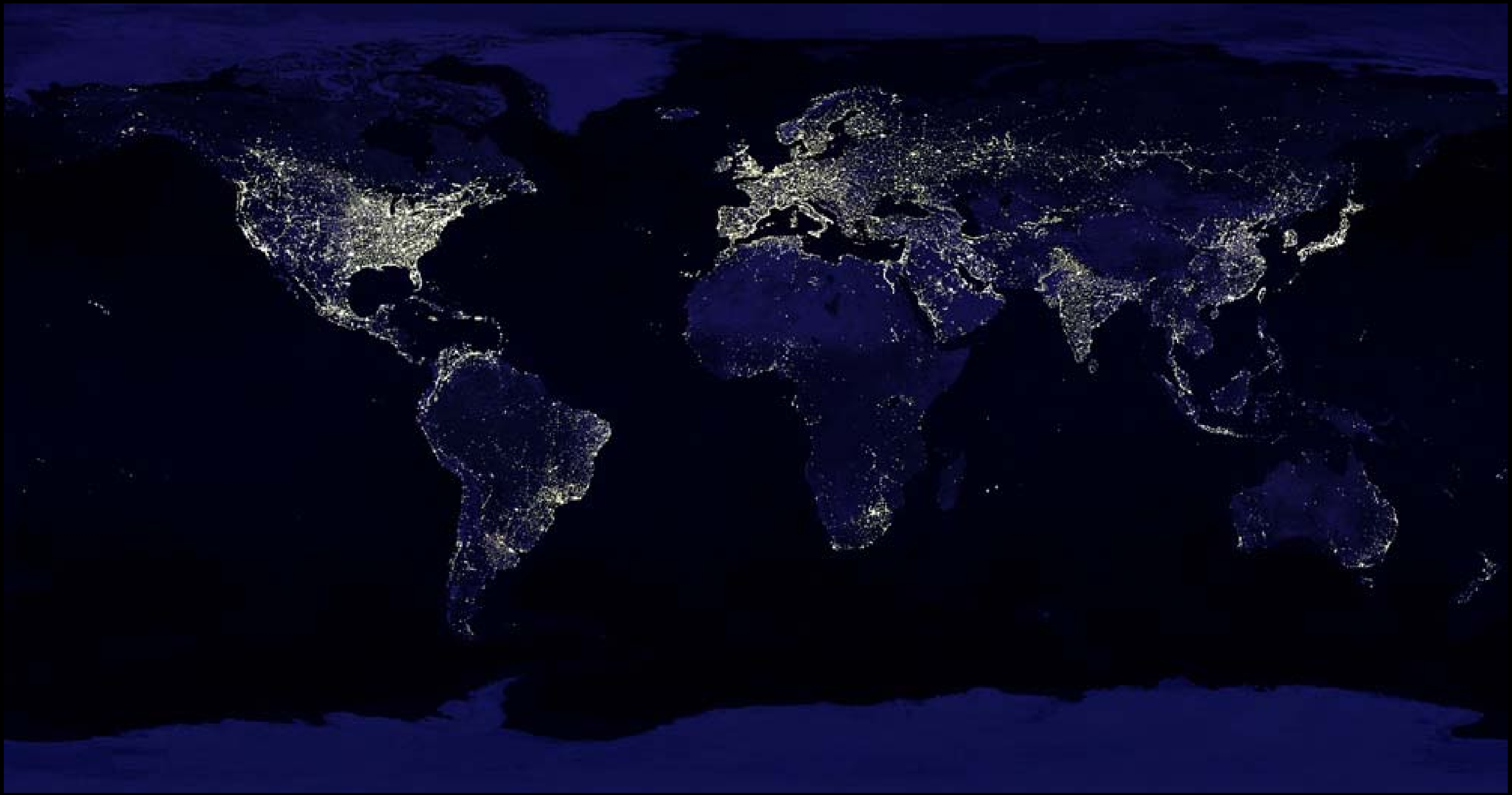
1 EJ= 278 TWh

Global Electricity Production

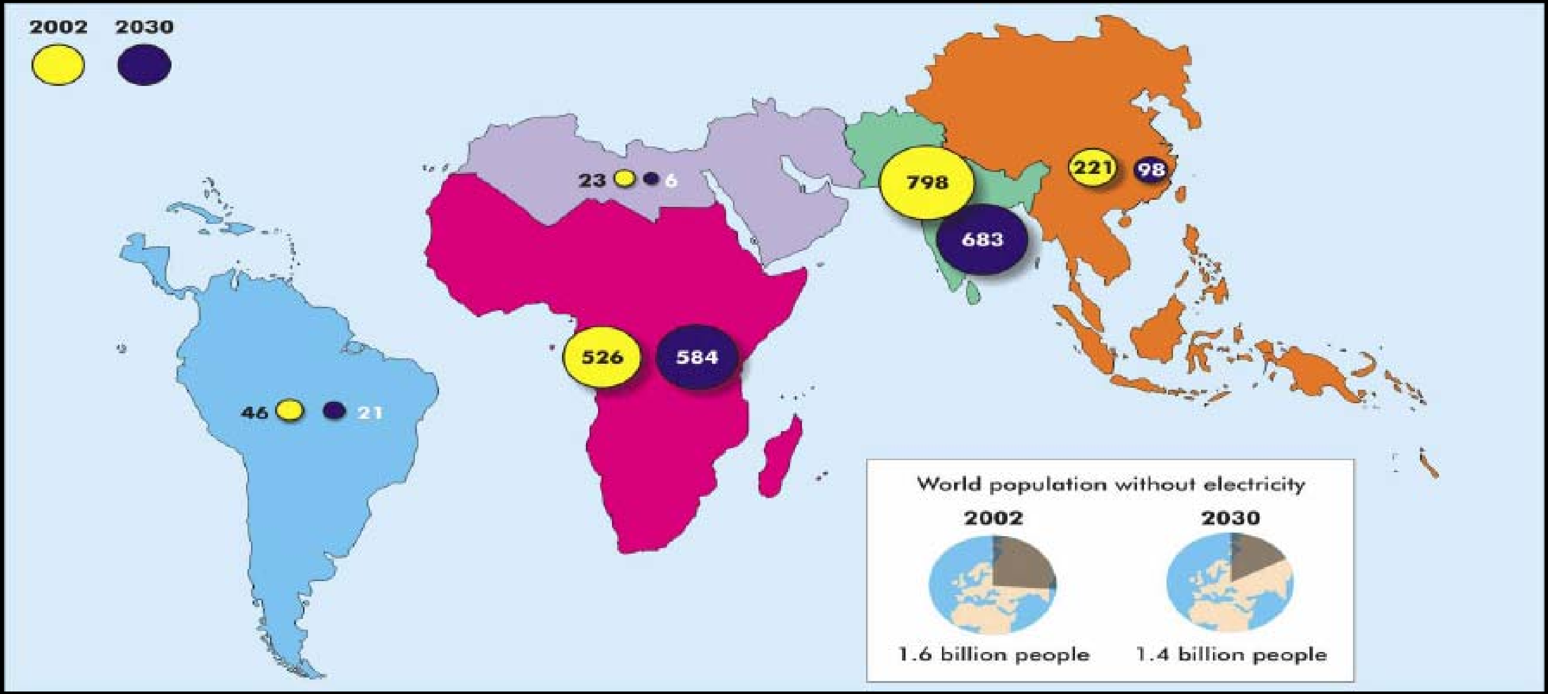


Sustainable Energy Science and Engineering Center

Global Electricity Consumption



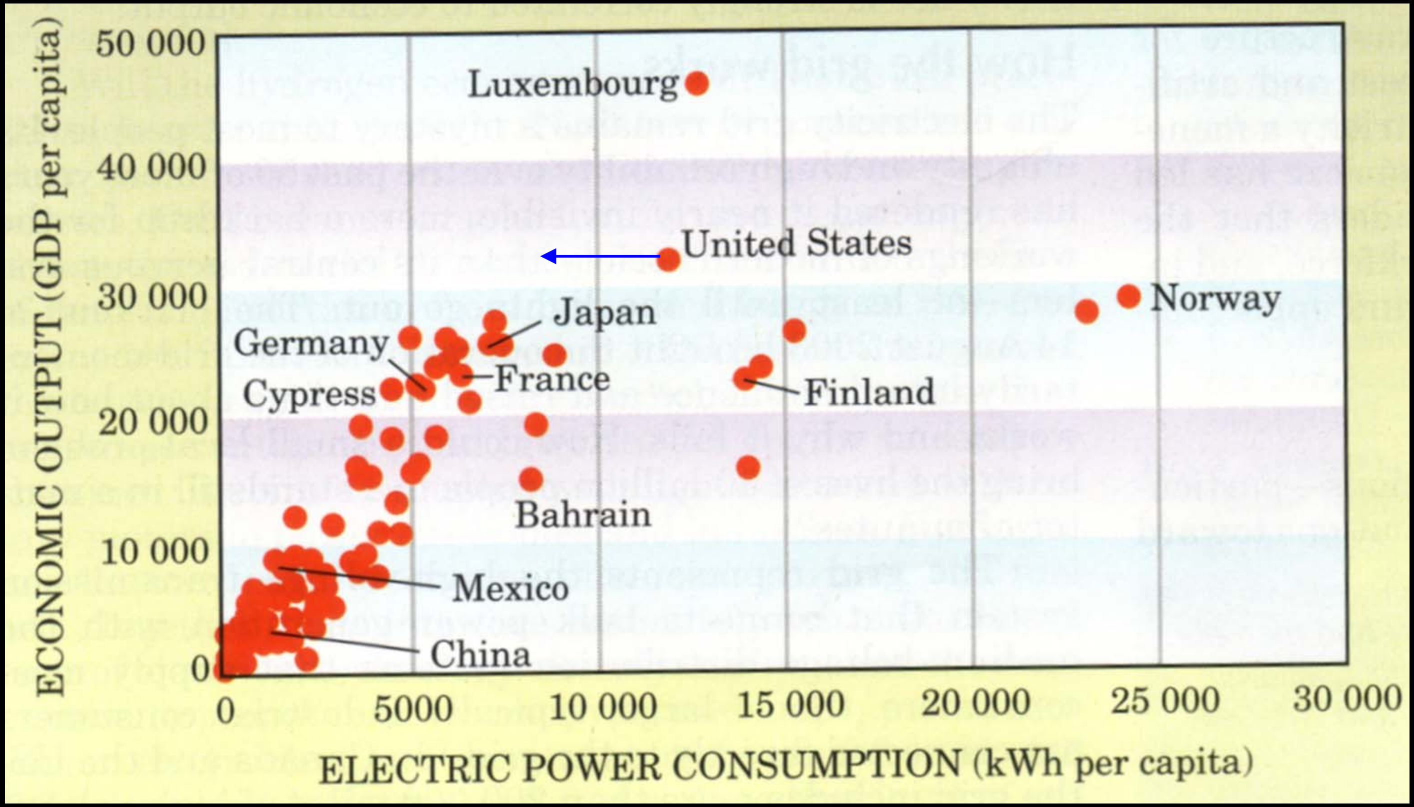
Population Without Electricity



Indicator of Human Welfare	Commercial Share of Total Energy 0-20 %	21-40 %	41-100 %
Life Expectancy (Years)	59.8	69.0	69.5
Probability of not surviving to 40	21.7	9.4	9.1
School Enrollment (%)	52.4	65.4	76.9
Children Underweight (%)	40.9	15.1	11.9
No Access to Clean Water (%)	20.9	22.8	12.8

Source: World Energy Council, Cleaner Fossil Fuels Systems Committee

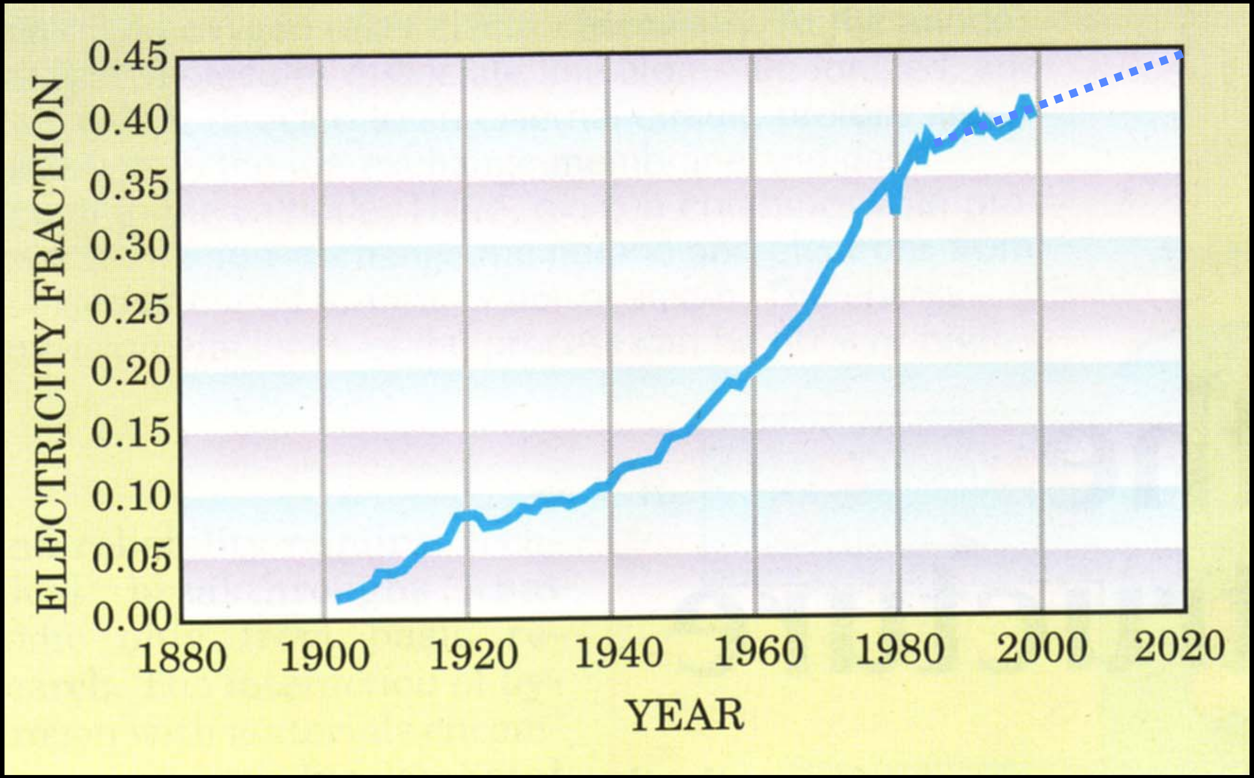
Economic Output



Wider use of electricity will lead to wider use of carbon intensive coal

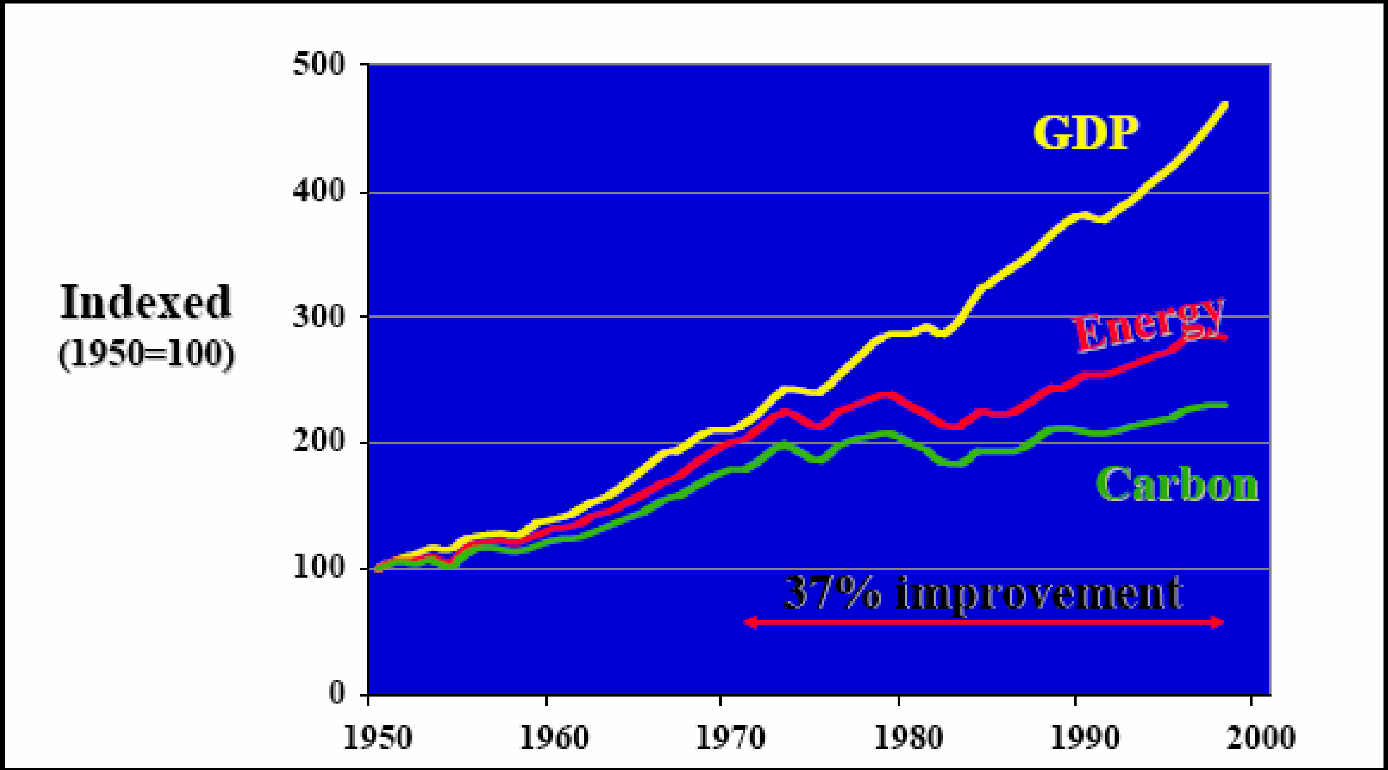
Source: Transforming the electricity infrastructure by Gellings & Yeager, Physics Today, December 2004.

US Energy Need



Source: Transforming the electricity infrastructure by Gellings & Yeager, Physics Today, December 2004.

US Efficiency Improvement

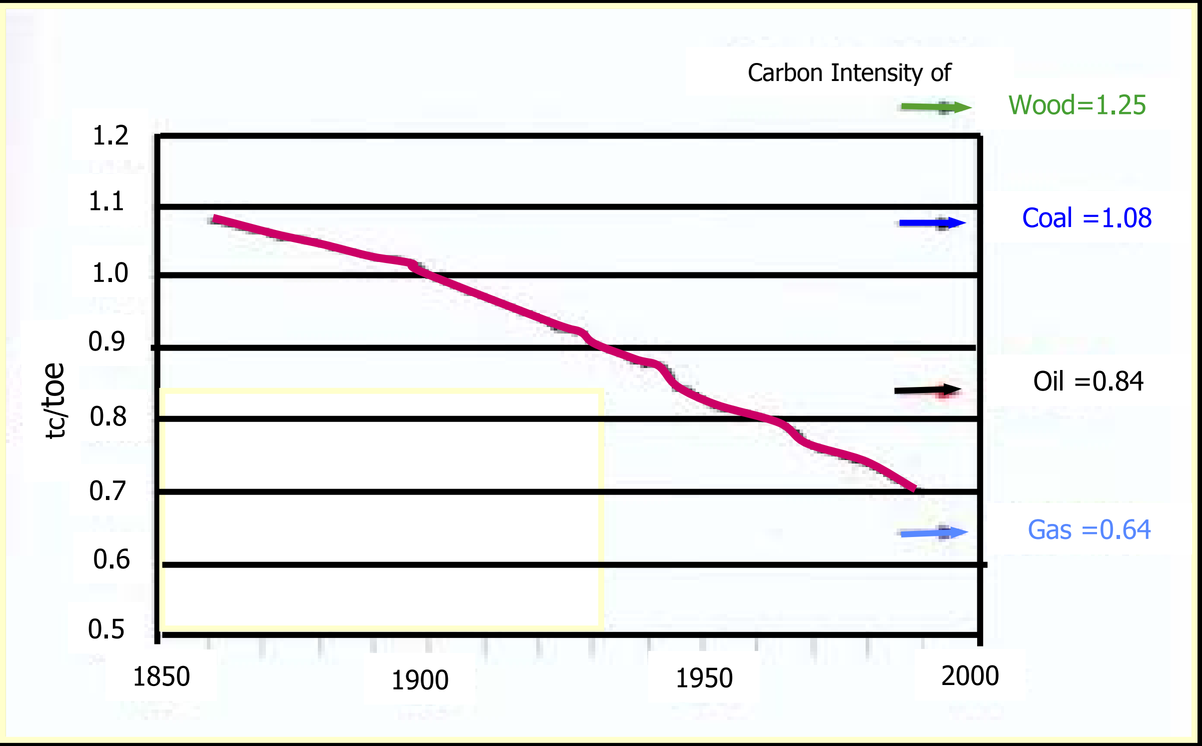


Since 1990, savings > $170 billion annually

Source: Daniel Kammen, UC Berkeley, ER 100 Lecture 2, Fall 2005

Carbon Intensity

tones of carbon / tones of oil equivalent



Global emissions are 16 gC/MJ and global use is 420 EJ ⟶ 7 GT (C)

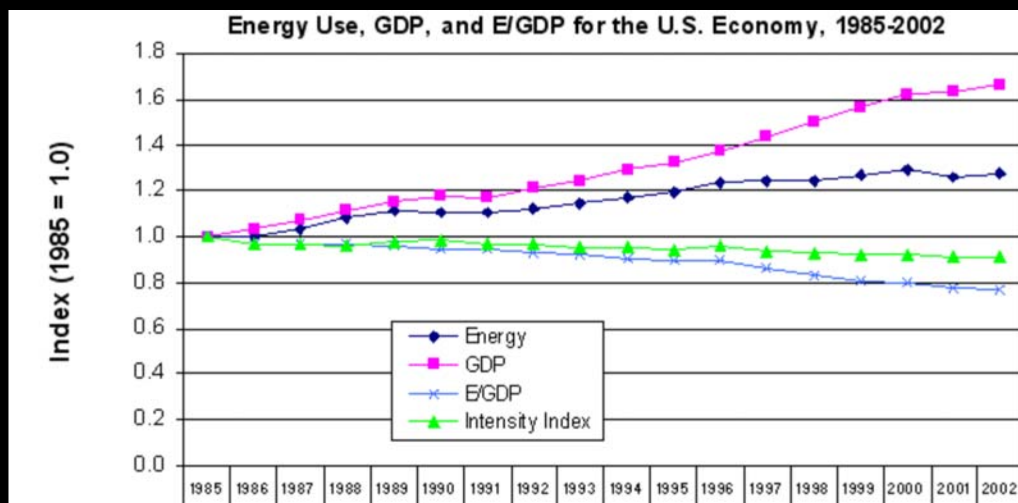
Source: Daniel Kammen, UC Berkeley, ER 100 Lecture 3, Fall 2005

Energy Intensity & Efficiency

Energy Intensity: quantity of energy required per unit output (e.g. GDP)

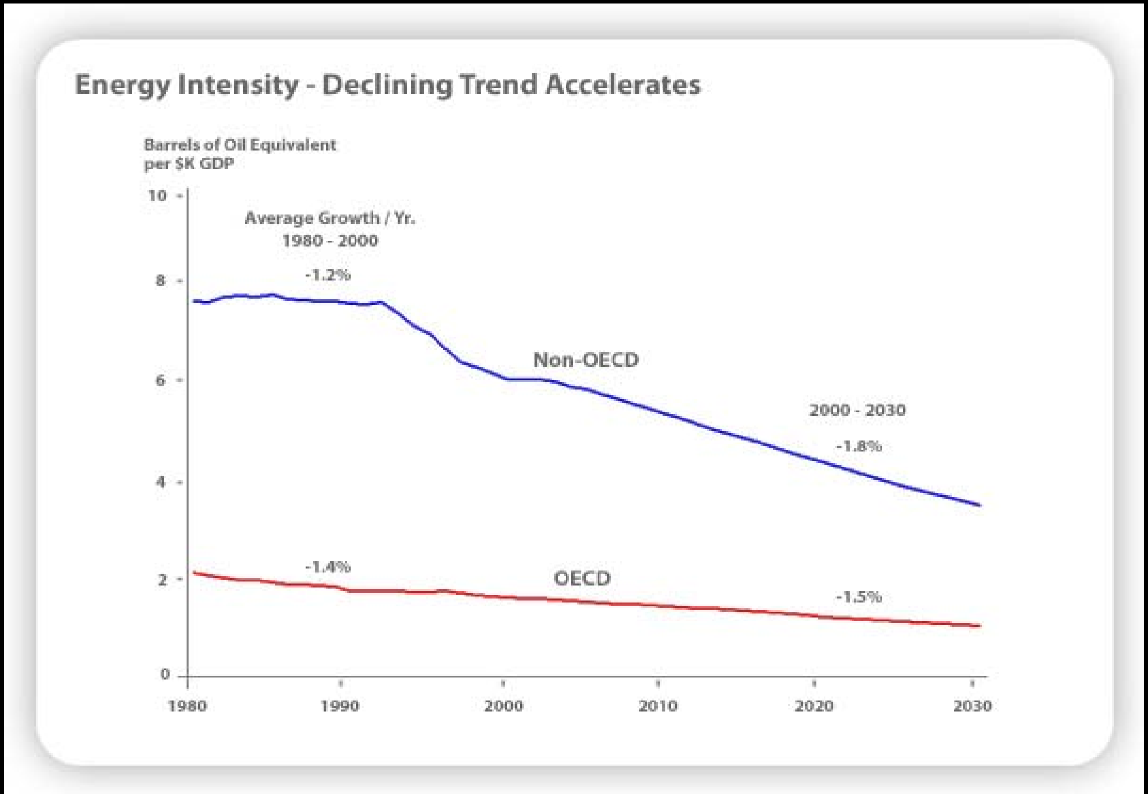
Energy Efficiency: a given level of service is provided with reduced amounts of energy

Efficiency improvements in processes and equipment can contribute to decreases in energy intensity.



	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Energy	1.00	1.00	1.04	1.08	1.11	1.11	1.11	1.12	1.15	1.17	1.19	1.23	1.24	1.25	1.27	1.29	1.26	1.27
GDP	1.00	1.03	1.07	1.11	1.15	1.17	1.17	1.21	1.24	1.29	1.33	1.38	1.44	1.50	1.56	1.62	1.63	1.67
E/GDP	1.00	0.97	0.97	0.97	0.96	0.94	0.94	0.93	0.92	0.90	0.90	0.90	0.86	0.83	0.81	0.80	0.77	0.76
Intensity Index	1.00	0.97	0.97	0.96	0.98	0.98	0.97	0.97	0.96	0.95	0.95	0.96	0.94	0.93	0.92	0.92	0.91	0.91

Energy Intensity



This chart shows the energy required to generate $1000 of GDP.

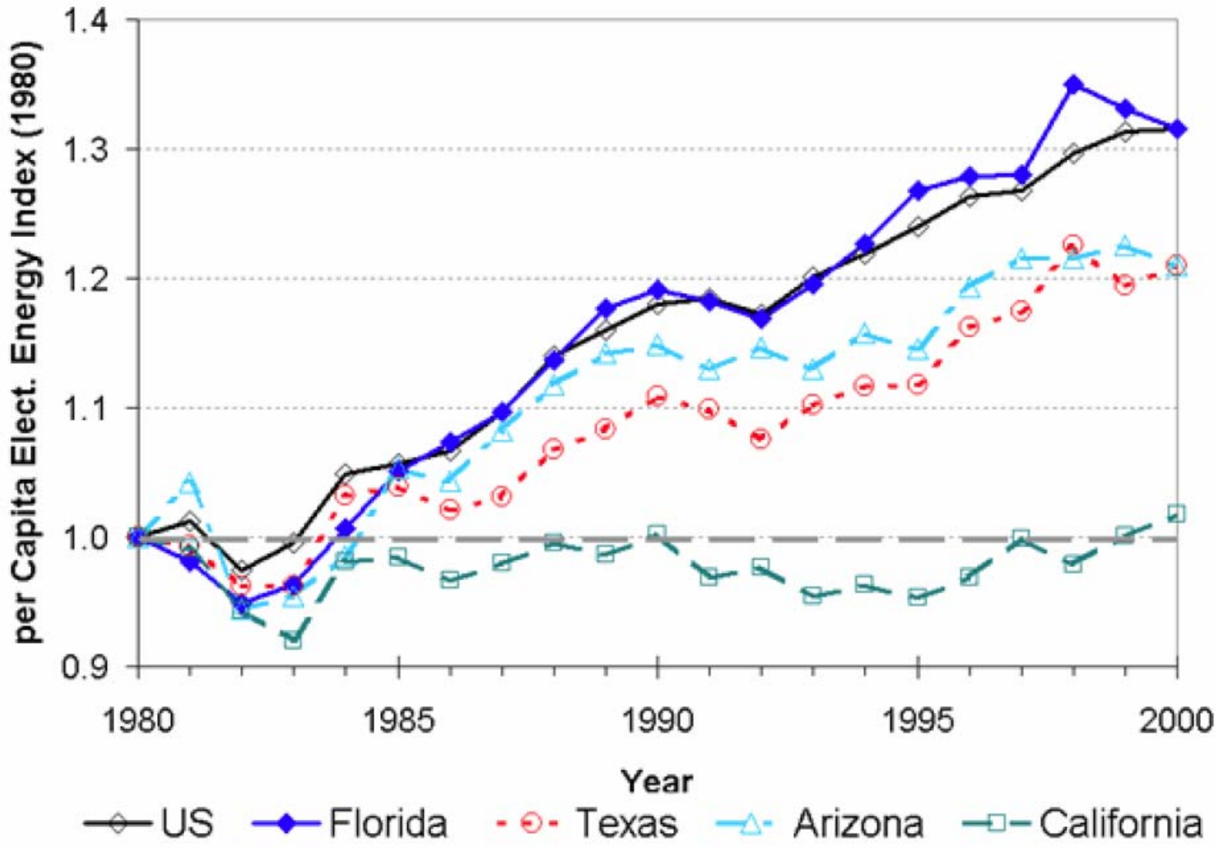
A downward slope with time reflects increasing energy efficiency.

As this chart illustrates, there are still significant opportunities for efficiency gains in developing nations.

But OECD nations are also expected to be increasingly efficient due to the introduction and use of new technologies in a wide variety of applications including personal transportation.

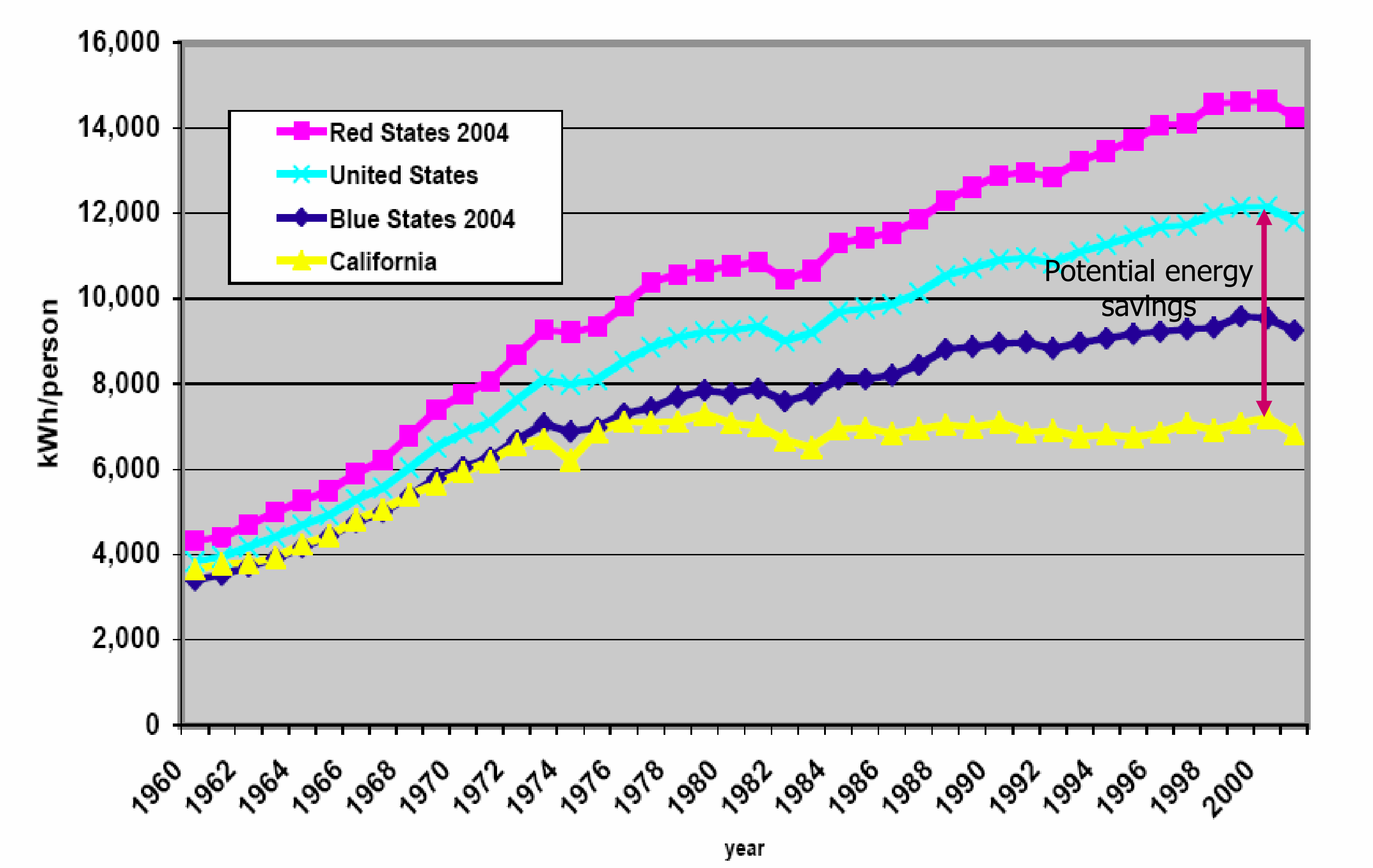
Source: exxonmobil.com/corporate/citizenship

Per Capita Energy Use



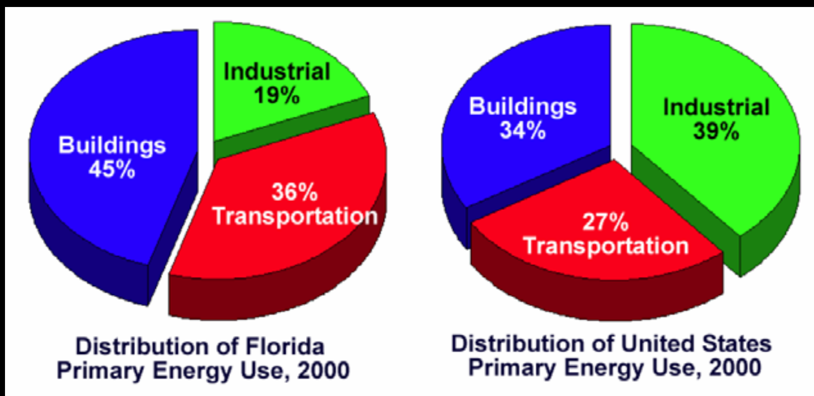
Per capita electrical energy use index for U.S. and selected states.

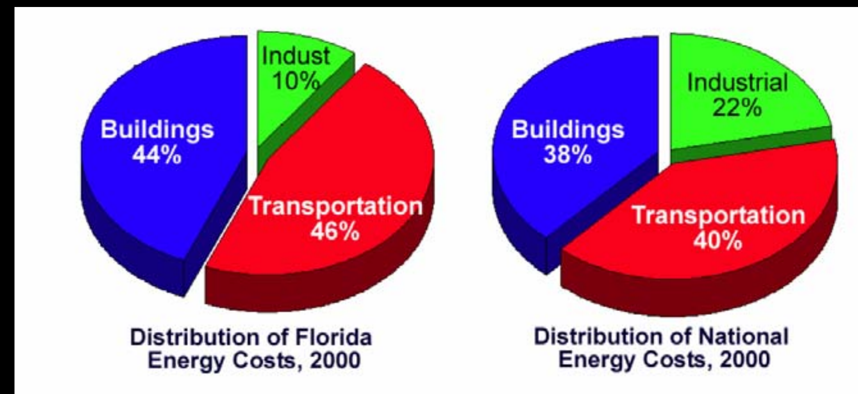
Per Capita Electricity Consumption

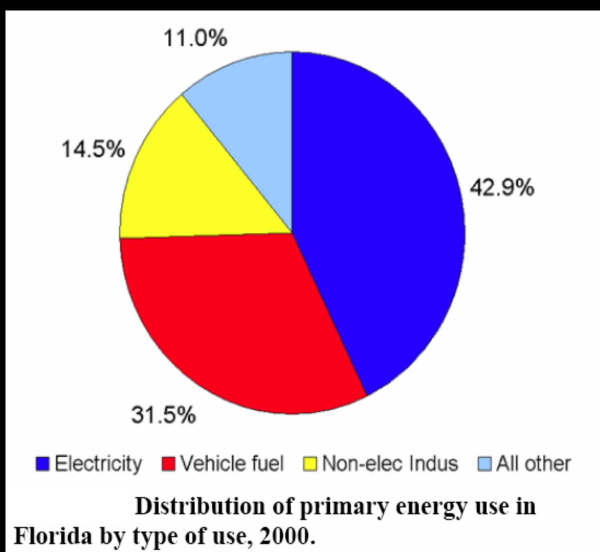


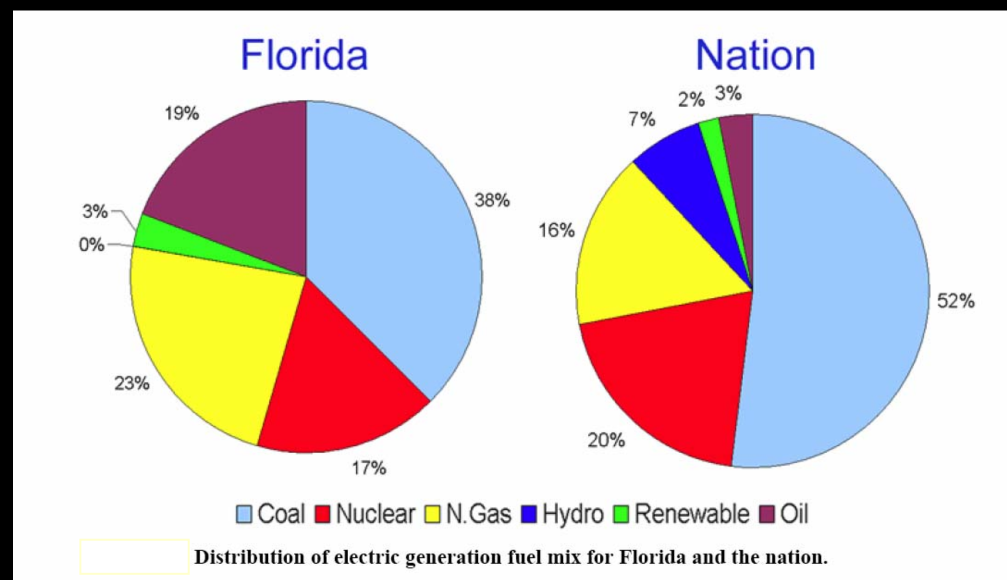
Source: Daniel Kammen, UC Berkeley, ER 100 Lecture 1, Fall 2005

Florida Energy Use









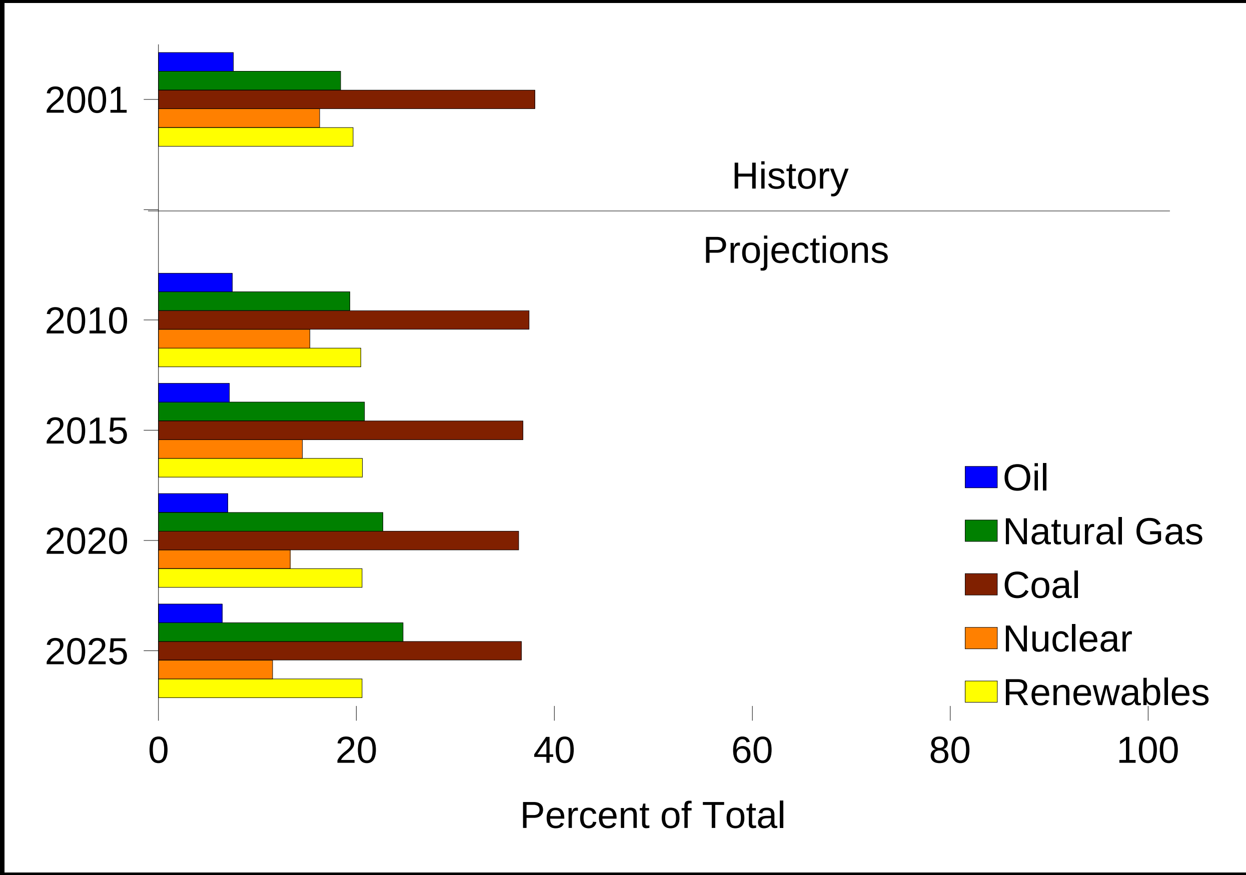
Source: Florida's Energy Future, DEP, January, 2004

Florida Electricity Generation

Table 1. Florida's Electric Utilities 2002 Ten-Year Plans – 2010 Installed Winter Capacity

Utility	Existing Capacity (MW)	Proposed Additions (MW)	Total 2010 Capacity (MW)	Reserve Margin	Peak Demand Reduction (MW)
Florida Power Corporation	9865	2828	12693	20%	1611
Florida Power & Light	20526	6450	26976	20%	1955
Gulf Power	2383	577	2960	15%	532
Tampa Electric Company	4361	1410	5771	20%	1091
Florida Municipal Power Agency	1317	396	1713	15-18%	7
Gainesville Regional Utilities	536	93	629	15%	18
JEA	2910	1219	4129	15%	153
Kissimmee Utility Authority	303	136	439	15%	8
City of Lakeland	791	270	1061	20-22%	67
Orlando Utilities Commission	1385	469	1854	15%	32
City of Tallahassee	733	107	840	17%	28
Seminole Electric Cooperative	4144	1640	5784	15%	248
TOTAL	49254	15595	66859	18% avg.	5750

Energy Use for Electricity Generation



Energy Consumption for Electricity Generation

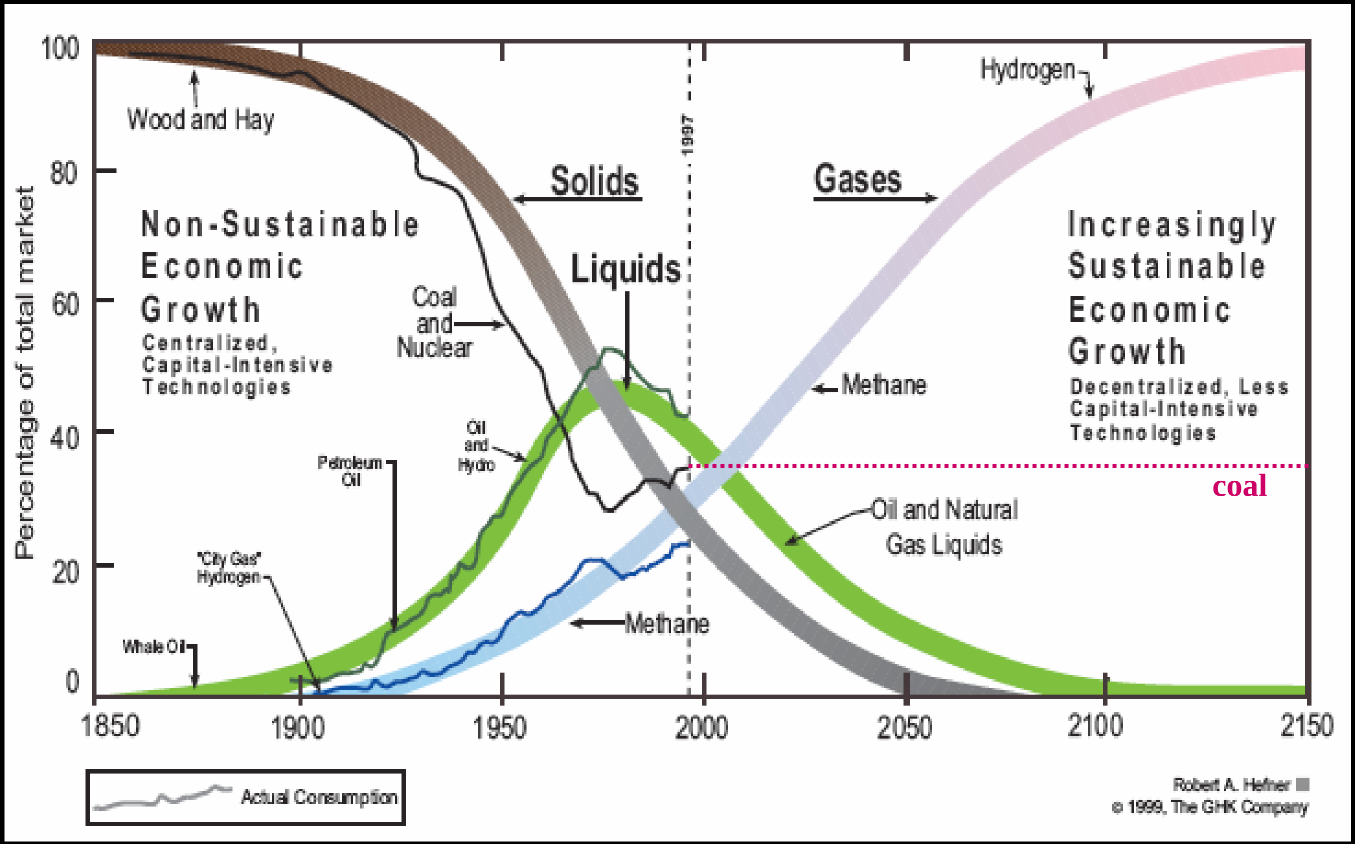
(Quadrillion Btu)

Region/Country	2001	Projections 2010	2015	2020	2025	Average Annual Percent Change, 2001-2025
Industrialized Countries						
Oil	5.1	4.5	4.8	5.0	5.3	0.1
Natural Gas	14.4	18.5	21.8	25.7	29.6	3.1
Coal	32.1	34.4	35.7	37.8	41.7	1.1
Nuclear	21.0	22.9	23.2	23.3	21.9	0.2
Renewables	16.4	19.5	20.8	21.9	23.1	1.4
Total	**89.0**	**99.8**	**106.4**	**113.6**	**121.5**	**1.3**
Eastern Europe/Former Soviet Union						
Oil	0.9	0.8	0.9	1.0	1.1	0.6
Natural Gas	8.1	10.2	11.9	14.1	16.5	3.0
Coal	6.8	7.9	8.1	8.1	7.9	0.6
Nuclear	3.0	3.4	3.5	3.2	2.9	-0.2
Renewables	3.1	3.8	4.2	4.2	4.4	1.6
Total	**21.9**	**26.2**	**28.5**	**30.6**	**32.8**	**1.7**
Developing Countries						
Oil	6.1	9.2	9.8	10.8	10.7	2.4
Natural Gas	7.1	8.9	11.3	14.3	19.0	4.2
Coal	22.2	30.6	35.7	41.0	47.1	3.2
Nuclear	2.2	3.5	4.7	5.4	5.7	4.0
Renewables	12.0	15.4	17.5	19.7	21.9	2.5
Total	**49.6**	**67.6**	**79.0**	**91.3**	**104.2**	**3.1**
Total World						
Oil	12.2	14.5	15.5	16.7	17.0	1.4
Natural Gas	29.6	37.7	44.9	54.1	65.2	3.3
Coal	61.1	73.0	79.5	86.9	96.7	1.9
Nuclear	26.2	29.8	31.4	31.8	30.4	0.6
Renewables	31.5	38.6	42.5	45.9	49.4	1.9
Total	**160.5**	**193.6**	**213.9**	**235.5**	**258.6**	**2.0**

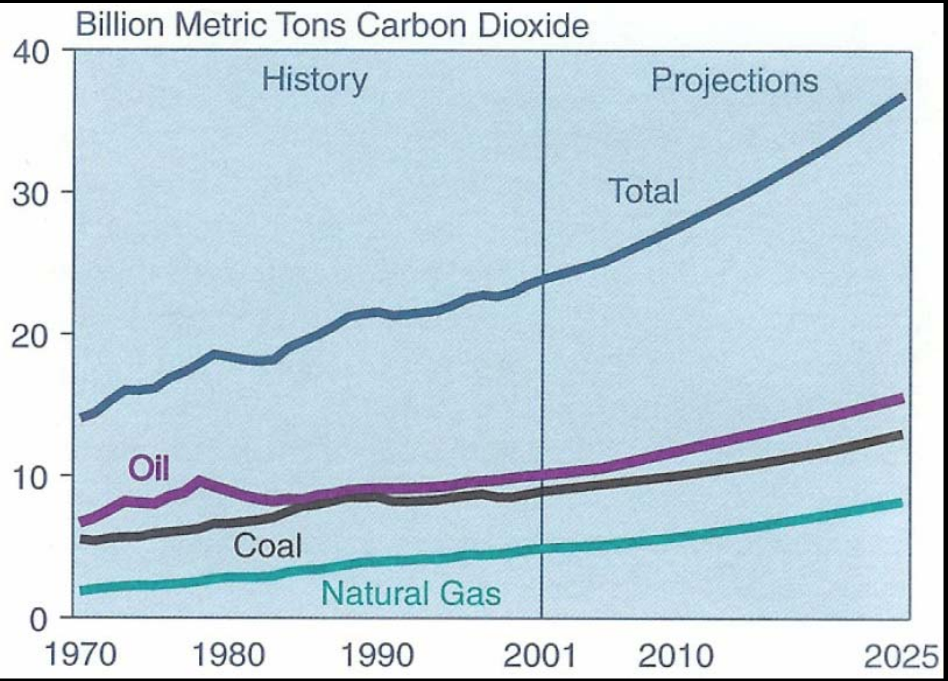
Note: Totals may not equal sum of components due to independent rounding.

Sources: **2001:** Energy Information Administration (EIA), calculated by the Office of Integrated Analysis and Forecasting, based on estimates of fuel inputs for electricity generation and assumed average generation efficiencies by fuel type. **Projections:** EIA, System for the Analysis of Global Energy Markets (2004).

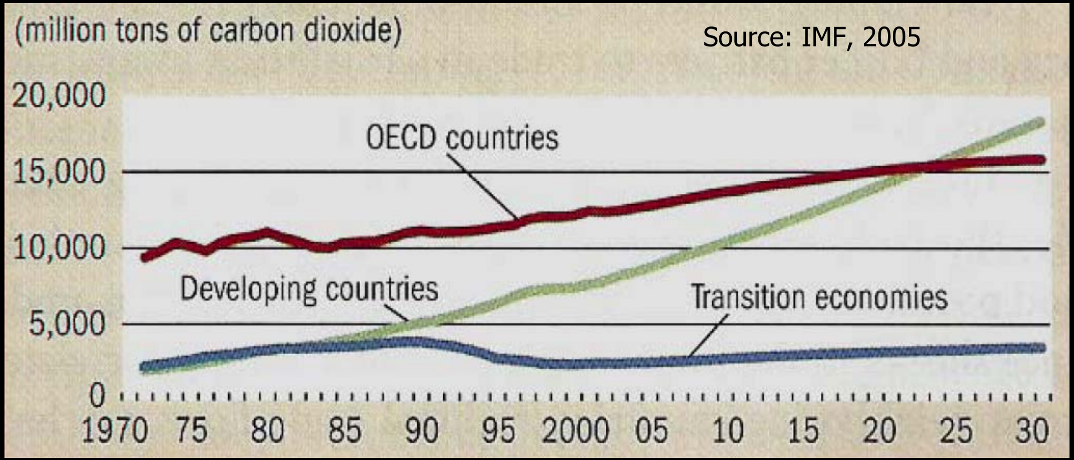
Global Energy Systems Transition



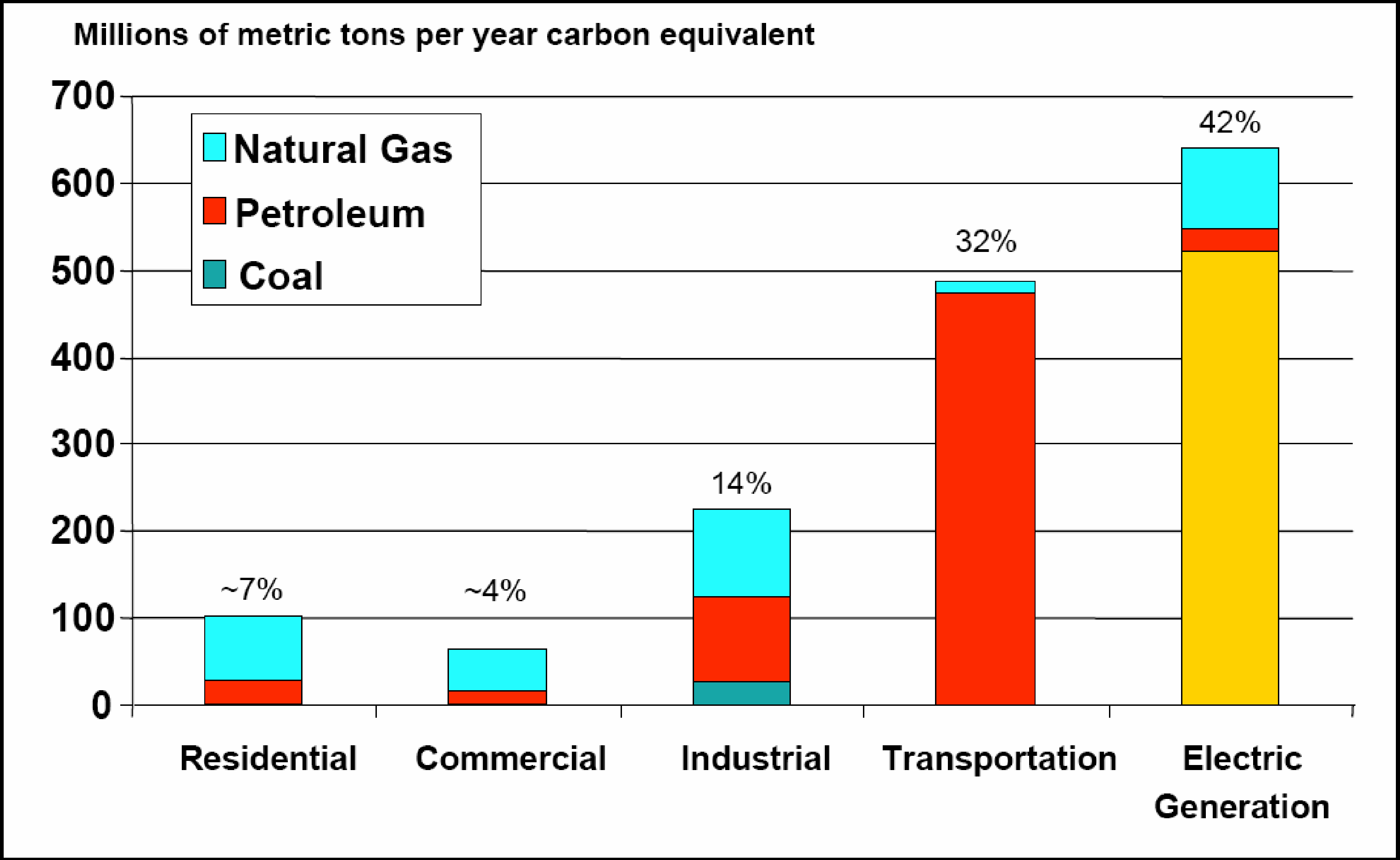
Global CO_2 Emissions



In the year 2020, CO_2 emissions in developing countries will overtake those in OECD.



US CO_2 Emissions in 2000



Coal Combustion

Coal is one of the most impure of fuels. Its impurities range from trace quantities of many metals, including uranium and thorium, to much larger quantities of aluminum and iron to still larger quantities of impurities such as sulfur.

Products of coal combustion include the oxides of carbon, nitrogen, and sulfur, carcinogenic and mutagenic substances, and recoverable minerals of commercial value, including nuclear fuels naturally occurring in coal.

Coal ash is composed primarily of oxides of silicon, aluminum, iron, calcium, magnesium, titanium, sodium, potassium, arsenic, mercury, and sulfur plus small quantities of uranium and thorium.

Fly ash is primarily composed of non-combustible silicon compounds (glass) melted during combustion. Tiny glass spheres form the bulk of the fly ash.

Since the 1960s particulate precipitators have been used by U.S. coal-fired power plants to retain significant amounts of fly ash rather than letting it escape to the atmosphere. When functioning properly, these precipitators are approximately 99.5% efficient. Utilities also collect furnace ash, cinders, and slag, which are kept in cinder piles or deposited in ash ponds on coal-plant sites along with the captured fly ash.

Coal Combustion

During combustion, the volume of coal is reduced by over 85%, which increases the concentration of the metals originally in the coal. Although significant quantities of ash are retained by precipitators, heavy metals such as uranium tend to concentrate on the tiny glass spheres that make up the bulk of fly ash. This uranium is released to the atmosphere with the escaping fly ash, at about 1.0% of the original amount. The retained ash is enriched in uranium several times over the original uranium concentration in the coal because the uranium, and thorium, content is not decreased as the volume of coal is reduced.

All studies of potential health hazards associated with the release of radioactive elements from coal combustion conclude that the perturbation of natural background dose levels is almost negligible. However, because the half-lives of radioactive potassium-40, uranium, and thorium are practically infinite in terms of human lifetimes, the accumulation of these species in the biosphere is directly proportional to the length of time that a quantity of coal is burned. Although trace quantities of radioactive heavy metals are not nearly as likely to produce adverse health effects as the vast array of chemical by-products from coal combustion, the accumulated quantities of these isotopes over 150 or 250 years could pose a significant future ecological burden and potentially produce adverse health effects, especially if they are locally accumulated. The potential impact of long-term accumulation of by-products in the biosphere should be considered.

Source: http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html

Coal-Fired Power Plants Air Pollution

Electric industry coal fired power plants contribute

- 96% of sulfur dioxide (SO_2) emissions
- 93% of nitrogen oxide (NO_x) emissions
- 88% of carbon dioxide (CO_2) emissions
- 99% of mercury emissions

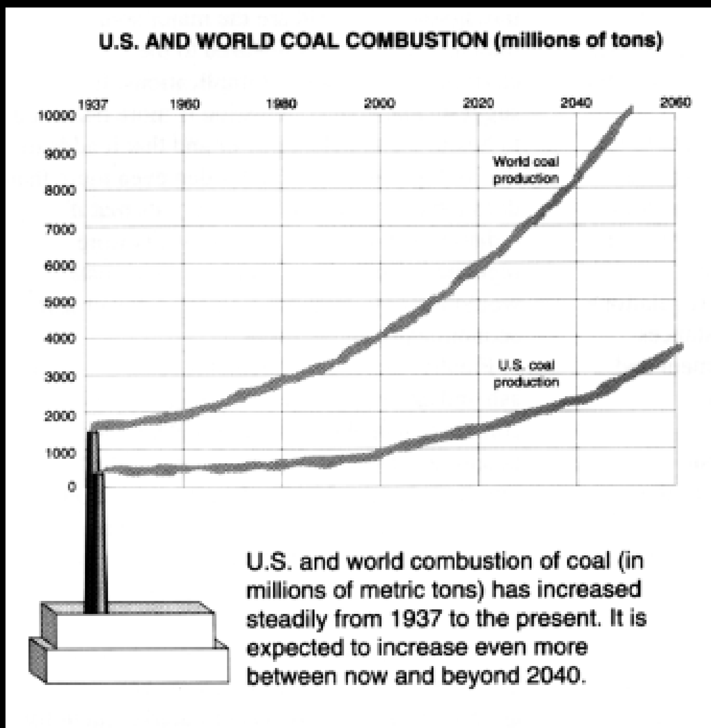
When nitrogen oxide (NO_x) reacts with volatile organic compounds (VOC's) and sunlight ground level ozone, or smog forms. Power plants are second only to automobiles as the greatest source of NOx emissions. NO_x emissions from huge dirty coal plants with tall smokestacks in the midwest are often blamed for increased smog levels in many eastern regions because smog and its precursor pollutants are easily transported hundreds of miles downwind from pollution sources. More than 137 million Americans continue to breath unhealthy, smog polluted air.

The burning of coal emits sulfur dioxide (SO_2) and nitrogen oxide (NO_x) gases, which can form fine particles, or soot, when they react with the atmosphere. In addition, coal-fired power plants also emit soot directly from their smokestacks.

Acid rain is formed when sulfur dioxide (SO_2) and nitrogen oxide (NO_x) react with water and oxygen in the atmosphere to form acidic compounds, most commonly sulfuric and nitric acid. These compounds can become incorporated into natural precipitation and fall to the earth as rain or snow. Coal-fired power plants are the largest source of SO_2, 66%, and second to automobiles in NO_x emissions.

Source: http://www.sierraclub.org/cleanair/factsheets/power.asp#return3

Global Coal Use and its Consequences



In an average year, a typical 500 MW (uses 1.4 million tones/year) power plant generates:

CO_2 : 3,700,000 tones

SO_2 : 10,000 tones

NO_x: 10,200 tones (equivalent to emissions by half a million modern cars)

CO : 720 tones

VOC's: 220 tones

Mercury: 77 kg

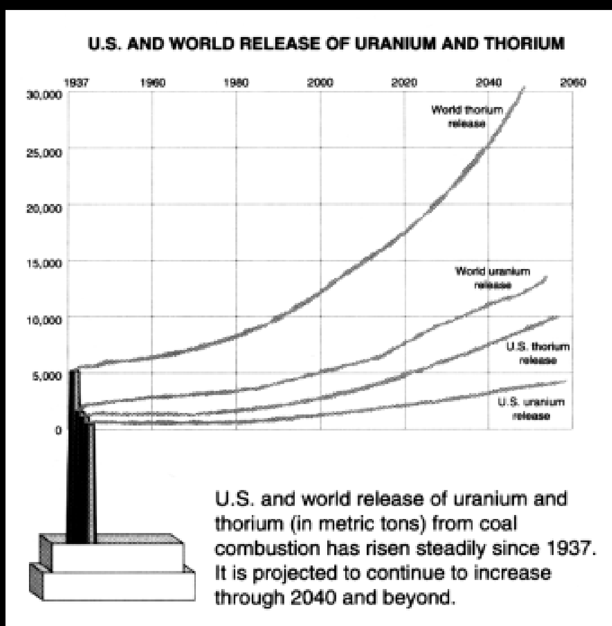
Arsenic: 102 kg

Lead: 52 kg

Source: http://www.ucsusa.org/clean_energy/coalvswind/c01.html

Coal Combustion

Trace quantities of uranium in coal range from less than 1 part per million (ppm) in some samples to around 10 ppm in others. Generally, the amount of thorium contained in coal is about 2.5 times greater than the amount of uranium. For a large number of coal samples, according to Environmental Protection Agency figures released in 1984, average values of uranium and thorium content have been determined to be 1.3 ppm and 3.2 ppm, respectively.



U.S. and world release of uranium and thorium (in metric tons) from coal combustion has risen steadily since 1937. It is projected to continue to increase through 2040 and beyond.

Based on the predicted combustion of 2516 million tons of coal in the United States and 12,580 million tons worldwide during the year 2040, cumulative releases for the 100 years of coal combustion following 1937 are predicted to be:

U.S. release (from combustion of 111,716 million tons):

- Uranium: 145,230 tons (containing 1031 tons of uranium-235)
- Thorium: 357,491 tons

Worldwide release (from combustion of 637,409 million tons):

- Uranium: 828,632 tons (containing 5883 tons of uranium-235)
- Thorium: 2,039,709 tons

Source: http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html

Radiation from Coal Power Plants

Typical concentration of radioactive material in coal is about 4 ppm.

A typical 500 MW coal plant burns approximately 4,000 tons of coal everyday. There are about 600 U.S. coal plants

The total emissions of radioactive material from a typical plant is about 32 pounds per day.

Of that, about 1 % is assumed to be released as fly ash in a modern plant with 10% in one with no scrubbers or bag house.

The rest goes into the unmonitored ash pile which is often right next to a body of water.

Global Warming

Burning fossil fuels such as coal releases carbon dioxide (CO_2) pollution. The US has four percent of the world's population yet emits 25% of the global warming pollution. Power plants emit 40% of US carbon dioxide pollution, the primary global warming pollutant. In 1999, coal-fired power plants alone released 490.5 million metric tons of CO_2 into the atmosphere (32% of the total CO_2 emissions for 1999). Currently there is 30% more CO_2 in the atmosphere than there was at the start of the Industrial Revolution, and we are well on the way to doubling CO_2 levels in the atmosphere during this century.

Coal is one of the true measures of the energy strength of the United States. One quarter of the world's coal reserves are found within the United States, and the energy content of the nation's coal resources exceeds that of all the world's known recoverable oil. Coal is also the workhorse of the nation's electric power industry, supplying more than half the electricity consumed by Americans.

A possible solution: Advanced coal fired power plant designs (eg: IGCC) which capture the green house gases and prevent them from entering the atmosphere (the carbon sequestration).

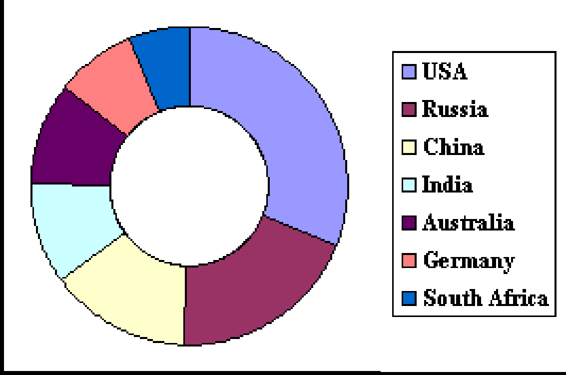
Source: http://www.sierraclub.org/cleanair/factsheets/power.asp#return3

http://www.doe.gov

World Coal Reserves

World coal reserves: 904,064 million tones ≈ 9×10^{11} tones

- United States ≈ 250×10^9 tones
- Russia ≈ 157×10^9 tones
- China ≈ 114×10^9 tones
- India ≈ 84×10^9 tones



Coal Production:

- United States ≈ 10^9 tones
- China ≈ 10^9 tones
- India ≈ 3×10^8 tones

Typical power plant consumption: 2800 tones/MW/year

Source: World Energy Council, 1999 Statistics

Environmental Impact of Coal

Percentage of the world's CO_2 emissions from coal, 1999: 38.2%

Percentage of U.S. sulfur dioxide emissions from coal-burning plants: 60%

Percentage of U.S. carbon dioxide emissions from coal-burning plants: 31%

Percentage of U.S. mercury pollution from coal-burning plants: 32%

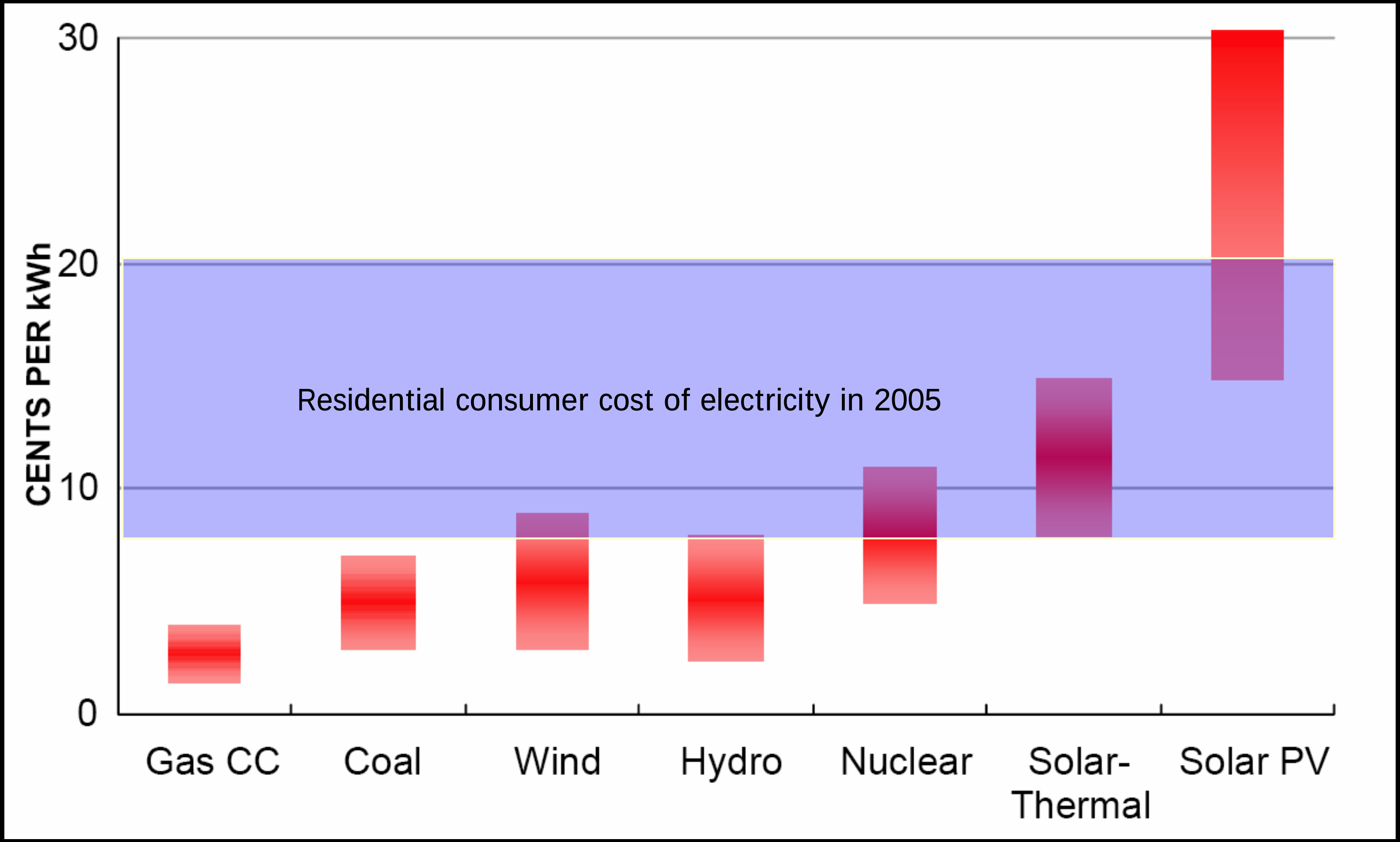
Source: Cost of Coal - PBS NOW program, 8/2/02

Average Retail Price of Electricity to Residential customers (¢/kWh).

Region	October 2005	October 2004
New England	13.31	11.95
Mid Atlantic	12.48	11.86
New York	15.48	14.6
South Atlantic	8.85	8.36
Florida*	9.58	9.02
Pacific Contiguous	10.06	10.37
California	11.93	12.56
Hawaii	20.21	18.13
US Total	**9.41**	**9.01**

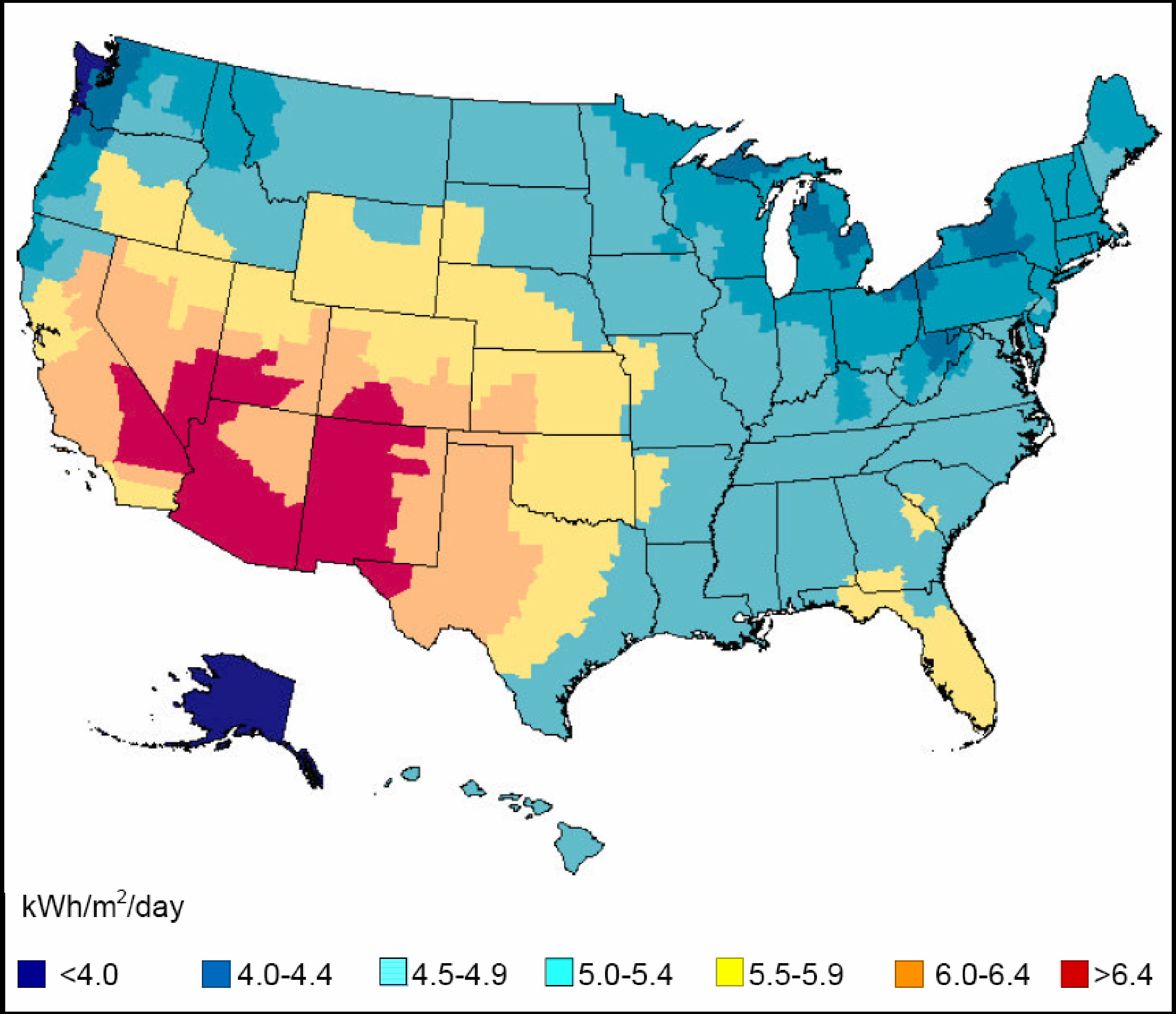
*In 2006, the rate in Florida will be increased to about 10.861 (¢/kWh)

Electricity Production Cost



Source: Exxon Mobil, 2002 and modified by AK

Daily Average Output for Plat Plate Collectors with Fixed Tilt Angle Chosen for Maximum Annual Output



Source: NREL, modified by LBNL