Sustainable Energy Science and Engineering Center

A Renewed Look at Sustainable Energy: the Solar Strategy

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Ouro Preto, Brazil

Objective

Present a synthesis of science and technologies related to

generation of electricity

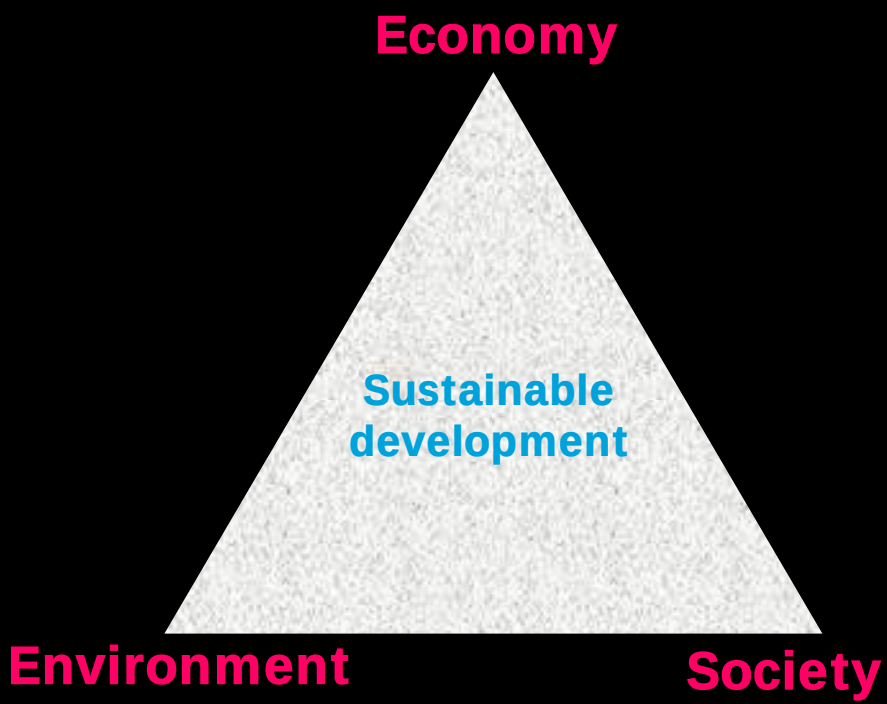
and

fuel for transportation

in

A Sustainable Energy Supply Scenario

Energy and Sustainability



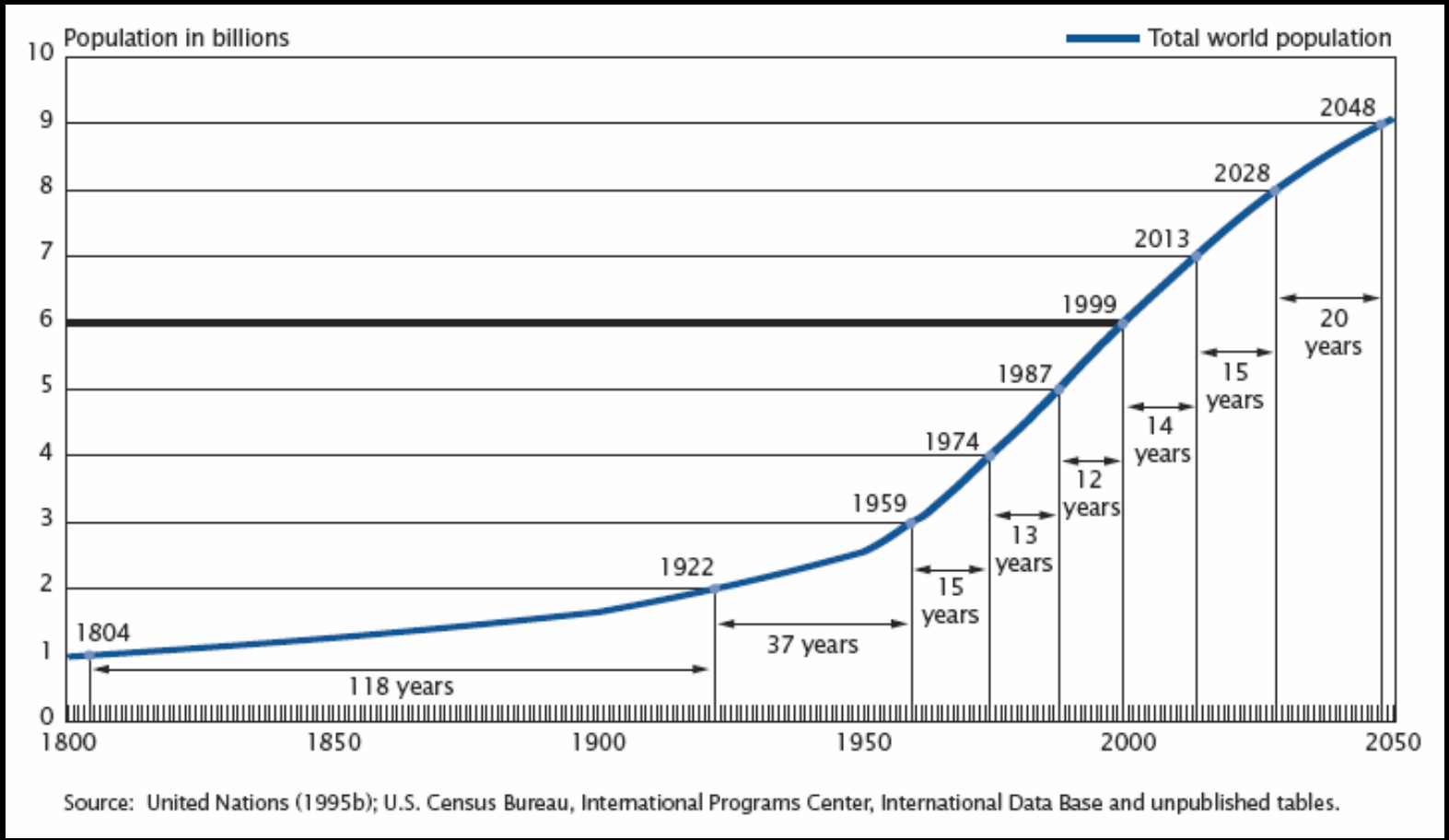
Economy: Per capita gross domestic product (GDP/population) and energy consumption per GDP (E/GDP)

Environment: The state of environment is greatly influenced by energy production methods. A measure of it can be the amount of green house gases, especially the CO_2 emitted per BTU (CO_2/E)

Society: Energy supply scenarios need to achieve a sense of social cohesion, cultural inclusion and people empowerment. The UN has defined a Human Development Index (HDI) which takes into account of indicators such as health, education and economic status. A strong correlation exists between HDI and energy use.

Challenge: *To fuel worldwide economic growth with secure and reliable energy supply without despoiling our environment and giving people the chance in shaping change for a preferable future.*

World Population



Source: United Nations (1995b); U.S. Census Bureau, International Programs Center, International Data Base and unpublished tables.

Good News: Growth rate is declining

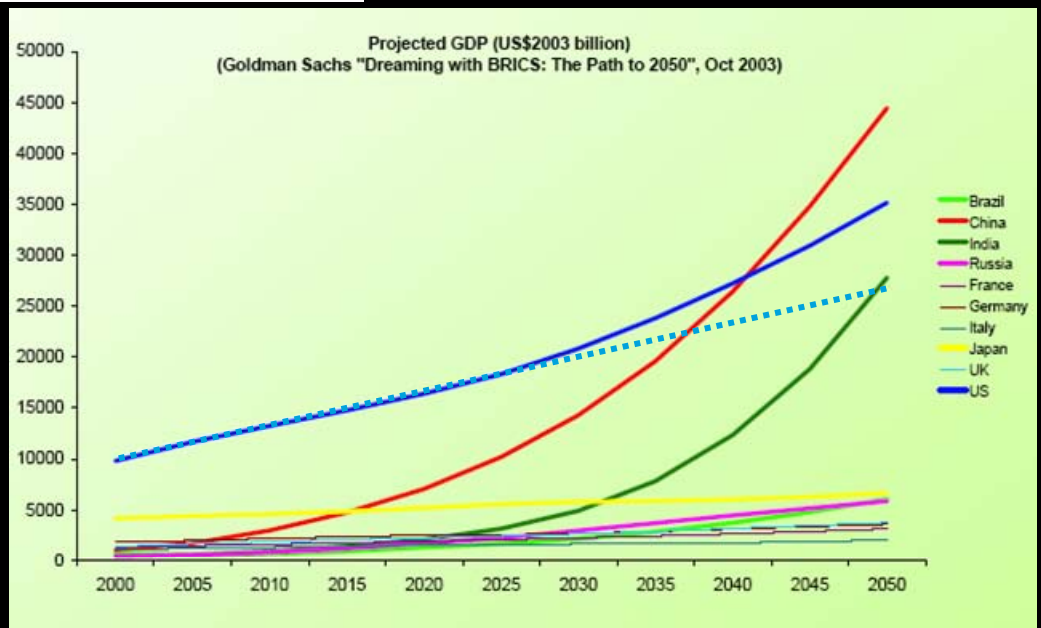
Top Ten GDP Countries

Table 1. Top ten GDP's in 2004

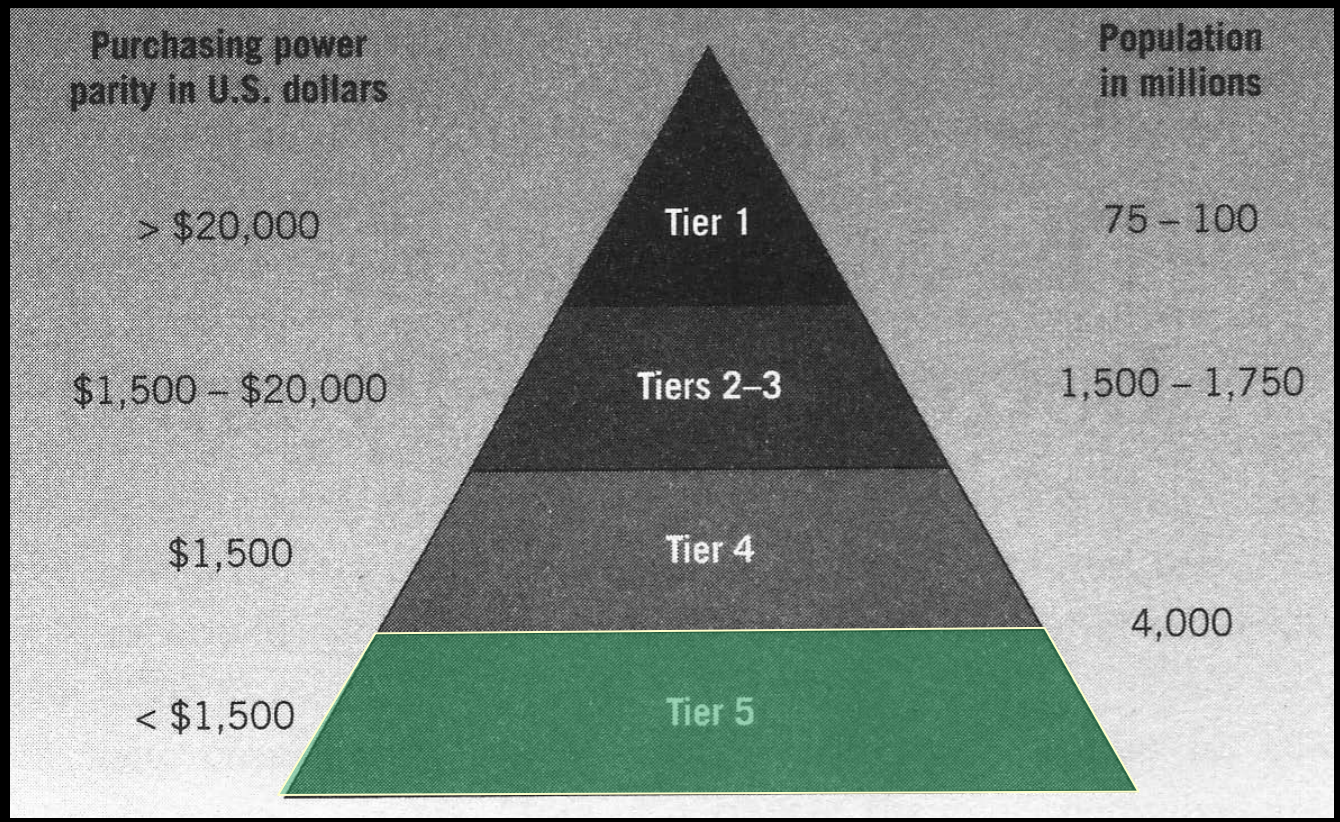
Ranking	*Economy*	*US dollars in millions*
1	United States	11,667,515
2	Japan	4,623,398
3	Germany	2,714,418
4	United Kingdom	2,140,898
5	France	2,002,582
6	Italy	1,672,302
7	China	1,649,329
8	Spain	991,442
9	Canada	979,764
10	India	691,876

Table 2. Top ten GDP's in terms of PPP in 2004[8]

Ranking	*Economy*	*US dollars in trillion*	*GDP per capita in US $*
1	United States	11.75	40,100
2	China	7.62	5,600
3	Japan	3.75	29,400
4	India	3.32	3,100
5	Germany	2.36	28,700
6	United Kingdom	1.78	29,600
7	France	1.74	28,700
8	Italy	1.61	27,700
9	Brazil	1.49	8,100
10	Russia	1.40	9,800

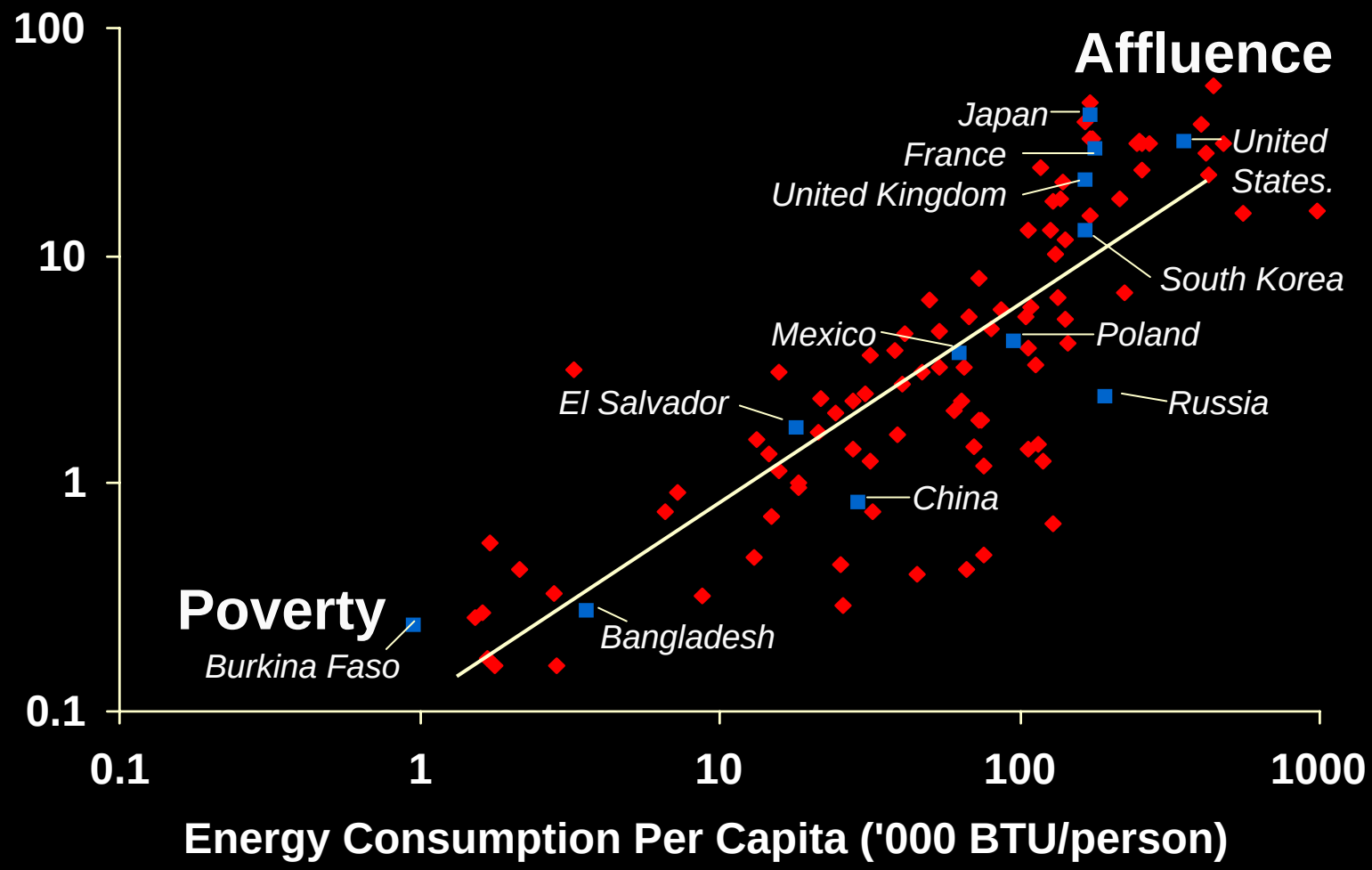


People Purchasing Power



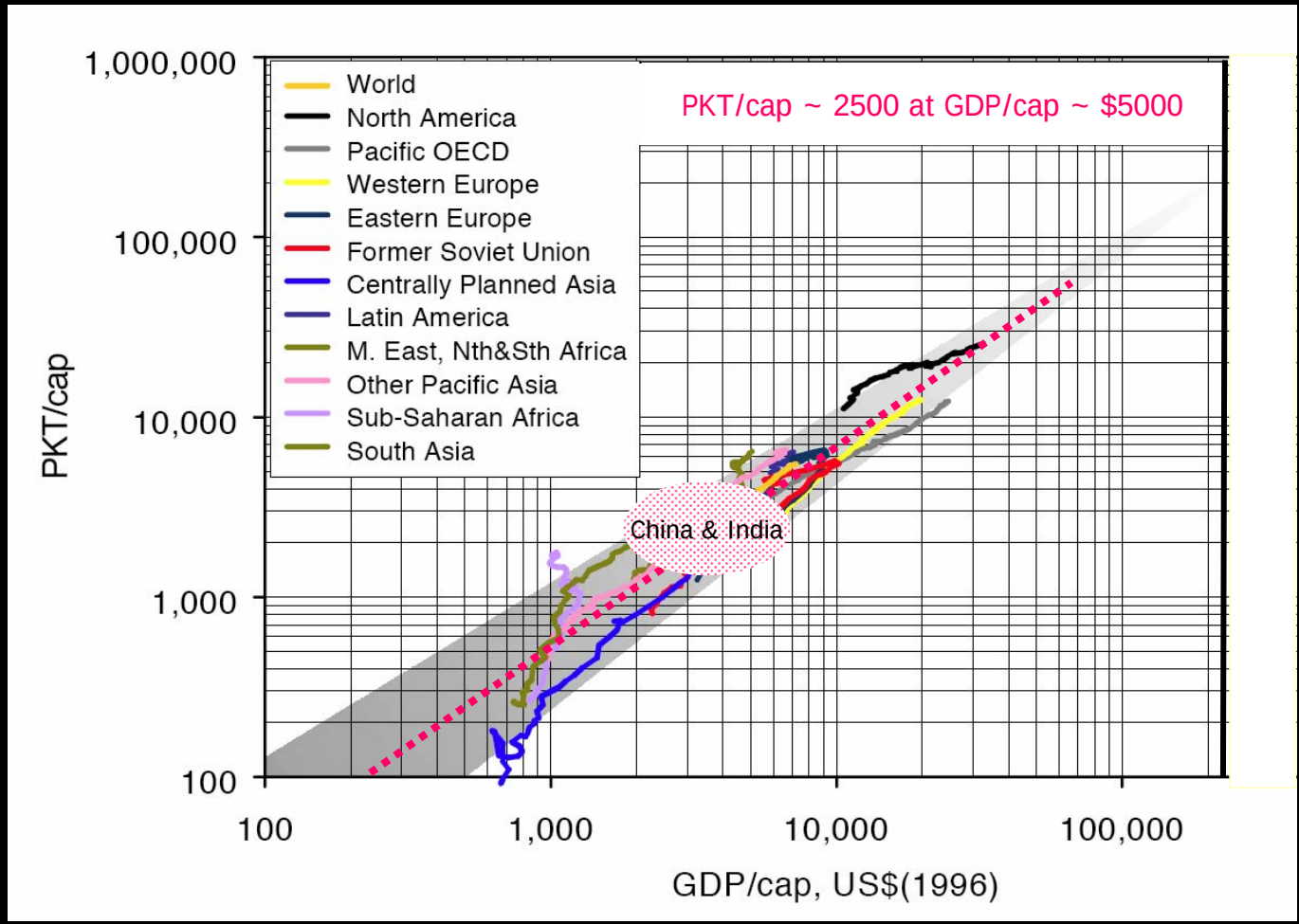
Challenge: Energy supply to people in Tier 5 with innovations at affordability level

Per Capita Energy Consumption and GDP



Source: Energy Information Administration, International Energy Annual 2000 Tables E1, B1, B2; Gross Domestic Product per capita is for 2000 in 1995 dollars. Updated May 2002

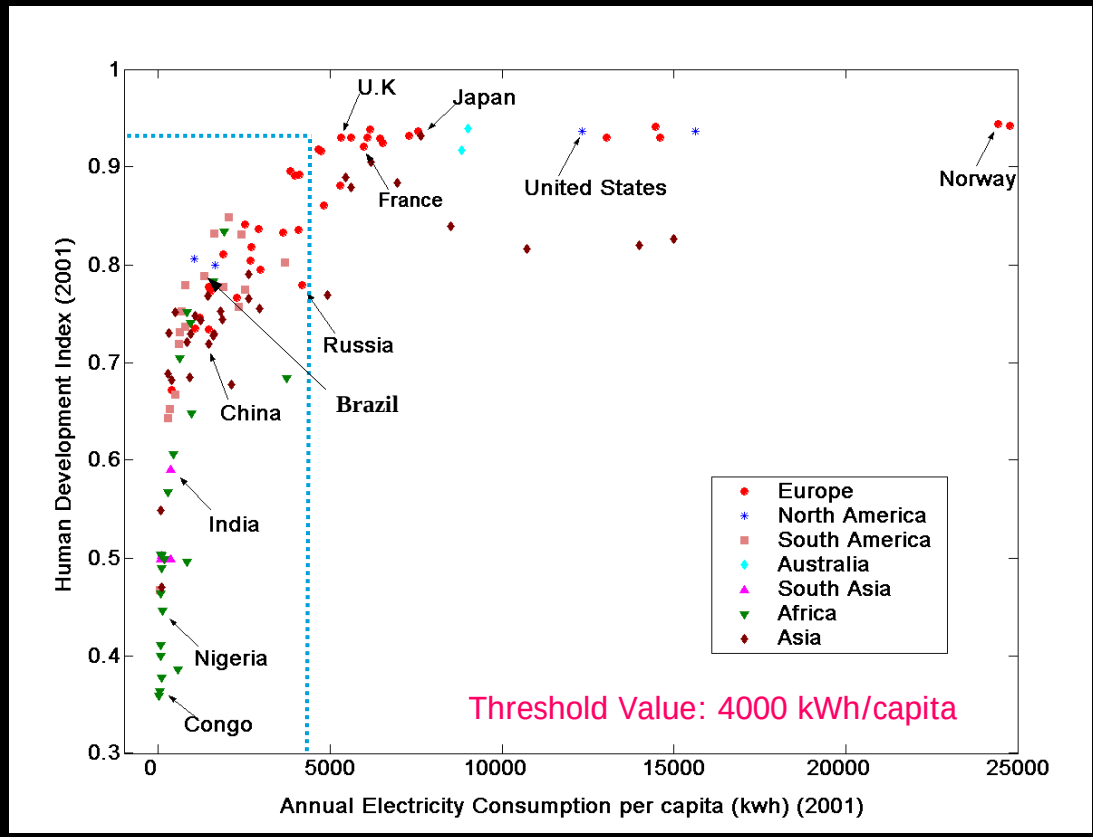
Car Driving and Per Capita GDP



PKT/cap: passenger km traveled per capita

Source: Andreas Schafer, University of Cambridge, UK

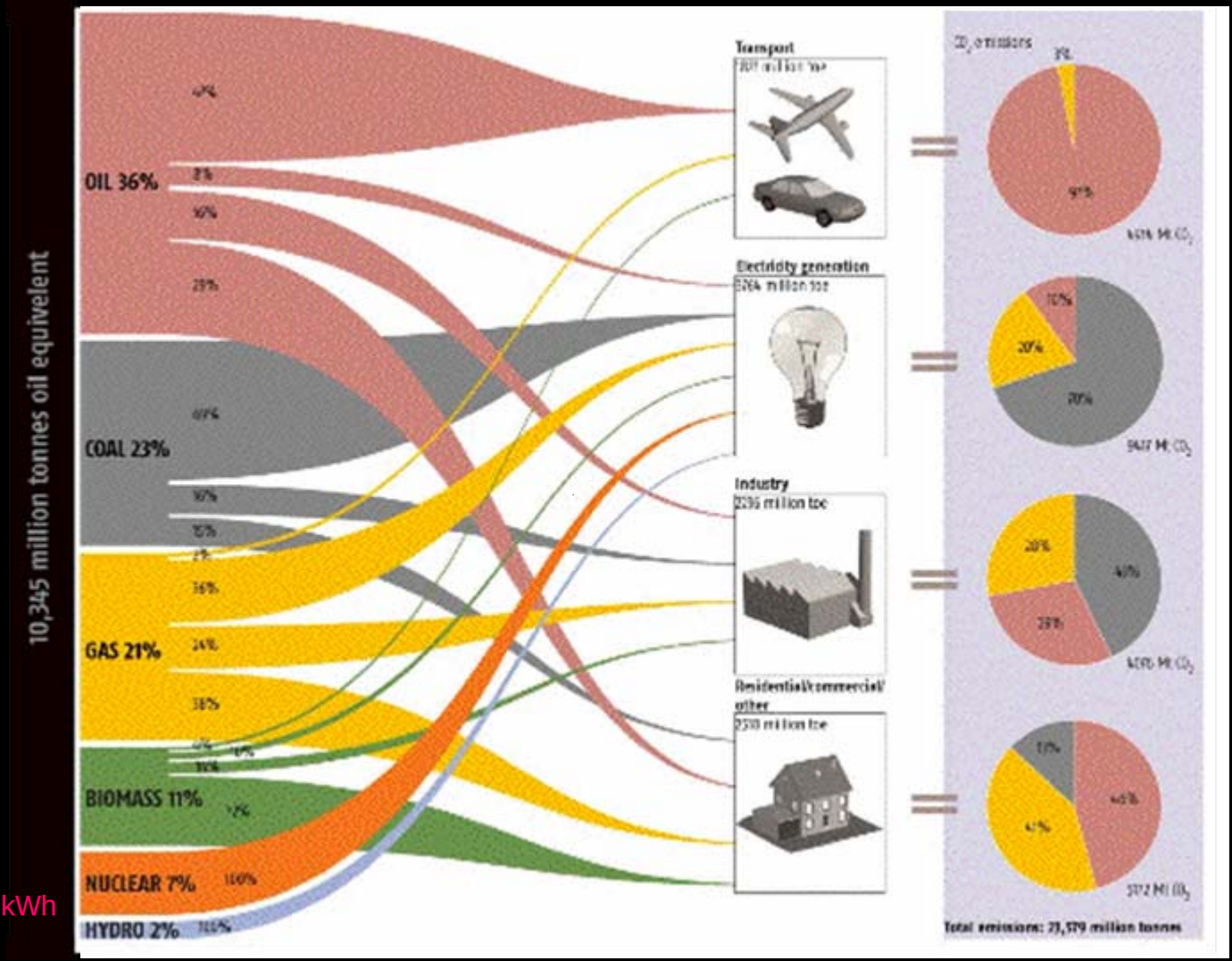
Per Capita Energy Consumption and HDI



HDI: Human development index - a composite measure of development based indicators: life expectancy, educational level and per capita gross domestic product. Each data point corresponds to a country. Modest increase in PCEC can lead to marked improvements in the quality of life in the developing nations.

Source: Alan D. Pasternak, Global energy futures and human development: A frame work for analysis, UCRL-ID-140773, Lawrence Livermore National Laboratory, U.S. DOE, 2003

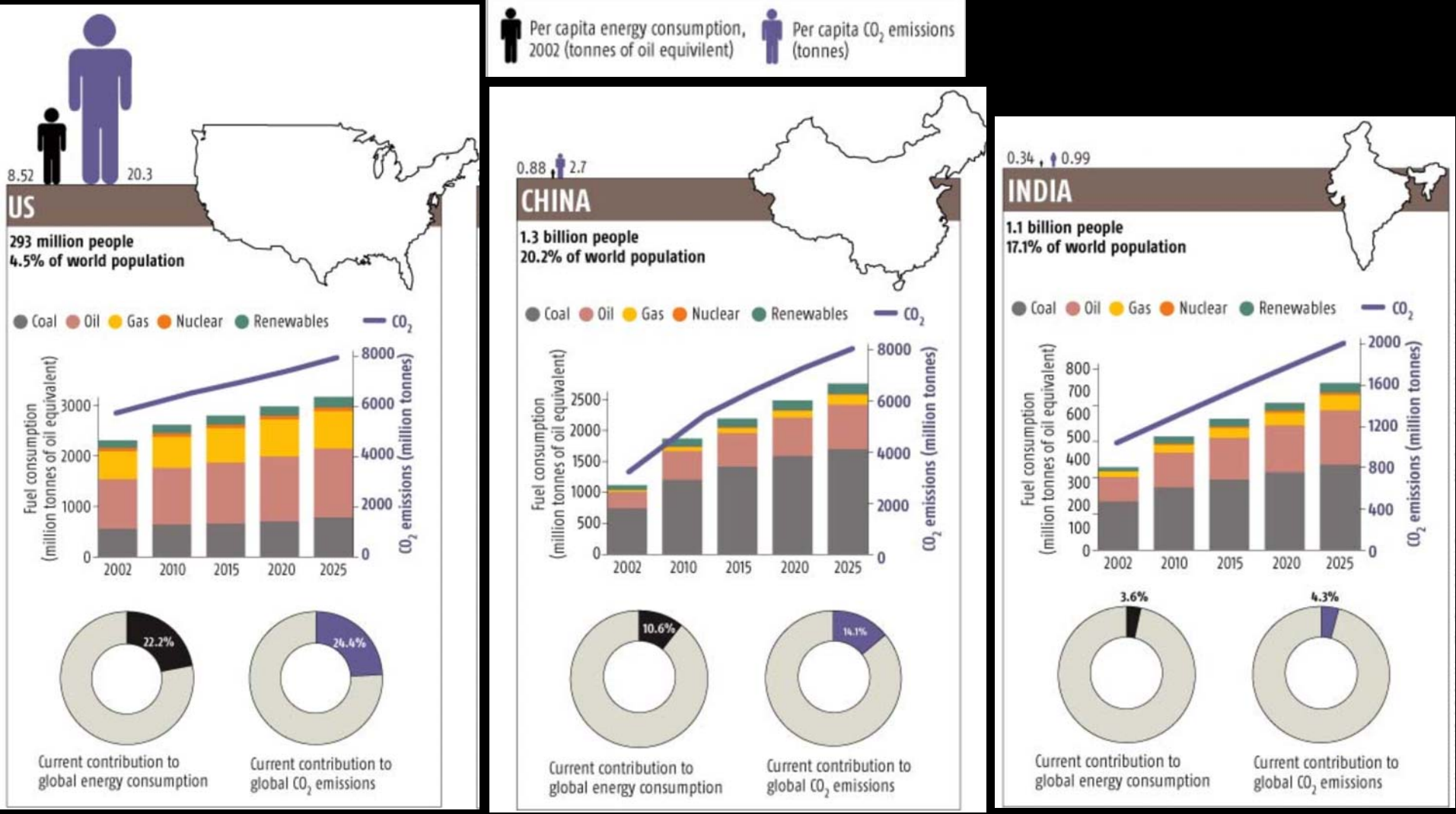
Global Annual Energy Use



1 toe = 1.64 x10^4 kWh

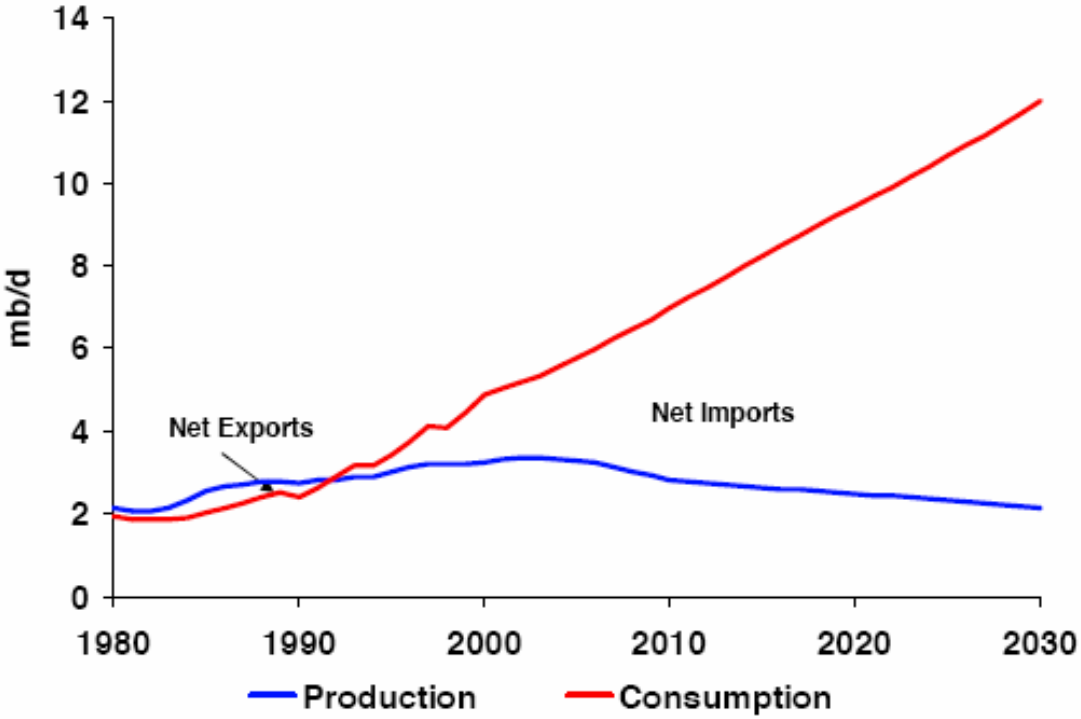
Source: NewScientist.com, September 3, 2005, Clean energy special: Gas-guzzling planet

Annual Energy Use



Source: NewScientist.com, September 3, 2005, Clean energy special: Gas-guzzling planet

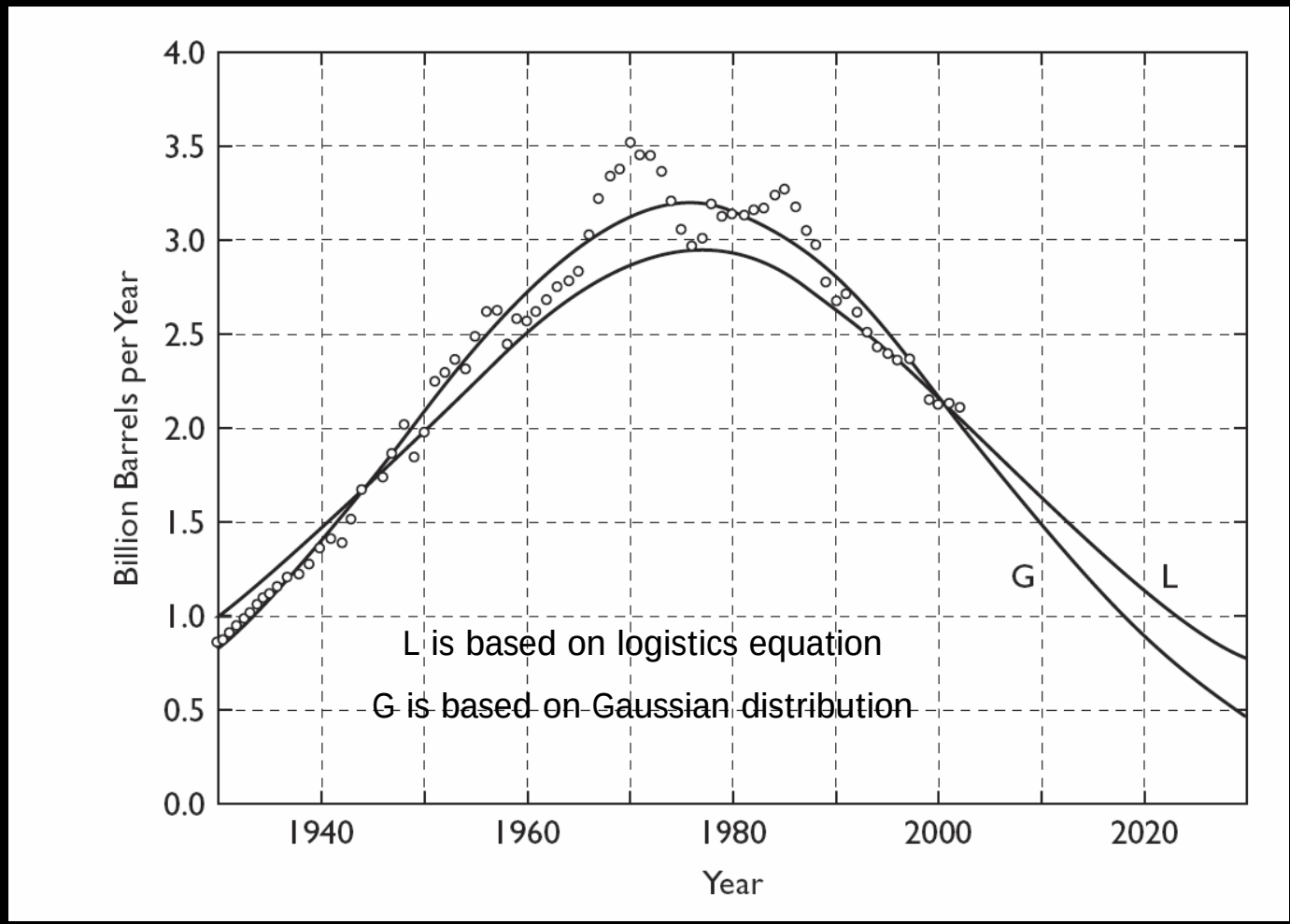
Demand for Oil in China



Rapid motorisation underpins strong oil demand growth. Net oil imports will rise from 1.7mb/d in 2001 to 9.8mb/d in 2030.

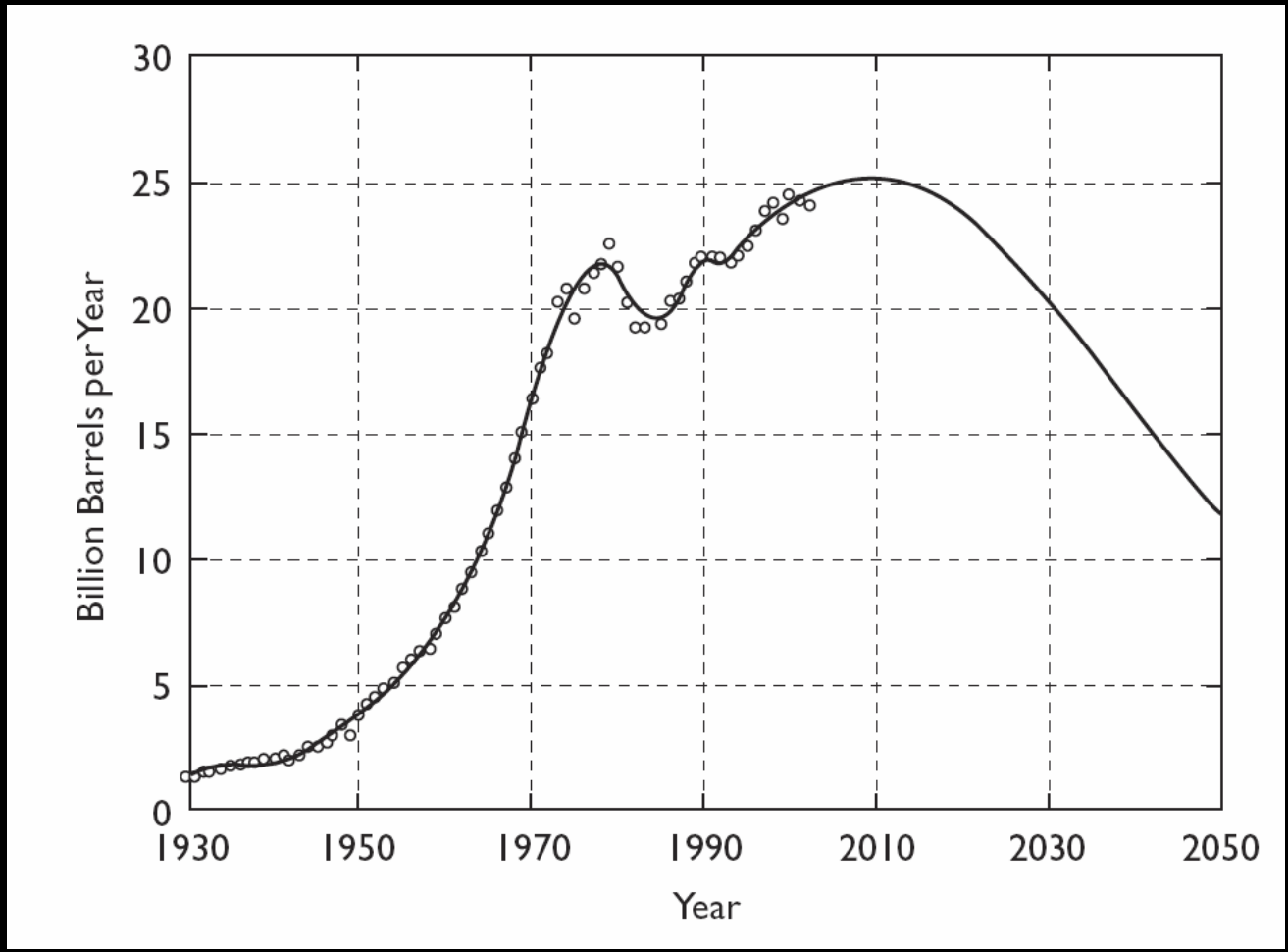
Oil imports will reach almost 10 mb/d in 2030, equivalent to US imports today.

US Annual Oil Production



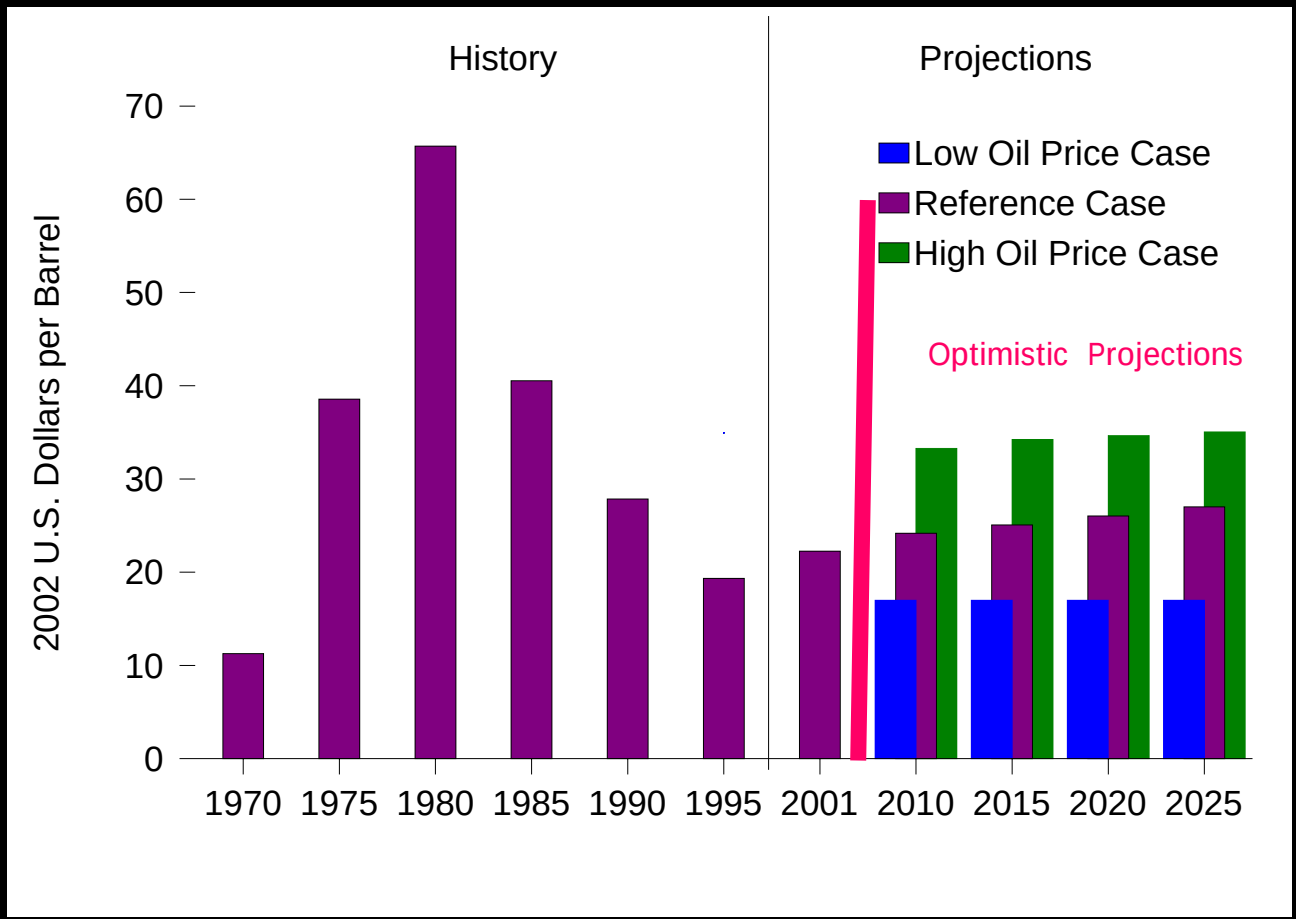
Source: Prediction of world peak oil production, Seppo A. Korpela, Ohio State University, 2003

Annual World Oil Production



Source: Prediction of world peak oil production, Seppo A. Korpela, Ohio State University, 2003

World Oil Prices



"International Energy Agency warned that if oil prices remained at $35 a barrel, or $10 above their 2001 levels, that would slash at least half a percentage point from world G.D.P. the next year"

NY times - August 11, 2004 - Global oil demand expected to exceed forecasts, Report says

$60 a Barrel will reduce the world GDP by 1.75% from 2001 levels (~ $785 Billion)

Source: EIA, *International Energy Outlook 2004*

Fossil Fuel Future

Dwindling reserves versus worldwide growth in demand will lead to energy prices beyond consumer's ability to pay - leads to political tension and violence.

Conventional oil and gas reserves will probably be exhausted between 2040 and 2050.

Coal is the worst possible fossil fuel (most polluting of the fossil fuels and the one that produces the greatest amount of the greenhouse gas CO_2 per unit energy), but the world has at least a 150 year supply of coal.

"Within a few generations at most, some other energy than that of combustion of fuel must be relied upon to do a fair share of the work of the civilized world."

*Robert H. Thurston** - *1901 in the Smithsonian Institution annual report*.

* Professor of Engineering at Cornell University

Major Global Climate Issues

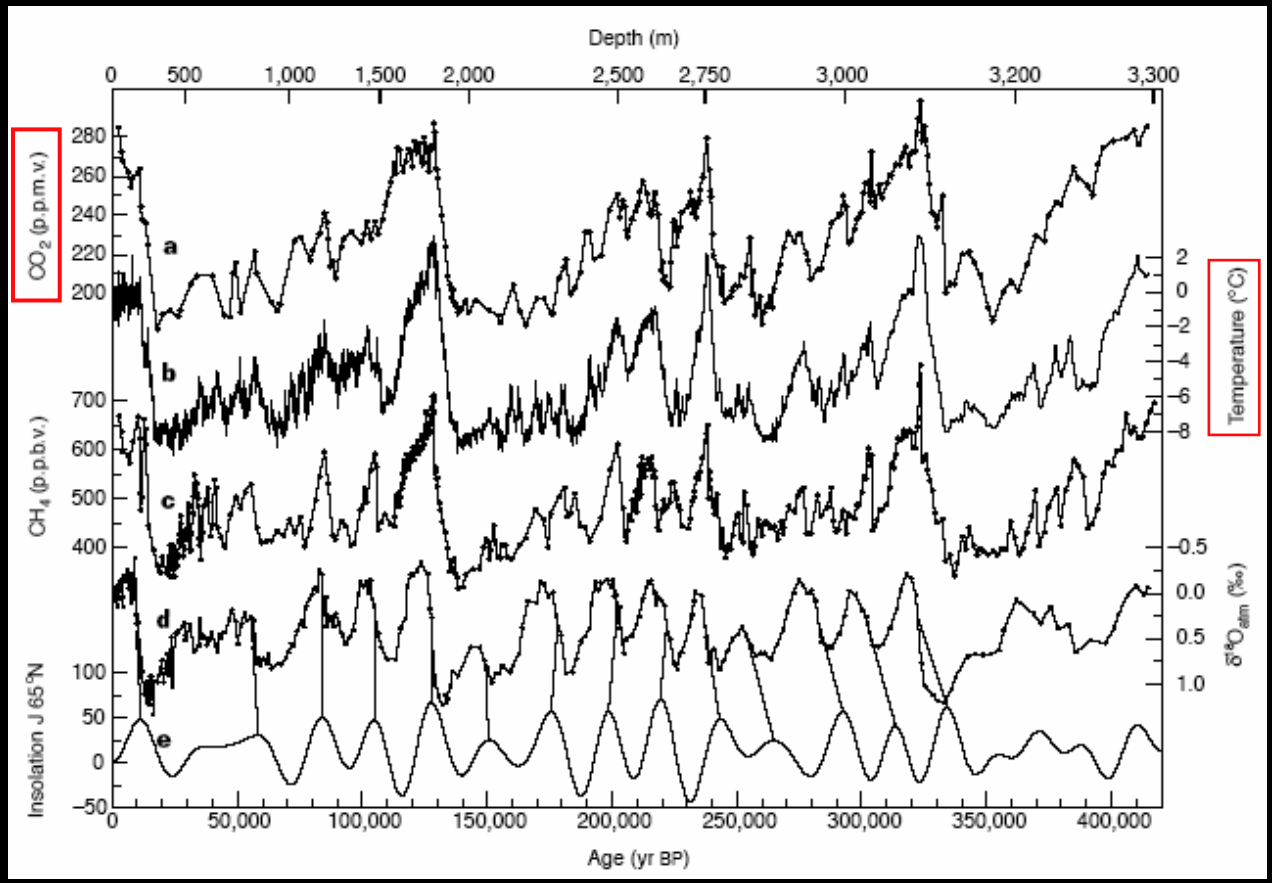
- Global stratospheric ozone (O_3) Reduction
- Global warming

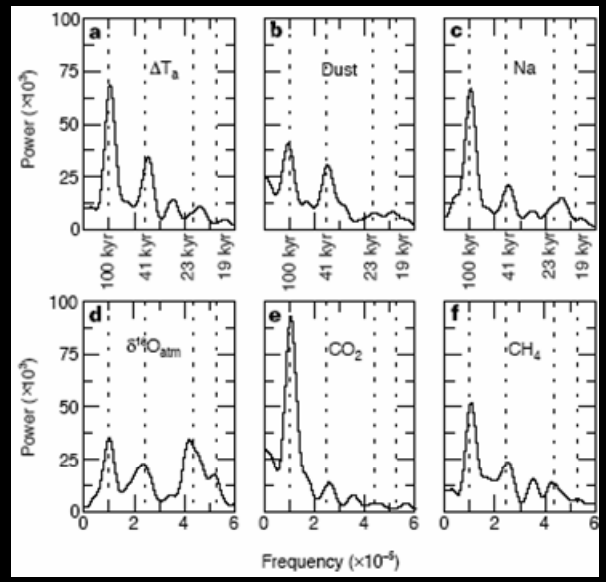
Climate Change

"Collapse of Mayan civilization is attributed to two centuries of dryness about 1100 years ago."

"About 5000 years ago a sudden drying converted the Sahara from a green landscape dotted with lakes to the scorching, sandy desert it is today." - Scientific American, November 2004.

Climate & Atmospheric History of the Past 420,000 years



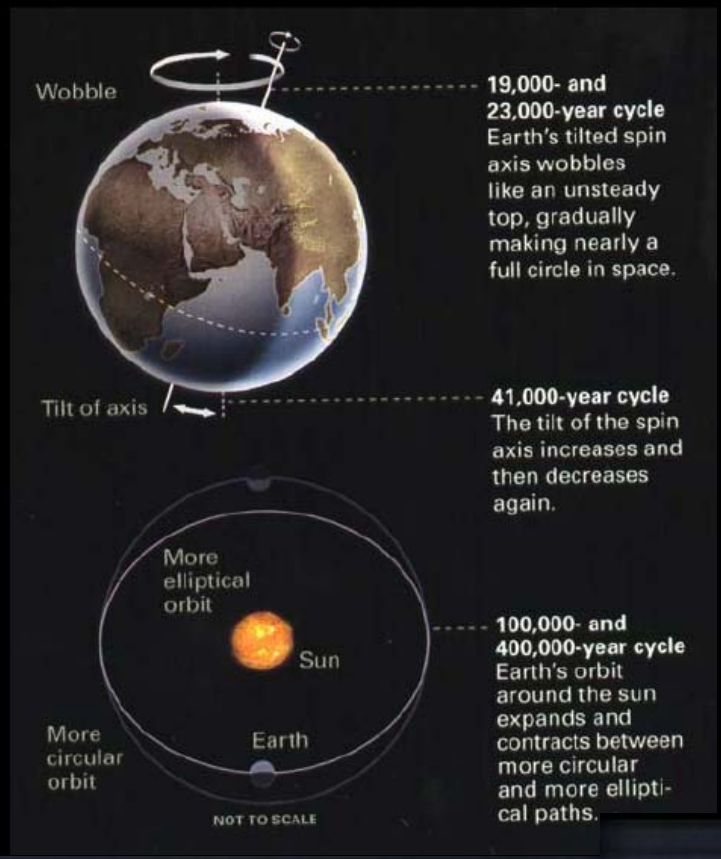


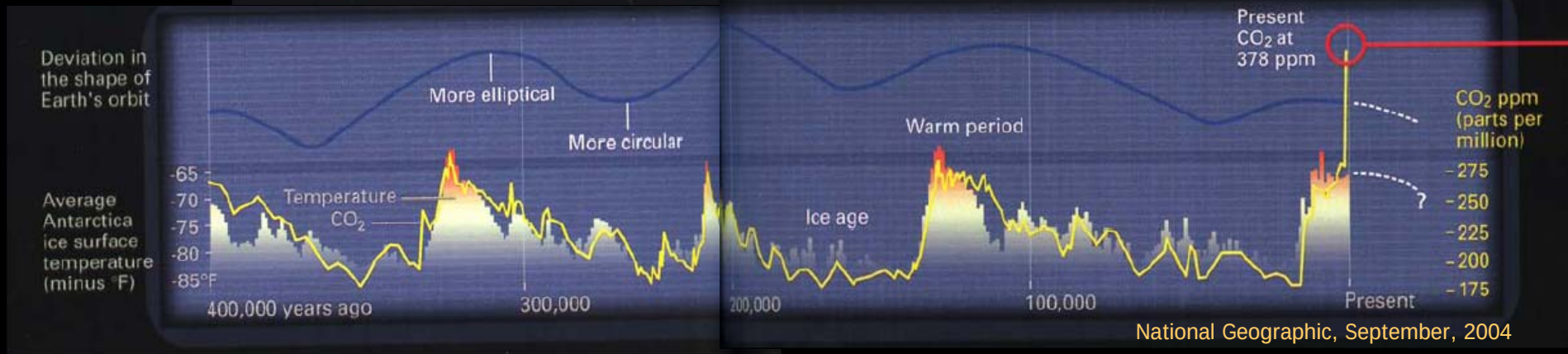
Spectral properties

Ref: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, J.R. Petit et.al, Nature, 399, 3, June 1999, 429 - 436.

Milankovitch cycles

Caused by gravitational attraction between planets of the solar system and Earth due to changes in the eccentricity of the Earth's orbit, obliquity of the Earth's axis and precession of the Earth's axis of rotation.

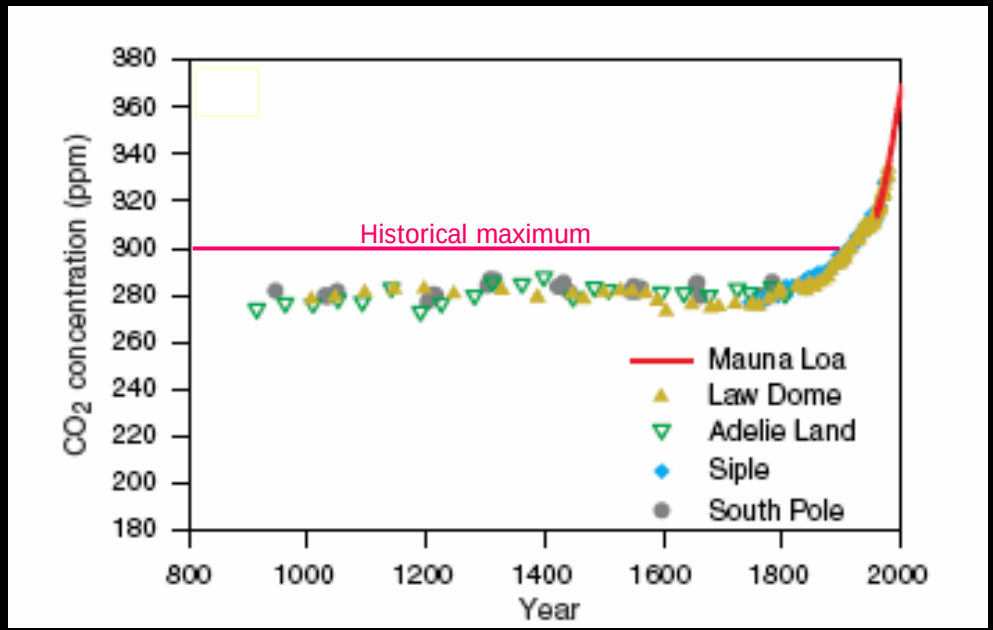




National Geographic, September, 2004

CO_2 Concentrations

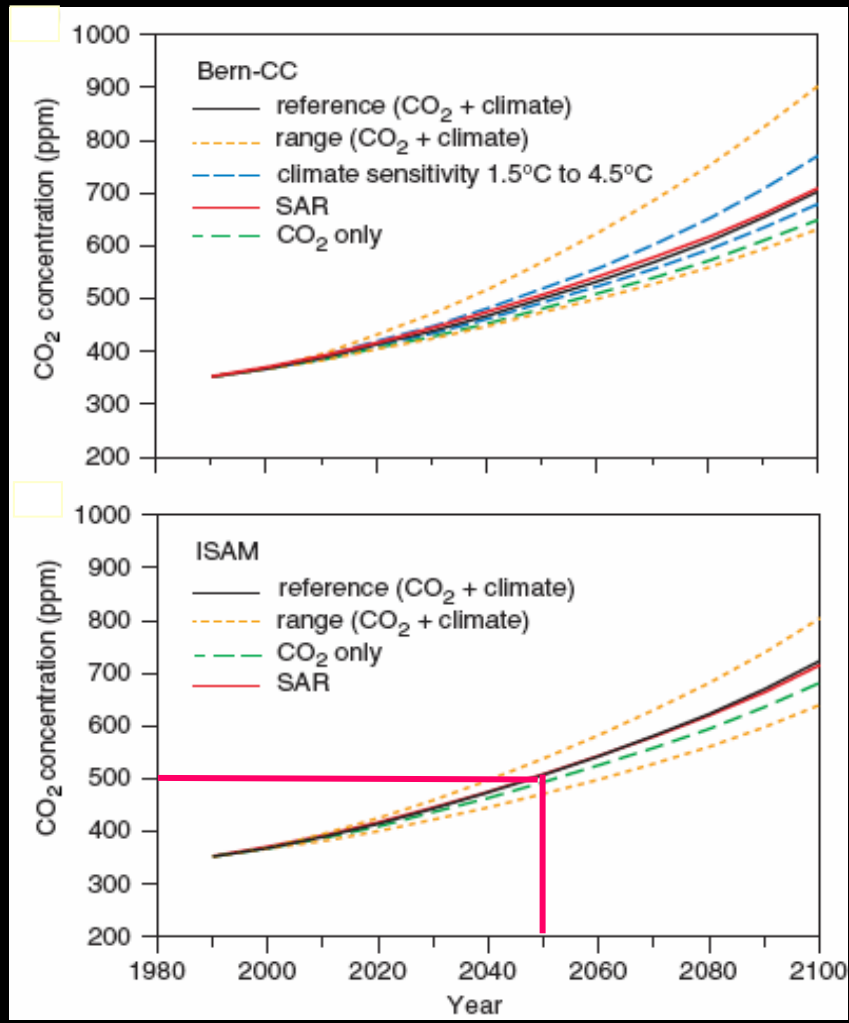
Recent past concentrations



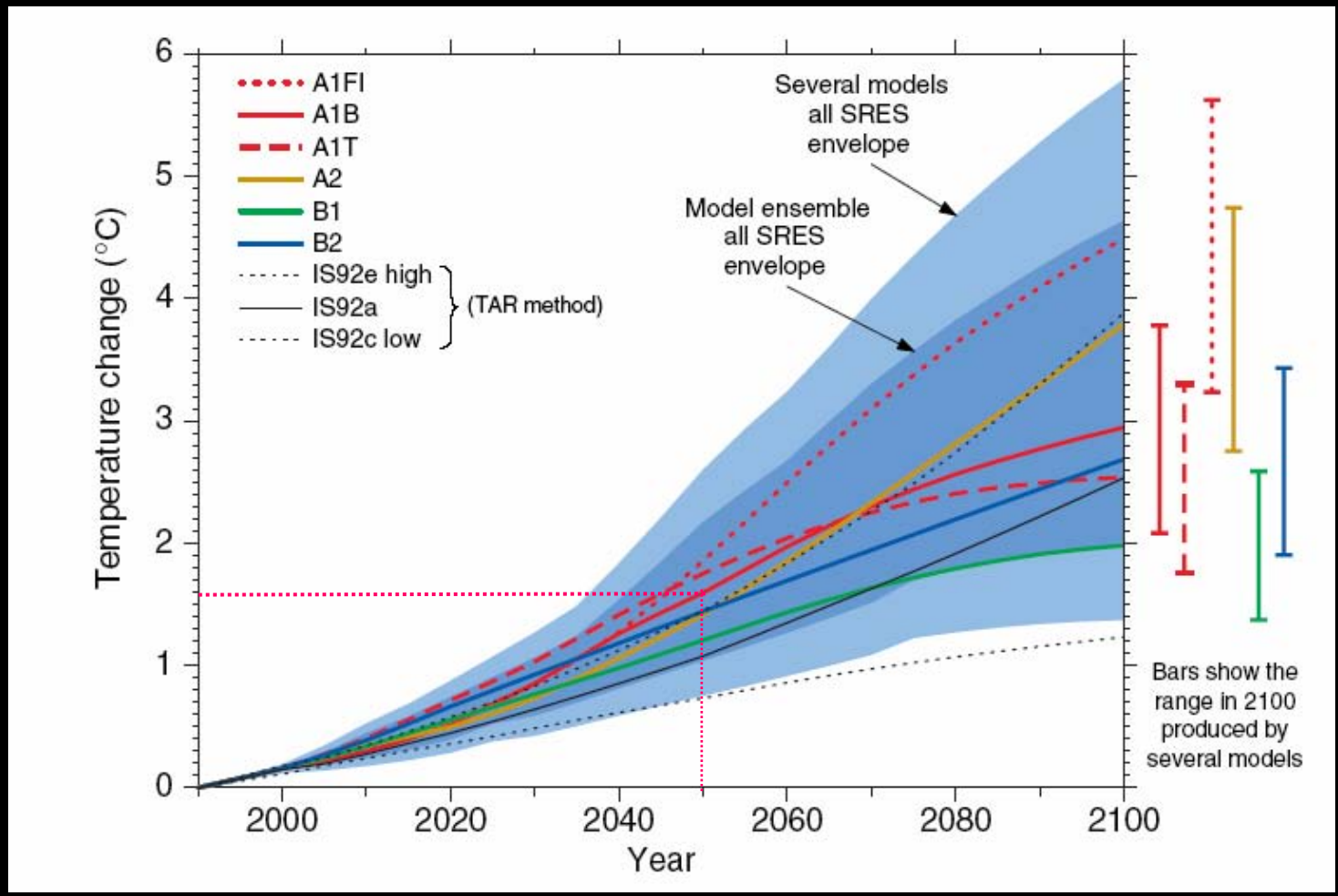
376 ppm in 2003

379 ppm in 2004

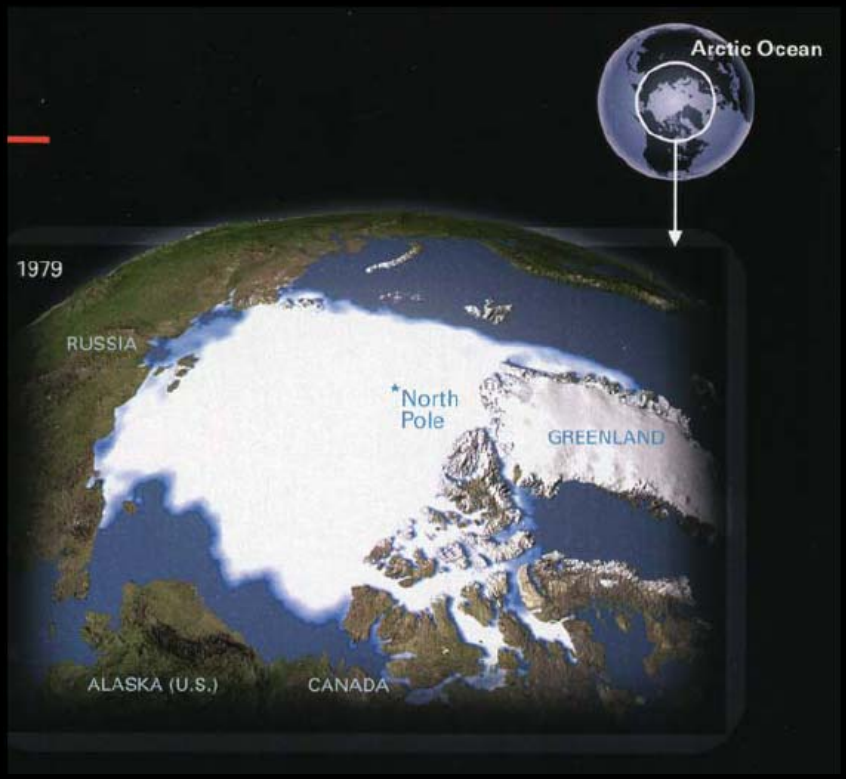
Projected concentrations



Global Temperature Change



Arctic Ice Cap



"Global warming should be more of worry than ever: it could be pushing the earth's climate closer to the thresholds that could unleash sudden changes faster"

China - Environment

Afternoon rush hour, cars clog Beijing's second ring road

Cyclists ride through the smog that hangs over Beijing's Tiananmen square

China - Environment

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China - Environment

400,000 people die prematurely every year in China from diseases linked to air pollution.

On certain days almost 25 percent of the particulate matter clotting the skies above Los Angeles can be traced to China.

China could eventually account for roughly a third of the California's air pollution.

China is wrestling with a lot of the same pollution problems that US wrestled with several years ago and that, to some extent, still grappling with today.

A law taking effect next year will require that China produce 10 percent of its energy from renewable sources by 2020.

Source: NY times, October 30, 2005, China's next big boom could be the foul air.

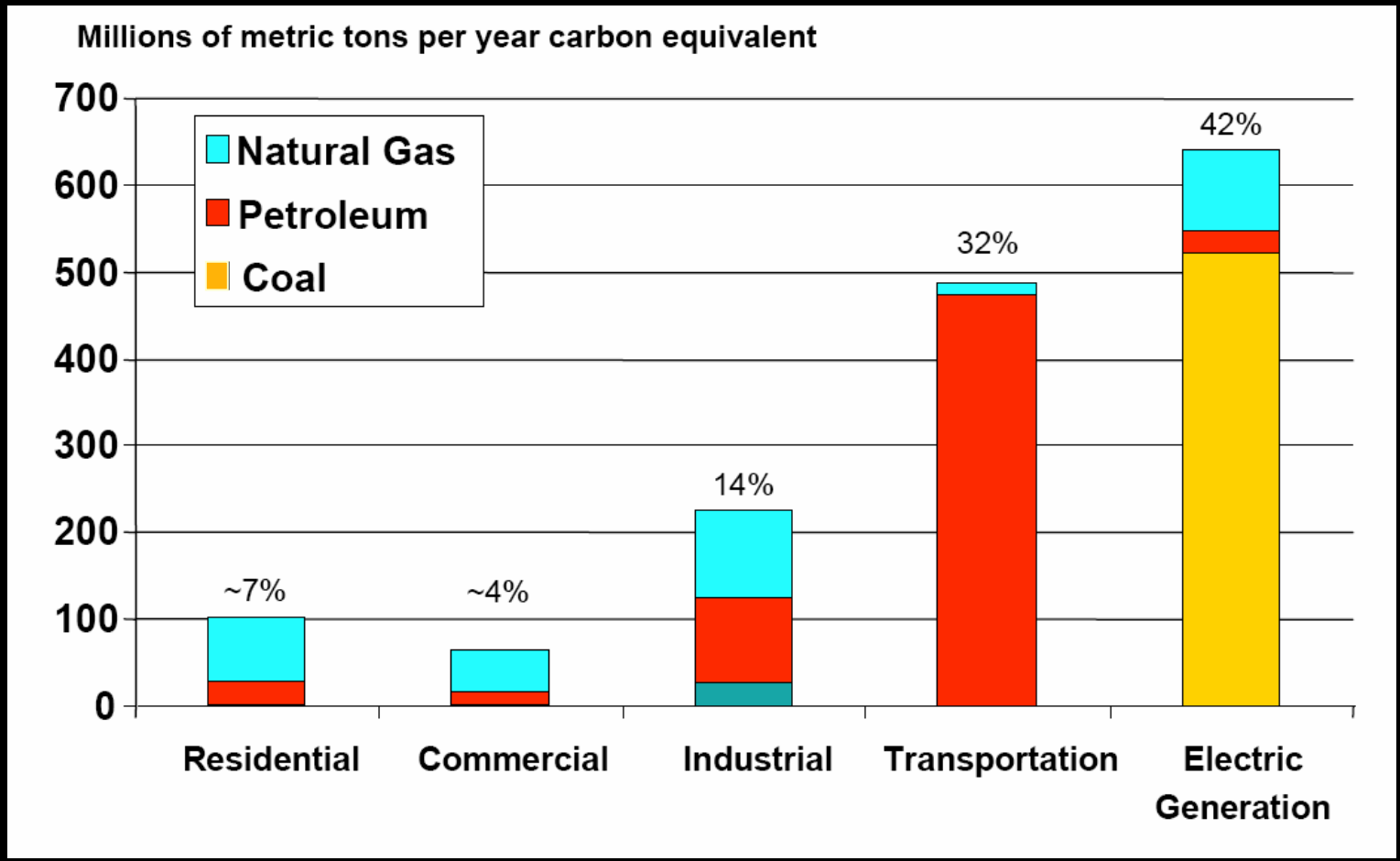
Climate Change - View point

"We have sufficient evidence that human-made climate change is the most far-reaching and almost certainly the most threatening of all the environmental challenges facing us," Gordon Brown, Britain's finance minister

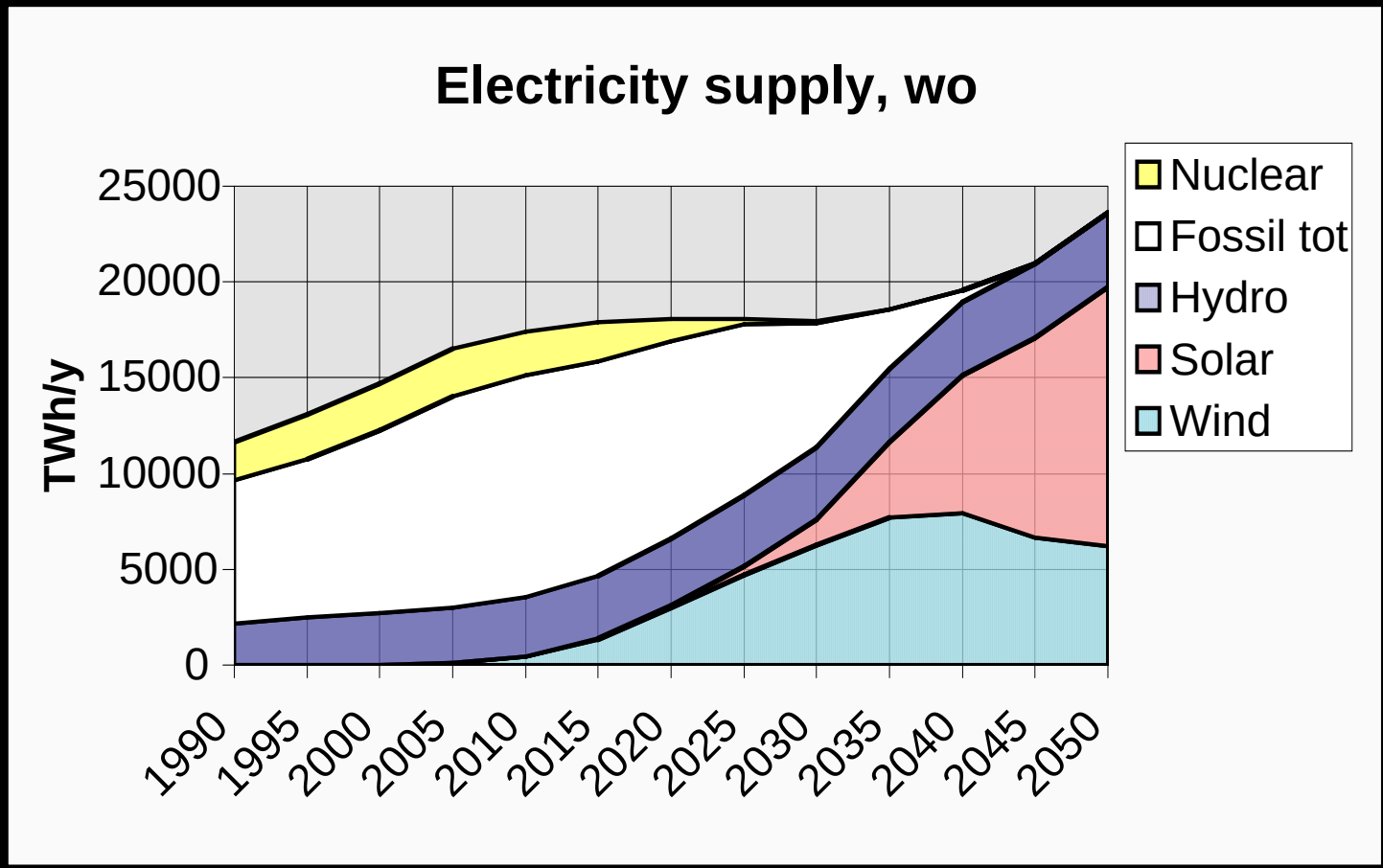
"We are still working on the issue of causation, the extent to which humans are a factor" in Global Warming - James L. Connaughton, chairman of the US Council on Environmental quality

Source: NY Times, March 16, 2005; http://nytimes.com/2005/03/16/international/asia/16climate.html

US CO_2 Emissions in 2000



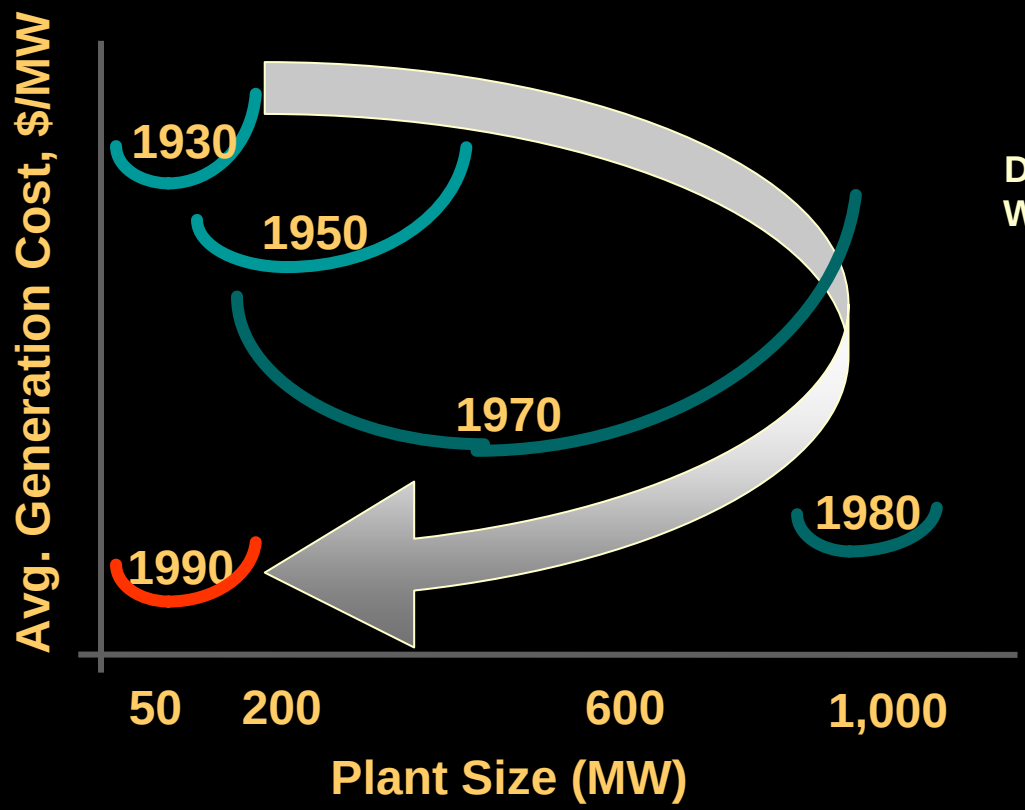
Sustainable Energy Vision



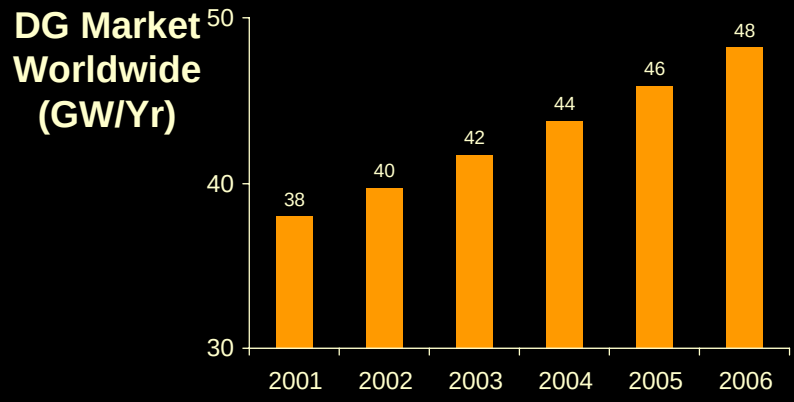
Source: Sustainable energy vision 2050, **Gunnar Boye Olesen**, INFORSE-Europe coordinator, Gl. Kirkevej 56, DK 8530 Hjortshoej, Denmark, email ove@inforse.org. Rio 2002

Distributed Power

Optimal generation plant size for a single plant based on cost per megawatt [MW], 1930-1990



Source: Mervin Brown, NREL



Source: John Cassidy, United Technologies Corp.

Wind Energy Potential

Globally: 27% of earth's land surface is class 3 (250-300 W/m^2 at 50 m) or greater

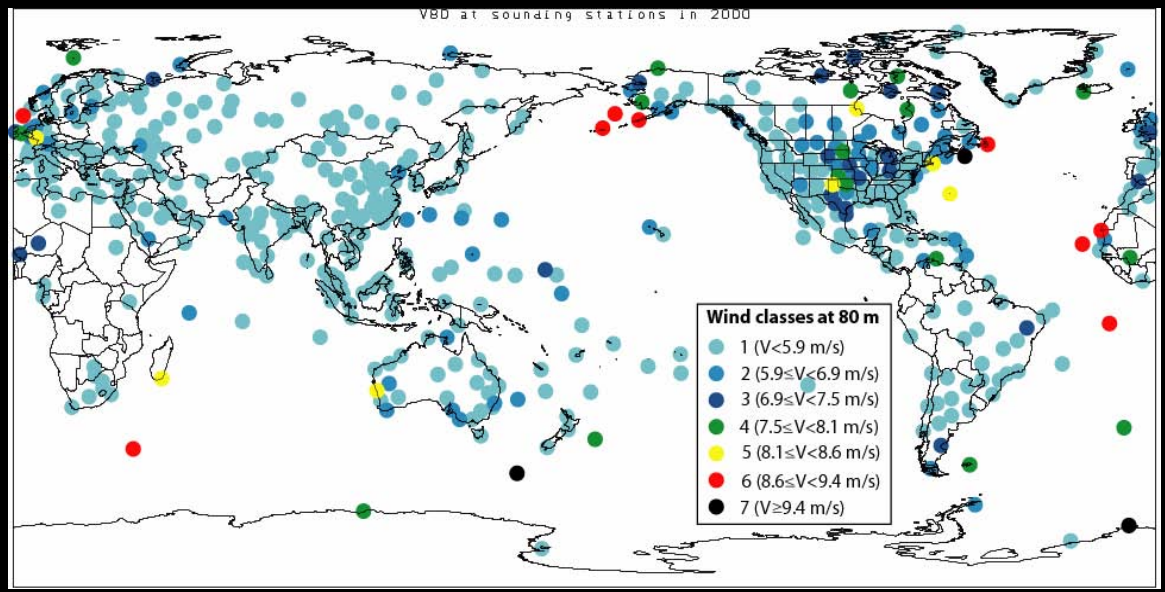
- potential of 50 TW

4% utilization of > class 3 land area will provide 2 TW

US: 6% of land suitable for wind energy development - 0.5 TW

US electricity consumption ~ 0.4 TW

Off shore installations provide additional resource



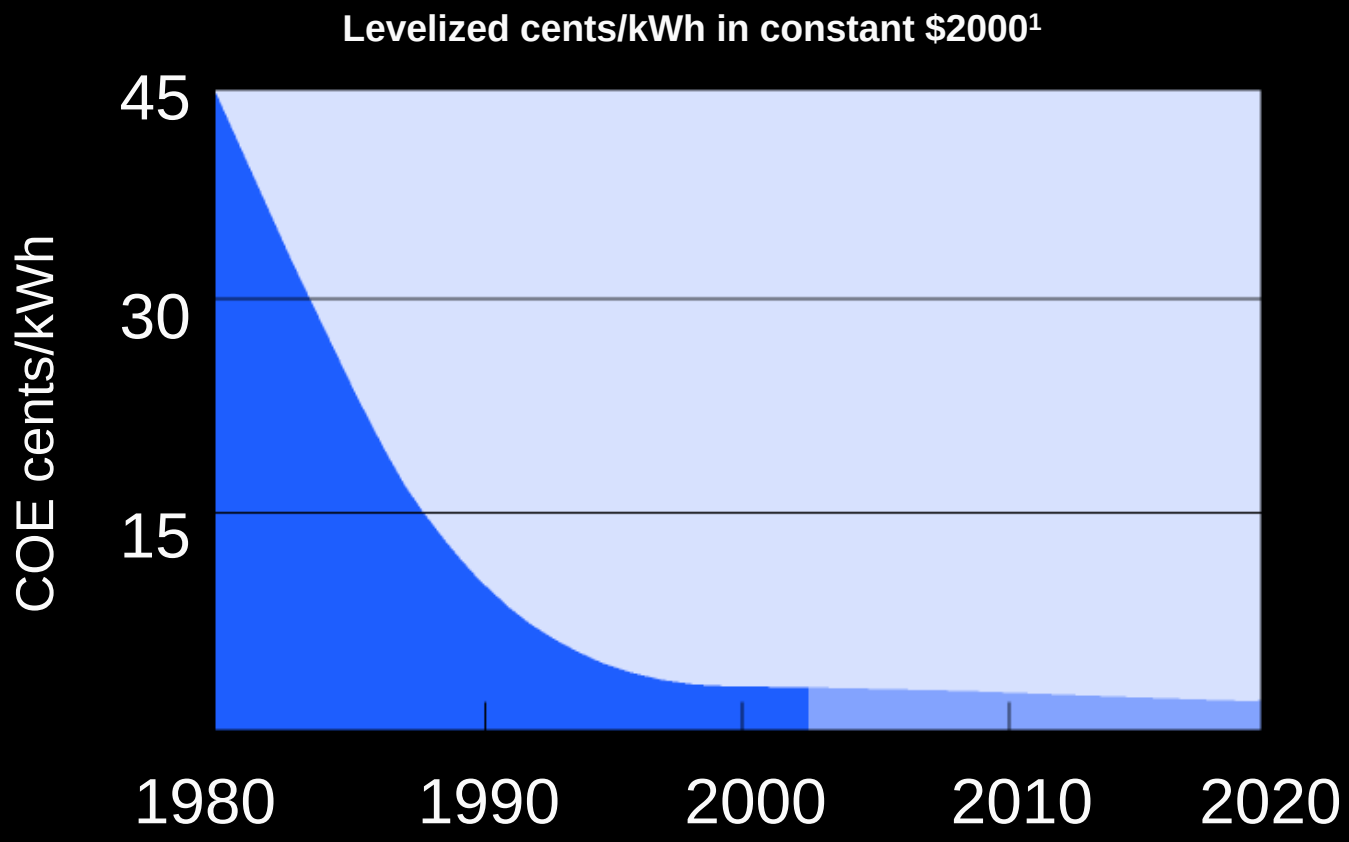
Cristina L. Archer and Mark Z. Jacobson, Evaluation of Global Wind Power, Stanford University, 2005

Enercon Offshore Prototype

Enercon 4.5MW 112 meter rotor

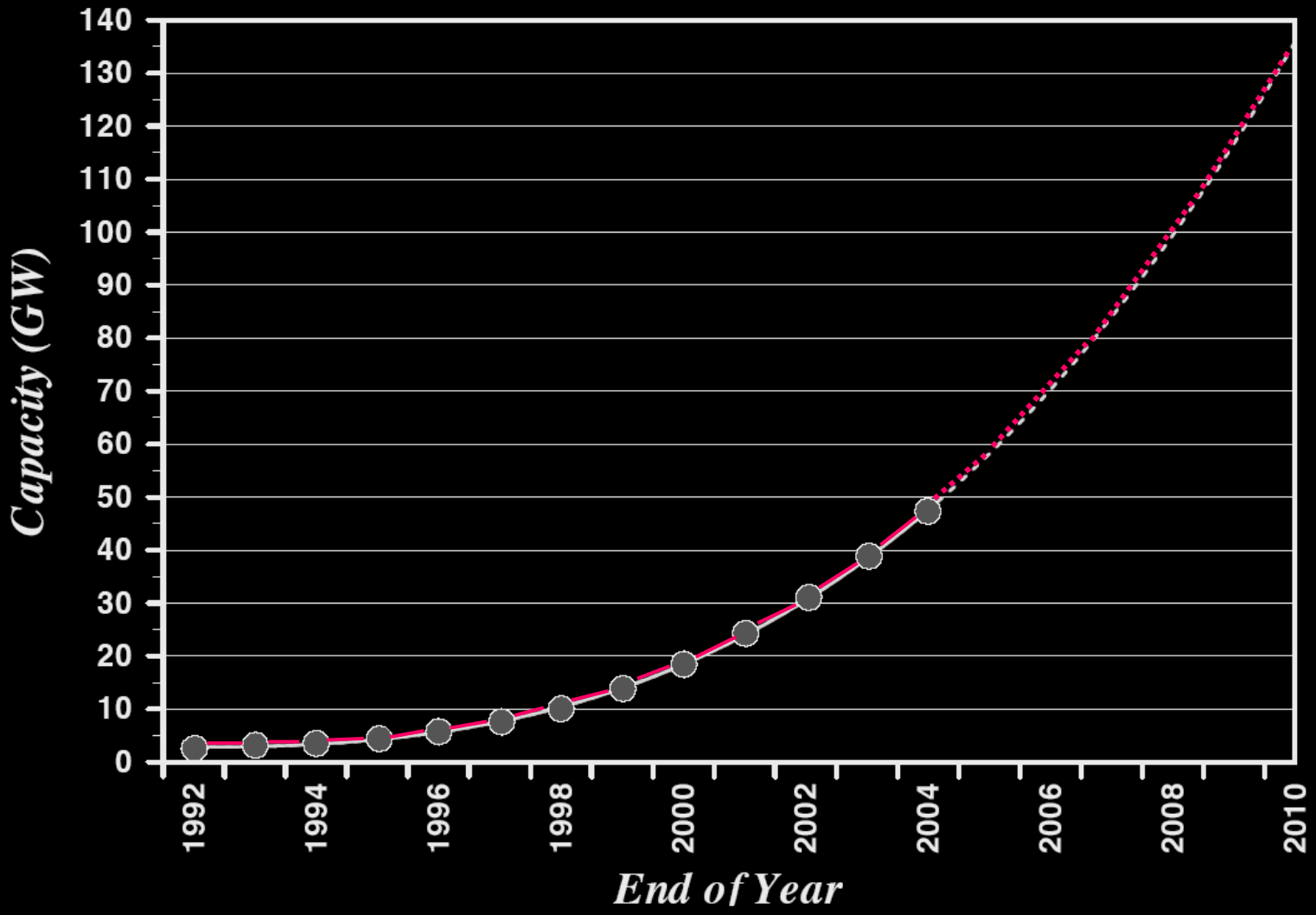
440 metric tonnes

Wind Energy Costs Trends



Source: NREL Energy Analysis Office
[1]These graphs are reflections of historical cost trends NOT precise annual historical data.
Updated: June 2002

Global Wind Energy Growth



Global Wind Energy

Country	2004 MW	% of total
Germany	16,629	35.1
Spain	8,263	17.5
United States	6,740	14.2
Denmark	3,117	6.6
India	3,000	6.3
Italy	1,125	2.4
Netherlands	1,078	2.3
United Kingdom	888	1.9
Japan	874	1.8
China	764	1.6

World Total: 47,317 MW

2004 Installations: 7,976 MW

Growth rate: 20%

2020 Prediction: 1,245,000 MW*

Equivalent to 1000 Nuclear power plants

12% of world electricity generation

* According to Wind Force 12

Solar Energy Potential

Theoretical: 1.76 x 10^5 TW striking Earth; 0.3 Global mean albedo

Practical: 600 TW

Conversion Efficiency: 10%

Electricity generation potential = 60 TW

Estimated Global Demand in 2050 = 20 TW

Solar Cell Land Area Required

6 Boxes at 3.3 TW Each = 20 TW

Solar Electricity

Solar-thermally generated electricity: Lowest cost solar electric source.

Complex collectors to gather solar radiation to produce temperatures high enough to drive steam turbines to produce electric power.

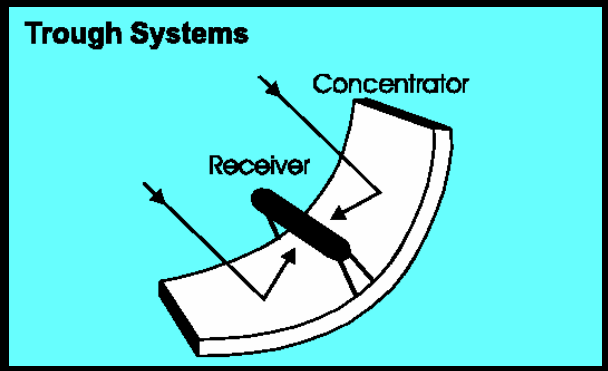
For example, a turbine fed from parabolic trough collectors might take steam at 750 K and eject heat into atmosphere at 300 K will have a ideal thermal (Carnot) efficiency of about 60%. Realistic overall conversion (system) efficiency of about 35% is feasible.

Solar Photovoltaic energy:

The direct conversion of sun's rays to electricity.

The efficiency (the ratio of the maximum power output and the incident radiation flux) of the best single-junction silicon solar cells has now reached 24% in laboratory test conditions. The best silicon commercially available PV modules have an efficiency of over 19%.

Parabolic-Trough Technology



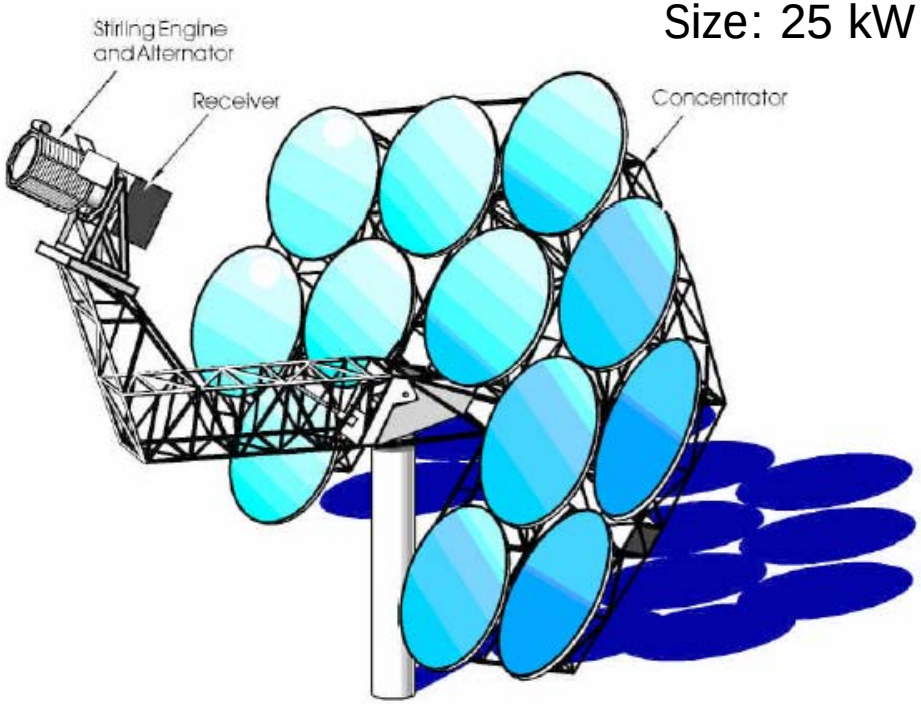
Parabolic trough-shaped mirrors to focus sunlight on thermally efficient receiver tubes that contain a heat transfer fluid.

Fluid Temperature: 665 K

Nine trough systems, built in 1980's are currently generating 354 MW in southern California

Source: US DOE

Solar Dish-engine

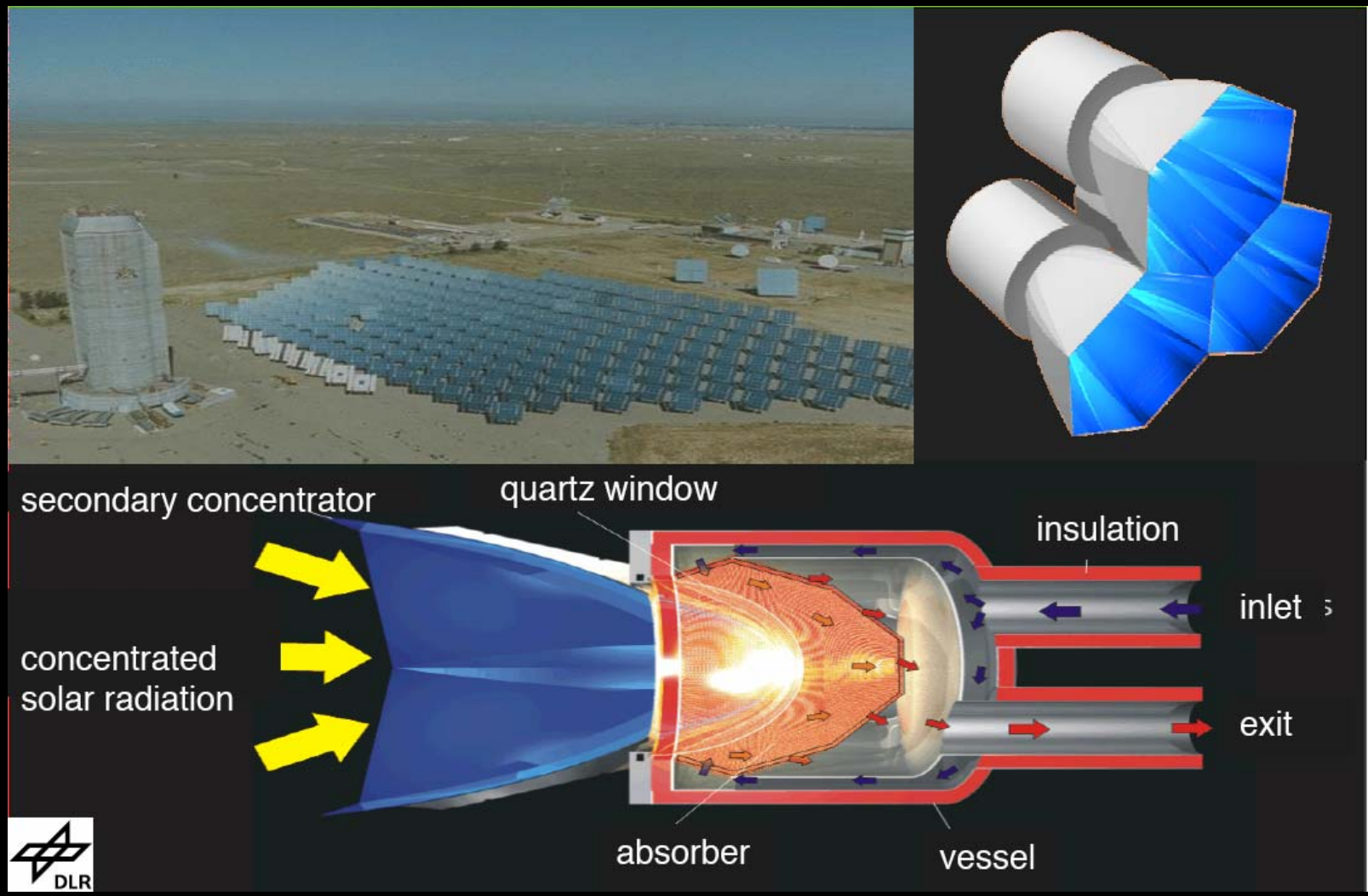


Stirling energy systems signed a 20 year power purchasing agreement with Southern California Edison to provide 500 MW power using 20,000 dishes (11.3m in diameter) in the Mojave Desert. The project occupies 18 km^2 of land area. The solar generator efficiency peaks at 29.4%.

Power costs are expected to be significantly less than US peak rate of 11.33 cents/kWh

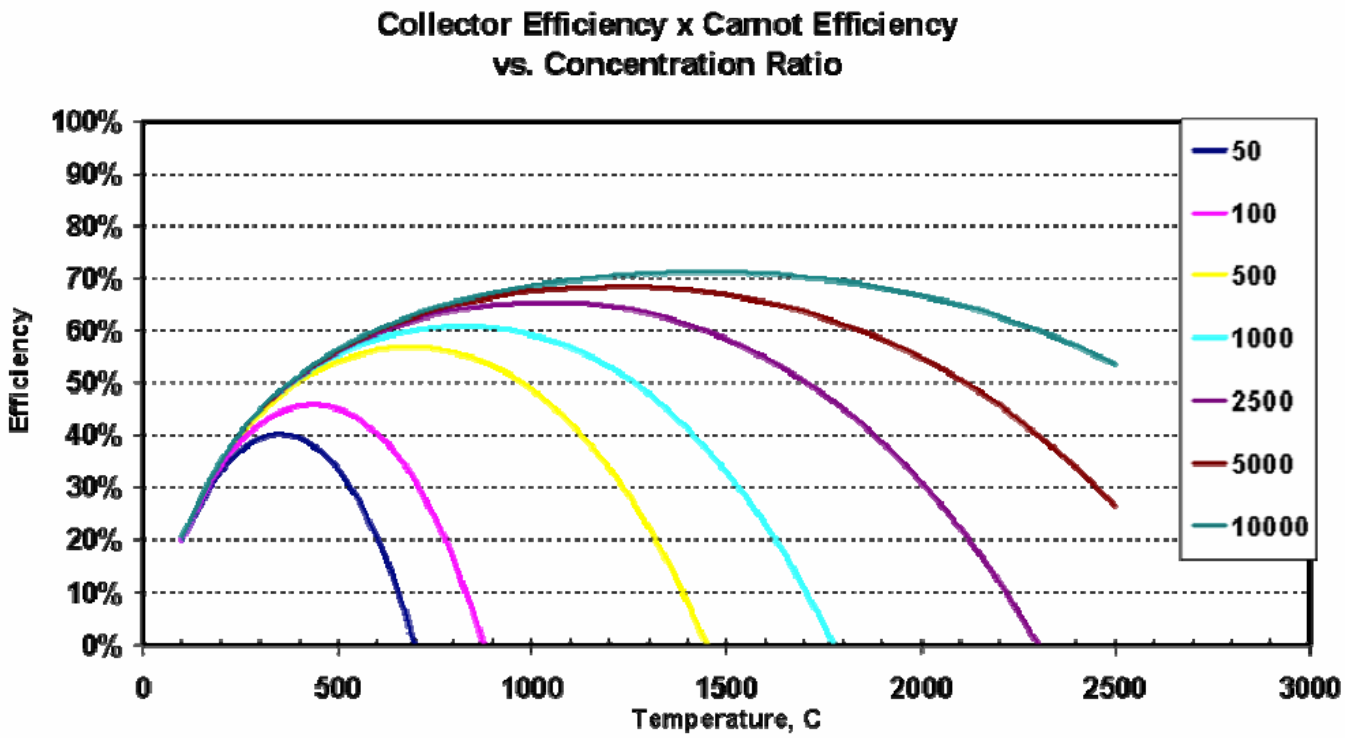
Source: IEE Review, October 2005

Advanced Tower

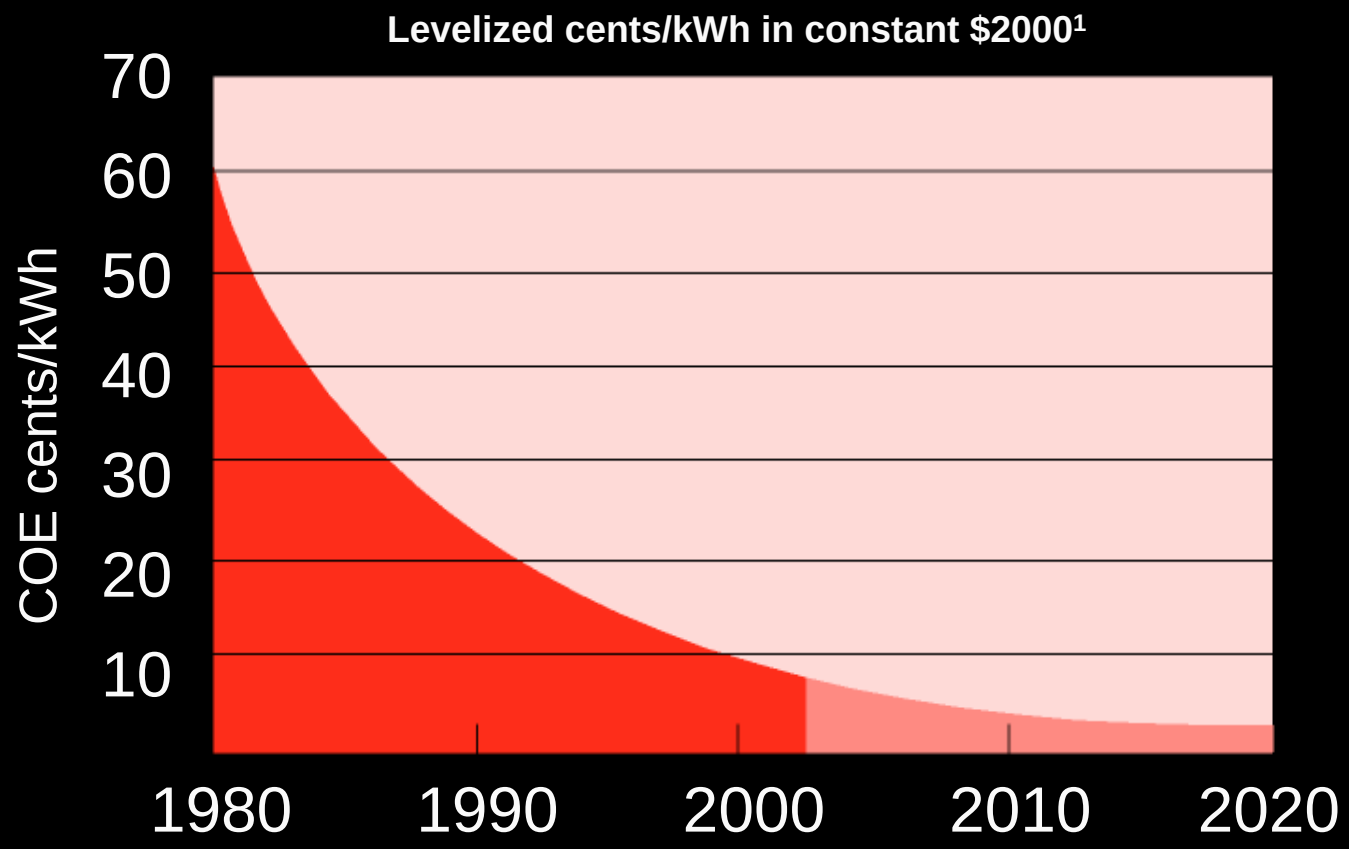


System Efficiency

$$\eta_{system} = \eta_{collector} * \eta_{process}$$

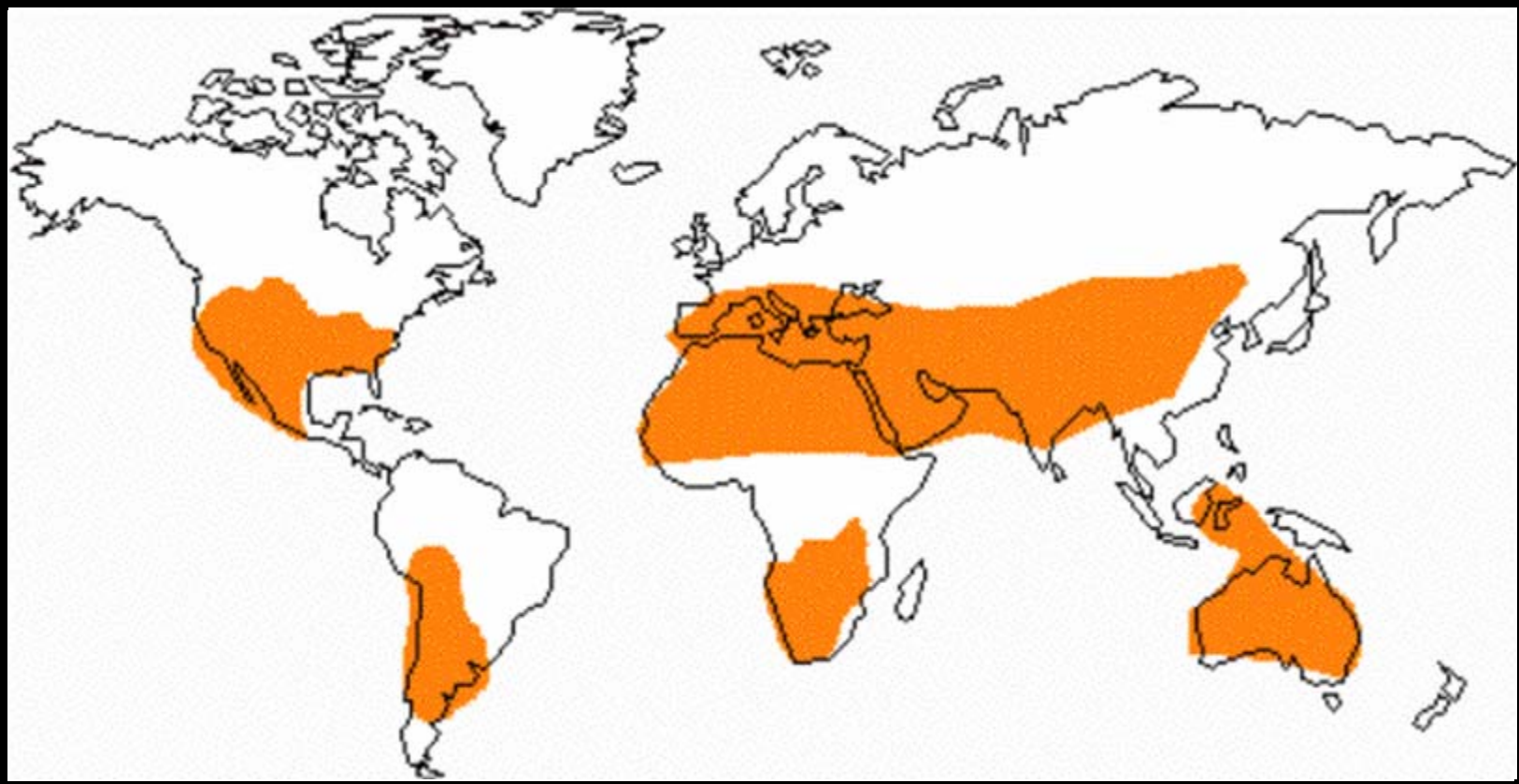


Solar Thermal

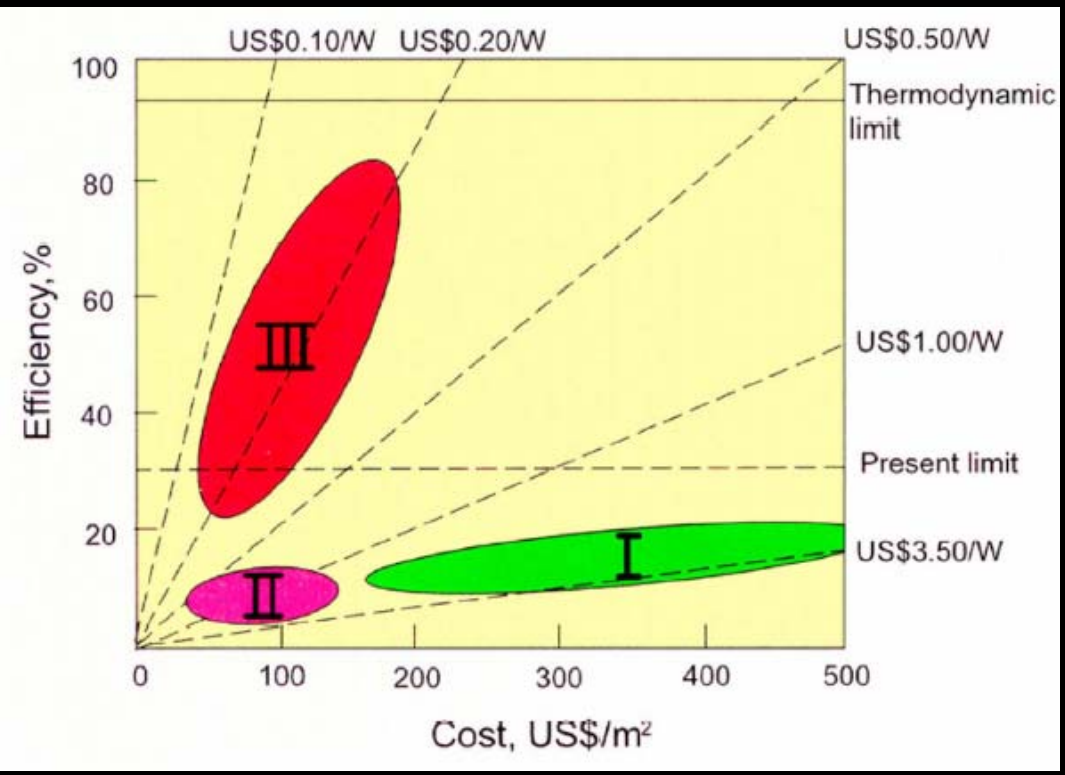


Solar Thermal Power Plant Potential

Comparably low power generation costs can be achieved wherever insolation reaches 1,900 kWh per square meter and year or more.



Photovoltaic Energy Conversion



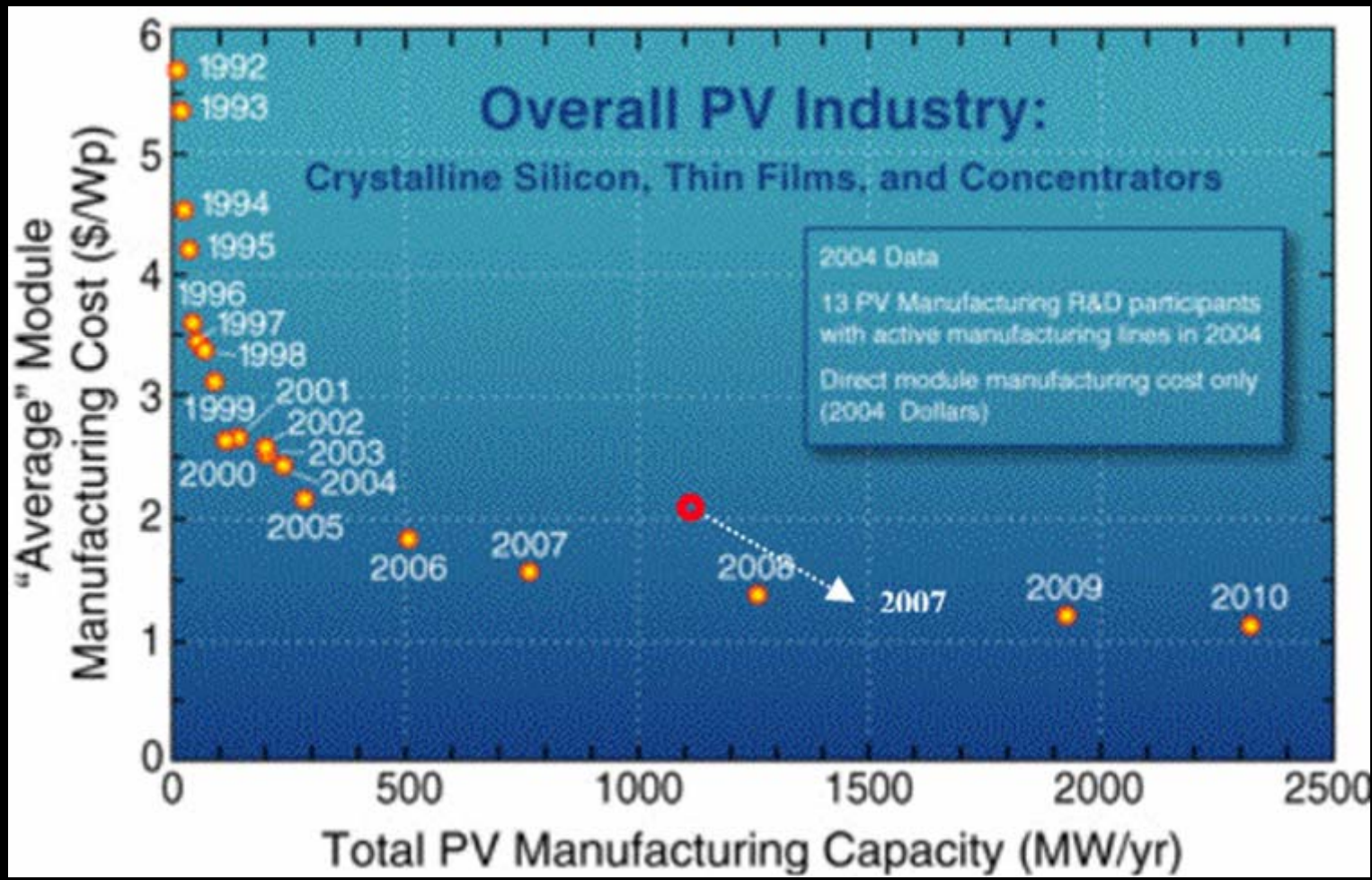
First generation (I): Crystalline PV

Second generation (II): Thin Film PV

Third generation (III): Based on nanotechnology using collections of atoms of semiconducting material. Films containing nanocrystalline structures and nanostructured conducting polymers are designed to absorb much of the solar spectrum. This technology will lead to PV cells made from thinly stacked plastic sheets converting solar energy to electricity with very high efficiency and at very low cost.

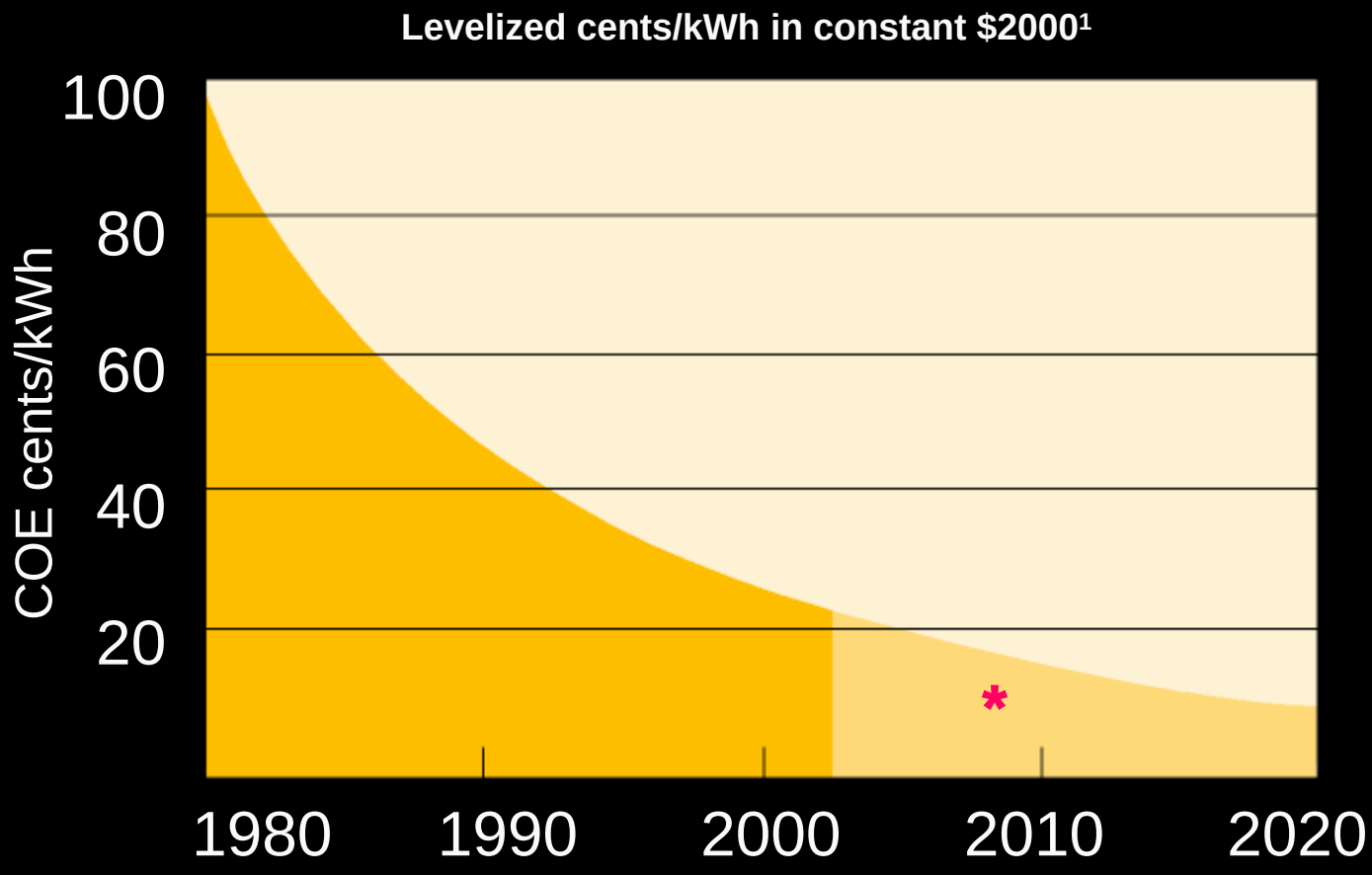
Photoelectrochemistry, an area of confluence between solar cell technology and battery or fuel cell technology, is playing role in the development of organic solar cells.

Cost of Photovoltaic Modules



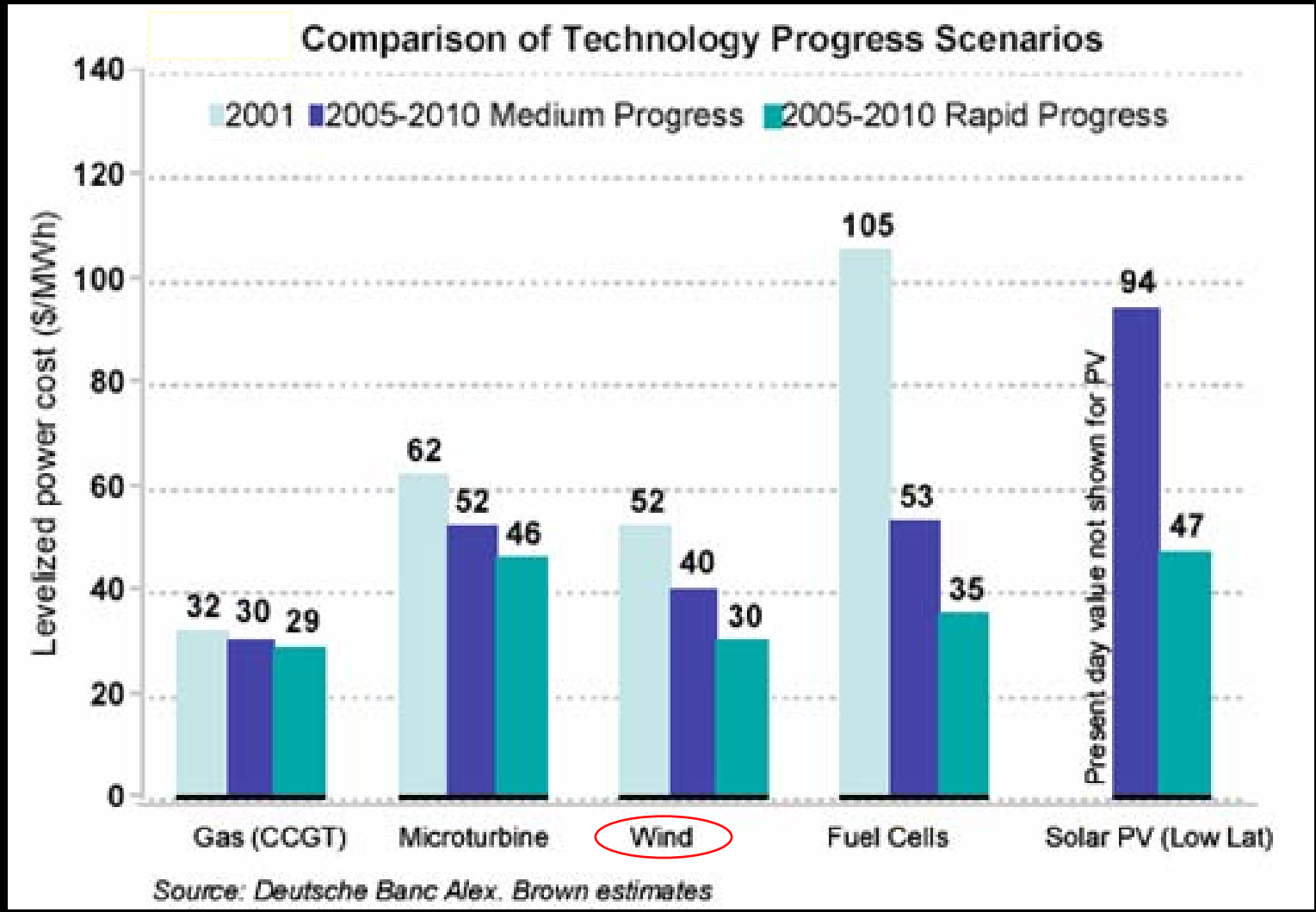
Starting in 2006 China's production: 400 MW_p/year

Photovoltaics Cost of Energy



Peak electricity cost in USA: 11.3 cents/kWh

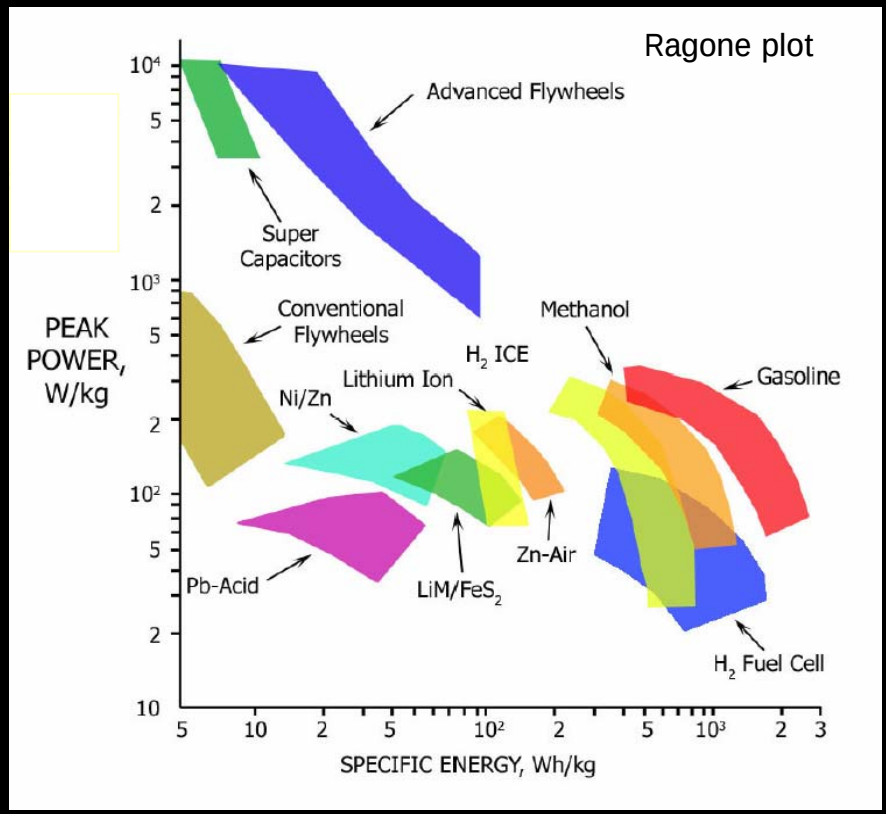
Power Cost


Comparison of Technology Progress Scenarios
2001
2005-2010 Medium Progress
2005-2010 Rapid Progress
Levelized power cost ($/MWh)
140
120
100
80
60
40
20
0
32
30
29
62
52
46
52
40
30
105
53
35
94
47
Present day value not shown for PV
Gas (CCGT)
Microturbine
Wind
Fuel Cells
Solar PV (Low Lat)
Source: Deutsche Banc Alex. Brown estimates

Renewable Energy Storage

Solar and wind energy sources are intermittent and regional.

They will become major sources of power if we find efficient ways to store and transport their energy.



Source: J.W.Tester, Sustainable Energy, MIT, 2005

Renewable Energy Storage and Fuel for Transportation

Hydrogen, the simplest molecule, can be used for storing energy and make it available where and when it is needed.

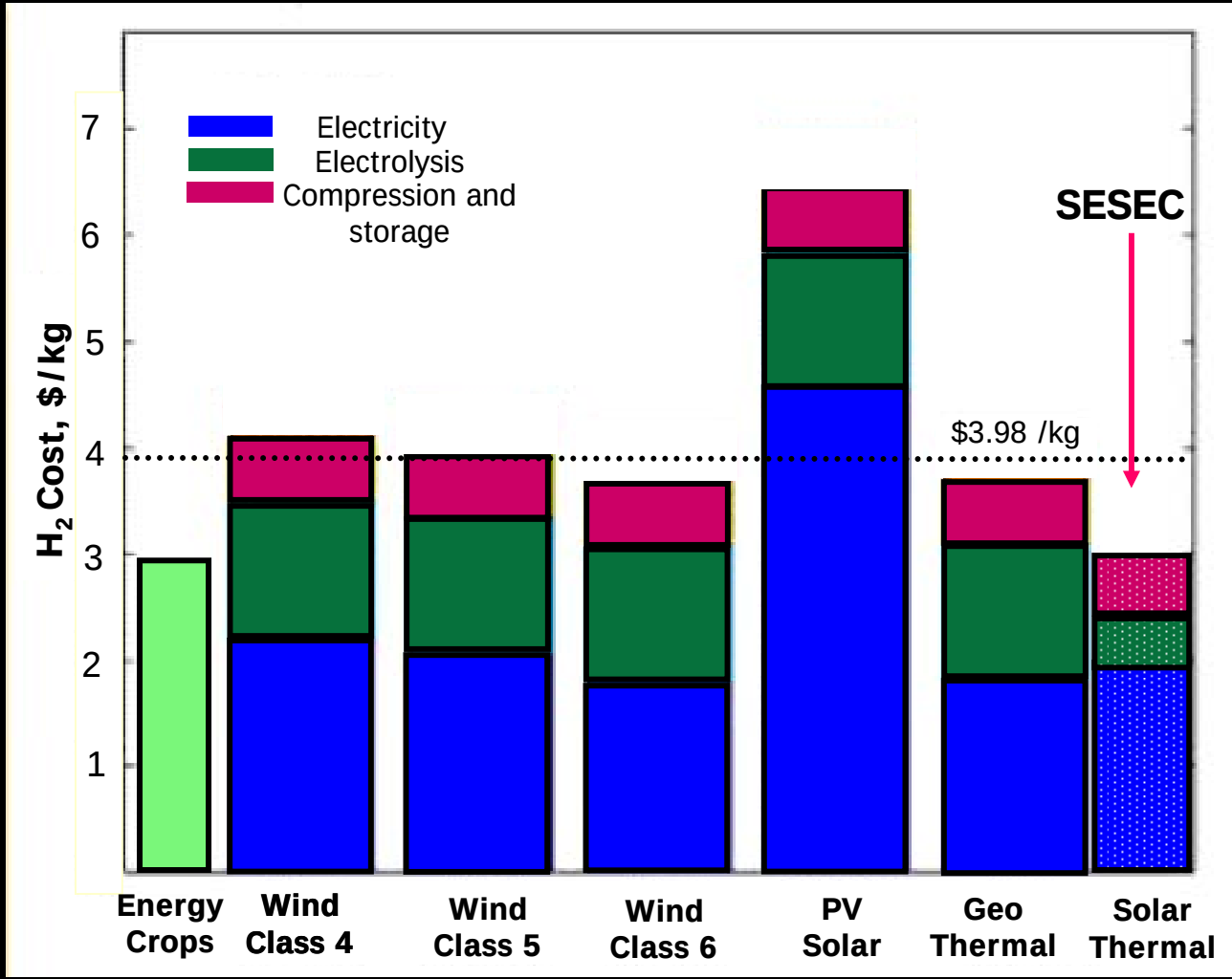
When used as a chemical fuel, it does not pollute

Hydrogen is not an energy *source* , but it is an energy *carrier* that has to be manufactured like electricity.

Hydrogen can be manufactured from many primary sources (from clean water and solar energy) - reduces the chances of creating a cartel.

Hydrogen Cycle: electrolysis → storage → power conversion

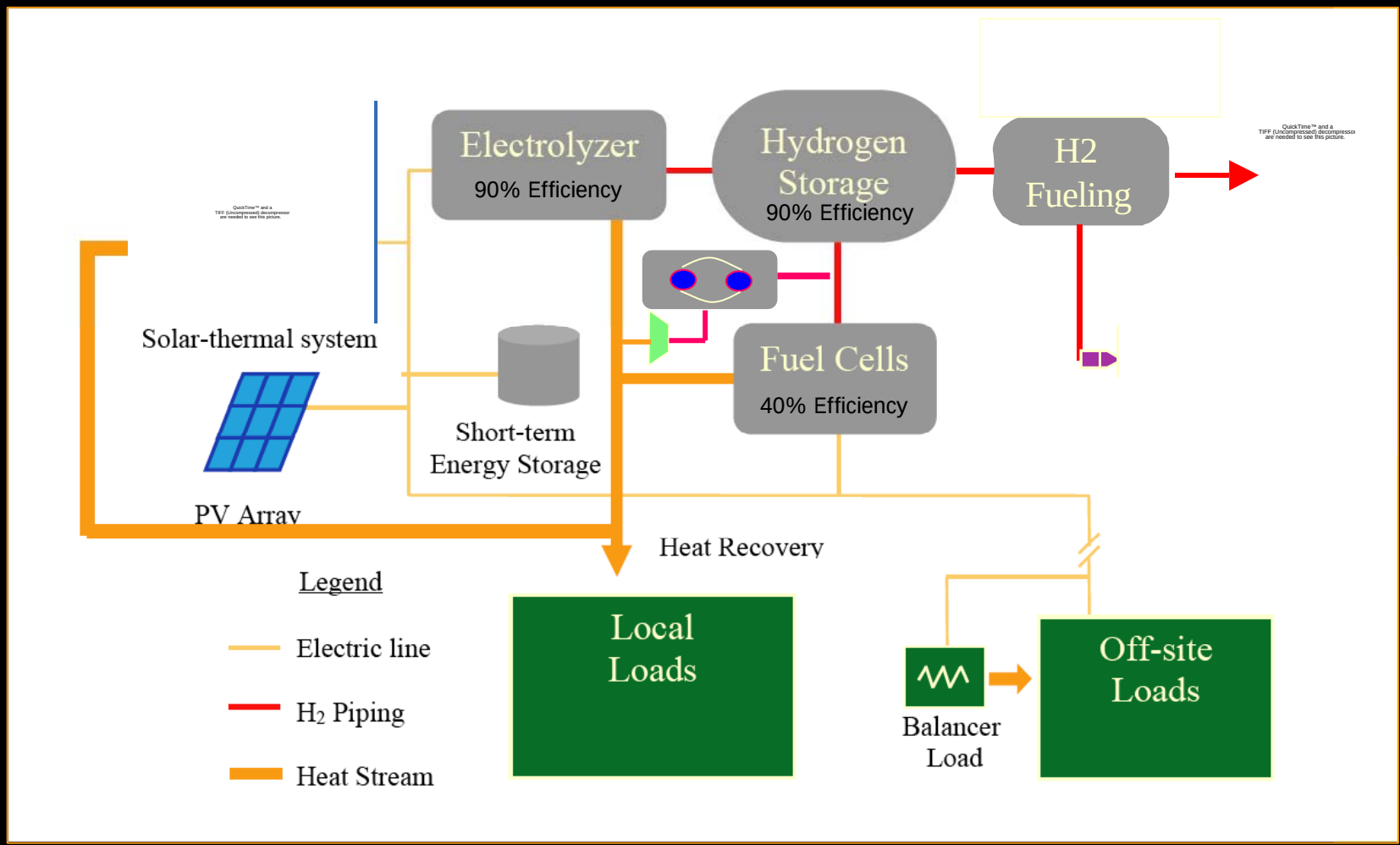
Renewable Hydrogen Cost



One Kg of hydrogen has roughly the same amount of energy as in one gallon of gasoline

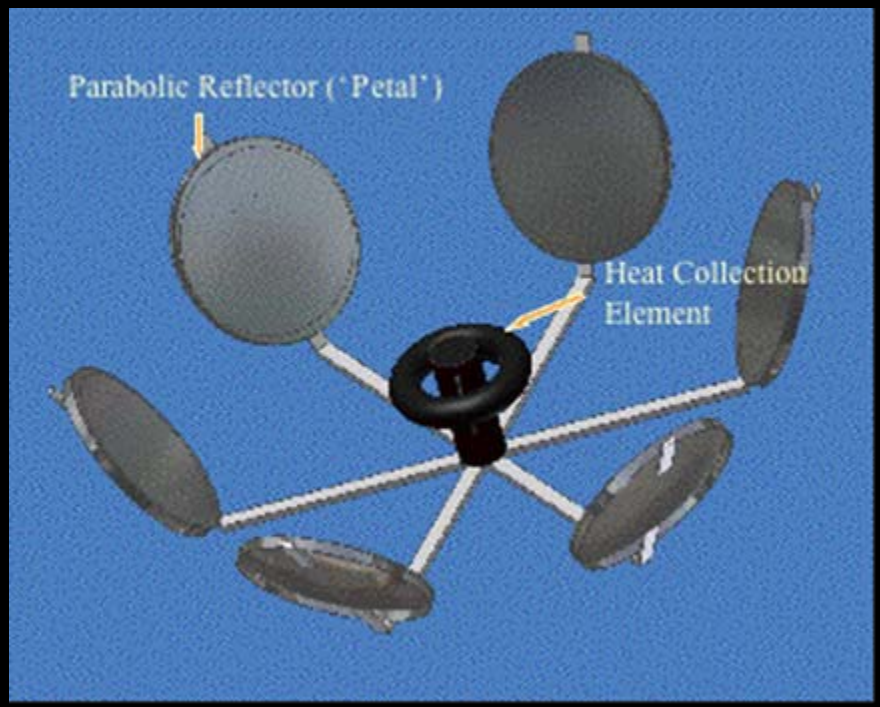
Duane B. Myers et al., 2003, Hydrogen from Renewable sources, Direct Technologies, inc, Arlington, VA 22201

SESEC Project - $1000/ kW



5 kW Solar-electricity & hydrogen generation System

Solar Concentrator

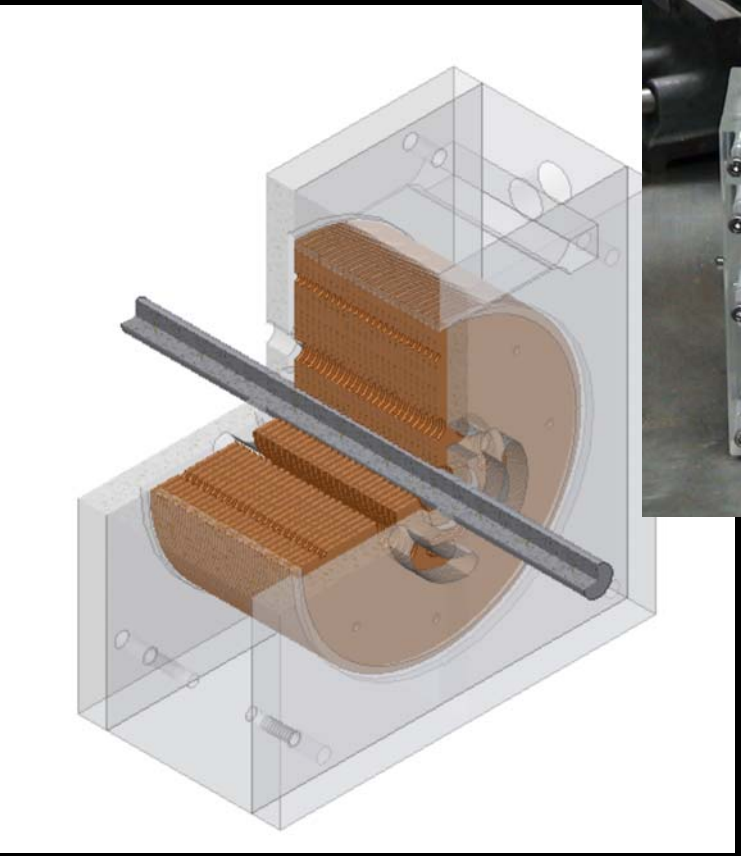


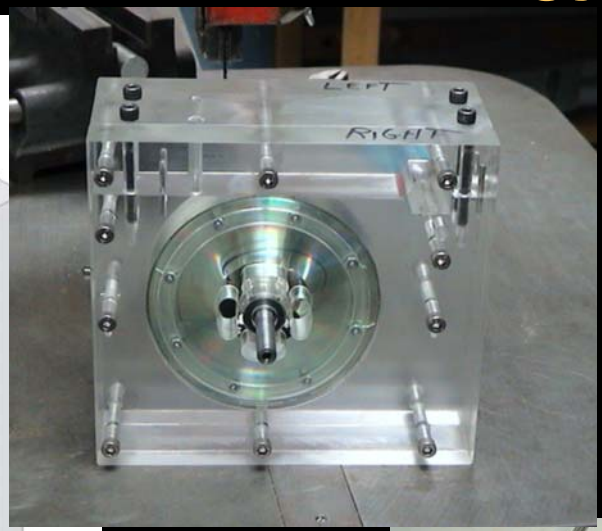
Steam generator

- Concentrates sunlight to a high temperature to 600K
  - Allows for the use of a heat engine for energy production at center focal point;

    ex. Tesla Turbine
- Each 'petal' independently moves and tracks the sun

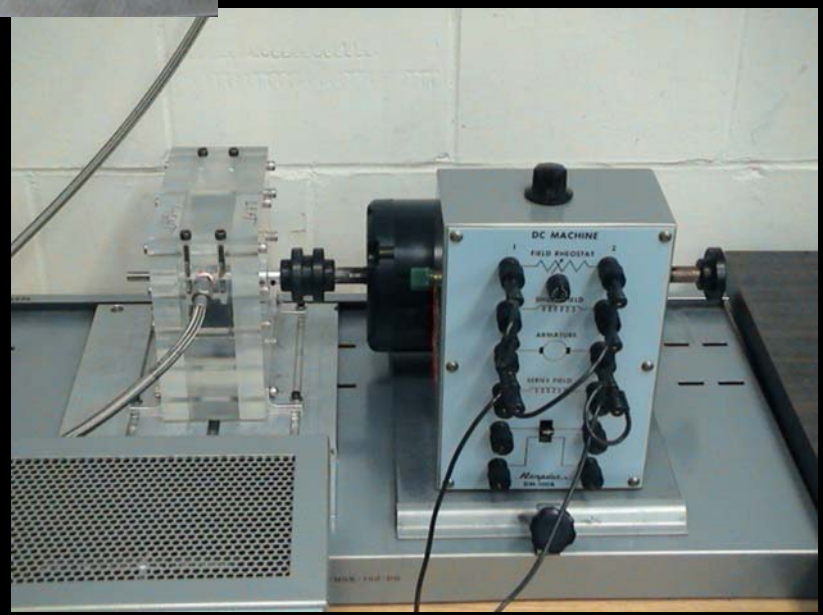
Heat to Electrical Energy Conversion





Tesla Turbine

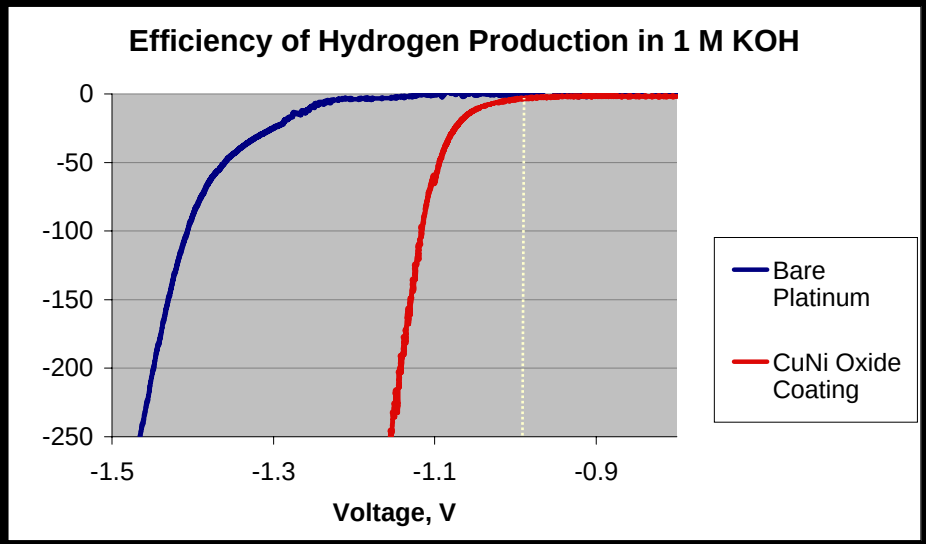
Flow between Parallel closely spaced disks results in energy transfer to the shaft using the boundary layer effect

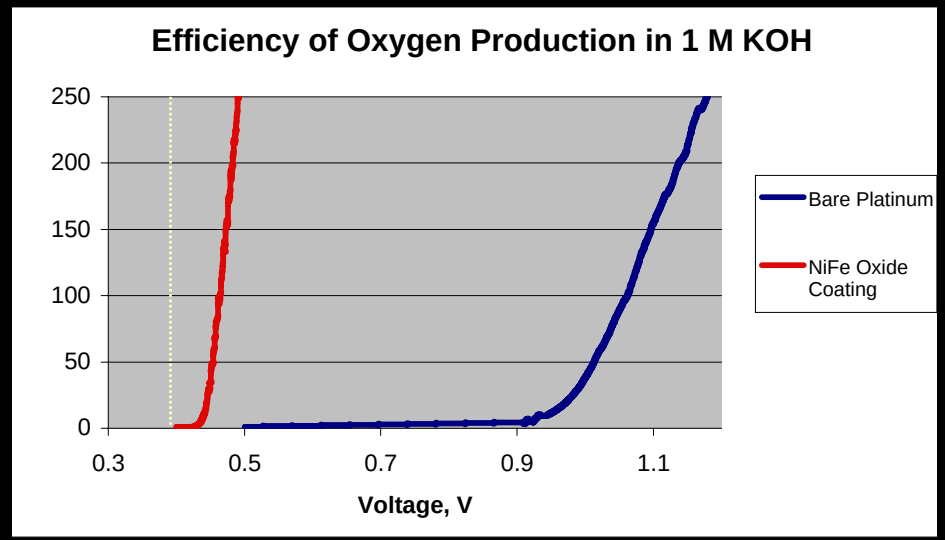


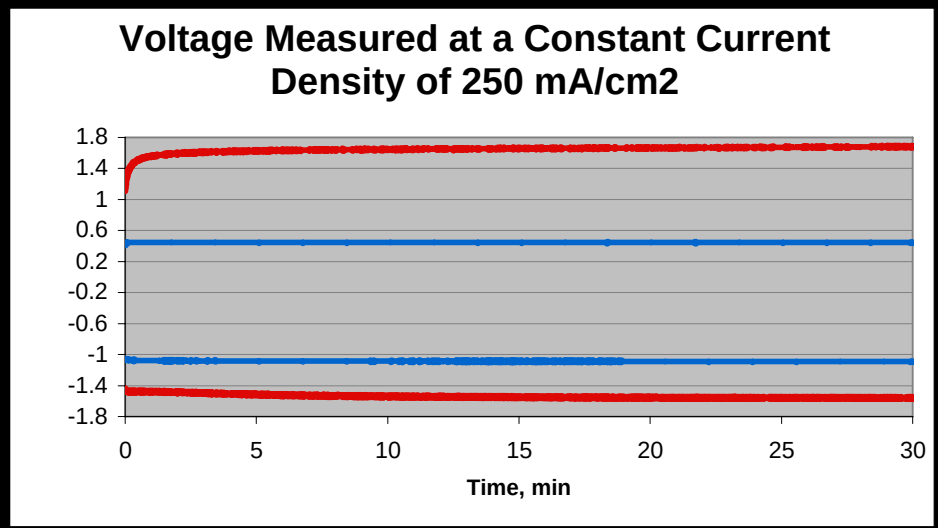
High efficiency, high RPM and low cost

Electrode Performance

pH 14 at room temperature and pressure







Metal Oxide Coating

Bare Platinum

$V_{total} = V_{oxidation} - V_{reduction}$

Matthew Merrill & Ralph Dougherty,
Florida state University, 9/2005

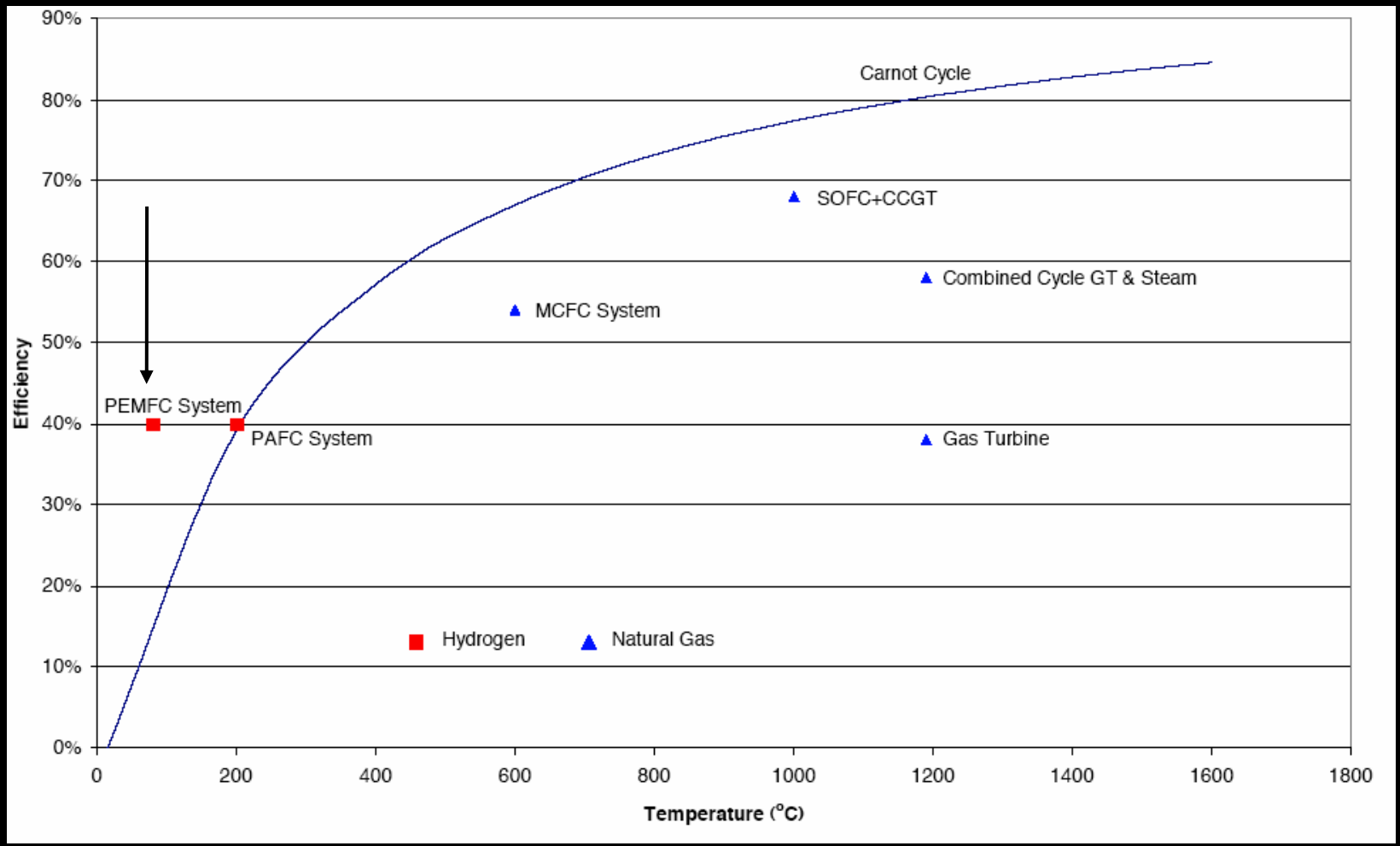
Electrode Performance

Comparison of Total Efficiency After 30 min of Constant Current Density

	Bare Platinum	Metal Oxide Coatings
10 mA/cm^2	54.0 %	95.9%
50 mA/cm^2	49.3 %	91.9%
250 mA/cm^2	41.4 %	85.5%

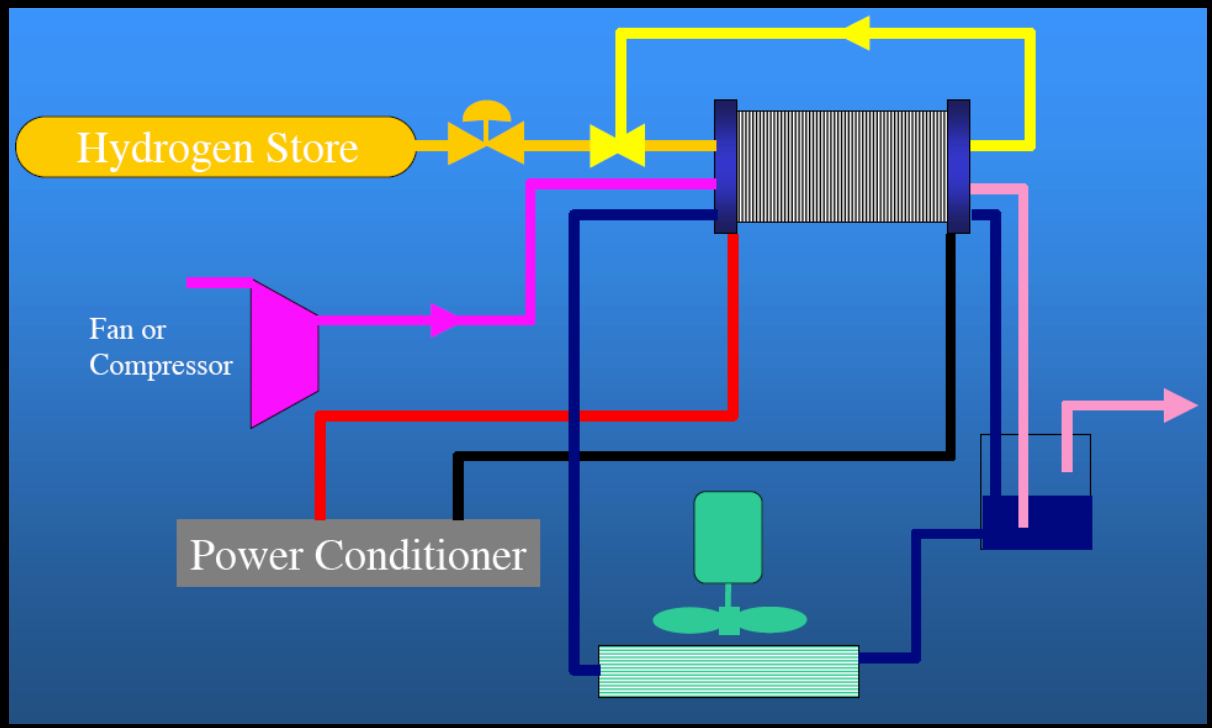
Efficiencies are based on the heat of formation of water from H_2 and O_2

Fuel Cell Efficiency



Source: http://www.h2net.org.uk/PDFs/EndUse/H2NET-2.pdf

Fuel Cell System



Fuel Cell Stack

Control System

Fuel Delivery

Air Delivery

Thermal Management

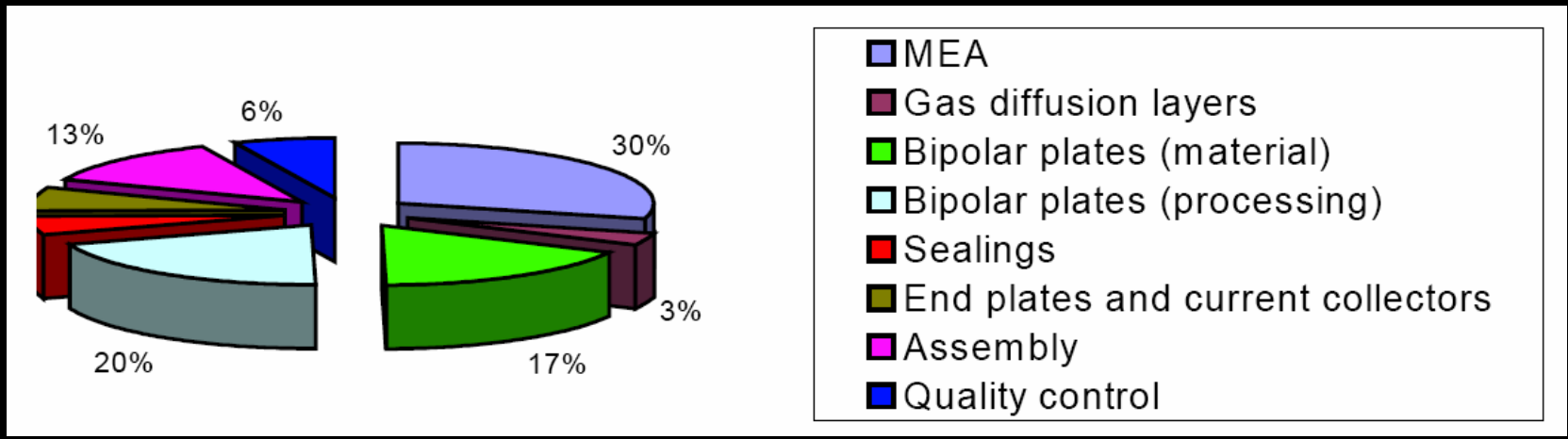
Water Management

Power Conditioning

Critical Materials and Costs

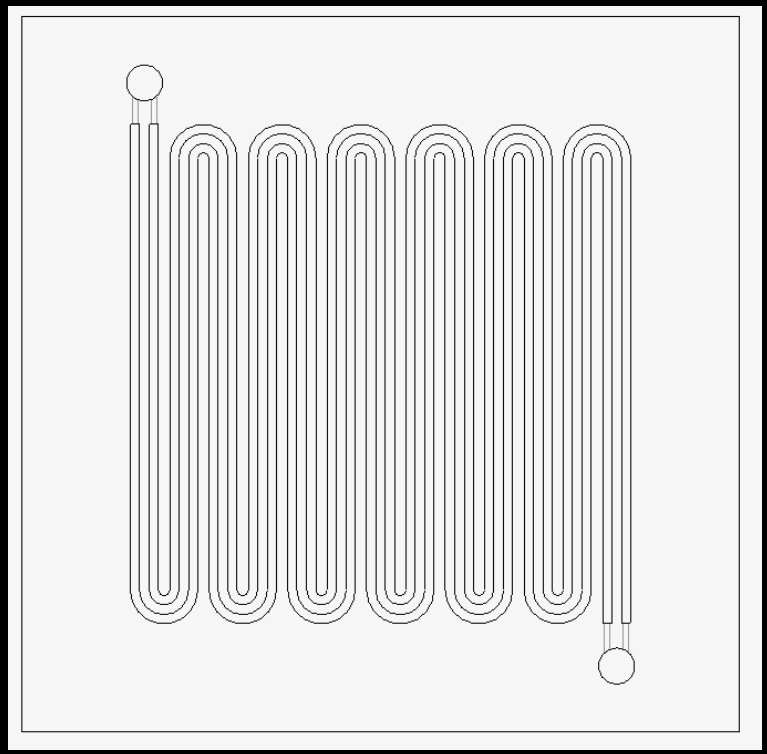
Example: Polymer Electrolyte Fuel Cell Stack (1 kW)

- Polymer membrane
- Catalyst (precious metals)
- Bipolar plate

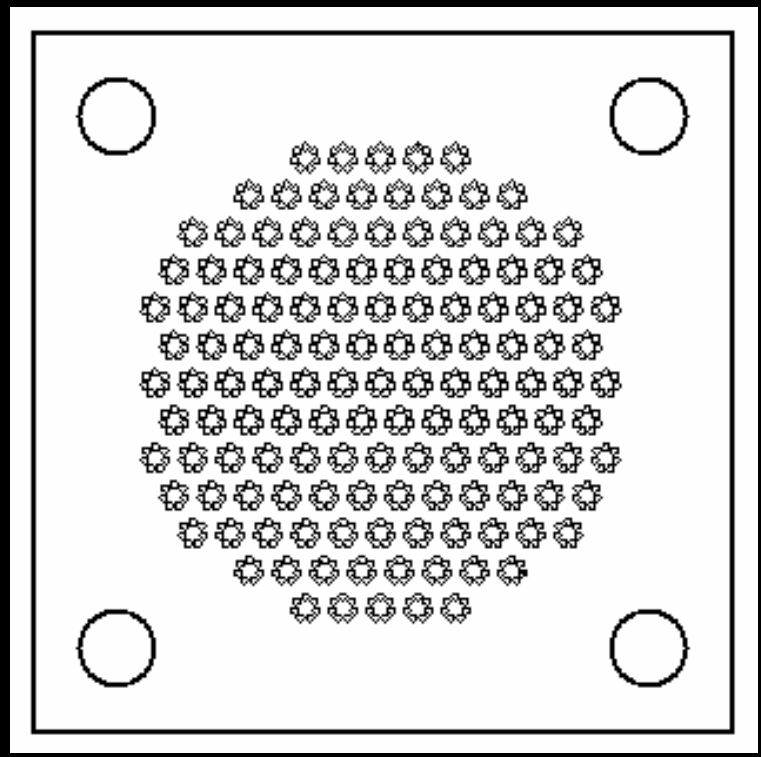


Source: Material development for cost reduction of PEFC by J. Garche, L. Jorissen & K.A. Friedrich, Center for Solar energy and hydrogen research, Baden-Wuerttemberg (ZSW), Germany

Bipolar Plate



Conventional - Graphite



New Design - Thermoset Plastic

Microjet impingement

Conclusion

"Our world society is presently on a nonsustainable course." The West, especially, is in peril: "The prosperity that the First World enjoys at present is based on spending down its environmental capital." Calamity could come quickly: "A society's steep decline may begin only a decade or two after the society reaches its peak numbers, wealth and power."

'Collapse': How the World Ends - Jared Diamond (2004)

Skepticism

1. "Heavier-than-air flying machines are impossible" - *Lord Kelvin; 1885*
2. "I don't think this business of television is likely to come to much" - *Sir J.J. Thomson; 1930*
3. "The gas turbine could hardly be considered a feasible application to airplanes" - *US national academy of Sciences, Committee on Gas Turbines; 1940*
4. "It is time to close the book on infectious disease" - *US Surgeon-General ; 1969*
5. "There is no reason anyone would want a computer in their home" - *Ken Olson, Founder of DEC; 1977*
6. *"640K ought to be enough for anybody" - Bill Gates; 1981*

Humanity's Top Ten Problems for next 50 years

1. **ENERGY**
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

2003	6.5	Billion People
2050	8-10	Billion People

Source: R.E. Smalley, Rice University

Inspiration

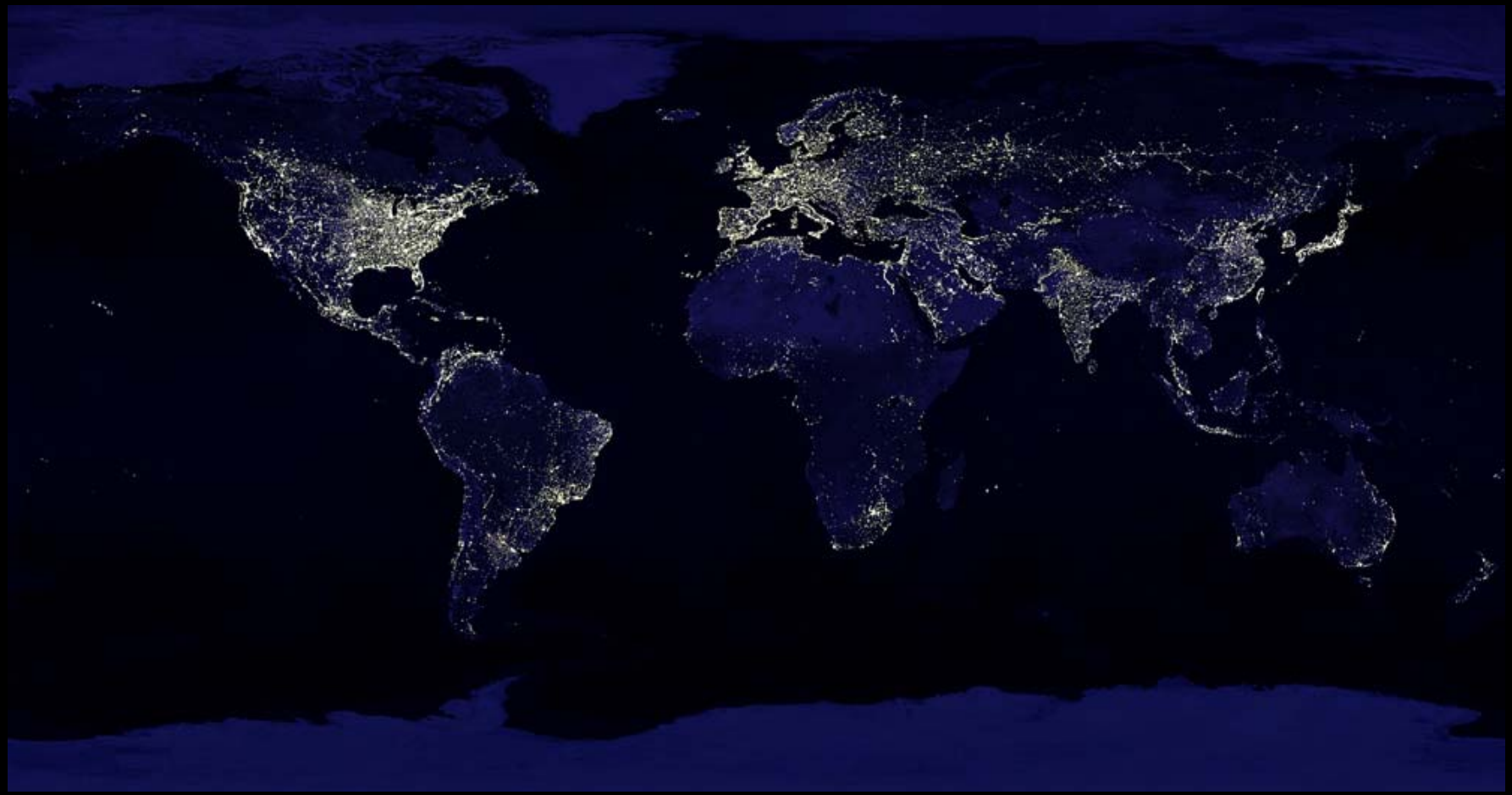
"When you are inspired by some great purpose, some extraordinary project, all your thoughts break their bonds, your mind transcends limitations, your consciousness expands in every direction, and you find yourself in a new, great and wonderful world.

Dormant forces, faculties and talents become alive, and you discover yourself to be a greater person by far than you ever dreamed yourself to be."

Patanjali, - First to third century BC

Courtesy of John H. Shinn, Senior Staff Adviser, Global Issues, ChevronTexaco

World at Night



THANK YOU