The World's Energy Problem and what we can do about it

American Academy of Arts and Sciences

Berkeley

November, 2007

The Energy Problem

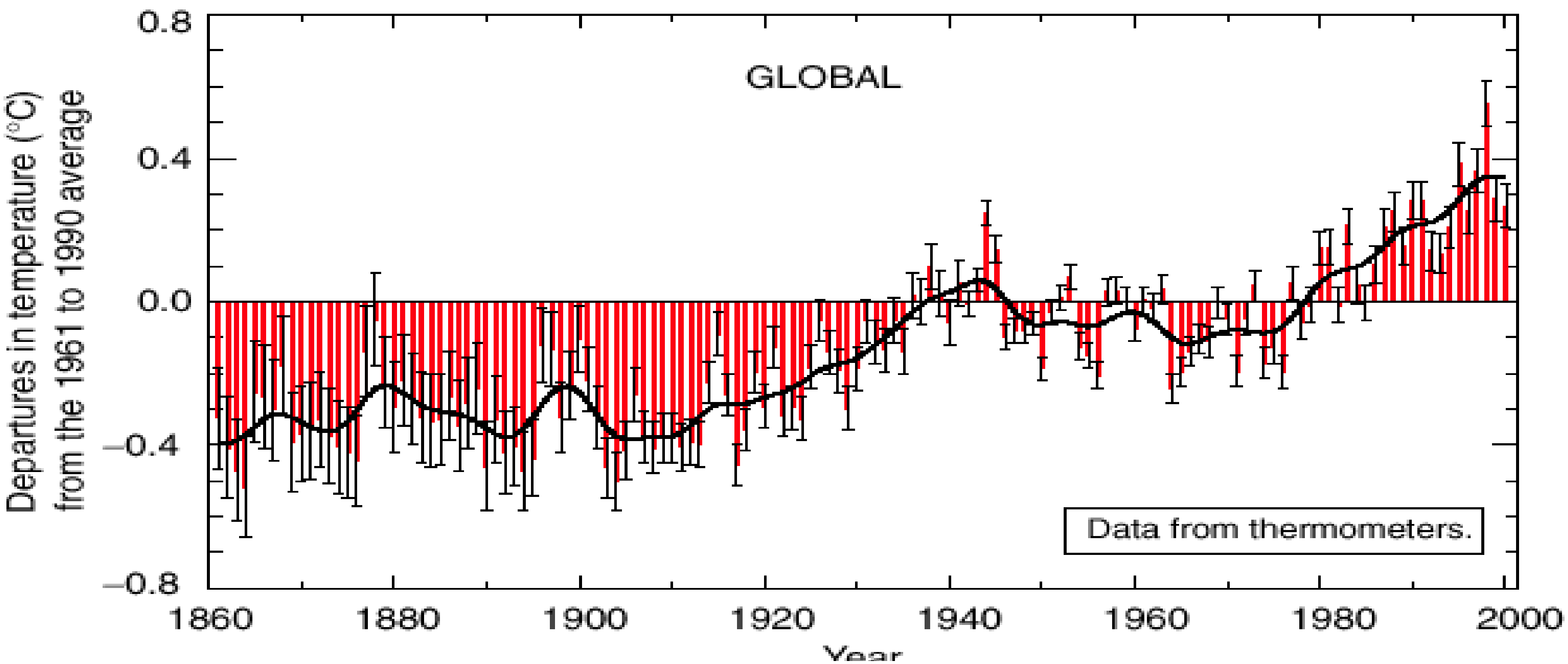
(1) Environmental concerns, especially Climate Change.

(2) 2–3 billion people worldwide currently lack access to modern forms of energy.

(3) Potential for geopolitical conflict due to escalating competition for energy resources.

Variations of the Earth's surface temperature for:

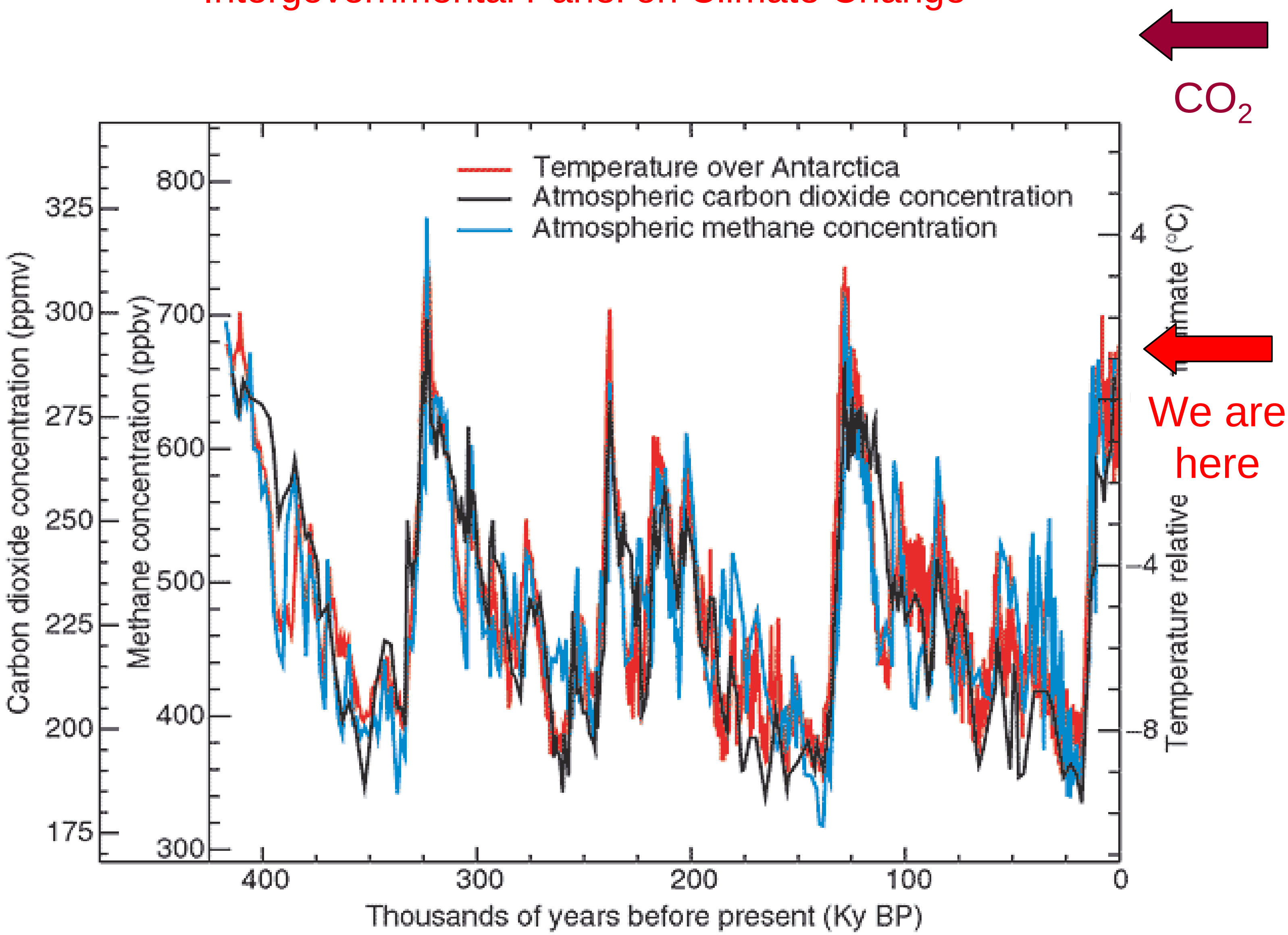
(a) the past 140 years



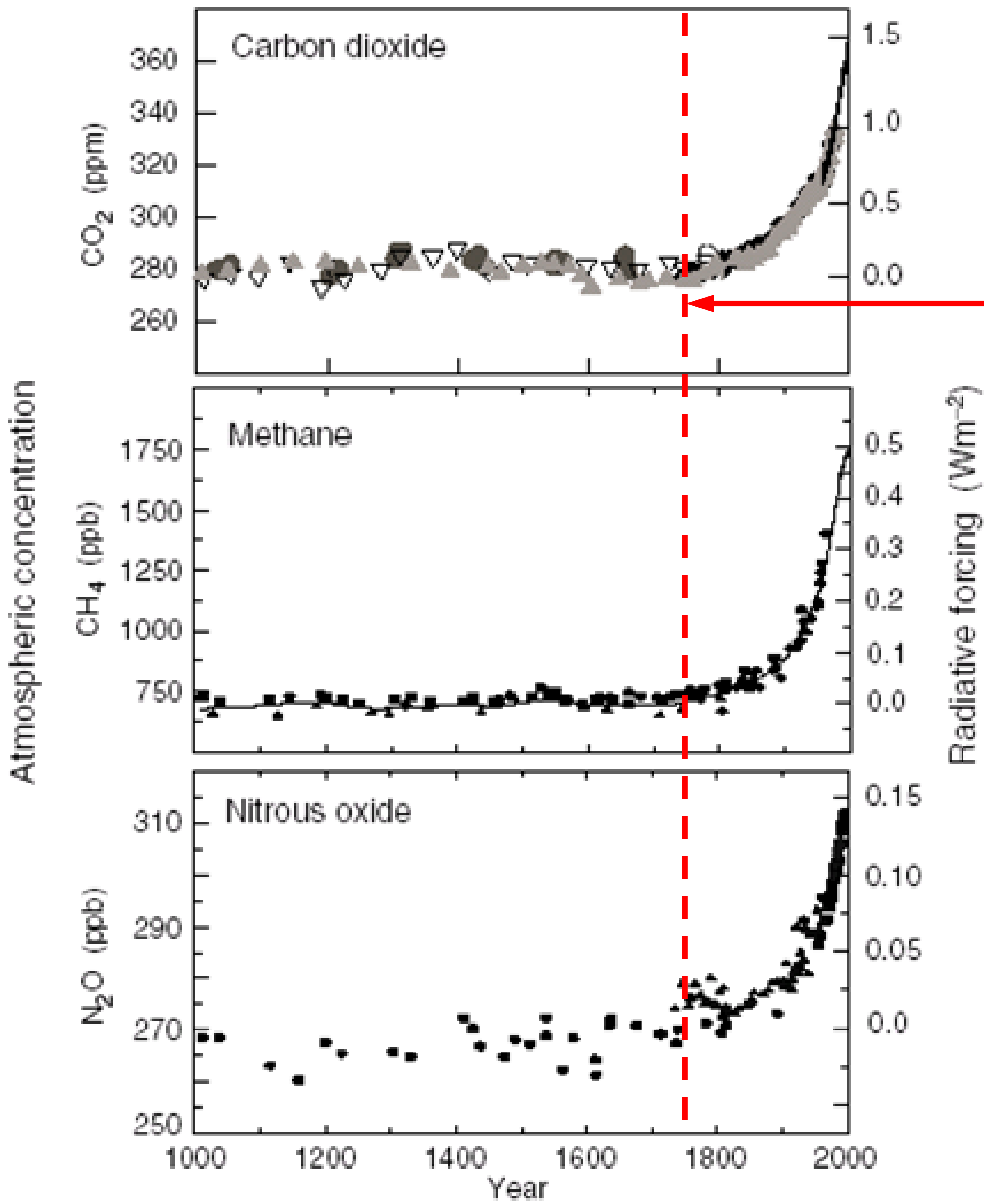
140 years is nothing by geological time scales!

Temperature over the last 420,000 years

Intergovernmental Panel on Climate Change

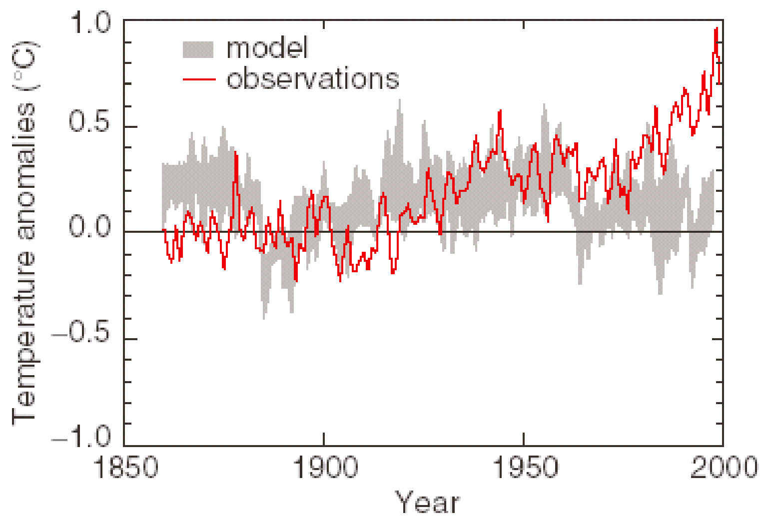


Concentration of Greenhouse gases

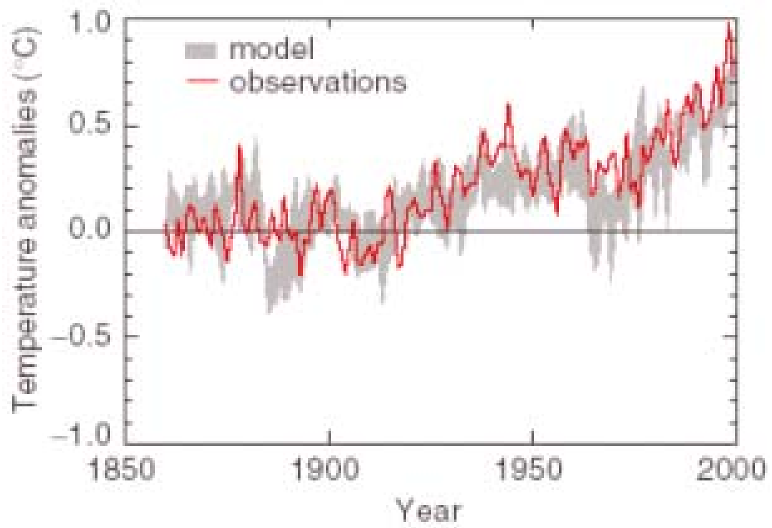


1750, the beginning of the industrial revolution

Temperature rise due to human emission of greenhouse gases



Climate change due to natural causes (solar variations, volcanoes, etc.)



Climate change due to natural causes and human generated greenhouse gases

Potential effects of climate change could lead to:

- Increased damage from storms, floods, wildfires
- Property losses and population displacement from sea-level rise
- Productivity of farms, forests, & fisheries
- Increased species extinction
- Spread of disease (malaria, cholera, dengue fever, …)
- Water Shortages

Emissions pathways, climate change, and impacts on California

Proceedings of National Academy of Sciences (2004)

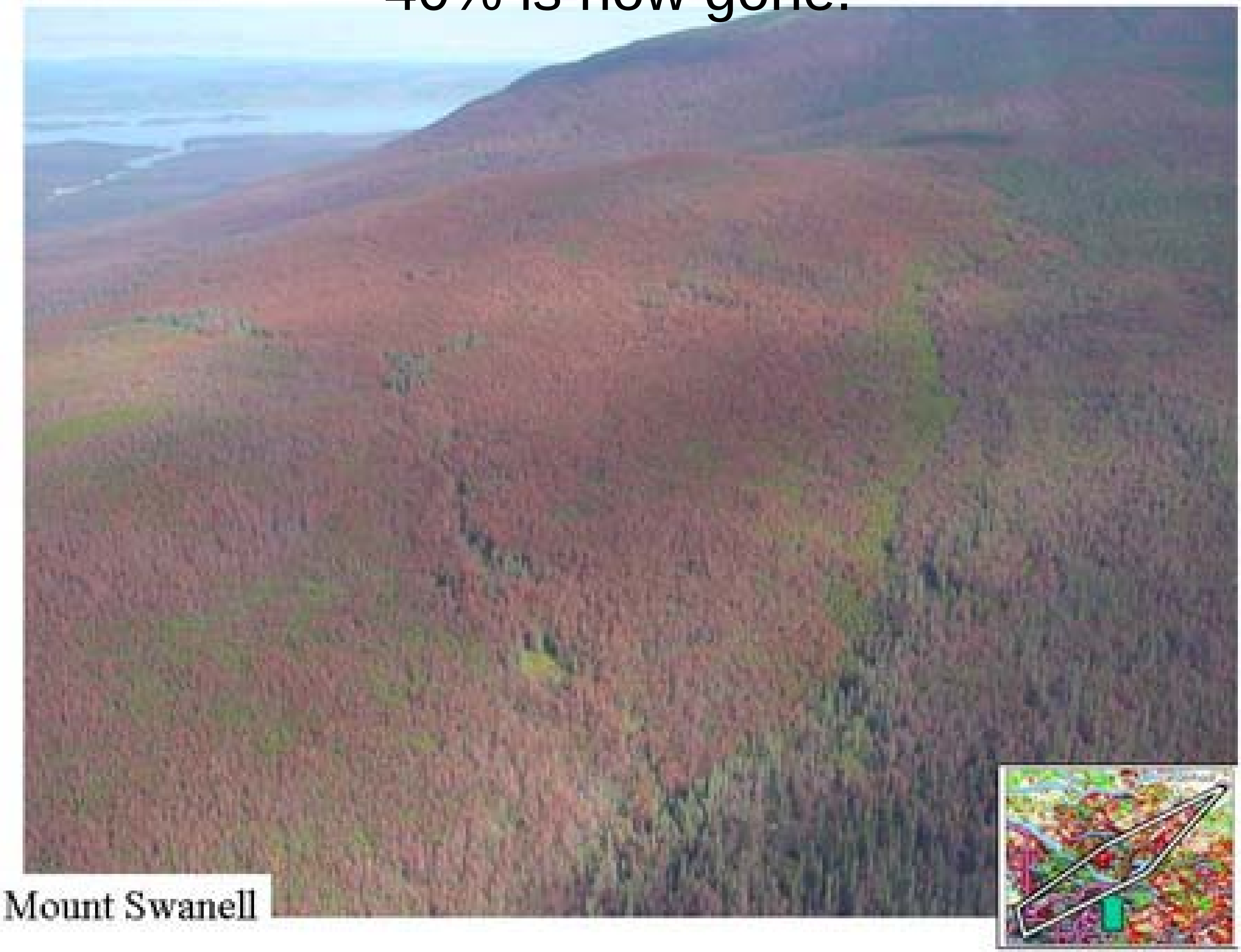
Using two climate models that bracket most of carbon emissions scenarios:

	B1	A1 fi
Heat wave mortality:	**2-3x**	**5-7x**
Alpine/subalpine forests	**50–75%**	**75–90%**
Sierra snowpack	**30–70%**	**73–90%**

British Columbia: ~ 78% of the pine forests predicted to be dead within a decade due to pine beetle infestation.

78% of British Columbia pine will have died by 2013.

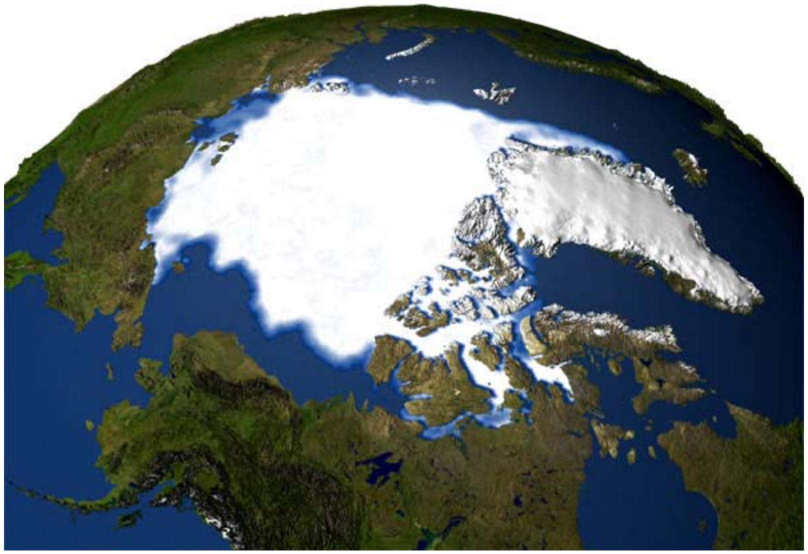
~ 40% is now gone.



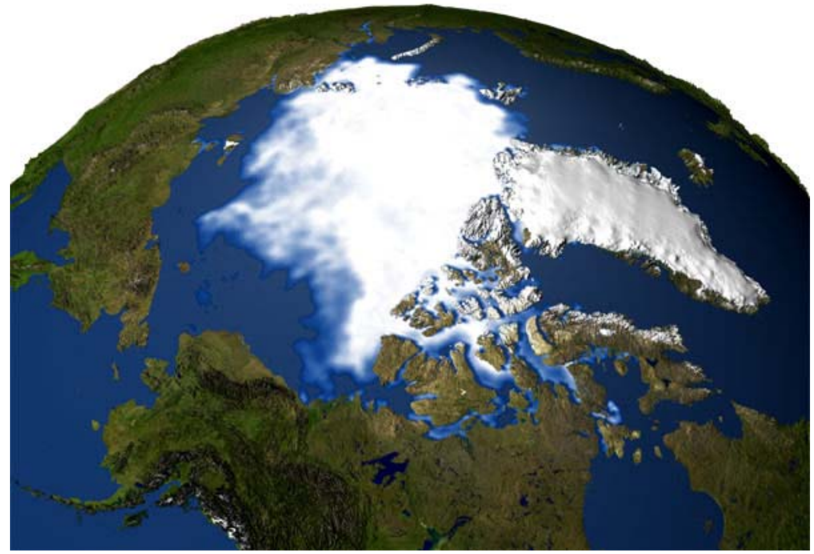
50 years: 14 meter avg. decrease world wide.

Tibetan glacier (serves 1/3 the population of the world) is shrinking by ~1.2m / yr

Positive feedback: melting *reflective* ice and snow is replaced by absorbing dark oceans.



September melt, 1979



September melt, 2002

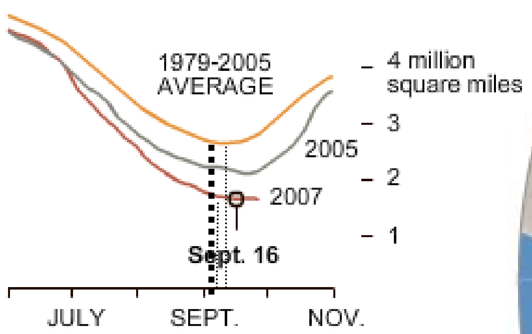
The data from different instruments:

- Multi-channel microwave radiometer (Nimbus 7 satellite)
- Microwave imagers attached to the Defense Meteorological Satellite Programs.

More recent Arctic melting data

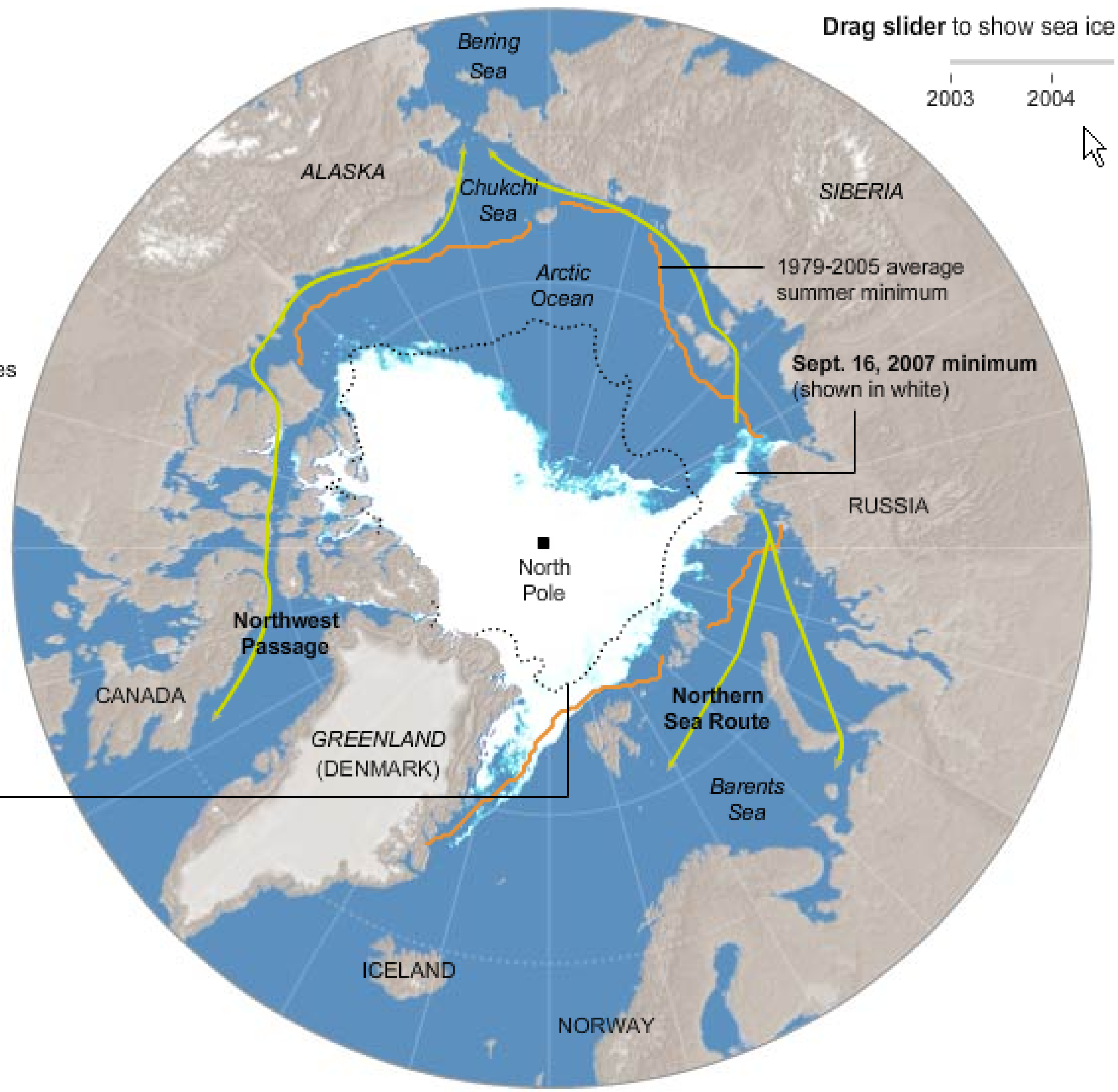
SUMMER SEA ICE
This summer saw a record-breaking loss of Arctic sea ice. Experts attribute the changes to the interaction of wind, weather, ice drift, ocean currents and greenhouse gases.

SUMMER SEA ICE EXTENT*

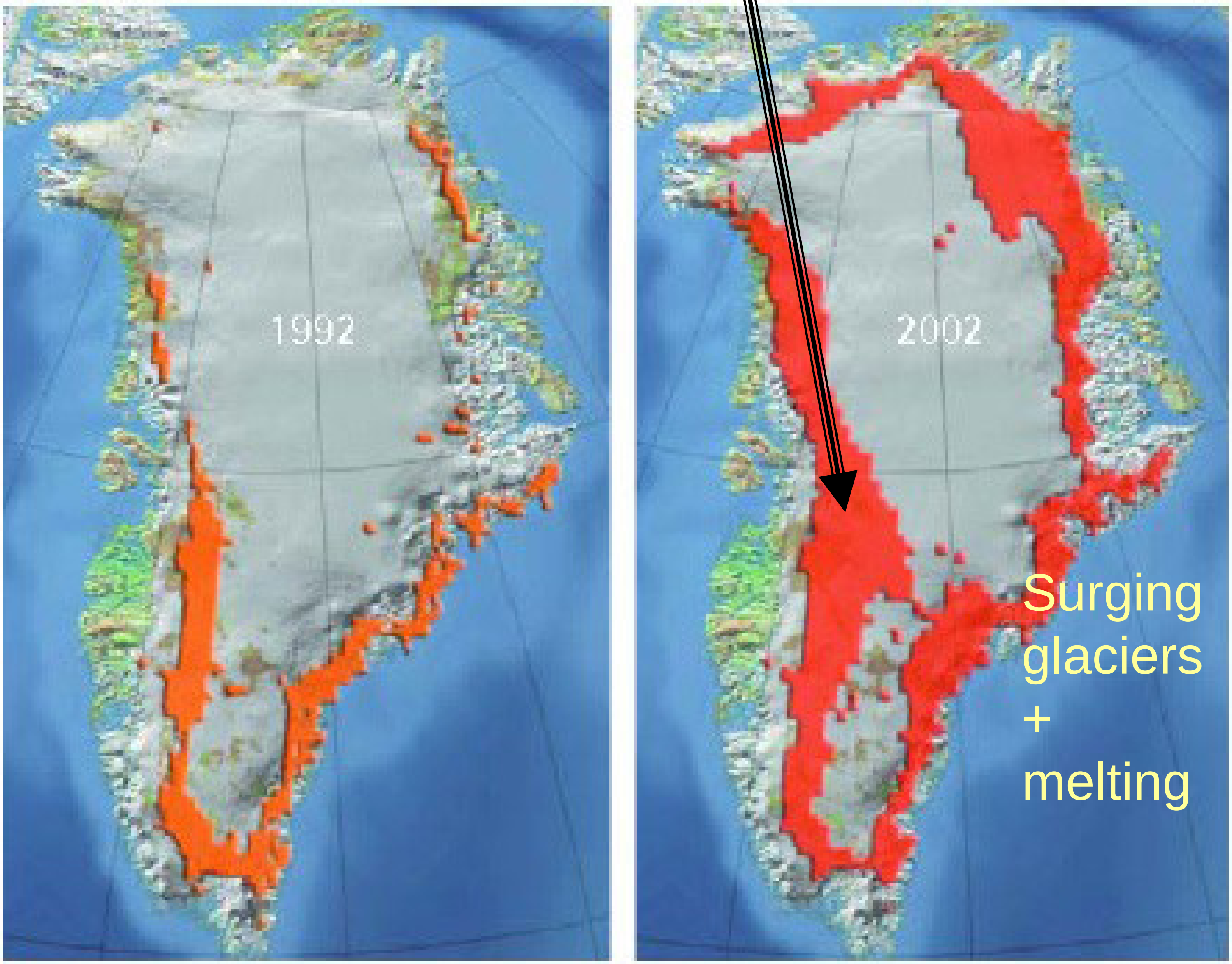


**Sea ice extent is the area of ocean covered by at least 15 percent ice.*

PERENNIAL SEA ICE
Ocean within this boundary had been covered with ice year-round since satellite records began in 1979. This summer was the first time that part of the perennial sea ice was open water.



Greenland Ice Sheet: 70m thinning



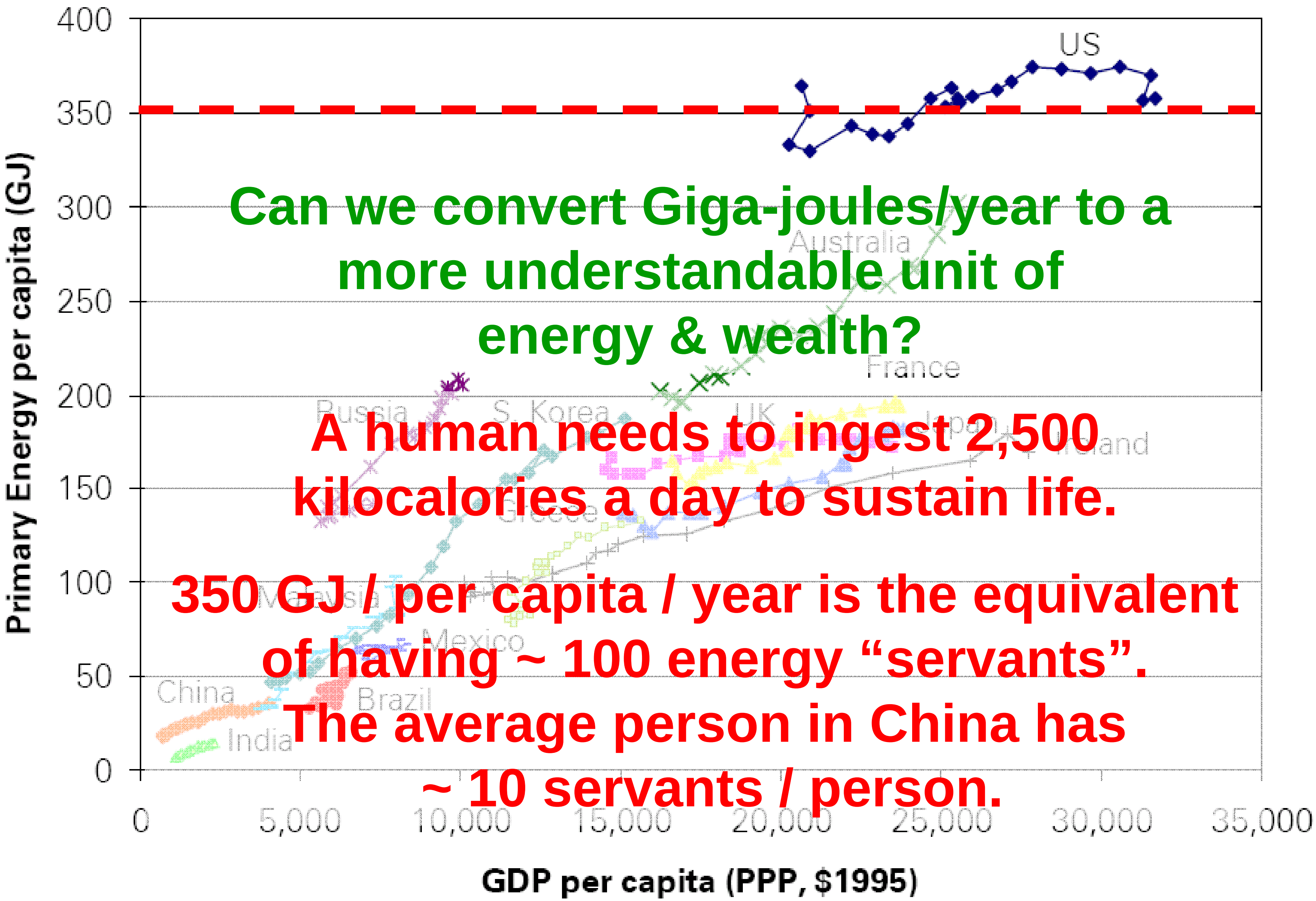
Record melt of 2002 was exceeded in 2005

Unstable Glaciers

Surface melt on Greenland ice sheet descending into moulin, a vertical shaft carrying the water to base of ice sheet.

Source: Roger Braithwaite

Energy demand vs. GDP per capita



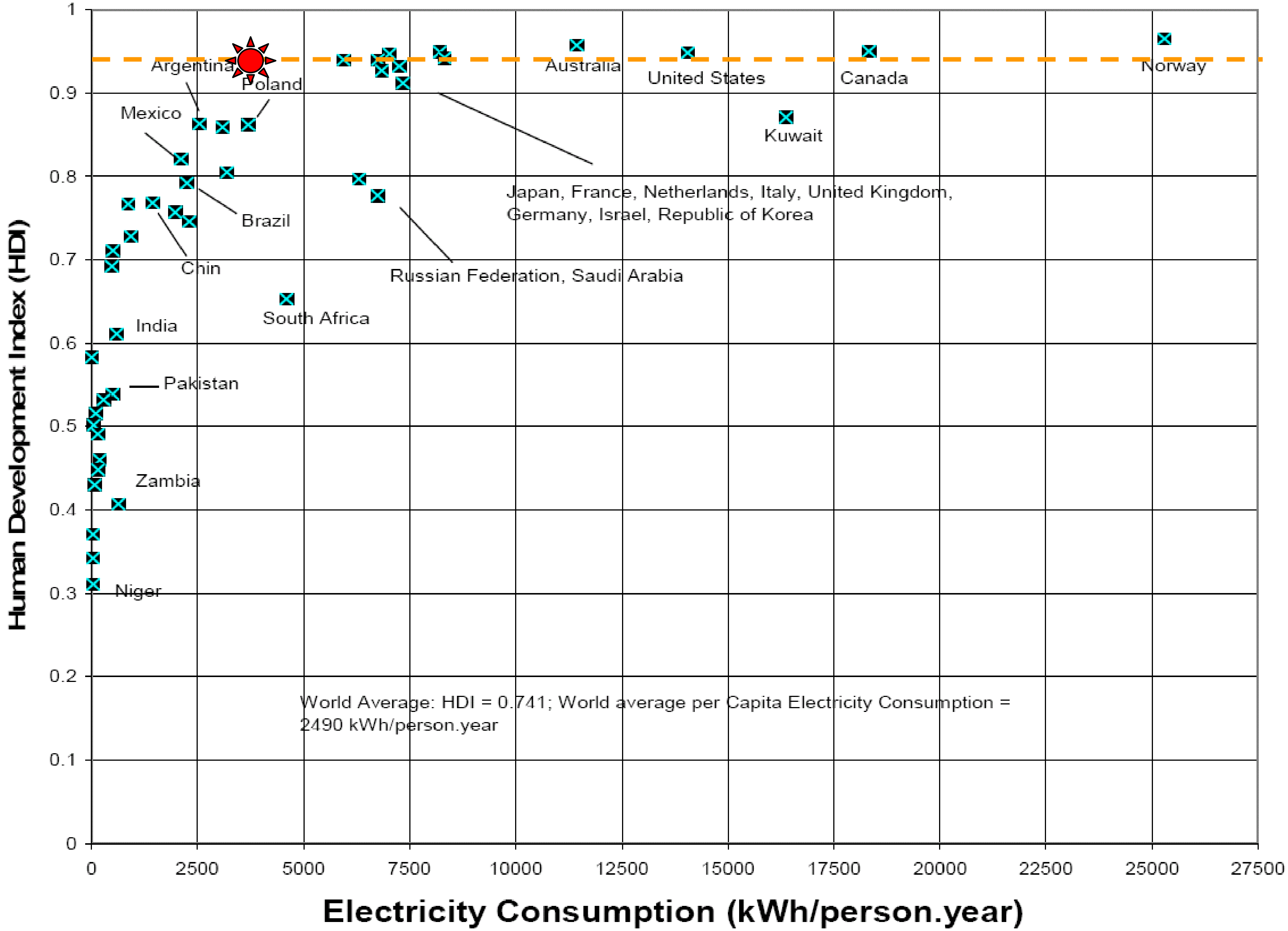
Can we convert Giga-joules/year to a more understandable unit of energy & wealth?

A human needs to ingest 2,500 kilocalories a day to sustain life.

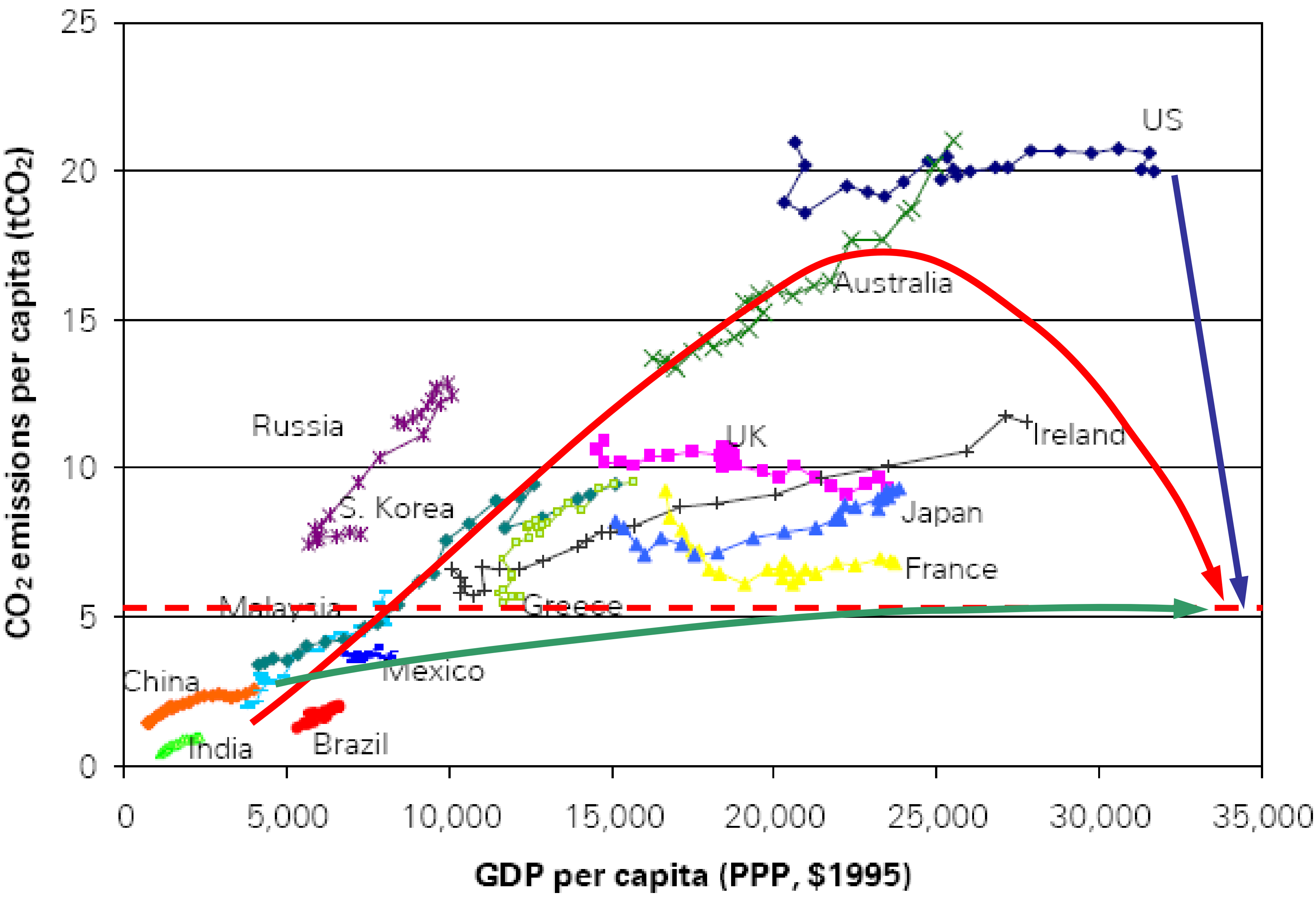
350 GJ / per capita / year is the equivalent of having ~ 100 energy "servants". The average person in China has ~ 10 servants / person.

Source: UN and DOE EIA

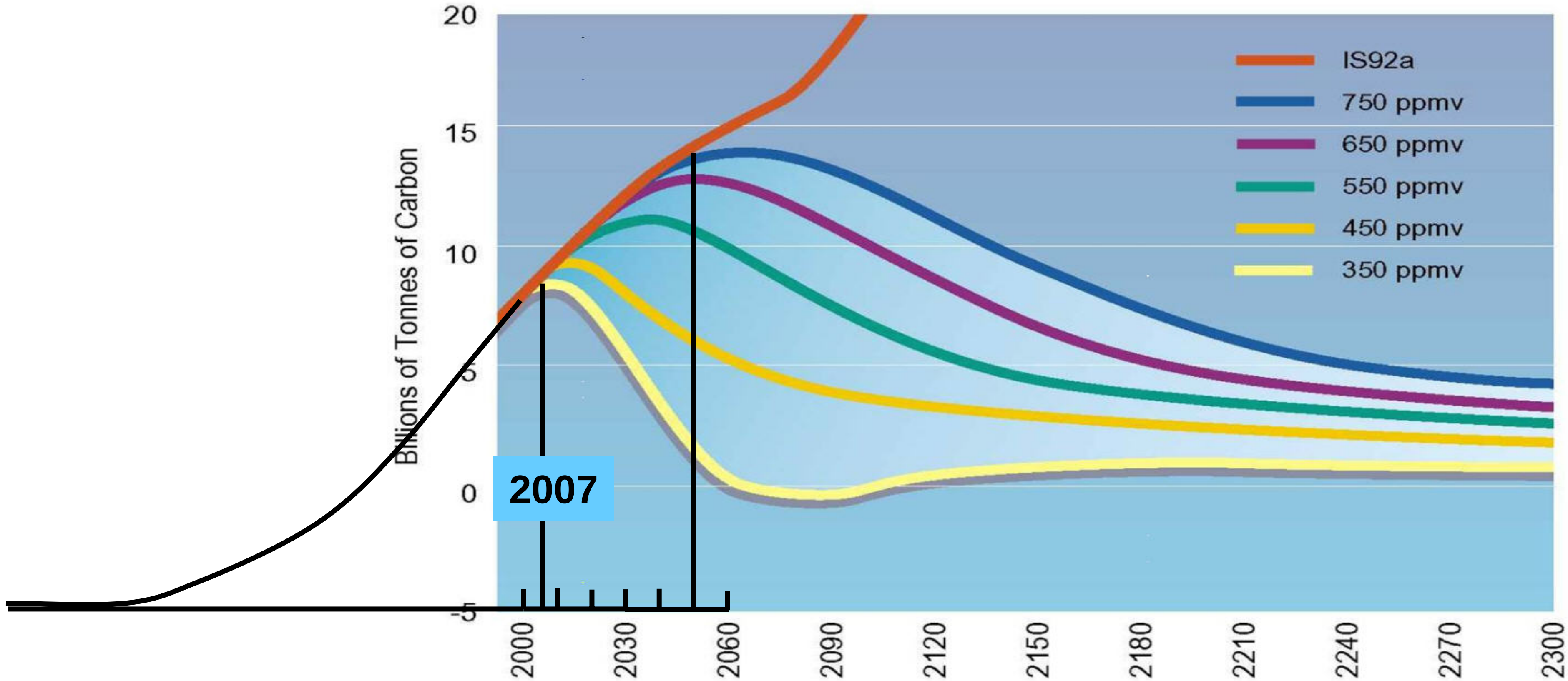
Human Development Index vs. Energy Consumption



CO_2 emissions of selected countries



Emissions Trajectories for atmospheric CO_2 concentration ceilings



Source: Fourth Assessment of the Intergovernmental Panel on Climate Change; Summary for Policy Makers, February 2007.

A dual strategy is needed to solve the energy problem:

1) Maximize energy efficiency and minimize energy use

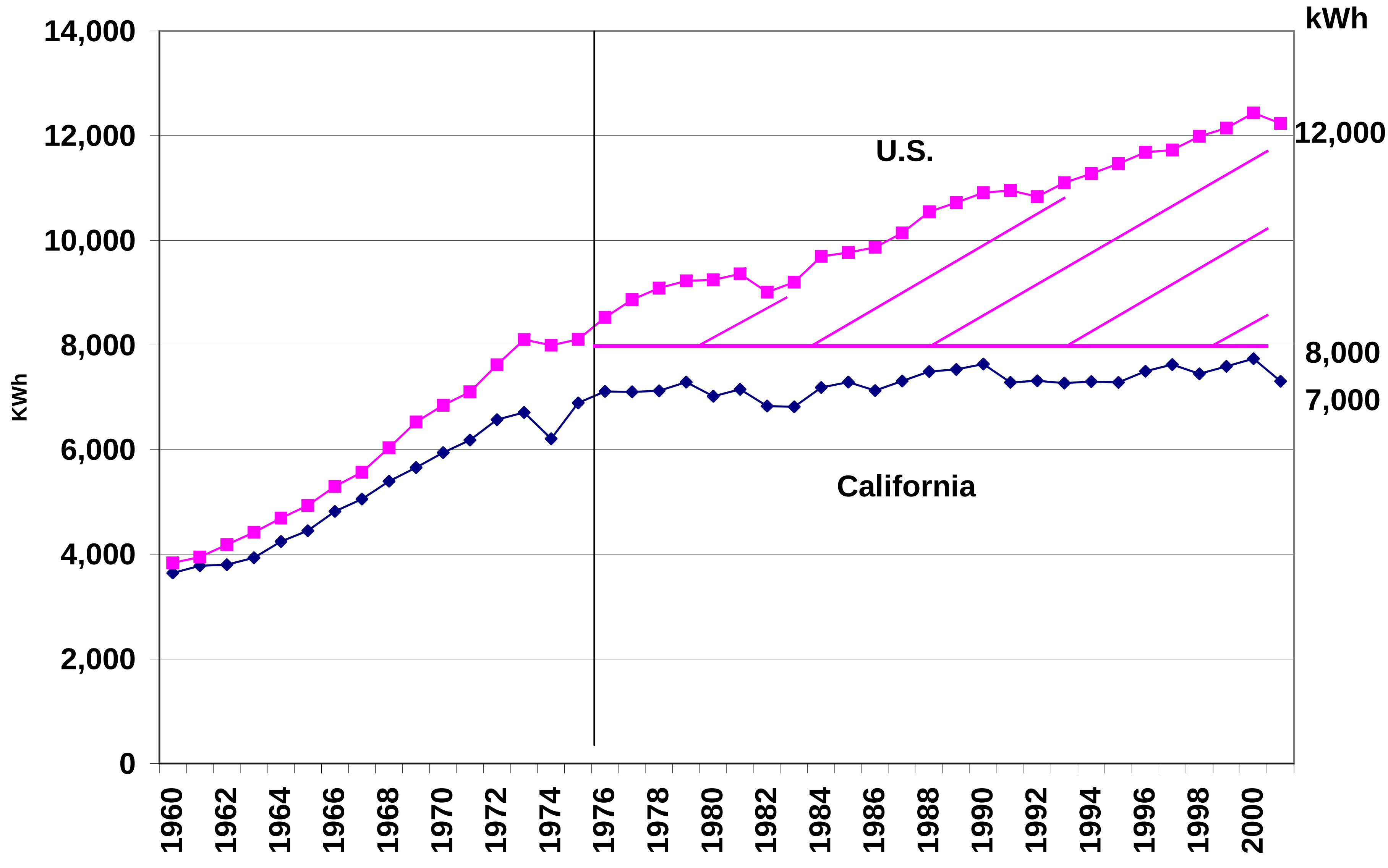
2) Develop new sources of clean energy

A combination of incentives, fiscal polices, and regulations will be needed.

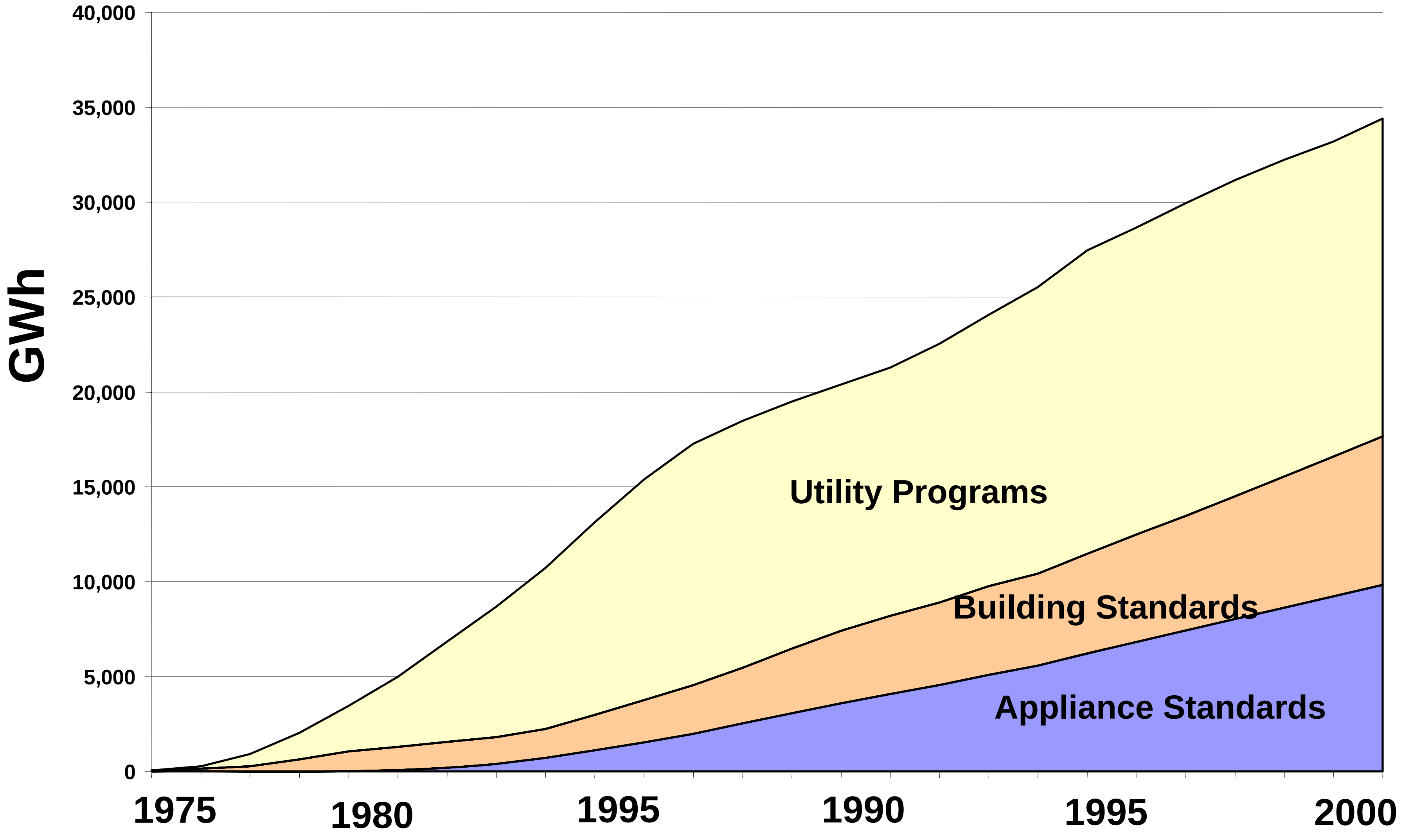
Free markets will fail if there is a "commons problem":

- Water and air pollution
- International fishing
- Access to clean water across national borders
- Climate change

Electricity Consumption/person in the US and California



Half of the energy savings in California were made by separating utility profits from selling more energy



Source: Mike Messenger, Calif. Energy Commission Staff, April 2003

A Low Energy High Rise: the New San Francisco Federal Building

- Natural ventilation in tower – no mechanical cooling or ventilation in open-plan perimeter office space
- Exposed structural concrete for thermal inertia
- Extensive use of natural lighting
- Designed with state-of-the-art computer simulation tools

Potential supply-side solutions to the Energy Problem

- Coal, tar sands, shale oil, …
- Fusion
- Fission
- Wind
- Solar photocell and thermal
- Bio-mass
- Energy storage

International Energy Agency (IEA) forecast

67% of the world supply of coal:

US	27%
Russia	17%
China	13%
India	10%

Coal is the default option of the US, China, and India.

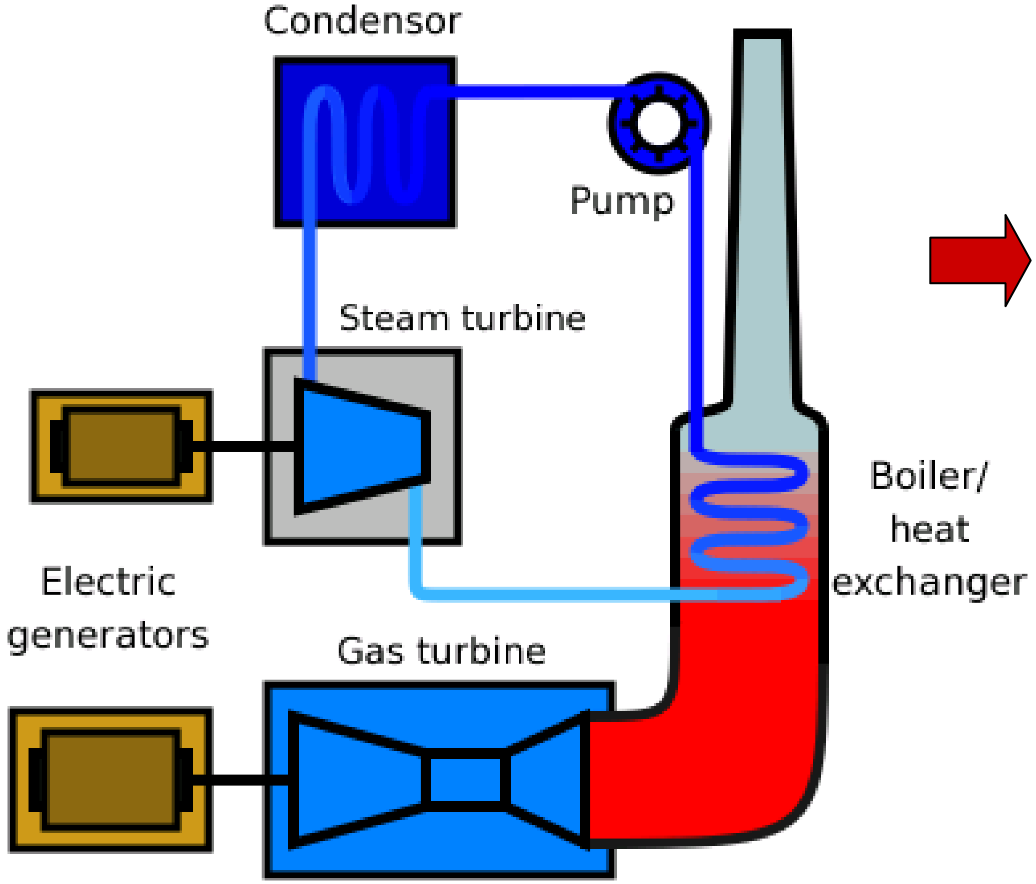
Carbon emission in the next 30 years will add 3x more CO_2 emission than the previous history of all humanity!

There is abundant fossil energy from coal, methane coal beds, tar sands, shale oil, ... for at least 400 years.

The Efficiency of Coal Burning Plants

- **50% may be possible with Supercritical Steam boilers, but new, temperature resistant metals are needed.**
- **The same technology can allow oxygen-burn boilers and at-the-stack retro-fit capable CO_2 capture.**
- **Natural gas is 60% efficient.
(80% with co-generation)**
- **IGCC can also use turbine technology (~60%), but capital costs are becoming prohibitive.**

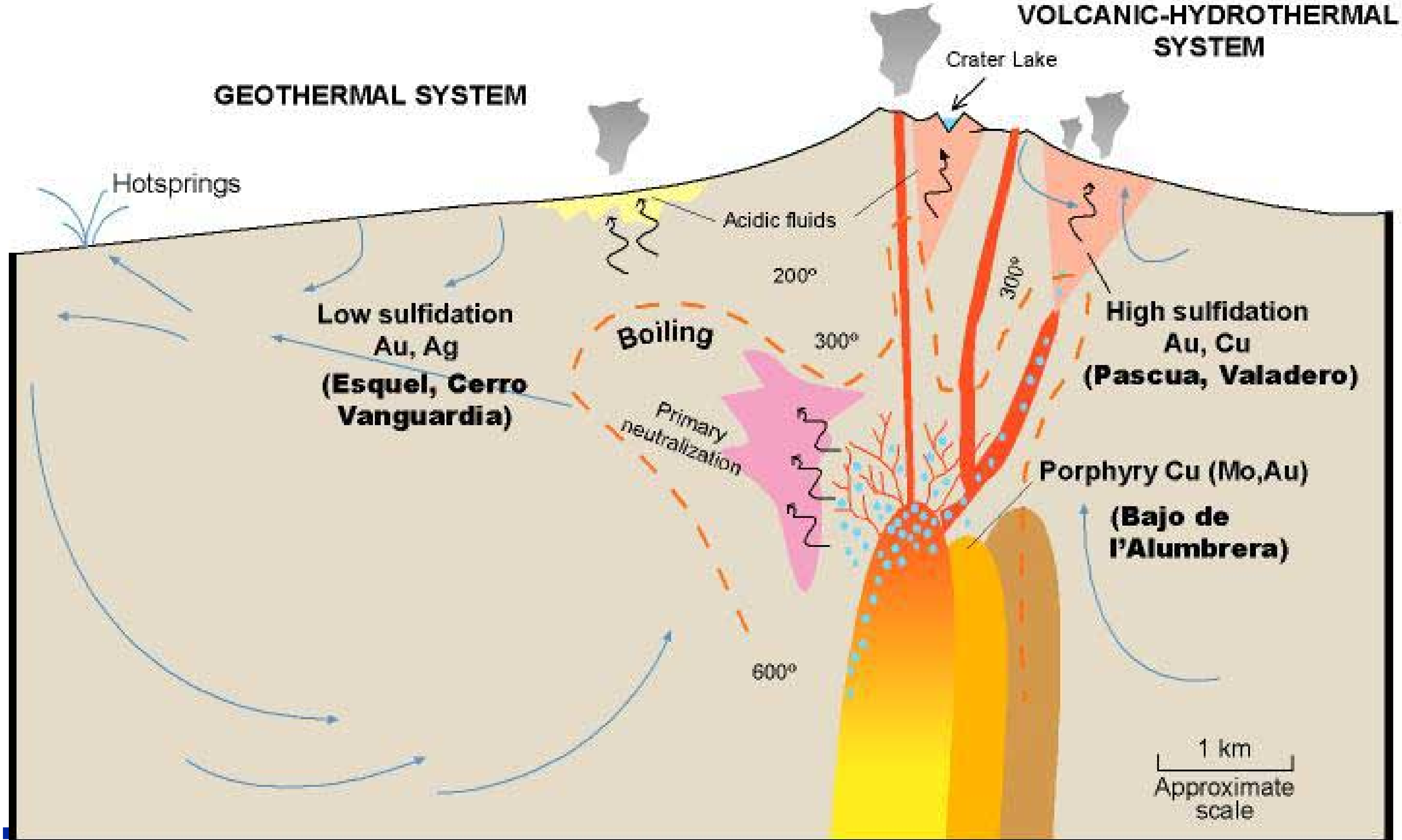
A **combined cycle** power plant employs two or more thermodynamic cycles



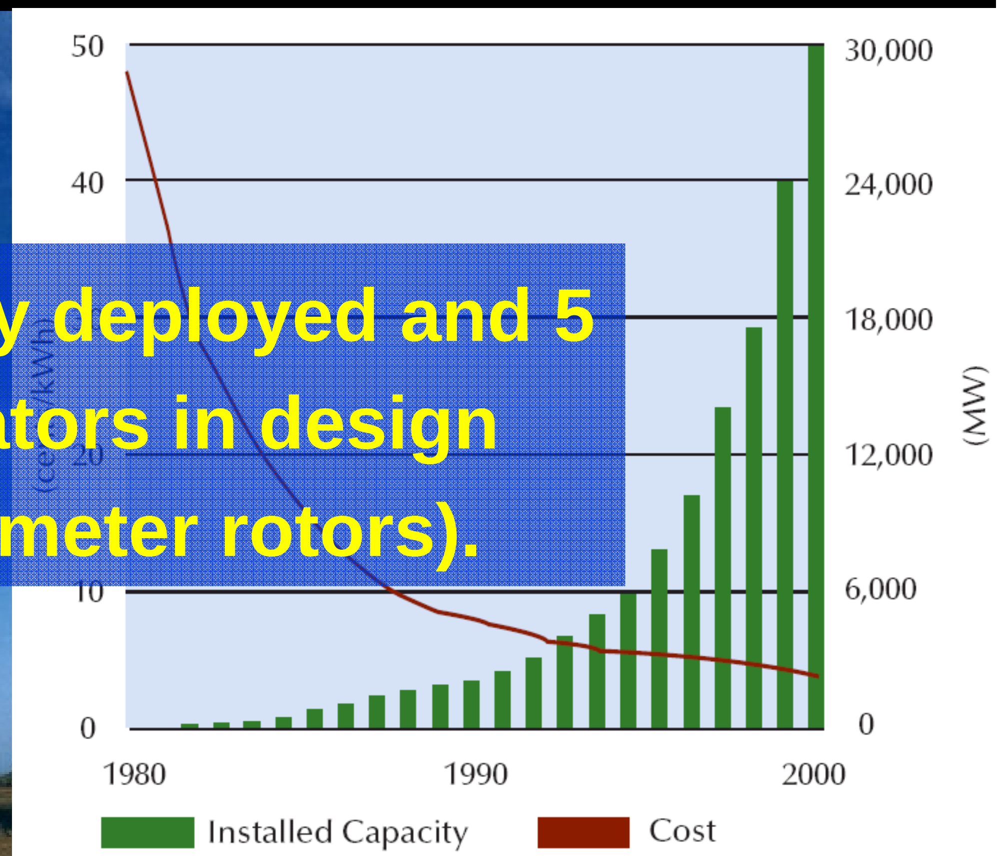
Final use of low-temperature heat is used for space and water heating. (Co-generation)

Geothermal/Hydrothermal Systems

- Schematic Cross-Section

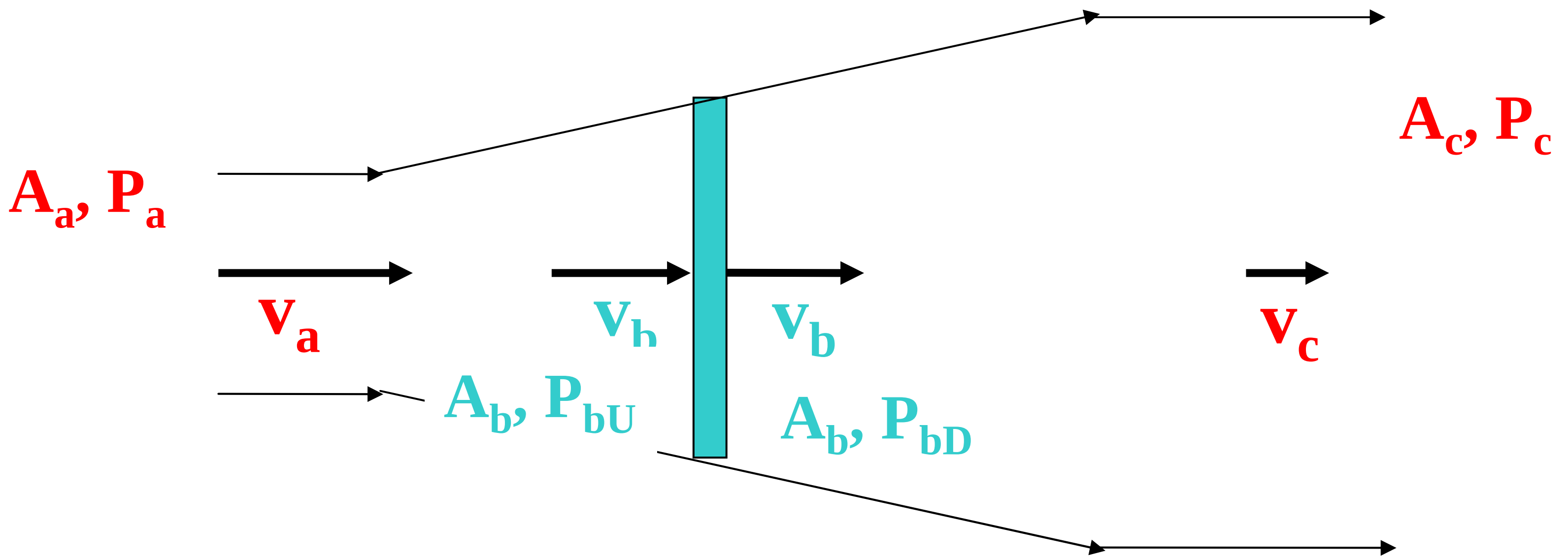


Modest but **stable** fiscal incentives were essential to stimulate long term development of power generation from wind



3 MW capacity deployed and 5 MW generators in design (126 m diameter rotors).

The Betts Limit:



Assuming conservation of mass for incompressible flow and conservation of momentum,

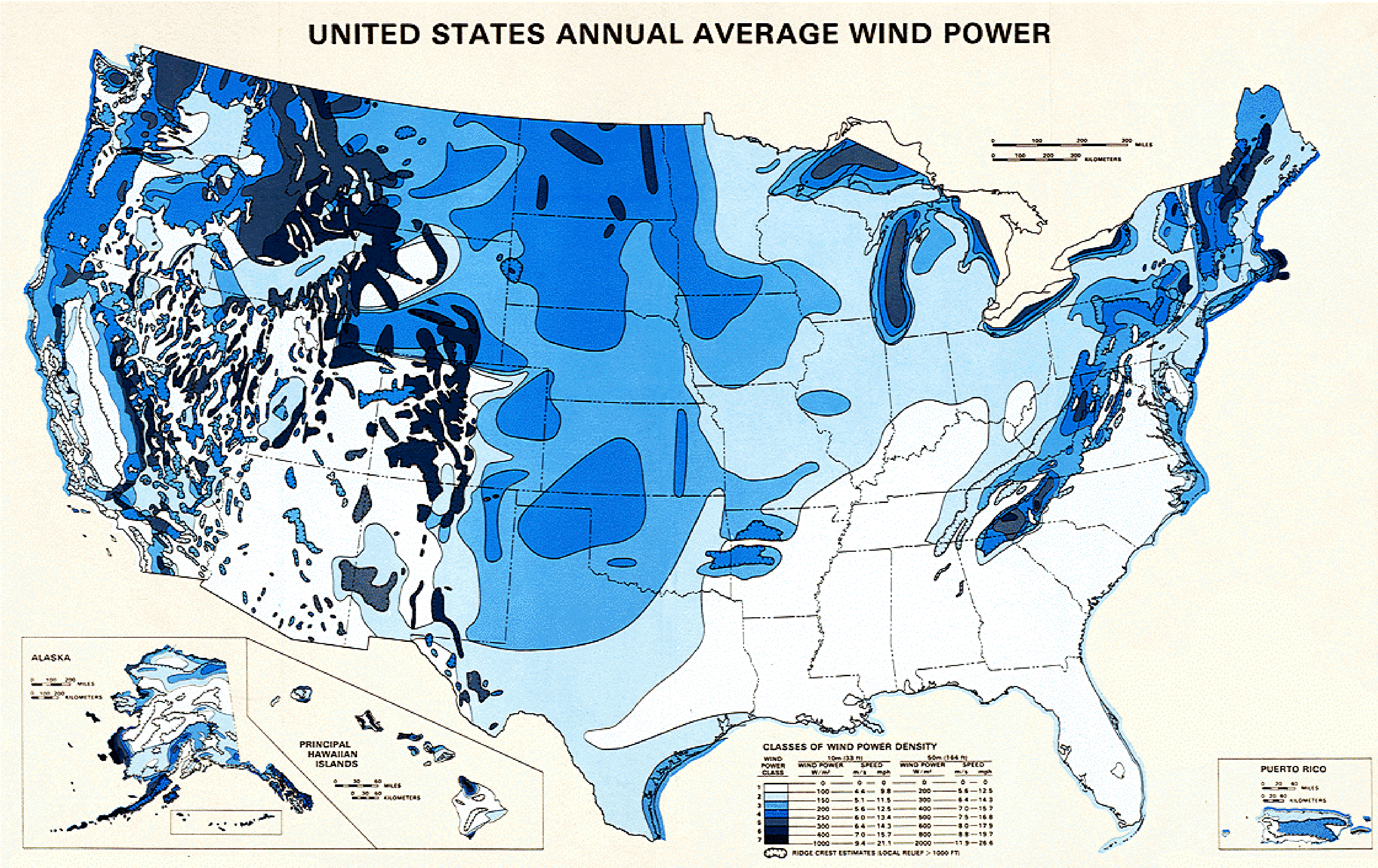
Maximum kinetic energy delivered to a wind turbine

$= 16/27\ (½)mv^2$

~ 0.59 of kinetic energy

The biggest turbines capture ~ 5/6 of this amount.

Wind sites in the US

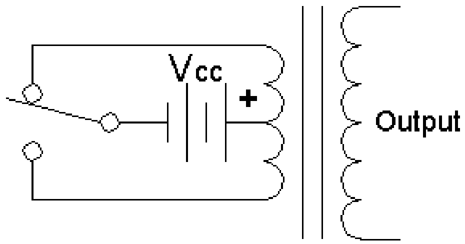


Advantages of High Voltage DC over AC transmission:

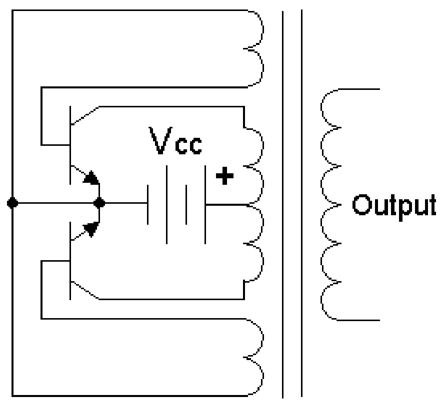
After 500km, HVDC is less expensive!

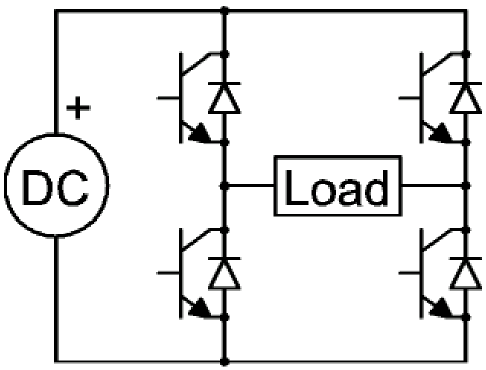
- Two conductors vs. 3 or 4 for AC.
- Radiative and dielectric losses are much less.
- Capacitance losses
  (energy used to charge and discharge the capacitance of the cable)
- HVDC can carry more power/conductor at constant DC voltage than dealing with peak AC voltage.
- More robust power grid.

DC to AC inverters

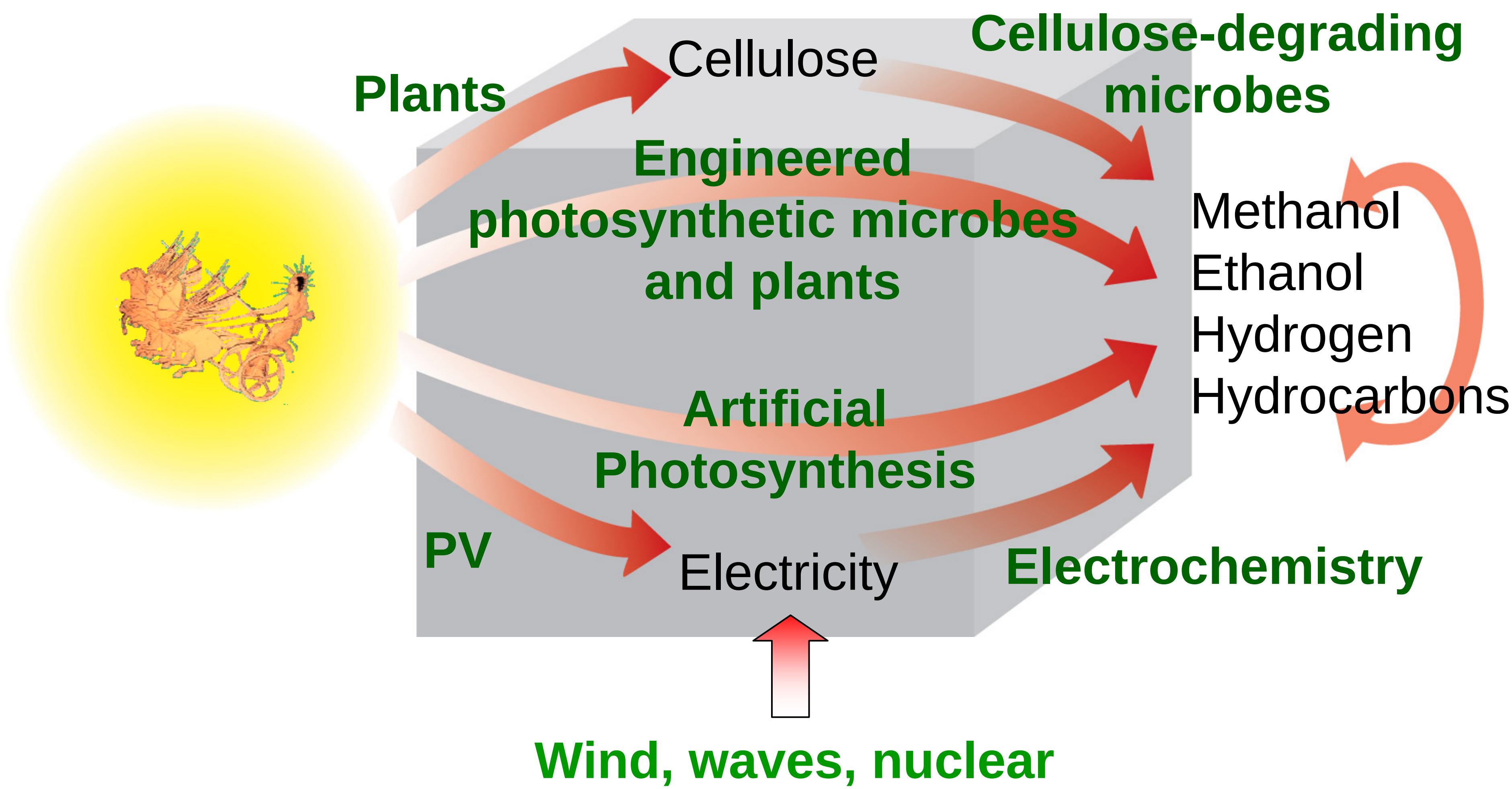


A switch is used to rapidly switch current from a DC source through one end of the primary winding.

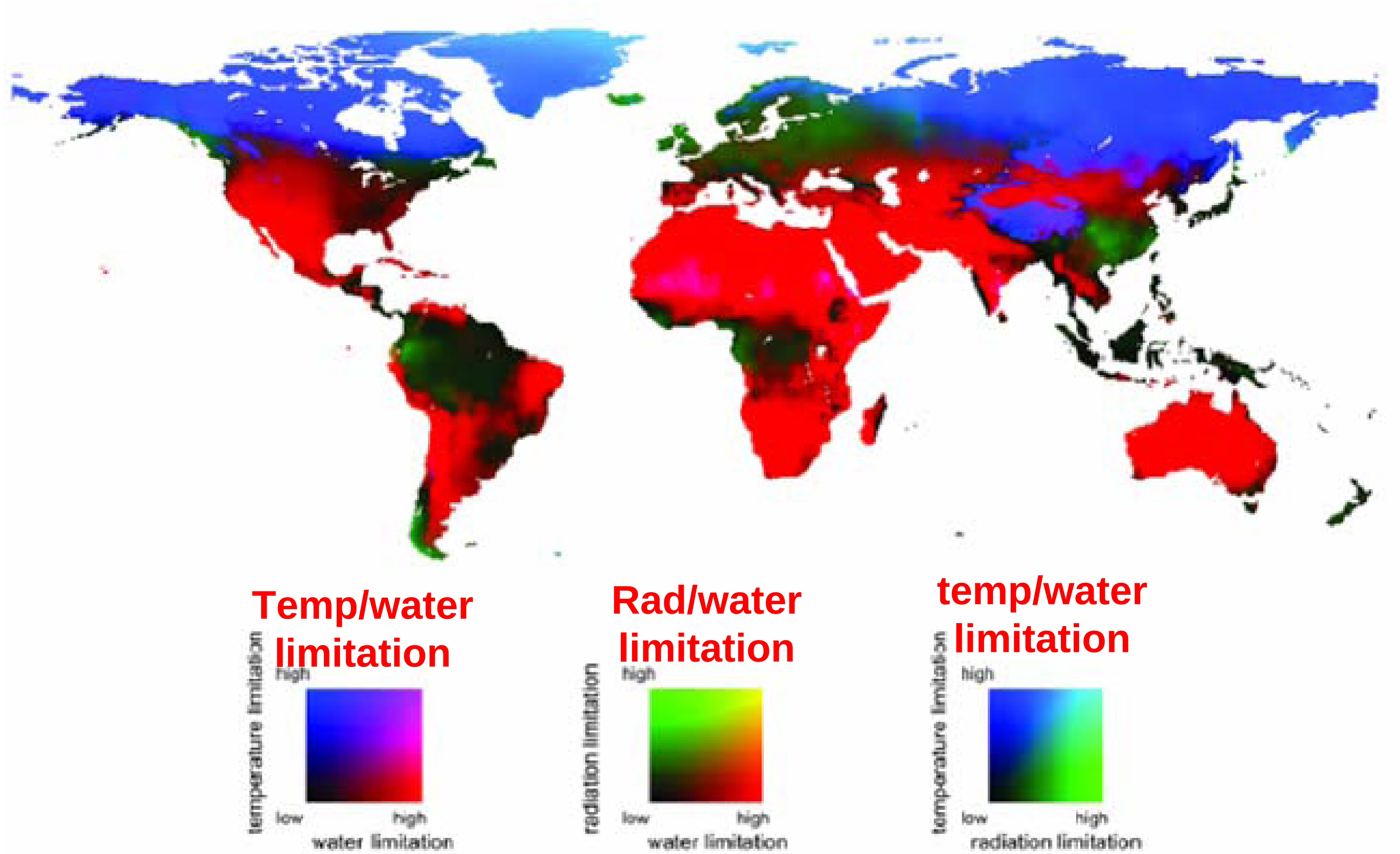




Helios: Lawrence Berkeley Laboratory and UC Berkeley's attack on the energy problem

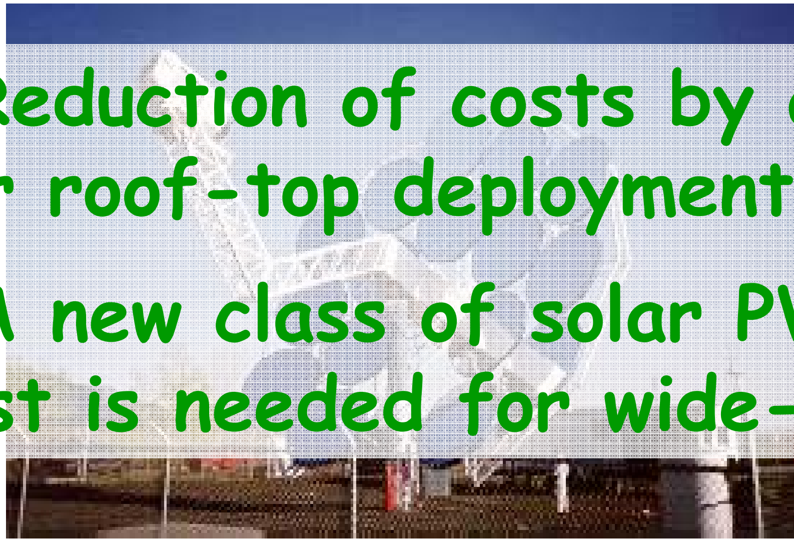


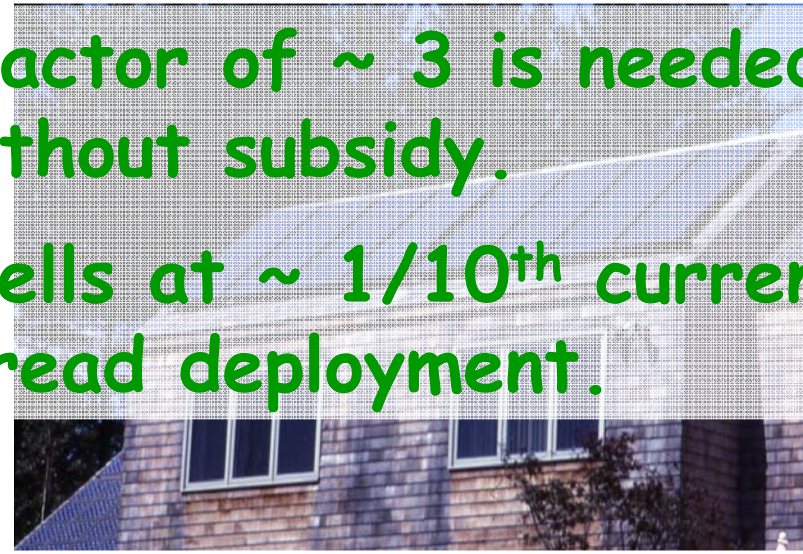
Limiting factors for plant productivity



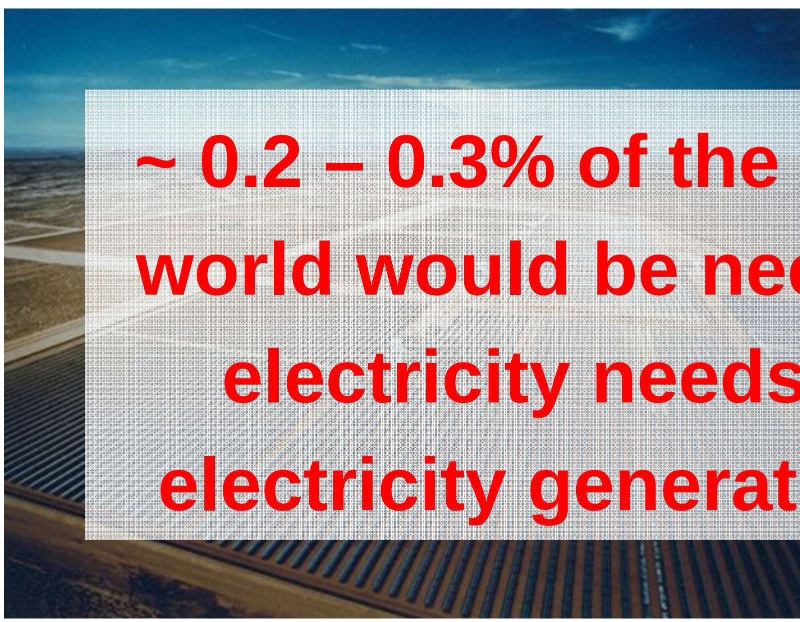
Baldocchi et al. 2004 SCOPE 62

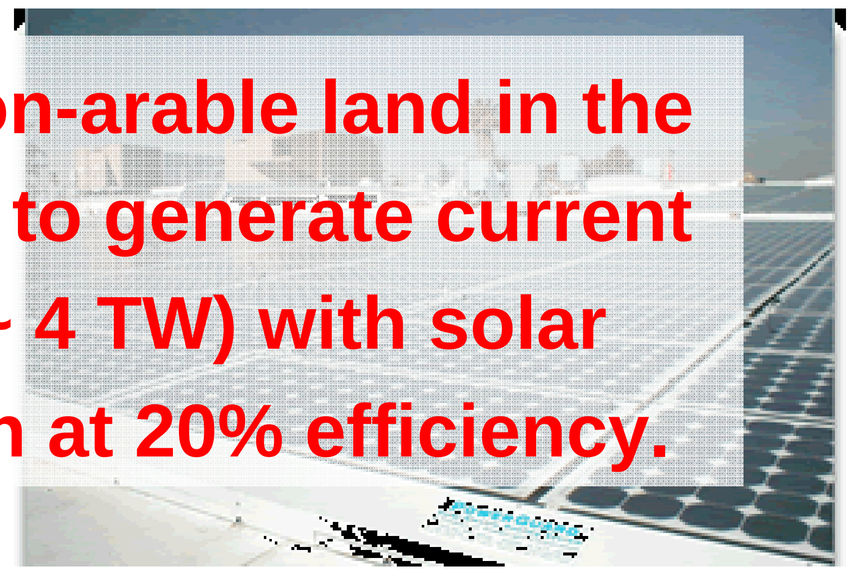
Solar thermal | **Solar photovoltaic**





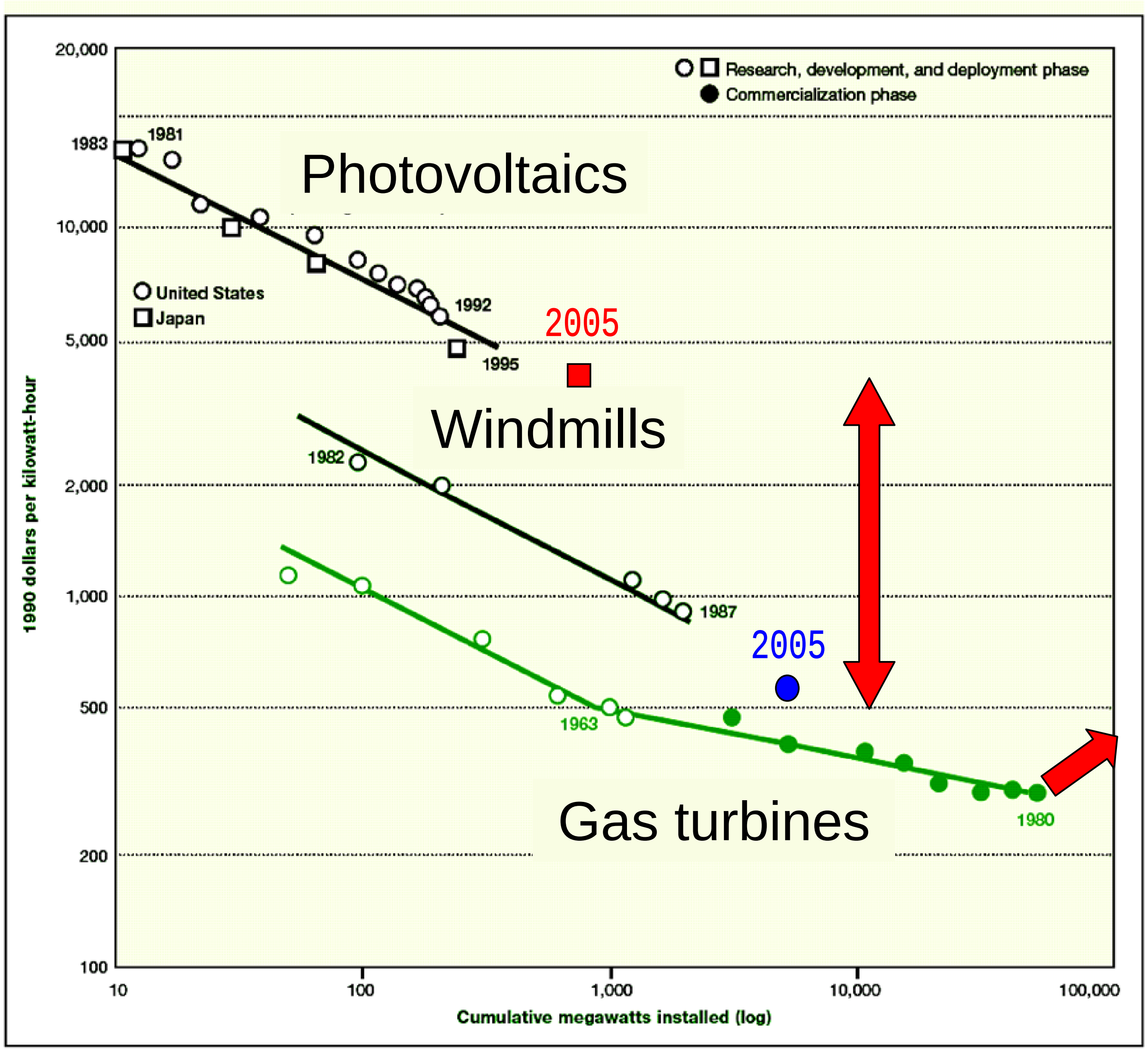
- Reduction of costs by a factor of ~ 3 is needed for roof-top deployment without subsidy.
- A new class of solar PV cells at ~ $1/10^{th}$ current cost is needed for wide-spread deployment.





~ 0.2 – 0.3% of the non-arable land in the world would be need to generate current electricity needs (~ 4 TW) with solar electricity generation at 20% efficiency.

Cost of electricity generation
(1990 dollars/kilowatt hour)



Sunlight to energy via Bio-mass

Sunlight
CO_2, H_2O,
Nutrients

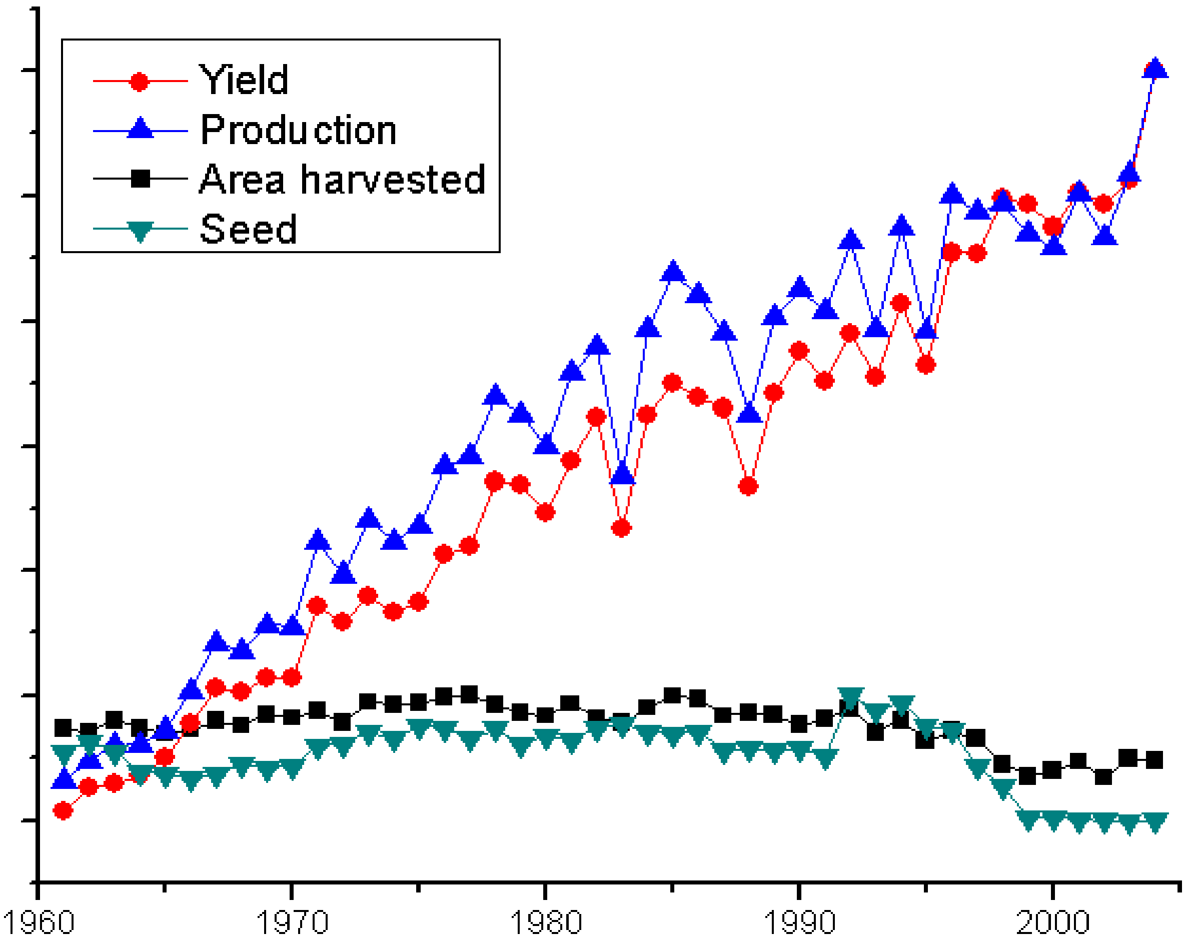
→ Biomass → Chemical energy

More efficient use of water, sunlight, nutrients.

Drought and pest resistant

Improved conversion of cellulose into fuel.
New organisms for biomass conversion.

World Production of Grain (1961 – 2004)



1960:
Population = 3 B

2005:
Population = 6.5 B

Source: Food and Agriculture Organization (FAO), United Nations

Feedstock grasses (*Miscanthus)* is a largely unimproved crop.

Non-fertilized, non-irrigated test field at U. Illinois can yield

10x more ethanol / acre than corn.

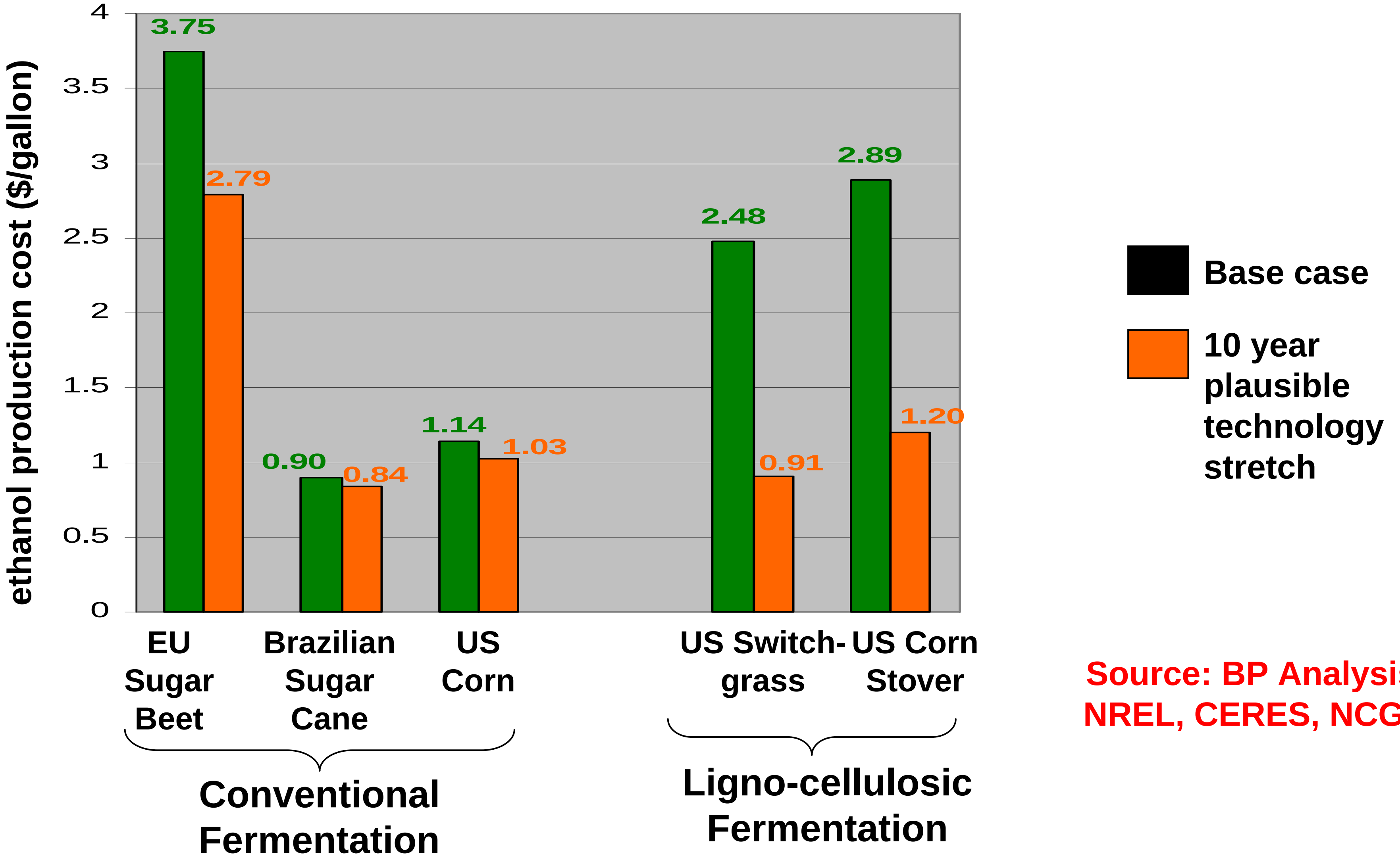
50 M acres of energy crops plus agricultural wastes (wheat straw, corn stover, wood residues, etc.) can produce ***half*** to ***all*** of current US consumption of gasoline.

Advantages of perennial plants such as grasses:

- No tillage for ~ 10 years after first planting
- Long-lived roots establish symbiotic interactions with bacteria to acquire nitrogen and mineral nutrients.
- Some perennials withdraw a substantial fraction of mineral nutrients from above-ground portions of the plant before harvest.
- Perennials have lower fertilizer runoff than annuals. (Switchgrass has ~ 1/8 nitrogen runoff and 1/100 the soil erosion of corn.)

Current and projected production costs of ethanol

Courtesy Steve Koonin, BP Chief Scientist



Source: BP Analysis, NREL, CERES, NCGA

Energy Biosciences Institute

$50M/ year for 10 years

Joint Bio-Energy Institute (JBEI)

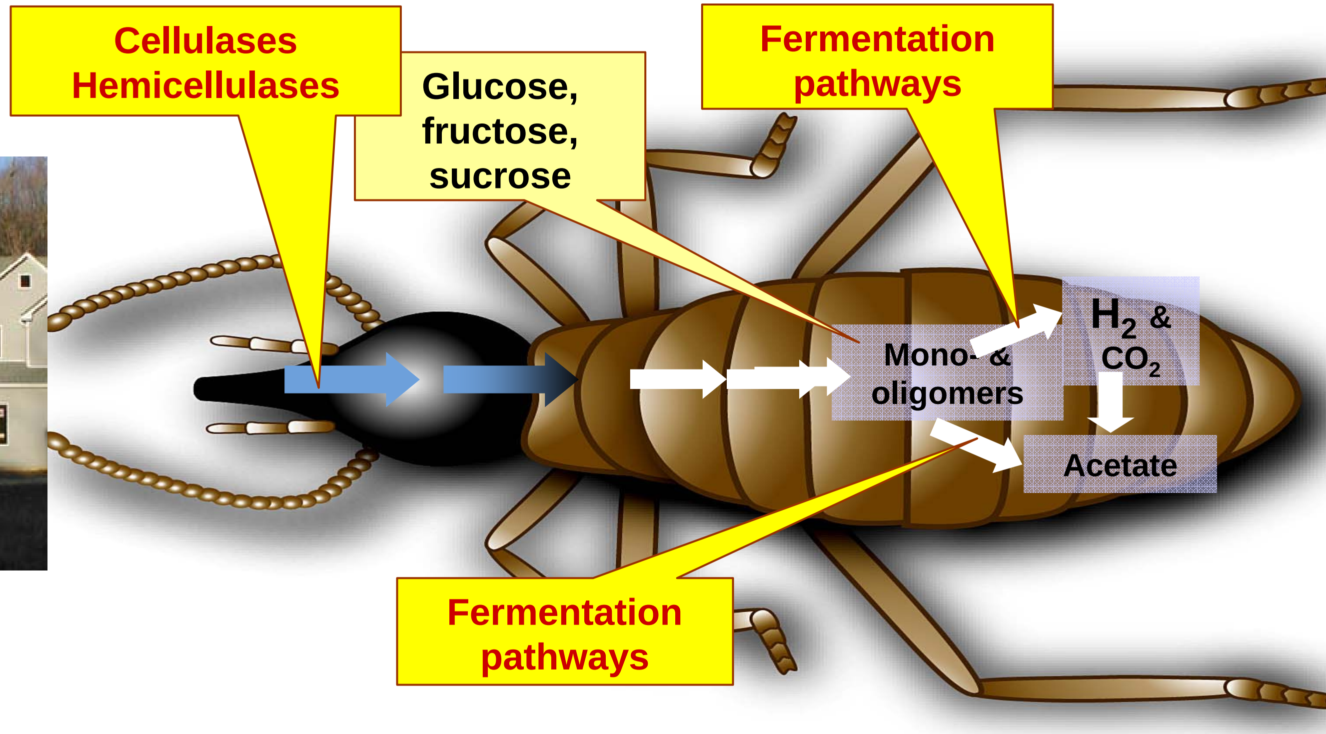
LBNL, Sandia, LLNL, UC Berkeley, Carnegie Institute, UC Davis

$25M / year for at least 5 years

Lawrence Berkeley National Lab

Univ. Illinois, Urbana-Champaign

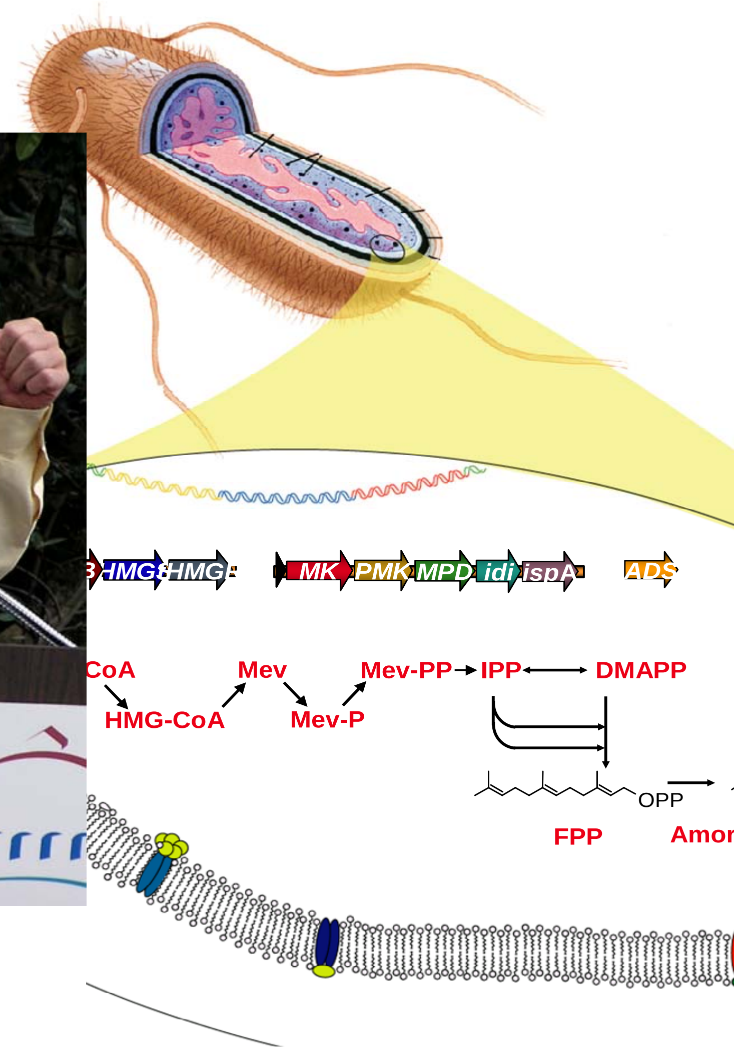
Termites have many specialized microbes that efficiently digest lignocellulosic material



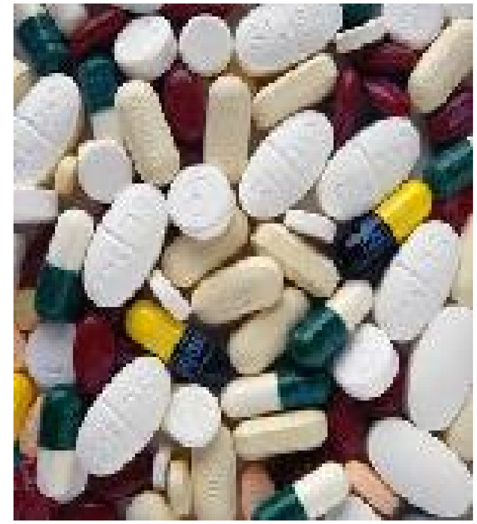
Production of artemisinin in bacteria

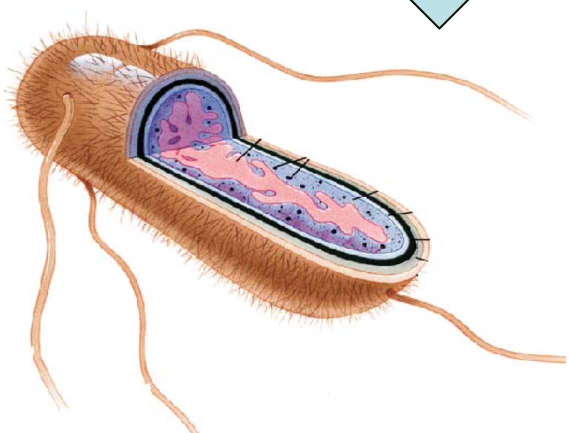
Jay Keasling

Director of Physical Biosciences Division



Research, Development & Delivery





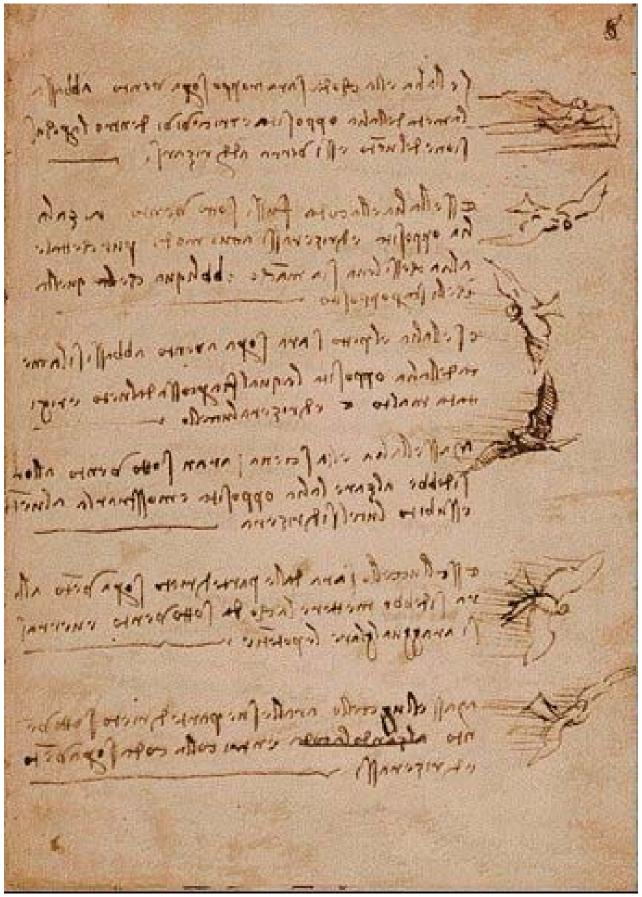
Keasling Laboratory

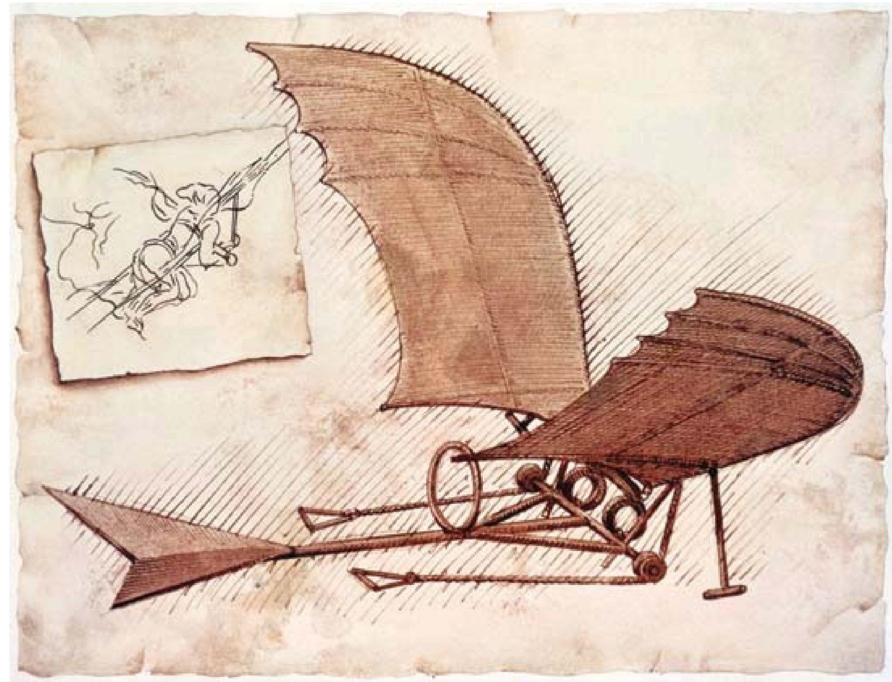
Amyris Biotechnologies

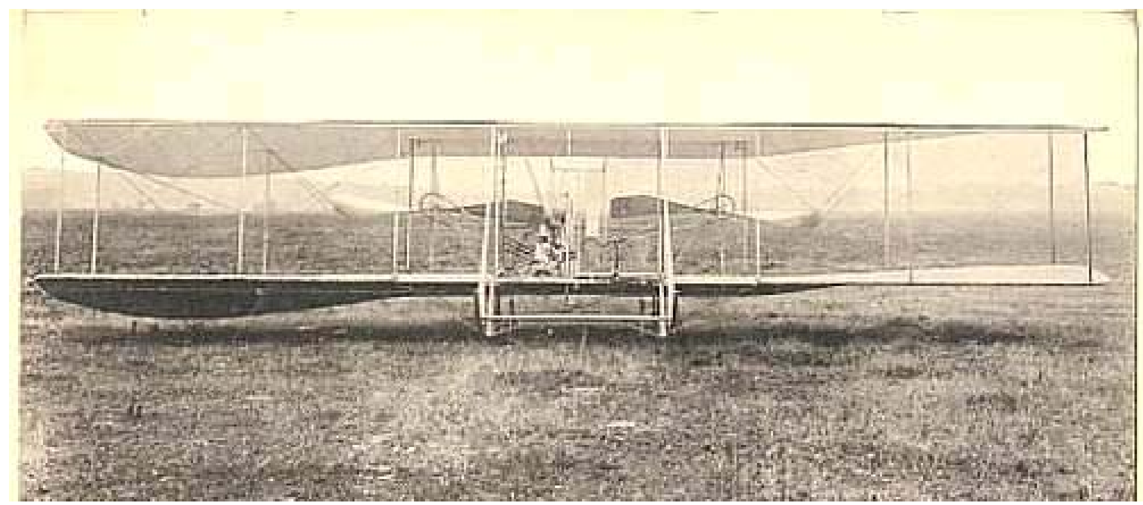
Institute for OneWorld Health

Cost 20¢ /cure

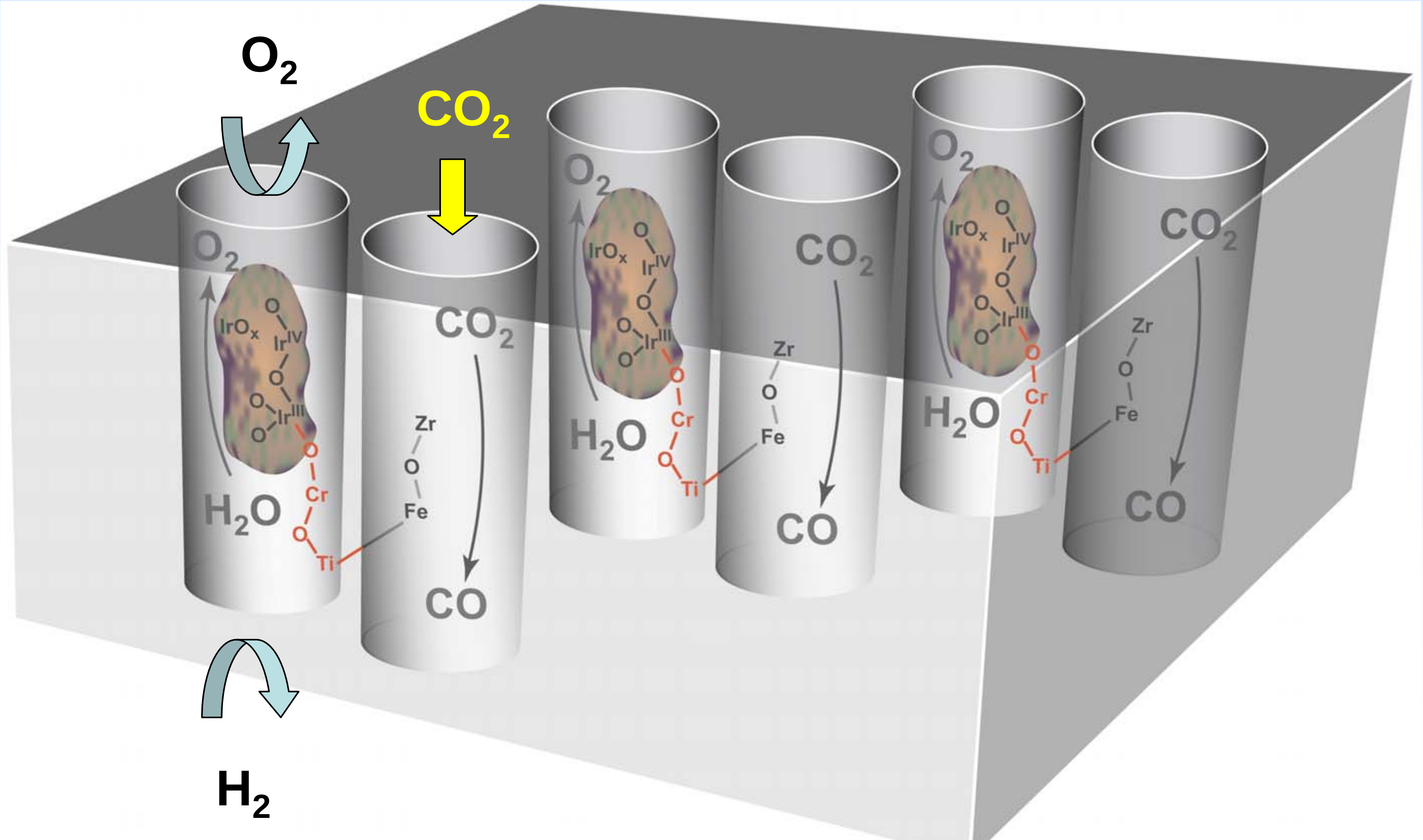
Man first learned to fly by imitating nature







Is it possible to engineer an artificial photo-synthetic system that is powered by either sunlight or electricity?



Lawrence Berkeley National Laboratory

3,800 employees, ~$520 M / year budget

11 employees were awarded the Nobel Prize,
(9 did their Nobel work at the Lab.)
(Over 55 Nobel Laureates either trained or had significant collaborations at LBNL)

Today:

~ 3% of the members of National Academy of Sciences,
18 in the National Academy of Engineering,
2 in the Institute of Medicine

The Helios Project

Helios Fund raising:

$500 M / 10 yr	BP
$125 M/ 5 yr	Department of Energy (Bio-fuels)
$ 8 - 10 M/yr	Department of Energy (Materials Science)
$ 3M → 12M?	Renewable Energy Chairs

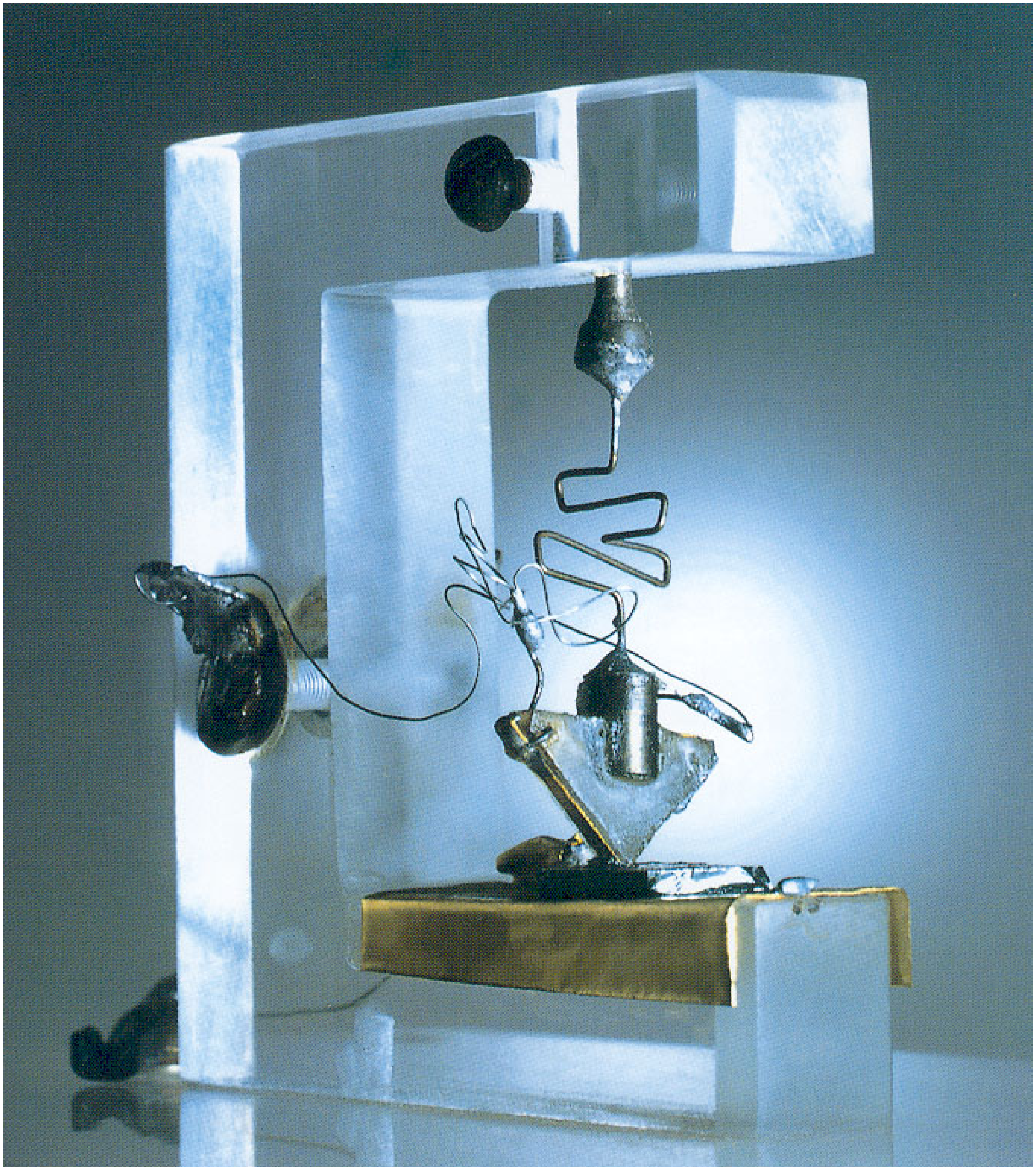
$160 M Building

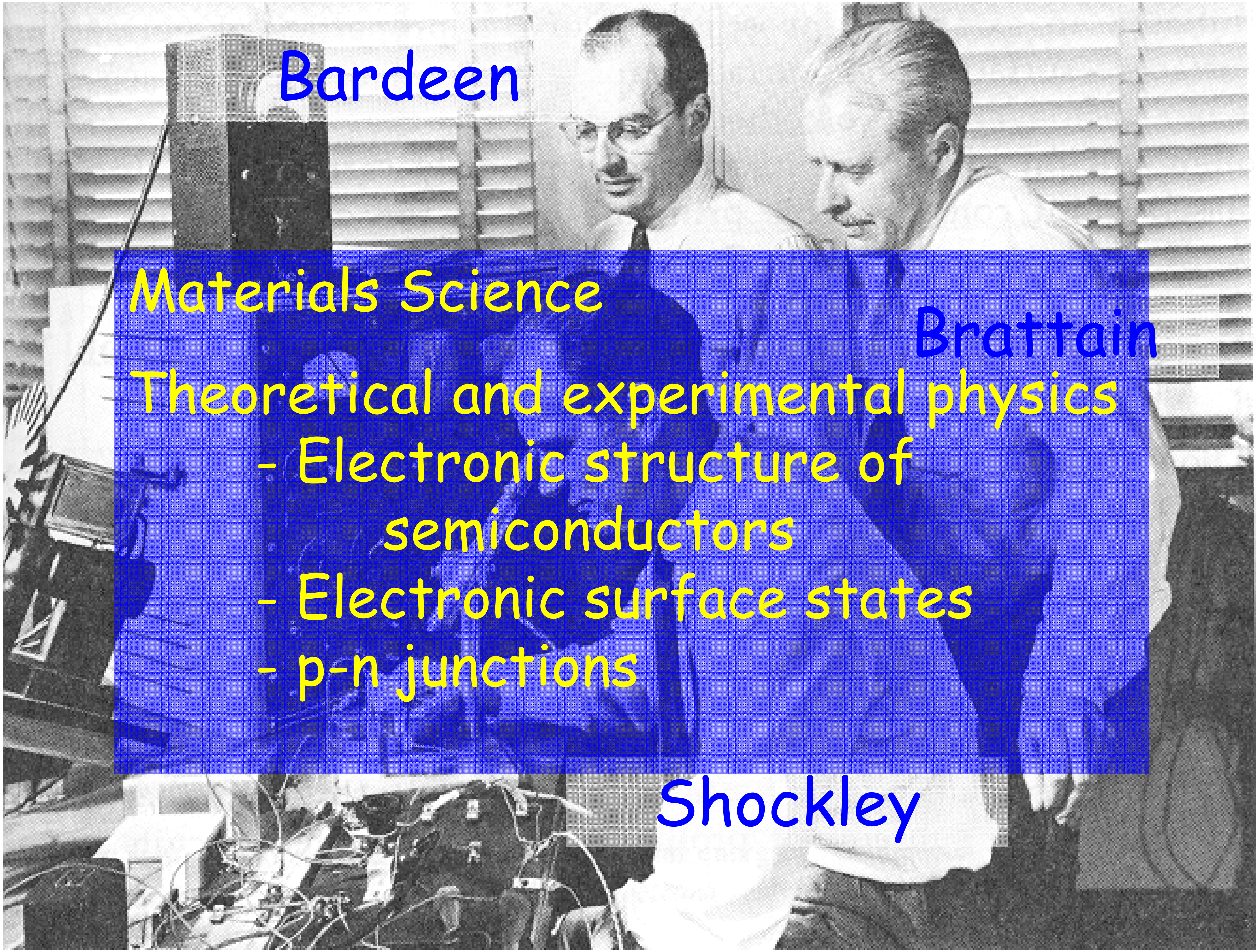
$70 M	State of California
$30-60 M	Univ. of California Bonds
$19 M	Private Donations
$10M	California Public Utility Commission
$XX M?	More Private Donors
$XX M?	Private Foundations

Industrial Partners (BP, Dow, IBM, Applied Materials, …)

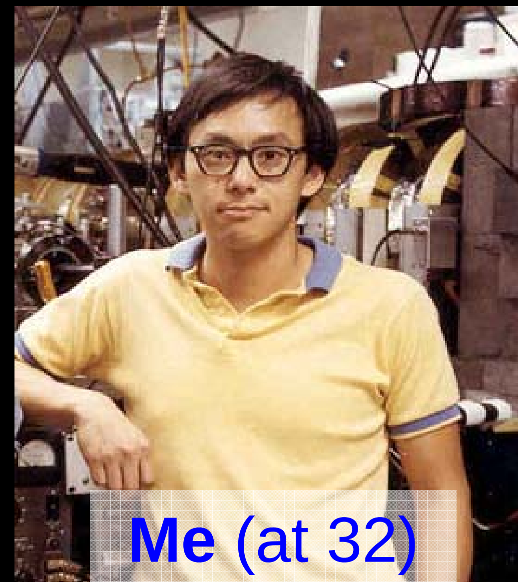
Bell Laboratories (Murray Hill, NJ)

15 scientists who worked at AT&T Bell laboratories received Nobel Prizes.




Bardeen
Materials Science
Brattain
Theoretical and experimental physics
- Electronic structure of semiconductors
- Electronic surface states
- p-n junctions
Shockley

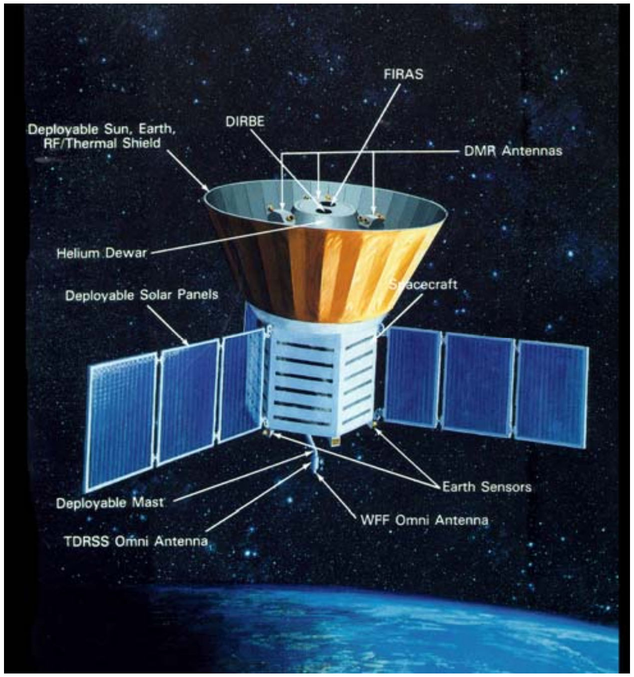
Nobel Prize Members at Bell Labs hired in 1977-78



E.O. Lawrence introduced the idea of "team science"

Ernest Lawrence, Robert Serber, Luis Alverez, Edwin McMillan, Robert Oppenheimer, Robert R. Wilson, …

The tradition of E.O. Lawrence continues …

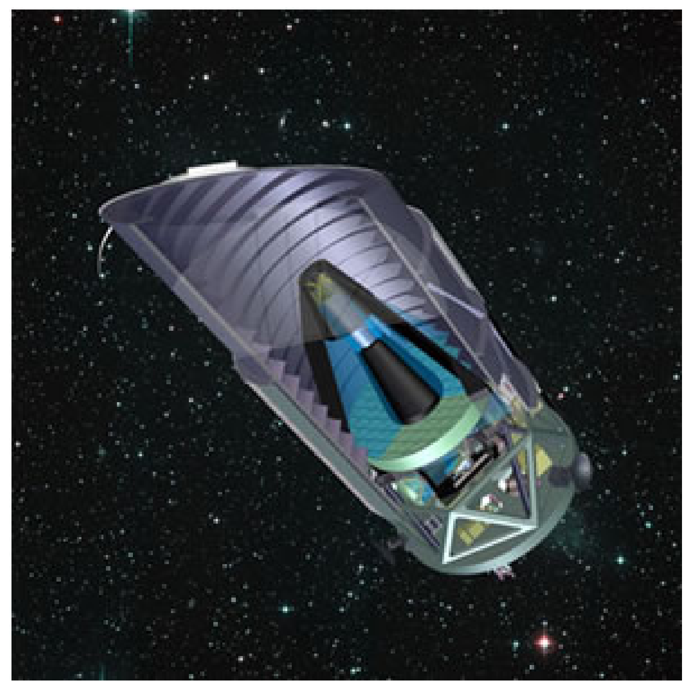


COBE: Cosmic Background Explorer

2006 Nobel Prize in Physics
George Smoot (LBNL & UCB) and
John Mather (Goddard)

Dark Energy

Saul Perlmutter (LBNL and UCB)
(2006 Run Run Shaw Prize,
Fretinelli Prize)

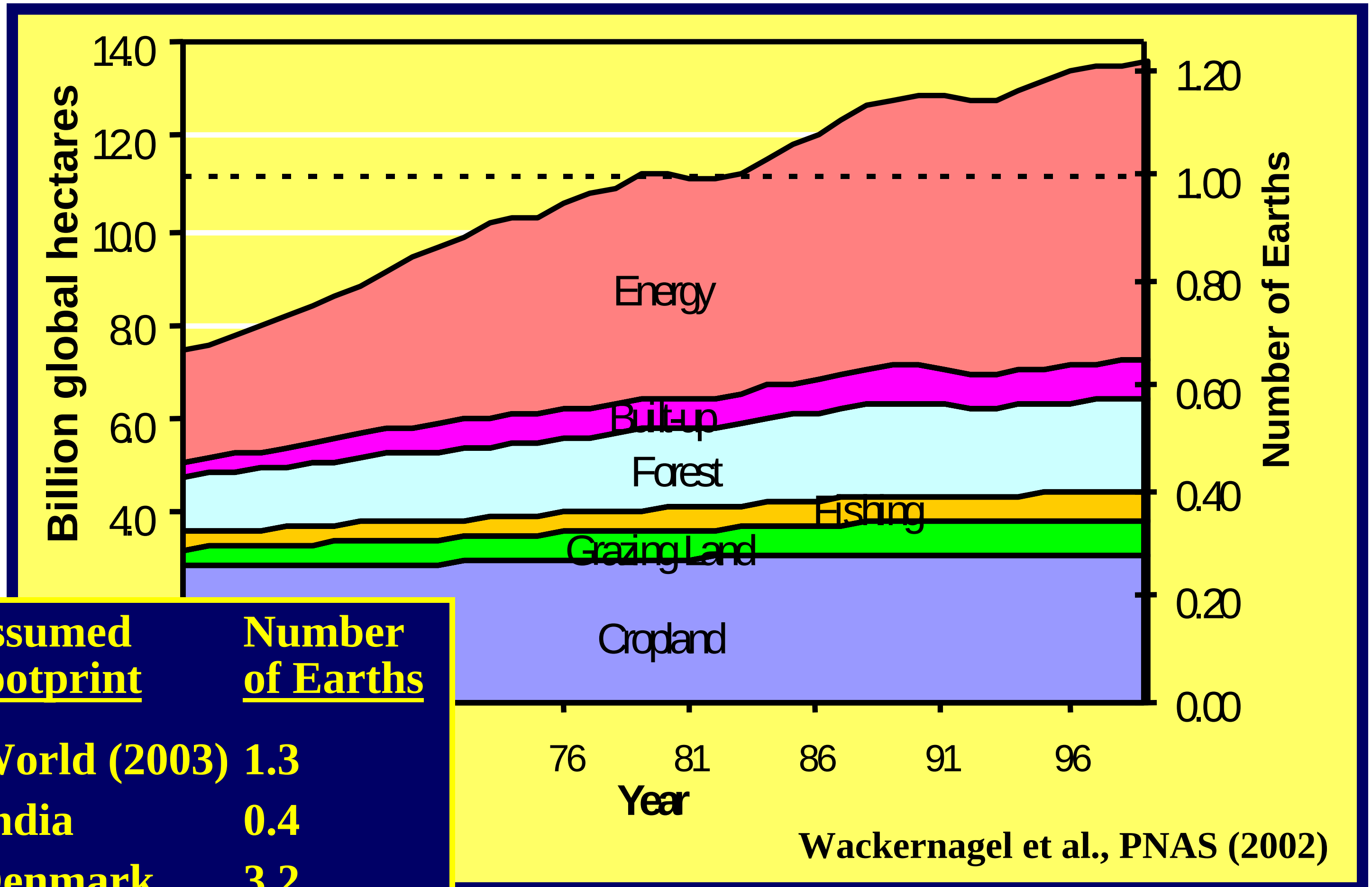


Organizational culture

- Individual genius was nurtured, but individuals were also encouraged to quickly form teams to rapidly exploit ideas.
- The scientific direction was guided by collective wisdom and “managed” by top scientists with intimate, expert knowledge.
- Bold approaches were encouraged; some failure was expected, but there was an emphasis on recognizing failure quickly, and moving on to other opportunities.


Earthrise from Apollo 8 (December 24, 1968)

Environmental "footprint": Land area required for sustainable use



Wackernagel et al., PNAS (2002)

Population	Assumed Footprint	Number of Earths
6 billion	World (2003)	1.3
6 billion	India	0.4
6 billion	Denmark	3.2
6 billion	USA	5.2
10 billion	Denmark	5.1

www.footprintnetwork.org

There *are* solutions to the energy/climate change problem:

"We believe that aggressive support of energy science and technology, coupled with incentives that accelerate the concurrent development and deployment of innovative solutions, can transform the entire landscape of energy demand and supply …

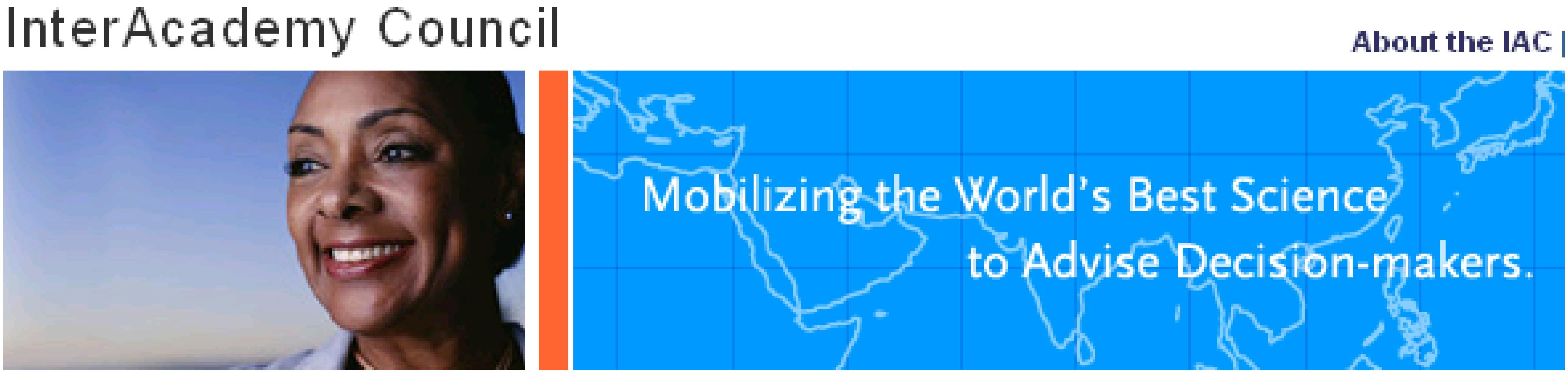
What the world does in the coming decade will have enormous consequences that will last for centuries; it is imperative that we begin without further delay."

“On December 10, 1950, William Faulkner, the Nobel Laureate in Literature, spoke at the Nobel Banquet in Stockholm,

… I believe that man will not merely endure: he will prevail. He is immortal, not because he alone among creatures has an inexhaustible voice, but because he has a soul, a spirit capable of compassion and sacrifice and endurance.’

With these virtues, the world can and will prevail over this great energy challenge.”

Steven Chu (USA) and José Goldemberg (Brazil)
Co-Chair’s Preface



"Lighting the Way: Toward a Sustainable Energy Future"

Public release: October 22, 2007

Co-chairs: Jose Goldemberg, Brazil
Steven Chu, USA