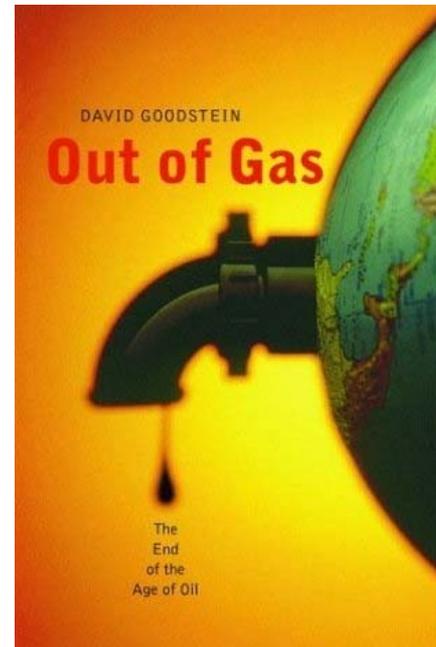


Out of Gas

The end of the age of oil

David Goodstein



Air Resources Board, November 30 , 2006

Energy Myths

- **\$3.00 a gallon is too much to pay**
- **Oil companies produce oil.**
- **We must conserve energy.**
- **When we run out of oil, the marketplace will take over**
- **There's enough fossil fuel in the ground to last for hundreds of years.**
- **Nuclear energy is dangerous.**
- **The greenhouse effect and global warming are bad.**

A Brief History of Energy

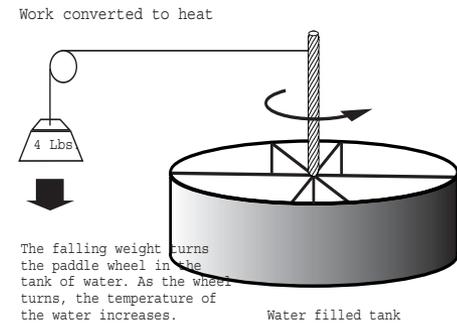
Caloric

**Count Rumford (Sir Benjamin Thompson),
1753-1814**

Many others

Credit

James Prescott Joule, 1818-1889



Forms of Energy

Kinetic

Organized

Random (Temperature)

Potential

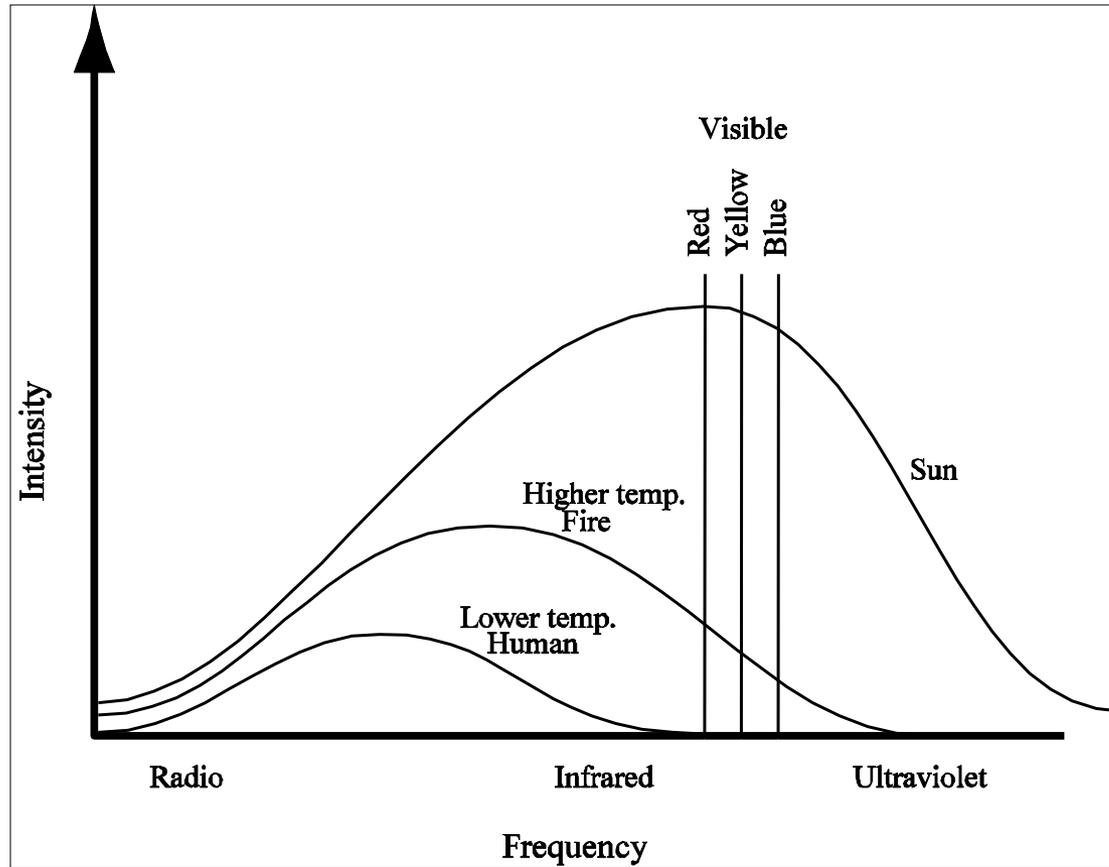
Gravitational

Chemical

Nuclear

etc.

Thermal Radiation

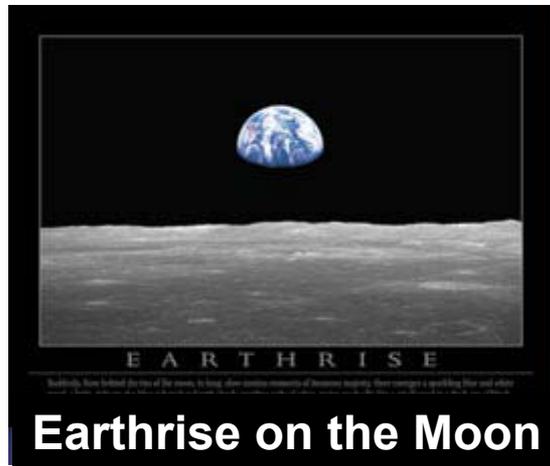


The Sun-Earth System



30% reflected
70% absorbed

The Sun-Earth System



30% reflected
70% absorbed

The Sun-Earth System

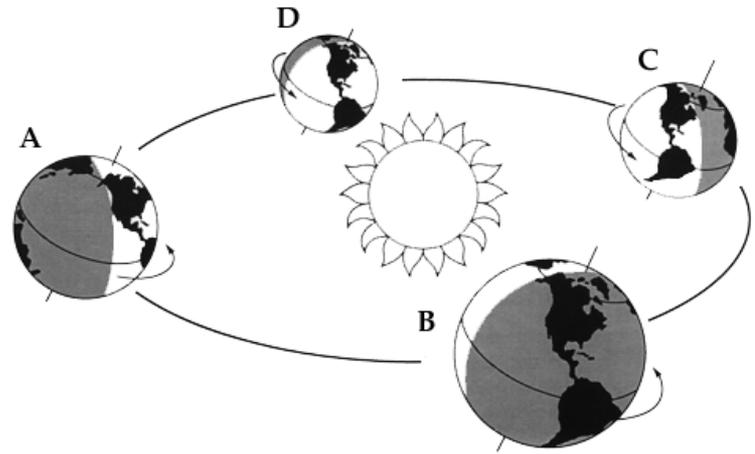


30% reflected
70% absorbed

$$T = 255 \text{ K} = -18 \text{ }^\circ\text{C} = 0 \text{ }^\circ\text{F}$$

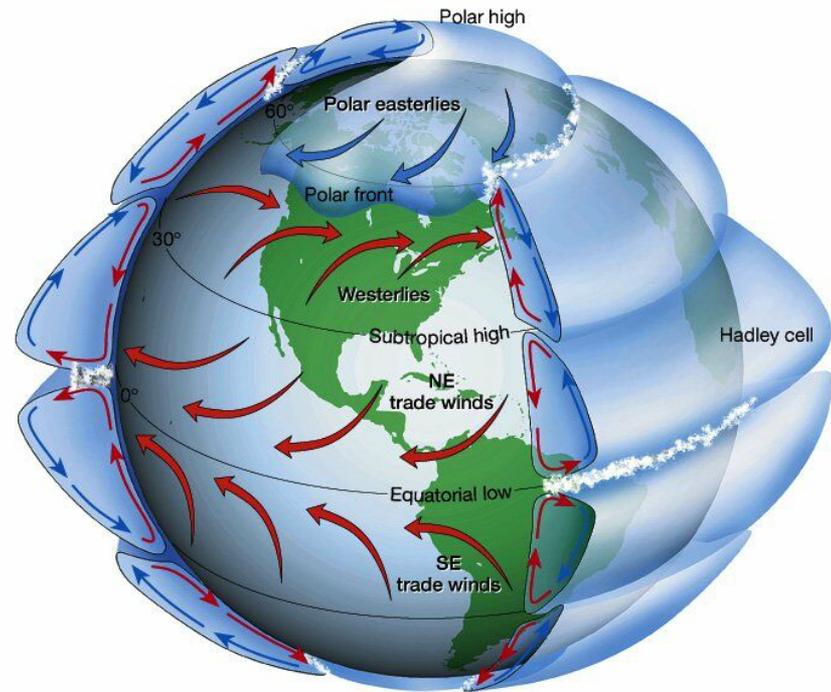
Earth's Climate

- **The tilted axis**



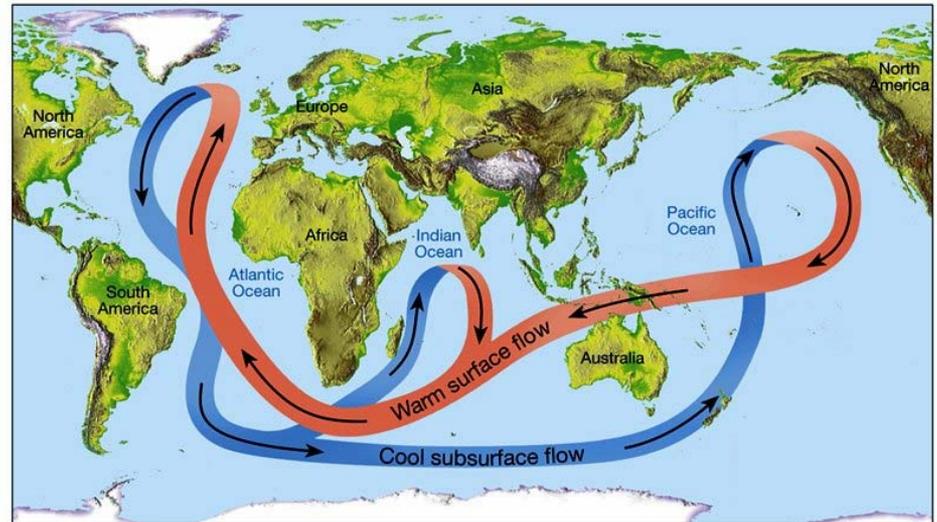
Earth's Climate

- The tilted axis
- The El Niño Cycle



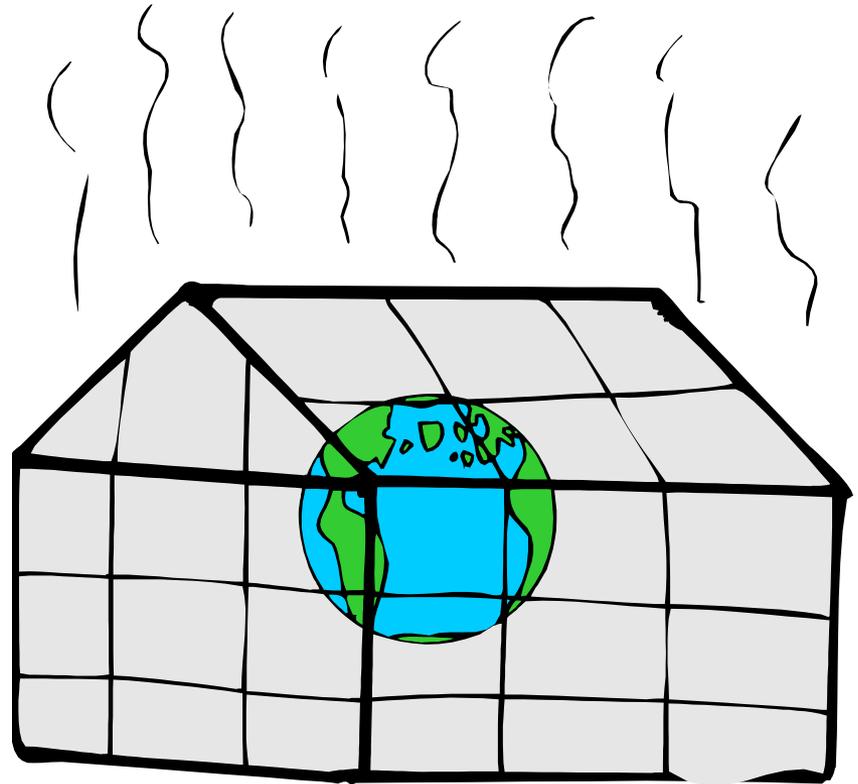
Earth's Climate

- The tilted axis
- The El Niño Cycle
- The Thermohaline Flow



Earth's Climate

- **The tilted axis**
- **The El Niño Cycle**
- **The Thermohaline Flow**
- **The Greenhouse Effect**



The Greenhouse Effect

(Preindustrial)

From the Sun: 343 W/m^2

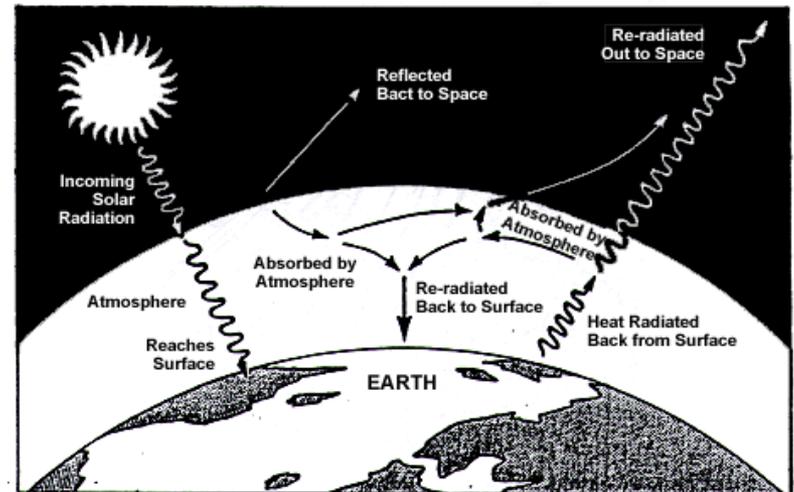
**Water vapor, methane,
Carbon dioxide, etc.**

88% Greenhouse

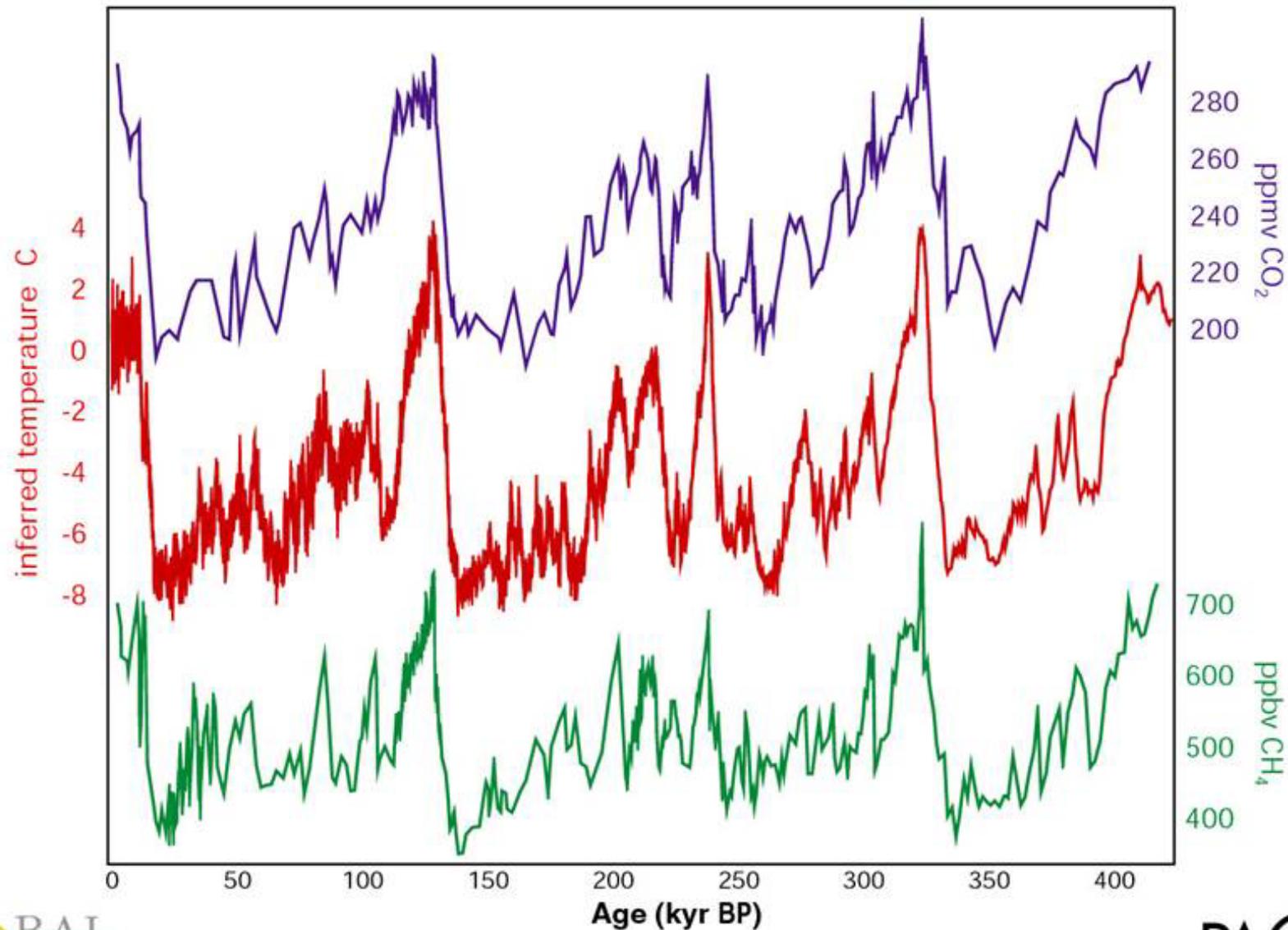
$T = 287\text{K} = 14^\circ\text{C} = 57^\circ\text{F}$

Feedback effects

Limiting cases



4 glacial cycles recorded in the Vostok ice core



Sources of Useful Energy

Before 1800:

Light from the
Sun

Coal

Oil seeps

Swamp gas



Nineteenth Century

Coal

Whale Oil

E. L. Drake, 1859, Titusville, PA.

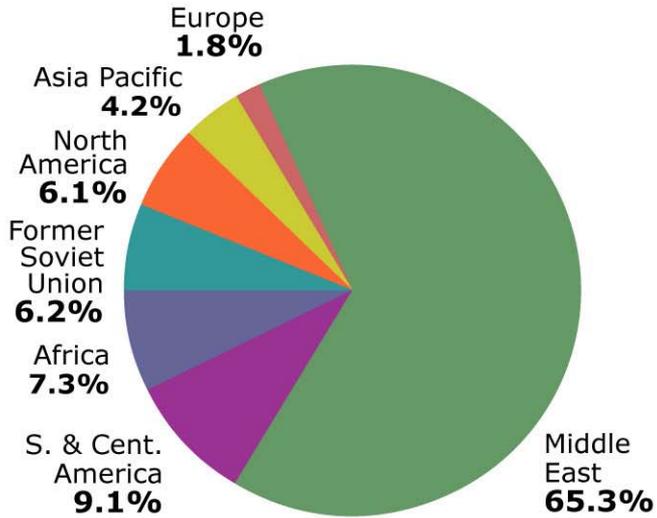
Illumination, Lubrication

Fuel

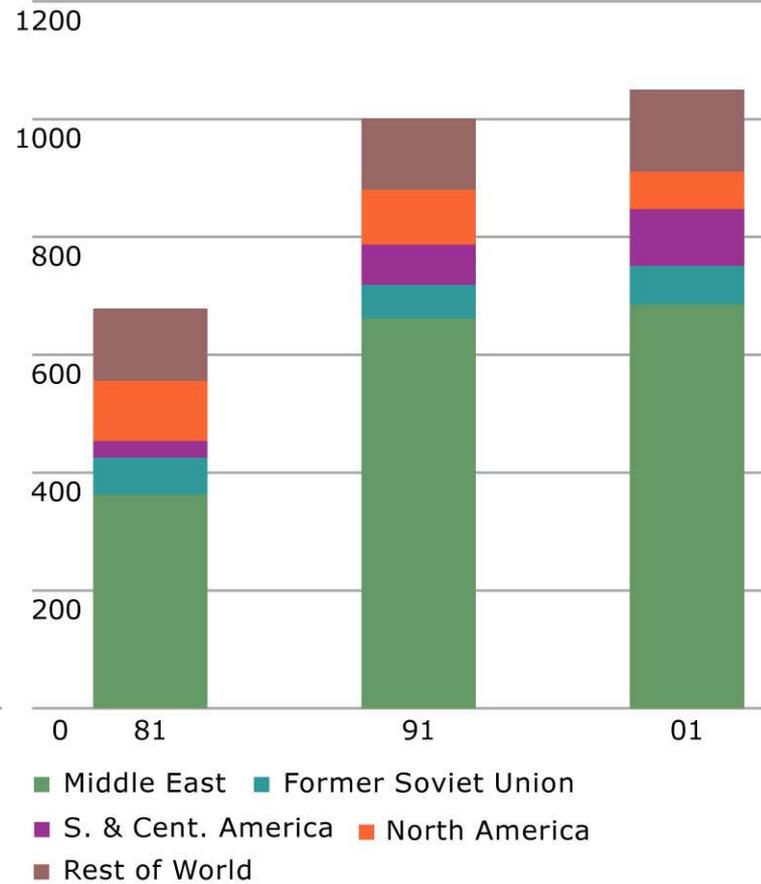
We can no longer live on light from the Sun

charts of distribution of proved oil reserves 2001

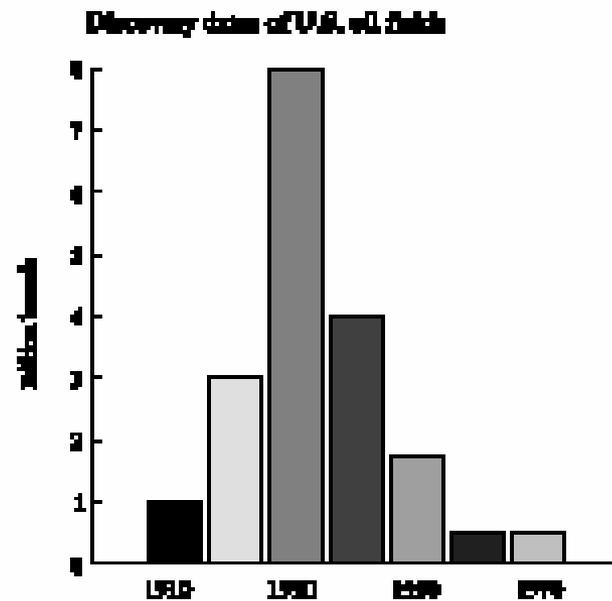
Thousand million barrels %



Thousand million barrels



M. King Hubbert



Hubbert's analysis

Q = All the oil that's been discovered

Q_0 = All the oil that ever existed

At first, discovery grows exponentially

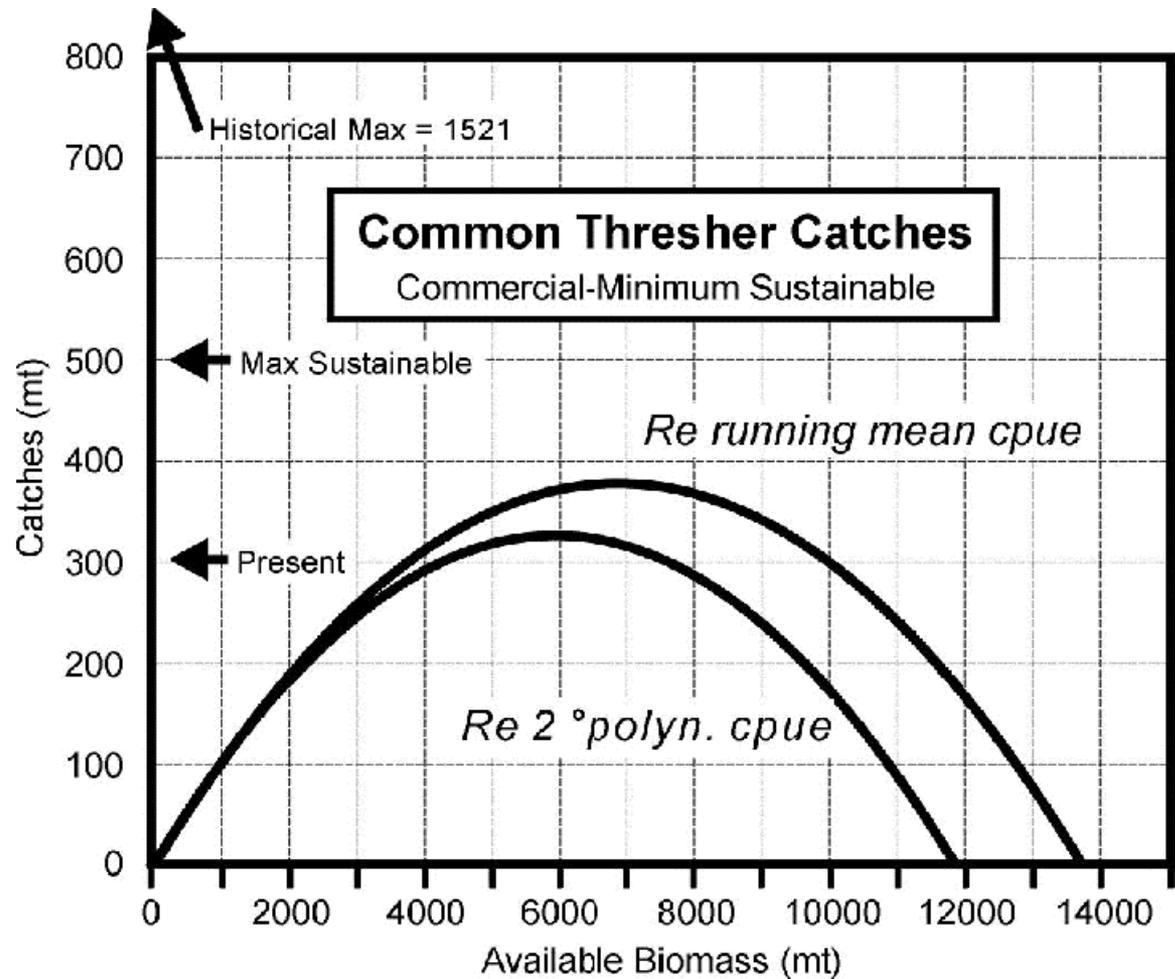
$$dQ/dt = aQ$$

But exponential growth slows down when Q is no longer small compared to Q_0 :

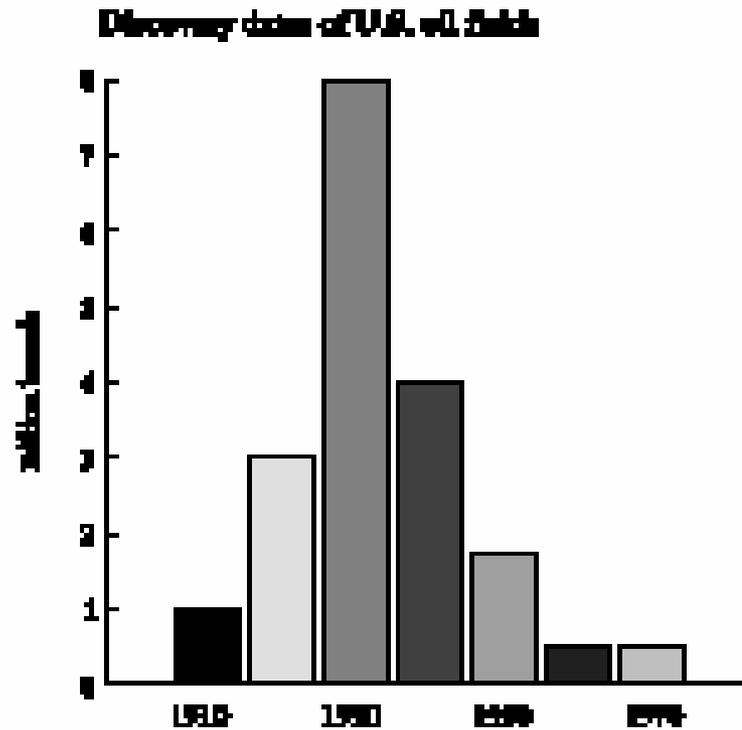
$$dQ/dt = aQ(Q_0 - Q)$$

The Logistic Equation

dQ/dt versus Q

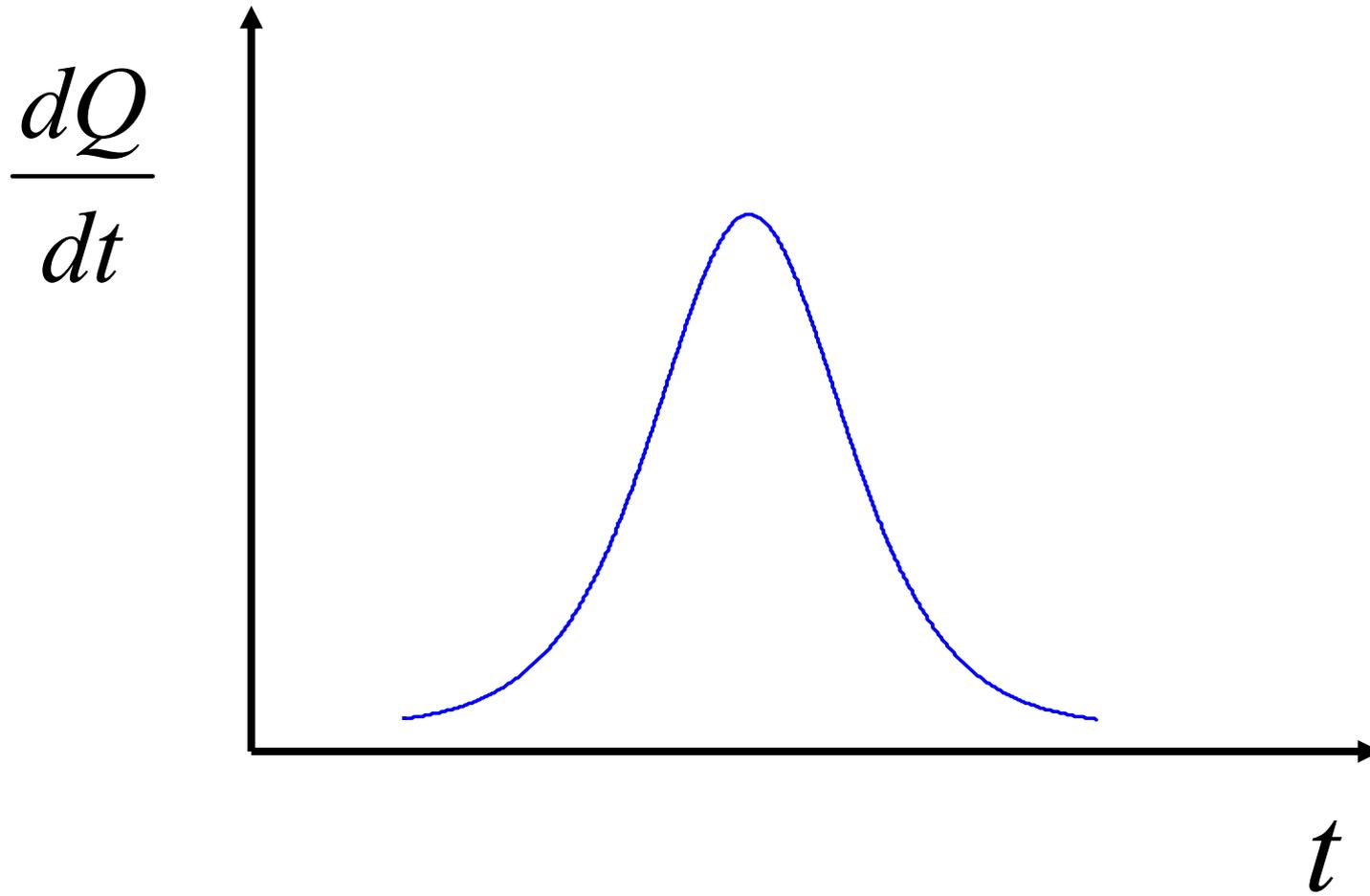


dQ/dt versus t

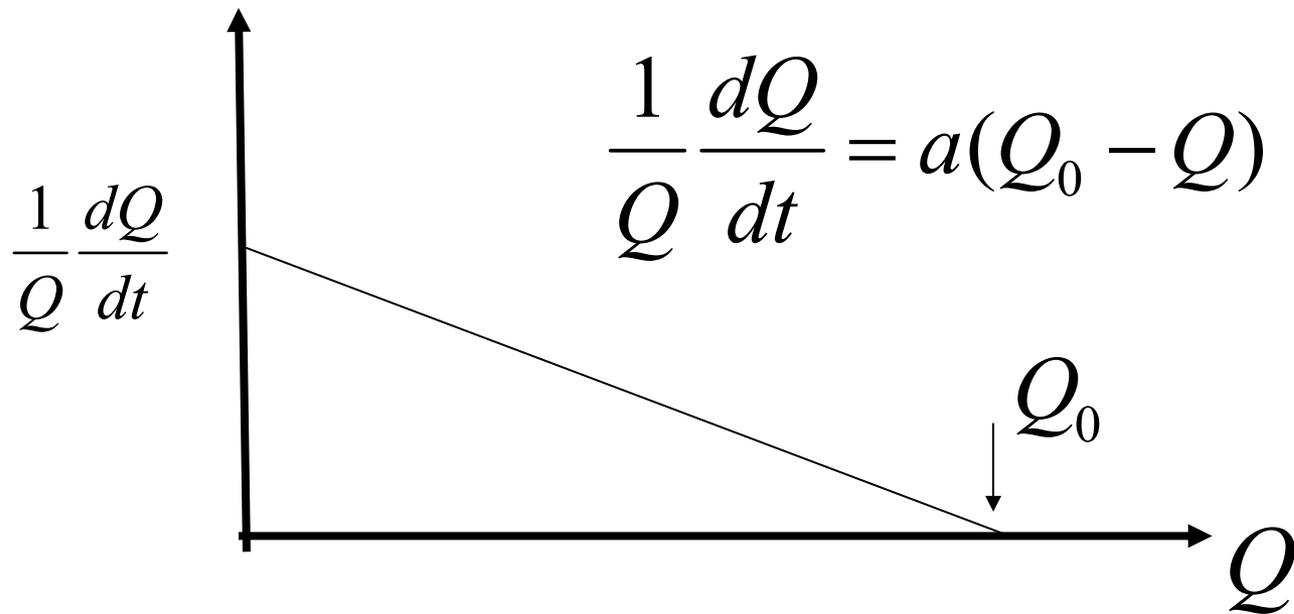


$$\frac{dQ}{dt} = Q_0 \frac{ae^{[a(t_0-t)]}}{[1 + e^{[a(t_0-t)}]^2}$$

The Logistic Curve



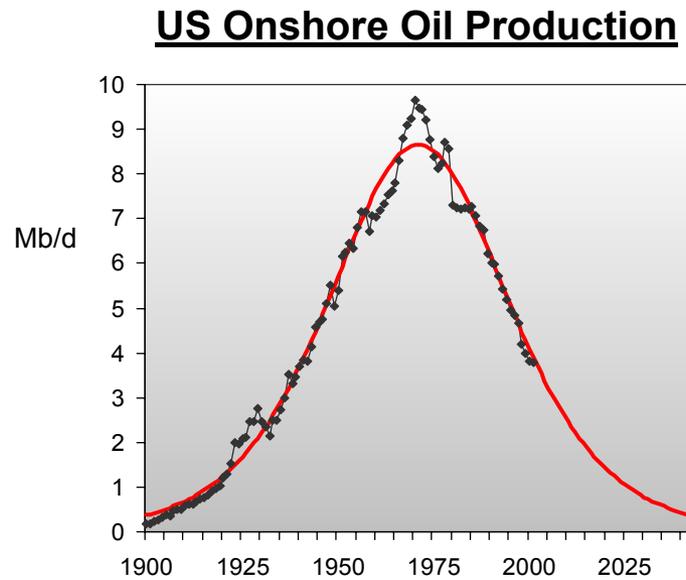
Extrapolating the declining rate of increase



Q_0 for the U.S. was 150 billion barrels

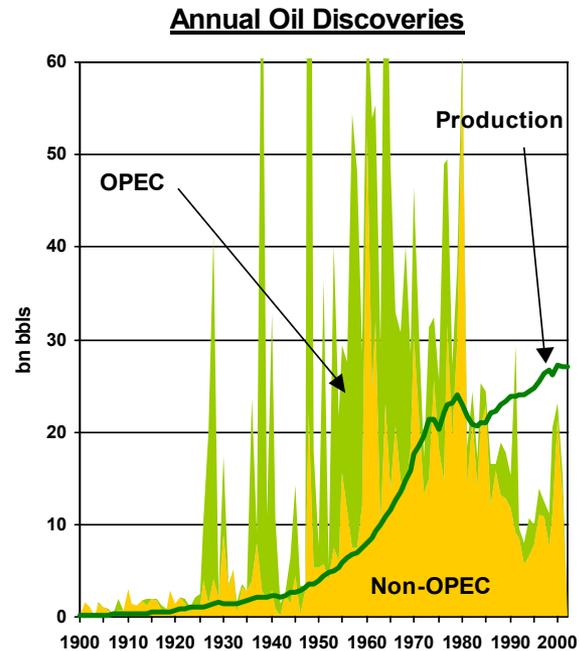
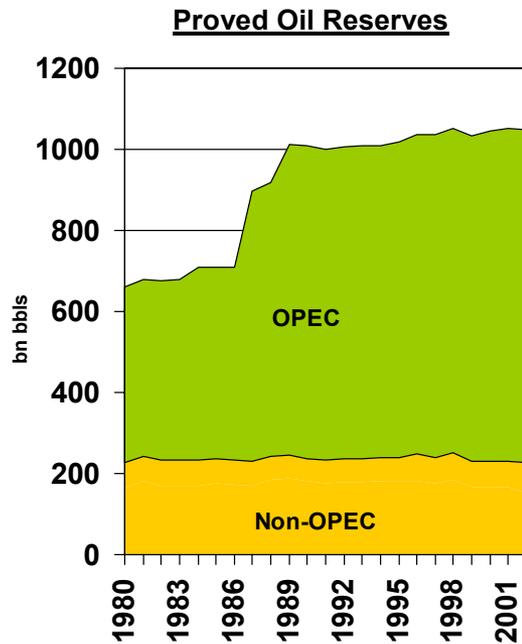
Fitting the data—Hubbert's Peak

Hubbert Curves



Reserves and Discovery

Oil Reserve Data

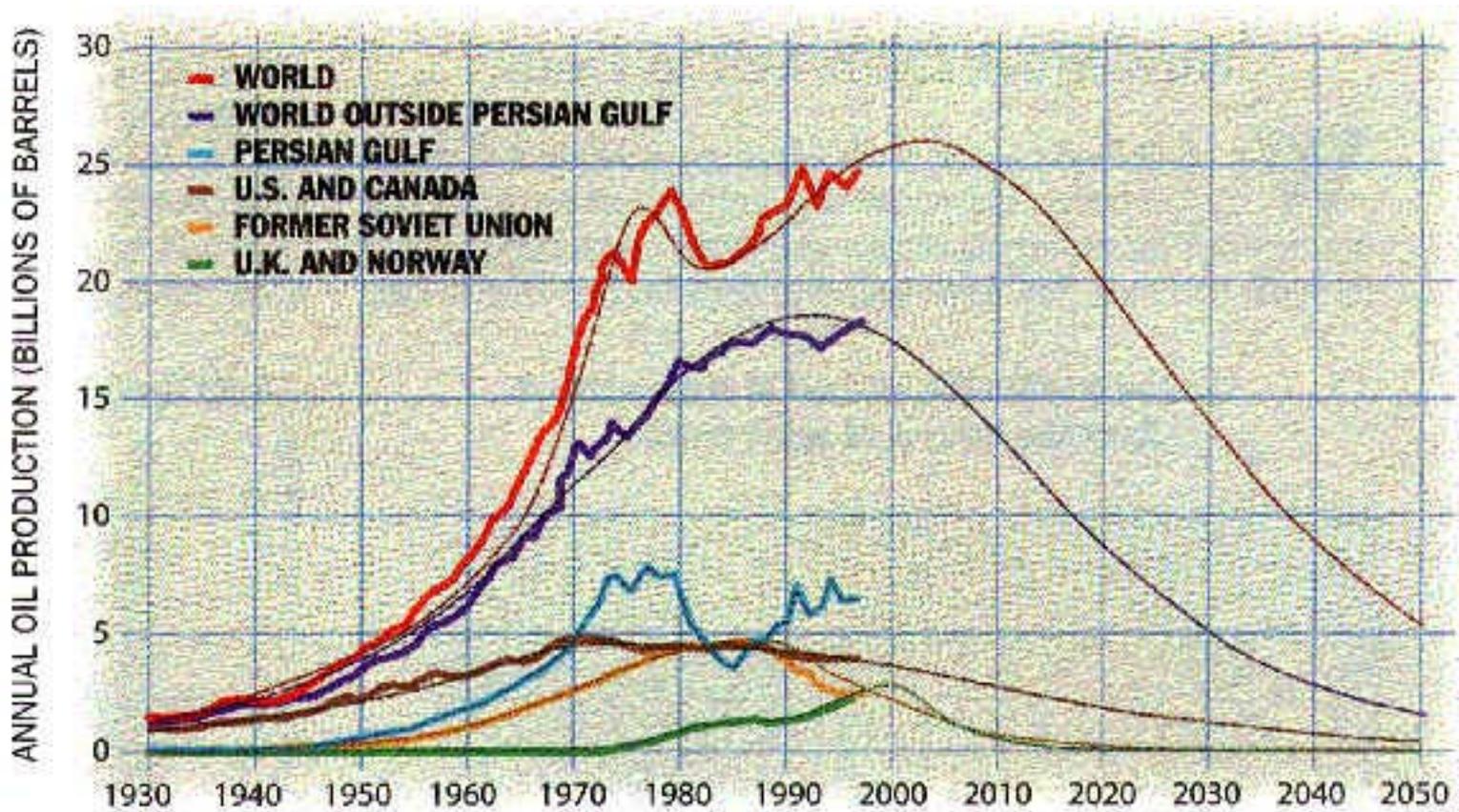


Source: BP Statistical Review of World Energy 2003



Model Calculation

Colin J. Campbell and Jean H. Laherrère Sci. Amer., 1998



Caution

- Used 1.8 trillion
- Technology = Discovery
- Increasing price makes more available
- “Reserve” numbers very soft
- Basic idea is right

Kenneth Deffeyes:

***The Texas Railroad Commission announced a
100% allowable for next month***

The San Francisco Chronicle, 1971

The New York Times, February 24, 2004

Forecast of Rising Oil Demand Challenges Tired Saudi Fields
By JEFF GERTH

...the country's oil fields now are in decline, prompting industry and government officials to raise serious questions about whether the kingdom will be able to satisfy the world's thirst for oil in coming years.

...

Some economists are ...optimistic that if oil prices rise high enough, advanced recovery techniques will be applied, averting supply problems.

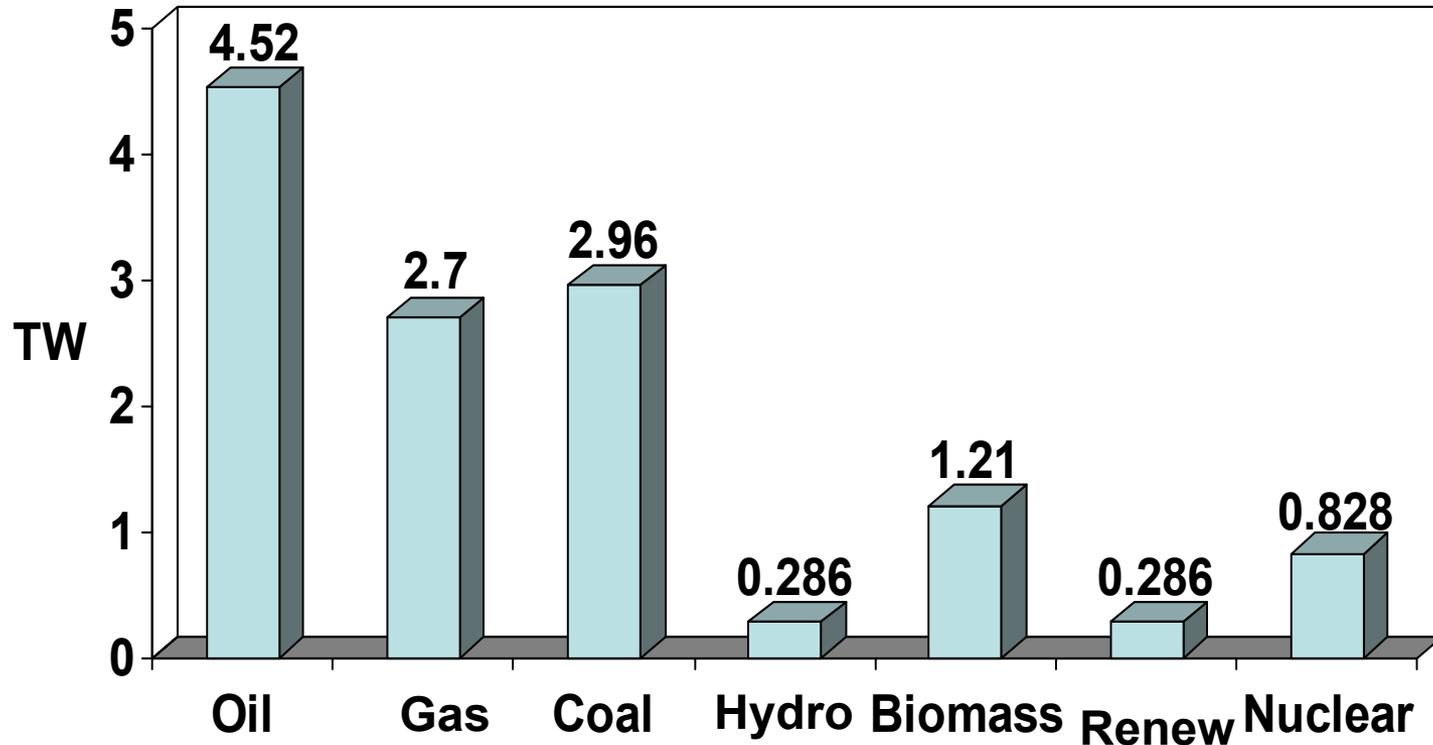
But privately, some Saudi oil officials are less sanguine.

Oil Users

- Petrochemicals
- Stationary power plants
- Home heating
- Transportation
 - Cars
 - Trucks
 - Planes
 - Ships
 - Trains



Global Energy Consumption, 1998



Total: 12.8 TW

U.S.: 3.3 TW (99 Quads)

Fossil Fuels

Oil

Natural gas

Shale oil

Methane hydrate

Coal



Coal

- Hundreds, maybe thousands years ***at present rate***
- Largest deposits in US
- Can be liquified substitute oil

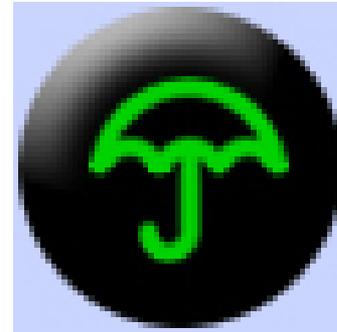
But

- Dirty (mercury, arsenic, sulfur)
- Greenhouse effect
- Increase rate x5 replace oil
- Increasing population
- Higher standard of living
- Hubbert's peak.—This century

What does the future hold?

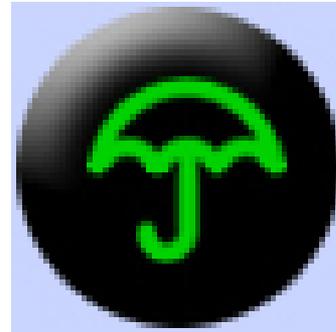
- Oil crisis very soon
- Fossil fuel will run out
- Unknown consequences for climate
- Solar flux plus nuclear
- Dilemma
 - Social, political
 - Technical

Technological Fixes Greenhouse Effect



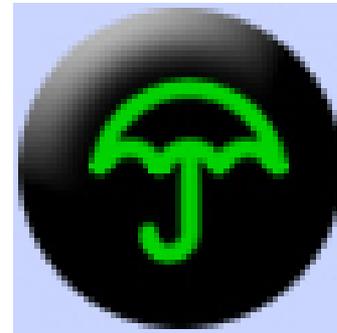
Technological Fixes Greenhouse Effect

- Parasol at L1

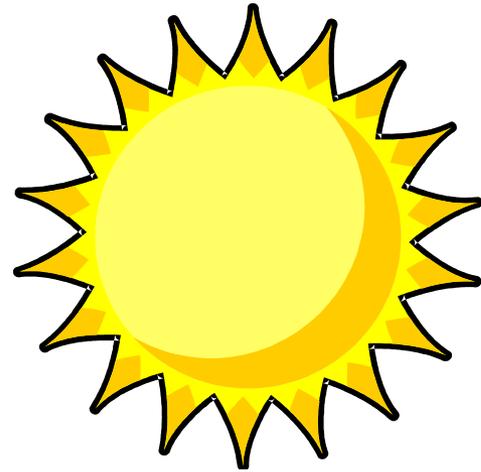


Technological Fixes Greenhouse Effect

- Parasol at L1
- Sequester CO₂

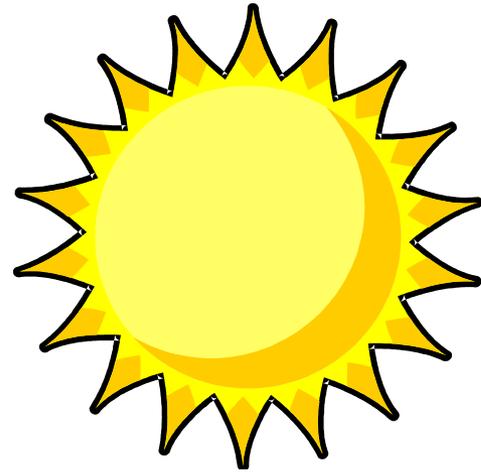


Solar



Solar

- Hydro



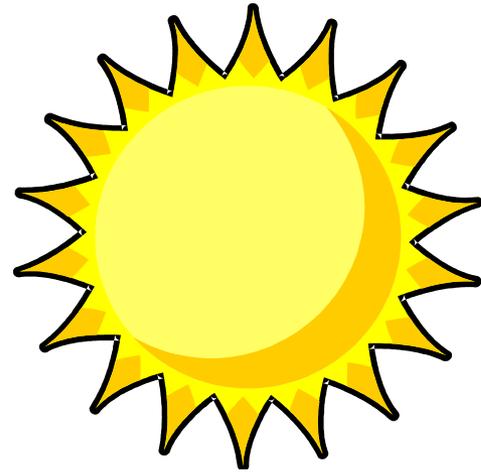
Solar

- Hydro
- Wind



Solar

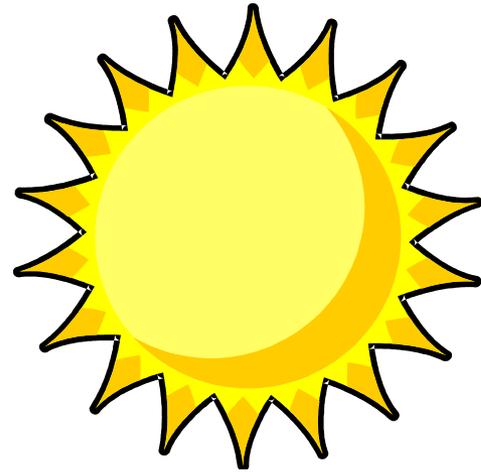
- Hydro
- Wind
- Biomass



Solar

- Hydro
- Wind
- Biomass
- PV

(10 TW = 220,000 km²)

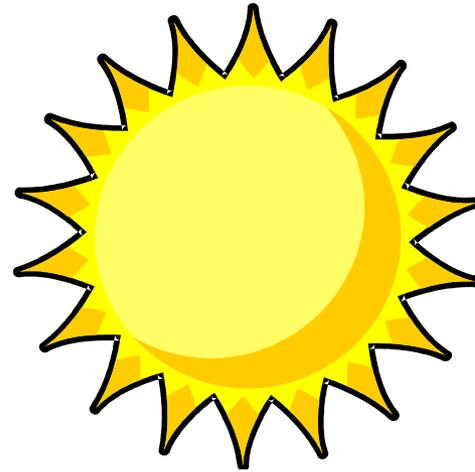


Solar

- Hydro
- Wind
- Biomass
- PV

(10 TW = 220,000 km²)

Total Solar Flux =
20,000 x 10 TW

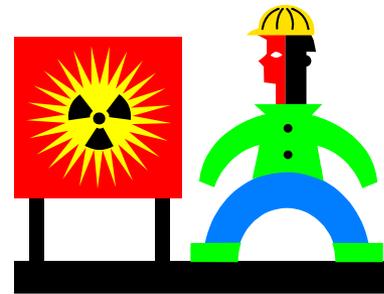


Conservation

(Amory Lovins, Rocky Mountain Institute)

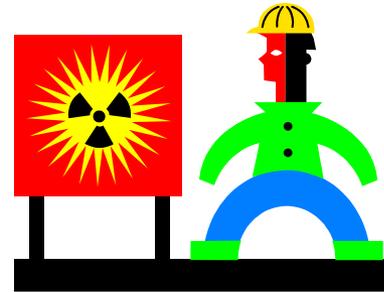
- Ultra light/strong materials
- Hybrids
- Efficient buildings, factories
- Fuel from switchgrass, poplar, sugar cane
- More efficient use electricity
- Feebates
- Etc.

Nuclear



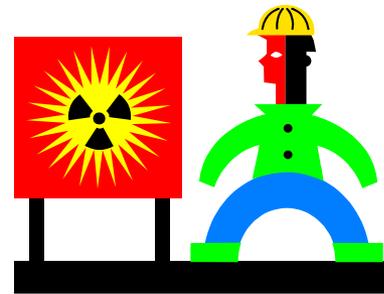
Nuclear

- Geothermal



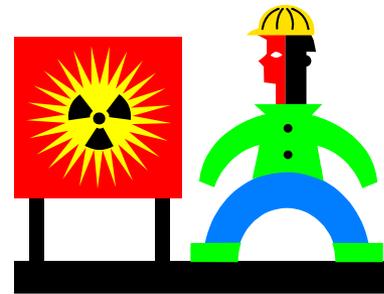
Nuclear

- Geothermal
- Fission



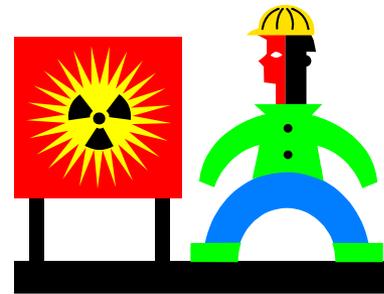
Nuclear

- Geothermal
- Fission
(10 TW = 10,000 GW
plants)



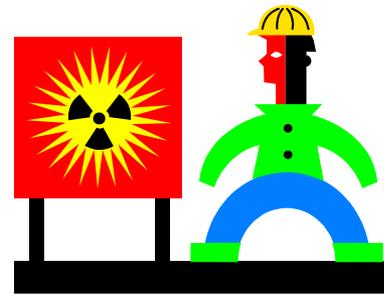
Nuclear

- Geothermal
- Fission
(10 TW = 10,000 GW plants)
- Fusion



Nuclear

- Geothermal
- Fission
(10 TW = 10,000 GW plants)
- Fusion
(1 gallon sea water = 300 gallons gasoline)



Transportation



Transportation

- Advanced batteries
- Hydrogen



Transportation

- Advanced batteries
- Hydrogen
- Other fuels



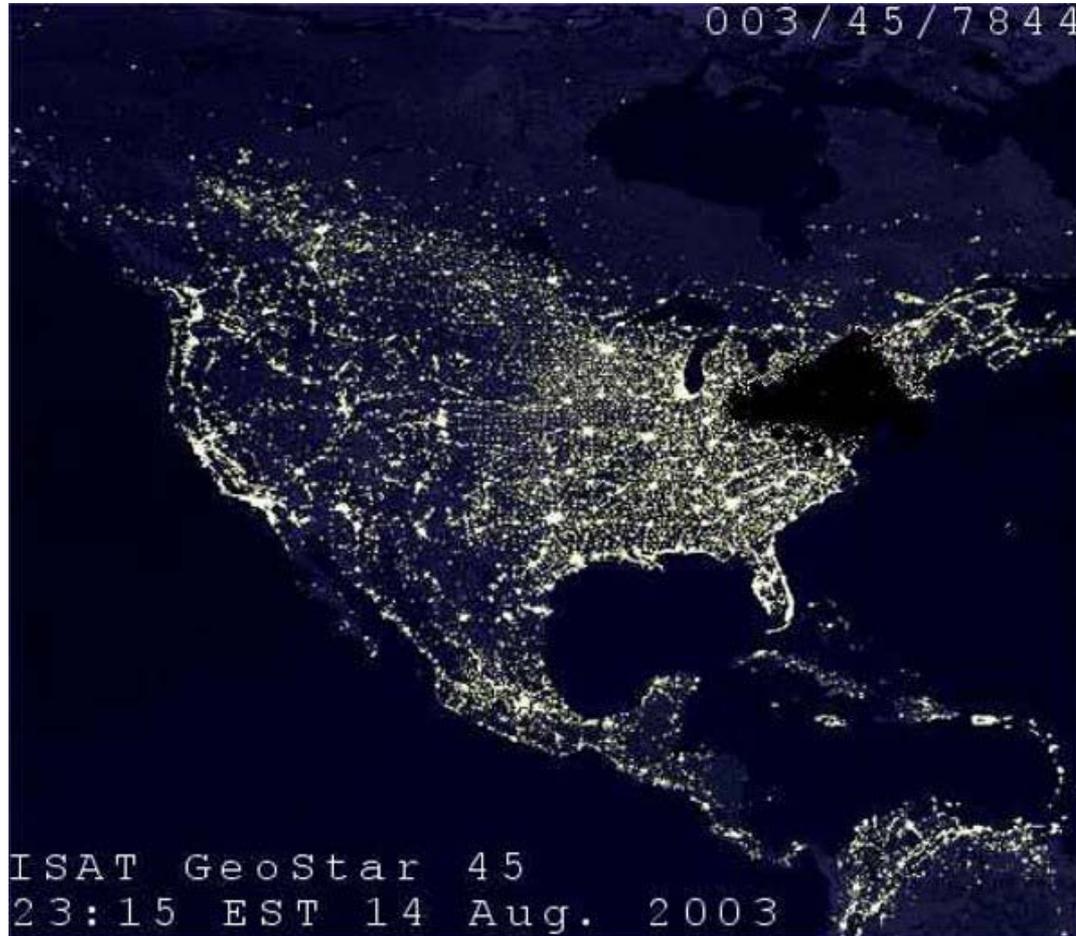
Transportation

- Advanced batteries
- Hydrogen
- Other fuels

We understand the
basic principles



003 / 45 / 7844



ISAT GeoStar 45
23:15 EST 14 Aug. 2003

Prediction

Civilization as we know it will come to an end sometime in this century, when the fuel runs out.

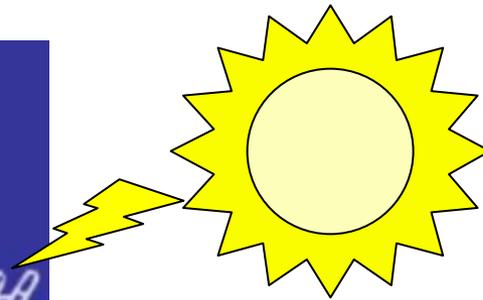


Stanford University

Global Climate & Energy Project

Toyota, ExxonMobil, GE, and Schlumberger

Lynn Orr



POWERING THE PLANET

Caltech's Center for Sustainable Energy Research (CSER)

Harry Atwater, Harry Gray, Sossina Haile,
Nathan Lewis, Jonas Peters

Steven Koonin at BP



Powering the Planet



Out of Gas

The end of the age of oil

David Goodstein

