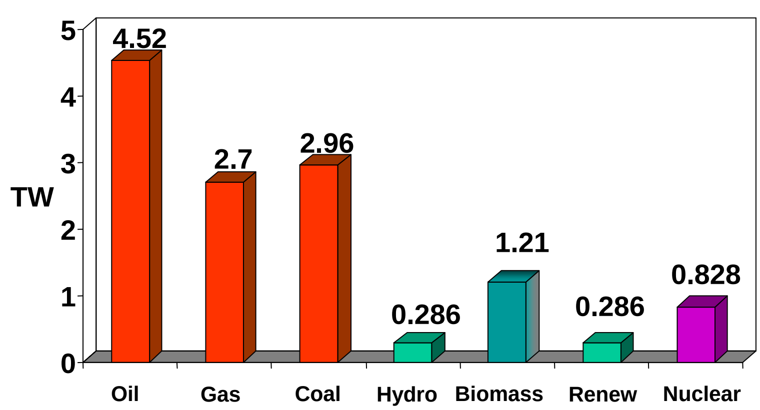
Lecture 1: Energy and Global Warming

MCB 113

13 March 2007

Note: Some of the material in this talk was donated by Chris Somerville.

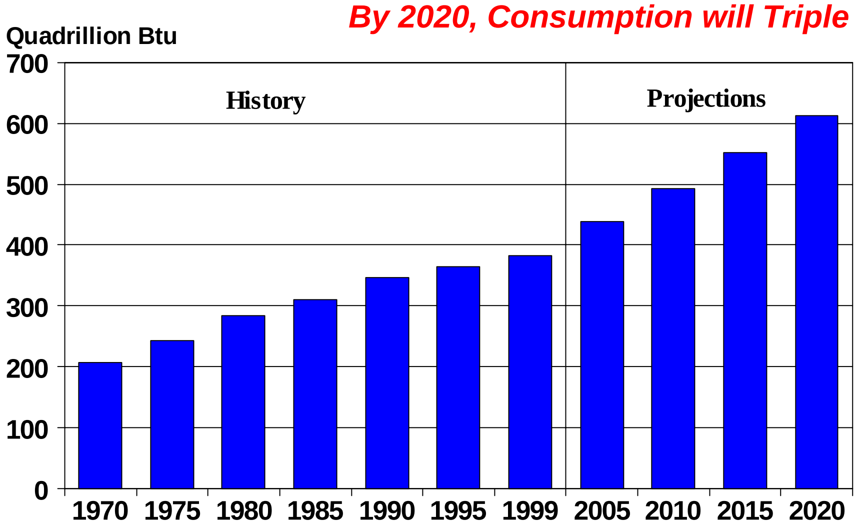
Mean Global Energy Consumption, 1998
(Total 12.8 TW)



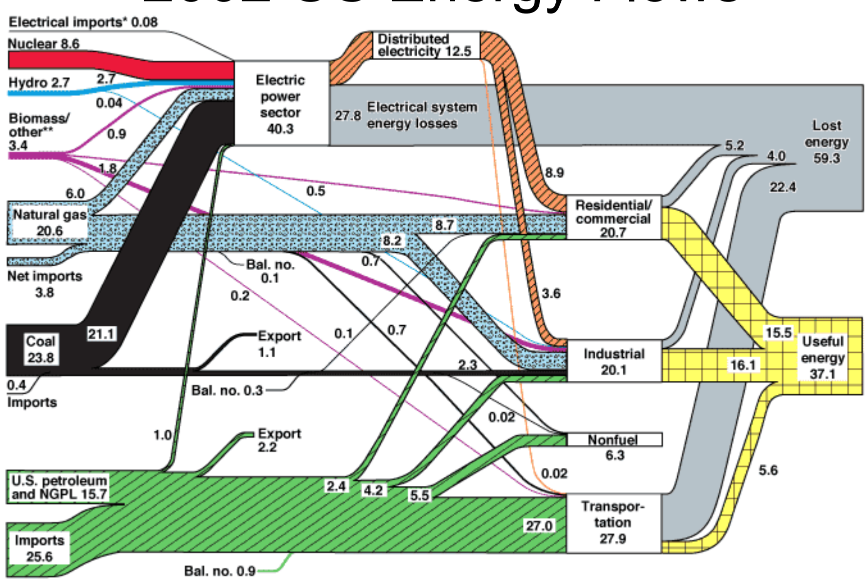
Nate Lewis, Caltech

Consumption of Energy Increased by 85% between 1970 and 1999

By 2020, Consumption will Triple



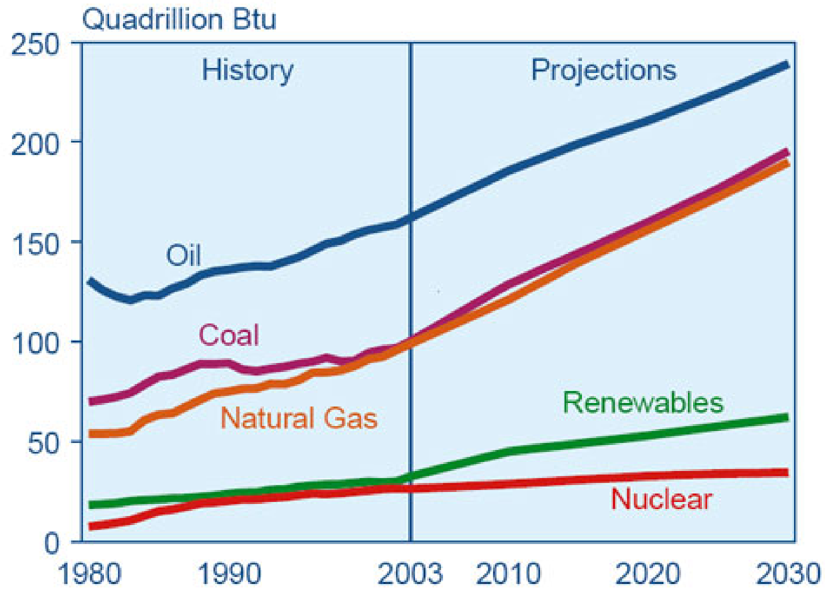
2002 US Energy Flows



Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2002*.
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

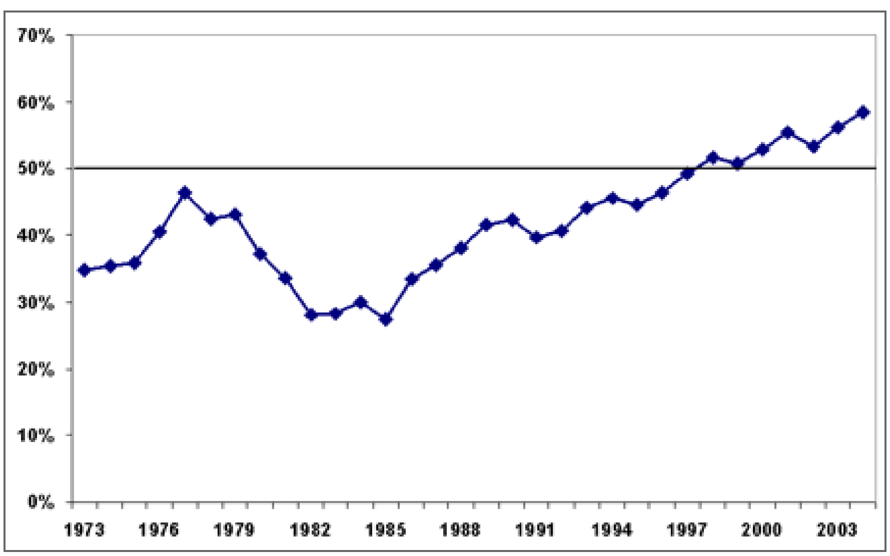
June 2004
Lawrence Livermore National Laboratory
http://eed.llnl.gov/flow

World marketed energy use by fuel type

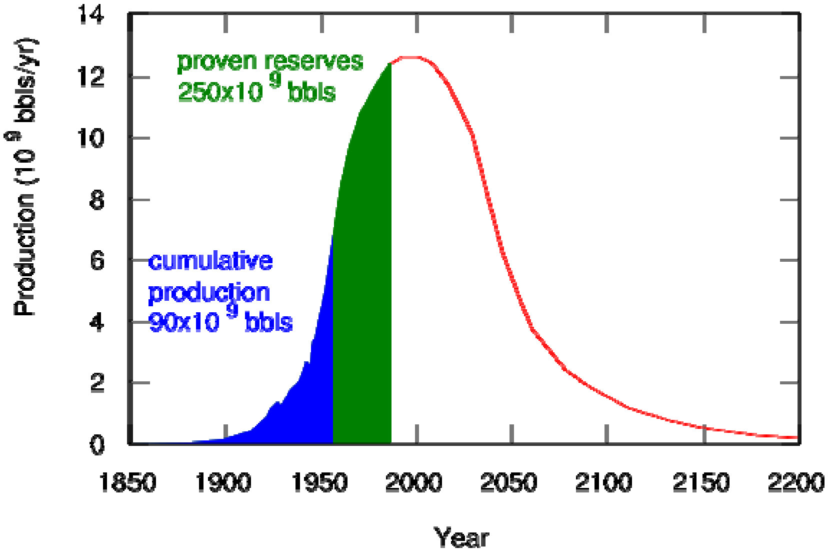


Source: Energy Information Administration

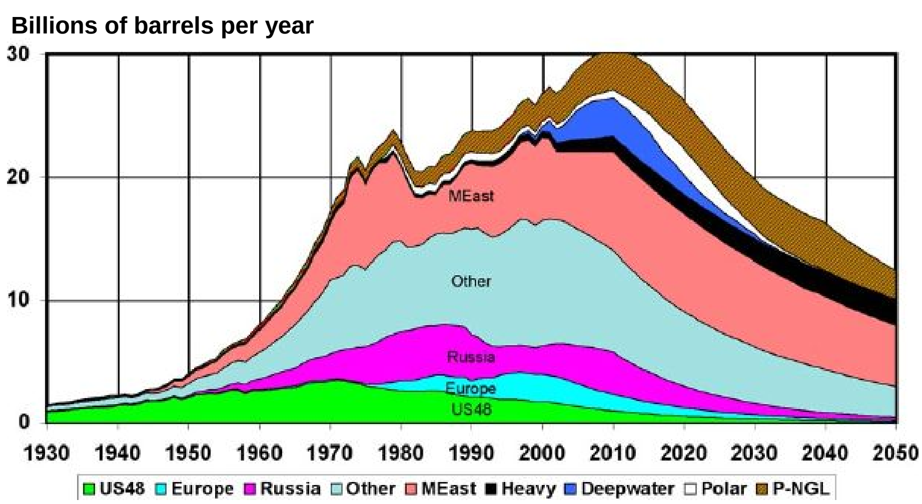
Net Petroleum Imports as a Percent of U.S. Petroleum Consumption



Hubbert Peak Theory for crude oil production

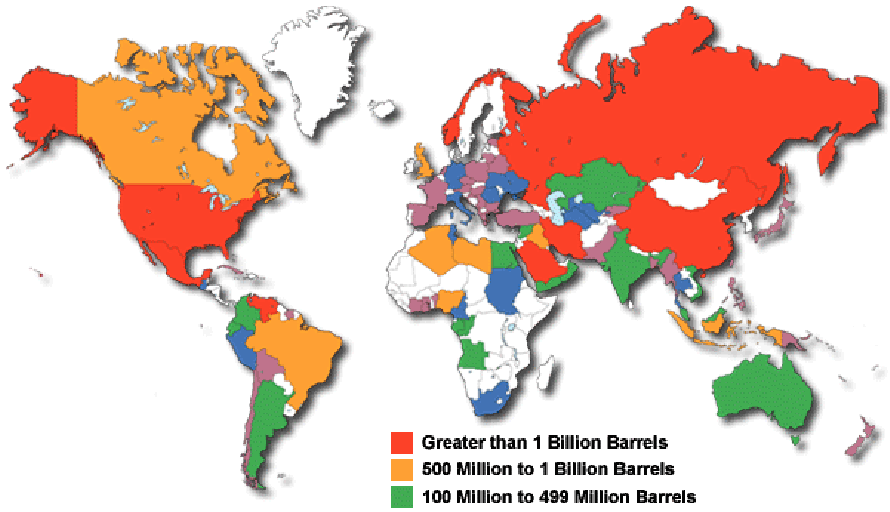


World Oil Production



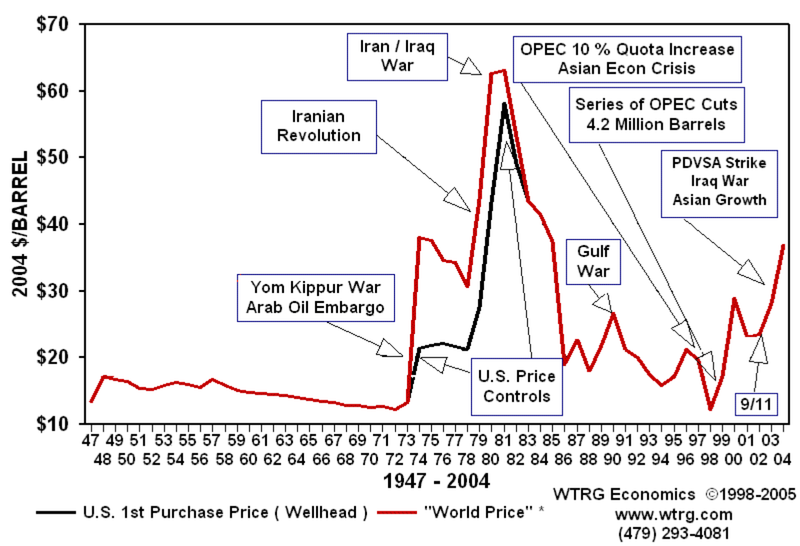
Note: NGL = Natural Gas Liquids
Source: info.energyscenariosireland.com

World Oil Production

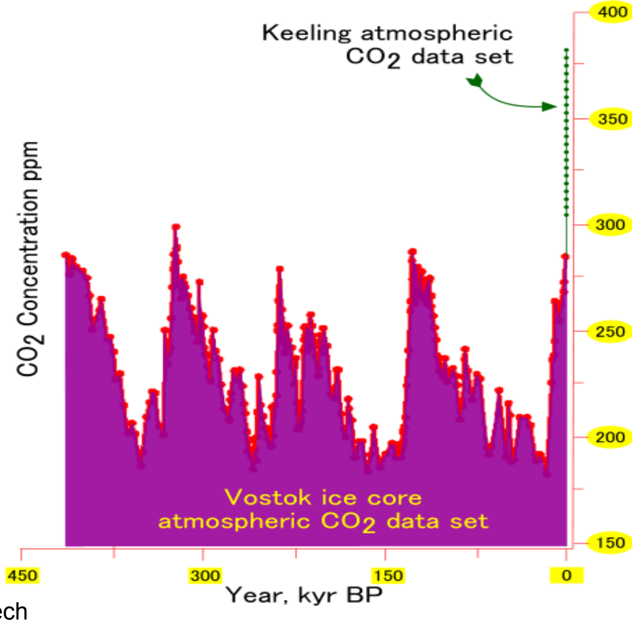


Source: *U.S. Energy Information Administration*, International Energy Annual, February 2003

Historical Price of Oil

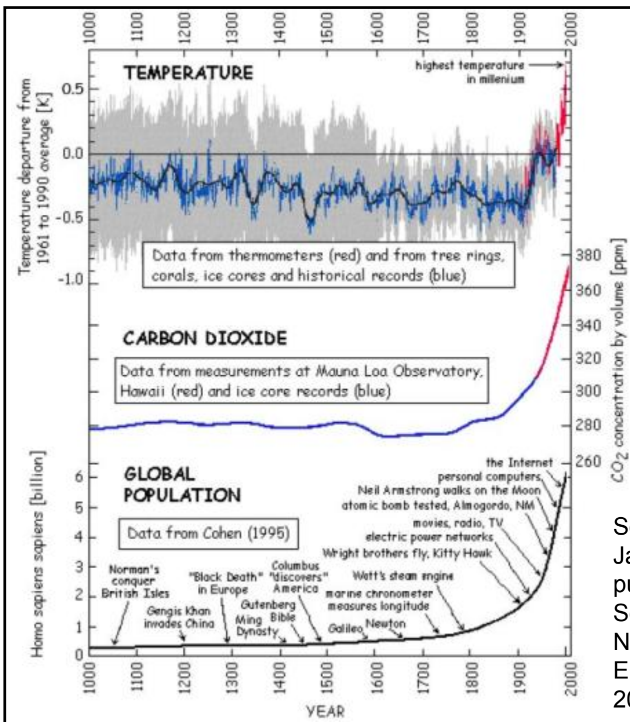


Atmospheric CO_2 is rising rapidly



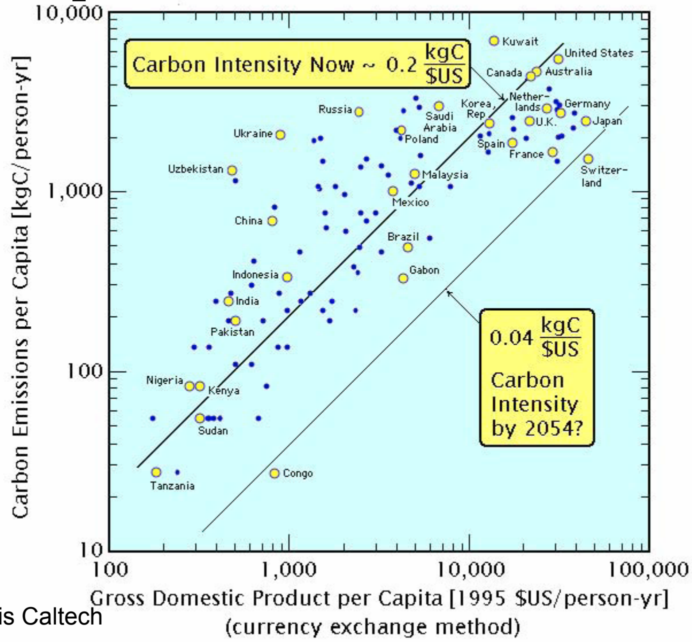
N. Lewis, Caltech

The world is warming



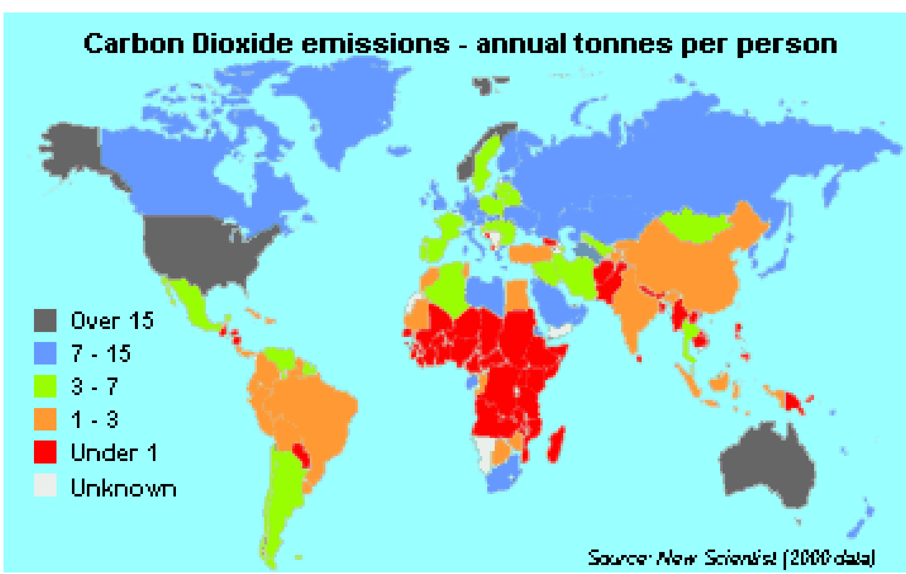
Source: Ken Caldeira, Atul Jain, and Martin Hoffert published on "Climate Sensitivity Uncertainty and the Need for Energy Without CO2 Emission", in the March 28, 2003 issue of science

CO_2 release rises with per capita GDP

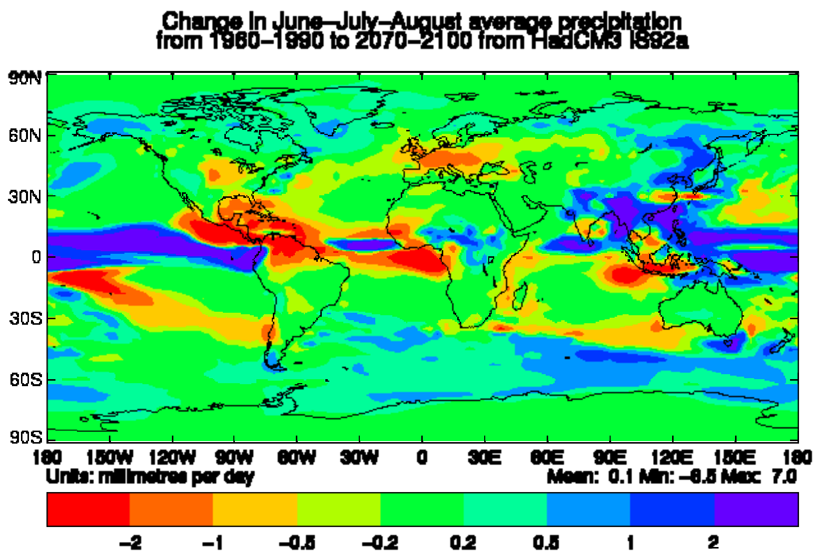


N. Lewis Caltech

Carbon emissions per capita

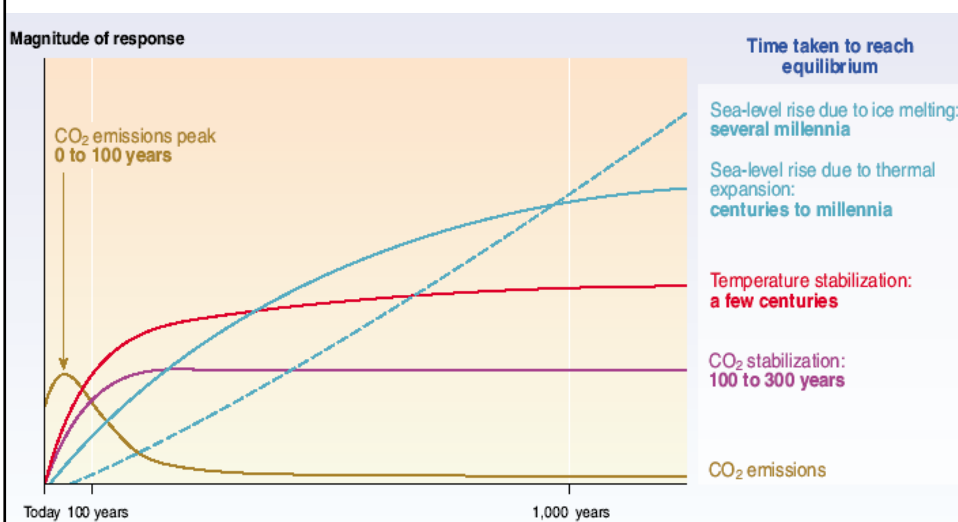


Predicted effects on rainfall



www.metoffice.com/research/hadleycenter

CO_2 concentration, temperature, and sea level continue to rise long after emissions are reduced

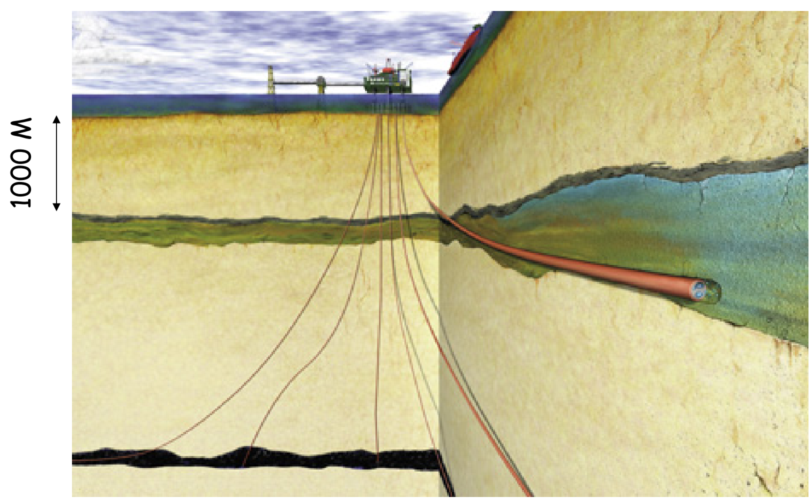


CO_2 neutral options
Estimated consumption 25 TW in 2050

- Nuclear
  - 1 new plant every 2 days for next 45 y
- Wind
  - 4 TW worldwide (~ 2 million windmills)
- Hydro, ocean, thermal
- Photovoltaics
- Sequestration
- Biomass

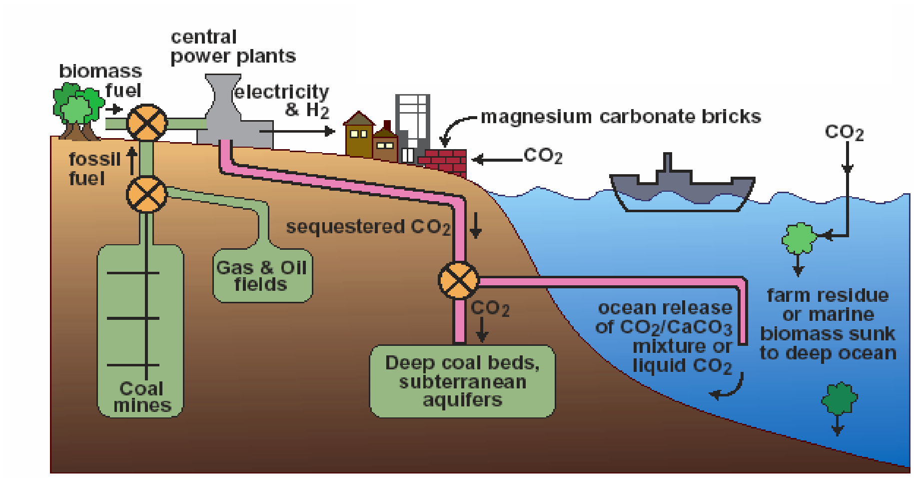
The Sleipner Experiment

1 million tons/y; capacity 600 B tons
7000 such sites needed



www.agiweb.org/geotimes

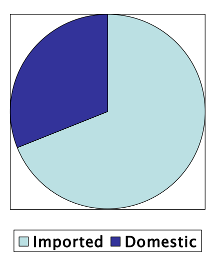
Basis for a "hydrogen economy"



Hoffert et al. Science 298,981

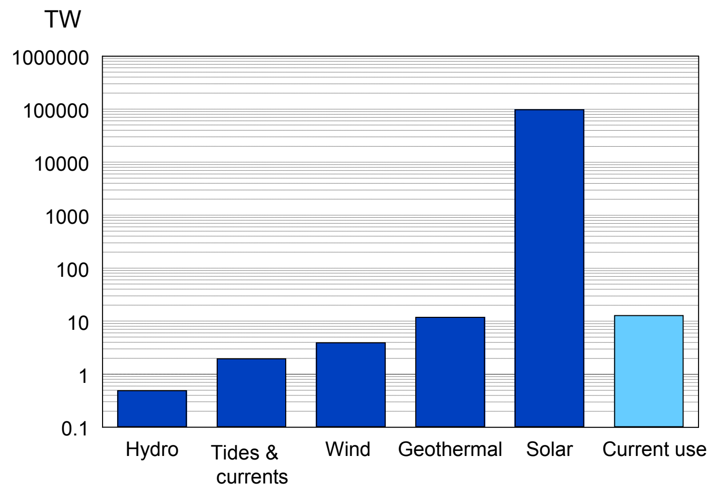
Why Biofuels?

- Reduce dependency on imports
  - Strategic issues
  - Balance of payments
  - Economic development
- Global climate change



6.4 bbl/year

Potential of underused renewable energy sources



How much would every roof contribute?

- $7x10^7$ detached single family homes in U.S.
- ≈2000 sq ft/roof = 180 m^2/home
- = $1.2x10^{10}$ m^2 total roof area
- Hence can (only) supply 0.25 TW, ≈7.5% U.S. Primary Energy Consumption

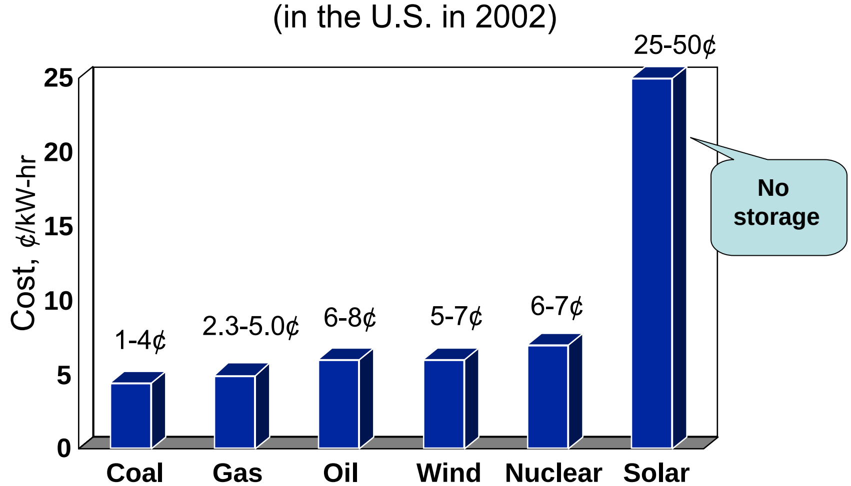
Nate Lewis, Caltech

~160,000 km^2 of photovoltaic devices would meet US energy needs

N. Lewis, Caltech

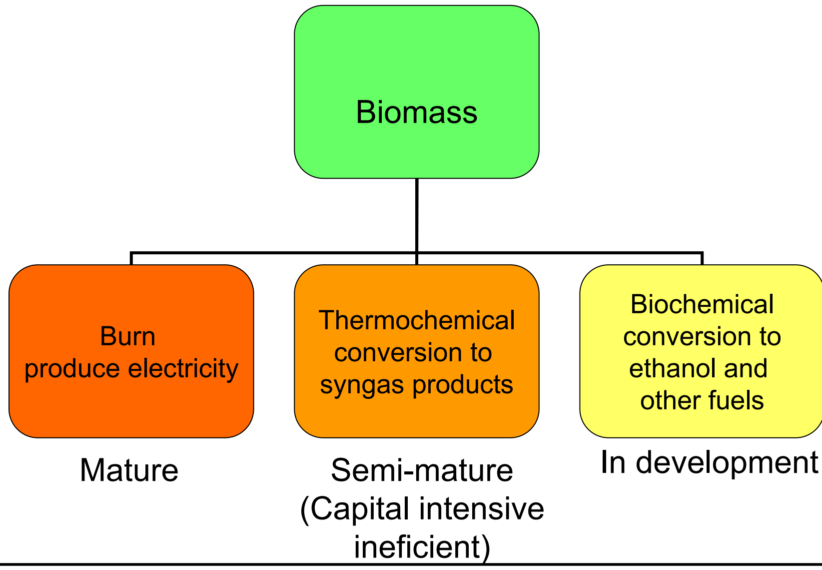
Production Cost of Electricity

(in the U.S. in 2002)

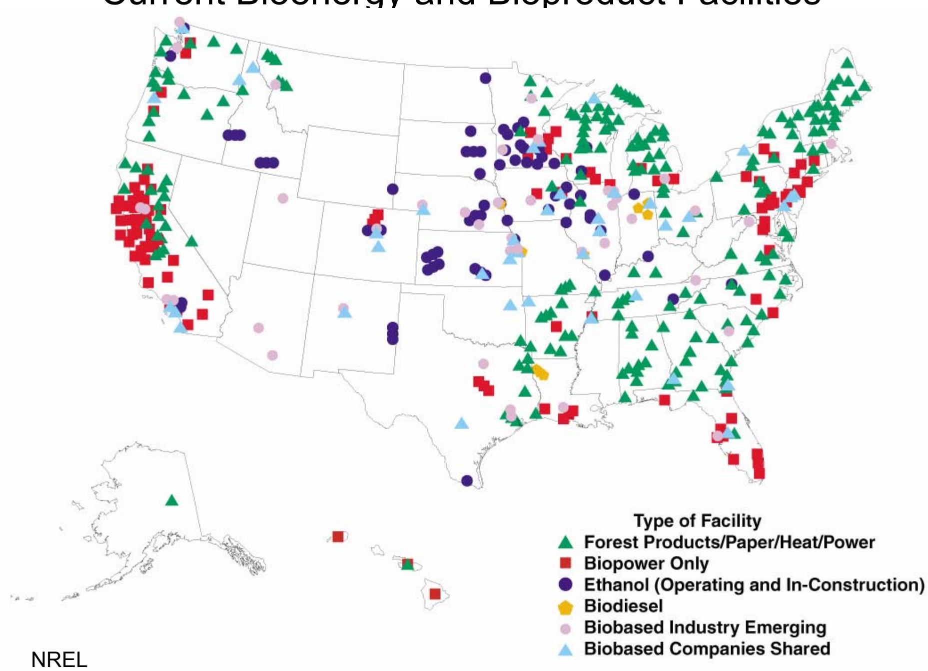


Courtesy of Nate Lewis, Caltech

How Biomass is Used for Energy

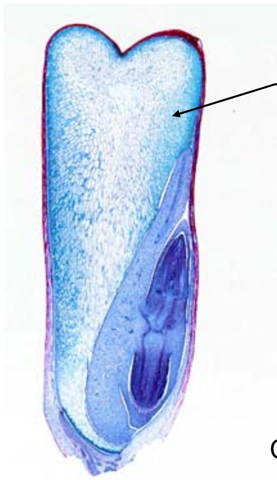


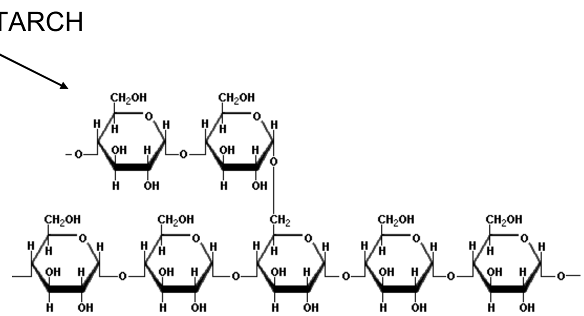
Current Bioenergy and Bioproduct Facilities



NREL

Chemical structure of starch

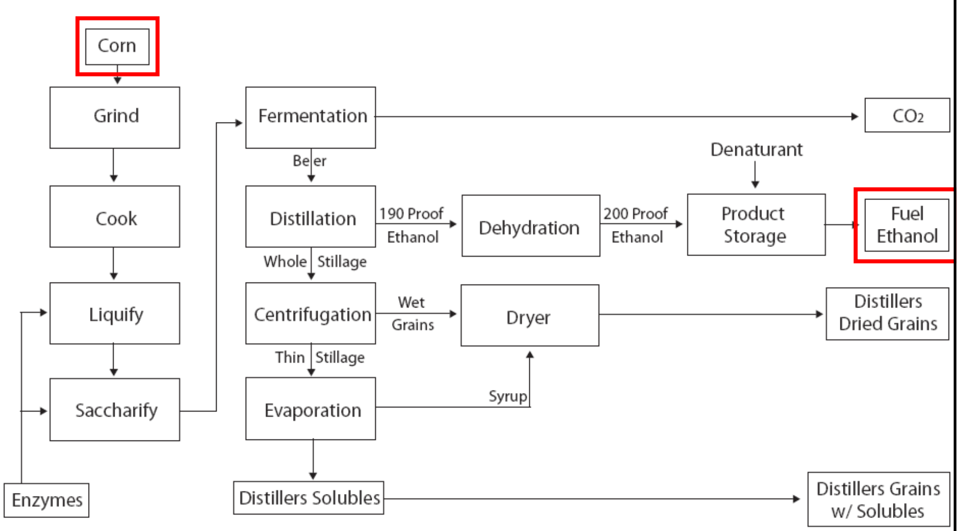




Corn yield averages 4.5 tons/acre at ~$77/ton

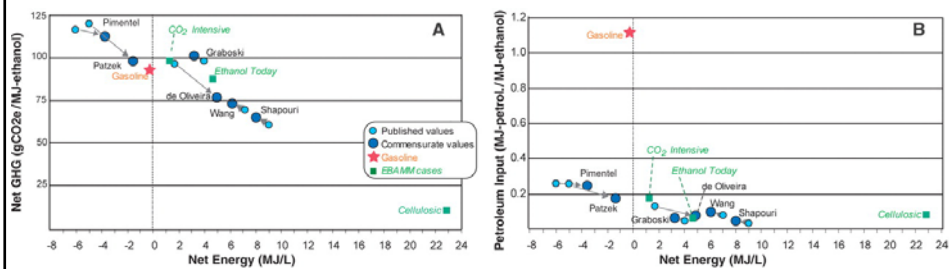
http://www.ucmp.berkeley.edu/monocots/corngrainls.jpg
http://www.scientificpsychic.com/fitness/carbohydrates1.html

Ethanol from Cornstarch



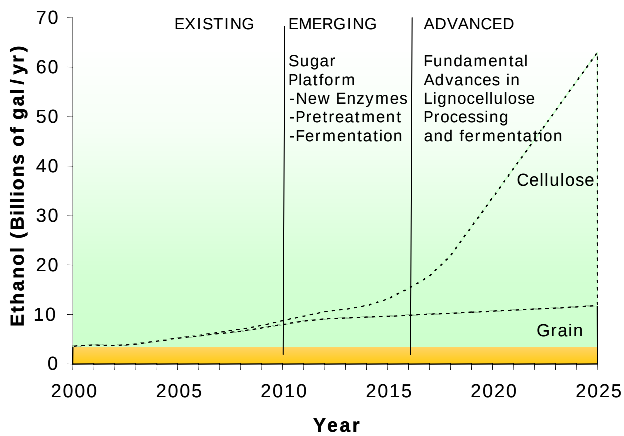
Source: www.ethanol.org

Net energy and net greenhouse gases for gasoline, six studies, and three cases



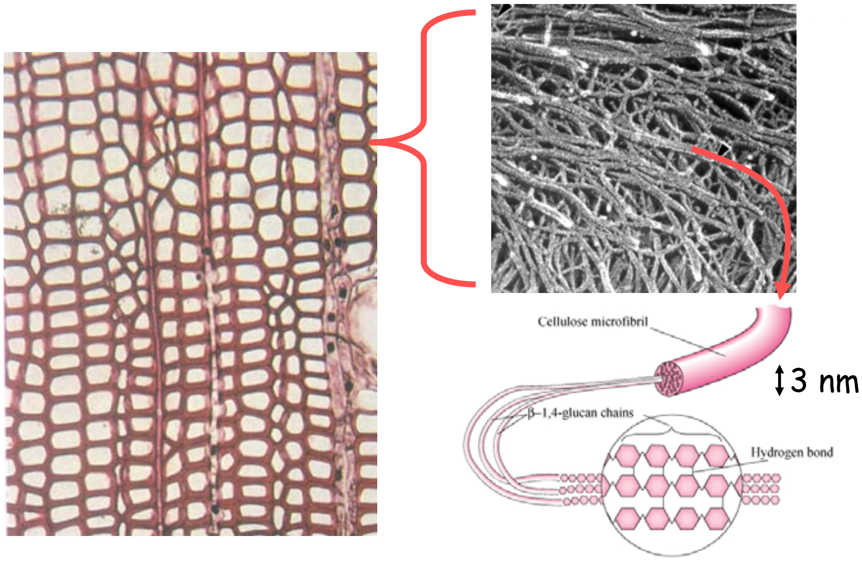
A. E. Farrell et al., *Science* **311**, 506 -508 (2006)

A DOE Ethanol Vision



Modified from Richard Bain, NREL

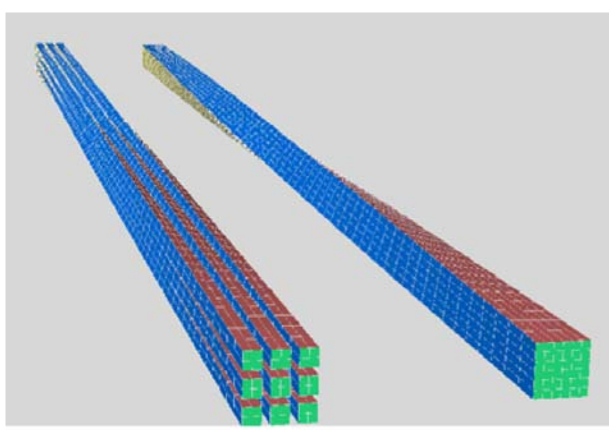
Plants are mostly composed of sugars



Section of a pine board

Polymerized glucose

Possible packing structures of cellulose

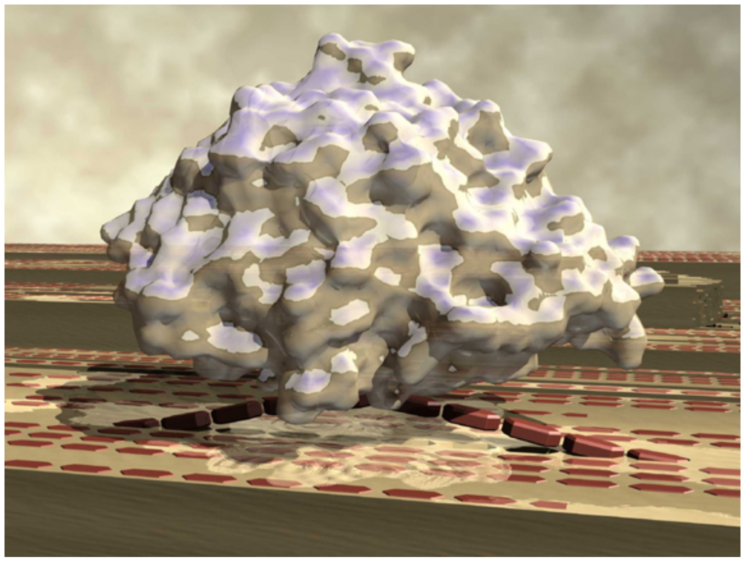


6(2x2)

6x6

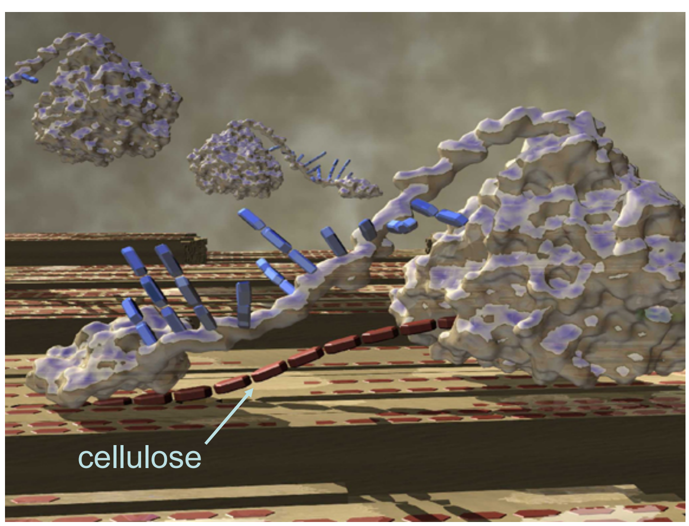
R. Atalla, unpublished

Cellulose is recalcitrant to hydrolysis



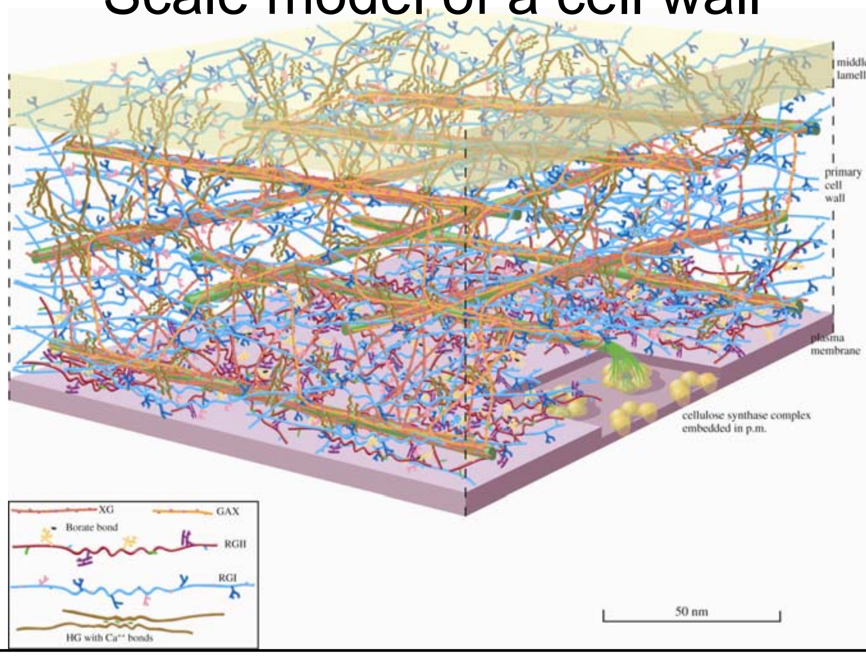
NREL

Cellulase hydrolyzing cellulose

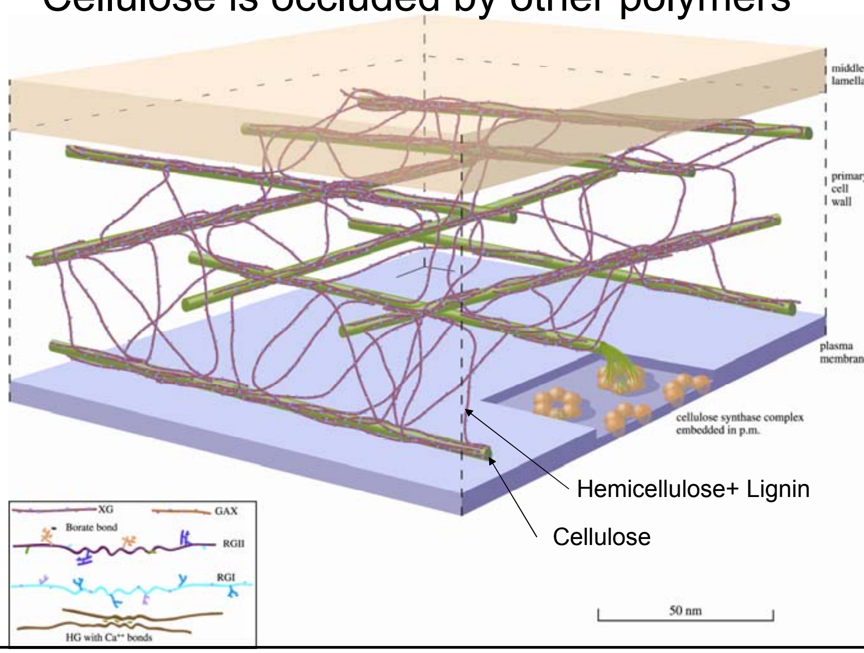


NREL

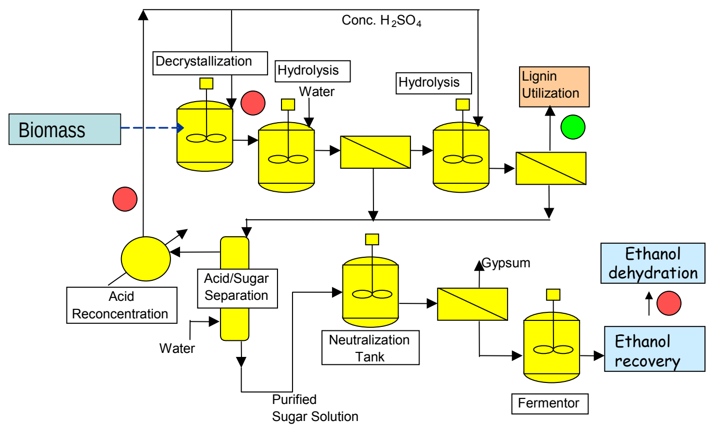
Scale model of a cell wall



Cellulose is occluded by other polymers

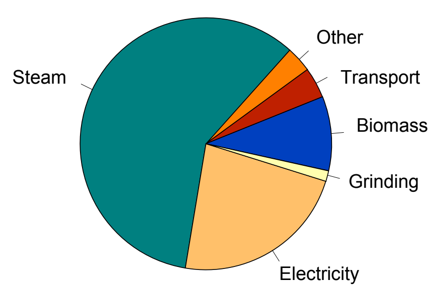


Linocellulose to ethanol process



The challenge is efficient conversion

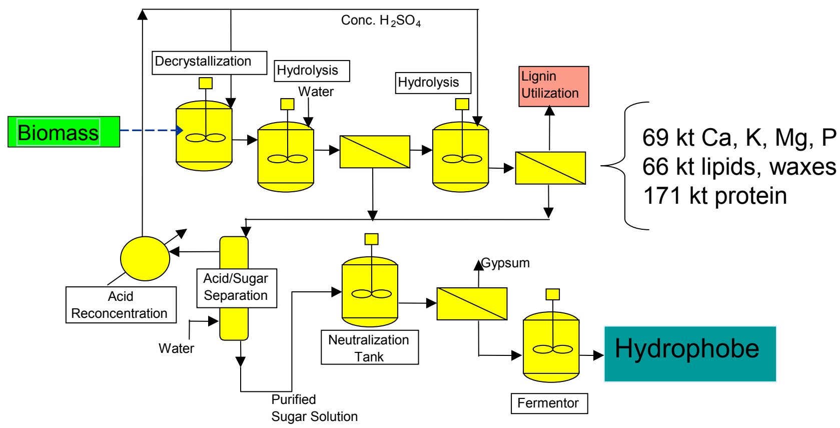
- Burning switchgrass (10 t/ha) yields 14.6-fold more energy than input to produce*
- But, converting switchgrass to ethanol calculated to consume 45% more energy than produced



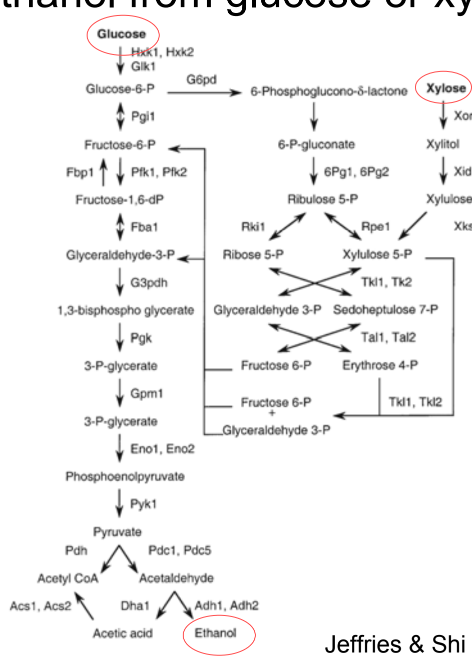
Energy consumption

*Pimentel & Patzek, Nat Res Res 14,65 (2005)

Linocellulose to Hydrophobe Process

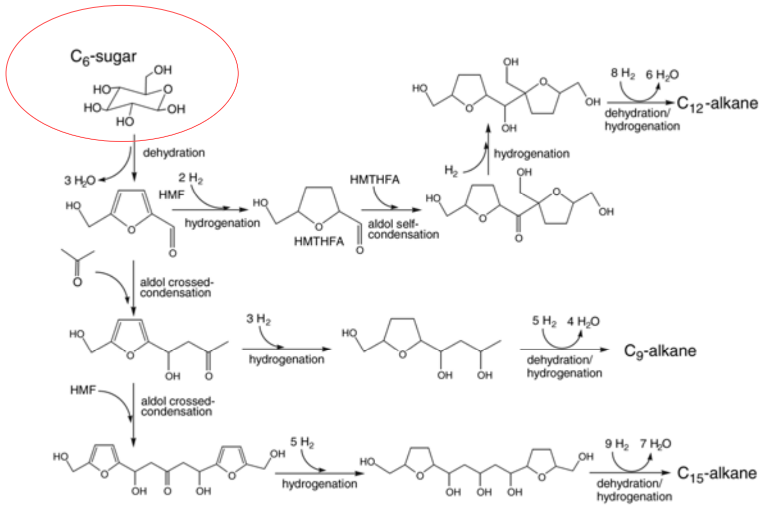


Ethanol from glucose or xylose



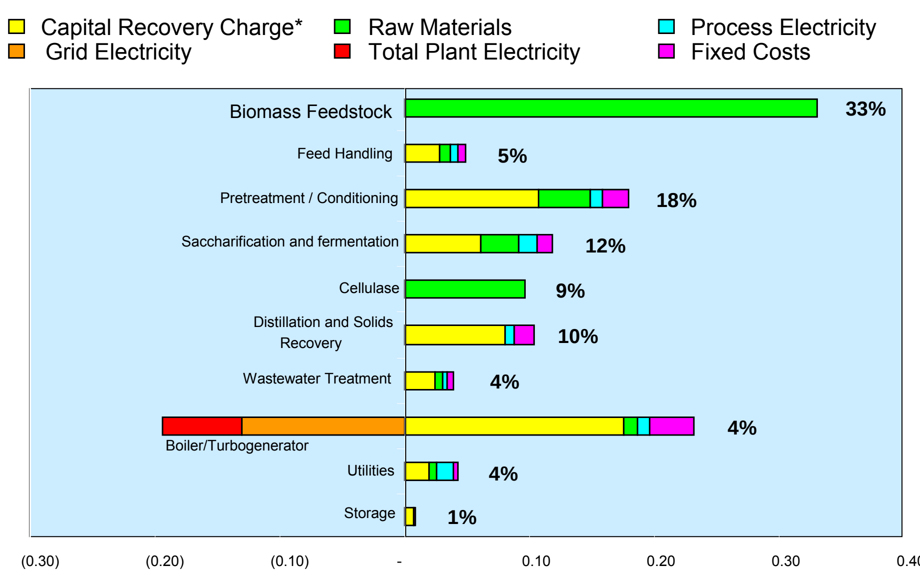
Jeffries & Shi Adv Bioch Eng 65,118

Conversion of sugar to alkanes



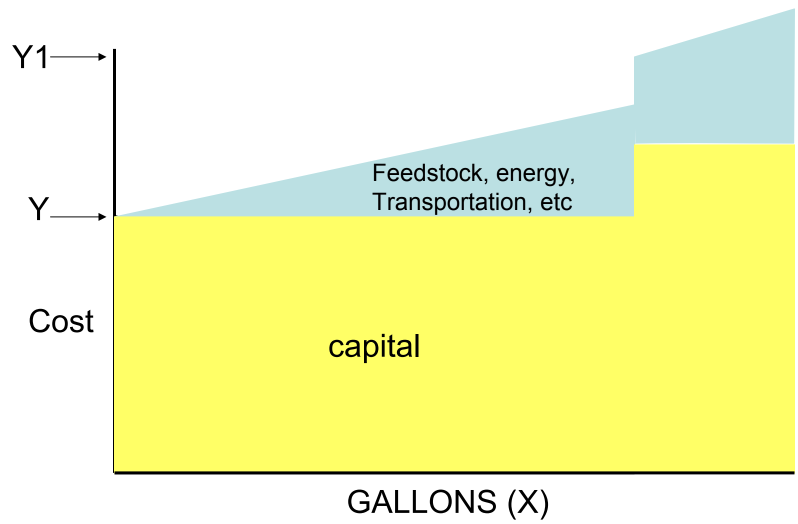
Huber et al., (2005) Science 308,1446

Relative cost factors of cellulosic ethanol

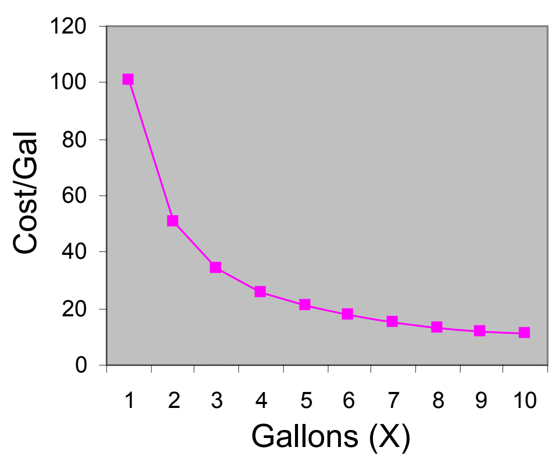


NREL Analysis

Cost/gallon = (Y + aX)/X



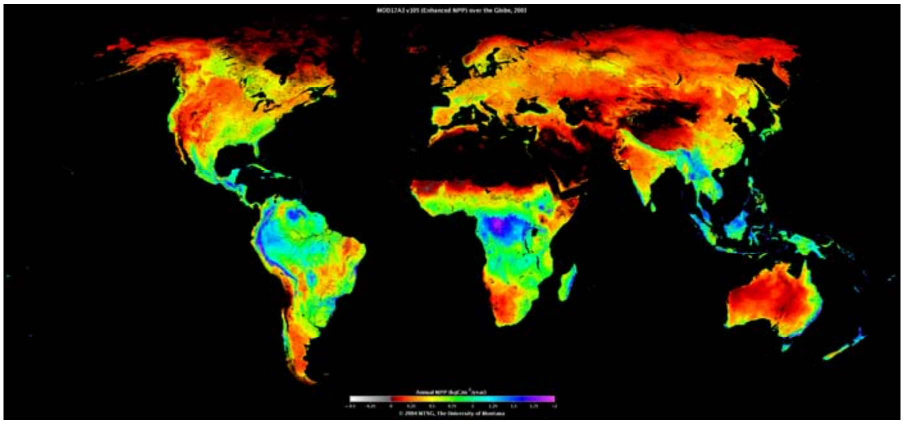
Plot of Cost/gal = (Y + aX)/X



At 15 t/a, 300 Mgal ~ 30% of all land in 20 mile radius

1 mi x 0.5 mi x 35 ft

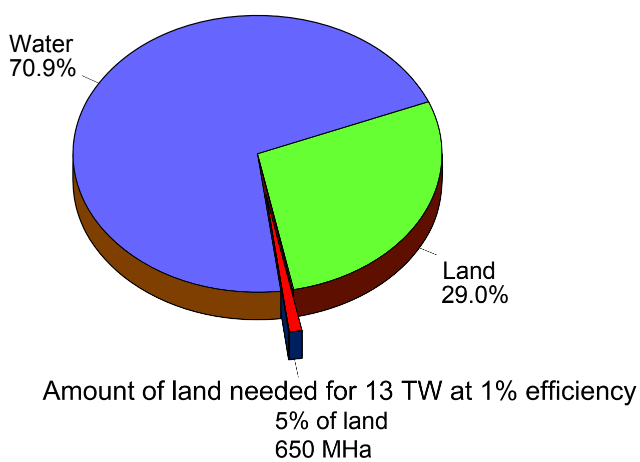
Is there enough land?



Estimated net primary productivity

University of Montana

90,000 TW of energy arrives on the earths surface from the sun



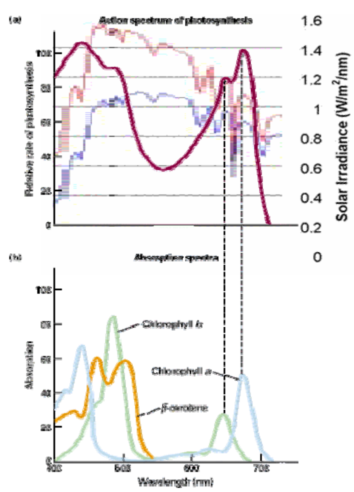
>2% yield is feasible

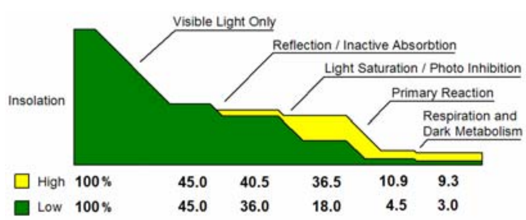
Yield of 26.5 tons/acre observed by Young & colleagues in Illinois, without irrigation

Courtesy of Steve Long et al

Why is photosynthetic efficiency so low?

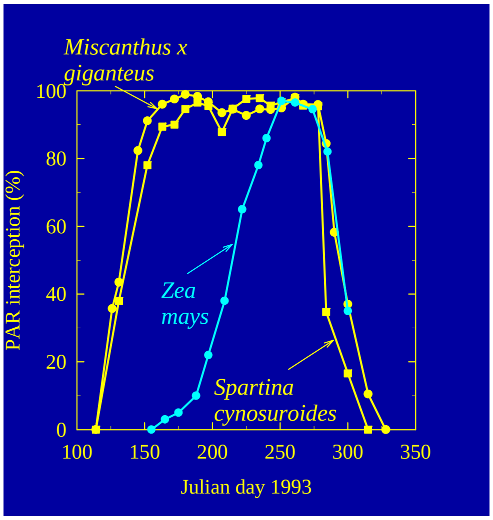
- Visible portion of spectrum
- Active areas of plants
- Photo-inhibition
  - Antenna length
- Electron transfer losses





Wes Hermann, Stanford

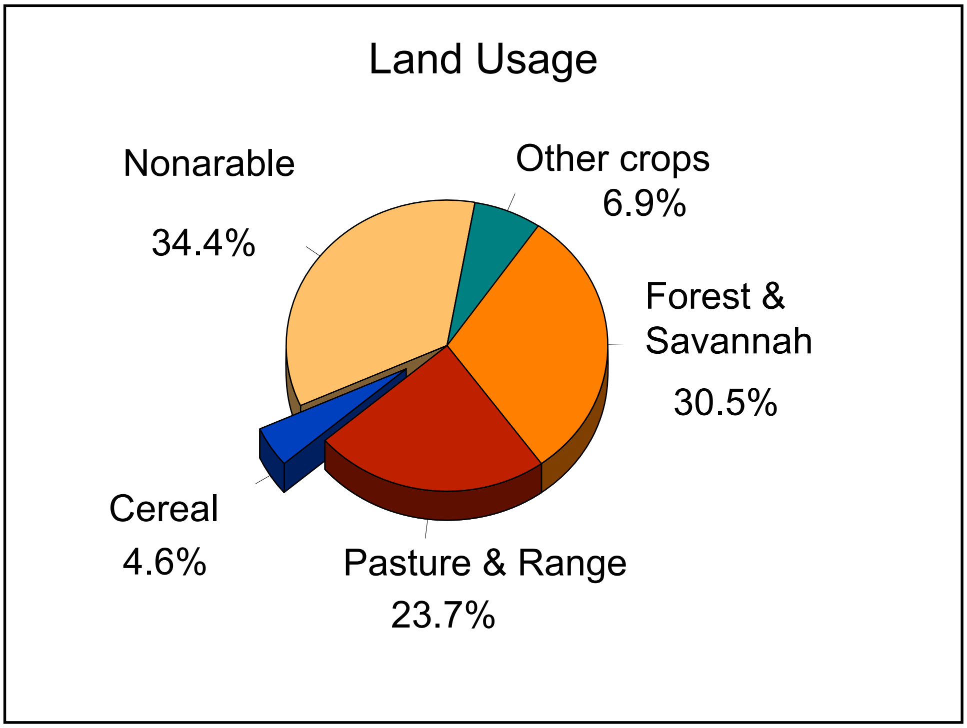
Perennials have more photosynthesis



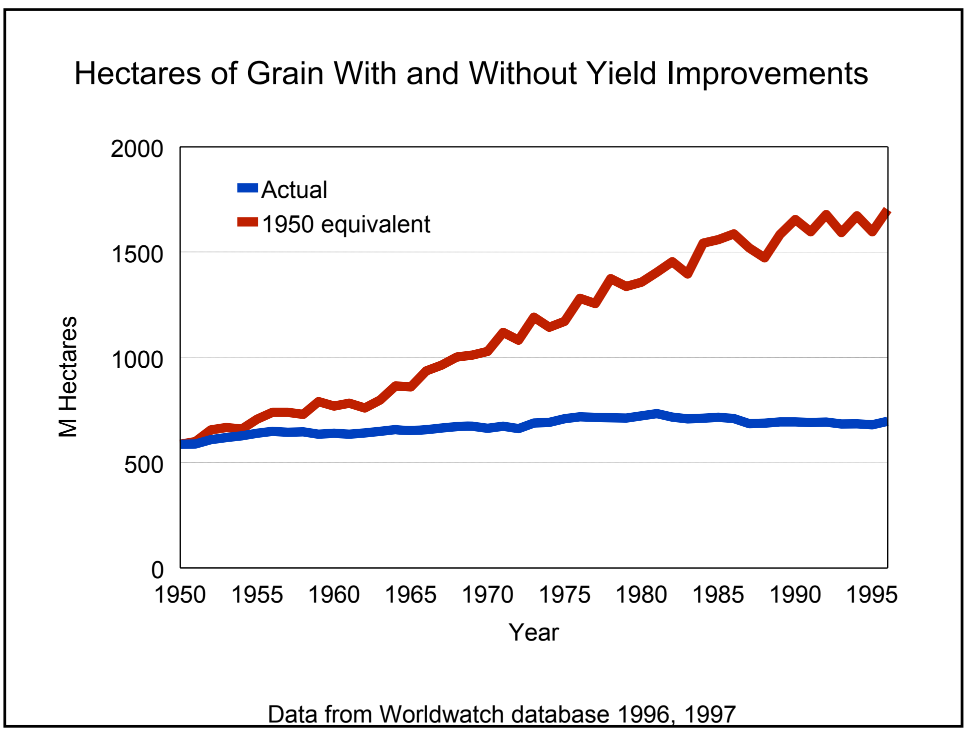
Courtesy of Steve Long, University of Illinois

Harvesting Miscanthus

http://bioenergy.ornl.gov/gallery/index.html

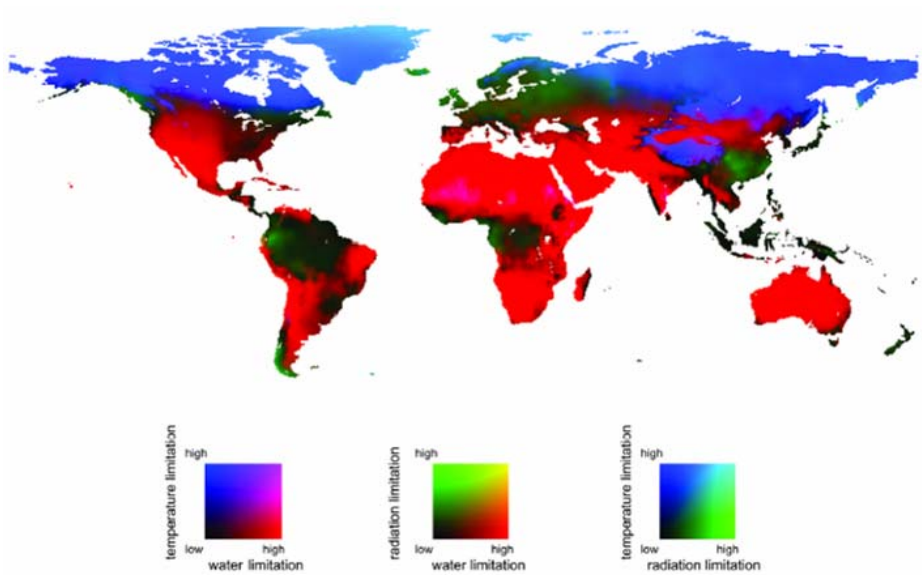


Land Usage
Nonarable
34.4%
Other crops
6.9%
Forest &
Savannah
30.5%
Cereal
4.6%
Pasture & Range
23.7%



Hectares of Grain With and Without Yield Improvements
2000
1500
1000
500
0
M Hectares
Actual
1950 equivalent
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
Year
Data from Worldwatch database 1996, 1997

Limiting factors for global NPP

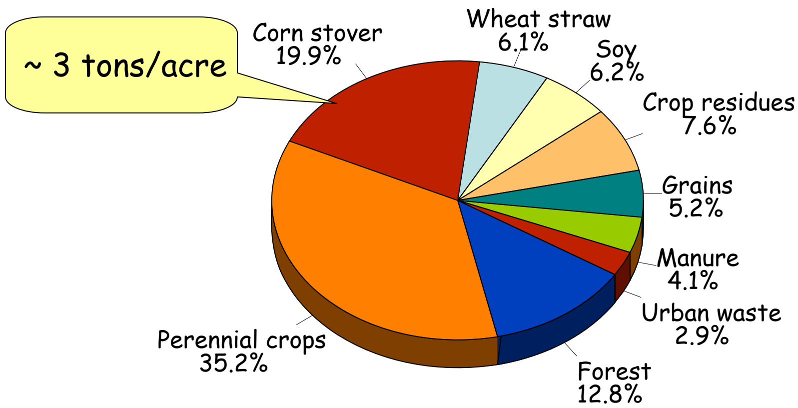


Baldocchi et al. 2004 SCOPE 62

Land use is fungible

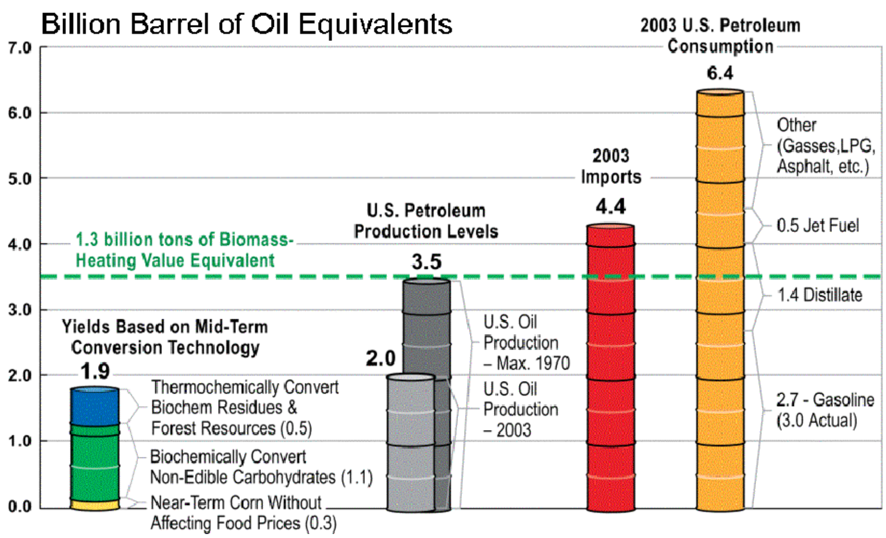
- High plant productivity is equally important for food and energy production
- Plant productivity is a function of many aspects of growth and development so a broad approach to knowledge creation is essential

US Biomass inventory = 1.3 billion tons



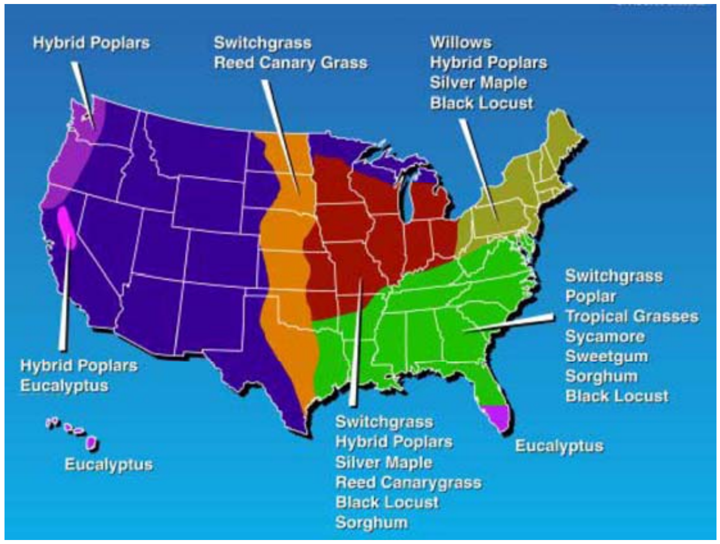
From: Billion ton Vision, DOE & USDA 2005

The 1.3 Billion Ton Biomass Scenario



Based on ORNL & USDA Resource Assessment Study by Perlach et.al. (April 2005)
http://www.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

Geographic distribution of biomass crops



Wright et al DOE-ORNL-EERE

Economics of Perennials are Favorable

CROP	Yield per Acre	Value $ @$35/t	Cost $	Profit $
Corn	160 bu	362	193*	170
Switchgrass	10 tons	350	138**	212
Miscanthus	15 tons	525	193	332

*USDA economic research service 2004
**50% as much fertilizer, no chemicals

Conclusions

- We can meet a significant proportion of our fuel needs from plants
  - If pressed, we could meet all our needs
- Productivity of energy crops is not yet optimized
- The industrial processing of energy crops to fuels is not yet optimized
- There are no insurmountable problems to achieving cost-effective, carbon-neutral solar energy production from plants

Comments

- Energy crops are expected to be more environmentally benign than production agriculture
  - Low fertilizer and chemical inputs
  - Late-harvest supports biodiversity
  - Mixed cultures possible
  - Many species can be used