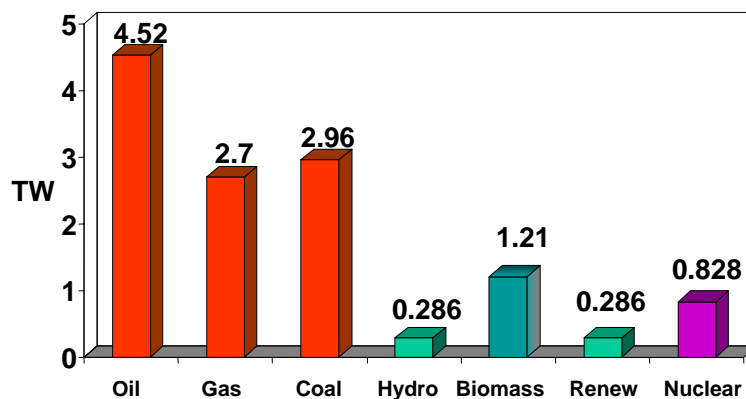


Lecture 1: Energy and Global Warming

MCB 113
13 March 2007

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

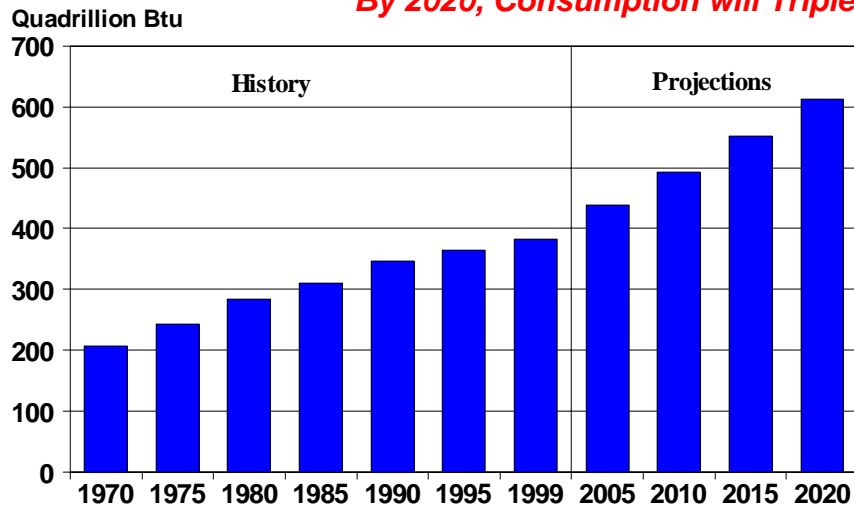
Mean Global Energy Consumption, 1998 (Total 12.8 TW)



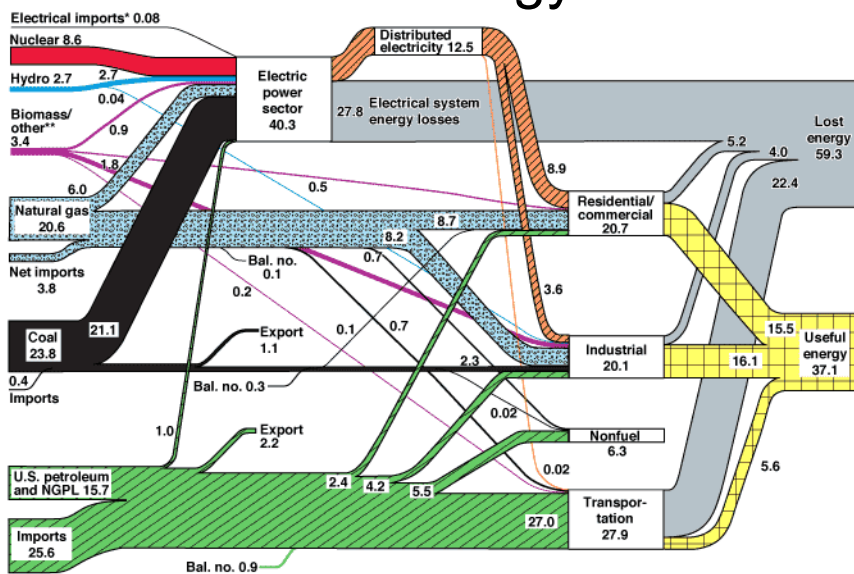
Nate Lewis, Caltech

Consumption of Energy Increased by 85% between 1970 and 1999

By 2020, Consumption will Triple



2002 US Energy Flows



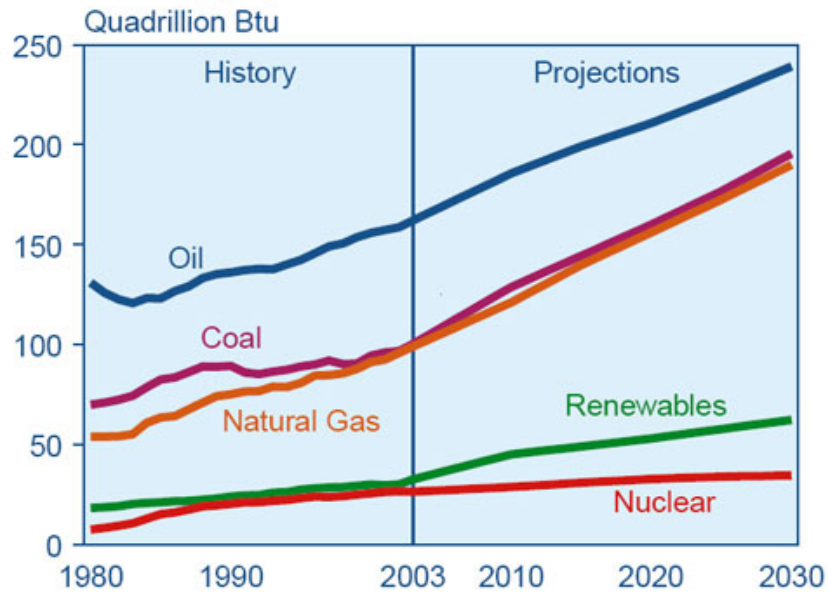
Source: Production and end-use data from Energy Information Administration, Annual Energy Review 2002.

*Net fossil-fuel electrical imports.

**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

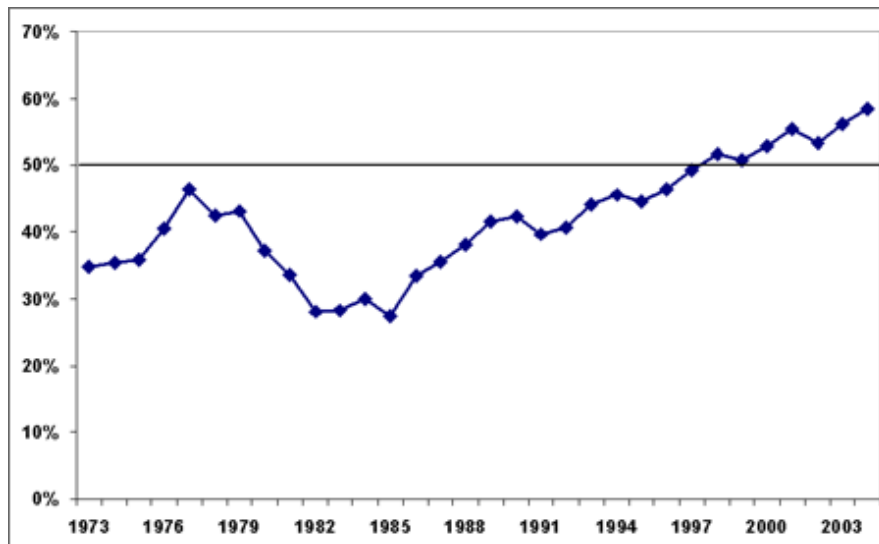
June 2004
Lawrence Livermore
National Laboratory
<http://feed.llnl.gov/flow>

World marketed energy use by fuel type

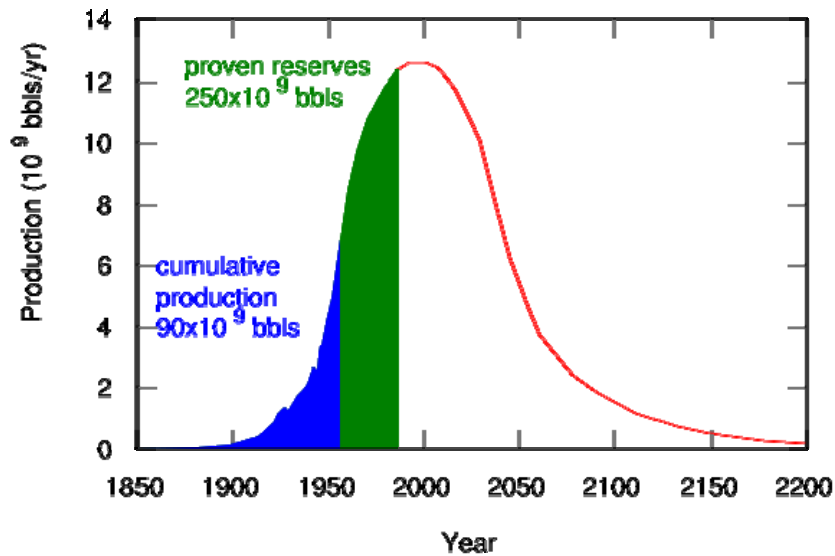


Source: Energy Information Administration

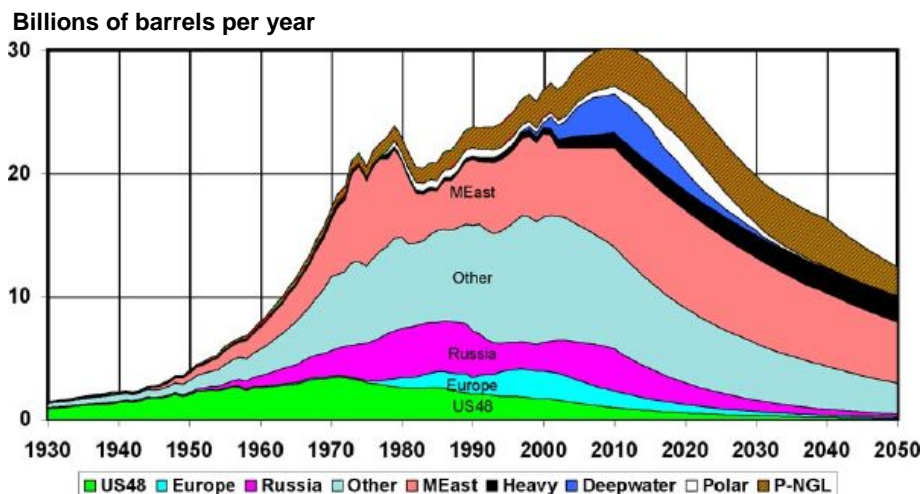
Net Petroleum Imports as a Percent of U.S. Petroleum Consumption



Hubbert Peak Theory for crude oil production



World Oil Production



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

2004 \$/BARREL

Iran / Iraq War

OPEC 10% Quota Increase
Asian Econ Crisis

Series of OPEC Cuts
4.2 Million Barrels

PDVSA Strike
Iraq War
Asian Growth

Gulf War

Iranian Revolution

Yom Kippur War
Arab Oil Embargo

U.S. Price Controls

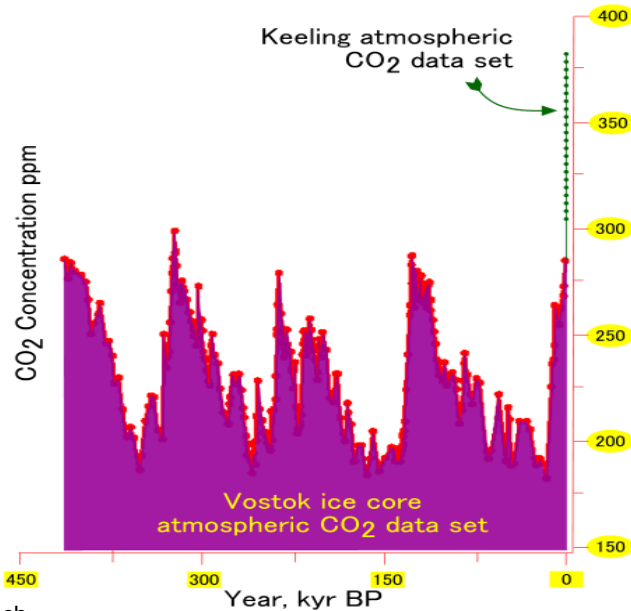
9/11

1947 - 2004

WTRG Economics ©1998-2005
www.wtrg.com
(479) 293-4081

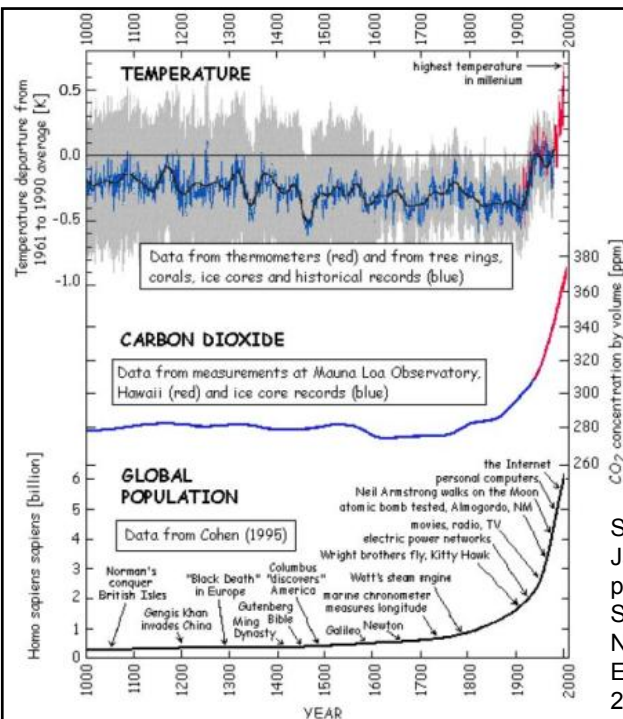
— U.S. 1st Purchase Price (Wellhead) — "World Price" *

Atmospheric CO₂ is rising rapidly



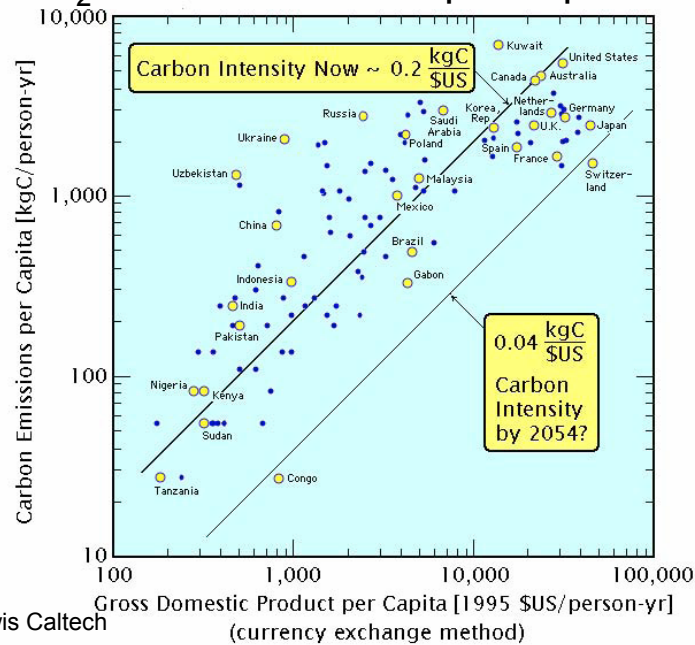
N. Lewis, Caltech

The world is warming

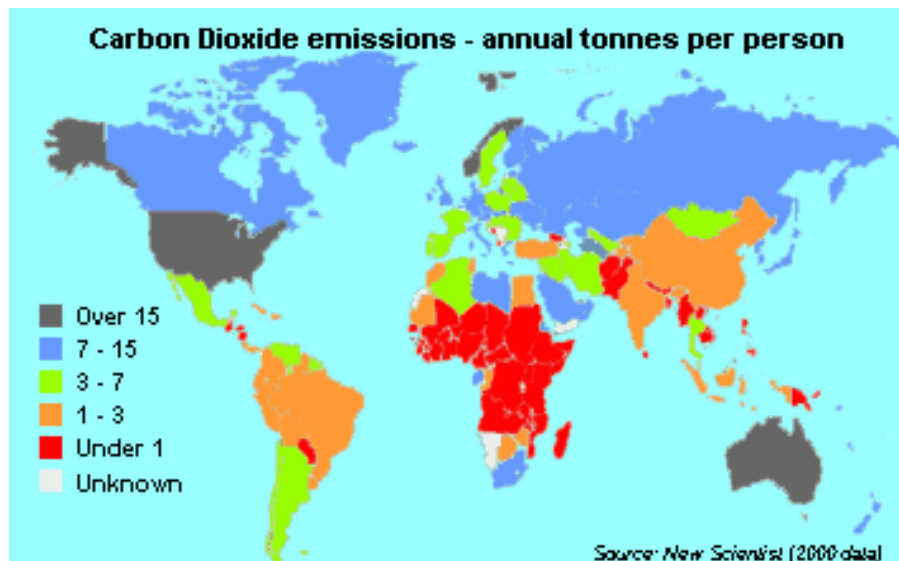


Source: Ken Caldeira, Atul Jain, and Martin Hoffert published on "Climate Sensitivity Uncertainty and the Need for Energy Without CO₂ Emission", in the March 28, 2003 issue of science

CO₂ release rises with per capita GDP

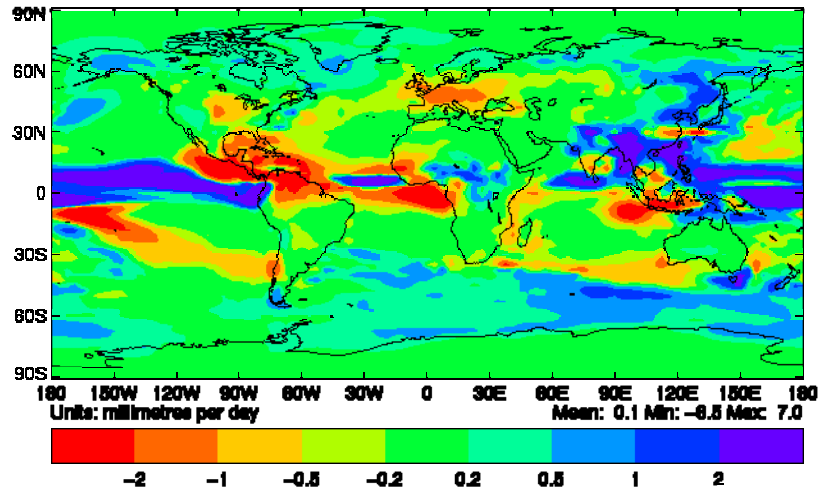


Carbon emissions per capita



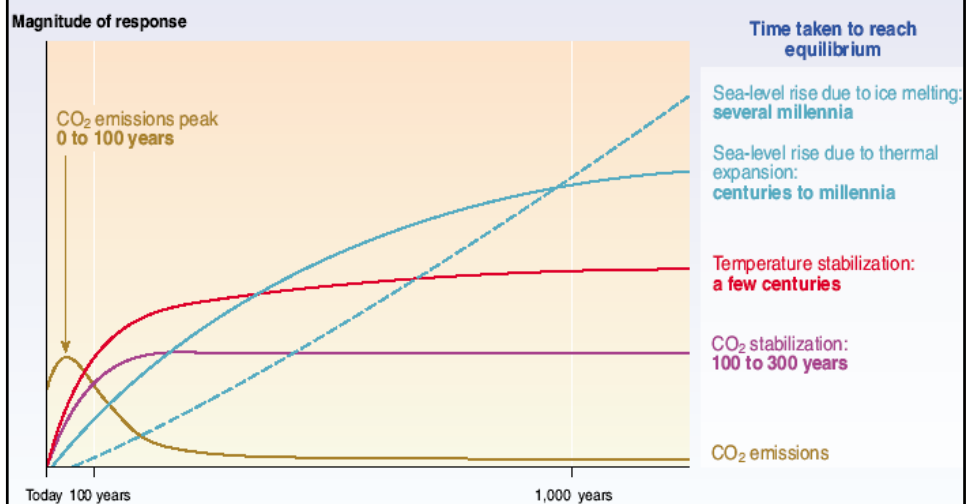
Predicted effects on rainfall

Change in June–July–August average precipitation
from 1980–1990 to 2070–2100 from HadCM3 1992a



www.metoffice.com/research/hadleycenter

CO₂ concentration, temperature, and sea level continue to rise long after emissions are reduced

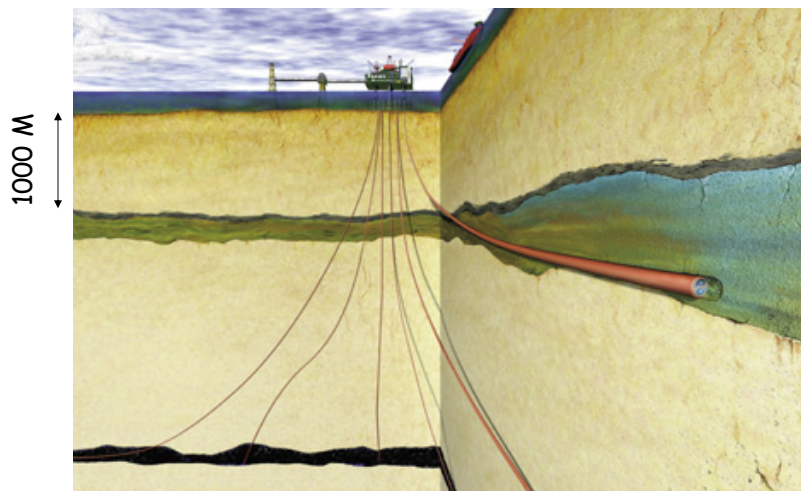


CO₂ neutral options
Estimated consumption 25 TW in 2050

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

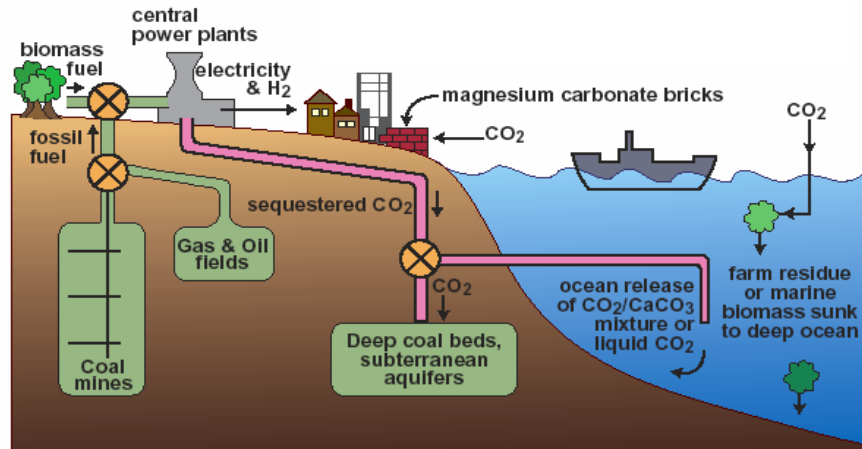
The Sleipner Experiment

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



www.agiweb.org/geotimes

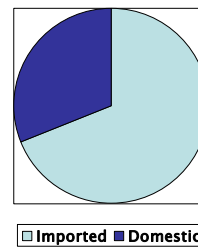
Basis for a “hydrogen economy”



Hoffert et al. Science 298,981

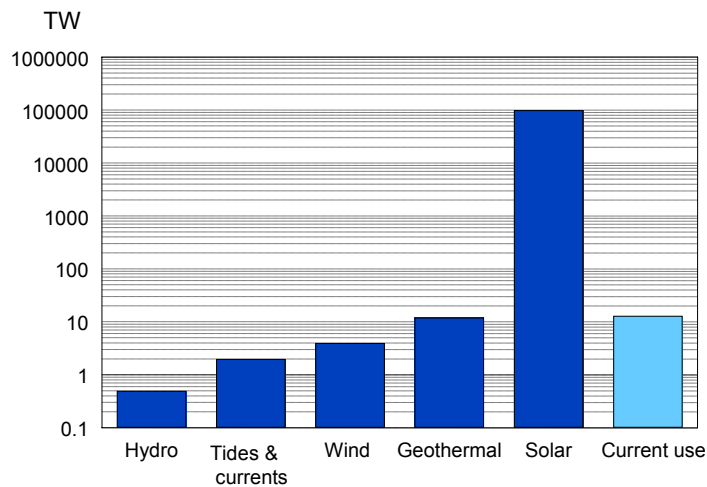
Why Biofuels?

- 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?

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

Nate Lewis, Caltech

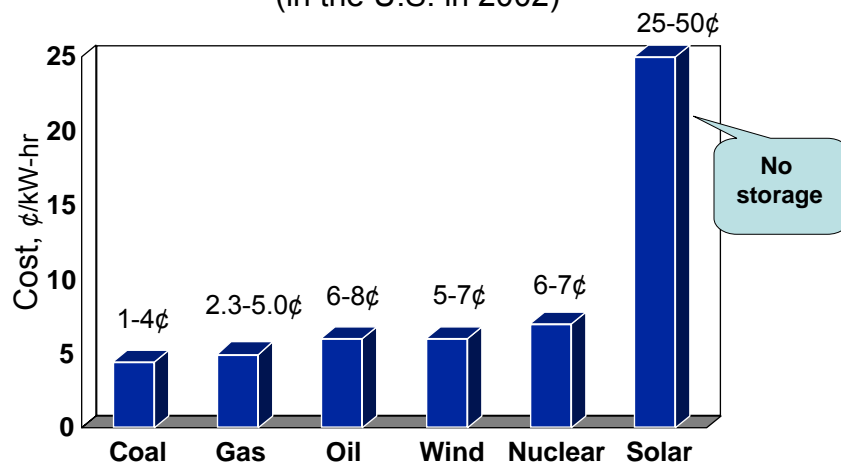
~160,000 km² of photovoltaic devices
would meet US energy needs



N. Lewis, Caltech

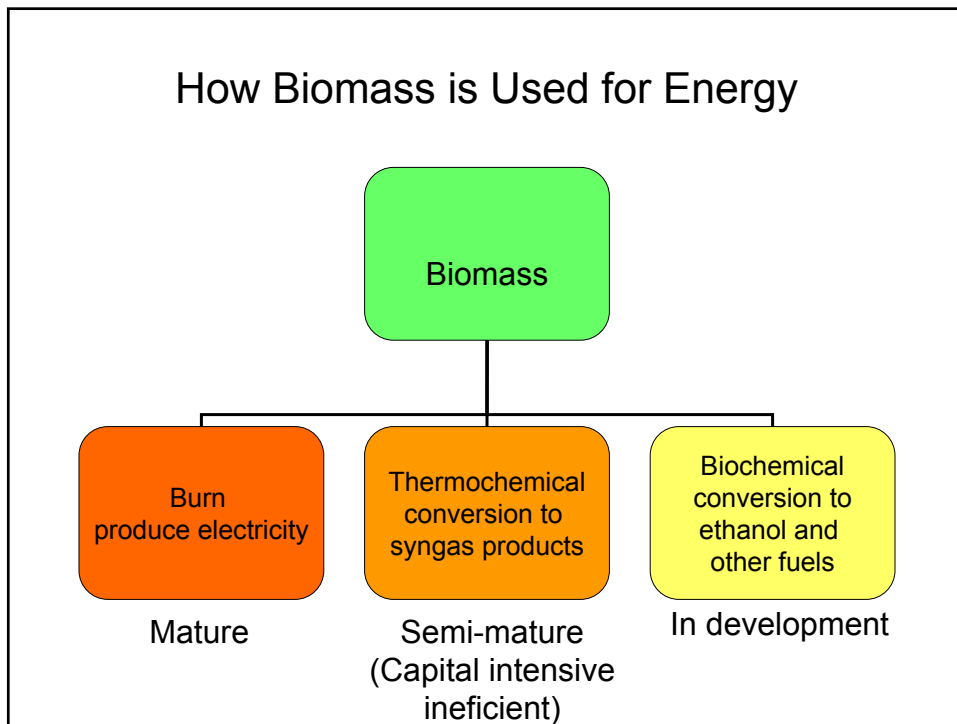
Production Cost of Electricity

(in the U.S. in 2002)

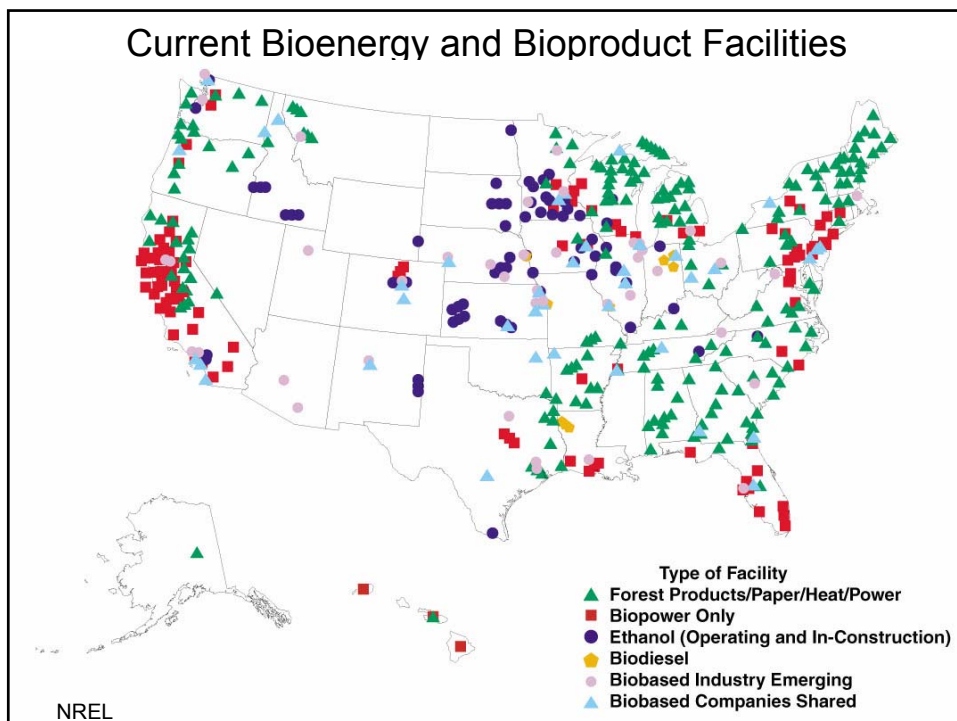


Courtesy of Nate Lewis, Caltech

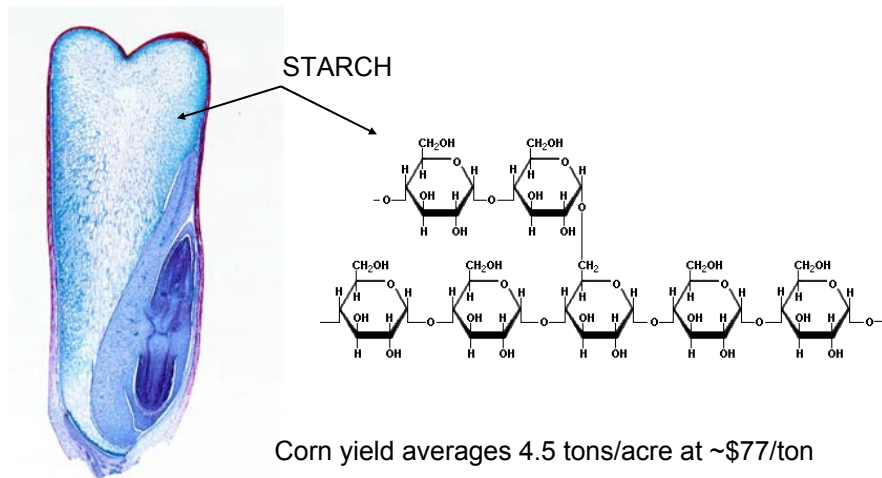
How Biomass is Used for Energy



Current Bioenergy and Bioproduct Facilities



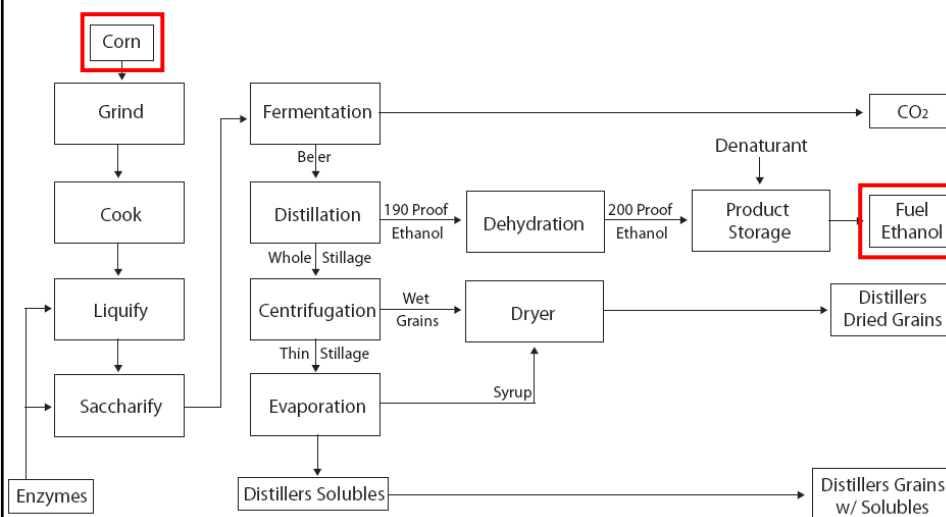
Chemical structure of starch



<http://www.ucmp.berkeley.edu/monocots/corngrains.jpg>

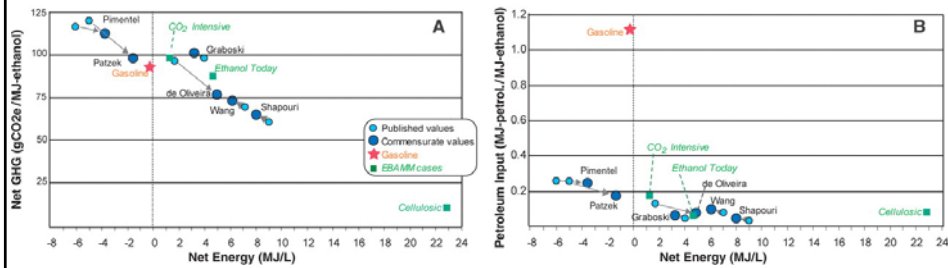
<http://www.scientificpsychic.com/fitness/carbohydrates1.html>

Ethanol from Cornstarch



Source: www.ethanol.org

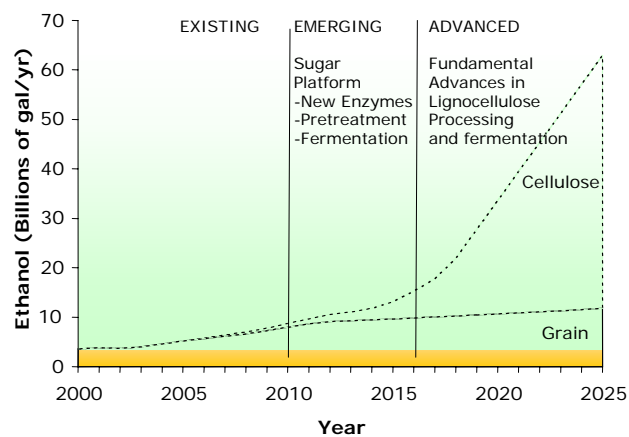
Net energy and net greenhouse gases for gasoline, six studies, and three cases



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

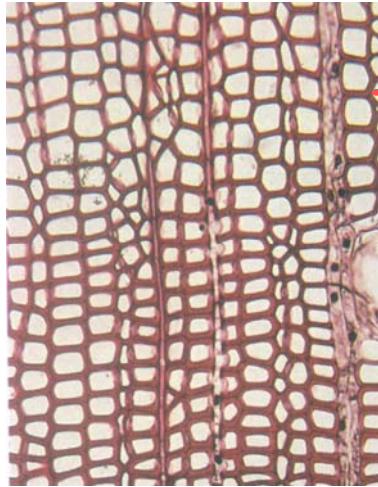


A DOE Ethanol Vision

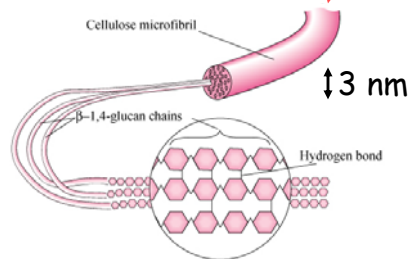
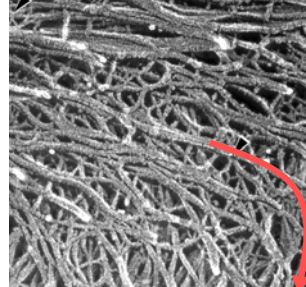


Modified from Richard Bain, NREL

Plants are mostly composed of sugars

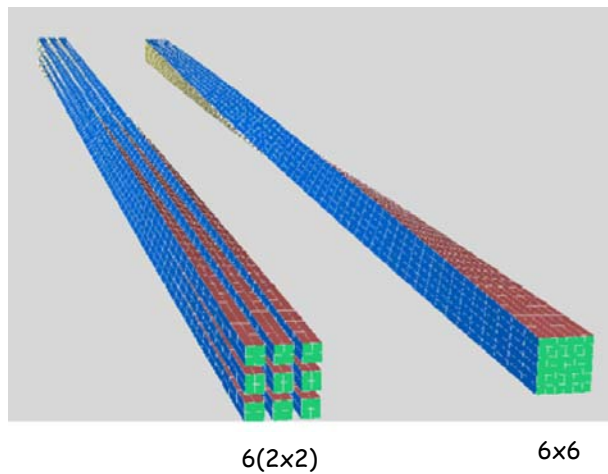


Section of a pine board



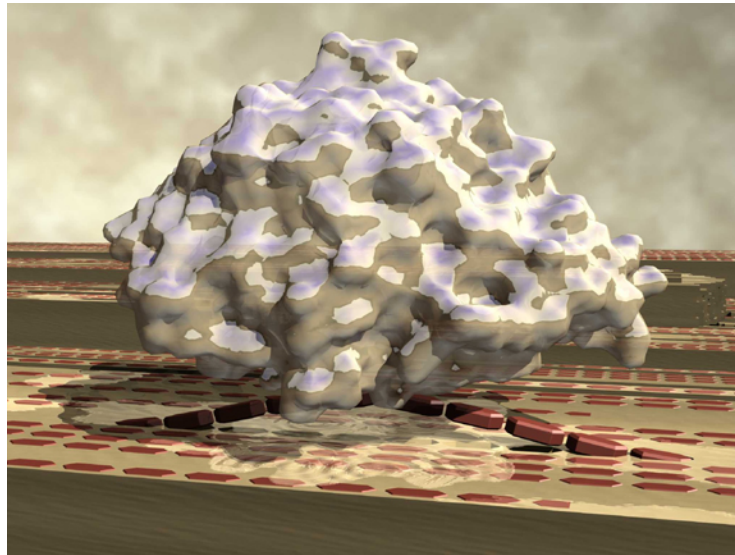
Polymerized glucose

Possible packing structures of cellulose



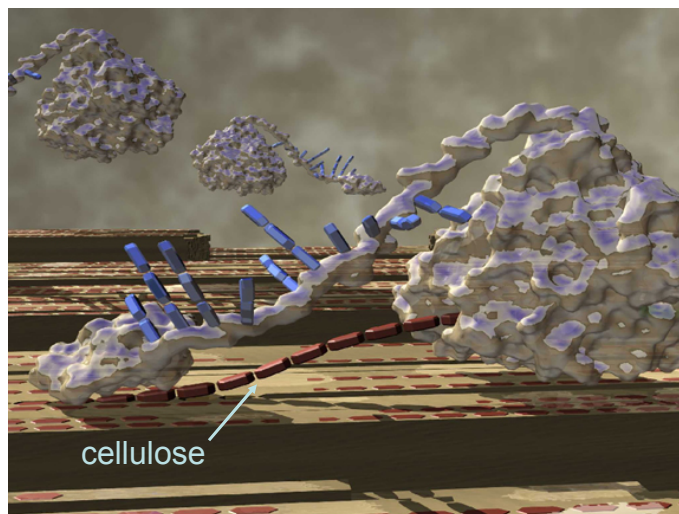
R. Atalla, unpublished

Cellulose is recalcitrant to hydrolysis



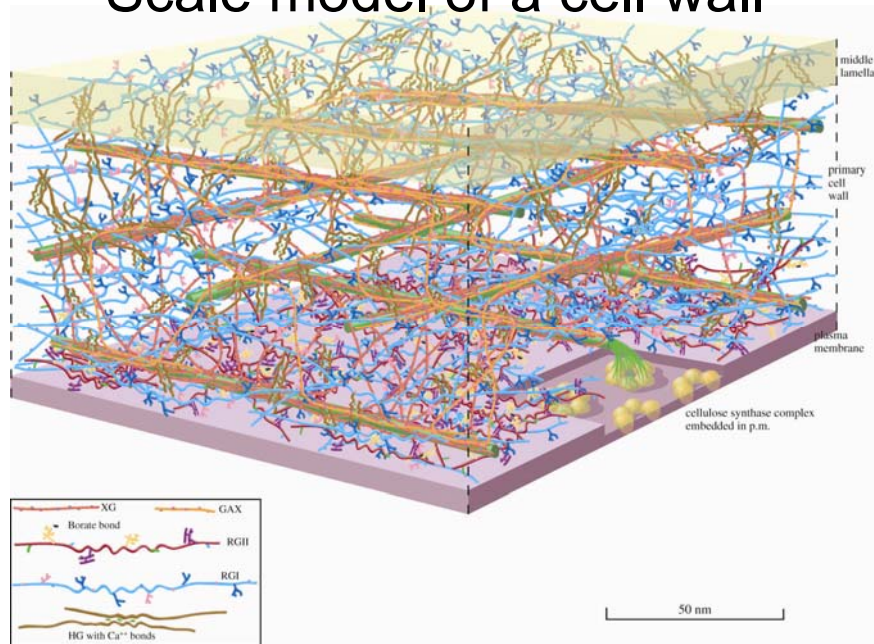
NREL

Cellulase hydrolyzing cellulose

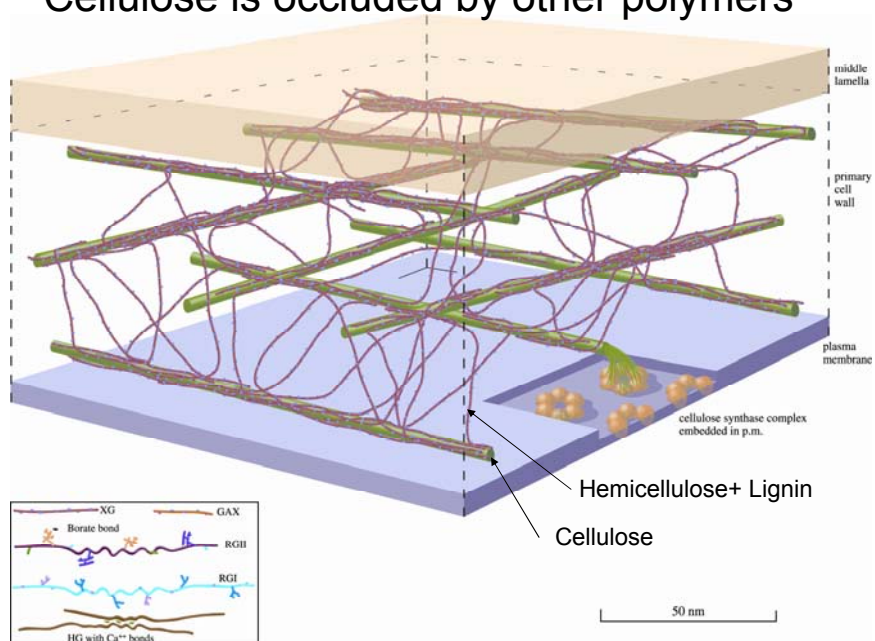


NREL

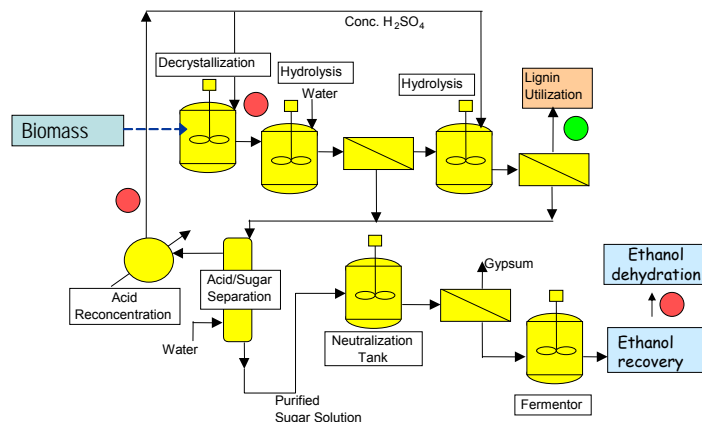
Scale model of a cell wall



Cellulose is occluded by other polymers

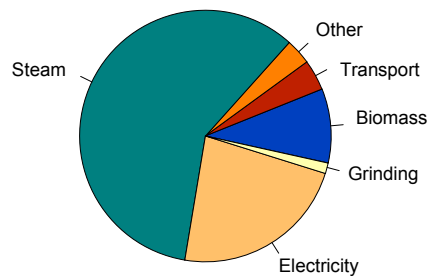


Linocellulose to ethanol process



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

The diagram illustrates the Linocellulose to Hydrophobe Process, showing the flow from Biomass to Hydrophobe through various chemical and biological steps.

Process Flow:

- Biomass** (green box) is the starting material.
- Decrystallization** (yellow tank) receives Biomass and **Conc. H_2SO_4** .
- Hydrolysis** (yellow tank) receives the output from Decrystallization and **Water**.
- Hydrolysis** (yellow tank) receives the output from the first Hydrolysis tank and **Conc. H_2SO_4** .
- Lignin Utilization** (red box) receives the output from the second Hydrolysis tank.
- Acid/Sugar Separation** (yellow tank) receives the output from the second Hydrolysis tank and **Water**.
- Acid Reconciliation** (yellow tank) receives the output from Acid/Sugar Separation and **Water**.
- Neutralization Tank** (yellow tank) receives the output from Acid/Sugar Separation and **Purified Sugar Solution**.
- Gypsum** (yellow tank) receives the output from the Neutralization Tank.
- Fermentor** (yellow tank) receives the output from the Gypsum tank and **Water**.
- Hydrophobe** (teal box) is the final product, receiving input from the Fermentor.

Outputs and Residues:

- 69 kt Ca, K, Mg, P**
- 66 kt lipids, waxes**
- 171 kt protein**

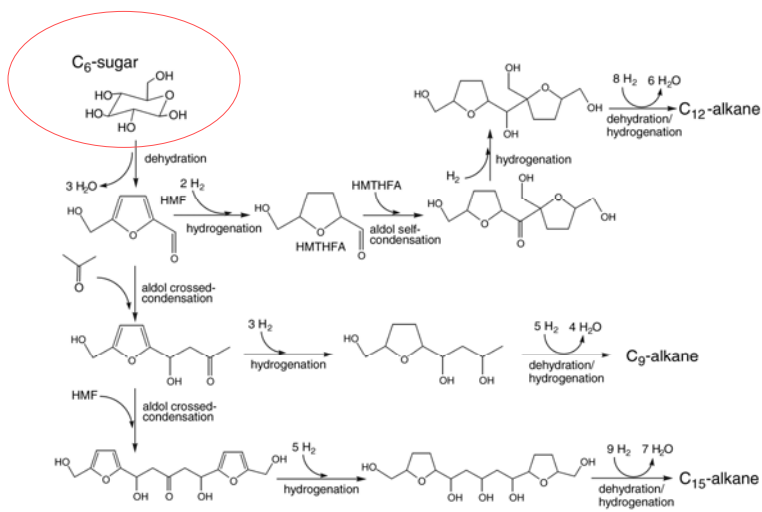
Ethanol from glucose or xylose

The diagram illustrates the metabolic pathways for the conversion of glucose and xylose to ethanol. The pathways are as follows:

- Glucose Pathway:**
 - Glucose is converted to Glucose-6-P by Hxk1, Hxk2.
 - Glucose-6-P is converted to Fructose-6-P by Pgi1.
 - Fructose-6-P is converted to Fructose-1,6-bisP by Pfk1, Pfk2.
 - Fructose-1,6-bisP is converted to Glyceraldehyde-3-P by Fba1.
 - Glyceraldehyde-3-P is converted to 1,3-bisphosphoglycerate by G3pdh.
 - 1,3-bisphosphoglycerate is converted to 3-P-glycerate by Pfk.
 - 3-P-glycerate is converted to Phosphoenolpyruvate by Gpm1.
 - Phosphoenolpyruvate is converted to Pyruvate by Eno1, Eno2.
 - Pyruvate is converted to Acetyl CoA by Pdh.
 - Pyruvate is converted to Acetaldehyde by Pdc1, Pdc5.
 - Acetaldehyde is converted to Ethanol by Adh1, Adh2.
- Xylose Pathway:**
 - Xylose is converted to Xylitol by Xor.
 - Xylitol is converted to Xylulose 5-P by Xid.
 - Xylulose 5-P is converted to Ribulose 5-P by Rpe1.
 - Ribulose 5-P is converted to Ribose 5-P by Rki1.
 - Ribose 5-P is converted to Glyceraldehyde-3-P by Tkl1, Tkl2.
 - Xylulose 5-P is converted to Sedoheptulose 7-P by Tkl1, Tkl2.
 - Sedoheptulose 7-P is converted to Fructose 6-P by Tal1, Tal2.
 - Fructose 6-P is converted to Glyceraldehyde-3-P by Tkl1, Tkl2.

The final product of the pathway is Ethanol, which is highlighted in a red circle.

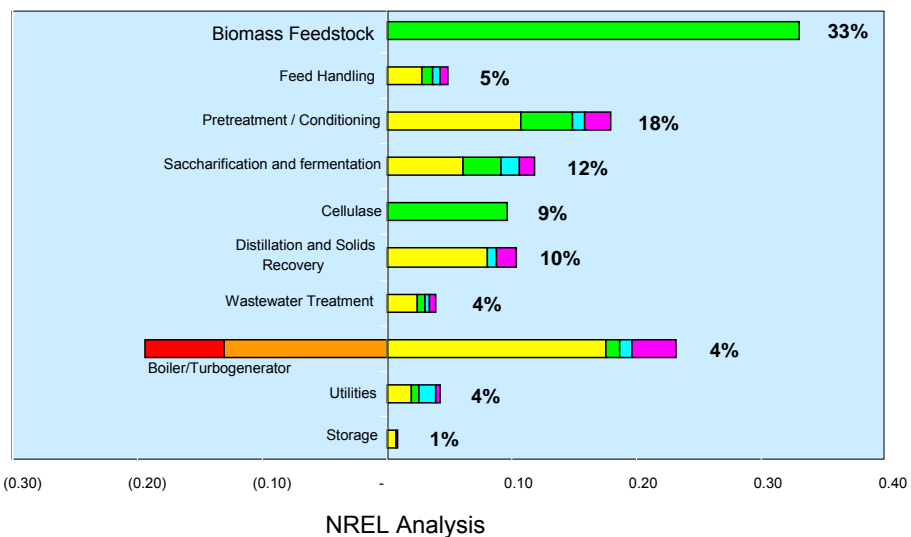
Conversion of sugar to alkanes

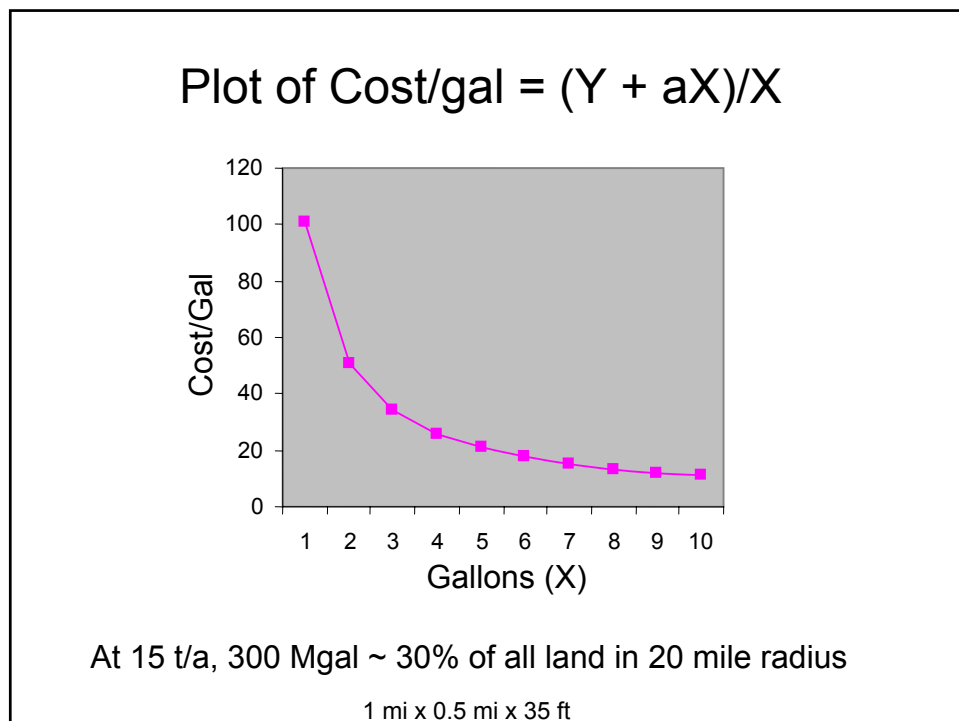
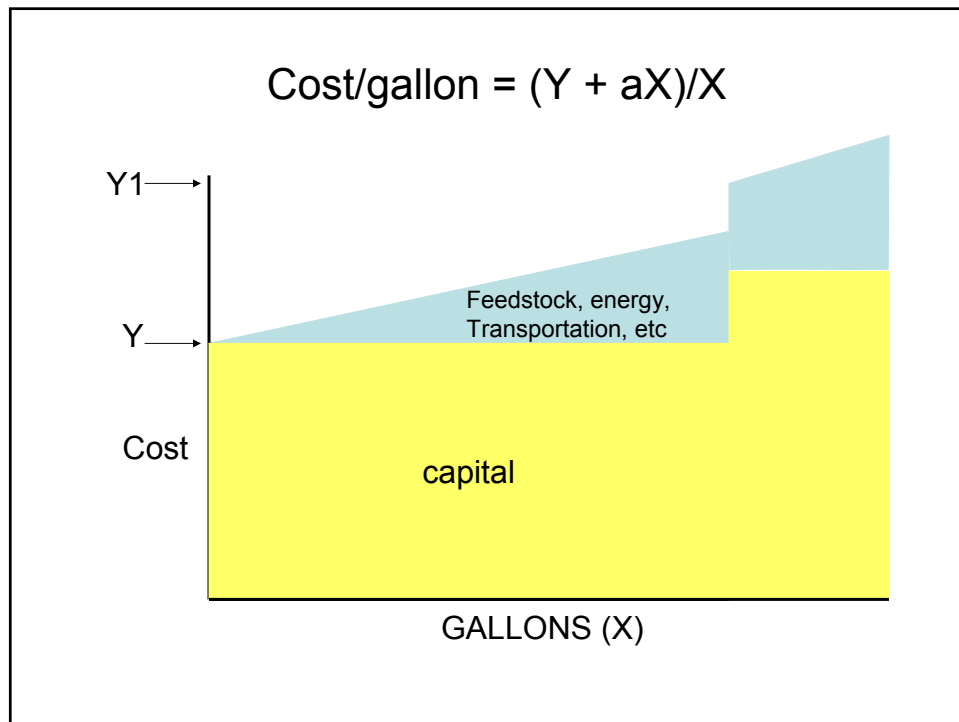


Huber et al., (2005) Science 308,1446

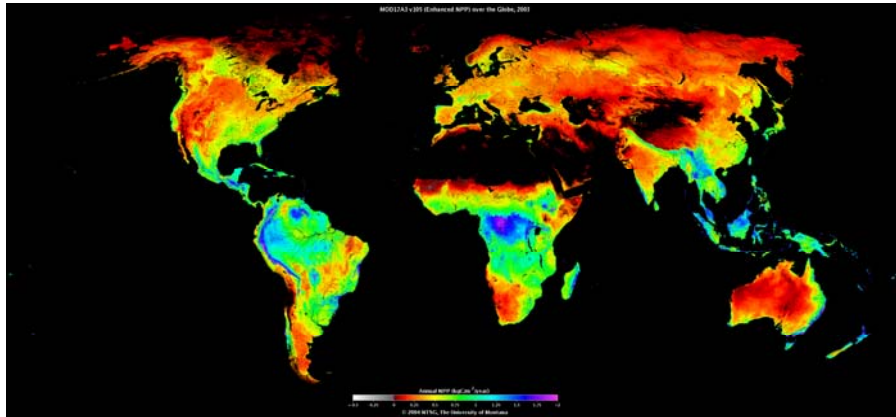
Relative cost factors of cellulosic ethanol

■ Capital Recovery Charge*
 ■ Raw Materials
 ■ Process Electricity
■ Grid Electricity
 ■ Total Plant Electricity
 ■ Fixed Costs





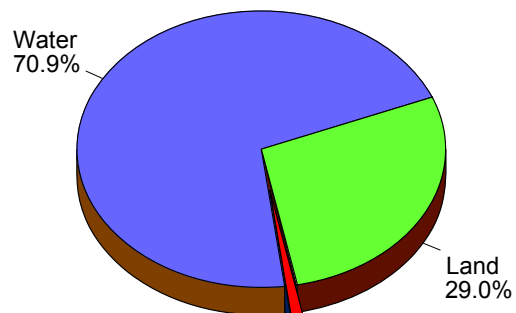
Is there enough land?



Estimated net primary productivity

University of Montana

90,000 TW of energy arrives on the earth's surface from the sun



Amount of land needed for 13 TW at 1% efficiency
5% of land
650 MHa

>2% yield is feasible

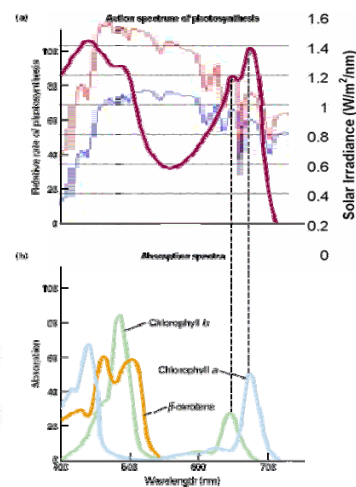
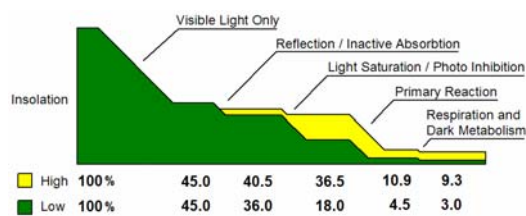
Yield of 26.5 tons/acre observed by Young & colleagues
in Illinois, without irrigation



Courtesy of Steve Long et al

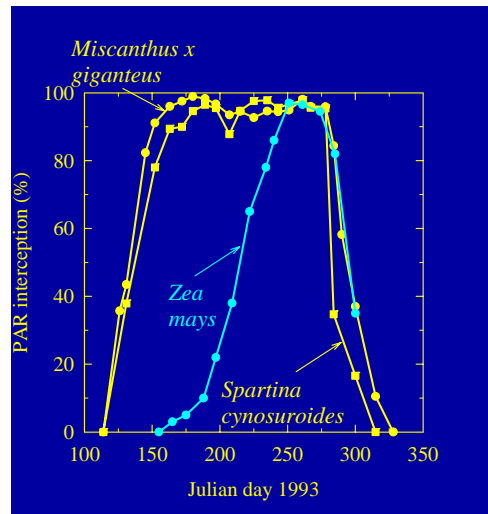
Why is photosynthetic efficiency so low?

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



Wes Hermann, Stanford

Perennials have more photosynthesis

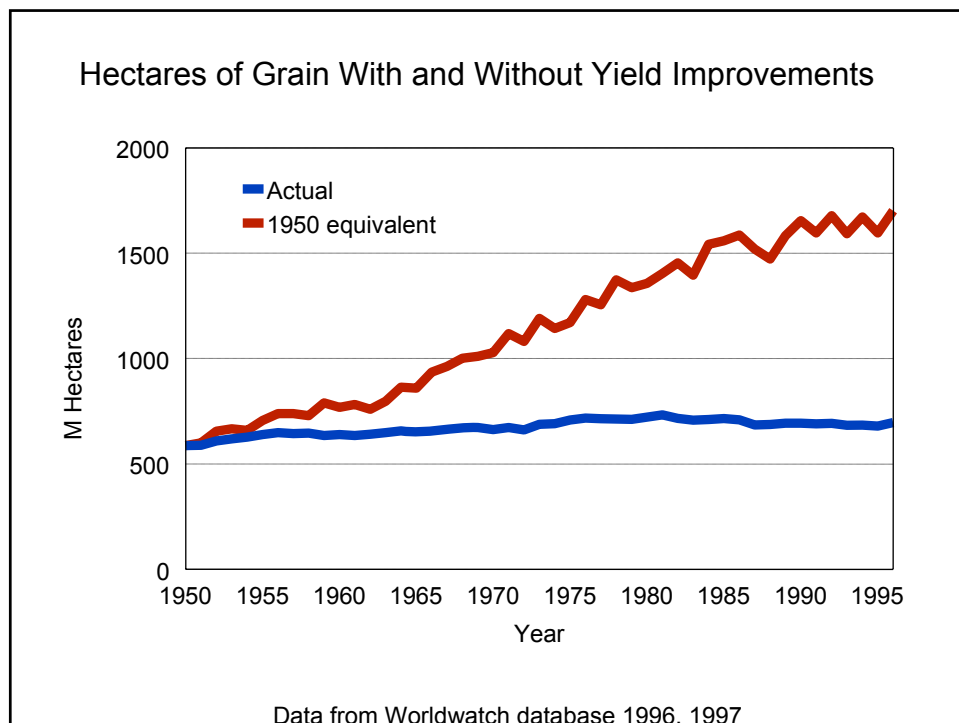
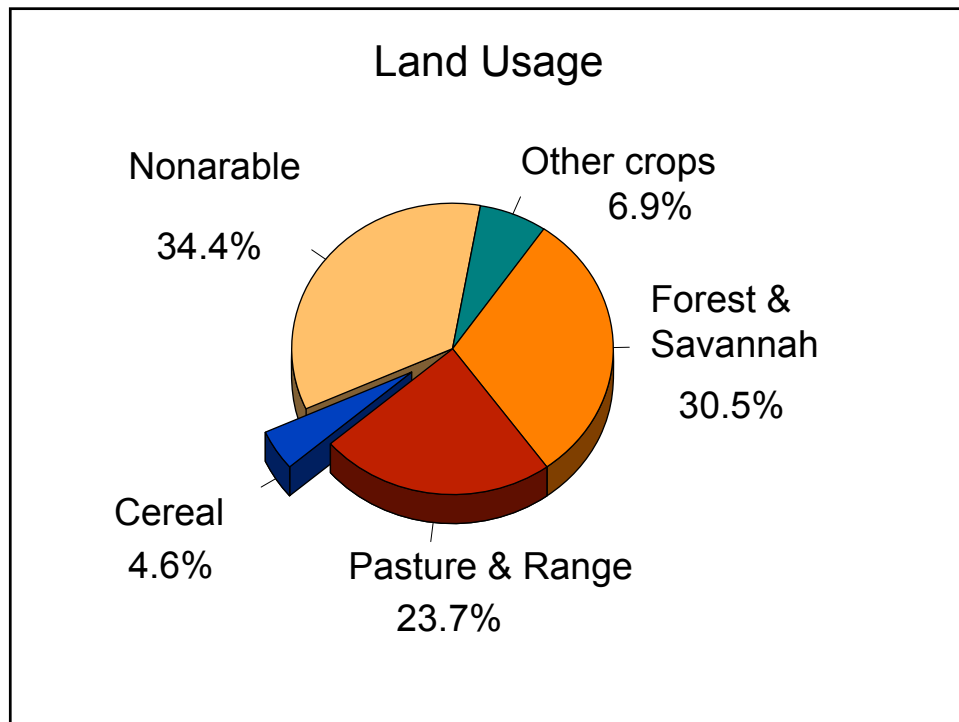


Courtesy of Steve Long, University of Illinois

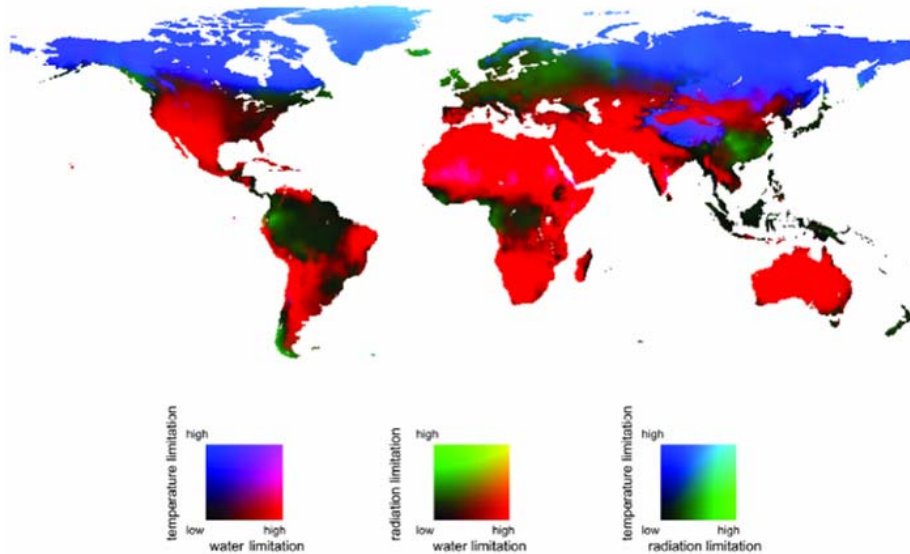
Harvesting Miscanthus



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



Limiting factors for global NPP

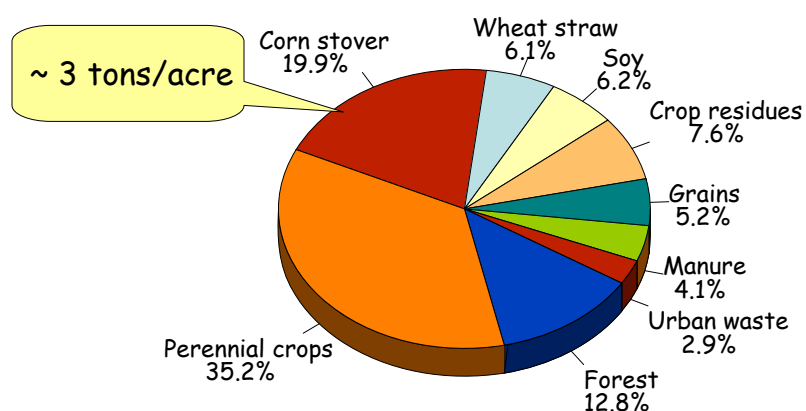


Baldocchi et al. 2004 SCOPE 62

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

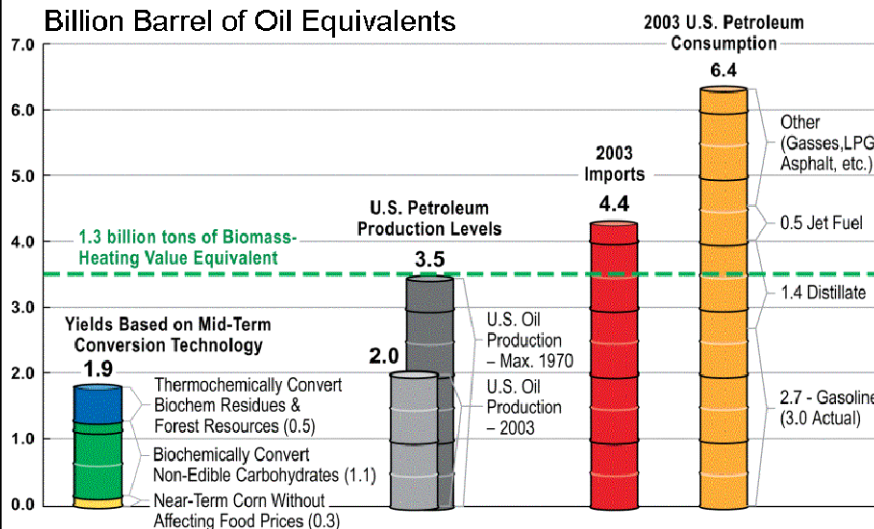
US Biomass inventory = 1.3 billion tons



From: Billion ton Vision, DOE & USDA 2005

The 1.3 Billion Ton Biomass Scenario

Billion Barrel of Oil Equivalents



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-FERE

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