Renewable Energy II:
Biofuels, Ethanol, Methanol, and Algae

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2015

Topic for today:

- **A discussion of the pros and cons of various aspects of meeting the energy needs of society by means of combustion of biomass, biofuels, and biowaste**

Lecture 20

28 April 2015

Concentrated Solar Power (CSP)

- Parabolic mirrors heat fluid that drives Stirling engine
  - Fluid is permanently contained within the engine's hardware
  - Converts heat to energy
  - Theoretical efficiencies often challenging to achieve

    http://en.wikipedia.org/wiki/Stirling_engine

- Highest electrical efficiencies for solar → lowest costs!

  http://www.powerfromthesun.net/Book

  http://www.oilcrisis.com/us/ca/CaliforniaCSP_Benefits200604.pdf

Kramer Junction, Calif

Fully operational in 1991: 350 MW capacity

Low output in 1992 due to Pinatubo aerosol!

Present operating cost: ~11 ¢ / kWh

Nevada Solar One

Output: 64 MW capacity / 134,000 MW-hr / year

Could supply all US electricity needs
if built over a ~ 130 mile × 130 mile area

Construction cost: ~$2 / kW-hr for one yr's prod

Hydro

Annual Production of Electricity, Three Gorges Dam

Year	Number of installed units	TWh
2003	6	8.607
2004	11	39.155
2005	14	49.090
2006	14	49.250
2007	21	61.600
2008	26	80.812
2009	26	79.470
2010	26	84.370
2011	29	78.290
2012	32	98.100
2013	32	83.270
2014	32	98.800

If Three Gorges had run 24 / 7 / 52 :

$$22{,}500 \text{ MW} \times 8760 \text{ hr} = 1.97 \times 10^{8} \text{ MWh}$$
$$= 1.97 \times 10^{8} \text{ MWh} \times 10^{6} \text{ W/MW} = 1.97 \times 10^{14} \text{ Wh}$$
$$= 1.97 \times 10^{14} \text{ Wh} \times \text{TW} / 10^{12} \text{ W} = 197 \text{ TWh}$$

- Three Gorges Dam, Yangtze River, China: 22,500 MW
  - Fully operational in 2012
  - Cost: $22.5 billion or 1 million $ / MW
  - Largest construction project in China since Great Wall
  - 1 million people displaced
  - Provides 3.0% of China's electricity needs

Source: http://en.wikipedia.org/wiki/Three_Gorges_Dam

Nevada Solar One

Project capacity: **64 MW** (power = energy / time)

Project output over 2012: **129,000 MW-hr** (energy, or power × time)

Number of hours in year = 365x24 = 8760

Capacity Factor = 129,000 MW-hr / (64 MW × 8760 hr) = **0.23**

Nevada Solar One

Output: 64 MW capacity

Could supply all US electricity needs
if built over a ~ 130 mile × 130 mile area

Construction cost: ~$2 / kW-hr for one yr's prod

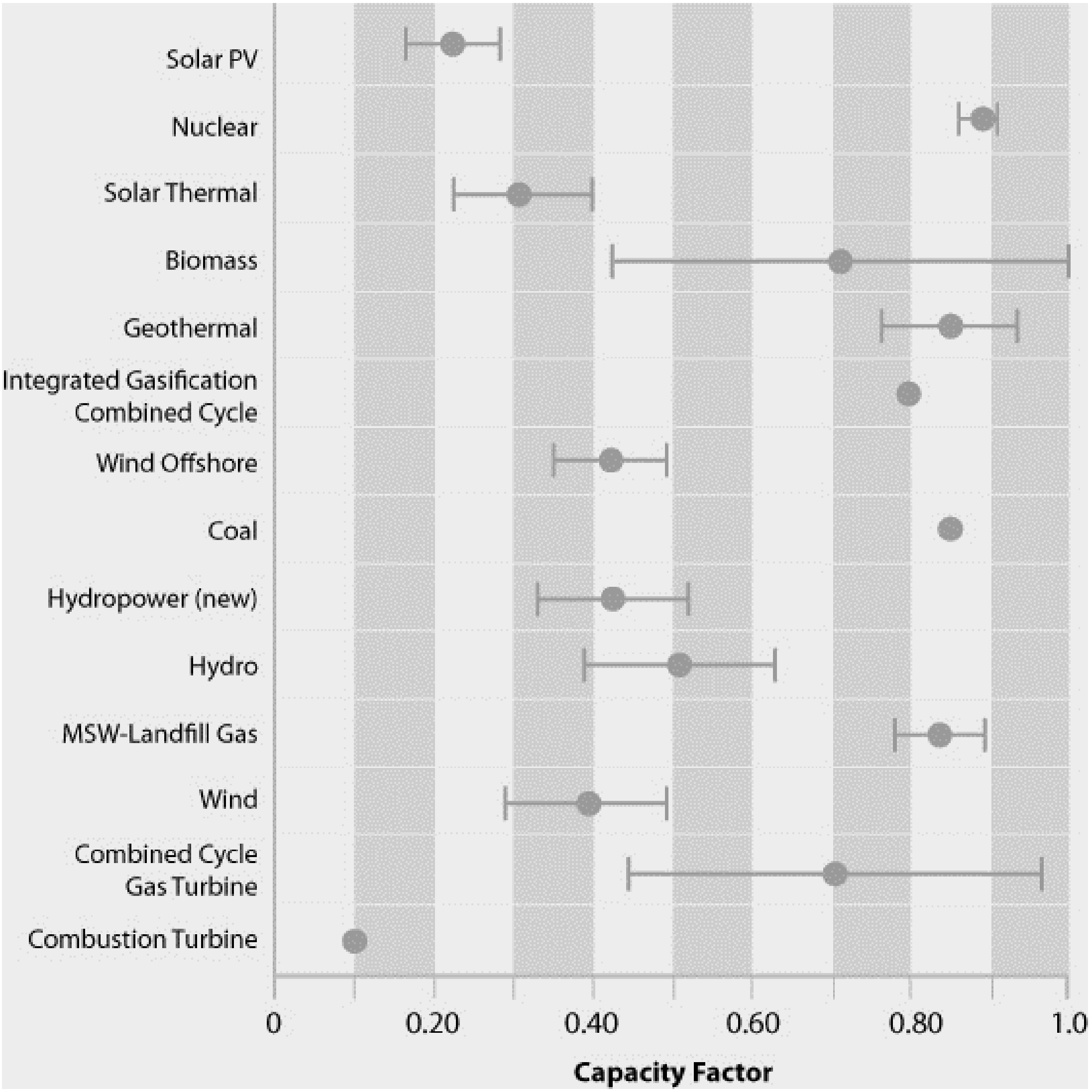
Production [edit]

Nevada Solar One's production is as follows.[20]

Year	GWh
2007	41.212
2008	122.687
2009	120.648
2010	133.000
2011	128.263
2012	128.935

http://en.wikipedia.org/wiki/Nevada_Solar_One#Production

Capacity Factor, Various Energy Sources



http://www.nrel.gov/analysis/tech_cap_factor.html

World Energy & Electricity Supply

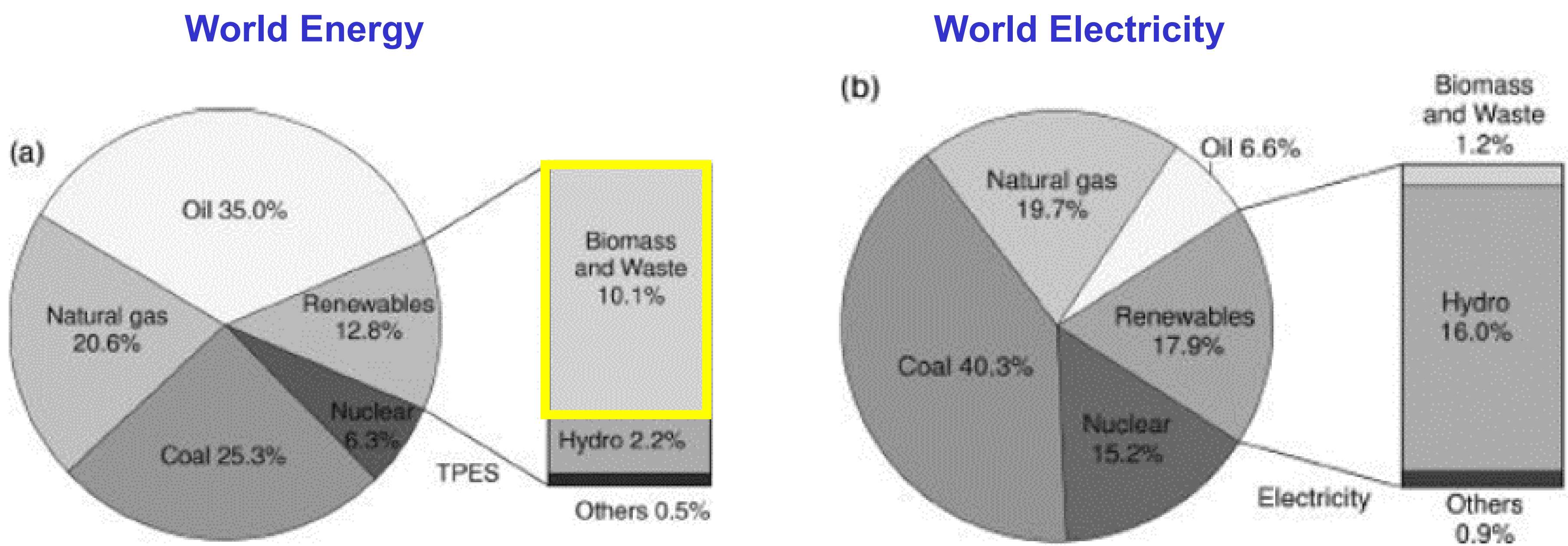


Figure 8.1 (a) Share of renewables in the world total primary energy supply (TPES) in 2005; (b) share of renewables in world electricity production in 2005. (Source: IEA Renewables Information 2007.)

Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009

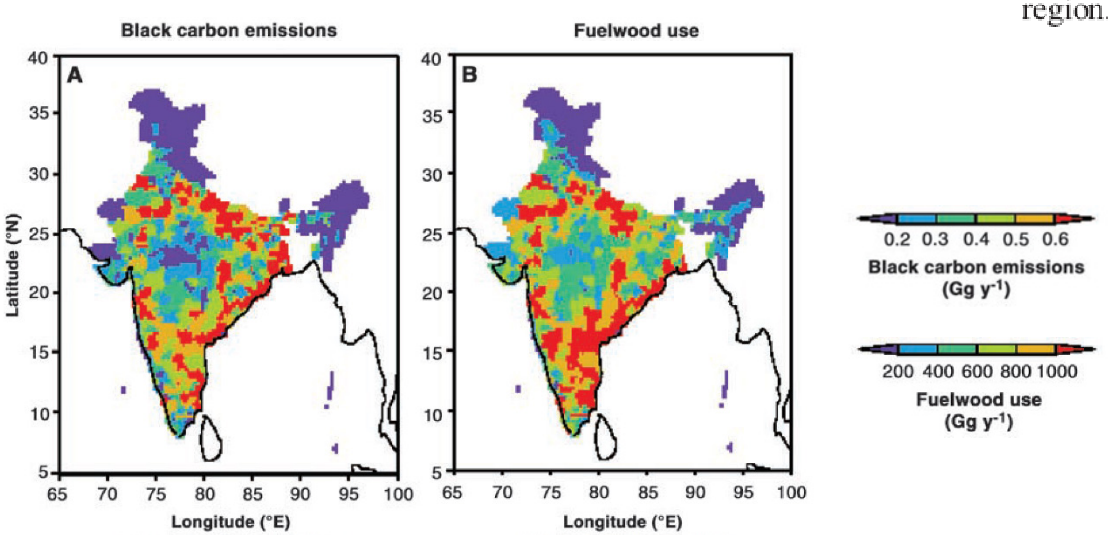
Largest energy source that does not involve combustion of fossil fuels is **Biomass and Waste**

Residential Biofuels in South Asia: Carbonaceous Aerosol Emissions and Climate Impacts

C. Venkataraman,[1*] G. Habib,[1] A. Eiguren-Fernandez,[2]
A. H. Miguel,[2] S. K. Friedlander[3]

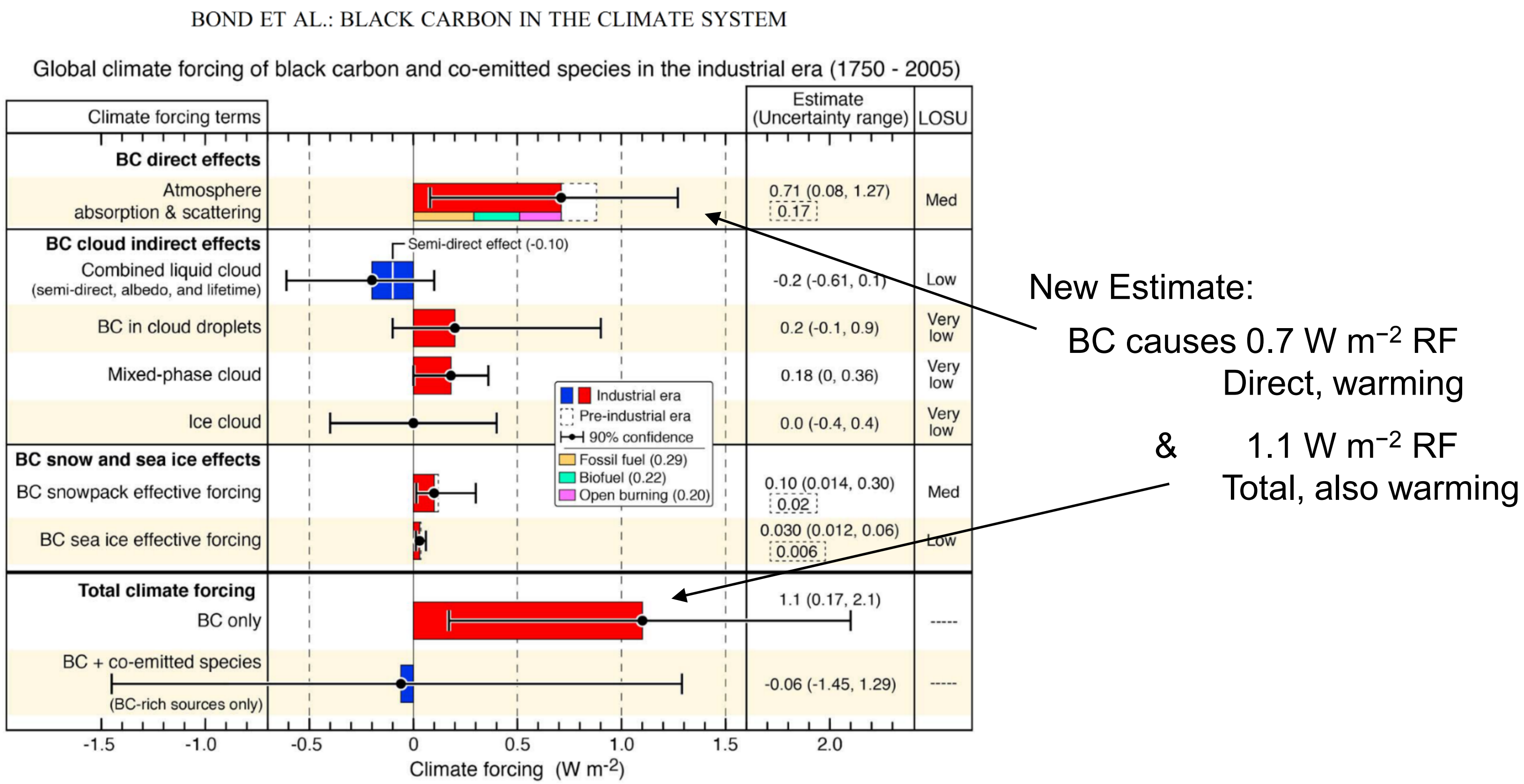
High concentrations of pollution particles, including "soot" or black carbon, exist over the Indian Ocean, but their sources and geographical origins are not well understood. We measured emissions from the combustion of biofuels, used widely in south Asia for cooking, and found that large amounts of carbonaceous aerosols are emitted per kilogram of fuel burnt. We calculate that biofuel combustion is the largest source of black carbon emissions in India, and we suggest that its control is central to climate change mitigation in the south Asian region.

4 MARCH 2005 VOL 307 SCIENCE



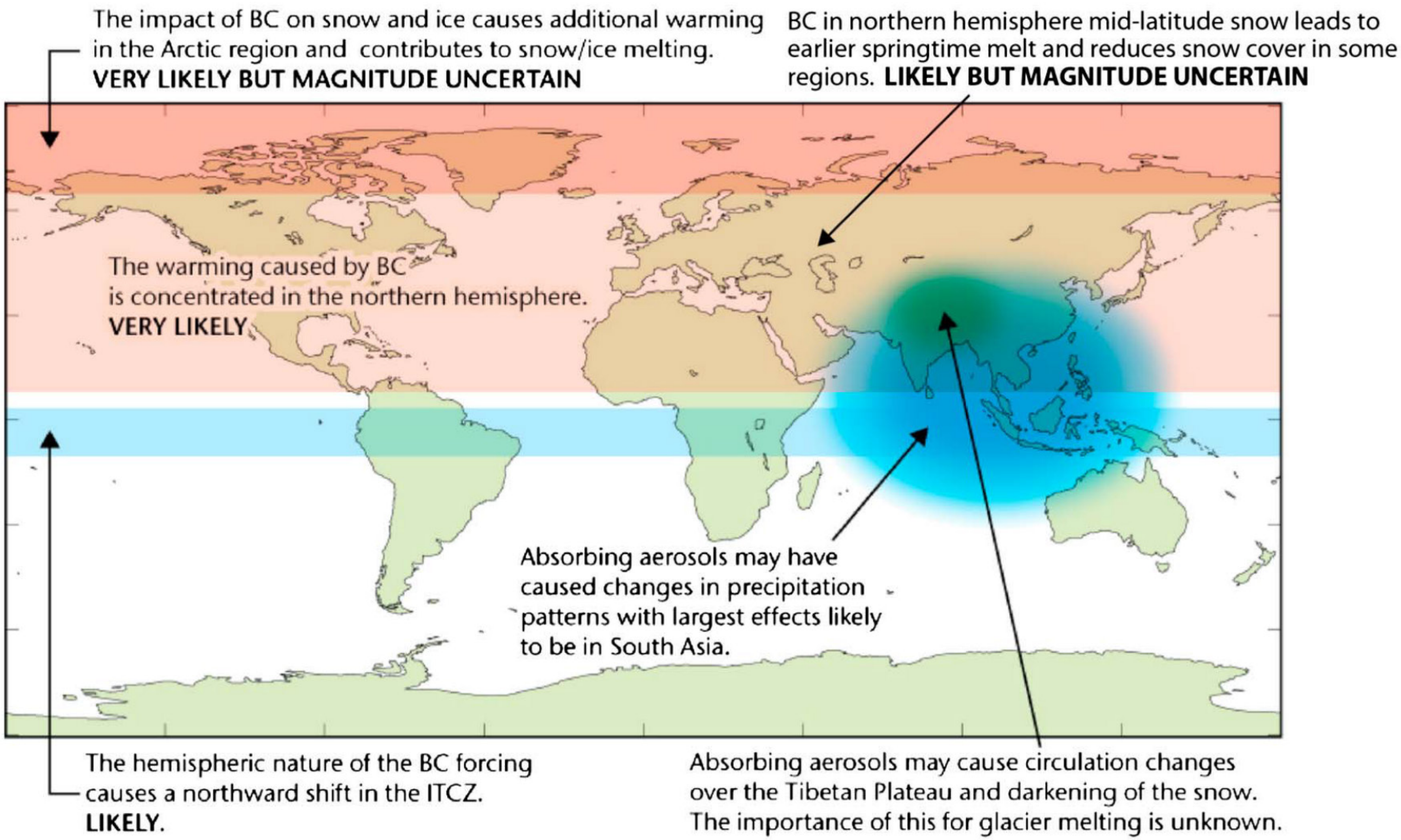
An analysis of the climate response of soot emissions from fossil fuel and biofuel combustion has suggested that control of soot, in addition to greenhouse gases, is an important measure to slow global warming, especially on short time scales (*6*, *7*). Our results suggest that biofuel combustion could significantly affect atmospheric BC concentrations in the south Asian region. The climate effects of biofuel combustion aerosols have been combined with the effects of open biomass burning in the scientific consensus reports of the Intergovernmental Panel on Climate Change (*29*). We suggest that biofuel combustion needs to be addressed as a distinct source, and that cleaner cooking technologies not only could yield significant local health and air quality benefits but also could have an important role in climate change mitigation in the south Asian region.

Black Carbon & Climate



Bond *et al*., JGR, 2013

Black Carbon & Climate



Bond *et al.*, JGR, 2013

Aerosol Direct RF of Climate, IPCC

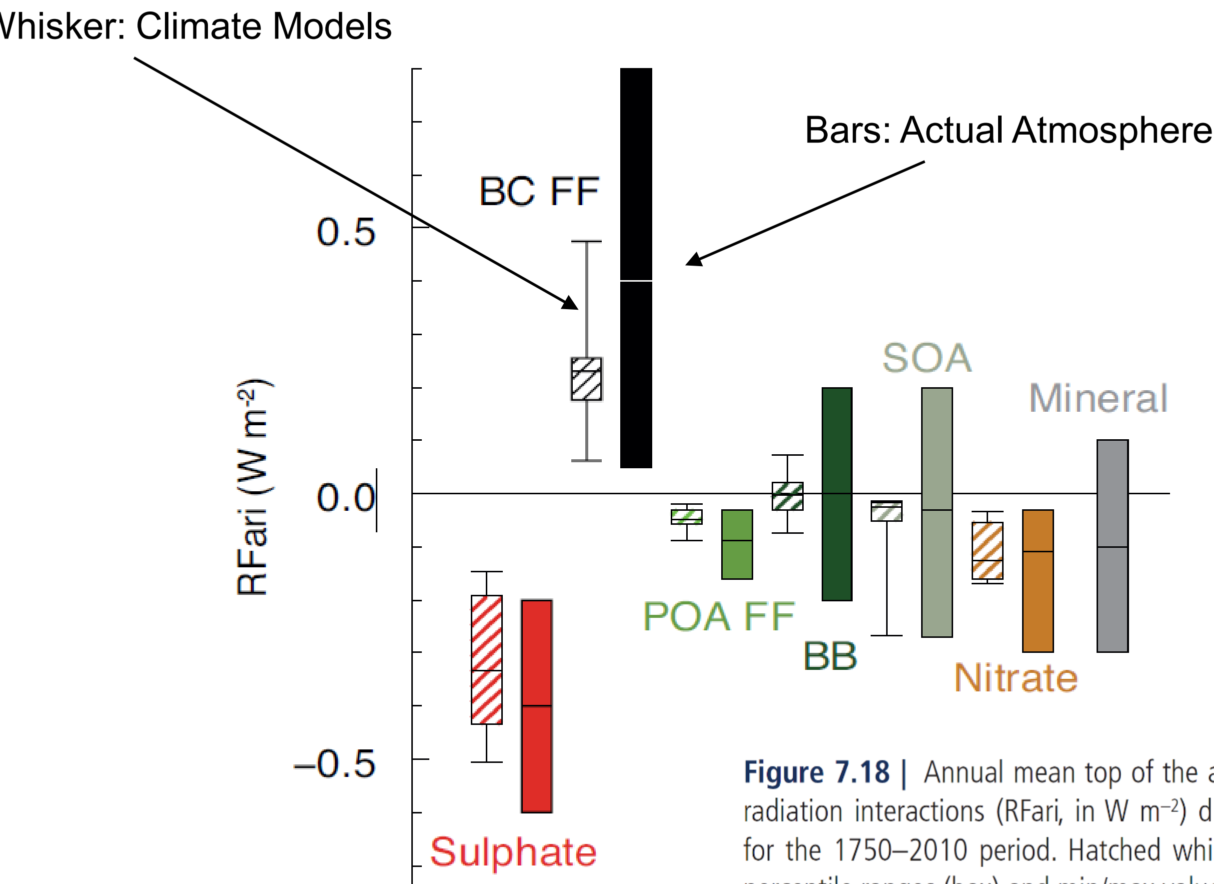
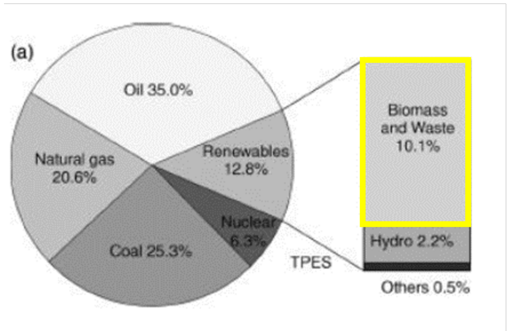
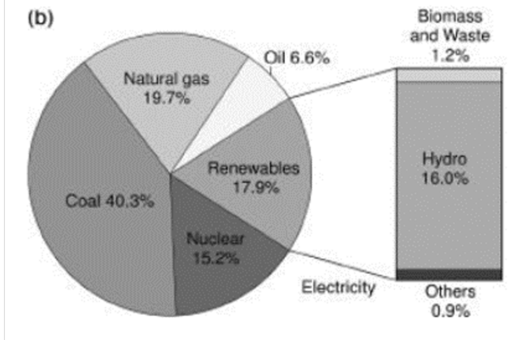


Figure 7.18 | Annual mean top of the atmosphere radiative forcing due to aerosol–radiation interactions (RFari, in W m^{-2}) due to different anthropogenic aerosol types, for the 1750–2010 period. Hatched whisker boxes show median (line), 5th to 95th percentile ranges (box) and min/max values (whiskers) from AeroCom II models (Myhre et al., 2013) corrected for the 1750–2010 period. Solid coloured boxes show the AR5 best estimates and 90% uncertainty ranges. BC FF is for black carbon from fossil fuel and biofuel, POA FF is for primary organic aerosol from fossil fuel and biofuel, BB is for biomass burning aerosols and SOA is for secondary organic aerosols.

IPCC (2013)





Surya – Sanskrit for Sun

- 65 villages (6500 homes) covering 1500 km^2, where most residents use wood for cooking, will be provided with either solar and/or biogas burners
- Air quality, soot, and particulates will be monitored for 6 months prior to installation of alternate cookers and for at least 1 year subsequent
- Indoor air quality will be measured in selected homes
- Outdoor air quality will also be monitored using NASA satellite instruments
- PI: V. Ramanathan, Scripps

http://www.projectsurya.org

The New York Times

BY DEGREES

Third-World Stove Soot Is Target in Climate Fight

Surya – Pilot Phase Findings

- **Pilot village included 485 households**
- **Cooking drives local outdoor black carbon concentrations**
- **New stove technologies could reduce emissions of $PM_{2.5}$ and CO by factors of 4 to 5**
- **Demonstrated an ultra low power wireless cell phone approach for measuring black carbon**

http://www.projectsurya.org/storage/prospectusinsert.pdf

EXPECTED OUTCOME

REGIONAL

Increase food and water supply, decrease mountain-glacier melt, decrease deforestation and aid in poverty alleviation.

GLOBAL

Contribute to the delay of the DAI threshold by up to few decades and saving 2 million lives yearly.

BACKGROUND

Global warming of more than 2°C is considered to be the threshold for dangerous anthropogenic interference (DAI).

Black carbon (BC) & non-CO_2 gases such as methane, ozone, halocarbons account for half of global warming and can be removed from the air 10x-100x faster than CO_2.

Biomass cooking (using dung, firewood, crop residues) is a major source of BC & ozone and leads to CO_2 emission by deforestation; it leads to severe air pollution which is the root cause of millions of cardiovascular & respiratory related deaths.

Surya will introduce cleaner cooking methods.

Photo Credit: Adam Ferguson, New York Times

GLOBAL POLICY

2020 - 2025
$20 Billion
Target: 3 Billion people worldwide

Funded and sustained by carbon credits, micro-financing, Global Environment Facility funds and foundations.

REPLICATION

2014 - 2020
$200 Million
Target: 10-20 Million people in Africa, Asia and Latin America.

PILOT PHASE

2009 - 2010
$ 0.8 Million
2,500 People

COMPLETED

DEMONSTRATION

2011 - 2013
$13.7 Million
Target: 50,000 people in North India

IMPLEMENTATION

Replace stoves in 10,000 homes with aid of multi-national team of scientists, engineers, health professionals and village leaders.

VALIDATION

Use data collected from cell phones, satellites and other cutting-edge technologies to quantify impacts on climates and health.
Develop metrics for carbon credits.

http://www.projectsurya.org/storage/ProjectSuryaWEB-Feb23.pdf

Project Surya: April 2015

Project Surya is:

- exploring how to include Short Lived Climate Pollutants including BC and O_3 producing gases (CO & VOCs) into carbon credit calculations, which will lead to more revenue for climate credits.

- distribute the funds from carbon credits directly to the participant women instead of the stove distributors or manufacturers

http://static1.1.sqspcdn.com/static/f/316880/20886420/1352224604787/ProjectSuryaLaunchesPilotCarbonCreditMarket.pdf

Electricity from Biomass

Table 8.1 Production of electricity from biomass and waste in 2006.

Data source: EDF and IEA key statistics.

Country	Production (TWh)	Percentage of world electricity production from biomass	Percentage of the country's total electricty production
United States	58.7	29.3	1.5
Germany	19.7	9.9	3.4
Brazil	14.6	7.3	3.9
Finland	11.8	5.9	14.0
Japan	11.6	5.8	1.1
United Kingdom	9.3	4.6	2.5
Canada	9	4.5	1.6
Spain	8.2	4.1	3.1
Rest of the world	57.2	28.6	0.6
World	200.1	100	1.2

Olah *et al*., *Beyond Oil and Gas: The Methanol Economy*, 2009.

Electricity from Biomass: Overview

Courtesy A. Truman Schwartz

Fig 4.24, *Chemistry in Context*

- Plant size average 20 MW
- Efficiencies range from 15 to 30% (electricity only) to 60% (electricity + heat)
  – co-firing uses biomass to supplement fossil fuel
- Use wood, agricultural residues, and municipal waste
- 85 plants in U.S generate some type of energy from waste
- Addresses energy need and growing “mountain of waste”:
  – waste converted to CO_2 and water; unburned residue about 10% of initial volume
  – iron-containing metals often recovered and recycled

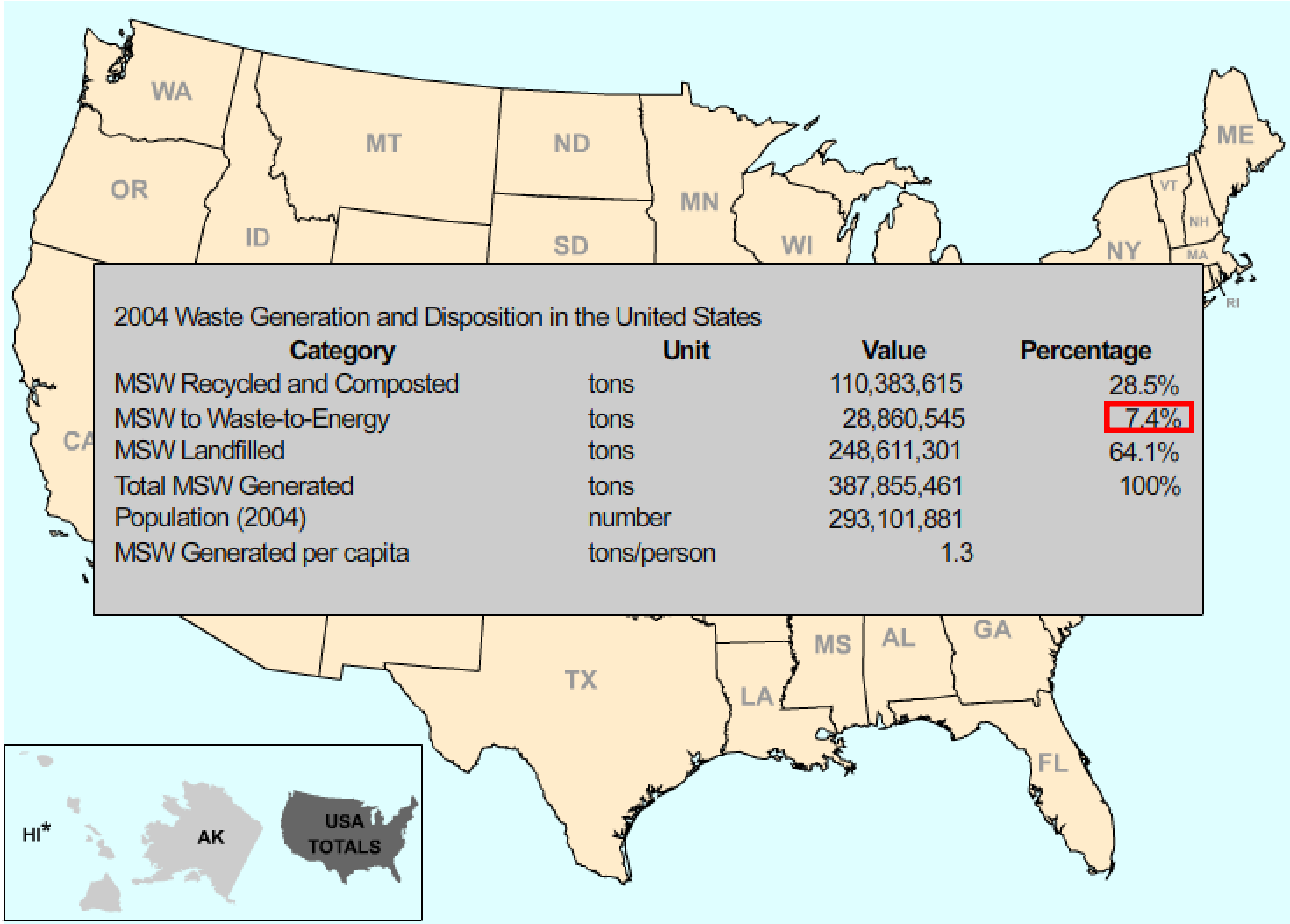
Electricity from Waste

Baltimore RESCO (Refuse Energy Systems Company) Plant
Russell Street & U.S Interstate 95 (shadow of Ravens Stadium)

- Opened in 1984
- Site of old pyrolysis plant
- Burns 2,250 tons of trash per day
- Metals recovered; volume of trash reduced by factor of 10
- Can generate 60,000 kW of electricity ⇨ 60 MW (2700 × size of UP solar array but only 6% typical nuclear plant)
- Heat used for direct steam heating / cooling downtown Baltimore
- One of 16 such plants in the U.S.

http://www.eia.doe.gov/kids/energy.cfm?page=RESCOE_Plant

Energy from Waste

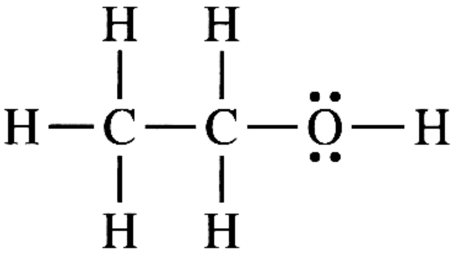


2004 Waste Generation and Disposition in the United States

Category	Unit	Value	Percentage
MSW Recycled and Composted	tons	110,383,615	28.5%
MSW to Waste-to-Energy	tons	28,860,545	7.4%
MSW Landfilled	tons	248,611,301	64.1%
Total MSW Generated	tons	387,855,461	100%
Population (2004)	number	293,101,881	
MSW Generated per capita	tons/person	1.3	

http://www.seas.columbia.edu/earth/recycle/

Ethanol



- Ethanol : C_2H_5OH
- Alcohol
- $C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$ (ΔH_f = 228 kJ/mol or 5 kJ/g)
- Reaction catalyzed by enzymes; theoretically, can be close to carbon neutral
- Ethanol combustion:

  $C_2H_5OH + 3\ O_2 \rightarrow 2\ CO_2 + 2\ H_2O$ + 29.7 kJ/g

  Heat release less than combustion of C_8H_{18} (47.8 kJ/g) because C_2H_5OH is already partially oxidized
- However … ethanol has a higher octane than gasoline

Ethanol Production

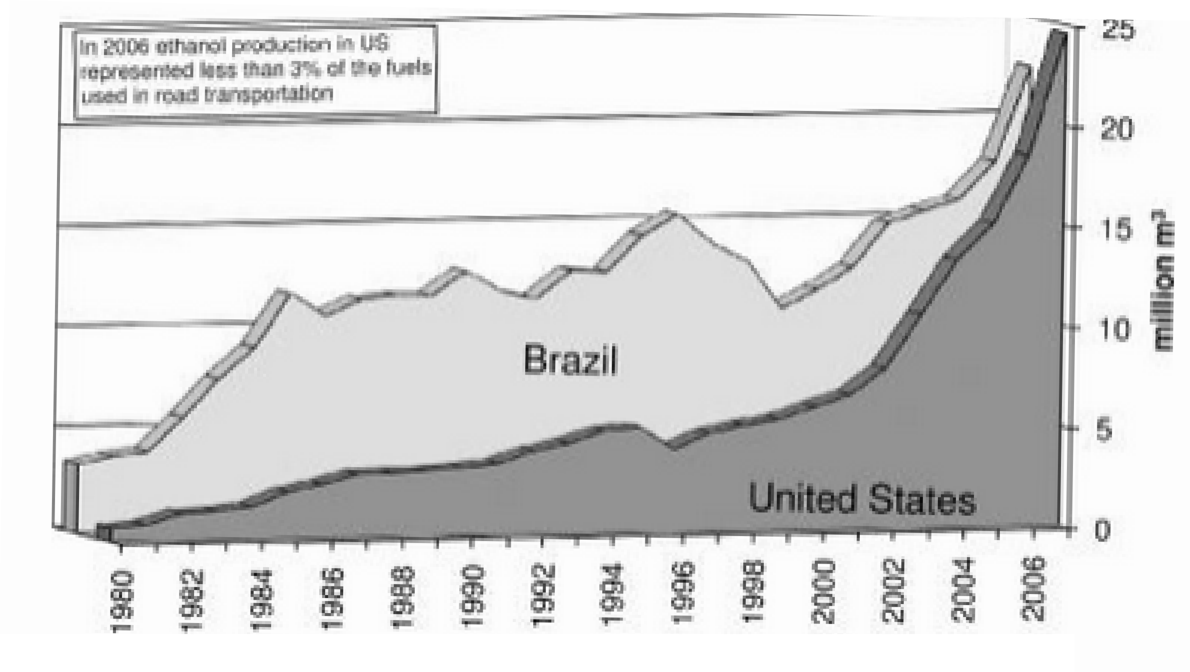
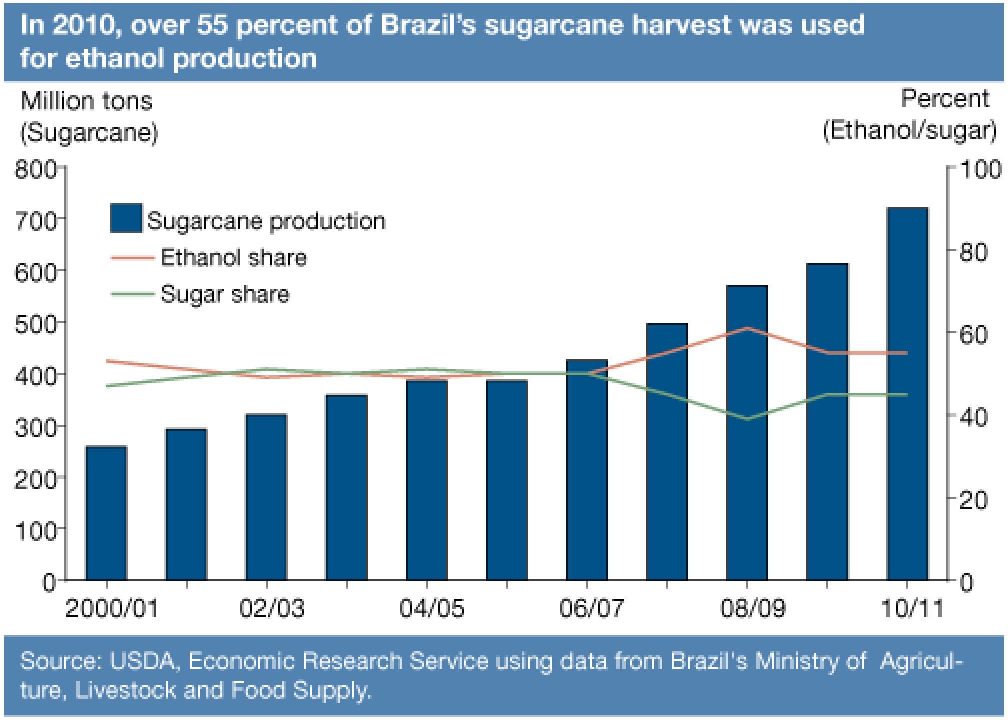


Figure 8.13 Historic production of ethanol in the United States and Brazil. (Based on data from Renewable Fuel Association and Sao Paulo Agroindustry Union (UNICA).)

Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009.

- U.S.: Ethanol produced from corn
- Brazil: Ethanol produced from sugar cane, which thrives in tropical climate

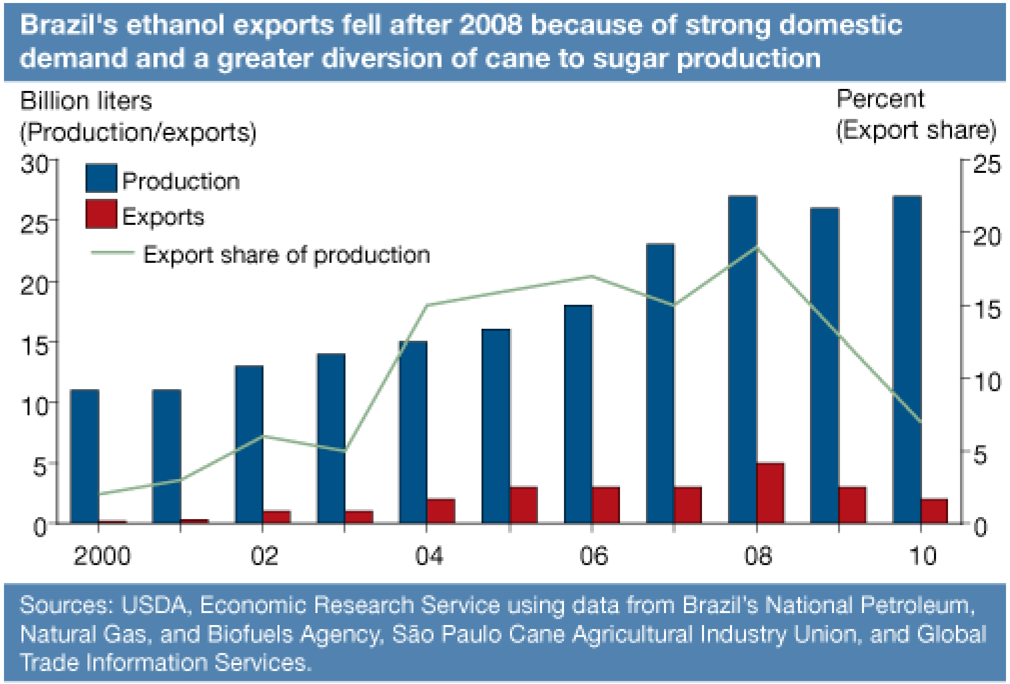
Ethanol Production: Good News



http://www.ers.usda.gov/amber-waves/2011-december/can-brazil-meet-the-world%E2%80%99s-growing-need-for-ethanol.aspx

- Brazil: Ethanol produced from sugar cane, which thrives in tropical climate
  - energy to convert sugar to ethanol supplied by burning bagasse (sugar cane husk)
- About half cars in Brazil are "flex fuel vehicles (FFV)"
  - can run on 100 percent ethanol or any ethanol-gasoline mixture.
- Ethanol accounts for ~40% of non-diesel fuel use in Brazil
- 2010: Brazil produces 26% of world ethanol (US produces most)

Ethanol Production: Bad News



http://www.ers.usda.gov/amber-waves/2011-december/can-brazil-meet-the-world%E2%80%99s-growing-need-for-ethanol.aspx

- **Annual Brazil ethanol production < 1 day world petroleum consumption**
- **Brazil consumes nearly all the ethanol it produces due to high domestic demand**

Ethanol Production

- McElroy article suggests considering refinement cost, transportation cost, and energy content of ethanol, “the energy captured in the ethanol exceeds the fossil energy consumed in its production by no more than ~25 %”
- McElroy did not consider _______________

Ethanol Production

- Raging debate over "green" aspects of both sugar and corn based biofuels:

  Excellent point/counterpoint: http://cen.acs.org/articles/85/i51/Costs-Biofuels.html

Land Clearing and the Biofuel Carbon Debt

SCIENCE VOL 319 29 FEBRUARY 2008

Joseph Fargione,[1] Jason Hill,[2,3] David Tilman,[2]* Stephen Polasky,[2,3] Peter Hawthorne[2]

Increasing energy use, climate change, and carbon dioxide (CO_2) emissions from fossil fuels make switching to low-carbon fuels a high priority. Biofuels are a potential low-carbon energy source, but whether biofuels offer carbon savings depends on how they are produced. Converting rainforests, peatlands, savannas, or grasslands to produce food crop–based biofuels in Brazil, Southeast Asia, and the United States creates a "biofuel carbon debt" by releasing 17 to 420 times more CO_2 than the annual greenhouse gas (GHG) reductions that these biofuels would provide by displacing fossil fuels. In contrast, biofuels made from waste biomass or from biomass grown on degraded and abandoned agricultural lands planted with perennials incur little or no carbon debt and can offer immediate and sustained GHG advantages.

[1]The Nature Conservancy, 1101 West River Parkway, Suite 200, Minneapolis, MN 55415, USA. [2]Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul, MN 55108, USA. [3]Department of Applied Economics, University of Minnesota, St. Paul, MN 55108, USA.

Ethanol Production

- Raging debate over "green" aspects of both sugar and corn based biofuels:

  Excellent point/counterpoint: http://cen.acs.org/articles/85/i51/Costs-Biofuels.html

SCIENCE VOL 319 29 FEBRUARY 2008

Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change

Timothy Searchinger,[1]* Ralph Heimlich,[2] R. A. Houghton,[3] Fengxia Dong,[4] Amani Elobeid,[4] Jacinto Fabiosa,[4] Simla Tokgoz,[4] Dermot Hayes,[4] Tun-Hsiang Yu[4]

Most prior studies have found that substituting biofuels for gasoline will reduce greenhouse gases because biofuels sequester carbon through the growth of the feedstock. These analyses have failed to count the carbon emissions that occur as farmers worldwide respond to higher prices and convert forest and grassland to new cropland to replace the grain (or cropland) diverted to biofuels. By using a worldwide agricultural model to estimate emissions from land-use change, we found that corn-based ethanol, instead of producing a 20% savings, nearly doubles greenhouse emissions over 30 years and increases greenhouse gases for 167 years.

[1]Woodrow Wilson School, Princeton University, Princeton, NJ, USA. German Marshall Fund of the U.S., Georgetown Environmental Law and Policy Institute. [2]Agricultural Conservation Economics, Laurel, MD, USA. [3]Woods Hole Research Center, Falmouth, MA, USA. [4]Center for Agricultural and Rural Development, Iowa State University, Ames, IA, USA.

Ethanol Production

- Raging debate over "green" aspects of both sugar and corn based biofuels:

  Excellent point/counterpoint: http://cen.acs.org/articles/85/i51/Costs-Biofuels.html

The New York Times

Biofuels Threaten Fertilizer

By KEITH BRADSHER and ANDREW MARTIN
Published: April 30, 2008

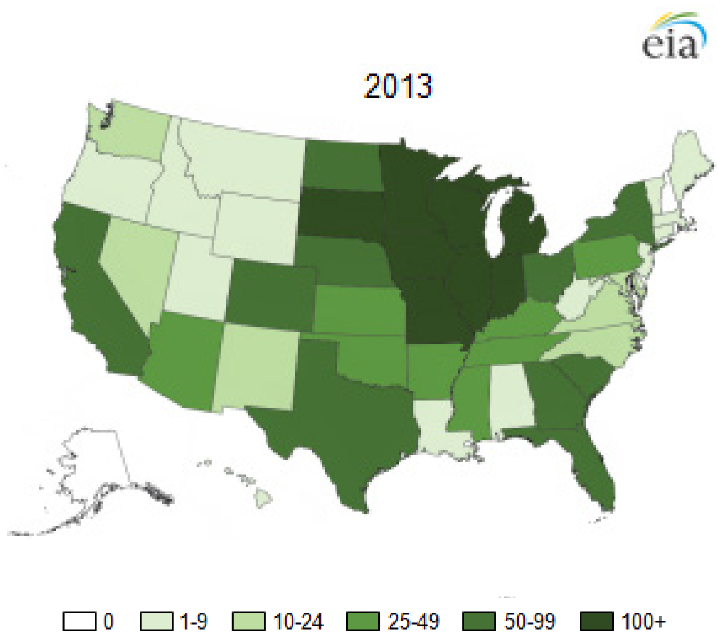
The squeeze on the supply of fertilizer has been building for roughly five years. Rising demand for food and biofuels prompted farmers everywhere to plant more crops. As demand grew, the fertilizer mines and factories of the world proved unable to keep up.

Some dealers in the Midwest ran out of fertilizer last fall, and they continue to restrict sales this spring because of a limited supply.

"If you want 10,000 tons, they'll sell you 5,000 today, maybe 3,000," said W. Scott Tinsman Jr., a fertilizer dealer in Davenport, Iowa. "The rubber band is stretched really far.

Ethanol Production: US

- Despite these debates the "show goes on"
  - US produced 14 × 10^9 gallons of ethanol in 2014
  - 83 million acres (**20% of cultivated land area**) harvested for corn
  - ~40% of US corn produced goes to ethanol production
  - US govt subsidiy of ethanol, $0.45/gallon, expired Jan 2012 leading to rise in fuel prices: http://green.autoblog.com/2012/01/18/u-s-ethanol-subsidy-expiration-may-be-driving-up-gas-prices
  - Present debate focused on Renewable Fuel Standard: http://www.washingtonpost.com/news/energy-environment/wp/2015/04/10/epa-says-it-will-get-back-on-schedule-in-issuing-rules-for-biofuels



Chemistry in Context

McElroy, Ethanol Illusion, *Harvard Magazine,* Nov-Dec 2006.

http://www.eia.gov/todayinenergy/images/2014.03.07/main.png

http://www.forbes.com/sites/jamesconca/2014/04/20/its-final-corn-ethanol-is-of-no-use

One Last Comparison:

In prior lectures, we have looked at market forces such as:

- Cost of Fossil Fuel ↑
- Cost of Electricity from Renewables ↓

as well as complete life cycle effects of various options:

- Carbon release (early) and methane release (late) from areas flooded for hydro
- N_2O associated with fertilizer production for biofuels

There is one more comparison that could be vital for society to consider, for <u>large-scale transition</u> to energy production from some means other than combustion of fossil fuel

Biofuels and Diesel

- Fuels made from recycled restaurant waste have a CH ratio conducive for use in ***diesel*** engines and not ***gasoline*** engines

- Gasoline engine: spark plug ignites fuel/air mixture (Otto cycle)
- Diesel engine: compression ignites fuel in combustion chamber (Diesel cycle)

- Gasoline: C_8H_{18}
- Diesel fuel: $C_{10}H_{20}$ to $C_{15}H_{28}$ (average $C_{12}H_{23}$)

- Main advantage of diesel: better fuel economy due to higher engine efficiency
- Disadvantages:
  - past fuel has contained high amounts of sulfur
  - past engines have released large amounts of NO_x
  - fuel gels in cold weather!

- Diesel cars much more common in Europe than the U.S. but:
  diesel cars making a comeback in the U.S.
  http://www.practicalenvironmentalist.com/automobiles/2011-diesel-cars-usa.htm

Sources:
http://en.wikipedia.org/wiki/Diesel_engine
http://en.wikipedia.org/wiki/Diesel_fuel
$mart Power by William H. Kemp, Hushion House Publishing
http://www.scientificamerican.com/article.cfm?id=why-european-diesel-cars

Biofuels and Diesel

- Fuels made from recycled restaurant waste have a CH ratio conducive for use in ***diesel*** engines and not ***gasoline*** engines

Advantages of biodiesel:

- Low sulfur
- Biodegradable
- Climate friendly (C that is combusted recently pulled from atmosphere!)
- Can be "brewed" at home

FuelMeister II™
Personal Biodiesel Processor!
Azure Biodiesel Company
Sully, Iowa 50251

http://www.azurebiodiesel.com/contact.shtml

Disadvantage of biodiesel:

- Weak solvent that could soften rubber hoses, seals, and gaskets over time
- Supposedly, B20 blends (20% biodiesel) combined with modern use of synthetic materials minimize risk … nonetheless, ***vehicle warranty could be compromised by use of biofuels***

For more info see:
http://www.makebiodiesel.com
http://www.biodiesel.org
http://www.biodiesel-canada.org

The Methanol Economy ®

- Methanol: CH_3OH
- Alcohol
- Methanol combustion:

$$2\ CH_3OH + 3\ O_2 \rightarrow 2\ CO_2 + 4\ H_2O + 41.4\ kJ/g$$

Heat release considerable more than ethanol (29.7 kJ/g) and close to that of C_8H_{18} (47.8 kJ/g)

- Octane of 107
- Very clean burning: little or no CO, NO_x, or particulates
- Can be used in “clean diesels”
- Presently used in Indy 500 race cars !

The Methanol Economy ®

- Methanol production from atmospheric CO_2:
  - $CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$
  - Exothermic by 49.3 kJ/mol ; nonetheless, need a catalyst
  - Need to capture CO_2 out of atmosphere (tall order!)
  - Need supply of H_2 that is “carbon neutral” (i.e., not from CH_4 !)

Today, 95% of the hydrogen produced in the U.S., roughly 9 million tons per year, uses a thermal process with natural gas as the feedstock. This process, called steam methane reformation (SMR), consists of two steps: 1) reformation of the feedstock with high temperature steam supplied by burning natural gas to obtain a synthesis gas, and 2) using a water-gas shift reaction to form hydrogen and carbon dioxide from the carbon monoxide produced in the first step.

STEAM METHANE REFORMATION

Step 1: $CH_4 + H_2O \Rightarrow CO + 3\ H_2$

Step 2: $CO + H_2O \Rightarrow CO_2 + H_2$

http://www.hydrogenassociation.org/general/factSheet_production.pdf

The Methanol Economy ®

- Methanol production from atmospheric CO_2:
  - $CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$
  - Exothermic by 49.3 kJ/mol ; nonetheless, need a catalyst
  - Need to capture CO_2 out of atmosphere (tall order!)
  - Need supply of H_2 that is "carbon neutral" (i.e., not from CH_4 !)
  - If electrolysis of seawater to yield H_2 could be powered by solar energy, and an energy efficient way to capture and concentrate atmospheric CO_2 could be devised (i.e., using KOH or MEA-monoethanolamine $(CH_2CH_2OH)NH_2$), then $CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$ would simulate photosynthesis and could provide a fuel that could be used in cars without major changes to present infrastructure

NOTE: methanol is corrosive to aluminum, zinc, and magnesium, and reactive with some plastics and rubber, so some systems specific to methanol would be needed

Algae as a Biofuel

Pros:

- High oil content
- Absorbs atmospheric CO_2
- Can use waste as fertilizer
- Not a food staple

Cons:

- Need sunny, warm conditions; certain areas preferred
- Growth limited by "self shading" effect; challenge to exploit entire volume of pond
- Water intensive (rules out many warm, sunny environs for large scale production)
- Efficient processing method still being researched
- Fertilizer intensive
- Water intensive

The promise of algae as an economically viable clean source of fuel is leading many groups to research the large scale viability of this potential resource.

http://www3.signonsandiego.com/stories/2009/apr/29/1n29biofuels005337-new-center-focus-algae-biofuels

http://cosmiclog.msnbc.msn.com/_news/2011/04/14/6471719-is-algae-biofuel-too-thirsty

http://stateimpact.npr.org/texas/2012/12/17/the-downside-of-using-algae-as-a-biofuel

Algae as a Biofuel

Wigmosta *et al.*, *Water Resources Res*, 13 April 2011 conclude:

Using current technology, 48% of petroleum needed for US transportation can be produced using:

- 5.5% of U.S. land area (lower 48)
- 3 times the total amount of water used for irrigation

Optimal placement of algae production facility in the humid Gulf Coast, southeastern seaboard, and Great Lakes regions would considerably reduce the water needed

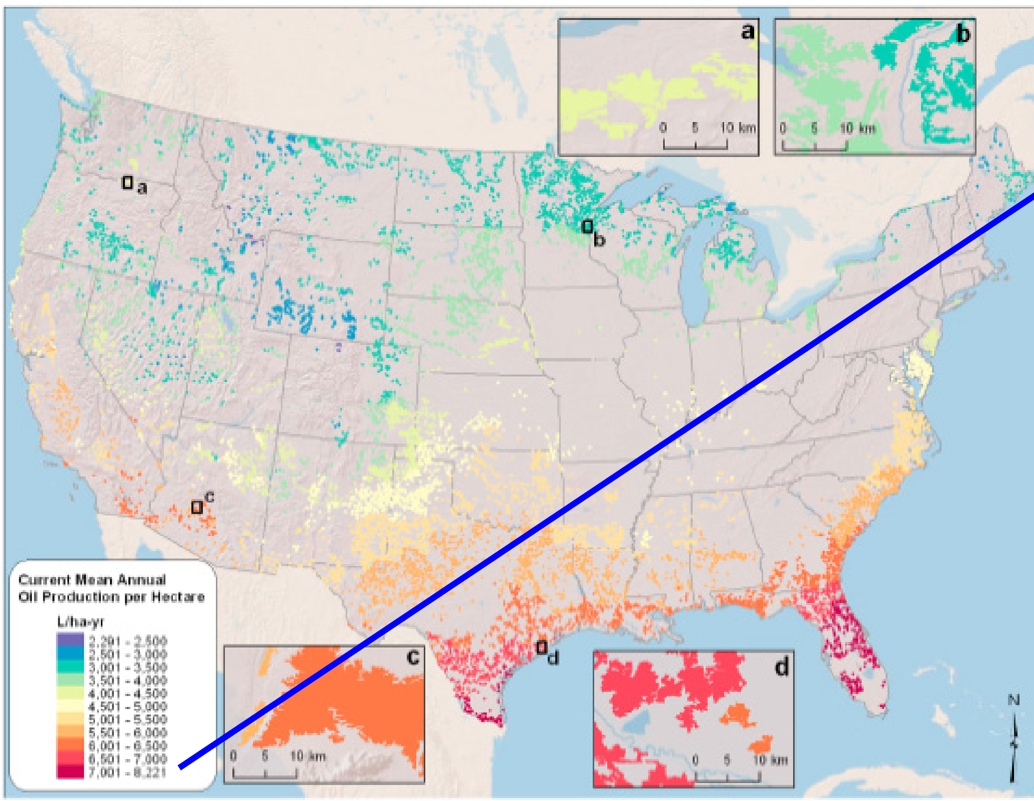


Figure 3. Mean annual biofuel production (L ha^{-1} yr^{-1}) under current technology plotted at the centroid of each pond facility.

High yield: 8000 L/ha/year:

U.S. uses 5.2×10^{11} L/year

Hence, need 6.5×10^{7} ha
or 2.5×10^{5} mi^2

500 x 500 miles
(7% land area, lower 48)
☹

http://www.eia.gov/tools/faqs/faq.cfm?id=23&t=1