Renewable Energy II: Biofuels and Ethanol

AOSC/CHEM 433 & AOSC/CHEM 633

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/spr2022
https://myelms.umd.edu/courses/137772

Today:

- **Pros and cons of various aspects of meeting energy needs of society by means of combustion of biomass, biofuels, and biowaste**

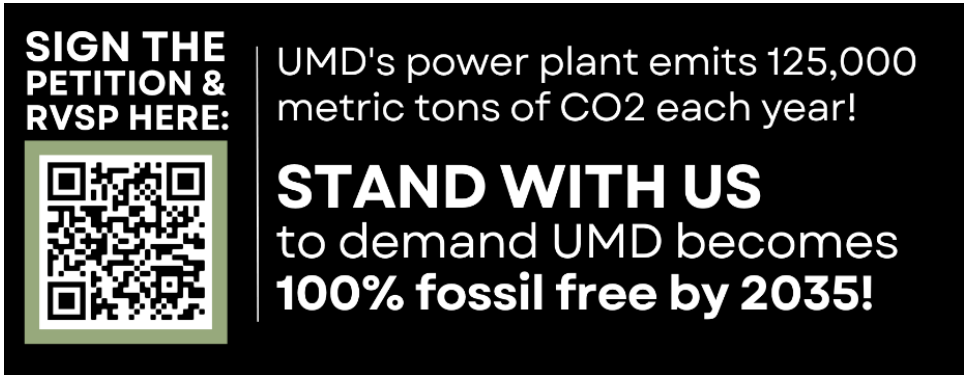
http://www.taxpayer.net/library/article/federal-subsidies-for-corn-ethanol-and-other-corn-based-biofuels

Lecture 20

26 April 2022

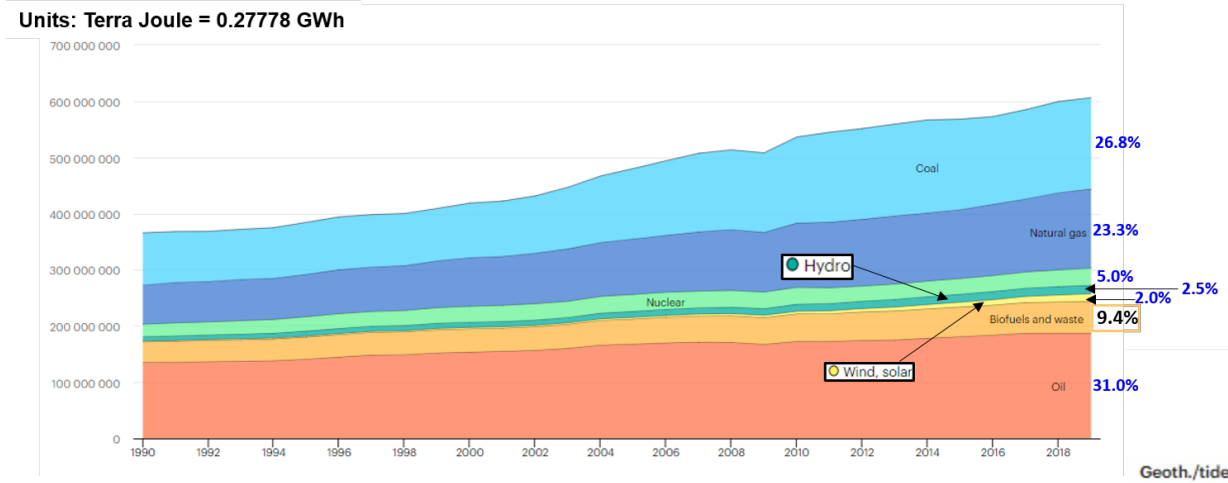
Announcements

- Review of second exam posted at:
  https://umd.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=16ea56e9-deab-42d0-b41c-ae7f012ef22a
- Problem Set 4 for 433 students only, due a week from today, has been posted at:
  https://umd.instructure.com/courses/1317772/quizzes/1515902
  Same link on class website and sent in class announcement
- Campus decarbonization protest Fri, 29 April, 3 pm:

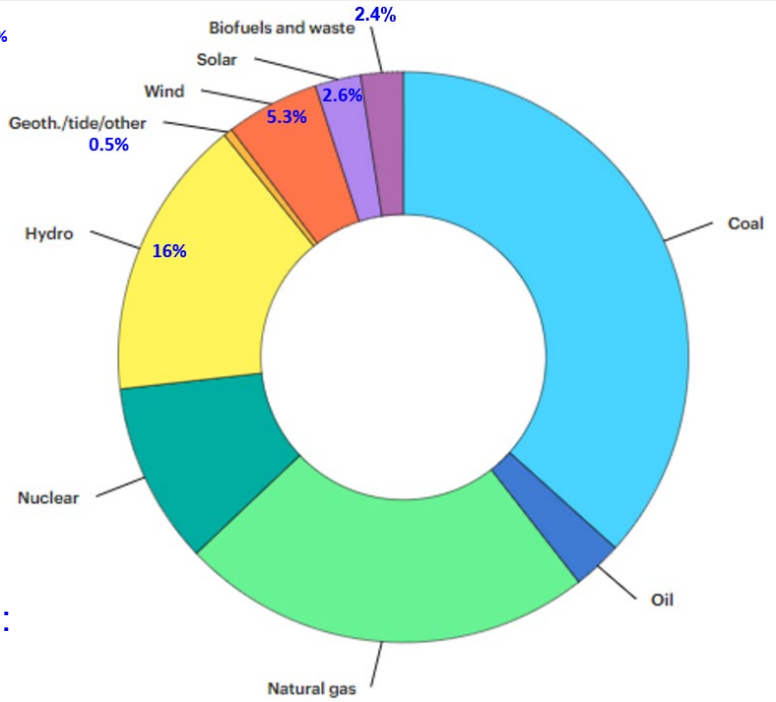


World Energy & Electricity Update: units of Energy

World energy generation mix, 1990 to 2019



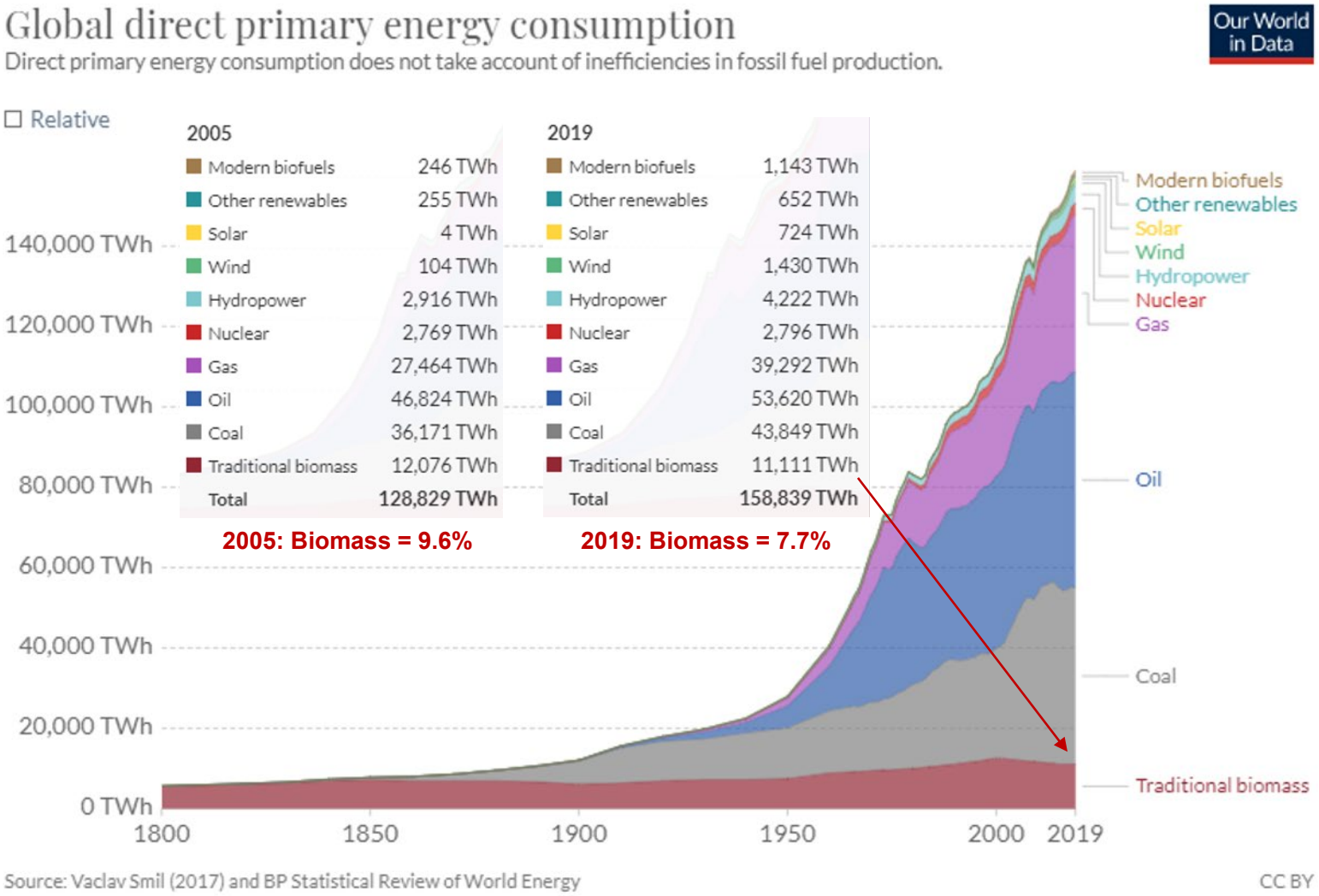
World electricity generation mix, 2019



In 2019, the world still obtained:
~9.4% of its **energy** &
~2.4% of its **electricity**
from the combustion of biofuels and waste

https://www.iea.org/data-and-statistics/charts/world-gross-electricity-production-by-source-2019

World Total Primary Energy Supply



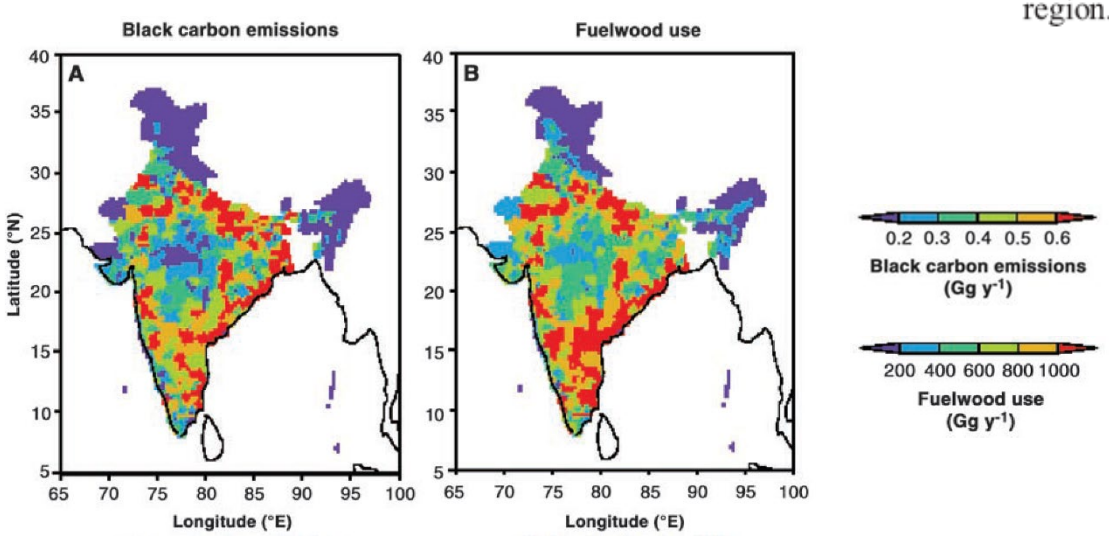
https://ourworldindata.org/energy

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]

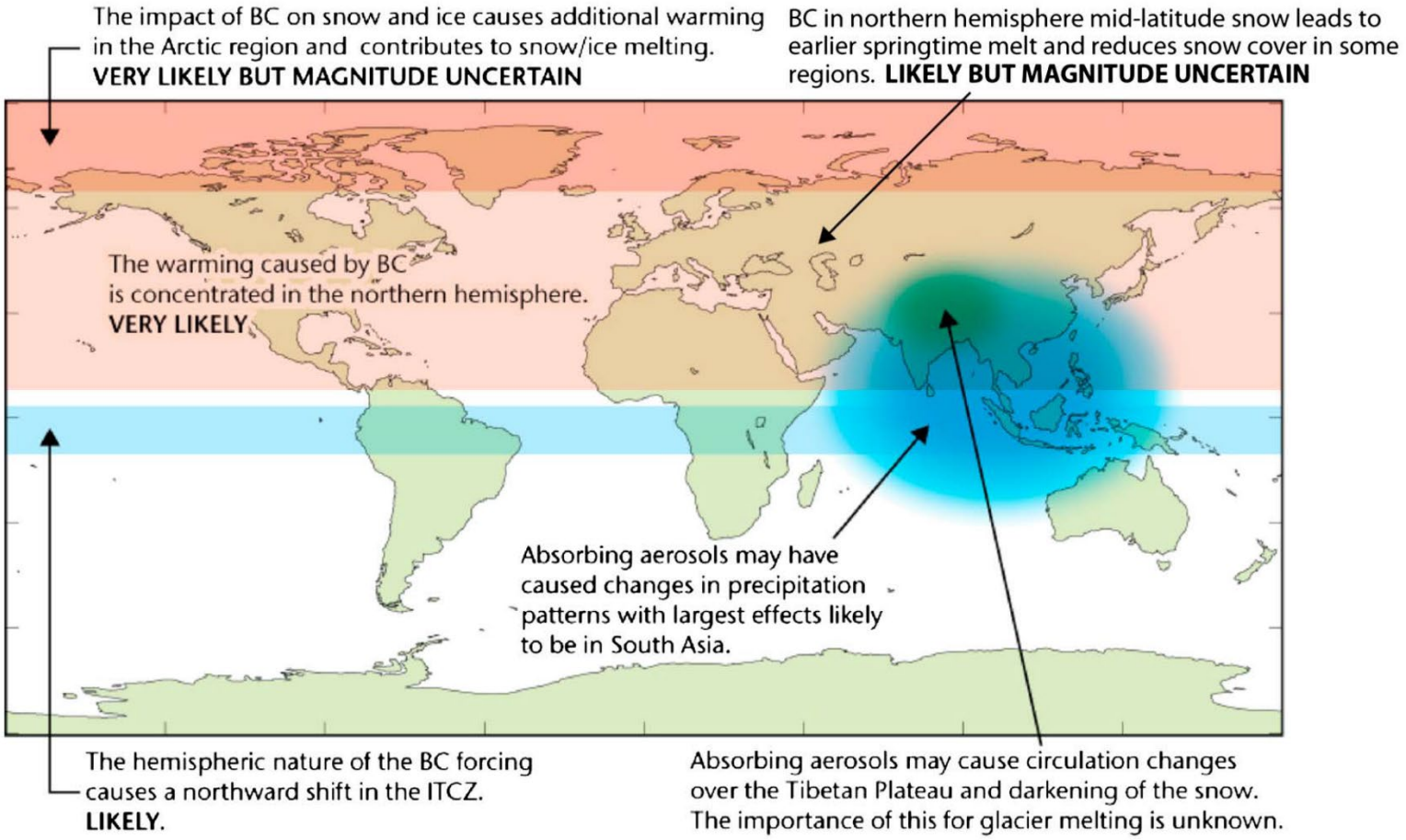
High concentrations of pollution particles, including "soot" or black carbon, exist over the Indian Ocean, but their sources and geographical origins are not well understood. We measured emissions from the combustion of biofuels, used widely in south Asia for cooking, and found that large amounts of 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.

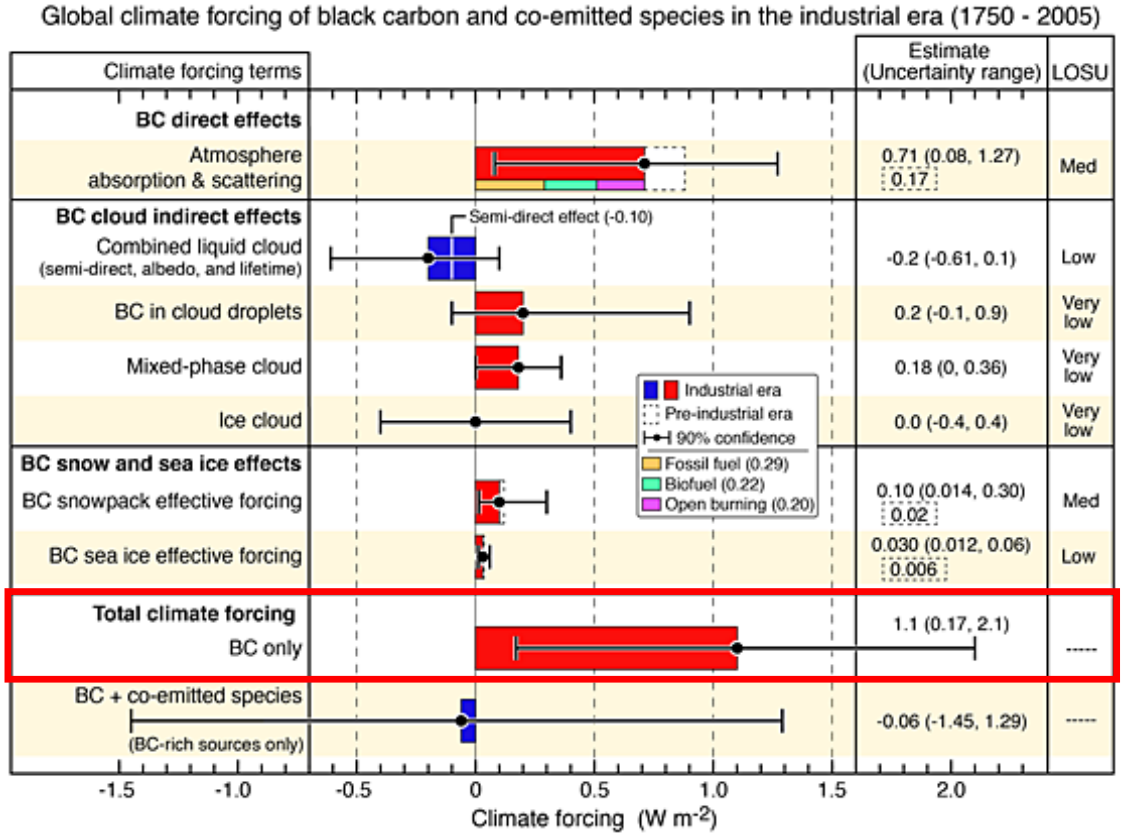
Black Carbon & Climate



Bond *et al.*, JGR, 2013

Black Carbon Aerosols

Bond *et al.*, Bounding the role of black carbon in the climate system: A scientific assessment, *JGR,* 2013



	Total Climate Forcing, Black Carbon Aerosols (W m^{-2})				
Report	IPCC (1995)	IPCC (2001)	IPCC (2007)	**IPCC (2013)**	**IPCC (2021)**
ΔRF, BC	0.1 (0.03 to 0.3)	0.2 (0.1 to 0.4)	0.2 (0.05 to 0.35)	0.4 (0.05 to 0.80)	**About 0.1**

UC San Diego News Center

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thisweek@ucsandiego By Robert Monroe | Nov 03, 2016 | Previous Issues | Subscribe

Creating a New Kind of Climate Warrior

Scripps researchers help rural women in India improve health and slow global warming through clean cookstove use

A woman in rural India using both a mud and clean cookstove at the same time with wall-mounted Nexleaf device monitoring usage. Photos by Tanvi Mishra

For several months out of the year, a band of brown haze almost a mile thick blankets northern India, trapped there by the Himalayas. It produces smog dense enough to be visible *indoors* in Delhi and other urban centers.

And daily, Indian women who are among the world's poorest people add mass to the choking pollution cloud when they feed kindling to homemade stoves. They spend several hours a day preparing meals huddled over the fire, breathing in smoke and increasing their risk of respiratory illness.

Lots of great info at https://ucsdnews.ucsd.edu/feature/creating_a_new_kind_of_climate_warrior

Cooking food over a traditional wood-burning stove is *believed to improve the taste*. It is also widely used to heat homes in many countries. However, it turns out that the risks associated with this cooking and heating method outweigh its benefits.

A new study from Canada found that regular exposure to the black carbon pollutants in wood smoke can increase the risk of cardiovascular diseases in women. Researchers from McGill University recorded levels of different types of air pollutants present in the rural Yunnan province of China. During the study, about 280 women wore air samplers to measure the fine particular matter present in the environment.

"We found that exposure to black carbon pollutants had the largest impact on women's blood pressure, which directly impacts cardiovascular risk…" researcher Jill Baumgartner from McGill's Institute for the Health and Social Policy said. The findings reported in PNAS support previous warnings released by experts. The small particles can remain many months in the lungs and can cause structural damage and chemical changes to the organ and also increase risk of heart attacks and strokes … The pollutants produced while burning wood in fireplaces, woodstoves, include **sulphur oxides**, **carbon monoxide**, **nitrogen oxides**, **polycyclic aromatic hydrocarbons**, **benzene**, **formaldehyde** and **dioxins**.

26 Aug 2014 http://www.ibtimes.co.in/traditional-wood-burning-stoves-bad-health-study-607692

Electricity from Biomass

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

Data source: EDF and IEA key statistics.

Country	Energy 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

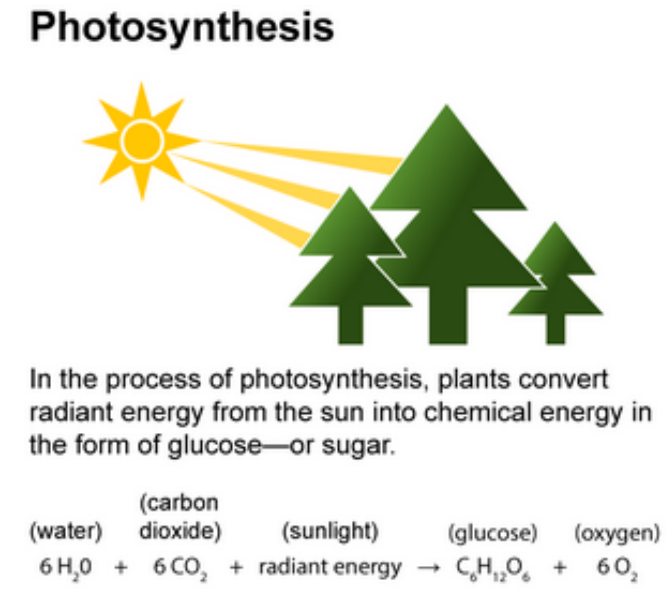
Olah *et al*., *Beyond Oil and Gas: The Methanol Economy*, 2009.

World electricity consumption (2006) = 19,000 TWh

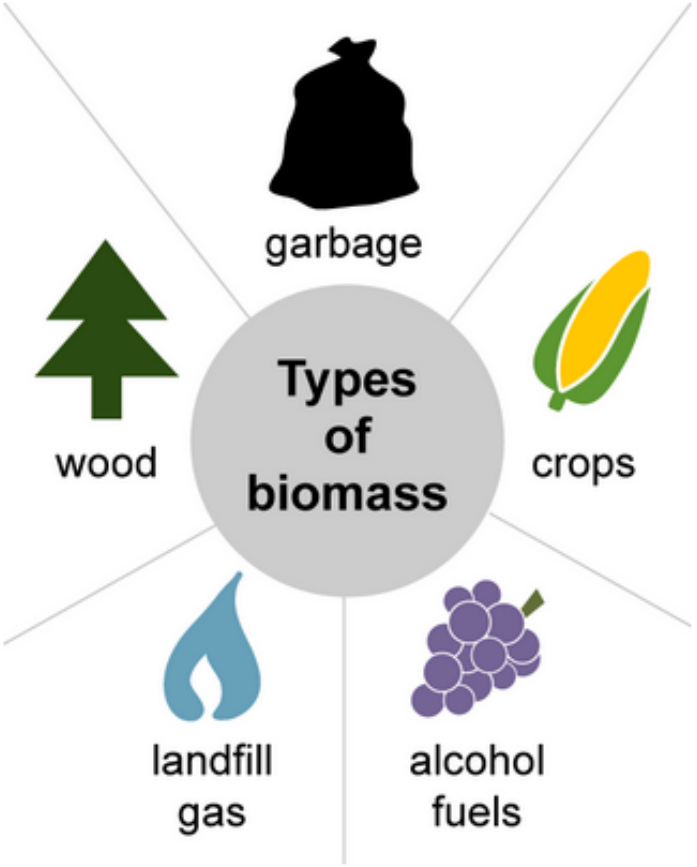
Electricity from Biomass = 200.1 TWh

2006: 200 / 19,000 = 0.011 ⇨ 1.1% of total world consumption
2019: 650 / 27,000 = 0.024 ⇨ 2.4% of total world consumption

Electricity from Biomass: Overview



Source: Adapted from The National Energy Education Project (public domain)



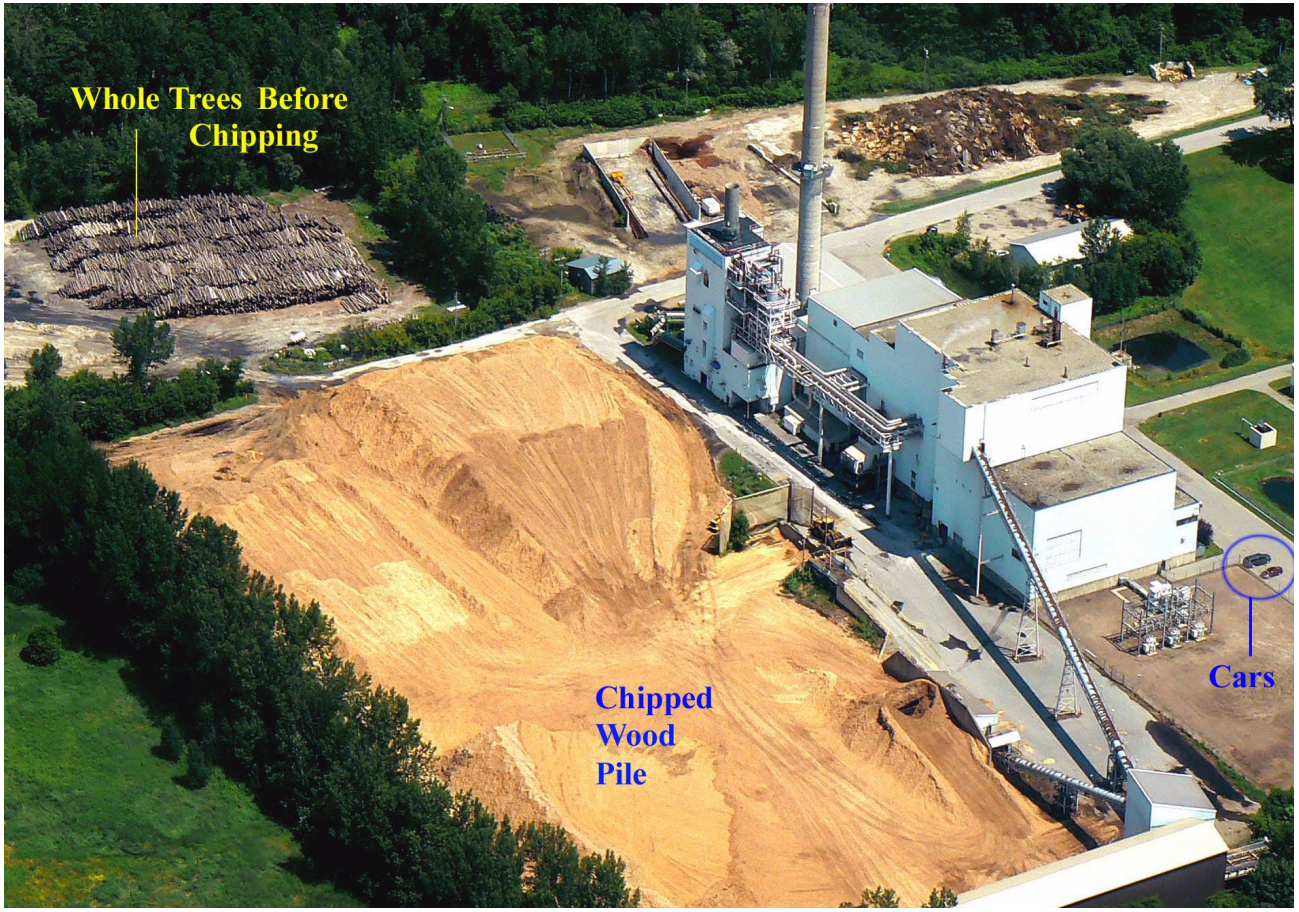
Source: Adapted from The National Energy Education Project (public domain)

https://www.eia.gov/energyexplained/biomass/

Electricity from Biomass: Overview

Typical coal plant: 670 MW
Typical nuclear plant: 1000 MW

McNeil Biomass Plant - Burlington, VT



https://sites.google.com/site/ecosytemadvocates/biomass-whole-trees

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

- 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 (900 × size of Univ Park Elem School 66 kW 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.

ENVIRONMENT BY FERN SHEN 11:42 AM APR 22, 2020

Baltimore will appeal Clean Air Act ruling, city solicitor says

The decision comes after lobbying by community and environmental activists, who held an Earth Day protest at the BRESCO incinerator today

Above: The tall smokestack of the Wheelabrator plant emits three times more pollutants than any other facility in Baltimore. (Brew file photo)

https://www.baltimorebrew.com/2020/04/22/baltimore-will-appeal-clean-air-act-ruling-solicitor-says

ENVIRONMENT BY FERN SHEN 11:42 AM APR 22, 2020

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Under pressure from community and environmental activists, the Young administration today said the city will appeal last month's federal court decision striking down the Baltimore Clean Air Act.

"I have recommended to Mayor Young that the city appeal Judge Russell's decision in the Wheelabrator case regarding the city's Clean Air Act," acting City Solicitor Dana P. Moore told *The Brew* this morning.

"He has concurred and authorized me to proceed," she said.

Moore said she entered her appearance in the case this morning and directed outside counsel to file a notice of appeal.

"Die-In" Protest

The decision came just as activists were **mounting** an Earth Day "die-in" protest on Russell Street near the Wheelabrator BRESCO incinerator, Baltimore's biggest source of industrial air pollution.

News of the mayor's decision broke after they concluded.

Protest organizers applauded the city's announcement, saying much is at stake in the battle to get the city to defend the Clean Air Act.

https://www.baltimorebrew.com/2020/04/22/baltimore-will-appeal-clean-air-act-ruling-solicitor-says

The Clean Air Act was enacted by the City Council to improve health outcomes for residents. It imposes stricter limits on nitrogen oxides, sulfur dioxide, mercury and other air emissions by large incinerators.

Wheelabrator and Curtis Bay Energy, a medical waste incinerator, challenged the new law and won a favorable ruling from U.S. District Judge George L. Russell III.

Russell said the law undermined the authority of state and federal governments to regulate air pollution. Wheelabrator has said it would be impossible to operate BRESCO profitably under the law's emissions strictures.

Reacting to today's news, United Workers' Greg Sawtell said he was "proud of the work everybody from the grassroots groups to our City Council did to get us here."

But he was already looking forward to the group's next goal, to persuade the city to end its relationship with Wheelabrator when the contract to burn Baltimore's trash at its BRESCO facility expires on December 2021.

To Dr. Gwen DuBois, of the Chesapeake Physicians for Social Responsibility, shutting down the incinerator is an equity issue.

"We wonder why people of color and low income people suffer more in Baltimore from from pandemics and environmental injustice, and a big part of this is we need to close BRESCO, so that people who are downwind don't inhale this, so that children don't get asthma," DuBois said, speaking at a news conference before the die-in.

"It's not fair, not right, and we don't need incineration," she said. "There are alternatives."

– Louis Krauss contributed to this story. •

https://www.baltimorebrew.com/2020/04/22/baltimore-will-appeal-clean-air-act-ruling-solicitor-says

BRIEF

Baltimore grants Wheelabrator 10-year contract extension, with emissions requirements, to settle suit

AUTHOR

E.A. Crunden
@eacrunden

UPDATED

Nov. 5 2020, 8:23 a.m. EST

PUBLISHED

Nov. 4, 2020

- Baltimore has granted Wheelabrator an extension to continue operating an incinerator owned by the Northeast Maryland Waste Disposal Authority until Dec. 31, 2031. The company would invest $39.9 million in emissions control upgrades, in a nod to community concerns around air pollution. Wheelabrator's contract is set to expire at the end of 2021.
- The city's Board of Estimates approved the extension on a 3-2 vote this morning. Multiple attendees slammed the day-after-election timing, with several community members calling it "appalling" and "inappropriate." A legal action challenging the approval has been filed by the Energy Justice Network (EJN), Trilogy Financial Group, and City Councilmembers Mary Pat Clarke and Ed Reisinger.
- At the heart of the back-and-forth is the city's 2019 Clean Air Act, which spurred Wheelabrator to sue. Court documents show that litigation is ongoing, although the new agreement would settle the case now. Acting City Solicitor Dana Moore said Baltimore was not in a strong position to win that suit, which played a role in the city's decision.

https://www.wastedive.com/news/baltimore-wheelabrator-lives-on-controversy-zero-waste/588279/

WBAL news: https://www.wbaltv.com/article/baltimore-wheelabrator-upgrade-to-lower-emissions/39398045#

Ethanol

Question 1 — 2 pts

Ethanol is frequently added to gasoline. According to *Chemistry in Context*, does this lead to better or worse gas mileage compared to use of pure octane, and, briefly, why is this the case?

- ○ The addition of ethanol (C_2H_5OH) to pure gasoline (C_8H_{18}) results in a higher octane rating, as well as ***increased*** fuel mileage because the blended fuel has ***higher*** energy content. As shown in Figure 4.16, hydrocarbons that are oxygenated tend to release ***more*** energy than hydrocarbons that lack oxygen.
- ○ The addition of ethanol (C_2H_5OH) to pure gasoline (C_8H_{18}) results in a higher octane rating, as well as ***reduced*** fuel mileage because the blended fuel has ***lower*** energy content. As shown in Figure 4.16, hydrocarbons that are oxygenated tend to release ***more*** energy than hydrocarbons that lack oxygen.
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Ethanol

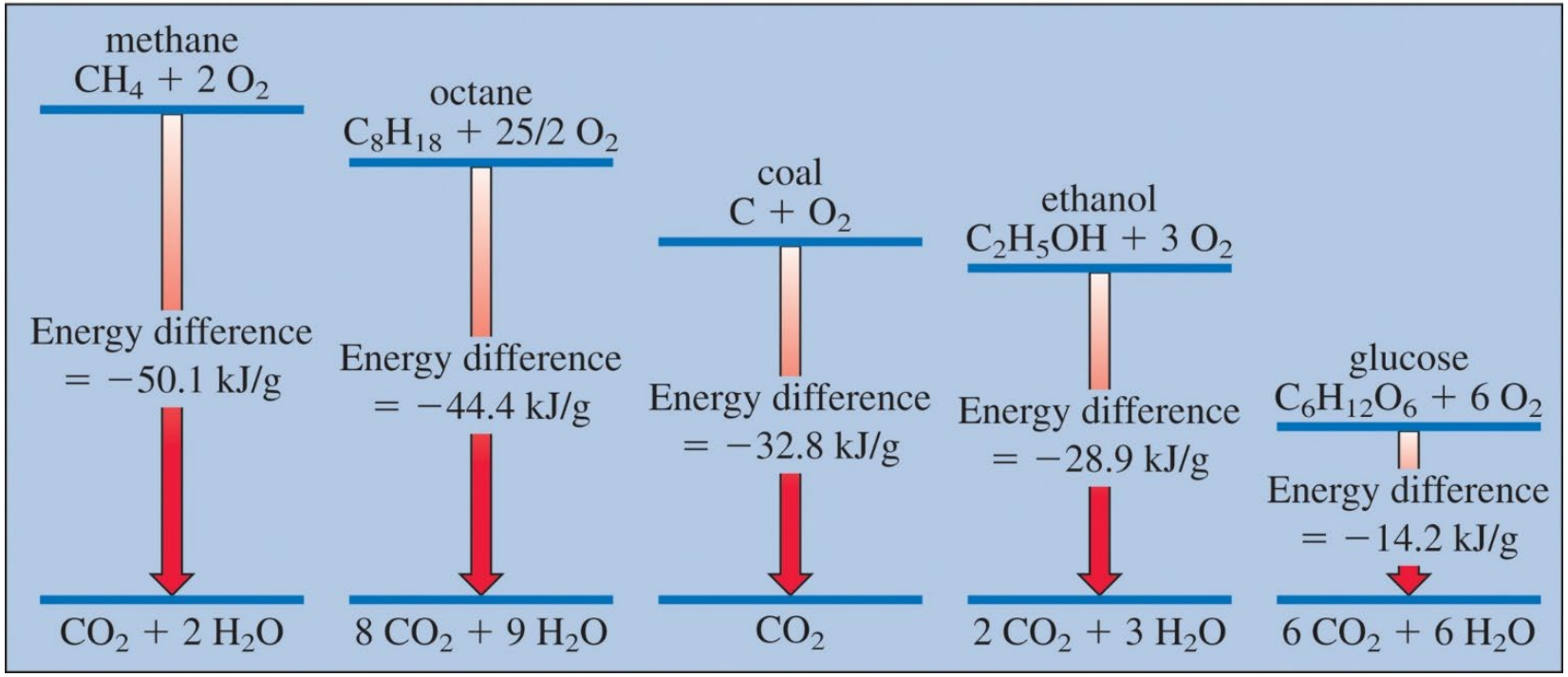
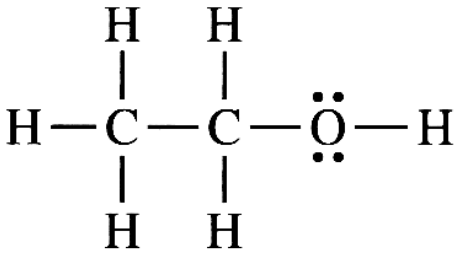


Fig 4.16. Energy differences (in kJ/g) for the combustion of methane (CH_4), n-octane (C_8H_{18}), coal (assumed to be pure carbon), ethanol (C_2H_5OH), and wood (assumed to be glucose).

Chemistry in Context

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

What is octane rating?

https://www.fueleconomy.gov/feg/octane.shtml

Ethanol Production

Question 2 2 pts

According to *Olah et al.*:

a) what crop is used by Brazil to derive almost all of its biogenic automotive fuel?

b) how is a waste product from this crop used to derive an additional benefit?

- ○ a) sugar cane
  b) sugar cane husk is ground and composted into fertile soil
- ○ a) corn
  b) corn husk is burned to generate heat that is used to add energy to the grid
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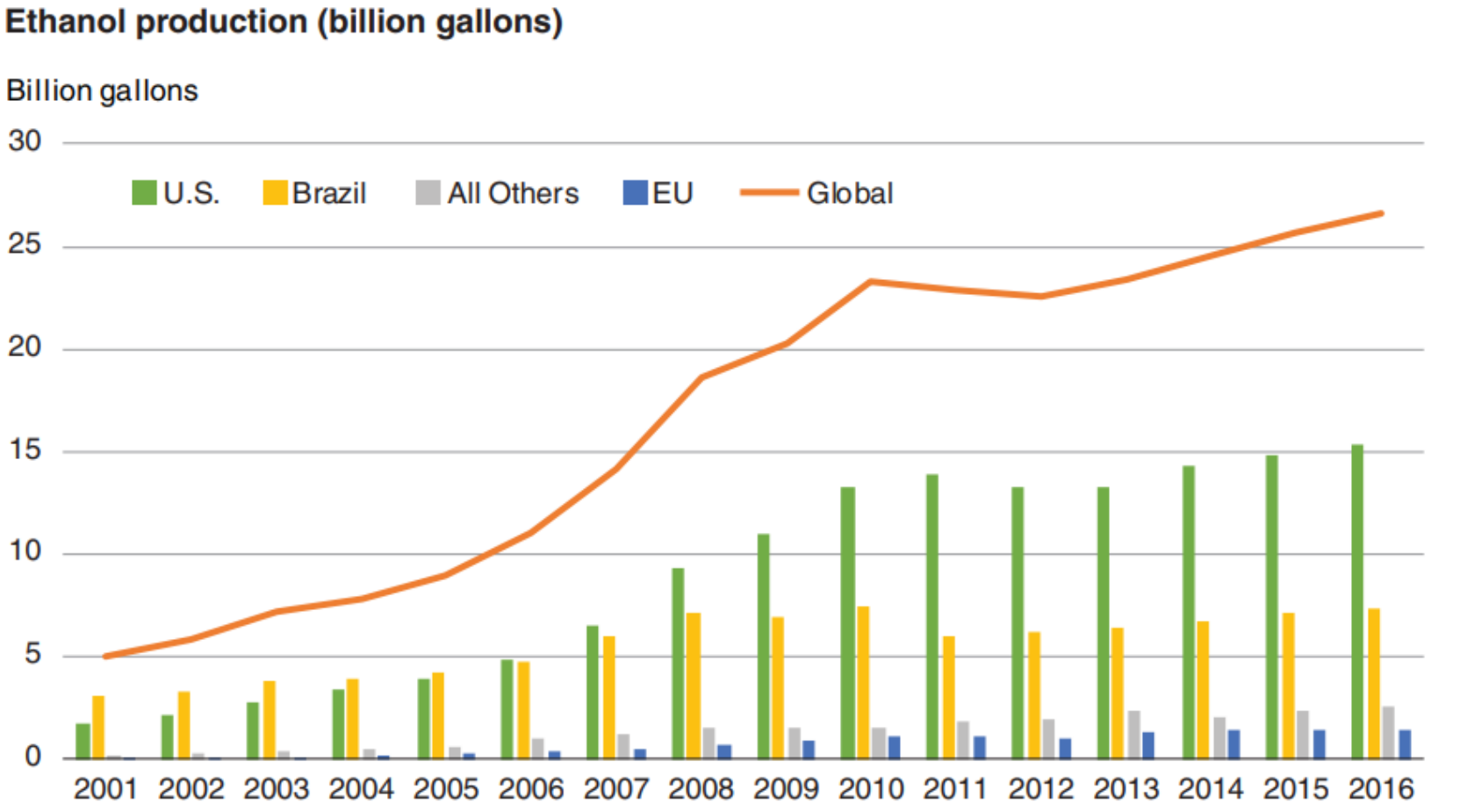
Ethanol Production

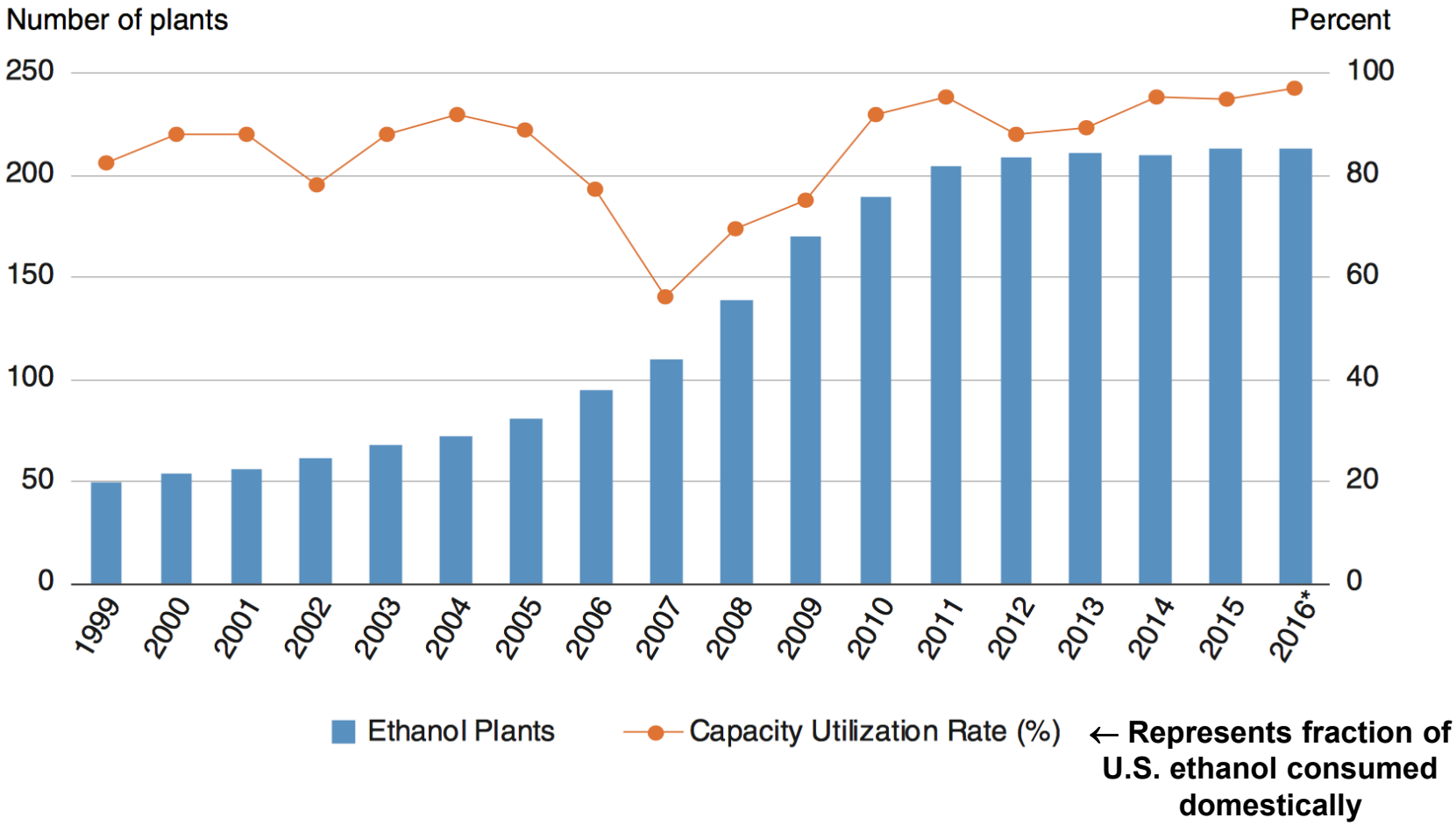


Source: U.S. Department of Energy, Energy Information Administration (EIA, 2016a), 2000-12 data; Renewable Fuels Association (RFA, 2017), 2013-16 data.

https://farmpolicynews.illinois.edu/2017/10/usda-ers-u-s-exports-ethanol/

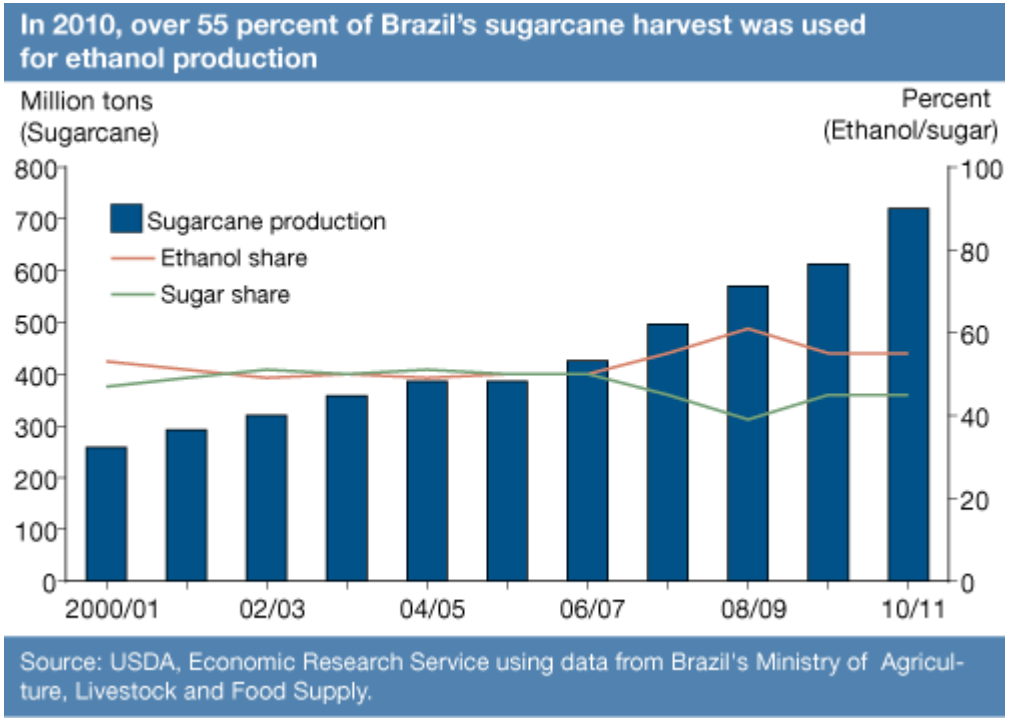
U.S. Ethanol Plants and Domestic Utilization

Figure 2
U.S. ethanol plants and utilization rate, 1999-2016*



https://farmpolicynews.illinois.edu/2017/10/usda-ers-u-s-exports-ethanol/

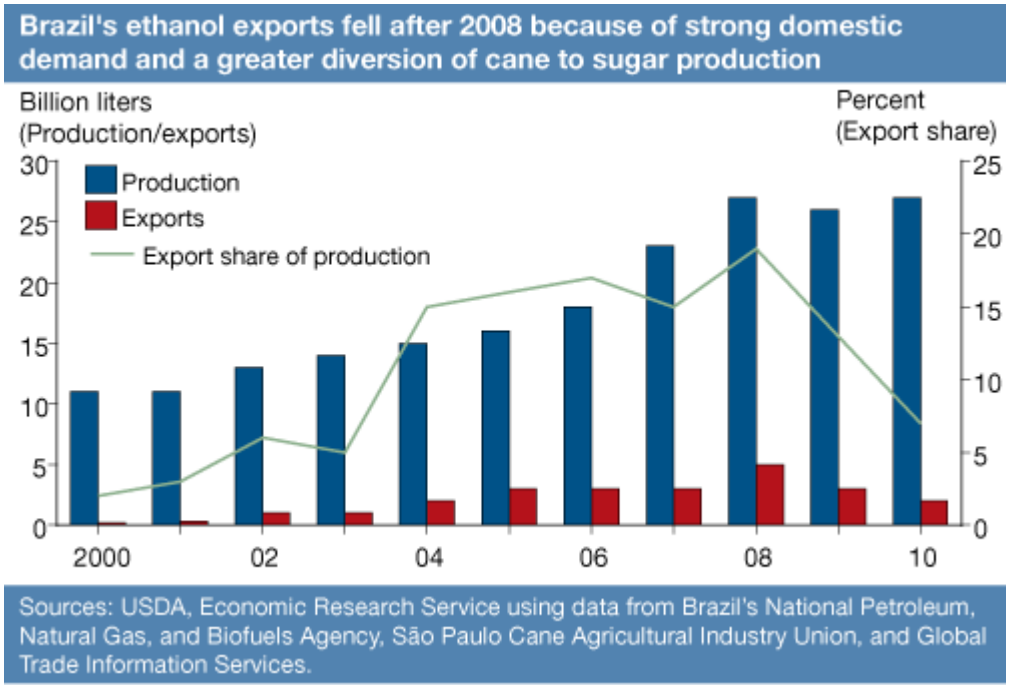
Ethanol Production: Good News



https://www.ers.usda.gov/amber-waves/2011/december/can-brazil-meet-the-world-s-growing-need-for-ethanol/

- 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



https://www.ers.usda.gov/amber-waves/2011/december/can-brazil-meet-the-world-s-growing-need-for-ethanol/

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

Ethanol Production Nuance

Question 3 3 pts

According to *Olah et al.*:

a) what is meant by the term "carbon debt"?

b) how often does it take to repay the "carbon debt" for current biofuels such as ethanol from corn and biodiesel from palm and soybean oil?

- ◯ a) carbon debt refers to the inequity in the release of GHGs between the developed and developing world
  b) it can take 35 to 450 years to repay this carbon debt
- ◯ a) carbon debt refers to the inequity in the release of GHGs between the developed and developing world
  b) it can take 10 to 20 years to repay this carbon debt
- ◯ a) carbon debt refers to the rise in CO_2 resulting from the conversion of land (i.e., deforestation) need to prepare fields for the growth of biofuels.
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  b) it can take 35 to 450 years to repay this carbon debt

Ethanol Production Nuance

Question 4 3 pts

Based on the *McElroy* article:

a) what crop is used by the United States to derive almost all of its biogenic automotive fuel?

b) why is production of biofuel from this crop not a clear environmental win?

- ○ a) corn
  b) the energy balance for the production of ethanol from corn is only marginally positive, and the production of ethanol from corn places pressure on the food supply:
- ○ a) corn
  b) the production of corn is incredibly water intensive, and the demand for water to produce corn is causing a major shortage of ground water
- ○ a) sugar cane
  b) the energy balance for the production of ethanol from sugar cane is only marginally positive, and the production of ethanol from sugar cane places pressure on the food supply
- ○ a) sugar cane
  b) the production of sugar cane is incredibly water intensive, and the demand for water to produce corn is causing a major shortage of ground water

Ethanol Production: Carbon Debt

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.

Nice summary of the debate over the climate benefit of sugar and corn based biofuels at:

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

Ethanol Production: Carbon Debt

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.

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

Ethanol Production: Fertilizer and Food Production

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.

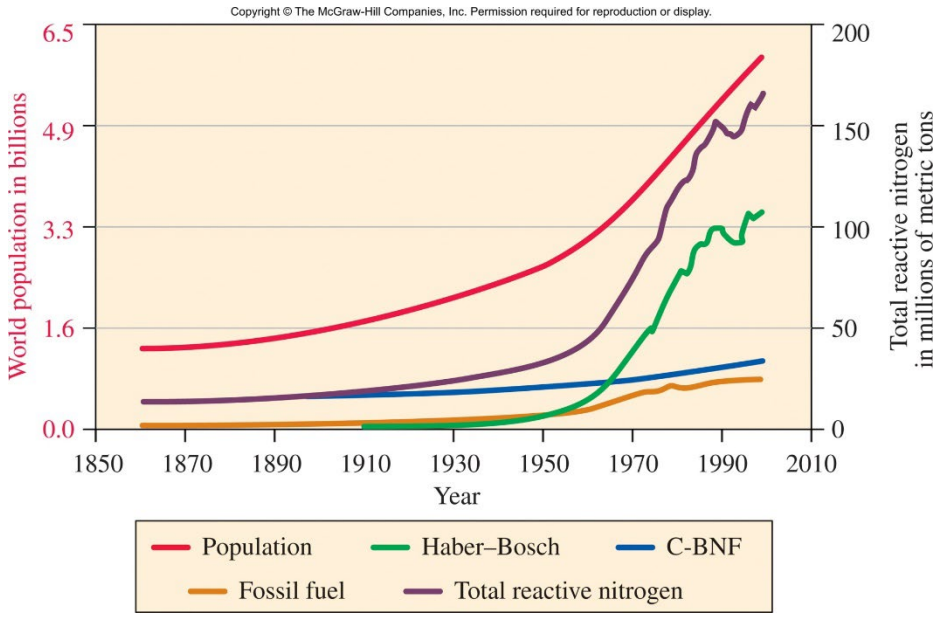


Fig 6.19, *Chemistry in Context*

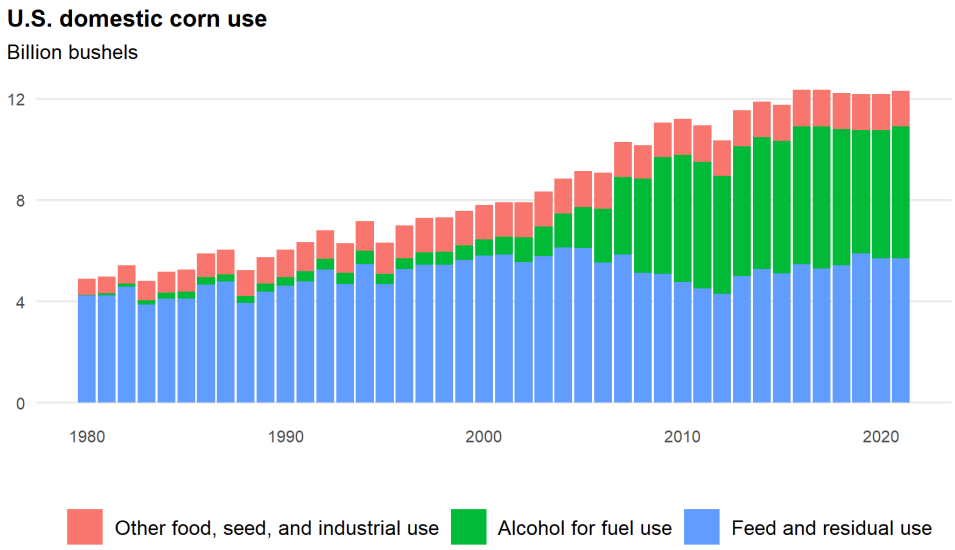
- Ammonium leached as nitrite or nitrate, contaminating water supply
- Ammonia converted to NO, increasing acidity of atmosphere and soils
- N_2O produced by NO and fertilizer production

Nice summary of the debate over the climate benefit of sugar and corn based biofuels at:

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

U.S. Ethanol Production: The Show Must Go On

- Despite these debates the "show goes on"
  - US produced 15.3×10^9 gallons of ethanol in 2016
  - 90 million acres (**20% of cultivated land area**) harvested for corn
  - ~50% of US corn produced goes to ethanol production
  - "The maze of historic subsidies for corn ethanol has allowed the federal government to pick winners and losers, distort energy and agriculture markets, and contributed to expansion and overproduction of corn and ethanol"
    https://www.taxpayer.net/energy-natural-resources/federal-subsidies-corn-ethanol-corn-based-biofuels

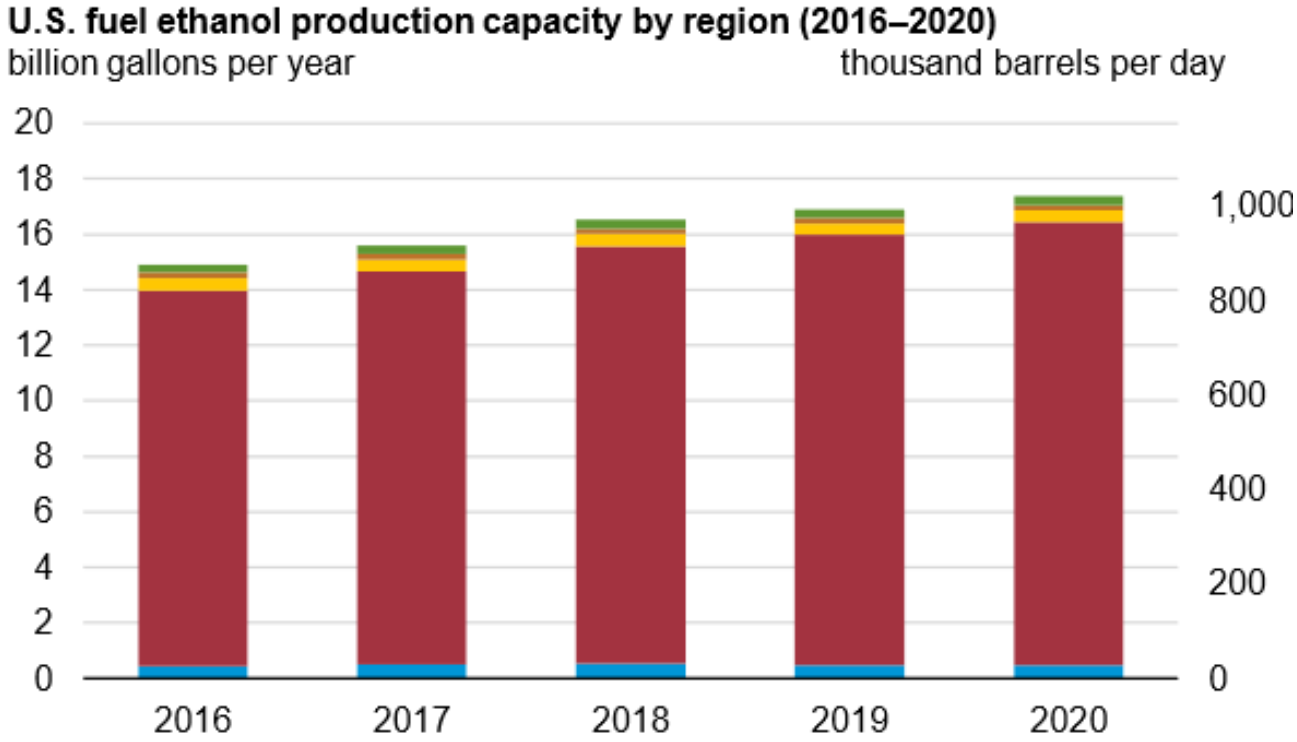


Chemistry in Context

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

https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=101522

U.S. Ethanol Update



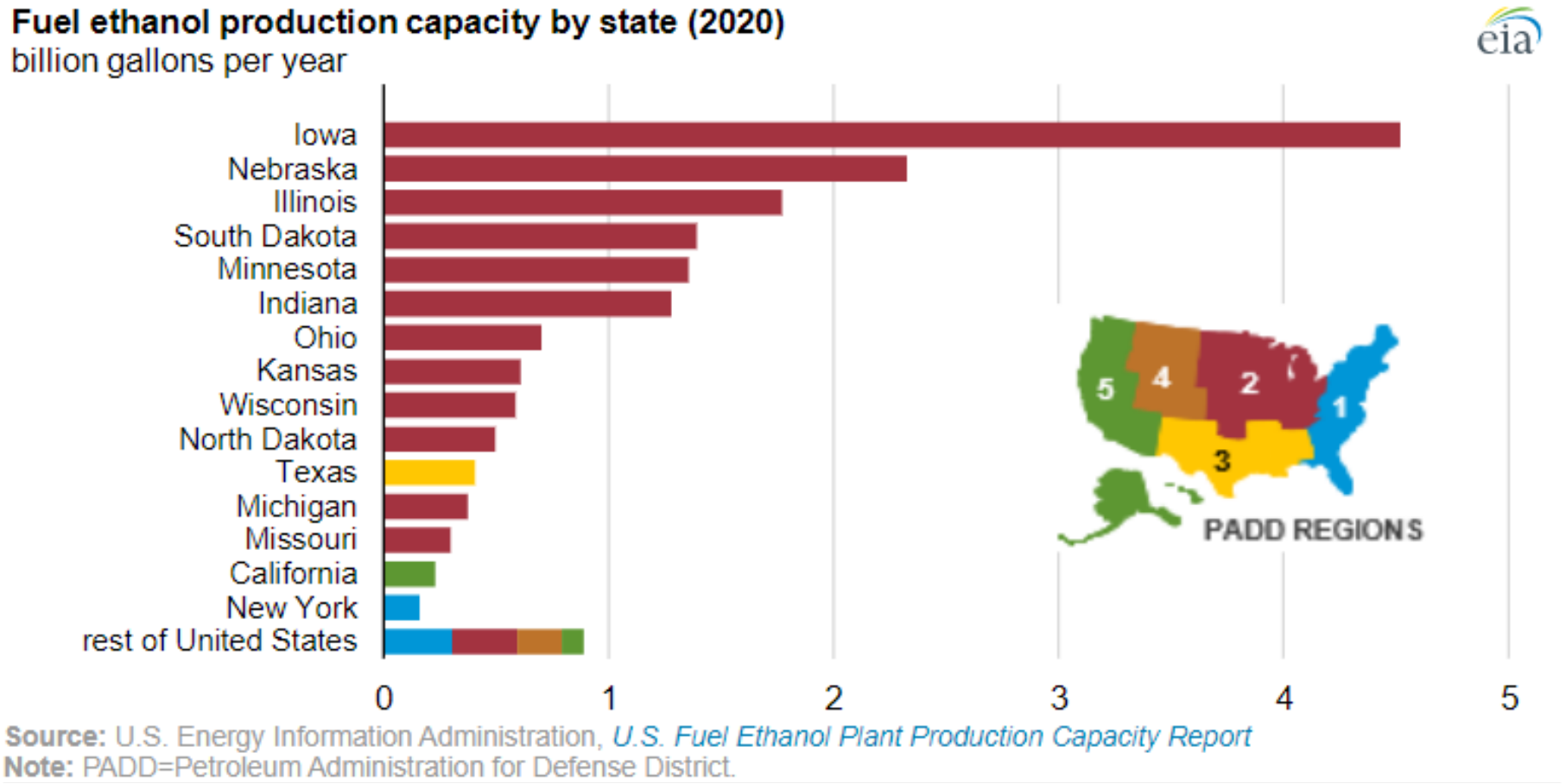
Source: U.S. Energy Information Administration, *U.S. Fuel Ethanol Plant Production Capacity Repo*

Note: PADD=Petroleum Administration for Defense District.

eia

https://www.eia.gov/todayinenergy/detail.php?id=45316

U.S. Ethanol Update



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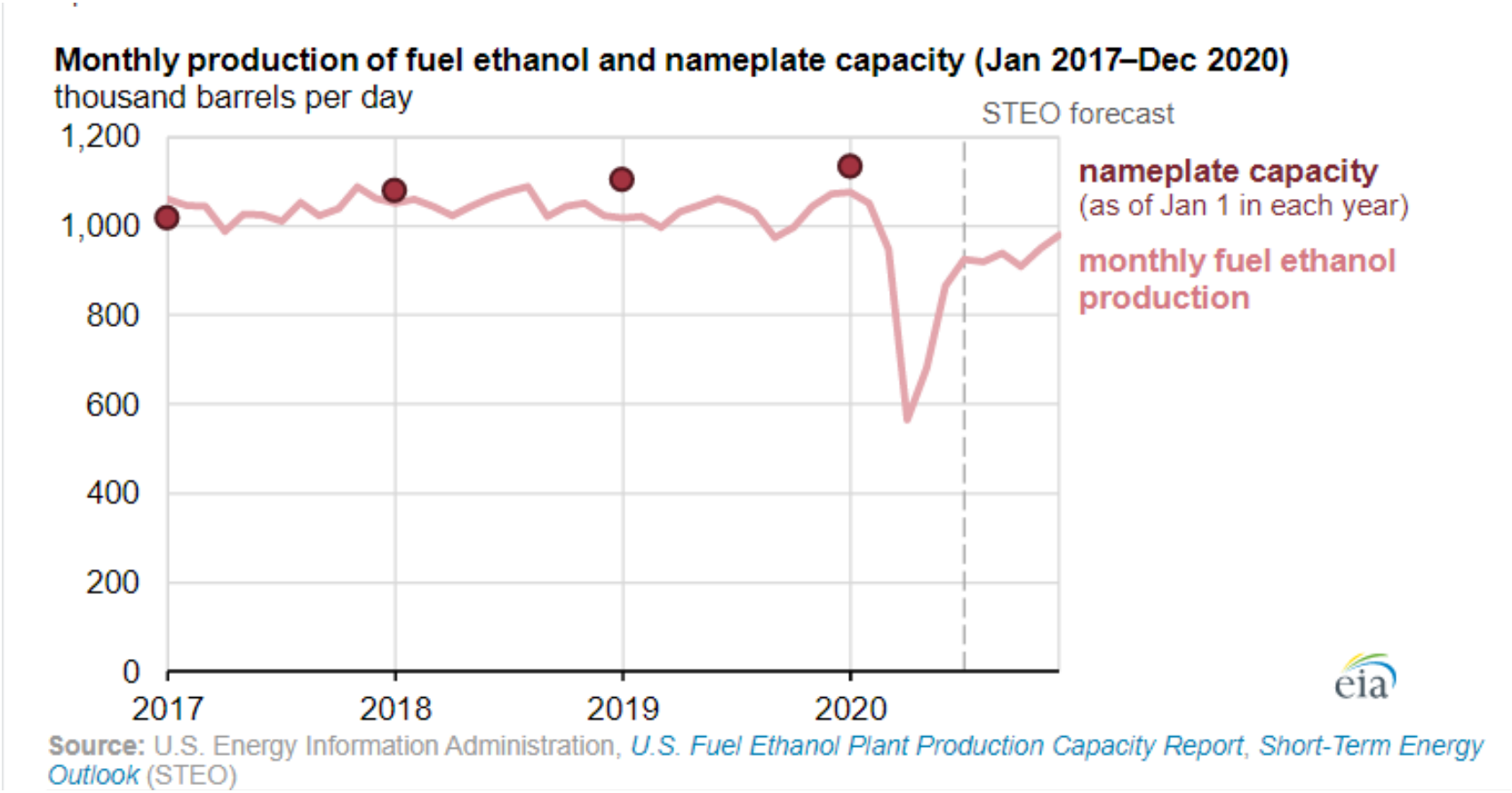
U.S. Ethanol Update



https://www.eia.gov/todayinenergy/detail.php?id=45316

U.S. Ethanol: High Stakes Politics

Biden will allow summertime sales of higher-ethanol gas.


By Lisa Friedman and Michael D. Shear

April 12, 2022

WASHINGTON — President Biden announced on Tuesday a plan to suspend a ban on summertime sales of higher-ethanol gasoline blends, a move that White House officials said was aimed at reducing gas prices but that energy experts predicted would have only a marginal impact at the pump.

The Environmental Protection Agency will issue a waiver that would allow the blend known as E15 — which is made of 15 percent ethanol — to be used between June 1 and Sept. 15. The White House estimated that approximately 2,300 stations in the country offer the blend and cast the decision as a move toward "energy independence."

"E15 is about 10 cents a gallon cheaper," Mr. Biden said, speaking after taking a tour of a production facility that produces 150 million gallons of bioethanol annually. "And some gas stations offer an even bigger discount than that."

"When you have a choice, you have competition," Mr. Biden added. "When you have competition, you have better prices."

https://www.nytimes.com/2022/04/12/business/economy/biden-ethanol-gas.html

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 large-scale transition to energy production from some means other than combustion of fossil fuel

Land Requirements

Table 8.2 Comparison of land requirements for typical power generation options.

Technology	Land use m^2/MW
110 MW geothermal flash plant (excluding wells)	1,260
20 MW geothermal binary plant (excluding wells)	1,415
49 MW geothermal FC-RC plant [1] (excluding wells)	2,290
56 MW geothermal flash plant (including wells, [2] pipes, etc.)	7,460
2,258 MW coal plant (including strip mining)	40,000
670 MW nuclear plant (plant site only)	10,000
47 MW (avg) solar thermal plant (Mojave Desert, CA)	28,000
10 MW (avg) solar PV plant[3] (Southwestern US)	66,000

(1) Typical Flash-Crystallizer/Reactor-Clarifier plant at Salton Sea, Calif.
(2) Wells are directionally drilled from a few well pads.
(3) New land would not be needed if, for example, rooftop panels were deployed in an urban setting.

http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf

Wind turbines: 125,000 to 200,000 m^2 / MW http://www.nrel.gov/docs/fy09osti/45834.pdf

Hydroelectric: enormous impact upstream of reservoir

- Annual ethanol production in Brazil < 1 day world petroleum consumption
- Sugar Cane: 650 gal/acre http://www.earth-policy.org/Books/PB2/PB2ch10_ss7.htm

  650 gal/acre × 3785.1 cm^3/gal × 0.789 g/cm^3 × 29.7 kJ/g = 5.8×10^7 kJ/acre

  5.8×10^7 kJ/acre/year = 1.83 kW/acre = 2,211,390 m^2/MW Yikes!
- Corn 350 gal/acre ⇒ 4,106,870 m^2/MW Yikes; Yikes!