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Converting CO_2 to jet fuel

Thought experiments on synjet fuel

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U.S. DEPARTMENT OF ENERGY
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Three things from this talk

- U.S. electric power = 15 EJ
  U.S. transportation = 27 EJ
- Efficiency gains should be priority 1 then alternative fuels
- Syn fuels (electrofuels) will require grid scale power

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U.S. uses 100 EJ of primary energy

Primary energy

- Energy as found in nature

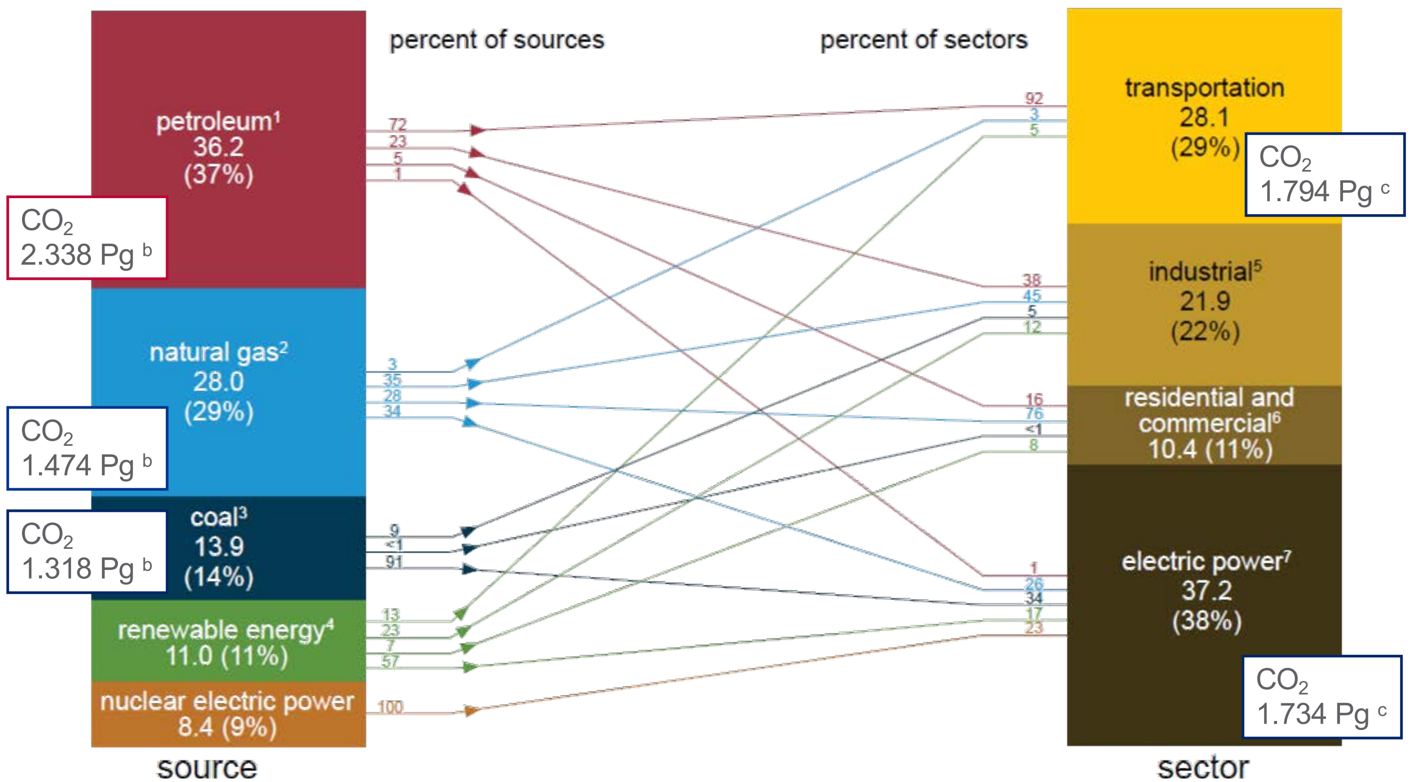
Sectors

- Transportation
- Industrial
- Residential
- Electrical power

a https://www.eia.gov/totalenergy/data/monthly/pdf/flow/css_2017_energy.pdf
b https://www.eia.gov/environment/emissions/carbon/index.php
c EPA carbon inventories

U.S. primary energy consumption by source and sector, 2017 [a]

Total=97.7 quadrillion British thermal units (Btu)



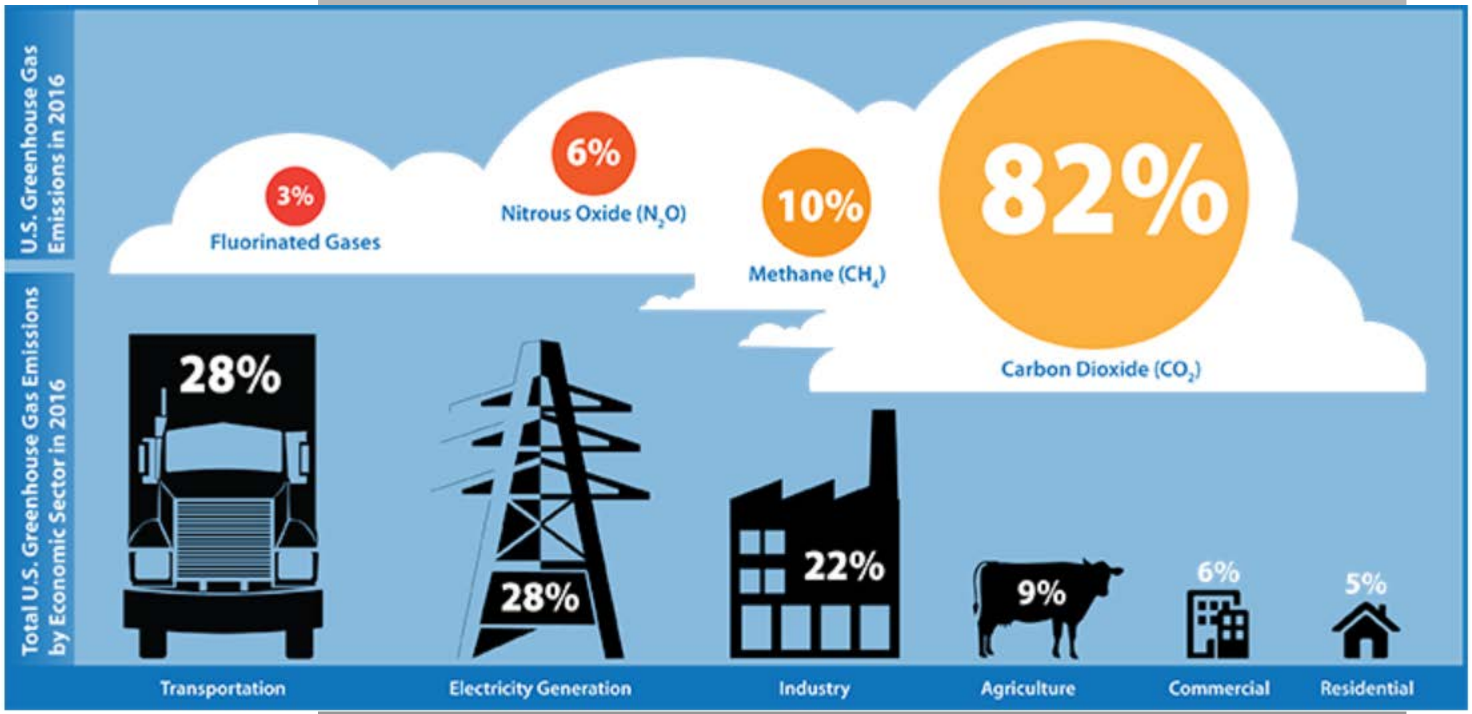
¹Does not include biofuels that have been blended with petroleum—biofuels are included in "Renewable Energy."
²Excludes supplemental gaseous fuels.
³Includes -0.03 quadrillion Btu of coal coke net imports.
⁴Conventional hydroelectric power, geothermal, solar, wind, and biomass.
⁵Includes industrial combined-heat-and-power (CHP) and industrial electricity-only plants.
⁶Includes commercial combined-heat-and-power (CHP) and commercial electricity-only plants.
⁷Electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public. Includes 0.17 quadrillion Btu of electricity net imports not shown under "source."

Notes: • Primary energy is energy in the form that it is accounted for in a statistical energy balance, before any transformation to secondary or tertiary forms of energy occurs (for example, coal is used to generate electricity). • The source total may not equal the sector total because of differences in the heat contents of total, end-use, and electric power sector consumption of natural gas. • Data are preliminary. • Values are derived from source data prior to rounding. • Sum of components may not equal total due to independent rounding.

Sources: U.S. Energy Information Administration, *Monthly Energy Review* (April 2018), Tables 1.3, 1.4a, 1.4b, and 2.1-2.6.

Transportation is responsible for 28% of greenhouse gas emissions

2017 U.S. greenhouse gas emission 6.4723 Pg



Greenhouse gas emissions by sector

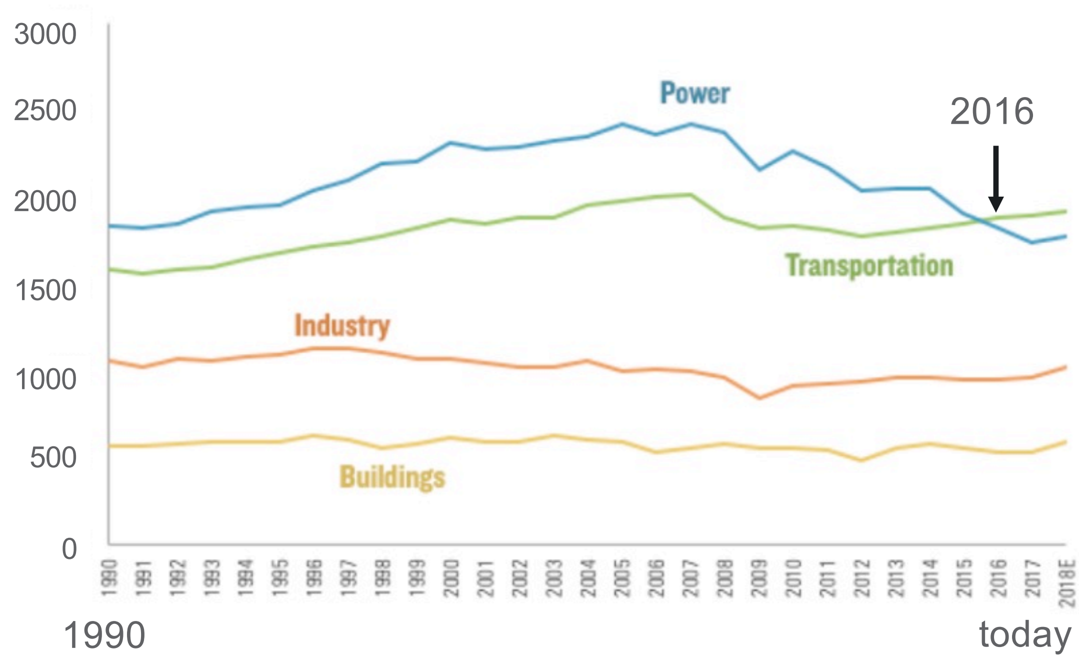
Reducing transportation's GHG footprint is the problem we are focused

Source: EPA; https://www.epa.gov/sites/production/files/2019-02/documents/us-ghg-inventory-2019-chapter-executive-summary.pdf

In 2016 transportation overtook power for the dubious lead

- Gasoline demand declines even as miles traveled increases
- Offset by robust growth in trucking and aviation (3% increase each)
- Challenge in decarbonizing transportation is heavy trucking and aviation

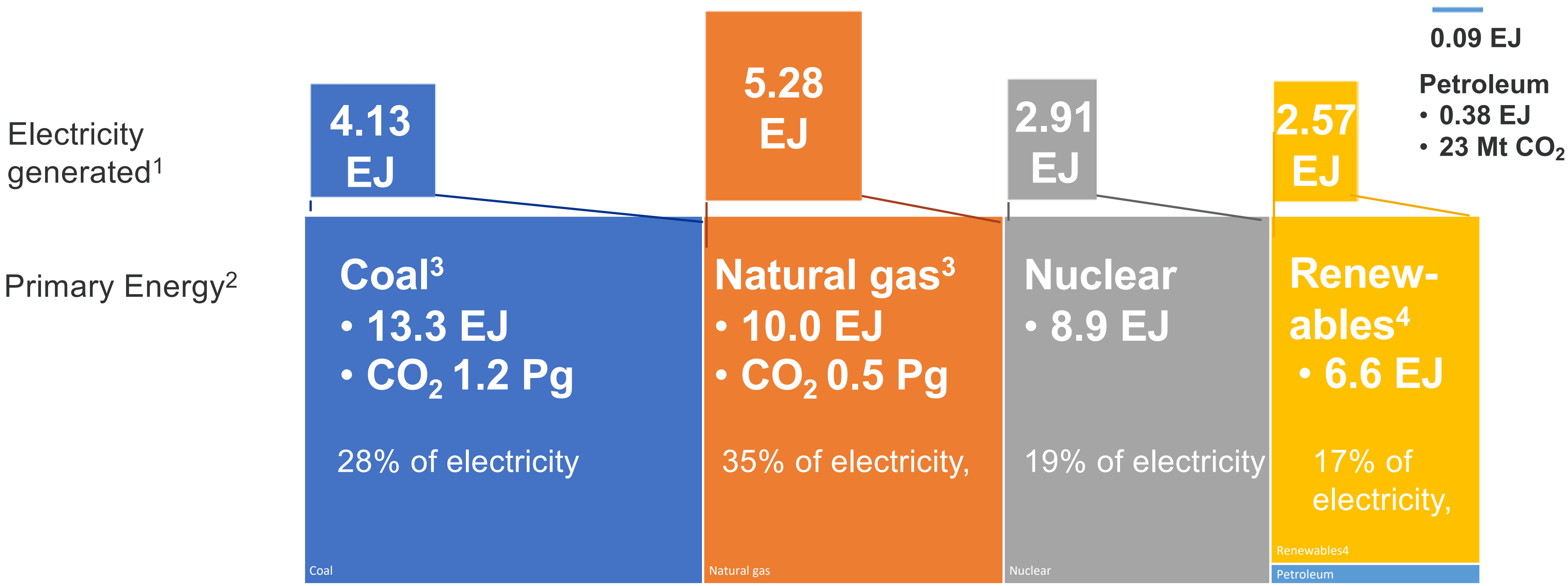
Energy Related CO_2 Emissions by Sector (Million metric ton)



Energy related CO_2 emissions from 1990 to 2018 (source Rhodium Group)

https://rhg.com/research/preliminary-us-emissions-estimates-for-2018/?utm_source=newsletter&utm_medium=email&utm_campaign=newsletter_axiosscience&stream=science

U.S. generates 15 EJ of electricity, 2018



9.5 EJ of electricity were generated from 24.7 EJ of fossil sources

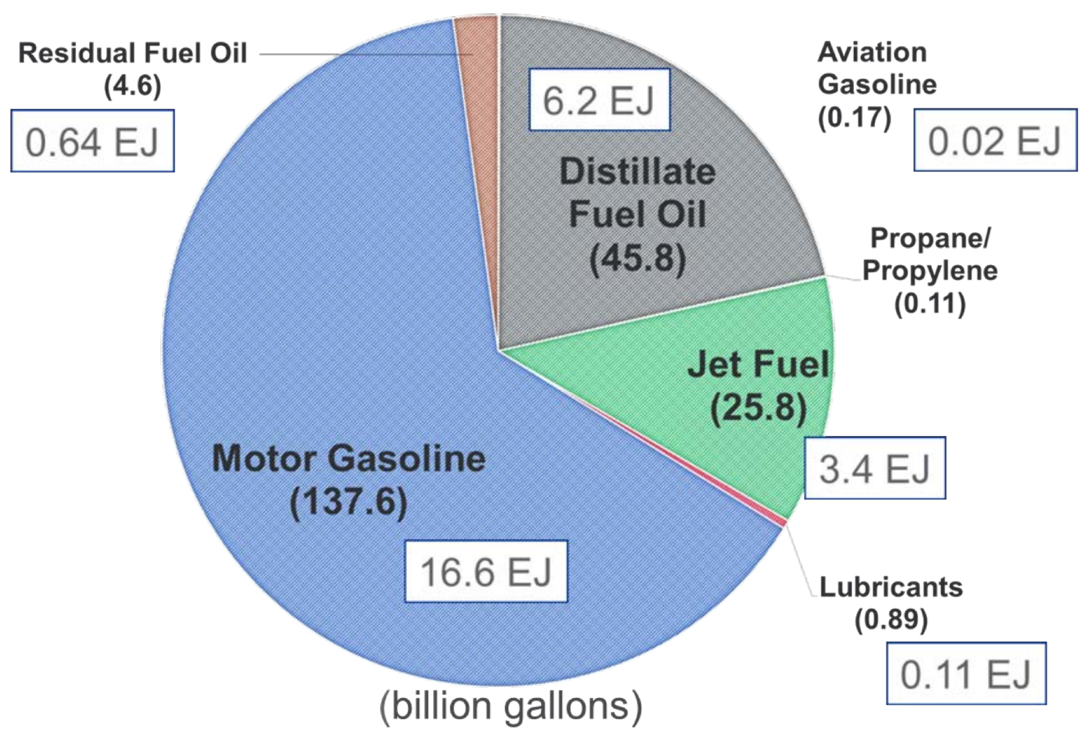
Renewables
- 17% of the mix today
- 24 – 44% of the mix in 2050

Nuclear not projected to grow
(EIA 2019 Outlook)

[1] tps://www.eia.gov/tools/faqs/faq.php?id=427&t=3
[2] https://www.eia.gov/totalenergy/data/monthly/pdf/flow/electricity.pdf
[3] based on EIA data for CO_2 emissions and primary energy sources, EPA estimates 1734 Mt (megaton) of CO_2 from electricity generation
[4] 80% is hydro and wind; biomass, solar, and geothermal make up rest[5]

U.S. uses 27 EJ of petroleum products, 3.4 EJ of jet fuel

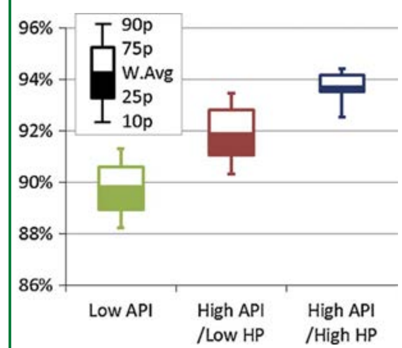
Petroleum products (215 billion gallons)[1]

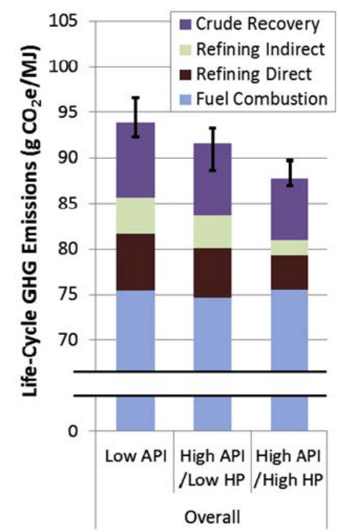


Petroleum refinery[2]

efficiency

CO$_2$



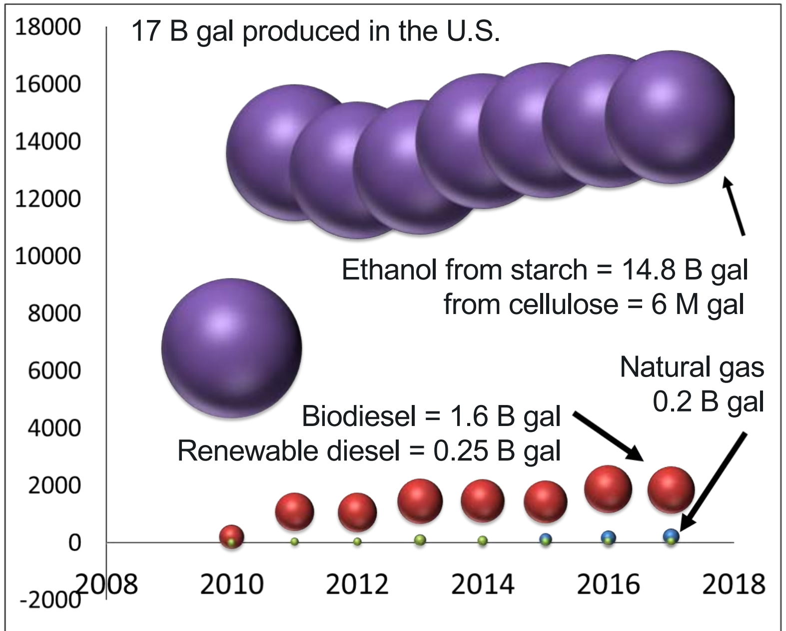


- 30 EJ of primary energy needed
- Life cycle = 90 g CO2/MJ

[1] https://www.eia.gov/totalenergy/data/monthly/index.php#petroleum

[2] Han et al. Fuel 157 (2015) 292-298 (https://doi.org/10.1016/j.fuel.2015.03.038)

U.S. biofuels production in 2017 was 1.4 EJ, which includes 0.035 EJ of renewable diesel



Data from EPA)

U.S. production, 2017[1]

1.4 EJ fuel produced (5%)

13 Tg CO_2 abated[2] (0.04% of transportation)

3.5 PJ of renewable diesel produced (1% of U.S. jet demand)

A decade after the Energy Independence and Security Act (EISA 2007)

[1] ethanol energy content = 26.7 MJ/kg, density = 0.789 kg/L
[2] GREET 2018 was used in this calculation. Based on building a blended fuel with ethanol and biodiesel and compared the g CO_2 of petroleum fuel of same energy content

U.S. cars travel 2.9 trillion miles using 15.8 EJ of fuel, 2017

Cars travel 2.9 trillion miles
Average fuel efficiency = 22 mpg[1]

Energy needed[1] 15.8 EJ

CO_2 footprint[2,3,5]

1.5 Pg

U.S. travel, 2017 (DOT)
LD short wheel base, 2.2 trillion miles
LD long wheel base 0.66 trillion miles

1. U.S. miles traveled and fuel economy for 2017 (DOT), gasoline LHV = 32 MJ/L diesel LHV = 36 MJ/L.
2. Based on EPA fuel economy for EV car 130 mpge or 26 kWh/100 mi (EPA).
3. GREET 2018, gasoline LCA 91.1 g CO2/MJ
4. GREET 2018 U.S. electric mix LCA 140.3 g CO2/MJ
5. Miotti et al. Environ. Sci. Technol. 50 (2016) 10795-10804.

Only 7 EJ of fuel needed if fuel economy were increased to 50 mpg

Cars travel 2.9 trillion miles
Average fuel efficiency = 22 mpg[1]

Energy needed[1] **15.8 EJ**

CO_2 footprint[2,3,5] **1.5 Pg**

Energy needed if fuel economy improved to 50 mpg[1] **7.0 EJ**

CO_2 footprint (50 mpg)[3,5] **0.7 Pg**

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Only 2.7 EJ of electricity would be needed if cars were electrified (battery)

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Energy needed to travel same distance by electric car[2] **2.7 EJ**

CO_2 footprint is highly dependent on fuel mix[5] **~0.7 Pg**

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CO_2 range dramatically dependent on region of the country and other factors

EVs convert about 59%–62% of the electrical energy to power at the wheels
Conventional gasoline vehicles convert about 17%–21% of the energy in fuels to power at the wheels

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Syn fuels (CO_2 and electricity) move light duty energy needs the wrong direction

Cars travel 2.9 trillion miles
Average fuel efficiency = 22 mpg[1]

Energy needed[1] **15.8 EJ**

CO_2 footprint[2,5] **1.5 Pg**

Energy needed if fuel economy improved to 50 mpg[1] **7.0 EJ**

CO_2 footprint (50 mpg)[3,5] **0.7 Pg**

Energy needed to travel same distance by electric car[2] **2.7 EJ**

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If instead electricity was used to make 7 EJ of syn gasoline?[6] **15 EJ**

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6. Idealized case based on thermodynamics converting CO_2 to CO and water splitting to produce H_2, 100% C efficiency to CO, 92% in fermentation, and 98% in catalytic step (stopping at ethanol gives similar result)

Electrifying a vehicle uses a fraction of the energy as producing a syn fuel from CO_2

Producing jet fuel may make sense because the opportunity to electrify the vehicle is limited

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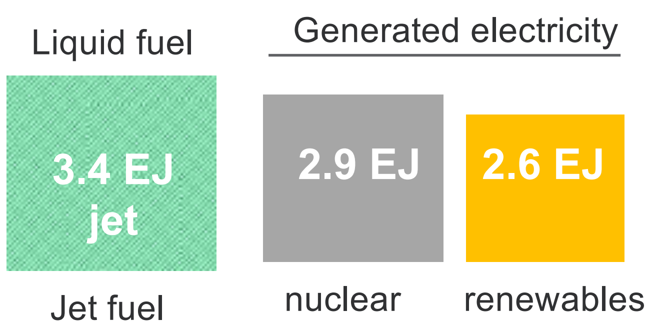
Converting CO_2 to jet fuel

Current state



Energy content in jet fuel consumed in the U.S. is equivalent to
- 23% of U.S. electricity generated
- 134% of renewable electricity
- 120% of nuclear electricity generated

A large portion of heavy trucking and marine fuels are candidates

How much electricity Is needed?

Chemicals can also be produced
primary feedstocks are ethylene, propylene, butadiene, aromatic (BTX) and syn gas

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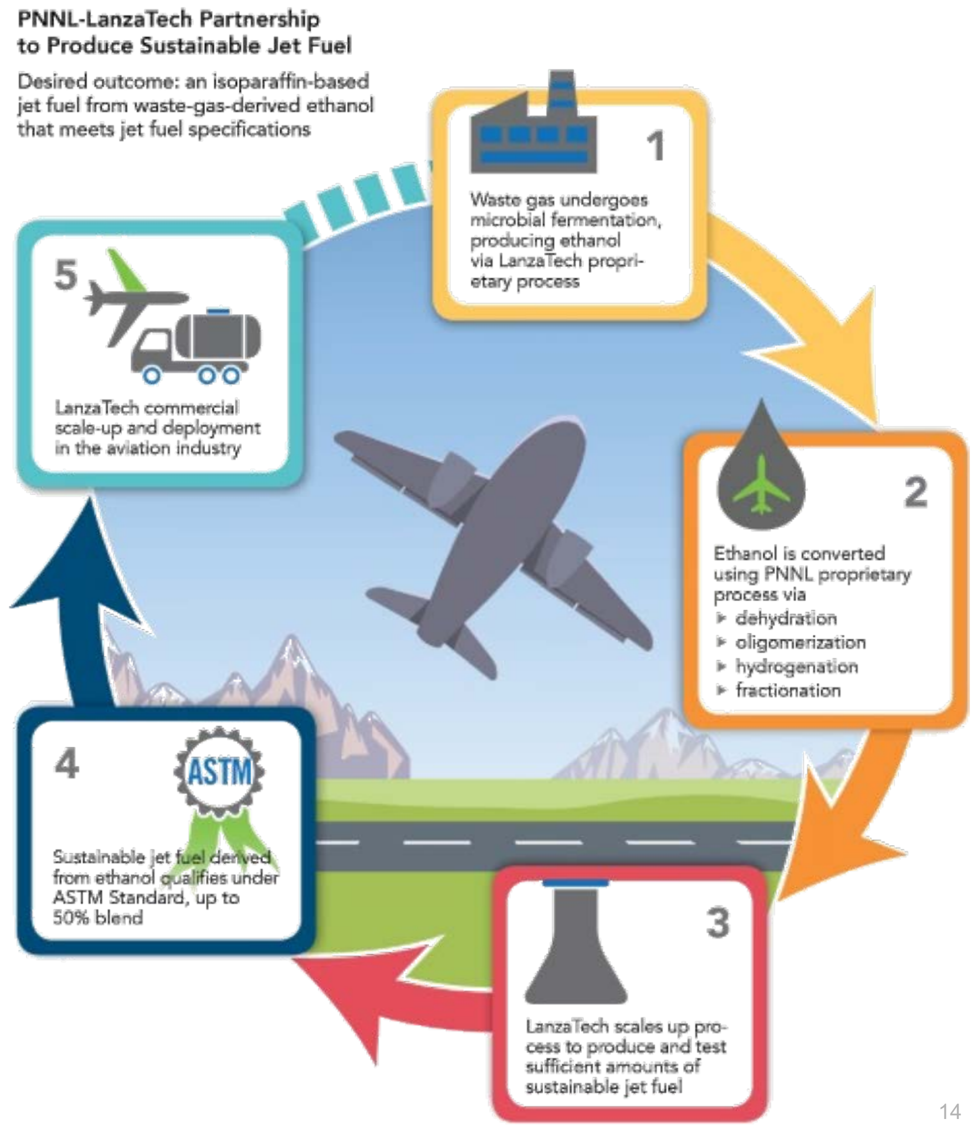
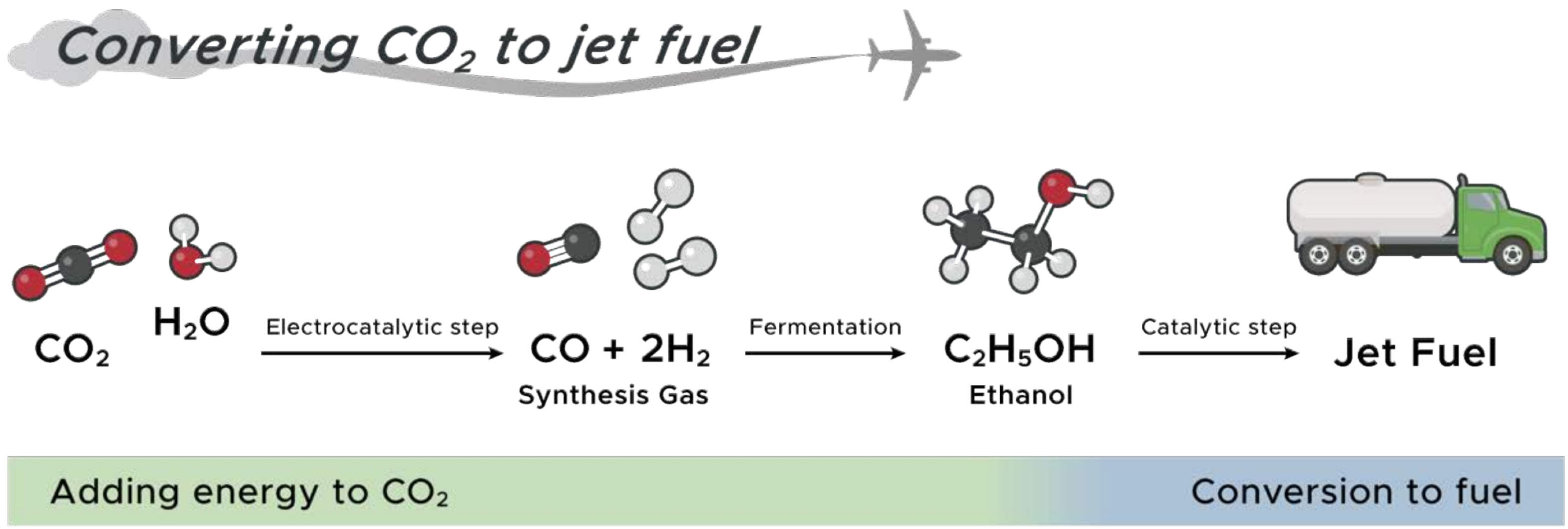
We have a solution for waste gas to jet fuel

- Hybrid fermentation-catalysis process
- High carbon efficiency (>90%) and highly selectivity to jet range iso-alkanes
- Need CO; H2 allows higher carbon efficiency

Converting CO_2 to jet fuel



Use minimum amount of electricity possible, e.g., CO_2 to CO and perhaps H_2O to H_2



1. Add energy
   - CO_2 to CO (electrolysis) 353 kJ/mol CO
   - H_2O to H_2 (electrolysis) 351 kJ/mol H_2

2. Convert gases into liquids (LanzaTech process)
   - Commercial
   - High carbon efficiency
   - Low temperature
   - High energy efficiency

3. Concentrate the energy and adjust the carbon structure (PNNL "Ethanol-to-Jet")
   - Pilot stage
   - High C efficient
   - High Energy Return on Investment

Corn ethanol facilities have clean, concentrated CO_2 that could be used to produce 15% of jet fuel

When sugar is fermented
carbon dioxide is co-produced

$$\underset{\text{sugar}}{C_6H_{12}O_6} = 2\ \underset{\text{ethanol}}{C_2H_6O} + 2\ \underset{\text{carbon dioxide}}{CO_2}$$

Ethanol Plant
Boardman, OR

	Typical plant	National amount
→ Ethanol	120 kt	44 Mt
→ CO_2	114 kt	42 Mt

kt = kiloton, Mt = megaton or Tg

Individual plant (40 M gal ethanol)

The CO_2 could be the raw material for

- 1.4 PJ (10 M gallon) of jet fuel

The ethanol could provide another

- 2.8 PJ (20 M gallons)

National level
CO_2 could be the raw material for

- 0.53 EJ (3.8 billion gallon) of jet fuel (15% of U.S. consumption)

If ethanol also converted

- 1.5 EJ (11 billion gallons) (44%)

At what cost?

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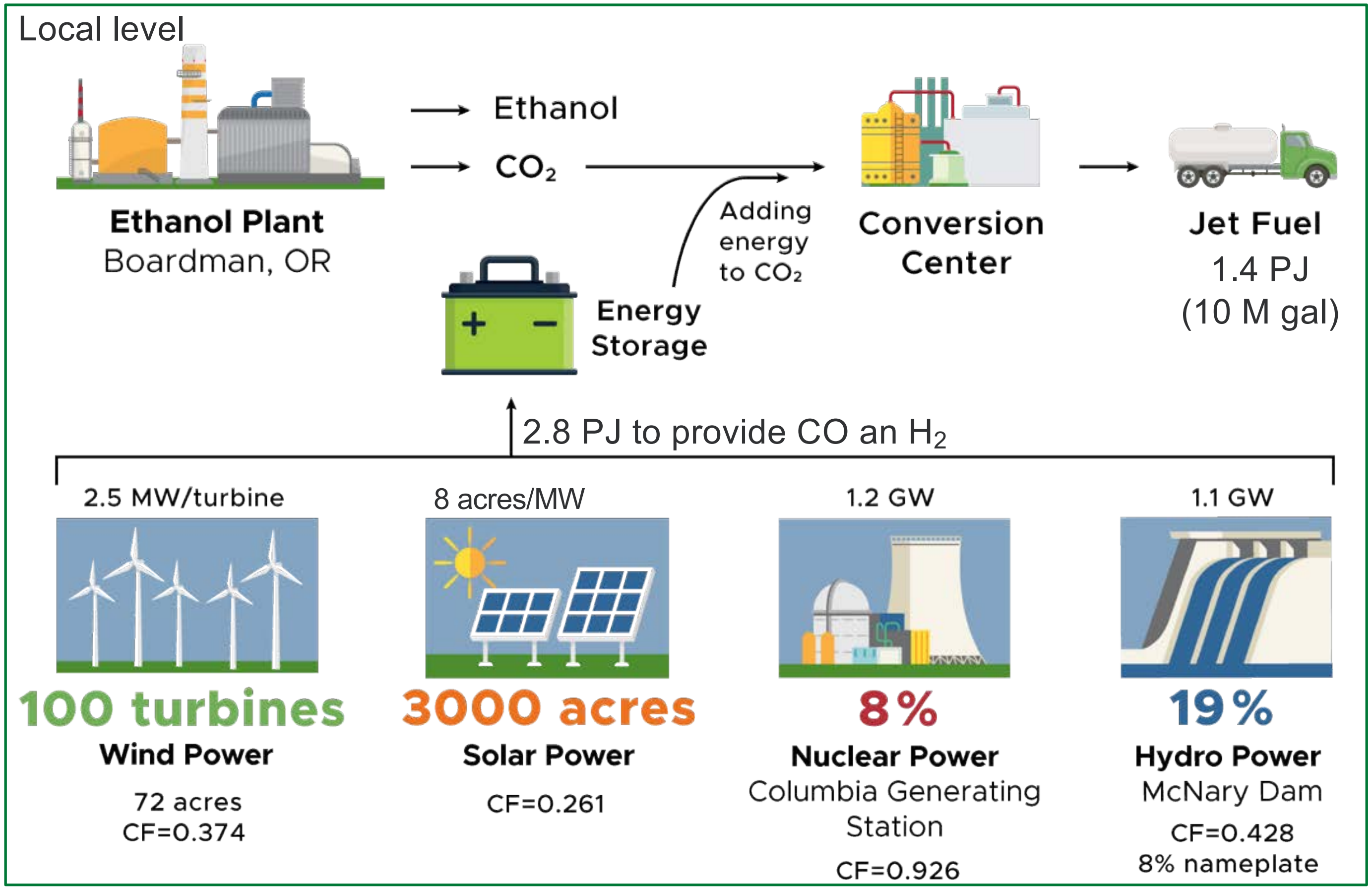
Even a small facility will require grid-scale electricity and energy storage

National level

- 1 EJ of electricity for raw materials to produce 0.53 EJ of jet fuel (15%)
- If the ethanol was also converted, 1.5 EJ (40%)
- In 2018 wind generation was 0.99 EJ, solar was 0.24 EJ
- Energy storage – in some form – is needed as the syngas to jet fuel process will run full time

Assumptions

- Production of syn gas based on $\Delta G° = nFE$, where n=2, F = 96,485 C/mol, E = 1.83 V (CO) and E = 1.82 V H_2 which comes to 12.6 MJ/kg CO and 175.6 MJ/kg H_2
- C efficiency for the syn gas to jet fuel exceeds 90% (demonstrated at large scale for syn gas to jet fuel under mild conditions)



wind: 2.5 MW turbine each 0.75 acre; solar: 250,000 kWh/acre for generation weighted land use

Raw materials cost can exceed fuel value

Converting CO_2 to jet fuel

Electricity at $0.025 kWh

CO Cost			H_2 cost		
At this price point ($/kg)	The CO cost on a per gal basis is ($/gal)	note	At this price point ($/kg)	The H_2 cost on a per gal basis is ($/gal)	note
0.09	0.65	1	$1.50	1.60	4
0.21	1.50	2	$1.85	2.00	5
0.6	4.30	3	$2.52	2.70	6

This thought experiment is to give an indication of raw materials cost in in an idealized case study

[1] This is the lowest cost possible, based on amount of electricity to meet thermodynamics requirement (for $\Delta G°$), no capture or conversion cost

[2] For example the goal case described in research sponsored by DOE Bioenergy Technologies Office at NREL

[3] selling price for pure CO, (note: CO in syn gas can be purchased for about $0.06/kg (U. Del

[4] arbitrary low number

[5] cost for H_2 from high temperature fuel cell (J.D. Holladay)

[6] cost for H_2 from water electrolysis (H2A)

Energy required to make syn gas based on $\Delta G = nFE$,
where n=2, F = 96,485 C/mol, E = 1.83 V (CO) or E = 1.82 V H_2
which comes to 12.6 MJ/kg CO and 175.6 MJ/kg H_2

Conclusion: syn fuels while intriguing will require grid-scale electricity and need lower cost H_2

U.S. uses nearly 2x petroleum products (transport) as we do electricity

- U.S. uses 15 EJ of electricity
- U.S. uses 27 EJ of petroleum products

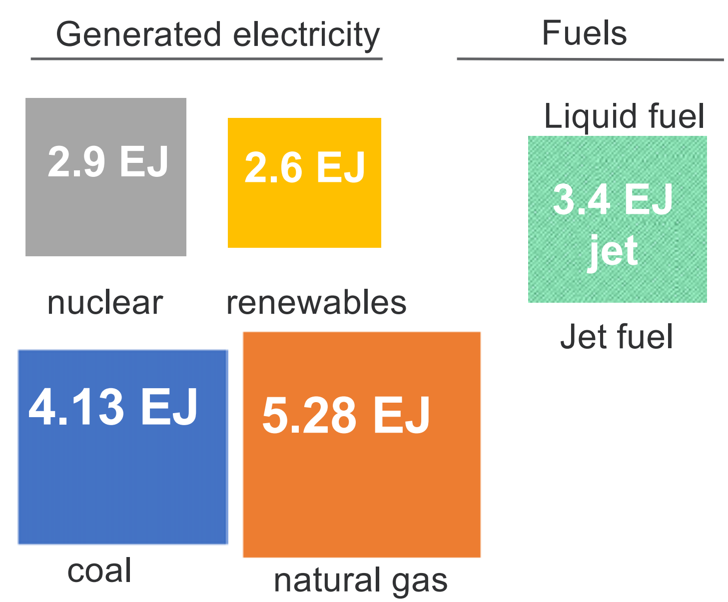
Do not make synfuels if an electric vehicle is possible

- Aviation has limited opportunities to electrify

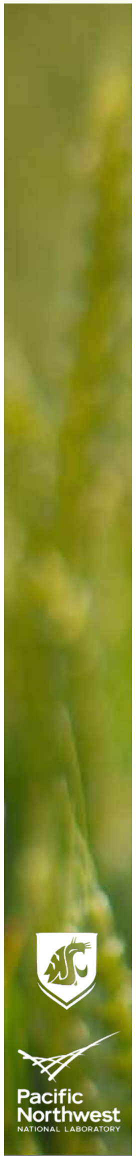
Syn fuels, if practiced, will require grid-scale electricity

- 1 EJ of electricity is needed to convert CO_2 and H_2O to CO and H_2 for 0.53 EJ of jet fuel
- Getting more industrial waste gas to fuels will be helped if we can lower cost of green H_2

What services do we need from the Grid of tomorrow?



17% from renewables
(7% from wind, 2% solar)



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Thank you

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To understand syn jet fuel we need to consider energy

Energy
- Energy is the ability to do work
- SI unit of energy is joule (J) and is kg m^2/s^2
- The U.S. uses roughly 100 exajoules of energy yearly

Power
- Power is energy over time
- SI unit of Power is watt (W) and is kg/m^2/s^3

How can I relate exa (E)?
- An Exa second is 32 billion years (more than 2x the age of the universe)
- The radius of the Milky Way Galaxy is 500 Em
- An EJ is the energy intake for about a 100 billion people (2,400 kcal/person)

Energy units

1 kJ = 0.95 Btu

1 kJ = 0.278 Wh

1kJ = 0.239 kcal

1 EJ = 0.95 Quad (10^{15} Btu)

1 Btu = 1.055 kJ

1 kWh = 3.6 MJ

1 kcal = 4.184 kJ

1 Quad = 1.055 EJ

Kilo (k) = 10^3 (thousand)
Mega (M) = 10^6 (million)
Giga (G) = 10^9 (billion)
Tera (T) = 10^{12} (trillion)
Peta (P) = 10^{15} (quadrillion)
Exa (E) = 10^{18} (quintillion)

U.S. renewable fuel production, 2017

Fuel by RIN[1]	million gallons	%
D6 Renewable fuel (-20% GHG)		88%
ethanol	14,850	
renewable diesel	0	
D4 Biomass-based diesel (-50% GHG)		11%
biodiesel	1,588	
renewable diesel	253	
renewable jet	2	
D5 Advanced Biofuels (-50% GHG)		0.3%
ethanol	26	
naphtha	21	
other	8	
D3/D7 Cellulosic (-60% GHG)		1.0%
ethanol	6	
natural gas (compressed)	156	
natural gas (liquified)	53	

[1] RIN = Renewable Identification Number, note: another 1.5 billion gal of renewable fuels were imported, totaling 19.4 billion gal RIN fuel

Comment on market and future growth

Gasoline (138 billion gal but shrinking)
D6 Ethanol capped at 15 billion gal (RFS)

Diesel market (46 billion gal)
Jet market (26 billion gal)
Lipid sourcing limiting growth

EtOH source is sugar cane
Naphtha is residual from renewable diesel

Natural gas vehicles use about 314 million oil equiv gal

Source: EPA, https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rins-generated-transactions