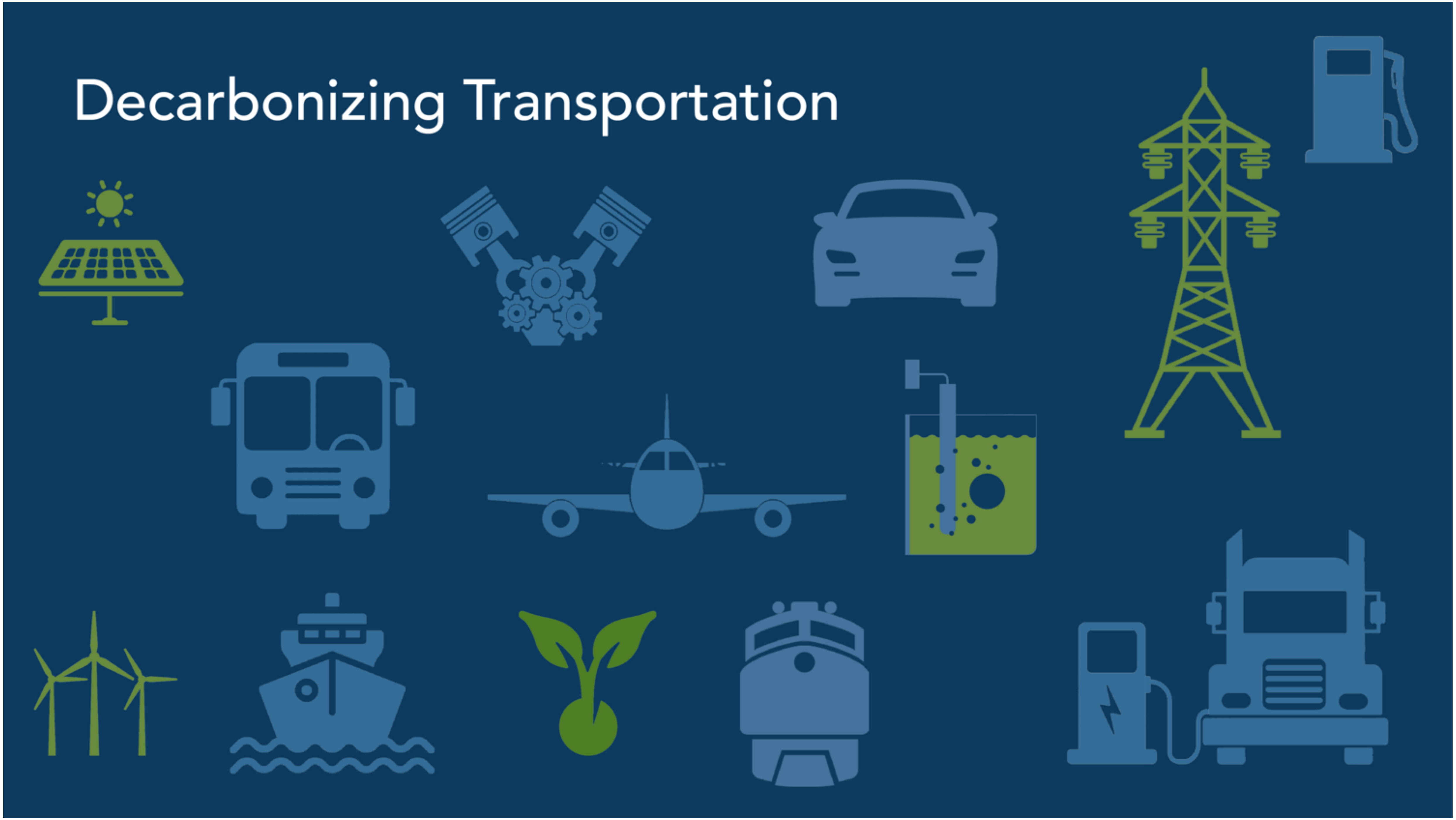
Our evolving fuels:
From petroleum, to biomass, to e-fuels?

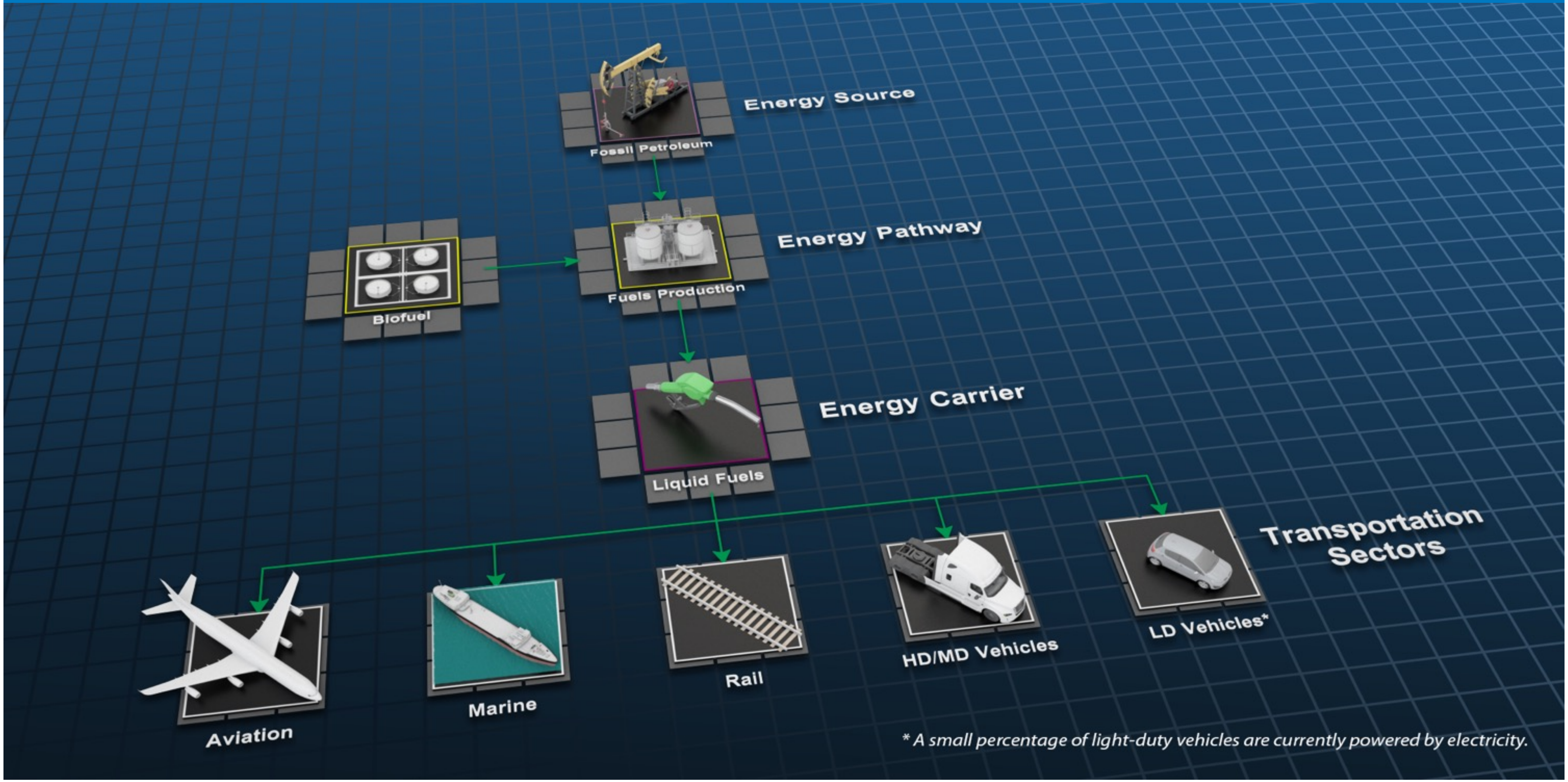
ASME ICEF 2020

John Farrell
National Renewable Energy Laboratory

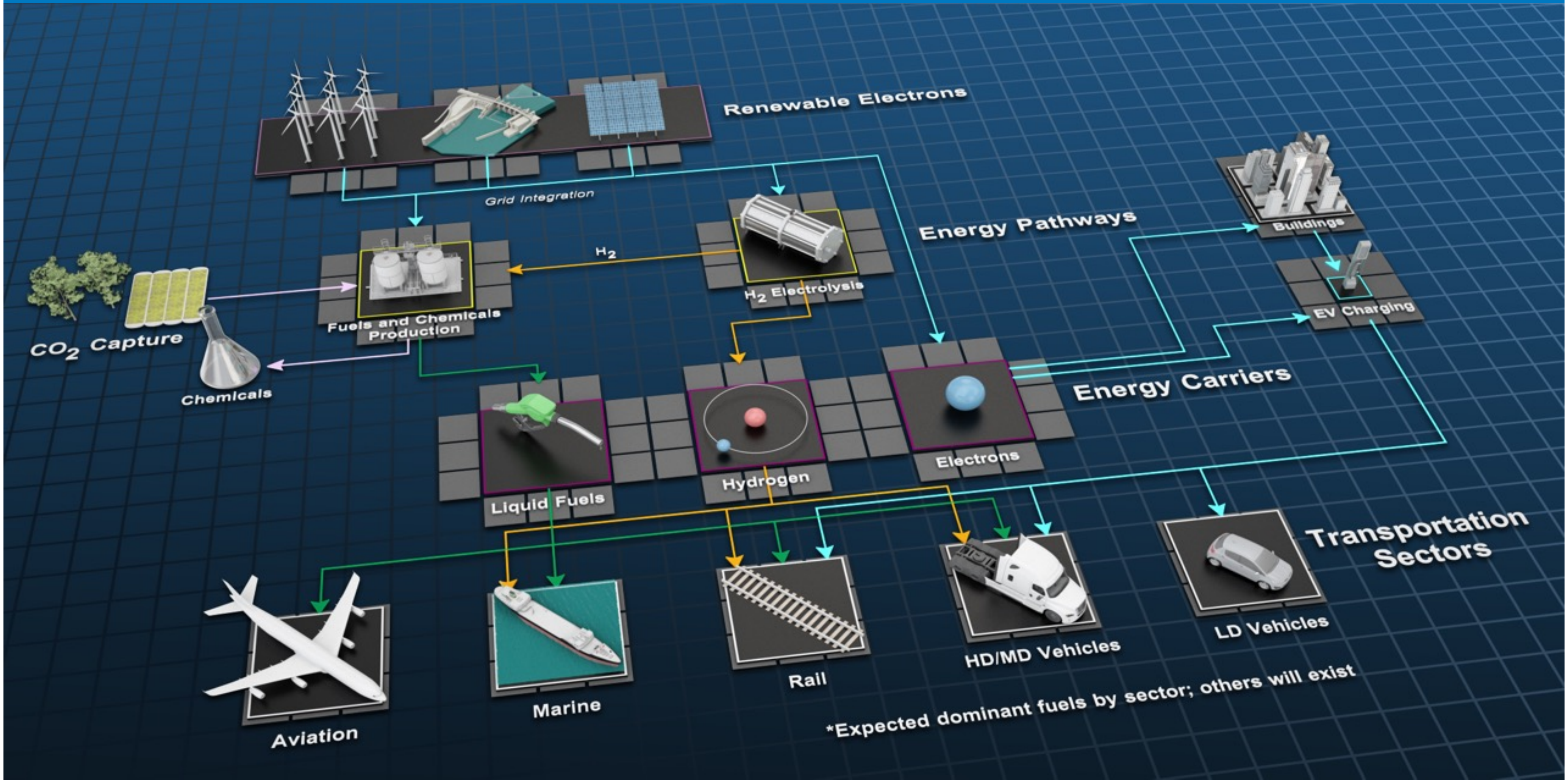
November 4, 2020


Decarbonizing Transportation

Today's Transportation System

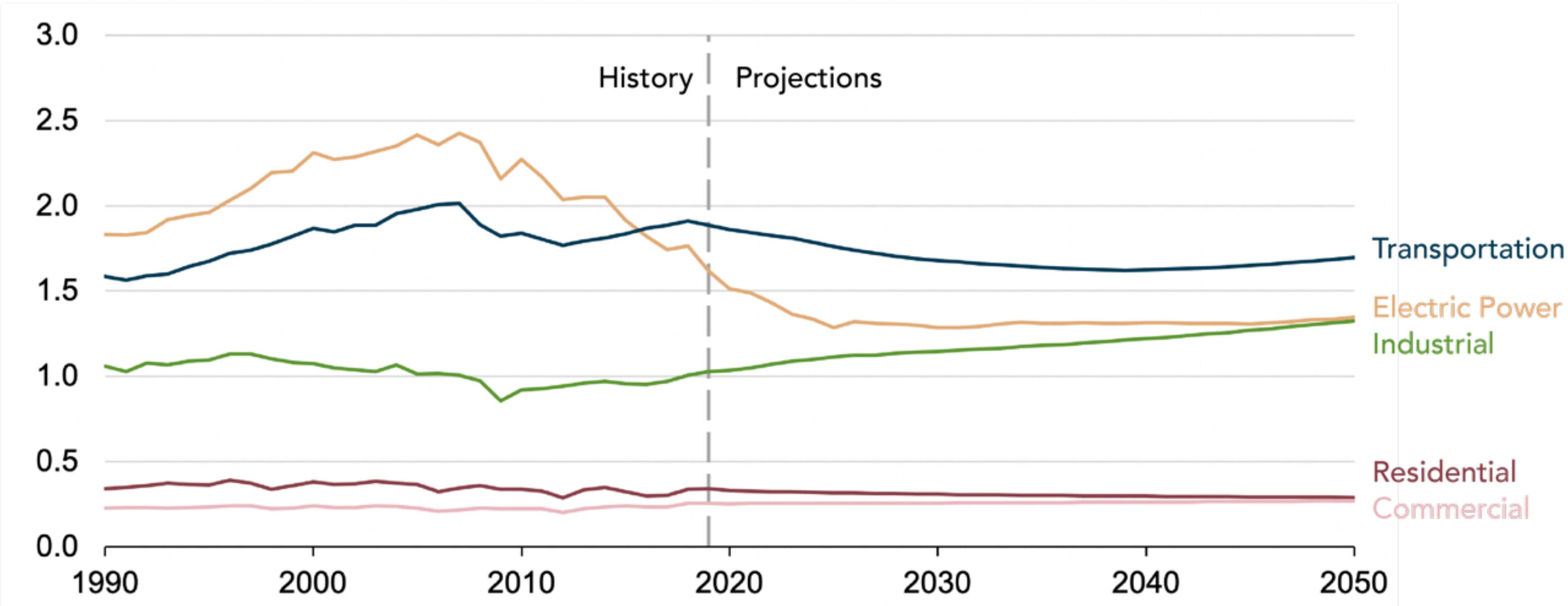


NREL's Vision for a Decarbonized Transportation Sector



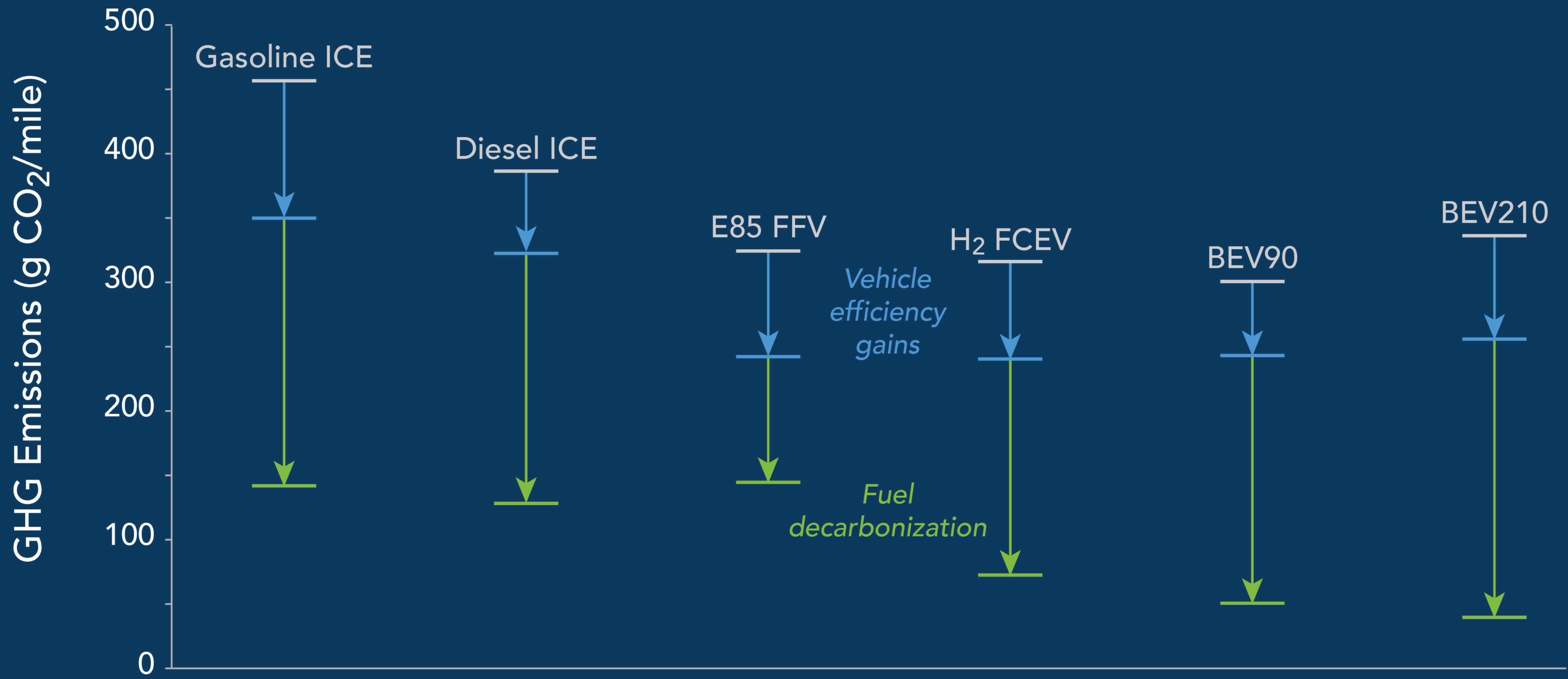
Transportation Expected to Dominate 2050 Energy Use

Energy-related CO_2 emissions by energy sector (EIA AEO2020 Reference case)
billion metric tons



https://www.eia.gov/outlooks/aeo/

Path to decarbonization: Improving both vehicles and fuels



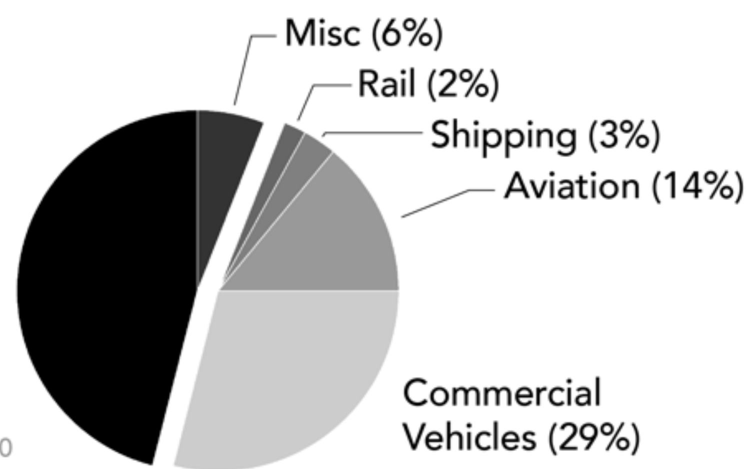
Adapted from A. Elgowainy et al., Cradle-to-Grave Lifecycle Analysis of U.S. Light Duty Vehicle-Fuel Pathways," 2016. Web. doi:10.2172/1254857

ICE = internal combustion engine; FFV = flex fuel vehicle; FCEV = fuel cell electric vehicle; BEV90 and BEV210 = battery electric vehicle with 90 and 210 miles of range, respectively

The Real Challenge: Low-Carbon Fuels for Large Vehicles

2050 Transport Energy Demand:

190 B gallons (27.6 EJ)



Source: EIA Annual Energy Outlook 2020

"Hard to electrify" transportation segment represents almost half of all demand in 2050

Total demand: 82 billion gallons/year (11.9 EJ)

Common sense guidelines (not rules) to selecting new fuels

Consider needs of legacy fleet

Minimize need for complex new engine designs required to work with “exotic” fuels

Prioritize cost—feedstock, conversion, infrastructure

Focus on scale

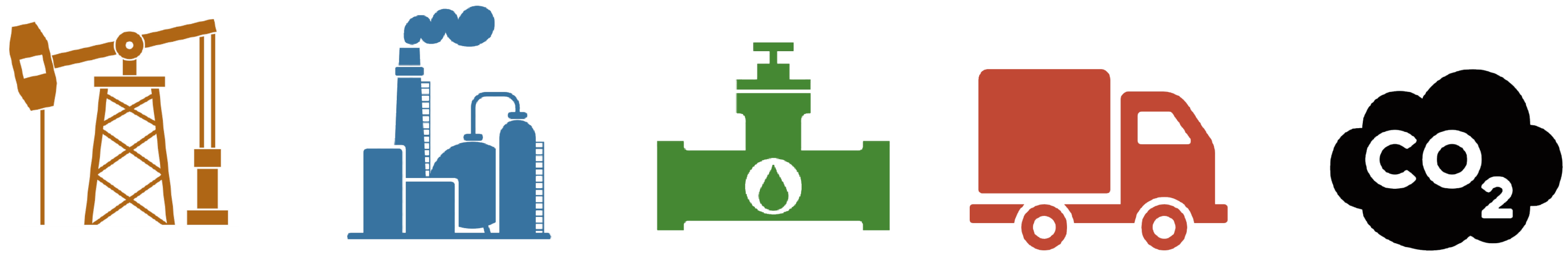
Emphasize high energy density


Petroleum

The problem of petroleum-based fuels in a decarbonization scenario

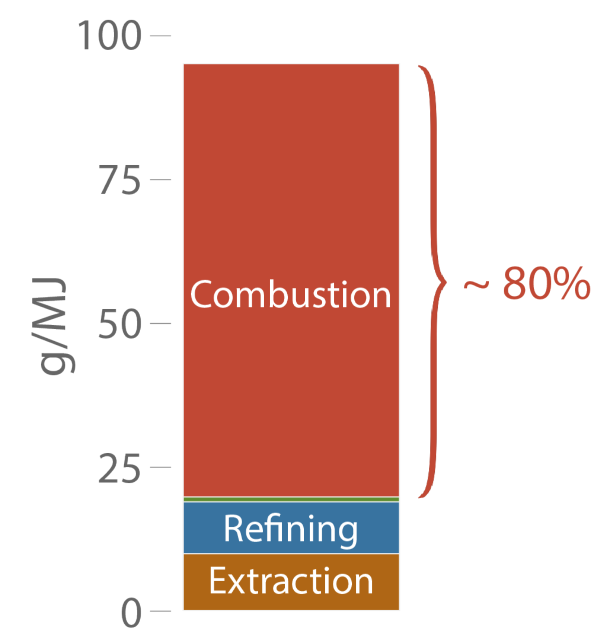
Well-to-wheel GHG emissions dominated by combustion

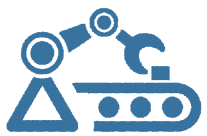
Extraction Refining Distribution Combustion



148 g/km + 132 g/km + 6 g/km + 1,079 g/km = 1,365 g/km

Well-to-tank Tank-to-wheel Well-to-wheel





Manufacturing life cycle emissions not considered here, though they can be significant
(~ 8-12 tons CO_2 per LD vehicle, which over 180,000 mile vehicle life is equivalent to ~ 40 g CO2e/MJ)

20% Even if we could sequester all emissions from extraction, refining, and distribution, the best we could hope to achieve is ~ 20% reduction in GHG emissions from petroleum-based fuels

WTW graphic adapted from https://www.cleanenergyfuels.com/compression/blog/natgassolution-part-1-clean-natural-gas-stack-race-reduce-emissions/ LD manufacturing emissions from Elgowainy eg al, Environ. Sci. Technol. 2018, 52, 2392–2399

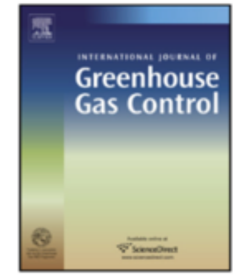
International Journal of Greenhouse Gas Control 37 (2015) 492–503

ELSEVIER

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc



Carbon negative oil: A pathway for CO_2 emission reduction goals

CrossMark

Katherine Y. Hornafius [a,*], J. Scott Hornafius [b,c]

[a] Miami University of Ohio, Advanced Inquiry Program, Oxford, OH, USA
[b] University of California at Santa Barbara, Earth Research Institute, Santa Barbara, CA, USA
[c] Elk Petroleum Limited, Sydney, Australia

iea | Countries | Fuels & technologies | Analysis | Data | Policies | About

Can CO2-EOR really provide carbon-negative oil?

Christophe McGlade, WEO Senior Analyst
Commentary — 11 April 2019

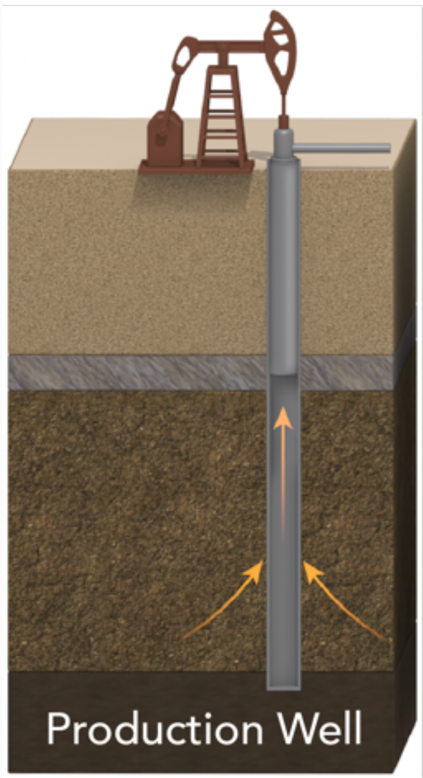
Cite Share

EOR = enhanced oil recovery

Primary

Recovery: up to 15%

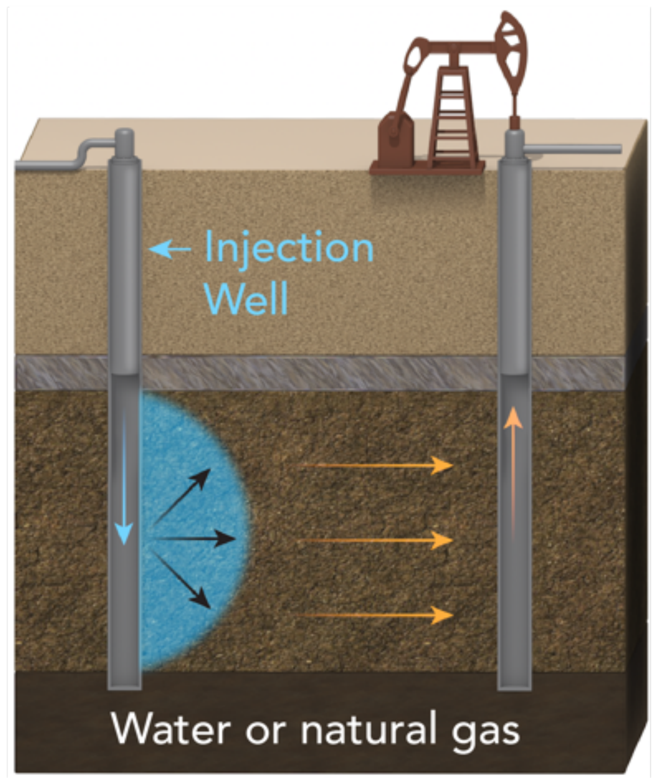
Reservoirs internal pressure pushes oil out



Secondary

Recovery: 20-40%

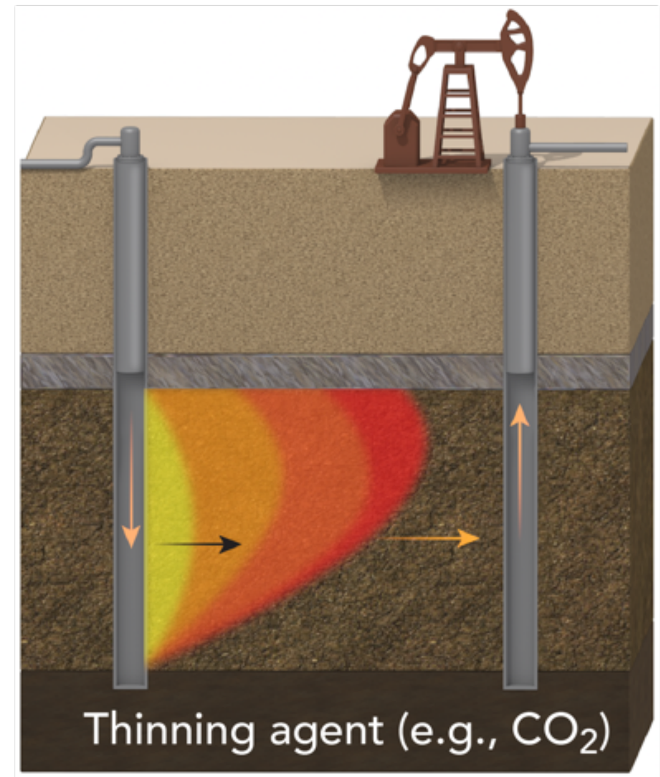
Water or natural gas pushes more of the oil out



Tertiary

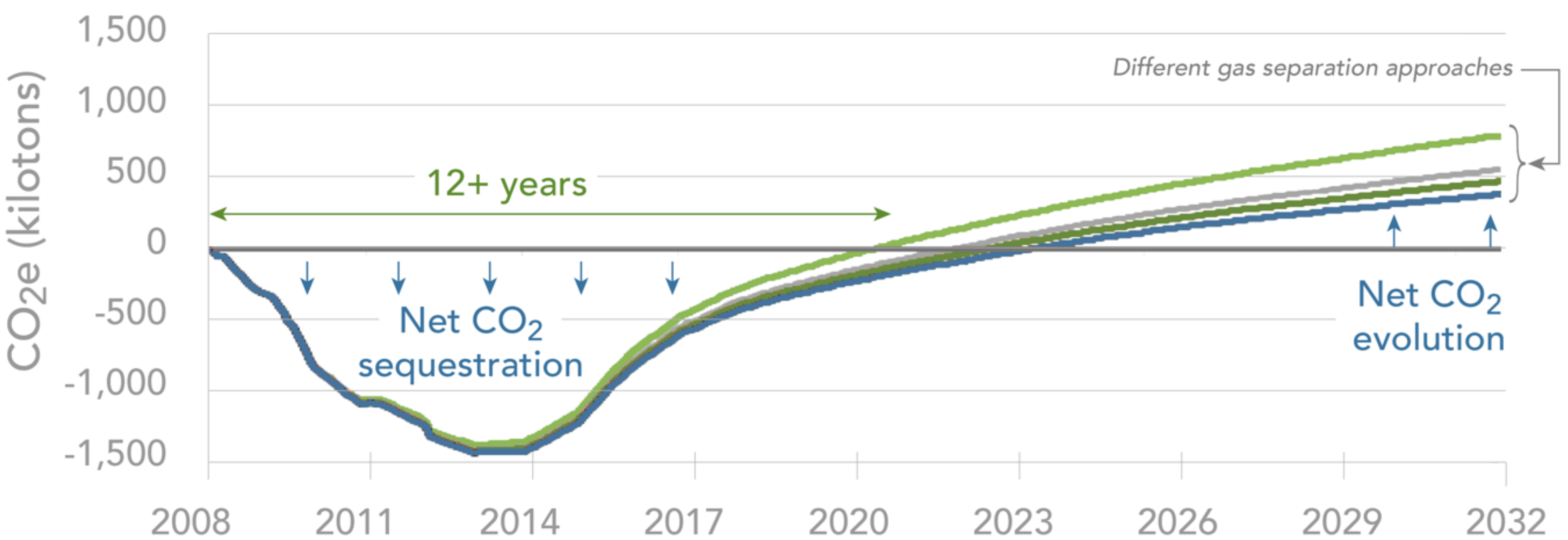
Recovery: Up to 60%

Chemicals (e.g., CO_2), heat, or microbes thin out remaining oil



Adapted from Atia and Mohammedi, DOI: 10.5772/intechopen.79278

Carbon balance for EOR is time-dependent



Simulation for Cranfield reservoir in Mississippi with strategies that include saline aquifer injection

EOR with simultaneous saline injection can yield negative carbon intensity for > decade of producing life of field

Adapted from Nunez et al., Energies 2019, 12, 448; doi:10.3390/en12030448

An assessment of EOR—CO_2 to reduce gasoline/diesel GHGs

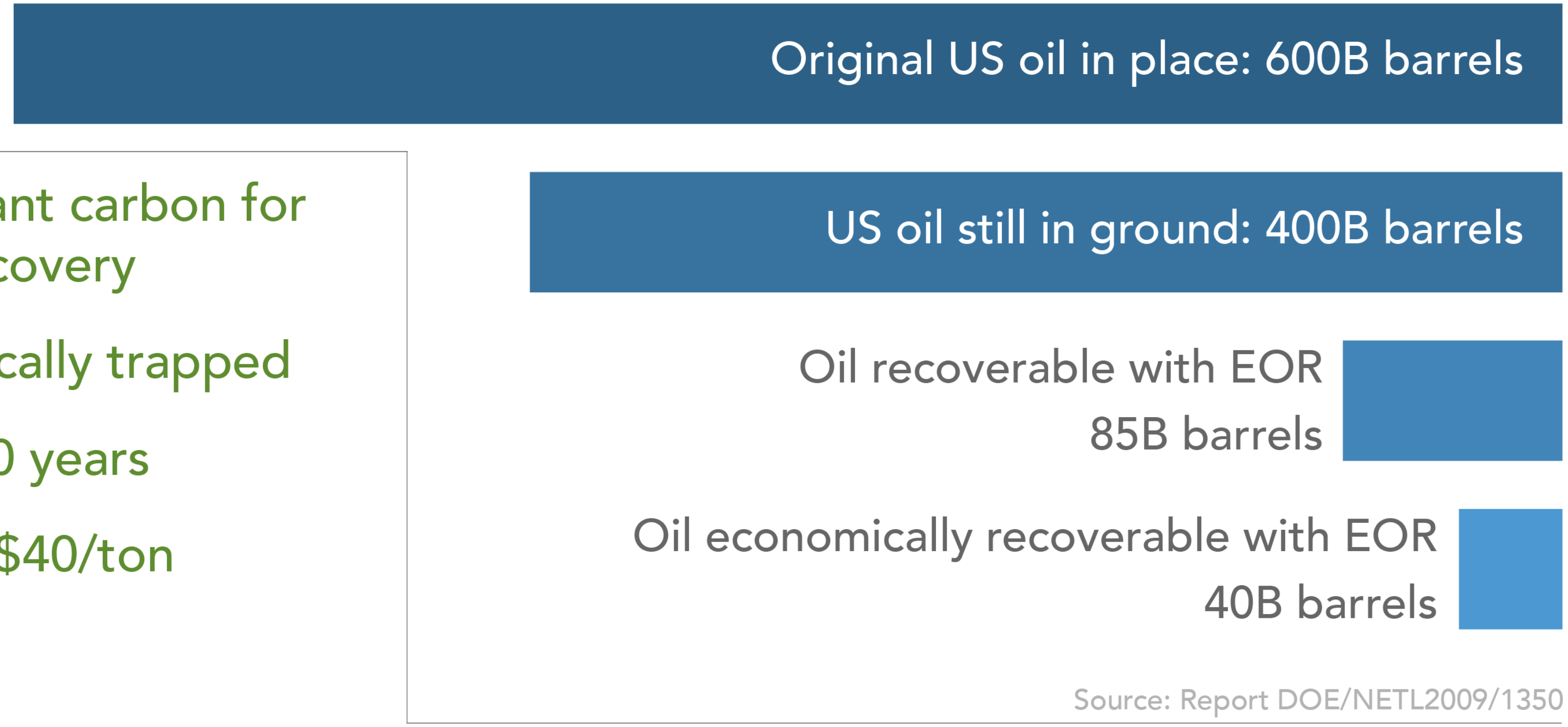
The pros:

CO_2-EOR can sequester significant carbon for many years during tertiary oil recovery

90–95% of CO_2 remains geologically trapped

Has been practiced for almost 50 years

Is economical at CO_2 costs of ~ $40/ton



The cons:

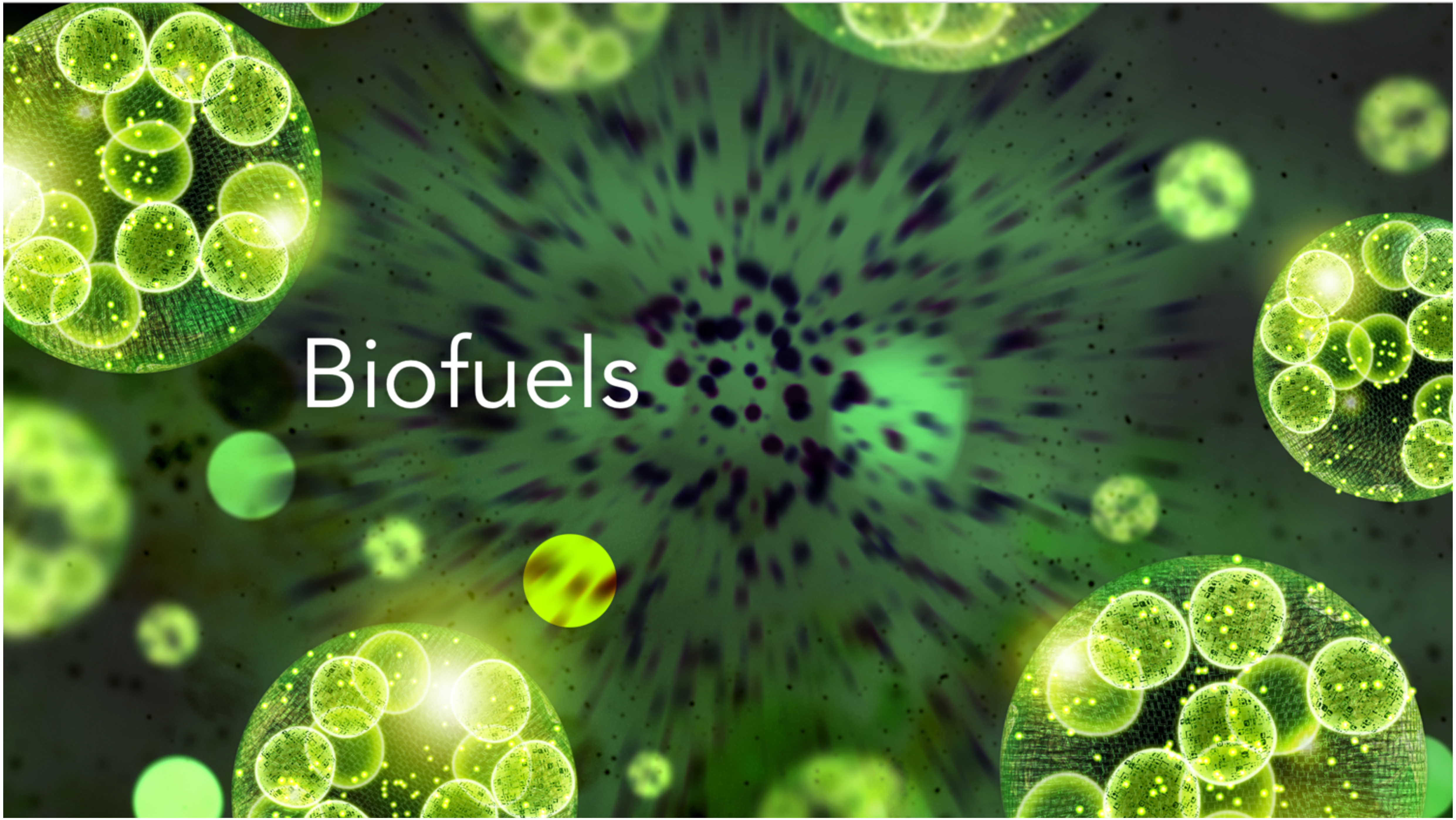
CO_2-EOR is only practiced during tertiary oil recovery (last part of a field's producing life)

Only suitable for 10-20% of remaining US oil (up to ~ 4 million barrels/day)

No good way exists to get CO_2 to fields; new pipelines needed - adds time, cost, emissions

Conclusion: CO_2-EOR can reduce petroleum GHGs ≤ 10%

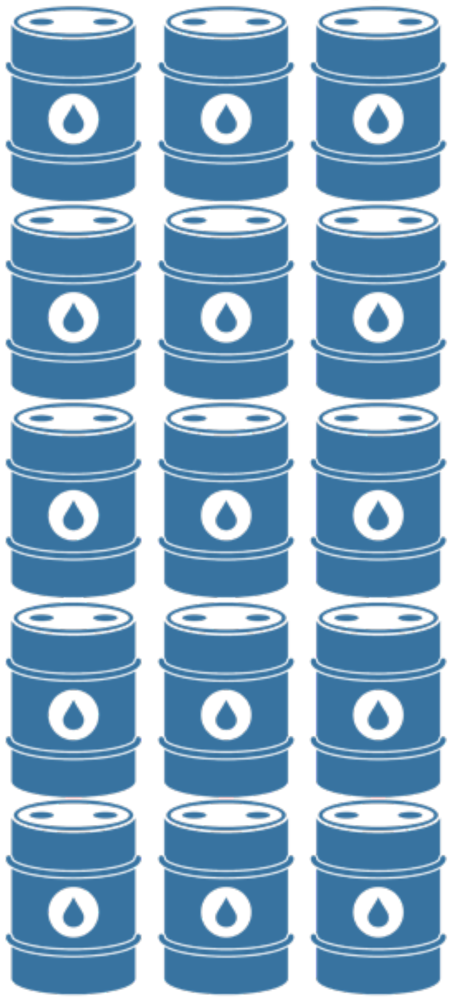
Biofuels

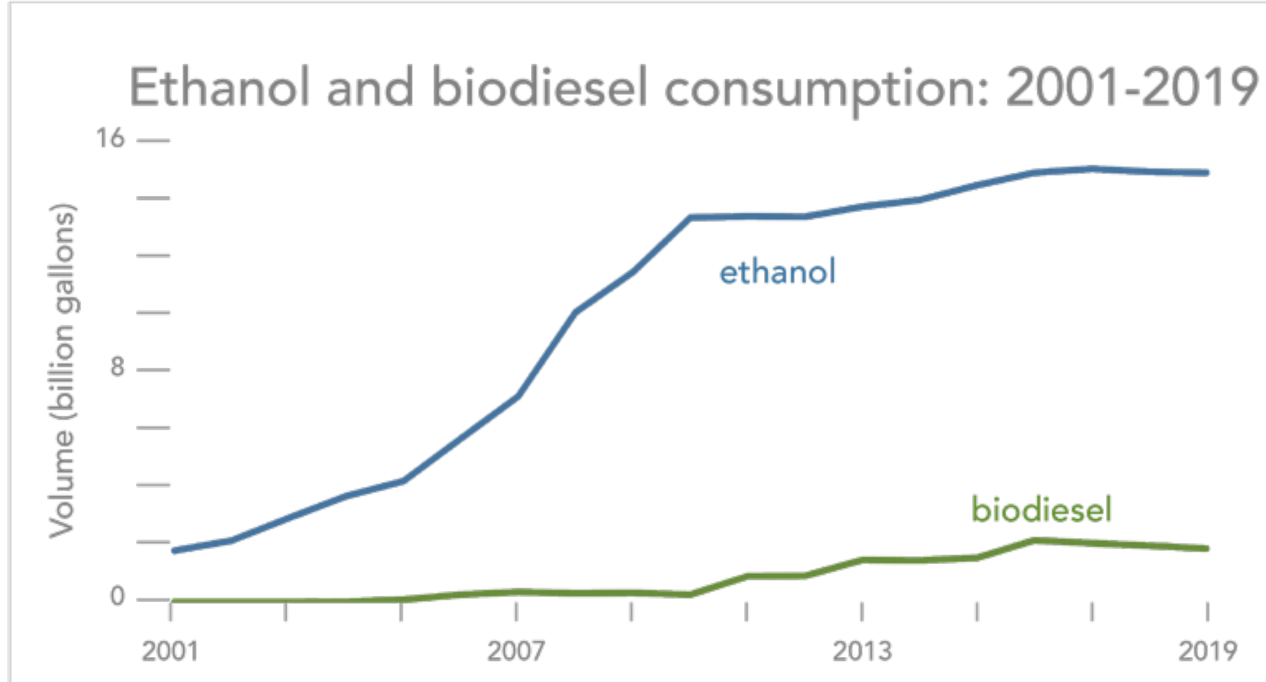


2019 Biofuel Production in U.S. ~ 18.2 billion gallons

~ 9% of 200 B gallon total fuel demand

Ethanol 15.0 B gal





Biodiesel
1.9 B gal

Renewable diesel
0.9 B gal

Renewable natural gas
0.04 B gal

Sustainable aviation fuel
0.002 B gal

Heating oil
0.002 B gal

2019 fuel volumes https://www.epa.gov/fuels-registration-reporting-and-compliance-help/public-data-renewable-fuel-standard

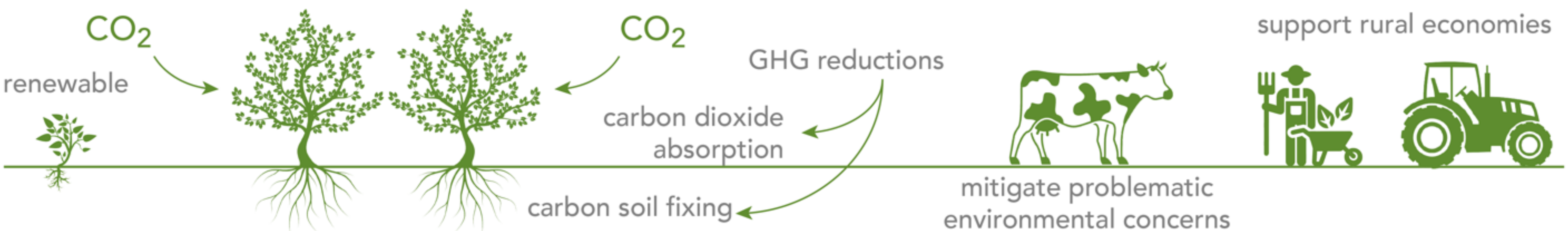
What is the potential for advanced biofuels?

Plant biomass provides 10% of global primary energy today and is expected to provide ~ 25% of primary energy in low-carbon scenarios for 2050

According to a 2016 DOE study, more than 1 billion tons of biomass can be domestically converted into biofuels and products.

Biomass could up to 50 billion gallons of liquid fuel in the U.S. annually by 2030 (~ 3× today's volume)

Beneficial biofuel attributes:



Rogers et al. 2016, An assessment of the potential products and economic and environmental impacts resulting from a billion ton bioeconomy. onlinelibrary.wiley.com/doi/10.1002/bbb.1728/full

Learning from the past: using waste streams to reduce costs

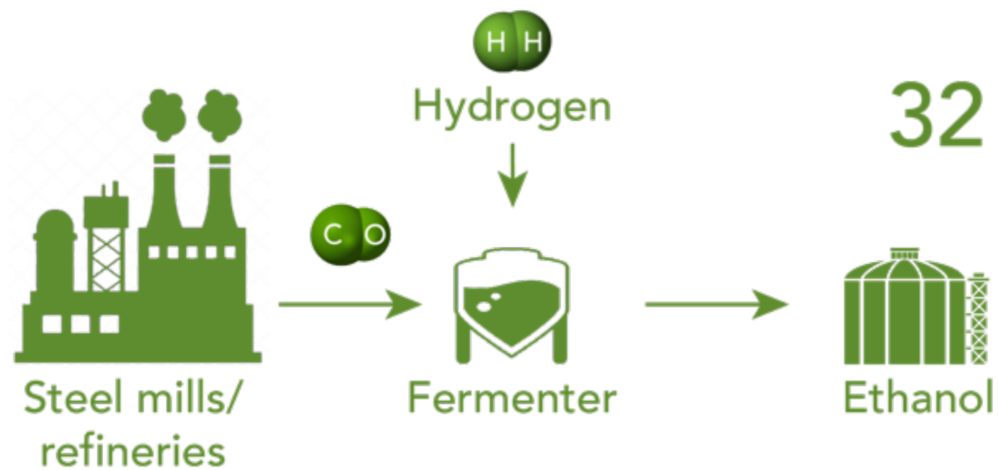
Feedstocks are the primary cost contributor to biofuels

Fuels from sugars fermentation are too expensive

$0.01 increase $0.20 increase

Aviation fuel example from Gruber, Patrick. 2018. Advanced Bioenergy Leadership Conference, Washington, D.C., February 28–March 2, 2018.

Opportunity: CO waste stream



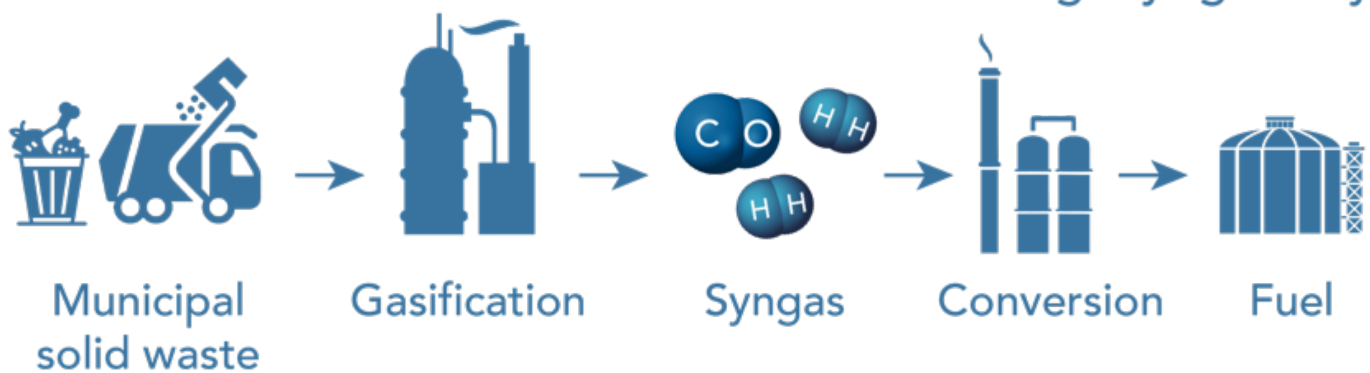
32 B gal/yr globally

LanzaTech commercial facility (16 Mgal/yr capacity) started in 2018

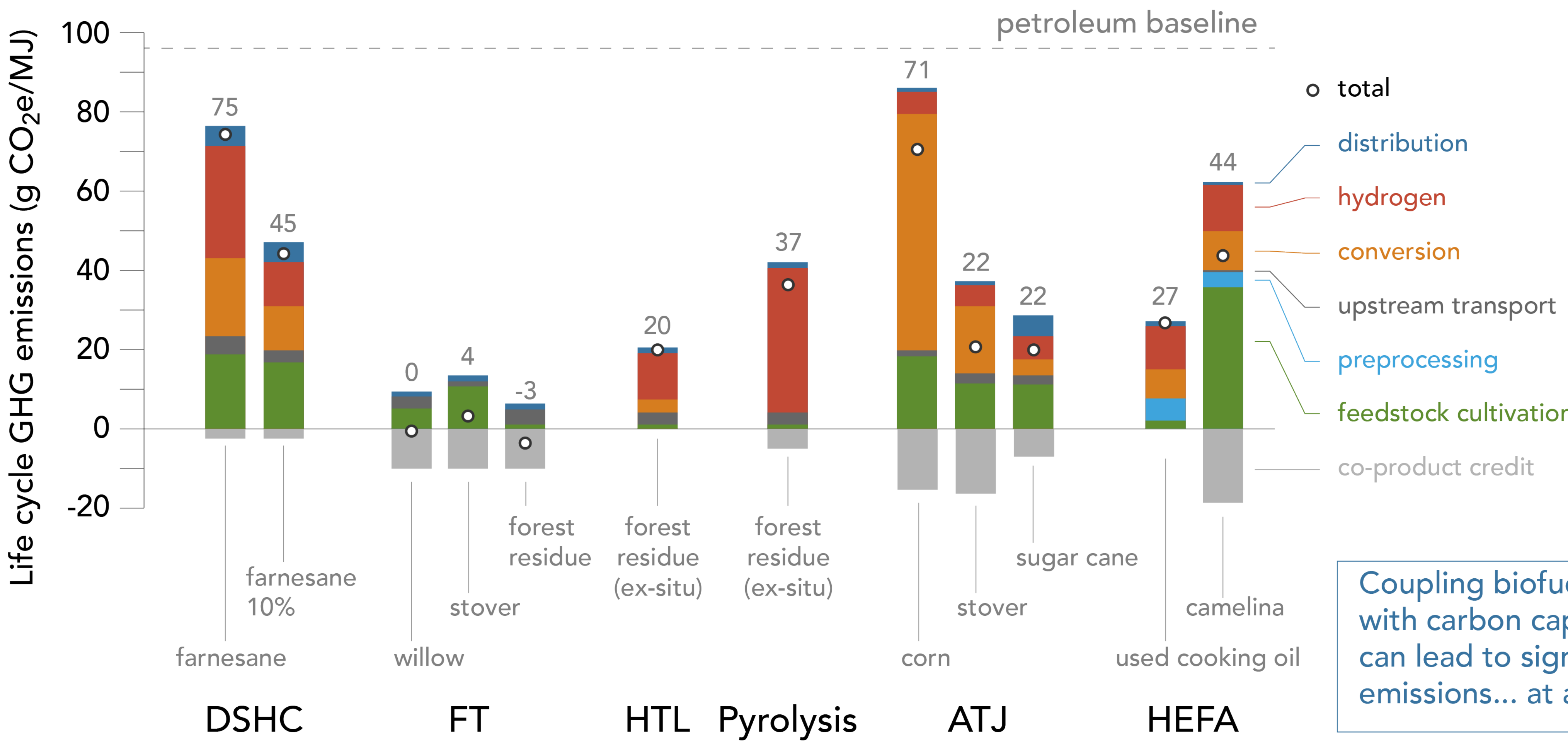
Other opportunity areas:

Opportunity: Municipal solid waste

18 B gal/yr globally



What is the GHG reduction potential for biofuels?



Coupling biofuel production with carbon capture/storage can lead to significant negative emissions… at a cost

GHG reduction potential varies greatly; near-zero life cycle emissions are possible

DSHC = direct sugar to hydrocarbon; FT = Fisher-Tropsch; HTL = hydrothermal liquefaction; ATJ = alcohol to jet; HEFA = hydroprocessed esters and fatty acids

Adapted from de Jong et al. Biotechnol Biofuels (2017) 10:64 DOI 10.1186/s13068-017-0739-7 renewable synthetic fuels

e-gasoline

e-fuels

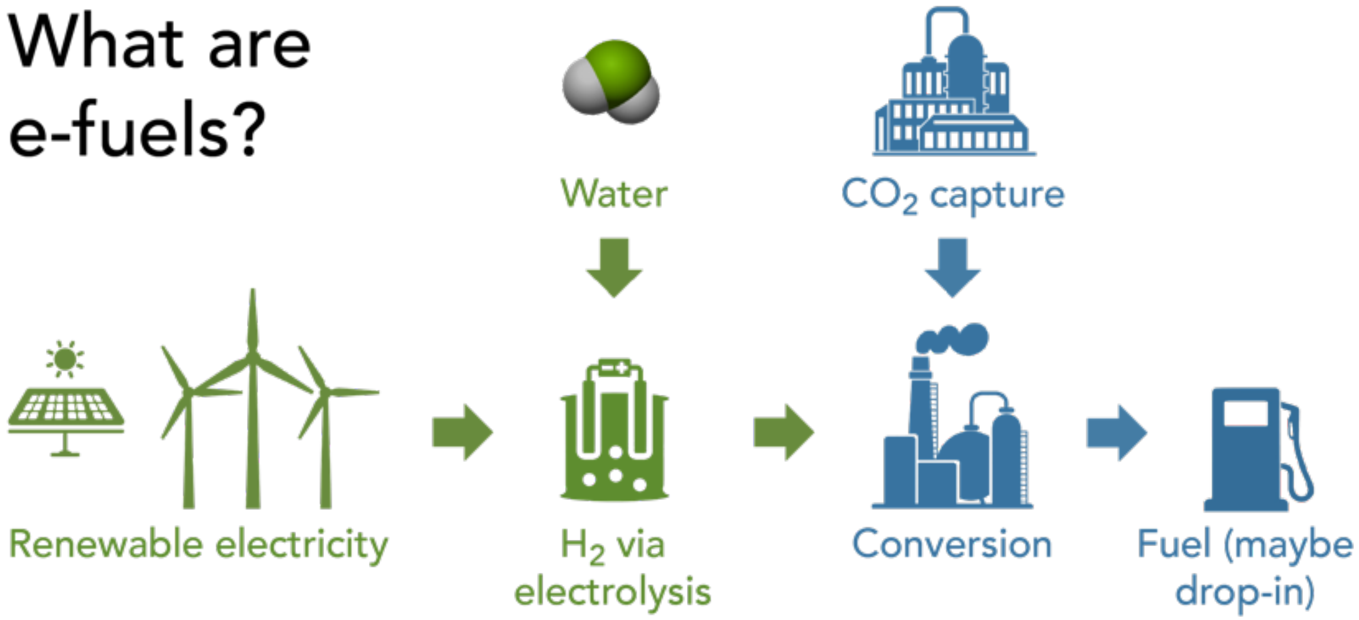
power-to-x

syn-fuels

e-diesel

electro-fuels

What are e-fuels?



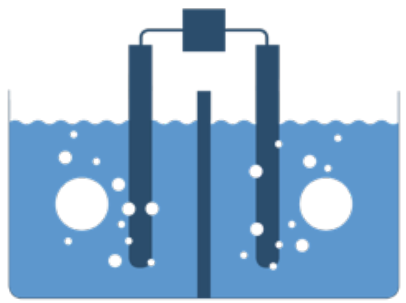
Typical e-fuel definitions assume green hydrogen production, with conventional chemical processes used to produce fuels

These "indirect thermochemical" production pathways are very mature, and hence low risk

FT	MTO/MTG	MOGD
Fischer-Tropsch	Methanol-to-olefins, gasoline	Mobil olefins to gasoline & distillate
ca 1925	*ca 1988*	*ca 1988*

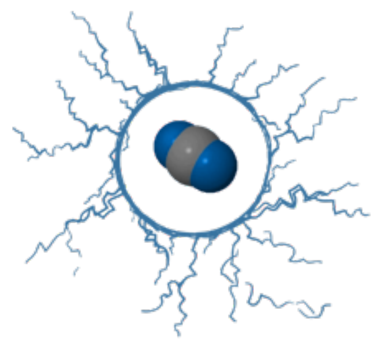
Other e-fuel routes exist that are earlier TRL and may have benefits vs current pathways

Direct electrochemical



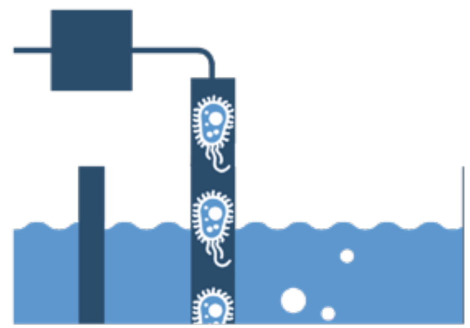
CO_2 converted directly to fuels or intermediates

Nonthermal plasma



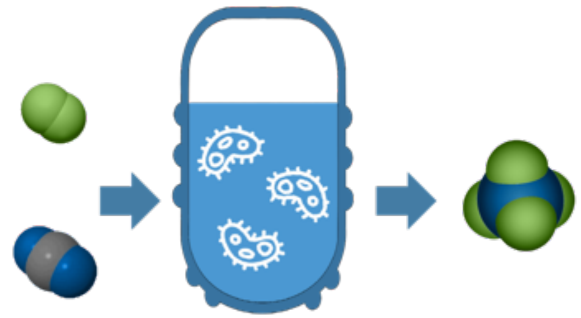
High voltage electrons convert CO_2 to fuels

Direct bioelectrochemical



Electrolysis with biocathode inoculated with microorganisms

Indirect bioelectrochemical



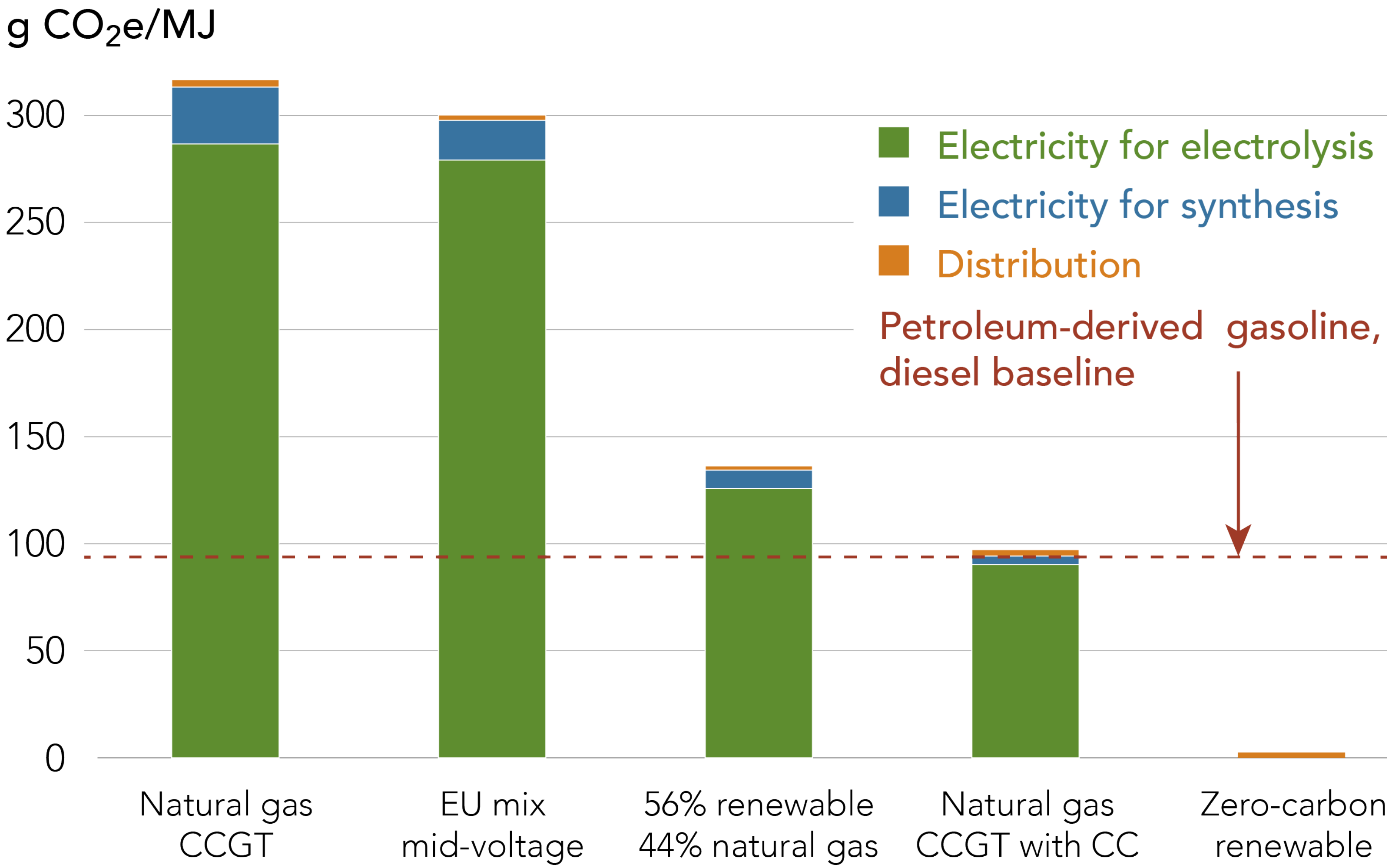
Biocatalysts convert CO_2 and H_2 to CH_4 and other products

Grim et al., Energy Environ. Sci., 2020, 13, 472

TRL = technology readiness level

What is the GHG reduction potential of e-fuels?

Lifecycle carbon intensity of electro-diesel



CCGT = combined cycle gas turbine; EU = European Union; CC = carbon capture

https://www.transportenvironment.org/sites/te/files/publications/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf

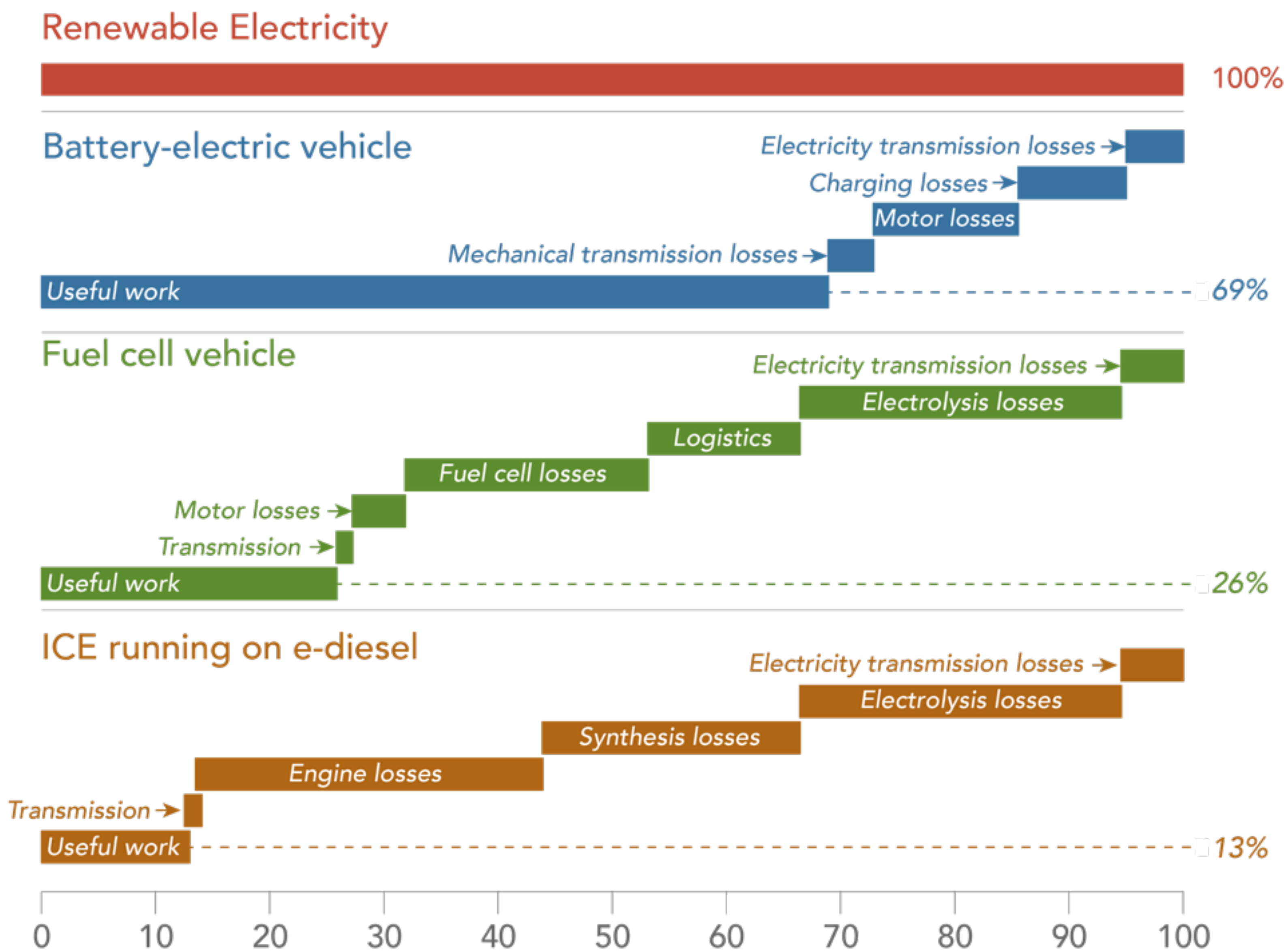
Electric grid needs to be > ~70% renewables for e-fuels to have lower carbon intensity than petroleum fuels

The main issue is NOT whether e-fuels can be low-GHG…

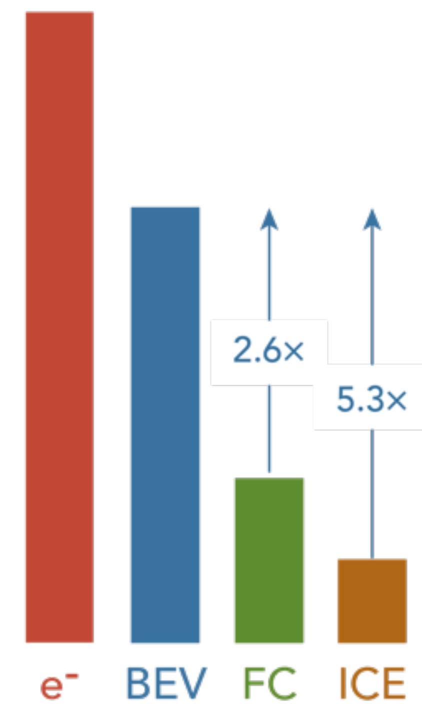
… with enough renewable energy, ANYTHING can be transformed into a low-GHG process

The real issue is how efficiently are the (scarce and precious) renewable electrons being used?

e-fuels produced from indirect thermochemical pathways have low energy efficiency

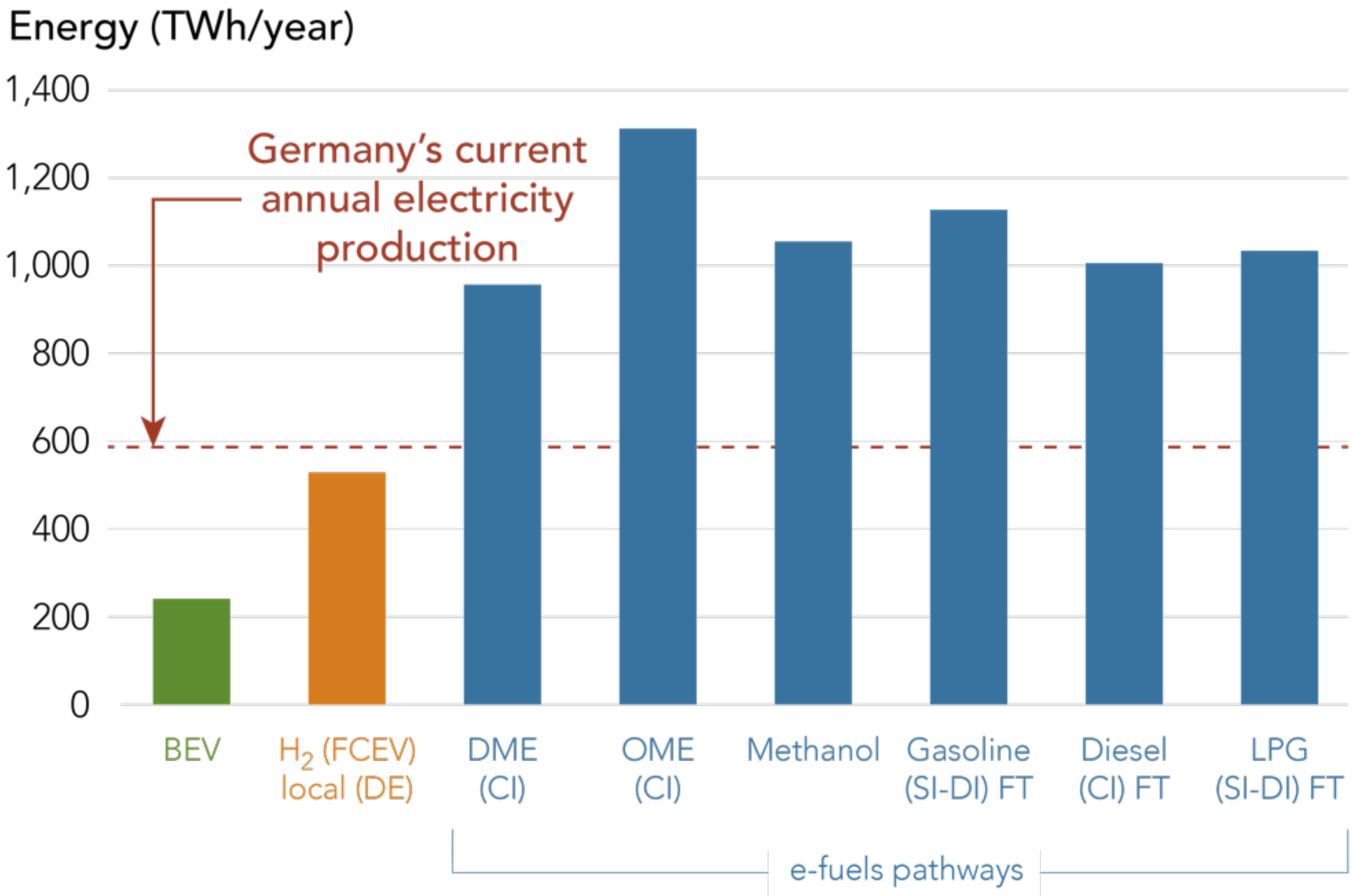


Adapted from: Sustainable synthetic carbon based fuels for transport: Policy briefing; 2019, The Royal Society



Using renewable electricity in BEV provides 2.6× energy to the vehicle wheels than operating a fuel cell vehicle, and 5.3× more efficient than operating an ICE on e-diesel

Future WTW Energy Requirement to convert 100% of Germany's LD and HD Fleet



Germany today: 50% renewables
Wind ~ 35% of total

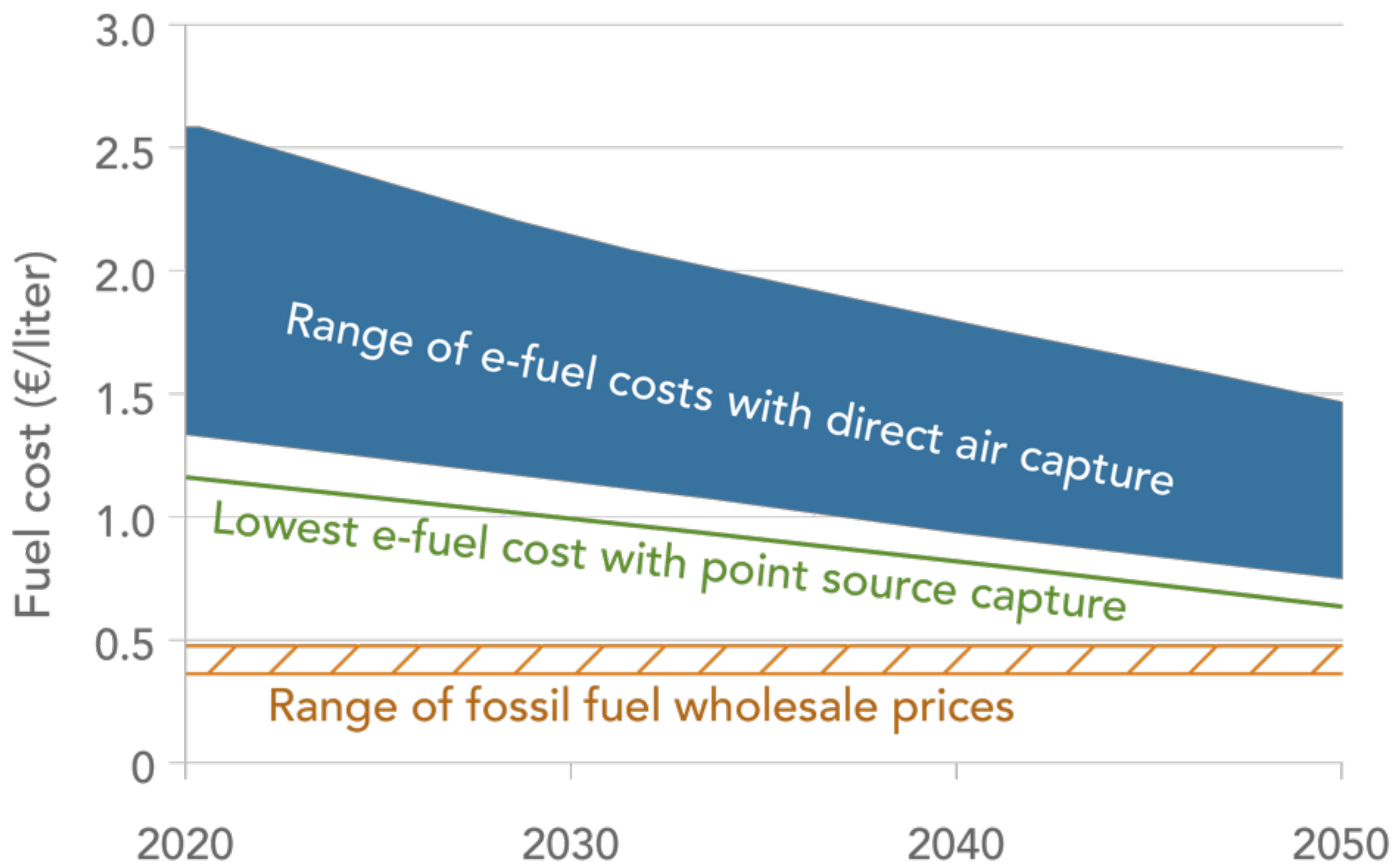
30,000 turbines (210 TWh/year)

Germany in future to replace all petroleum with e-fuels via wind

BEV: 11,000 new 5 MW turbines
FCEV: 23,000 new 5 MW turbines
e-fuel: ~40,000 new 5 MW turbines

https://www.fvv-net.de/fileadmin/user_upload/medien/materialien/FVV_Future_Fuels_Study_report_Defossilizing_the_transportation_sector_R586_final_v.3_2019-06-14__EN.pdf

And… e-fuels will be expensive



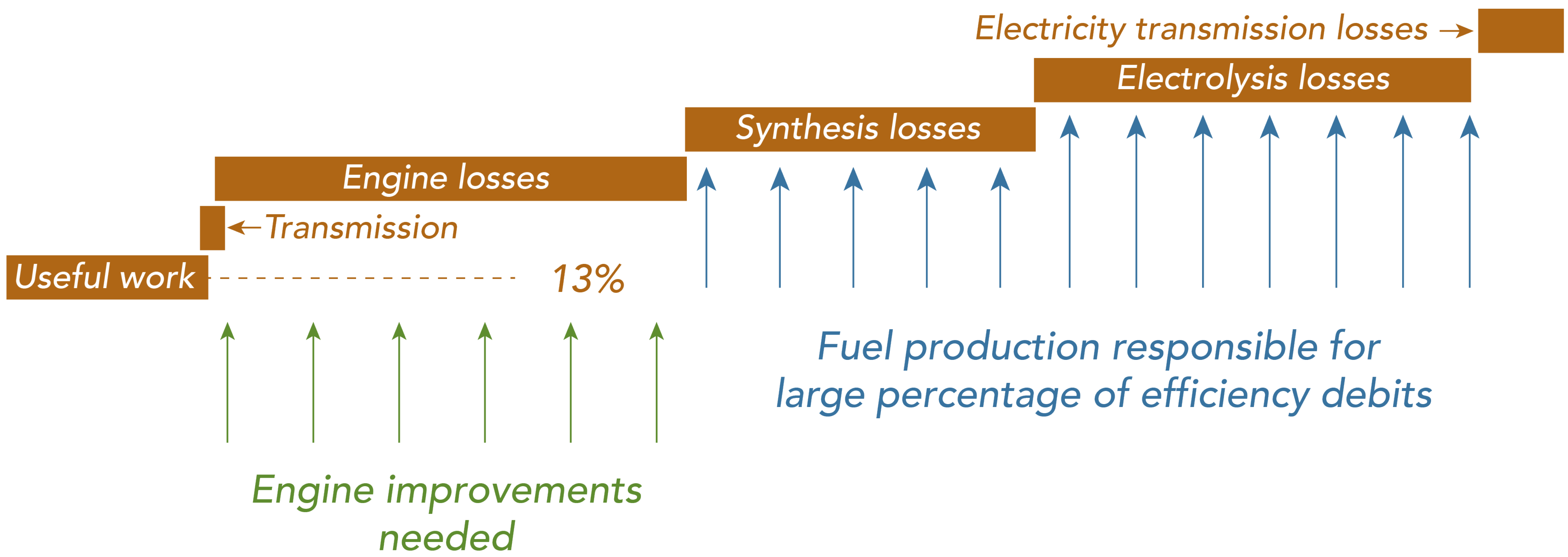
At best, e-fuels will be twice as expensive as petroleum-based fuels…

… and quite possibly more than that

https://www.fvv-net.de/fileadmin/user_upload/medien/materialien/FVV_Future_Fuels_Study_report_Defossilizing_the_transportation_sector_R586_final_v.3_2019-06-14__EN.pdf

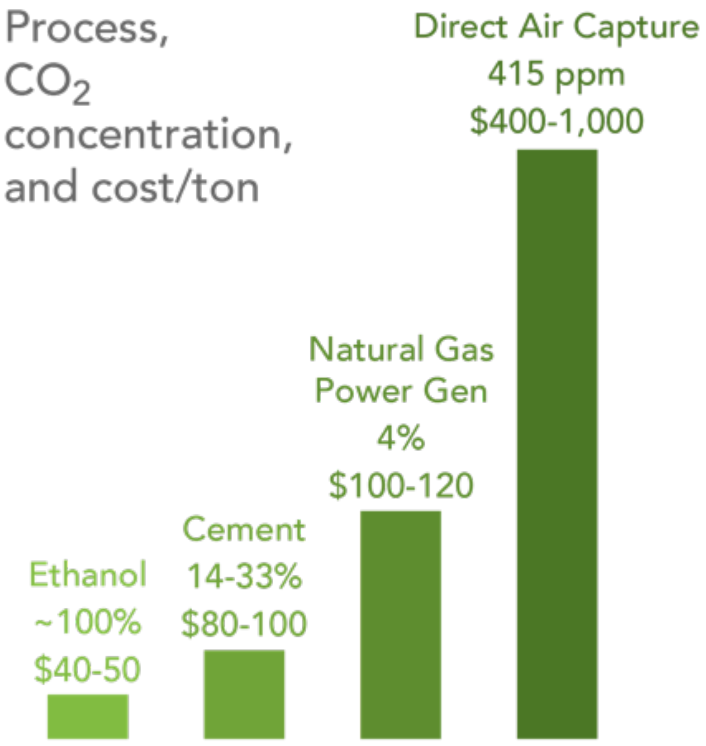
Are these e-fuels challenges insurmountable?

How do we close the efficiency gap with direct electrification?

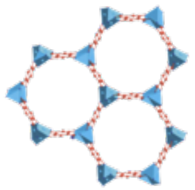


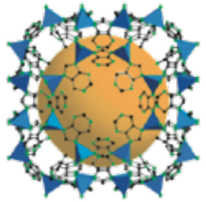
CO_2 capture costs depend on concentration of stream

Process, CO_2 concentration, and cost/ton



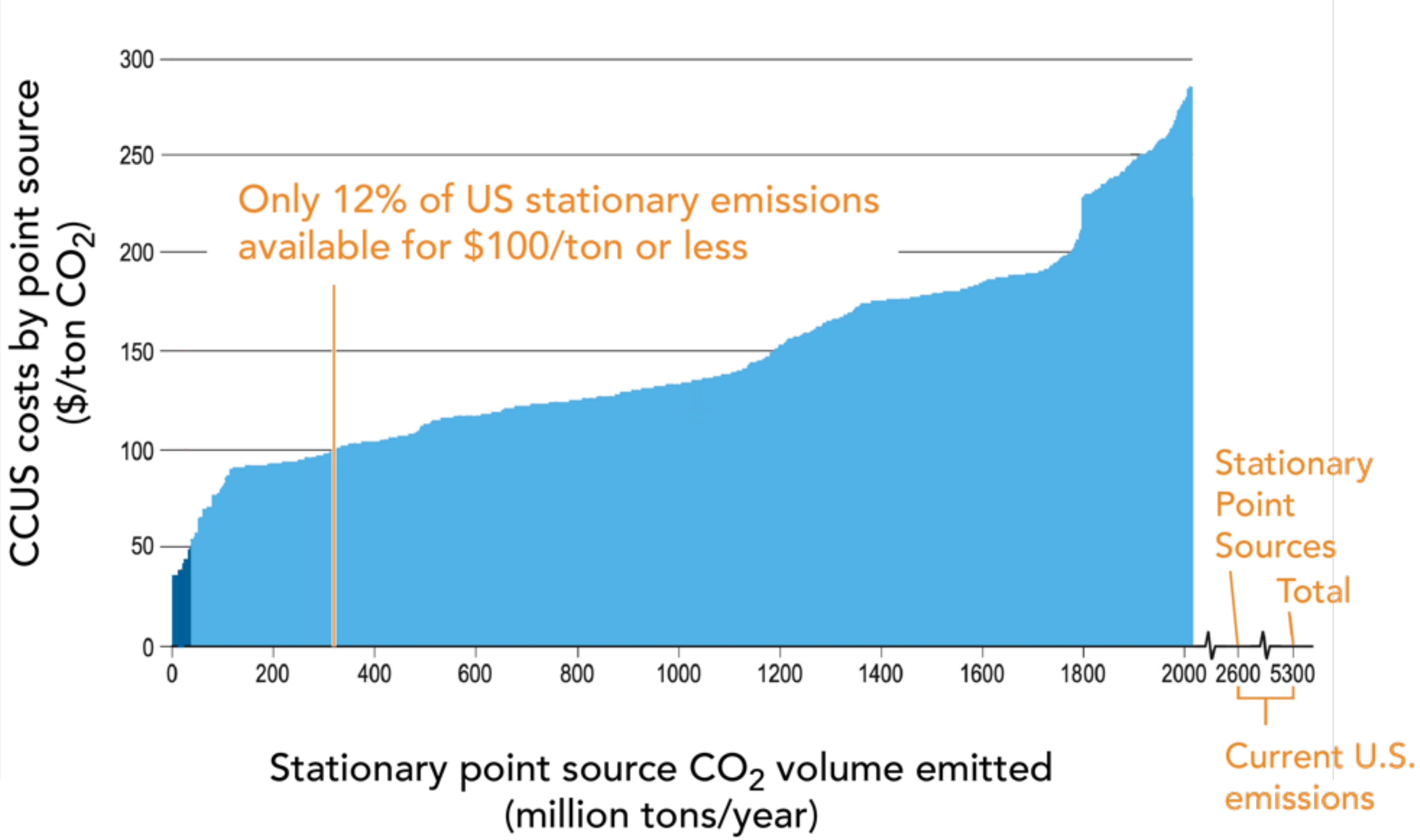
Research opportunities:





New materials for carbon capture

There is limited availability of high concentration (= low cost) CO_2 from stationary point sources

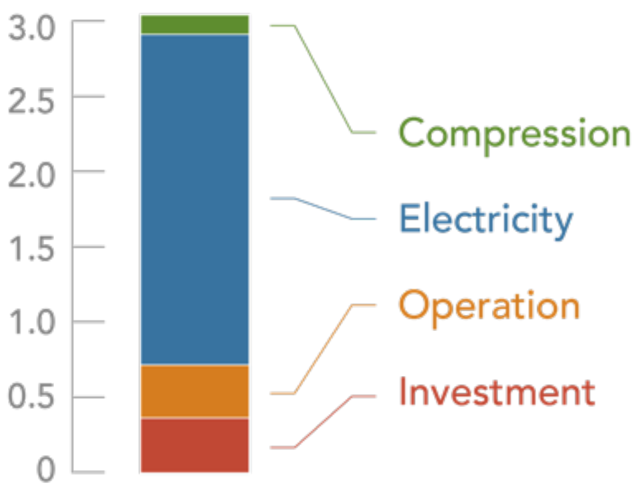


CCUS = carbon capture, use, and storage

Adapted from "Meeting the Dual Challenges: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage," National Petroleum Council, 2019

Improving electrolytic hydrogen production

Hydrogen production costs (€/kg)



Electricity is a major contributor (~70%) to cost

$0.02/kWh

Renewable energy costs needed to provide hydrogen at

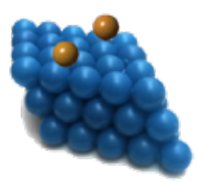
< $2/kg

(together with other technology advances)

Research needs

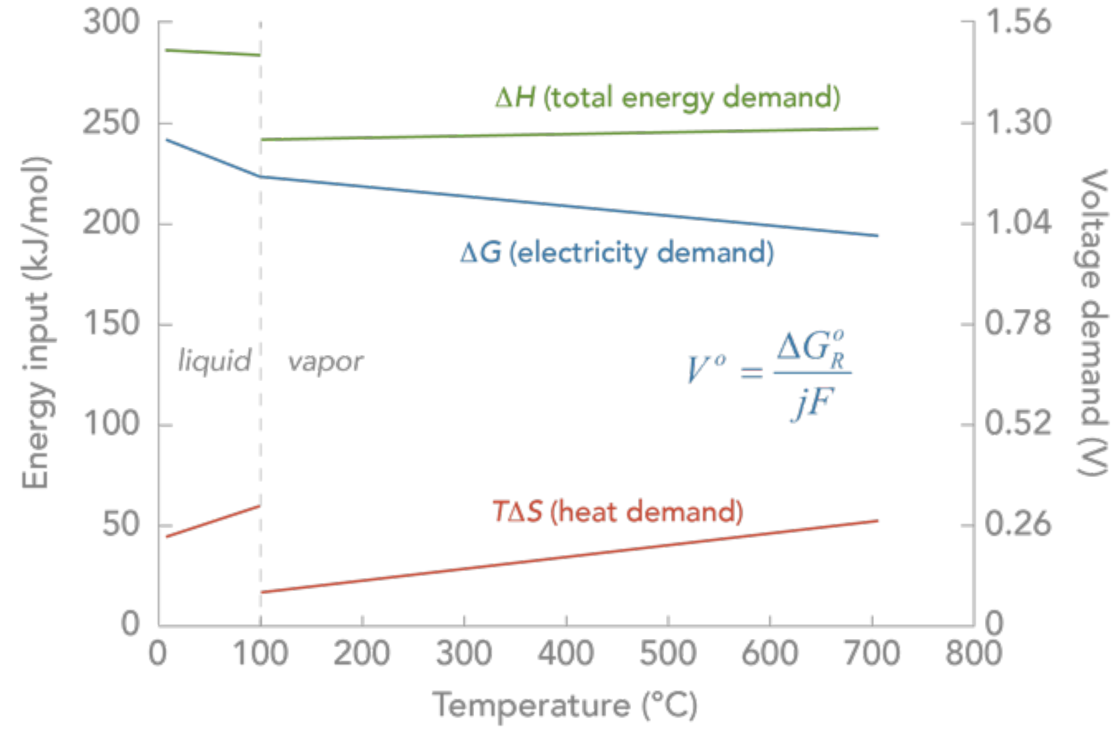
Integration with waste heat

High T materials/ corrosion



Improved catalysts and electrolytes

Benefits of conducting electrolysis at high T



60-70%

Current electrolyzer efficiency

~90%

Potential high-T electrolyzer efficiency

Kinetics and electrolyte conductivity also improved at high T

https://www.cder.dz/A2H2/Medias/Download/Proc%20PDF/PARALLEL%20SESSIONS/%5BS05%5D%20Production%20-%20Water%20Electrolysis/15-06-06/414.pdf

A (very) brief survey of electrochemical/bio-electrochemical conversion

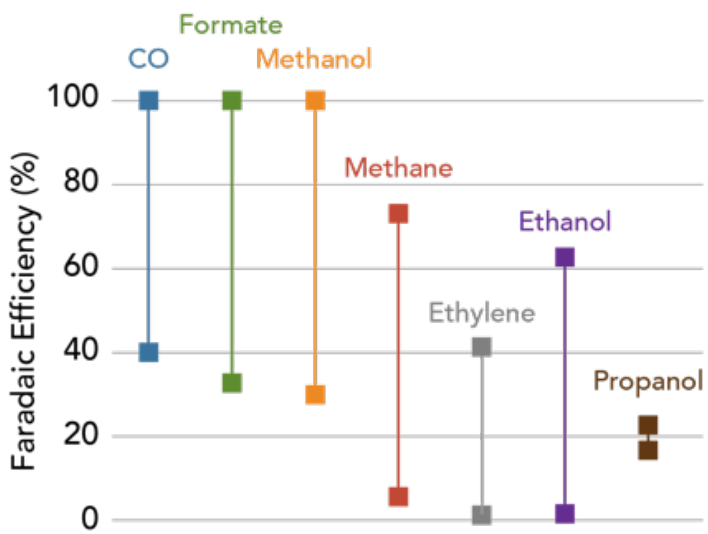
$$\varepsilon_{\text{Faradaic}} = \frac{z \cdot n \cdot F}{Q}$$

z = # of e⁻ required for given product

n = # of moles of given product

F = Faraday's constant

Q = total charge passed



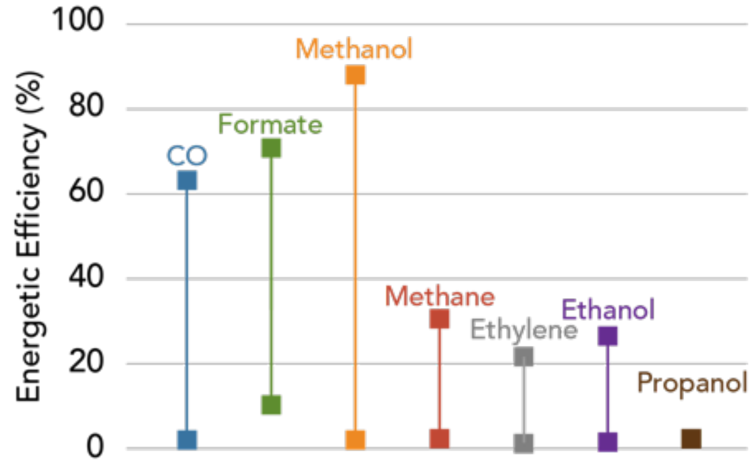
Range of Faradaic efficiencies from laboratory studies from 1985 - 2017; adapted from Jouny et al., Ind & Eng. Chem. Res. 2018 57 (6), 2165-2177, DOI: 10.1021/acs.iecr.7b03514

$$\varepsilon_{\text{energetic}} = \sum_i \frac{E_i^o \varepsilon_{i,\text{Faradaic}}}{E_i^o + \eta}$$

E_i^o = equilibrium cell potential for product i

$\varepsilon_{i,\text{Faradaic}}$ = Faradaic eff of product i

η = total cell overpotentials



Range of energetic efficiencies from laboratory studies from 1985 - 2017; adapted from Jouny et al., Ind & Eng. Chem. Res. 2018 57 (6), 2165-2177, DOI: 10.1021/acs.iecr.7b03514

Species	Rate of Formation[a]	Selectivity[b]	Energy Efficiency[c]	Current TRL[d]
Carbon Monoxide	High	High	High	High
Ethylene	High	Medium	Low	Low
Formate	Medium	High	Medium	Low
Methane	High	High	Medium	High
Acetate	Low	High	Medium	Low
Methanol	High	High	High	High

[a] High: >200 mA/cm² (or commercial TC), Medium: 200 >/>100 mA/cm², Low: <100 mA/m²
[b] High: >80%, Medium 80% > FE > 60%, Low: < 60%
[c] High: >60%, Medium 60% > EE > 40%, Low: < 40%
[d] High: Operated at TRL > 6, Medium: Operated TRL 4-6, Low: Operated TRL 1-3

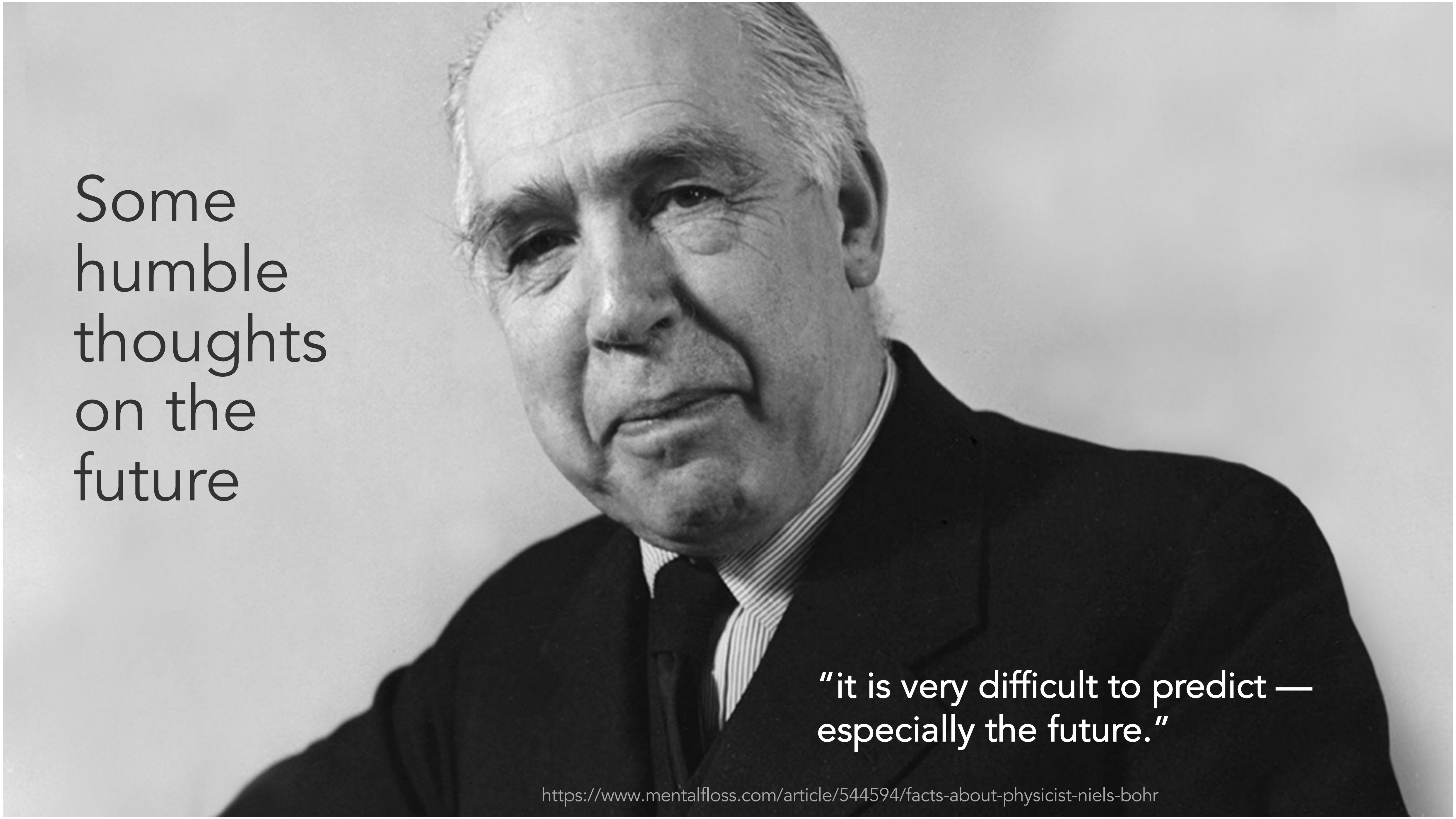
Fig. 12 Qualitative evaluation of product ease of formation.

Key takeaway: small molecules are most readily formed by electro- and bio-electrochemical processes

Direct synthesis of gasoline/diesel range fuels is a long term goal

Grim et al., Energy Environ. Sci., 2020, 13, 472

Some humble thoughts on the future



"it is very difficult to predict — especially the future."

https://www.mentalfloss.com/article/544594/facts-about-physicist-niels-bohr

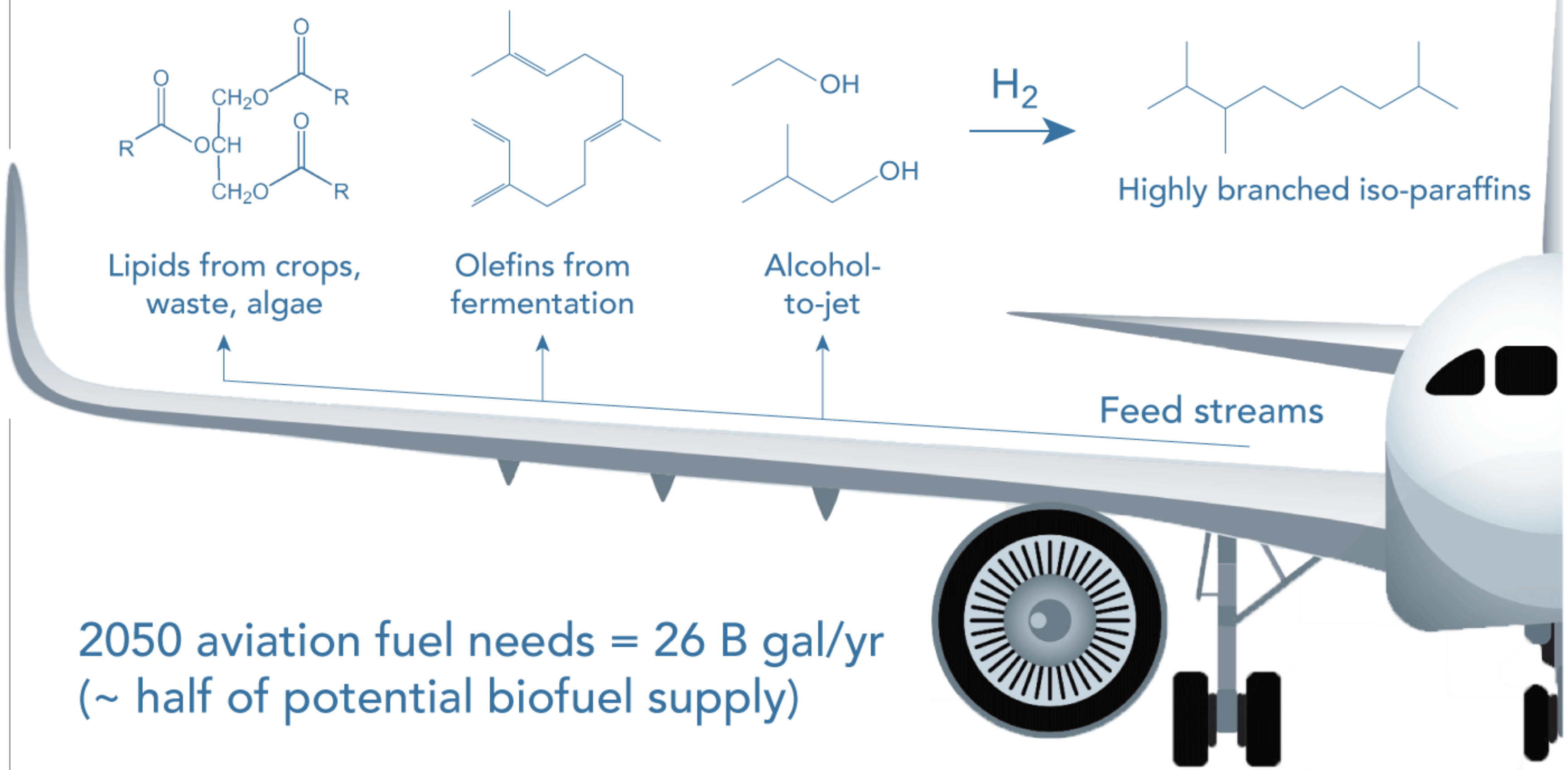
Key aviation opportunity: biofuels

Aviation fuel composition is tightly controlled for safety reasons - new drop-in fuels needed

Key research needs

- Reduce feedstock and conversion costs
- Reduce hydrogen use
- Feedstock diversification
- Process intensification to reduce capital costs

Biomass well suited to produce high-value jet blendstocks



2050 aviation fuel needs = 26 B gal/yr
(~ half of potential biofuel supply)

Sustainable Aviation Fuel: Review of Technical Pathways, Department of Energy, 2020

Key marine opportunities: minimally processed biofuels and ammonia

Marine engines are "omnivorous"; low quality of current HFO provides opportunities

Replacing HFO in large marine vessels with minimally processed, heavy biofuels or ammonia can reduce sulfur, CO_2, and criteria emissions

Key research needs

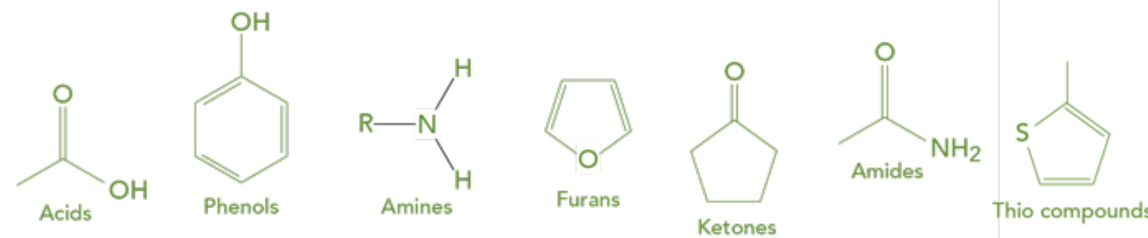
Optimizing engine operation with new fuels

Developing on-vessel fuel blending controls

Maximizing fuel cost, properties, & conversion

Process intensification to reduce capital costs

Biofuels:



Use of minimally processed fast pyrolysis bio-oil and HTL biocrude is a promising option

Ammonia:

80% of the energy consumed today in NH_3 synthesis is for H_2 production

Near term, NH_3 production will likely proceed via Haber-Bosch

Low faradaic efficiencies and current densities are persistent challenges to overcome with electrochemical ammonia synthesis

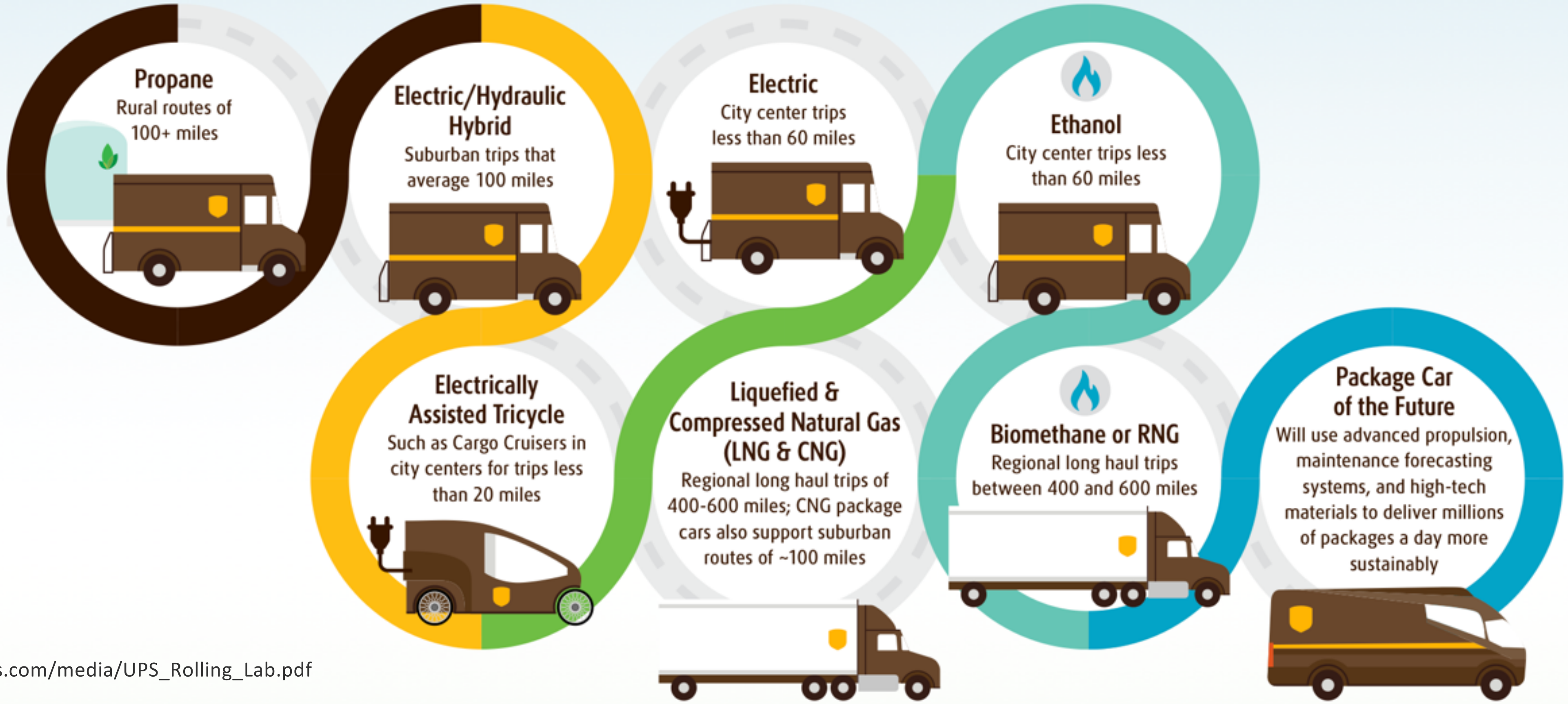
Understanding the Opportunities of Biofuels for Marine Shipping, ORNL/TM-2018/1080; bio-oil info from https://doi.org/10.1016/j.fuproc.2016.04.015; HTL = hydrothermal liquefaction

What about trucks?

UPS Rolling Laboratory

A diverse fleet of alternative fuel and advanced technology vehicles.

Through our rolling laboratory, we can determine how alternative fuels and advanced technologies perform in real-world operating conditions, quickly deploy viable options at scale, and spur market growth for alternative solutions.



https://sustainability.ups.com/media/UPS_Rolling_Lab.pdf

MD/HD vehicle opportunities

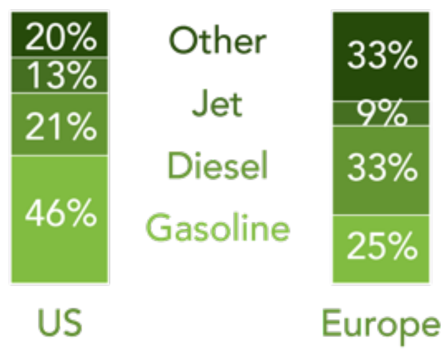
Significant incentive for transitioning MD/HD engines to gasoline-range fuels

LD electrification and meeting low-carbon jet/marine creates need to find outlet for lighter fuels

Key research needs

- Co-optimizing new fuel/ engine strategies
- Developing optimal hybrid powertrains
- Harmonizing powertrain options across diverse fleet
- Process intensification to reduce capital costs

Refinery integration

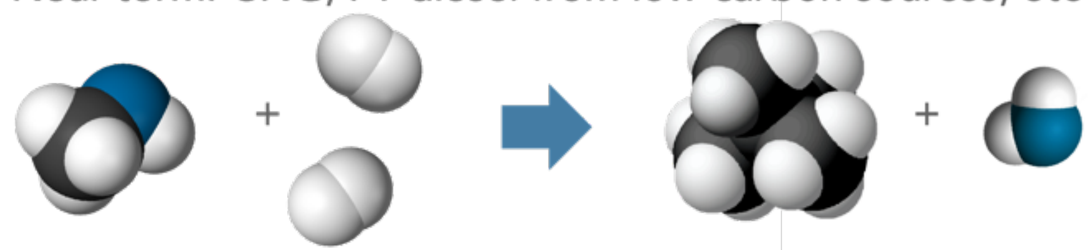


US refineries designed to maximize mogas production

Leveraging sevearal $trillion of US refining infrastructure needed to minimize cost

e-fuels

Near-term: CNG, FT diesel from low-carbon sources, etc



Longer-term: methanol-to-gasoline

Mogas = motor gasoline; refinery info from https://www.energy.gov/sites/prod/files/2014/03/f9/deer07_williams.pdf

Summary and parting thoughts

Abundant sources of low-carbon fuels for IC engines are needed to meet global decarbonization goals

Advanced biofuels can supply some of this need

e-fuels could be a longer-term technology that provides low-GHG options

We need to use our renewable electrons wisely

Getting to zero carbon will be really, really hard

The transition will be costly and difficult

The time to start is now

Thank You

www.nrel.gov/transportation

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided predominantly by the DOE Office of Energy Efficiency and Renewable Energy's Vehicle Technology Office and Fuel Cell Technologies Office. The views expressed in this presentation do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL

Transforming ENERGY