Achieving Zero Net Carbon: Decarbonizing the Transportation Sector

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California Bioresources Alliance Symposium
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DOE's National Laboratory System

NREL at a Glance

2,500

Employees,
including more than
600
early-career researchers and visiting scientists

World-class
facilities, renowned technology experts

nearly
820

Partnerships
with industry, academia, and government

Campus
operates as a living laboratory

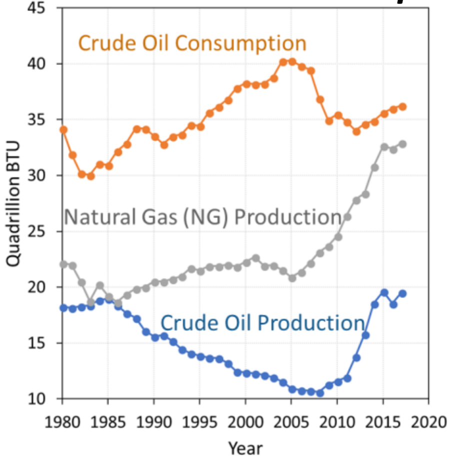
>$1B
annually

National Economic Impact

Megatrends and Economy-wide Decarbonization

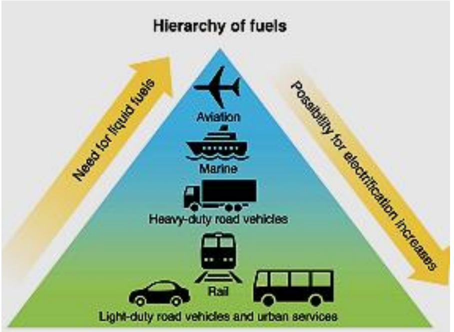
Trends in Carbon Management

Major Shifts in US Fossil Fuel Production and Consumption



Increased Electrification

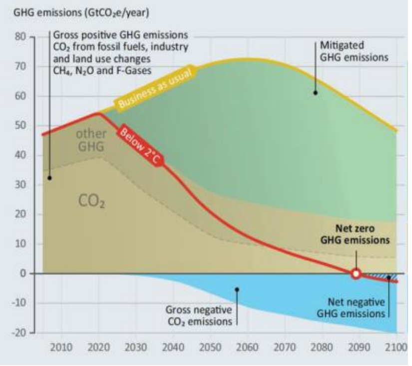
Decreasing costs for renewable electricity



International Maritime Organization

Reduce sulfur in marine bunker fuel from 3.5% to 0.5% as of 2020

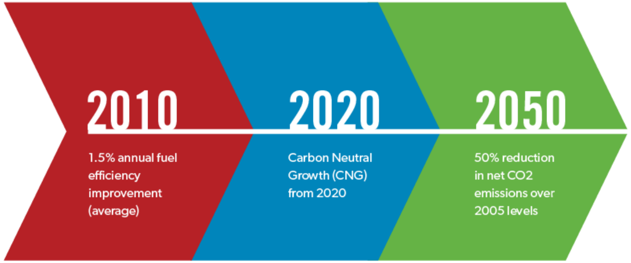
CO2 in the atmosphere: Need for Carbon-Negative Fuel Technologies



National Academy of Sciences

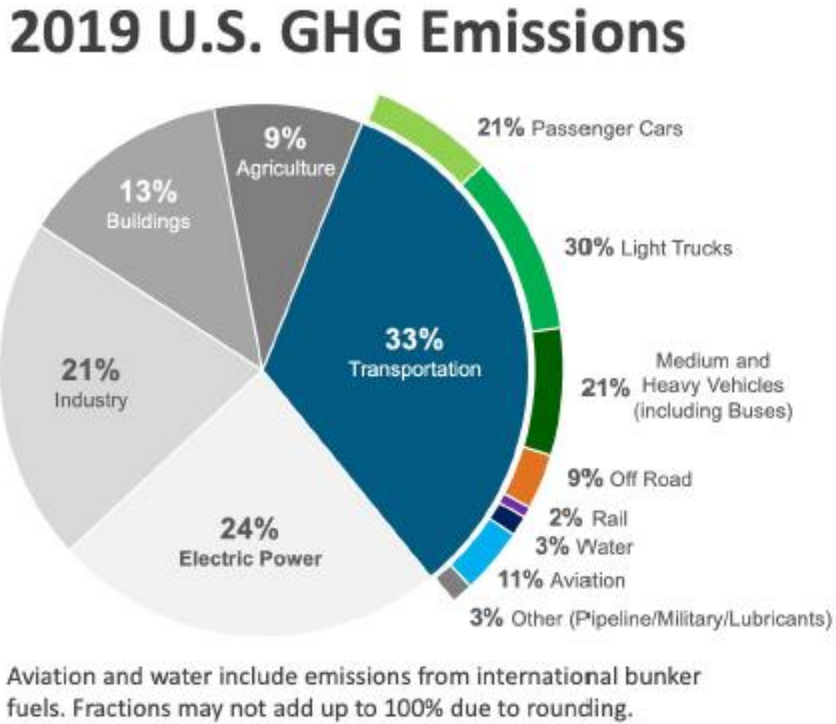
The Plastic Waste Nightmare

Sustainable Aviation Fuel



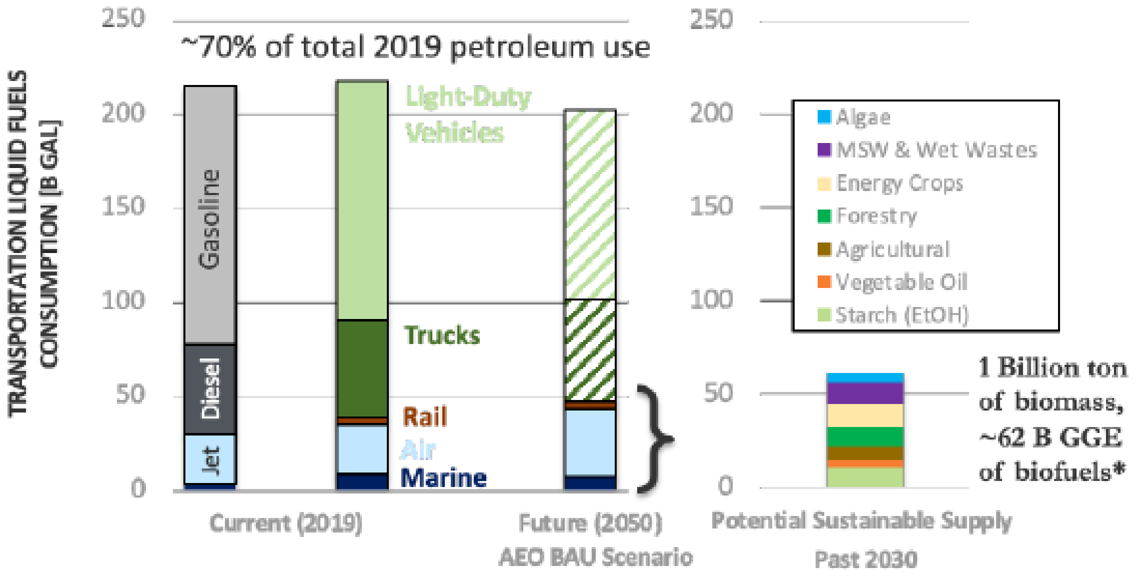
Airlines for America

Economy-wide Decarbonization



- **Transportation is the largest source of GHG emissions**
  - 50% of **energy expenditures and local pollution issues**
  - Significant implications for global competitiveness, trade, and domestic jobs
- **Transportation provides essential access to services and economic opportunities**
  - Must support demand for growth in **mobility options**

Biomass will be Critical to Achieving Objectives



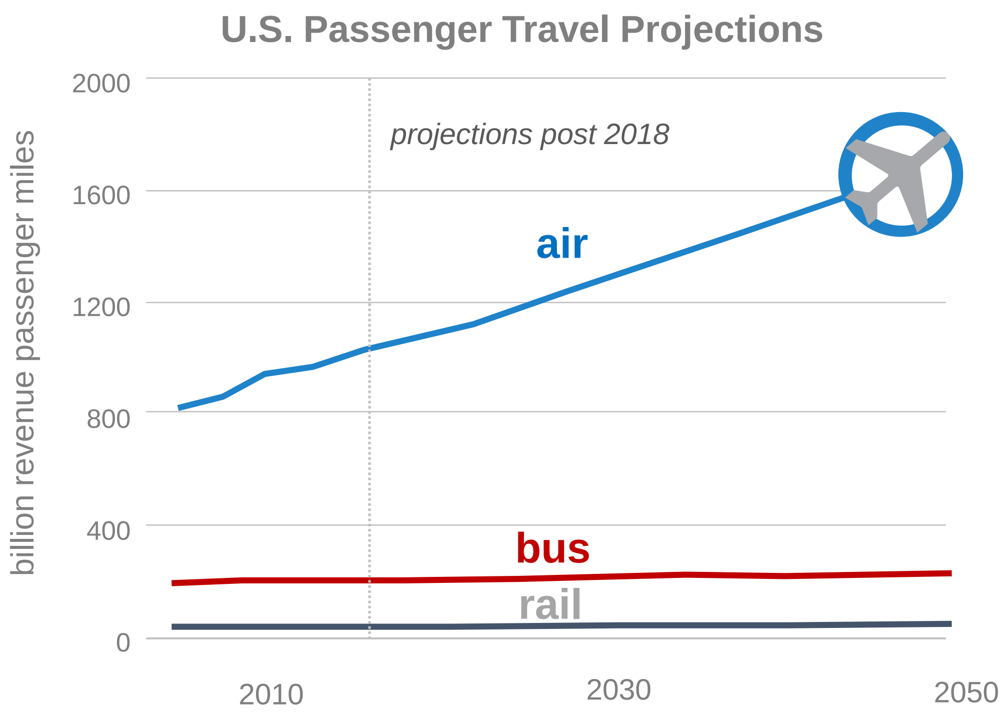
- Biomass can fully **supply future Aviation/ Maritime/Rail** (requires 75% of all feedstocks)
- Biggest market pull is **in sustainable aviation fuels** (SAF)
- DOE **has 3 large scale SAF Demo projects (Fulcrum, Red Rocks, Lanzatech)**
- Provides market for **current ethanol** (~17B gal, ~40% of corn production)

Sustainable Aviation Fuel (SAF)

Need for low carbon intensity fuels for aviation industry

- Air travel expected to nearly double by 2050 with jet fuel consumption making up 8% of transportation emissions

- U.S. consumes 26 billion gallons of jet fuel with limited prospects of commercial flight electrification

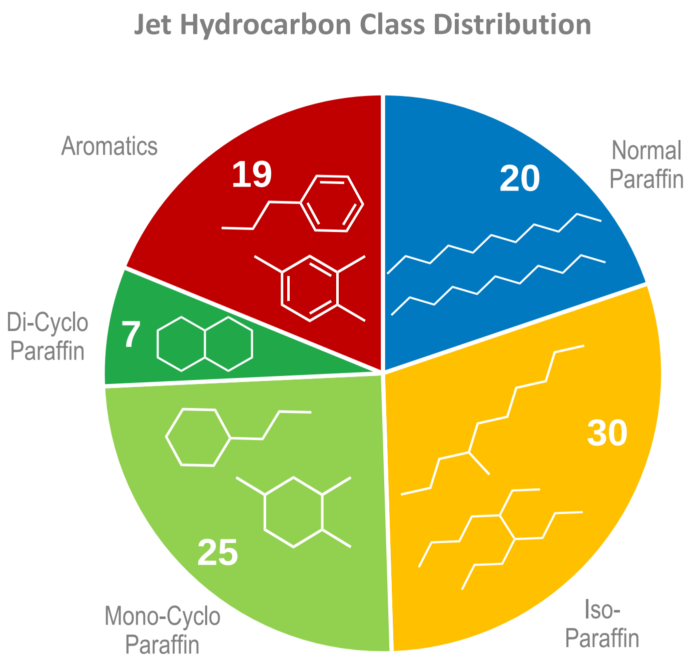


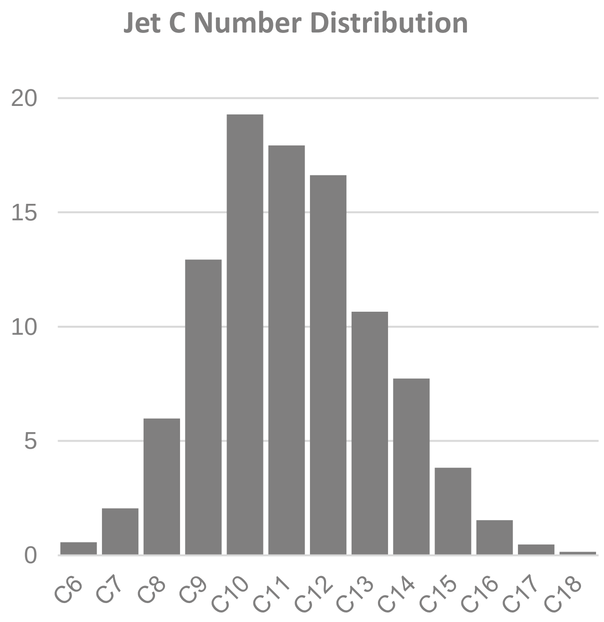
Sources: Bureau of Transportation Statistics; U.S. Energy Information Administration Outlook; Collins & McLarty (2020) Applied Energy, 265, 114787

Hydrocarbon Distribution and Chain Length Fulfill Specific Performance Goals

- Jet fuel comprised of 4 hydrocarbon types:
  1. Straight (normal paraffin)
  2. Branched (isoparaffin)
  3. Saturated ring (cycloparaffin)
  4. Unsaturated ring (aromatic)

- Typical jet fuel average carbon number is C11 with the majority of carbon chain lengths between C8 and C15



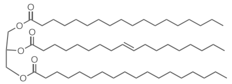
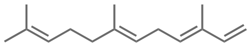
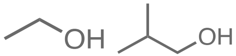
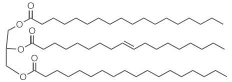
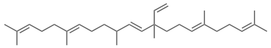


Sources: ASTM D1655; ASTM D7566; ASTM D4054; Holladay et al. (2020) DOE/EE-2041 8292

Currently seven ASTM annexes approved to produce SAF

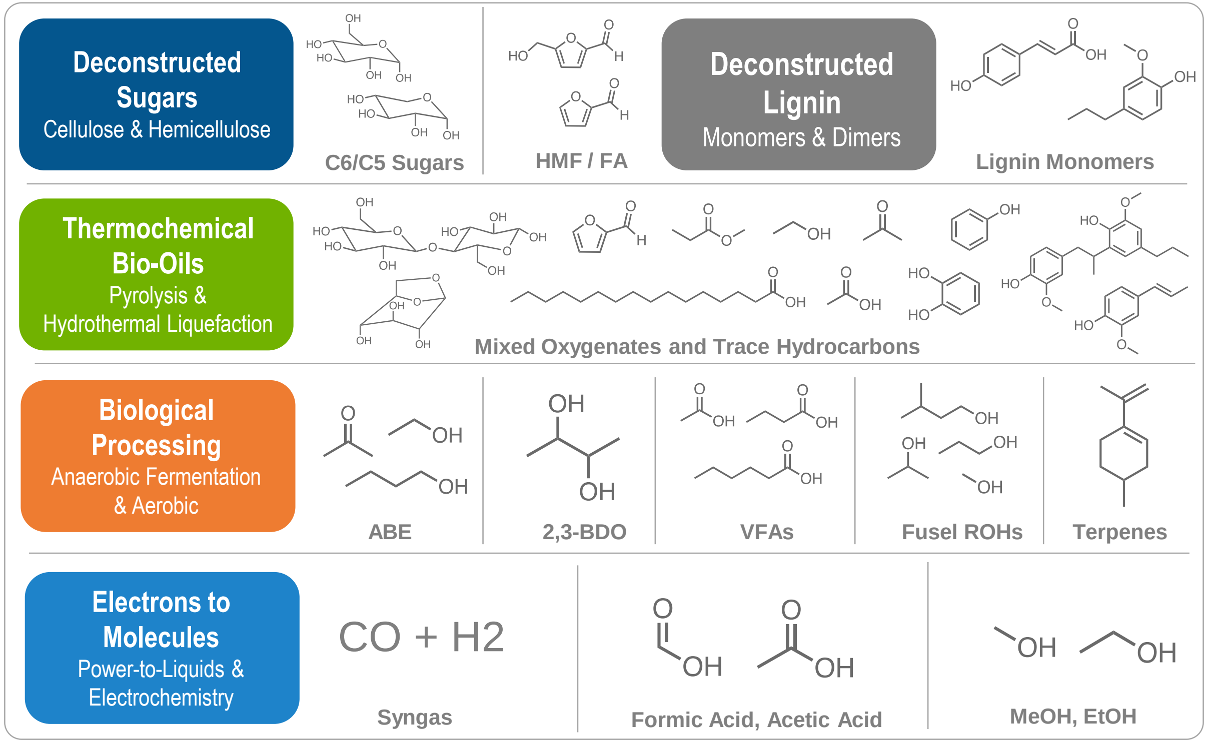
- Currently 7 ASTM approved SAF routes with intermediates that include lipids, alcohols, syngas, and biobased hydrocarbons (D7566)

- Several new SAF routes currently in ASTM evaluation process that include aqueous phase sugars to SAK (Virent), catalytic pyrolysis oil to SAF (Shell IH2), Alcohol to jet with aromatics (several)

	Starting Feedstock for SAF Route	
A1: FT-SPK 50% blend Fischer Tropsch Synthesized Paraffinic Kerosene	**Syngas**	CO + H_2
A2: HEFA-SPK 50% blend Hydroprocessed Esters & Fatty Acids Synthesized Paraffinic Kerosene	**Triglycerides & Fatty Acids**	
A3: HFS-SIP 10% blend Hydroprocessed Fermented Sugars Synthesized Isoparaffins	**Farnesene**	
A4: FT-SKA 50% blend Fischer Tropsch Synthesized Kerosene with Aromatics	**Syngas**	CO + H_2
A5: ATJ-SPK 50% blend Alcohol-to-Jet Synthesized Paraffinic Kerosene	**Ethanol & Isobutanol**	
A6: CHJ 50% blend Catalytic Hydrothermolysis Jet Synthesized Kerosene and Fatty Acids	**Triglycerides & Fatty Acids**	
A7: HC-HEFA SPK 10% blend Hydroprocessed Hydrocarbons & HEFA Synthesized Kerosene	**Algal Botryococcene**	

Source: ASTM D7566-20; Wang et al. (2016) NREL TP-5100-66291; Holladay et al. (2020) DOE/EE-2041 8292

Emerging routes to produce SAF from biomass and waste C

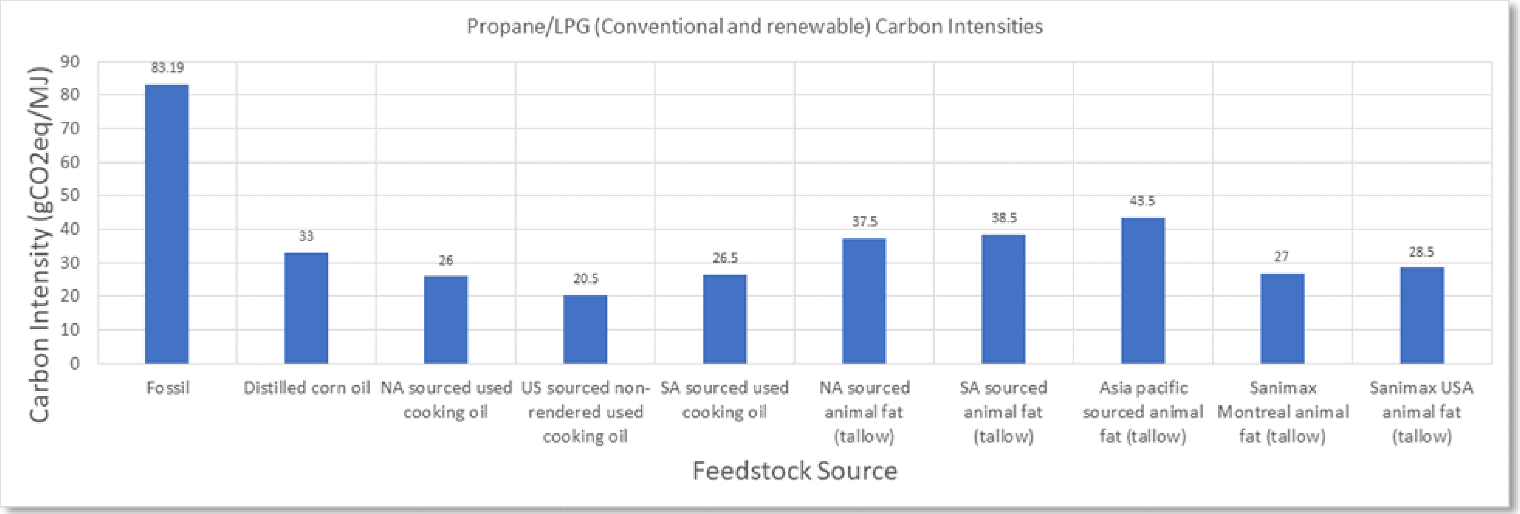


- Multiple biofuel technologies can produce SAF-range fuels from biomass and waste C
- Processes range from thermochemical, biological, hybrid, and electrochemical for biomass, waste, and CO2 feedstocks
- **Extensive chemical upgrading required to meet ASTM requirements**

Sources: Wang et al. (2016) NREL TP-5100-66291; Holladay et al. (2020) DOE/EE-2041 8292; Zhang et al. (2020) Recent Treads, Opportunities and Challenges of Sustainable Aviation Fuel; DOE (2021) BETO Project Peer Review

Feedstock is Important

CARB-certified carbon intensities for renewable propane



Additional feedstocks needed with new SAF conversion routes




Lignocellulosic Biomass (23 BGPY jet potential)

- Agricultural residues*	9.0 BGPY jet
- Forestry trimmings and residues*	7.1 BGPY jet
- Bioenergy crops by 2030*	7.4 BGPY jet

Assumes 34 gal of SAF range hydrocarbons per dry tonne of biomass, excluding other fuel cuts

Other Waste C Sources (10 BGPY jet potential)

- Inedible animal fats**	1.8 BGPY jet
- Animal manure**	4.7 BGPY jet
- Wastewater sludge**	2.0 BGPY jet
- Food waste**	2.7 BGPY jet
- MSW (paper, wood, yard)***	0.9 BGPY jet
- Industrial waste gas***	1.3 BGPY jet

BGPY = billion gallons per year; estimates of jet potential will vary based on conversion technology and feedstock composition

Sources: *2030 estimate from DOE 2016 Billion-Ton Report; **Bhatt et al. (2020) iScience, 23, 101221; ***CAAFI U.S. Jet Fuel production potential from wastes

- U.S. biomass and waste carbon availability has embedded energy content on par with current jet fuel consumption of 26 BGPY
- SAF provides links to agriculture, food security, and waste management with opportunities for cross-sector benefits at the intersection of energy and environment

Current SAF production in U.S. limited and competes with diesel

2020	2021	2022	2023
world energy 25 MPGY	Fulcrum BIOENERGY 7 MPGY	NESTE 25 MPGY	gevo 10 MPGY
NESTE 34 MPGY	RED ROCK BIOFUELS 6 MPGY	SkyNRG 34 MPGY	Go Sunshine drive clean, save green 29 MPGY
gevo DEMO		LanzaJet 10 MGPY	Fulcrum BIOENERGY 21 MGPY
TOTAL TBD		world energy 150 MGPY	ReadiFuels 24 MPGY

- New SAF capacity coming online within next 3 years with several pathways that expand feedstocks beyond FOGs
- New feedstocks includes lignocellulosic biomass, alcohol from industrial waste gas, and gasification of municipal waste and forestry residues

CAAFI COMMERCIAL AVIATION ALTERNATIVE FUELS INITIATIVE

Source: Commercial Aviation Alternative Fuels Initiative CAAFI.org

Thank You!

www.nrel.gov