



Sustainable Aviation Fuel: Decarbonizing American Aviation Through Agriculture

Jacob Miller, PhD
National Renewable Energy Laboratory Catalytic Carbon Transformation & Scale-up Center
National Council of State Legislators Agricultural Task Force Meeting
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NREL at a Glance

\$ 0.8B Research Portfolio

3,702 workforce, including:

- 2,721 regular/limited term
- 503 contingent workers
- 205 postdoctoral researchers
- 179 graduate student interns
- 94 undergraduate student interns

—as of 8/21/2023

World-class research expertise in:

- Renewable Energy
- Sustainable Transportation & Fuels
- Buildings and Industry
- Energy Systems Integration

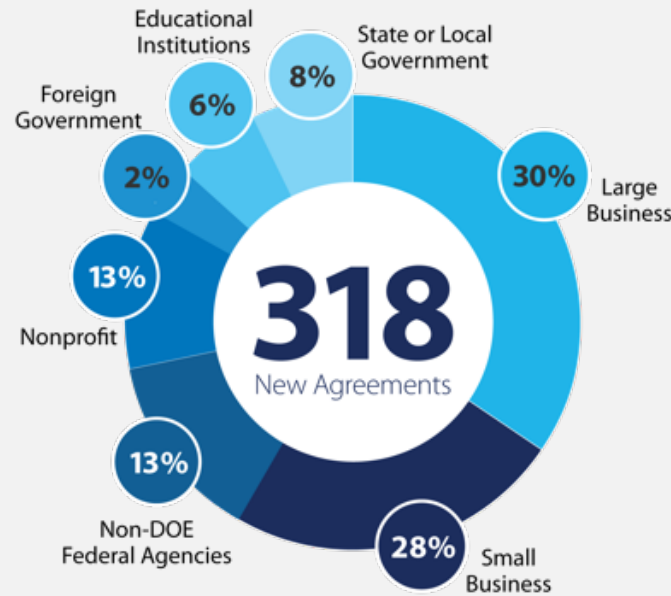
Partnerships with:

- Industry
- Academia
- Government

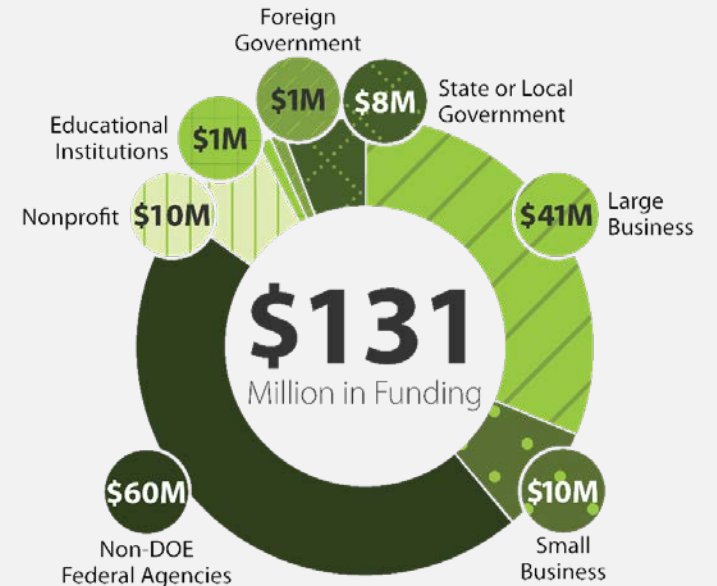
4 campuses operate as living laboratories



More Than 1,000 Active Partnerships in FY 2022



Agreements by Business Type



Funding by Business Type

Sustainable Aviation Fuel (SAF) Grand Challenge



3B
gallons annually by 2030

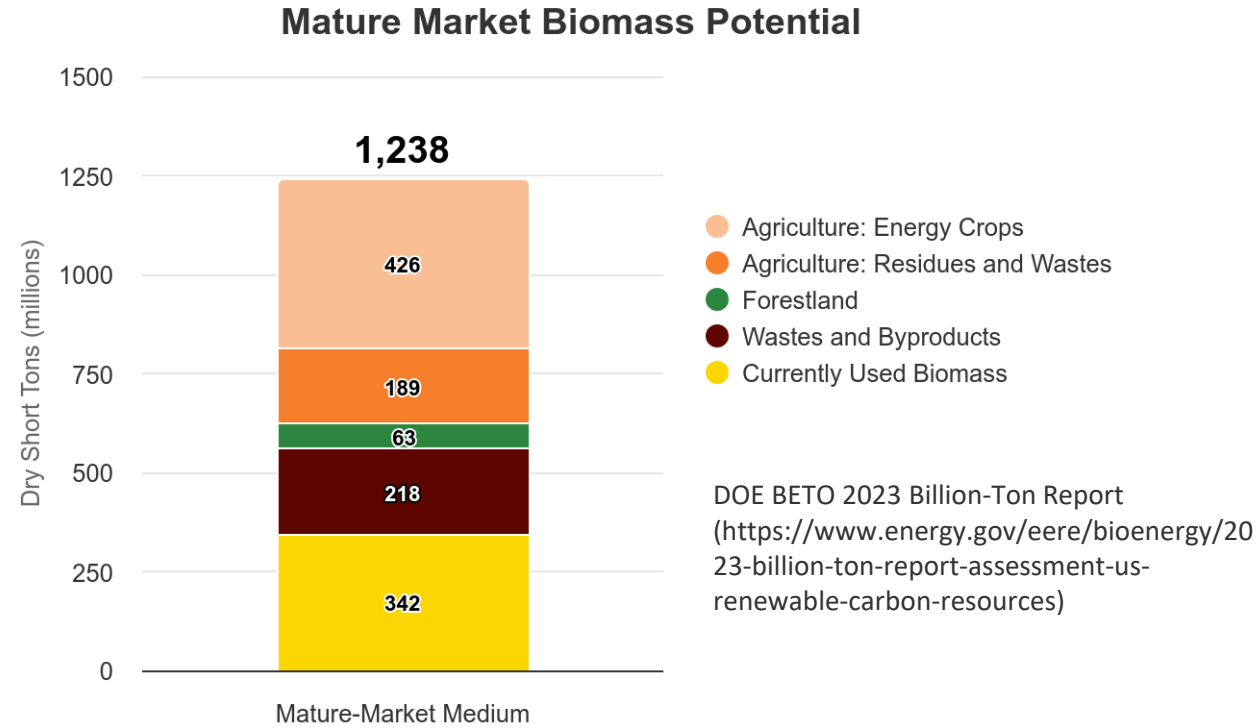
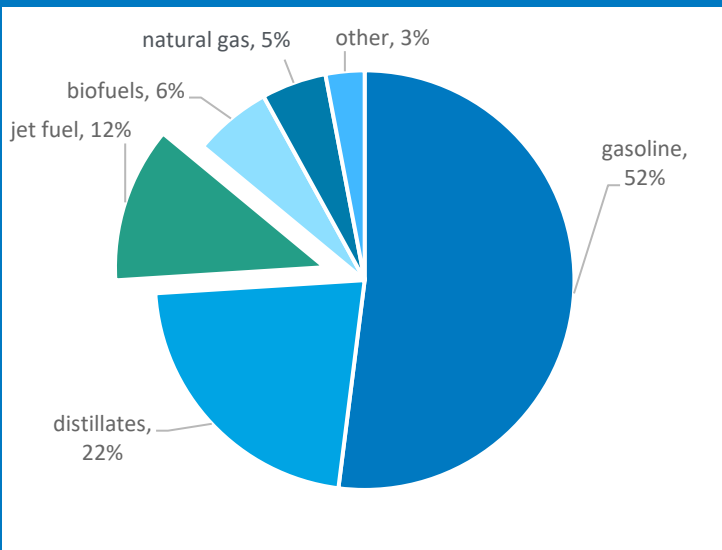
35B
gallons annually by 2050

~10% of US demand

100% of US demand

50% decreased life-cycle CO₂ emissions compared to petroleum jet fuel

US EIA: Transportation Energy Sources (2022)



Examples:

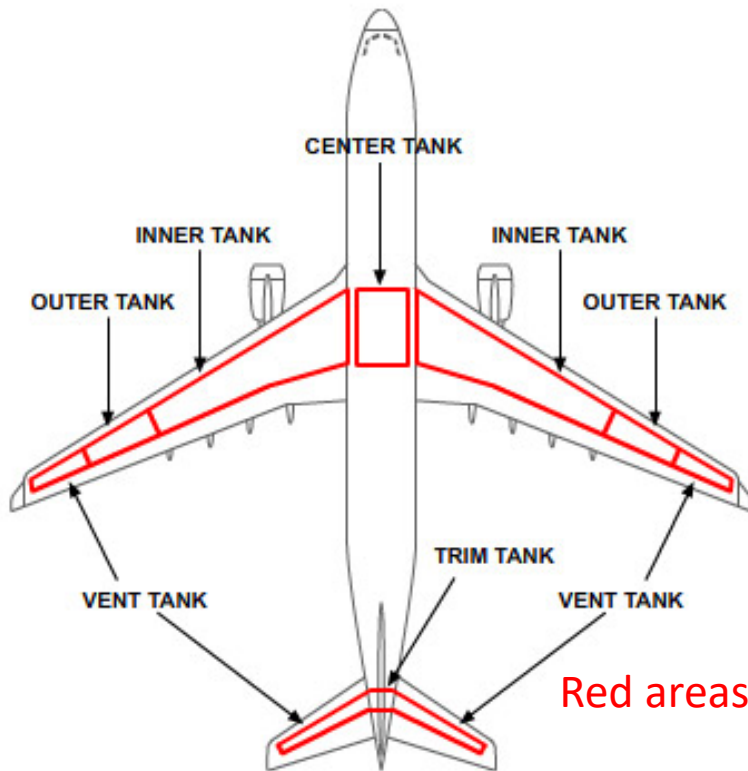
- Currently used: Corn to ethanol [150 million ton → 10.6 billion gal]
- Wastes/byproducts: Animal manure [38 million ton → 1 billion gal]
- Agriculture residues: Corn stover, wheat straw [175 million ton → 8.6 billion gal]
- Energy crops: Switchgrass, miscanthus [340 million ton → 16.8 billion gal]

SAF feedstock crops will not compete with food production.

SAF is uniquely suited for aviation, batteries and H₂ are not

Example-Boeing 777: Up to 41 wt% fuel

A330 Fuel System Engine Feed
TANK ARRANGEMENT



Red areas: fuel tanks

Property	Aviation fuel	Batteries	Liquid H ₂
Specific energy (energy per unit weight)	High (~43 MJ/kg)	Low (1/10th of jet fuel)	Very high (3x less than jet fuel)
Energy density (energy per unit volume)	High (~34 MJ/L)	-	Low (4/100th of jet fuel)

	2020	2025	2030	2035	2040	2045	2050
Commuter » 9-19 seats » < 60 minute flights » <1%	SAF	Electric or Hydrogen fuel cell	Electric or Hydrogen fuel cell	Electric or Hydrogen fuel cell	Electric or Hydrogen fuel cell	Electric or Hydrogen fuel cell	Electric or Hydrogen fuel cell
Regional » 50-300 seats » ~3% of industry CO ₂				and/or SAF	and/or SAF	and/or SAF	and/or SAF
Short haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO ₂	SAF	SAF	SAF	SAF potentially some Hydrogen	Hydrogen and/or SAF	Hydrogen and/or SAF	Hydrogen and/or SAF
Medium haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO ₂	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen	SAF potentially some Hydrogen	SAF potentially some Hydrogen
Long haul » 250+ seats » 150+ minute flights » ~30% of industry CO ₂	SAF	SAF	SAF	SAF	SAF	SAF	SAF

73%+ of aviation CO₂ emissions likely to be/must be decarbonized by SAF

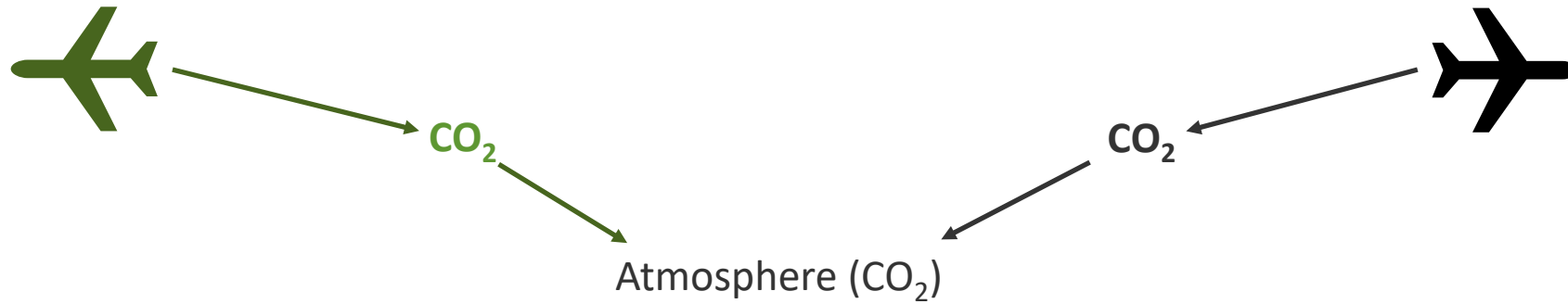
https://www.faa.gov/lessons_learned/transport_airplane/accidents/C-GITS

Yu et al. *Applied Energy* (2020) 271, 115169
Air Transit Action Group Waypoint 2050 Report

Biogenic carbon makes SAF sustainable

Airplane using SAF (~0.13-0.22 mi/gal)

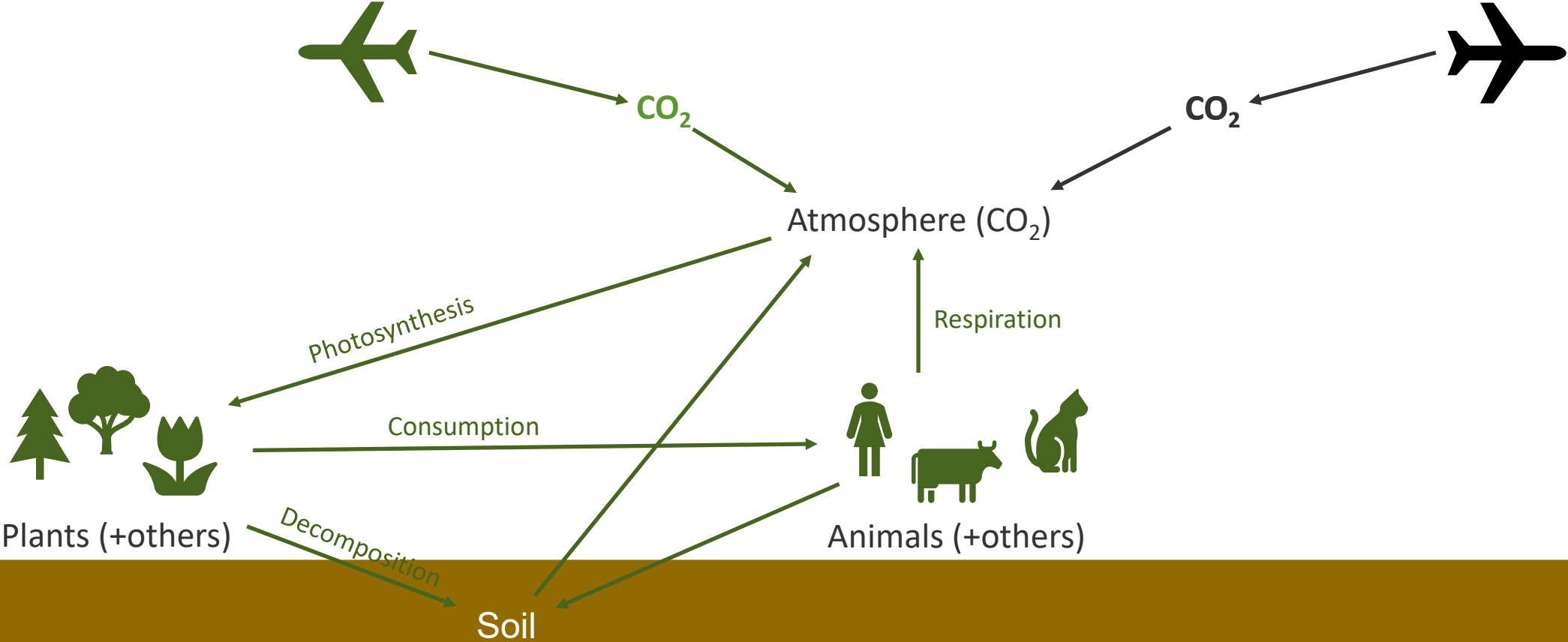
Airplane using fossil jet (~0.13-0.22 mi/gal)



Biogenic carbon makes SAF sustainable

Airplane using SAF (~0.13-0.22 mi/gal)

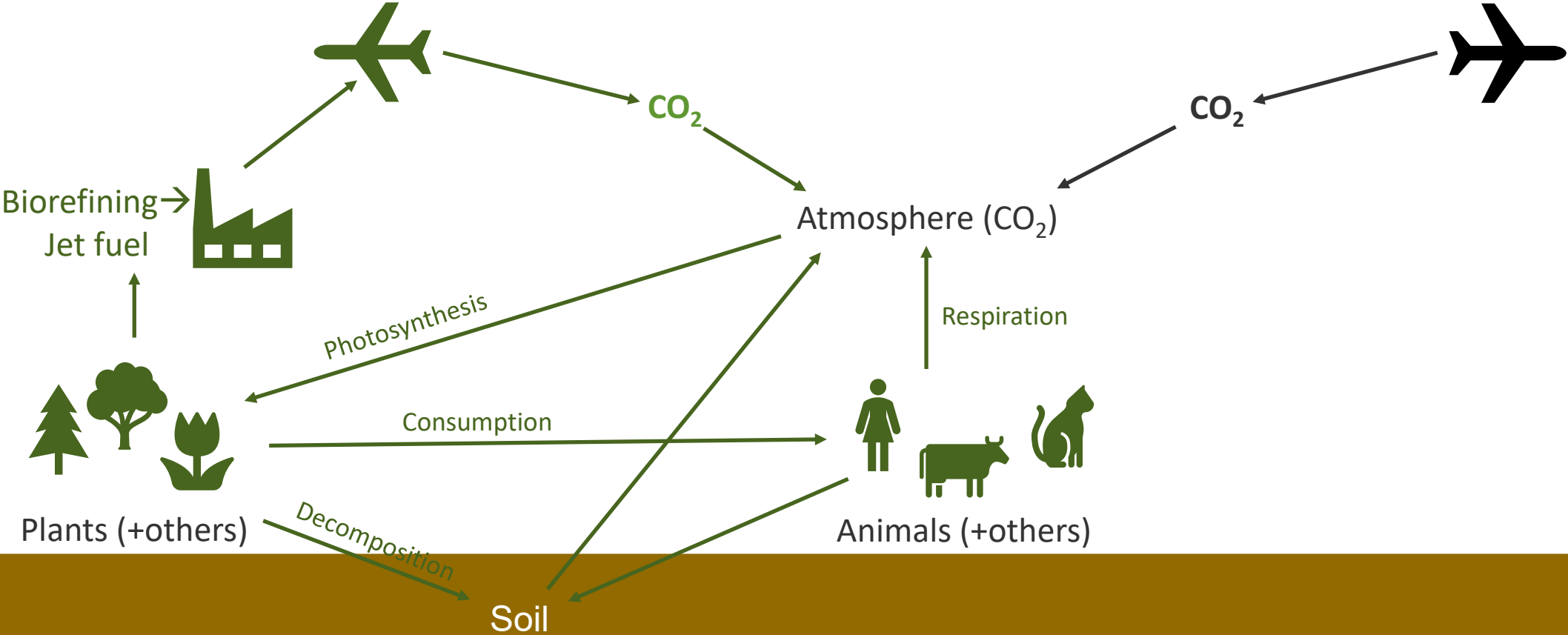
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Biogenic carbon makes SAF sustainable

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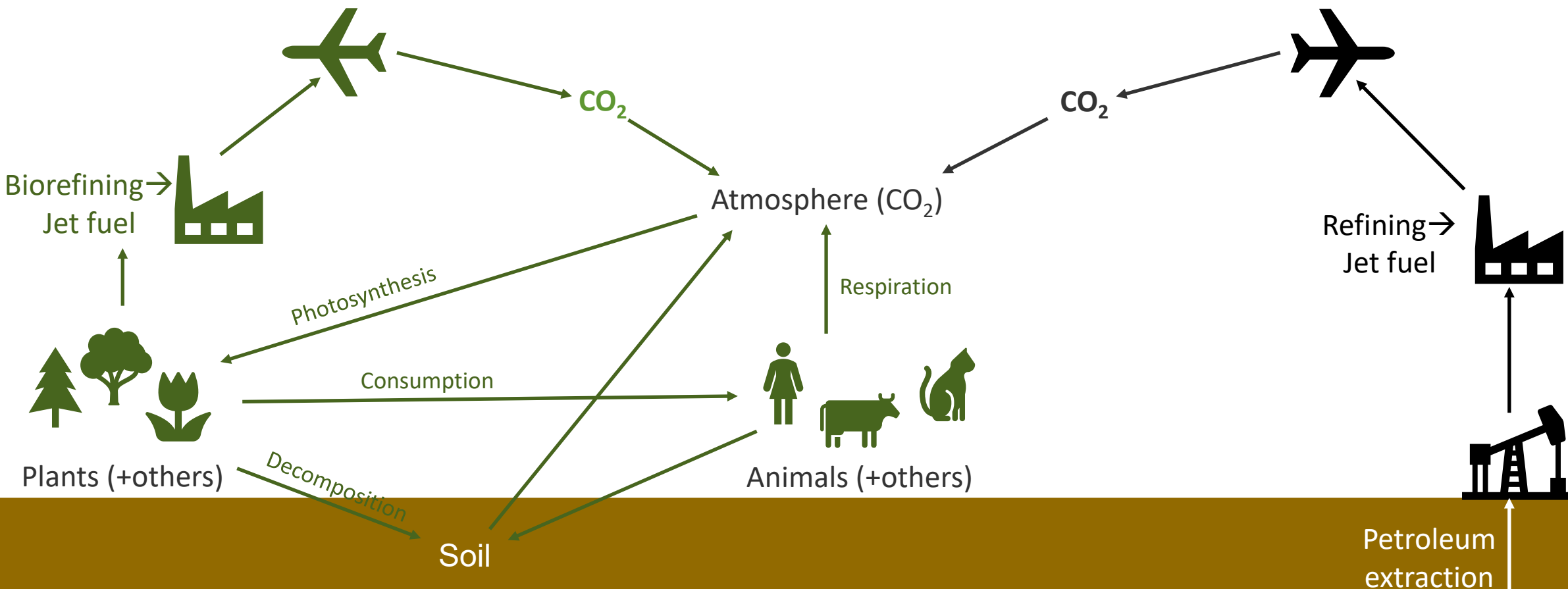
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Biogenic carbon makes SAF sustainable

Airplane using SAF (~0.13-0.22 mi/gal)

Airplane using fossil jet (~0.13-0.22 mi/gal)

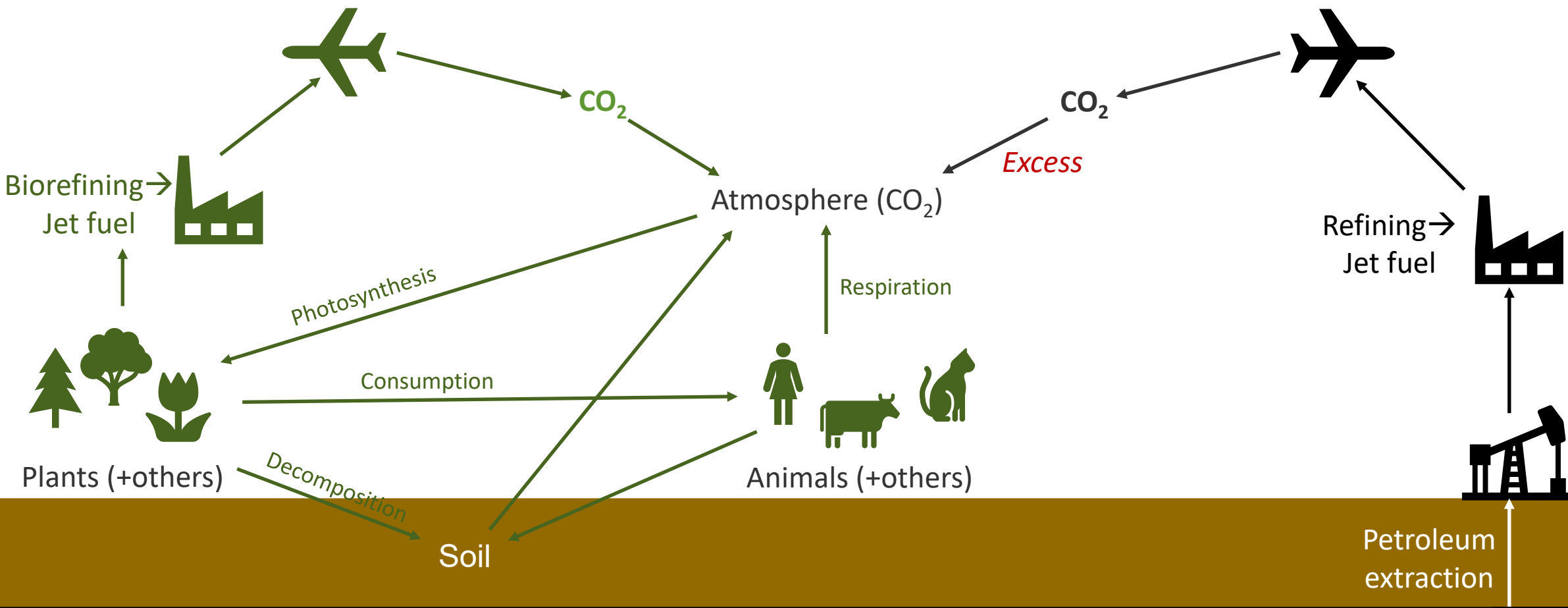


Fossil fuels

Biogenic carbon makes SAF sustainable

Airplane using SAF (~0.13-0.22 mi/gal)

Airplane using fossil jet (~0.13-0.22 mi/gal)



Fossil fuels

Life cycle analysis quantifies excess CO₂ emissions

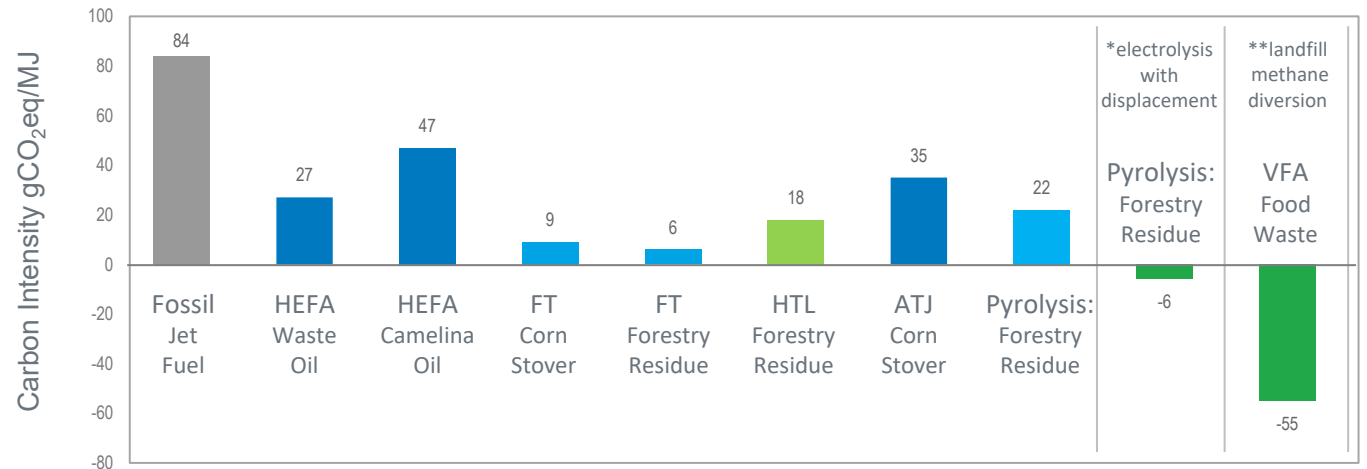
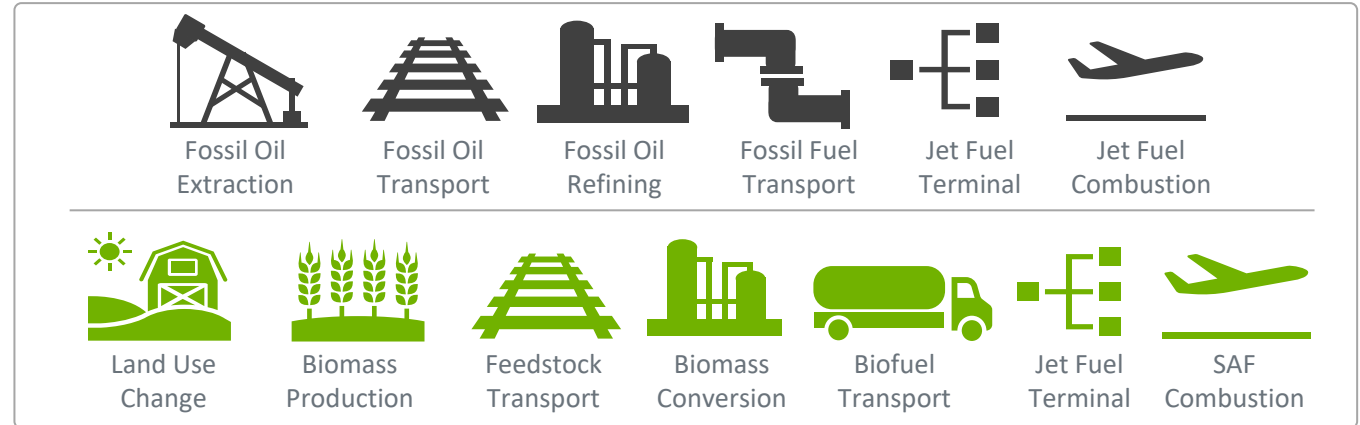
- Life cycle analysis provides a framework for comparing SAF carbon intensity to fossil jet that includes field-to-fuel production

Farming practices can influence SAF carbon intensity. Minimize it with...

- Using low-emission farming equipment
- Short supply chains (collection, conversion facilities near farms)
- Low fertilizer and pesticide use

...and maximize SAF subsidies tied to low carbon intensity!

Life Cycle Analysis for Fossil Jet Fuel and SAF



Sources: de Jong et al. (2017) Biotech for Biofuels, 10, 64; Gelfand et al. (2020), 54, 28961-2974; Ringsred et al. (2021) Applied Energy, 287, 116587; Huq et al. (2021) PNAS, 118, 13

Jet fuel is a highly engineered liquid energy carrier

Jet fuel requires high energy density; low temp performance for high altitude; minimum flash point for safe handling

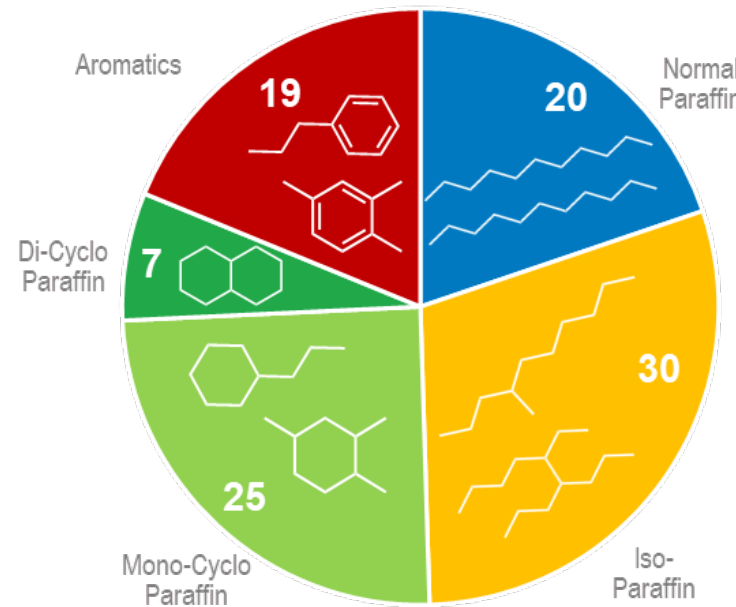
Jet fuel Has Multiple Functions:

- coolant (heat transfer media)
- lubricant
- hydraulic fluid
- ballast fluid
- swelling agent
- capacitance agent
- energy source

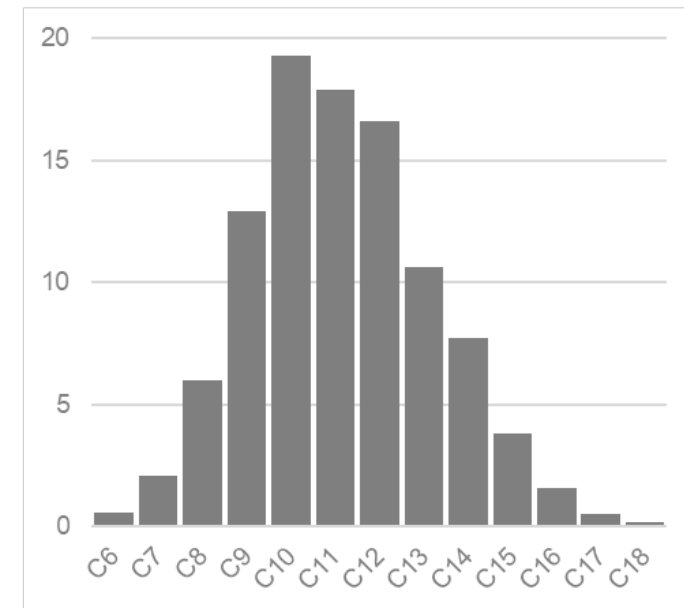
Jet fuel property specifications:

- ASTM D1655
- ASTM D7566
- ASTM D4054

Jet Hydrocarbon Class Distribution



Jet C Number Distribution



SAF must mimic the properties of fossil jet fuel.

Eight ASTM-approved pathways can all use agricultural products

Vegetable oils, animal fats, algal oils

Cellulosic and non-cellulosic sugars
(via fermentation)

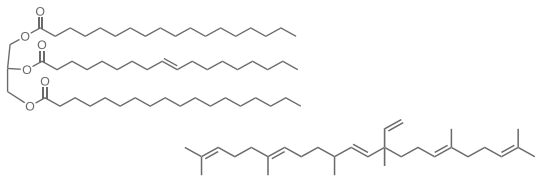
Any plant material or waste
(via gasification)


Why are there no SAFs approved up to 100%?

- **Technical barriers:** Systematically replicating every property of a complex molecular mixture from scratch is hard!
- **Regulatory barriers:** ASTM has not released requirements for 100% SAF (in progress) because stakeholders (jet manufacturers, FAA, etc.) are risk averse, want to introduce SAF slowly.

<https://www.ers.usda.gov/media/d0pdfuvx/soybean-banner.jpg?format=jpg&quality=85>

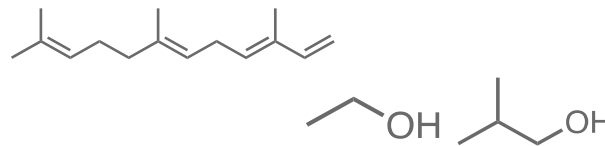
Ex: Soybeans




- Annex A2: 50% 
- Annex A6: 50%
- Annex A7: 10%

<https://nebraskacorn.gov/wp-content/uploads/2023/12/HowCornisUsed-JULYCORN-2-1920x1080-1.jpg>

Ex: Corn grain or processed corn stover



- Annex A3: 10%
- Annex A5: 50% 
- Annex A8: 50%

<https://www.biocycle.net/wp-content/uploads/2012/08/30b.jpg>

Ex: Woody waste



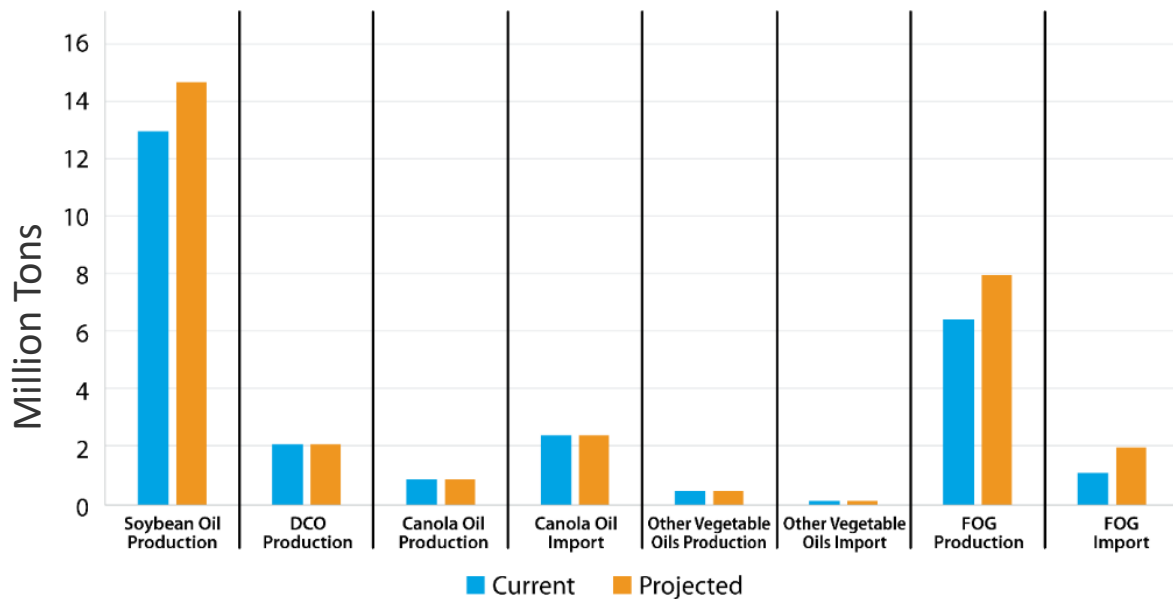
- Annex A1: 50%
- Annex A4: 50%

Annex=ASTM-approved pathway

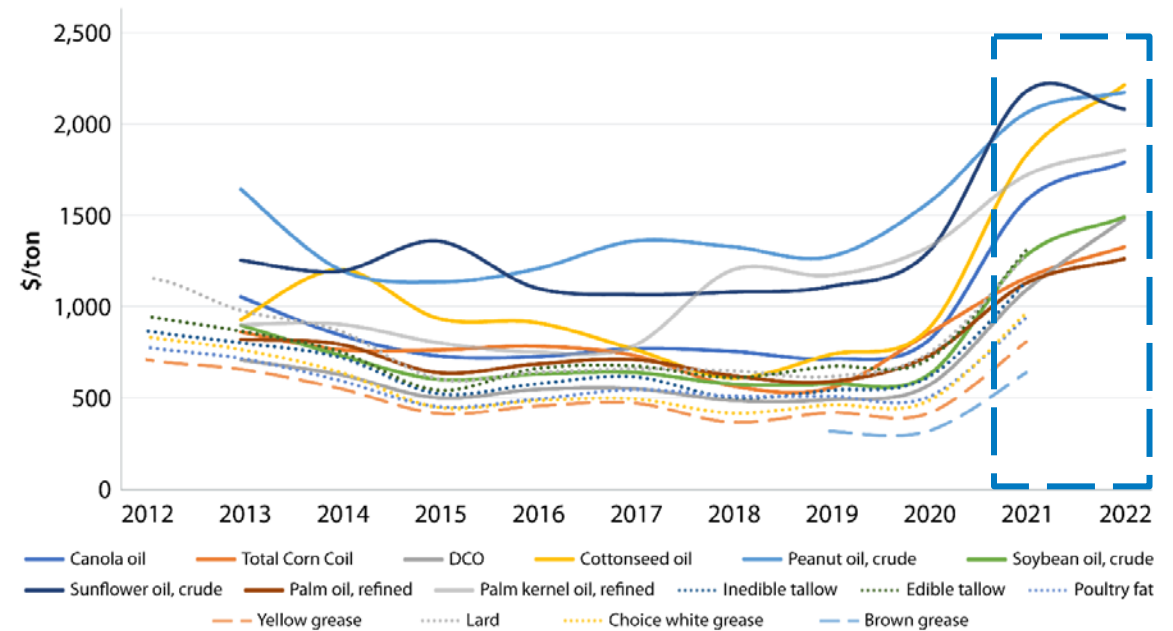
Fats, oils, and greases supply most SAF today, but supply limited

2022: 23 MM ton fats, oils, and greases (FOG) consumed by the biofuels industry to produce 4.7 billion gallons fuel (SAF and diesel)

Domestic FOG production will not increase significantly (14%) - *price increase due to constrained supply*



Current and projected HEFA feedstock supply (2030–2032)



NREL working with industrial partners on multiple SAF approaches

Cover crops and grasses

NREL Has Developed a Continuous Process for Production of Alder Fuel's "Green Biocrude", Which Can be Upgraded in Existing Petroleum Refineries

Field-to-Fuel Production of Carbon-Negative Sustainable Aviation Fuel from Regenerative-Agriculture Biomass

Alder CRADA

- Scale-up and derisk Alder Green Crude technology
- Collect data for industry driven stage-gate matrices
- On track to build process design packages (FEL-2/3)

DOE FOAs

- Scale-up of Biotechnologies Pre-Pilot for Biofuels
- Demonstration scale FOA

Food waste, animal manure

NREL VFA – SAF Catalytic Process Produces Normal and Iso alkane SAF Blendstocks From Wet Waste

NREL catalytic technology upgrades volatile fatty acids from arrested anaerobic digestors to ketones, which can then be upgraded to SAF

- 70/30 blend of VFA-SAF/Jet A meets critical SAF properties
- Bolt-on solution for existing AD systems and refineries
- Technology has been licensed to Alder Fuels
- SCUBA FOA for Scaleup of starting in Q2FY23
- Partners include BioVeritas, RPD, WSU and United Airlines
- Culmination of FOA: VFA-SAF demonstration flight (by 2026)

Corn stover

Ethanol From Corn Stover 2nd Generation Sugar Can be Upgraded via the D3MAX / LanzaJet Corn Stover to SAF Process

- For each ton of corn, about a ton of Stover is produced, and about 1/3 of this can be converted to SAF
- NREL provides DMR technology and enzymatic hydrolysis to produce 2nd generation sugar
- In a 3.5-year DOE project, our industry partner will demonstrate reliable, low-GHG production of an intermediate ethanol product from corn stover in a fully integrated, 10 ton per day pilot-scale facility

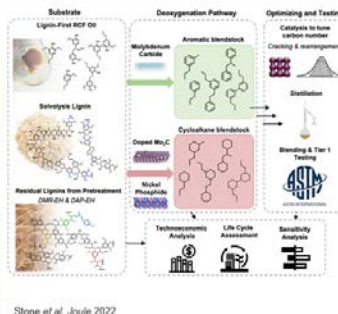
Lignin Conversion to SAF Blendstocks

Collaboration with MIT, Argonne National Lab, and University of Washington

Project focused on converting lignin from wood & ag residues to aromatics & cycloalkanes

Our continuous process achieves 87% of theoretical carbon yield and ~1% oxygen retention from poplar lignin over an earth-abundant, stable catalyst without the need for solvents

- Impact**
- Decarbonization of the transportation sector by enabling both aromatics and cycloalkanes for bio-based jet fuel
 - Working actively on scale-up with industry partners
 - Based on the projected availability of lignin harvested in the U.S. alone by 2040, we estimate that **more than ~50% of the global jet fuel demand could be met by the carbon present in lignin alone**
 - Aromatic chemicals of immediate interest to industry can be used for applications such as bio-based lubricants and working fluids, alongside fuels



Integration of Electrochemistry With Fermentation: Formate as an Energy Source To allow Sugar Fermentation with no net CO₂ Generation

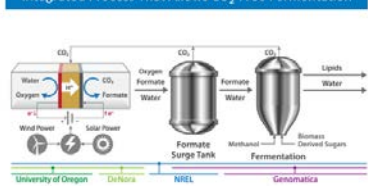
Technology Summary

- Develop and demonstrate an integrated process that electrochemically generates formate from CO₂ and use the formate as an energy source for the fermentation of sugars to fatty acid methyl esters (FAME) without net CO₂ generation.
- Formate provides reducing equivalents for sugar fermentation.
- Chemical looping reactor system that takes advantage of intermittent low-cost electricity from wind and solar resources.

Technology Impact

- Generation of low cost and low carbon intensity FAME feedstock for generation of renewable diesel and sustainable jet fuel.
- Technology can be applied to use formate as energy source for other fermentations

Integrated Process That Allows CO₂-Free Fermentation

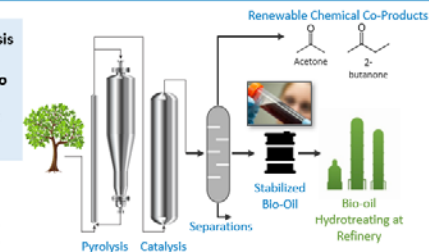
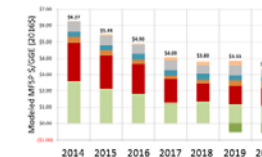


- CI for the generated FAME of this process is 35 gCO₂/MJ
- Utilizing enhanced farming technologies would allow the generated FAME to have a CI of 23 gCO₂/MJ, (similar to tallow feedstocks)

Catalytic Fast Pyrolysis (CFP): SAF via Stabilized Bio-Oil

NREL is developing catalytic fast pyrolysis technologies for converting non-food biomass and waste solid feedstocks into Sustainable Aviation Fuel (SAF) blendstocks through hydrotreatment of stabilized bio-oil

Biofuel production costs below \$3/GGE



Product meets key ASTM Int'l jet fuel property specifications

SAF Fraction	Density @ 15°C, g/cm ³	Freeze Point, °C	LN ₂ Visc, mPa.s	SIMDIS ₁₀ , °C	SIMDIS ₅ , °C	
ASTM D1655	-	max -40	>42.8	\$205	\$300	
CFP Oil 1	39%	834	<-70	43.1	174	249
CFP Oil 2	40%	833	<-70	43.2	170	257

Woody biomass, corn stover

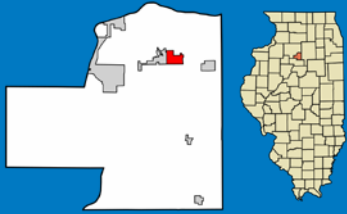
Sugar fermentation CO₂ byproduct

Cover crops and grasses

SAF can bring new opportunities to American agricultural communities



My great-grandma, grandpa, and a sheep

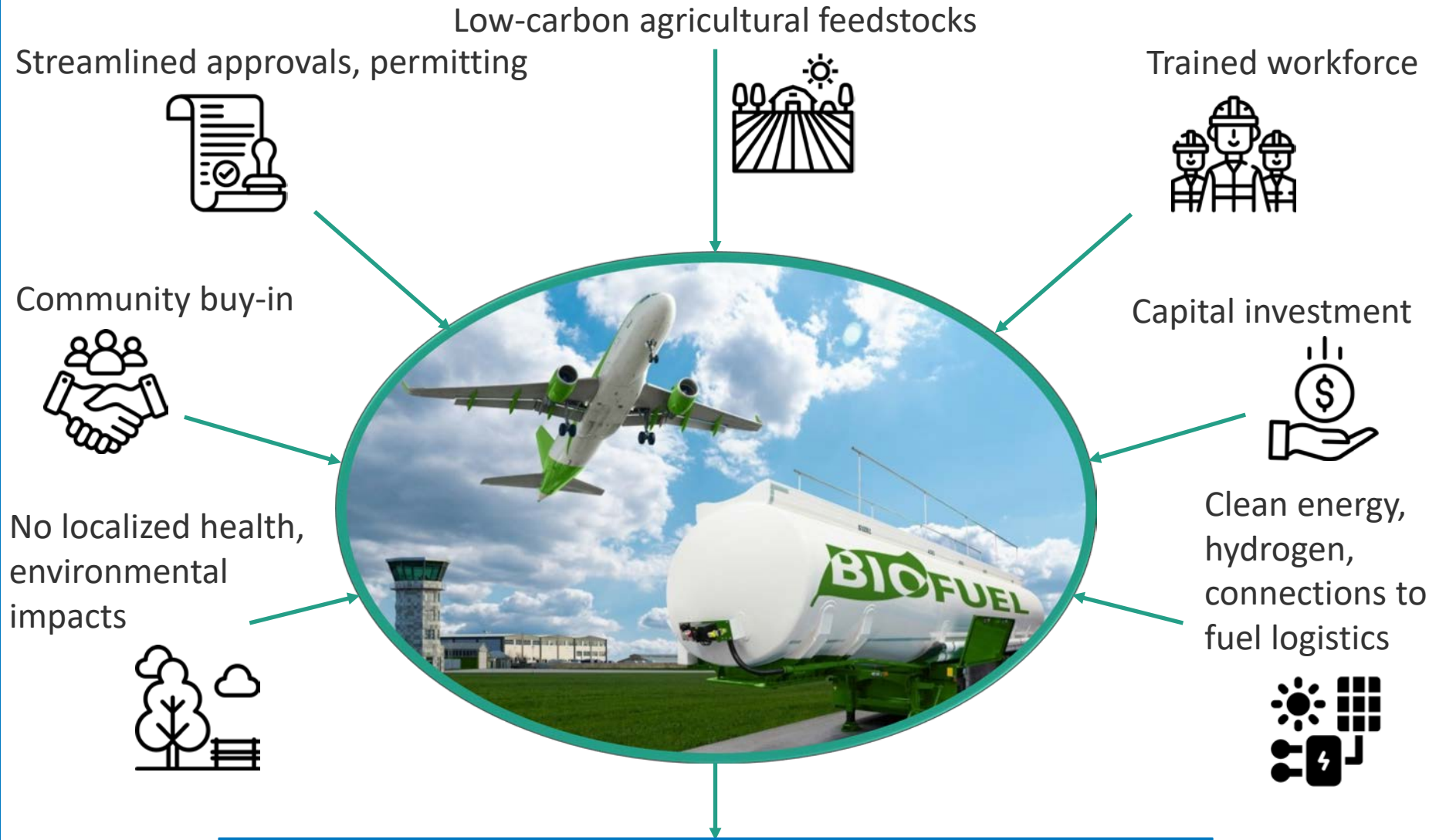


Granville, IL; pop: 1359

1957 My mom (baby) and her siblings



2024



- High-quality jobs
 - Tax revenue
 - Growth of community institutions
 - Contribution to energy independence goals
- Strengthened agricultural communities***



Thank you

www.nrel.gov



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ENERGY | Energy Efficiency &
Renewable Energy
BIOENERGY TECHNOLOGIES OFFICE

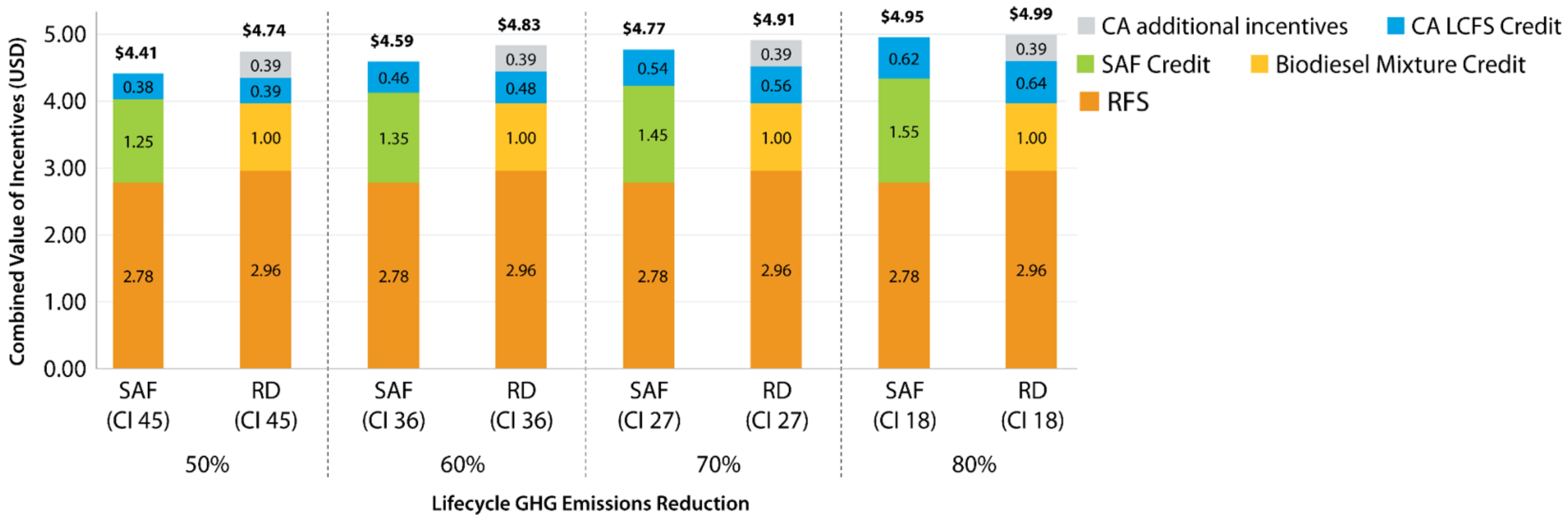
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NREL/PR-5100-90186

3. State of SAF Production Process: Policies

- **Renewable Diesel (RD) is a major competitor for SAF**
- The structure of the combined federal and state incentives (**for California**).

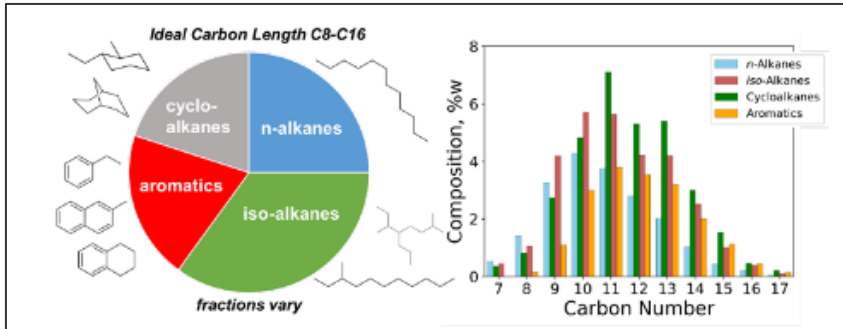
a) 2023-2024



- **RD has a slightly advantage (\$0.04-0.33) over SAF.** This advantage is mainly due to the extra \$0.39 allocated to RD based on **CA avoided diesel deficit**.

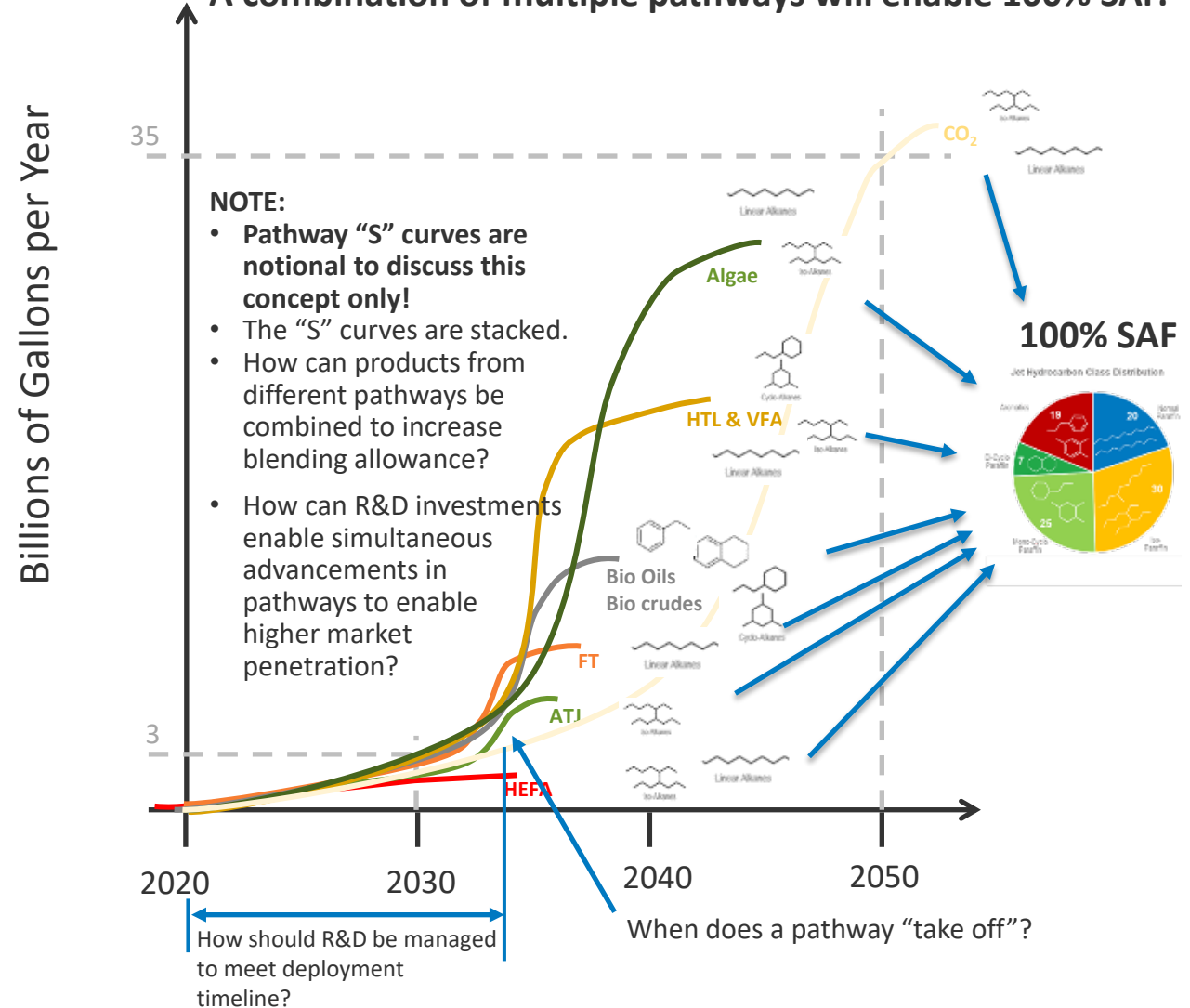
We Can Initially Produce Single Blendstocks, But Will Soon Have to Produce Blends of Multiple Molecule Classes To Avoid Deployment Limits

“S” curves will also inform the strategy to meet 100% SAF (not a single blendstock).



- SAF has well defined ratios of molecule classes.
- Most SAF pathways can only make blendstocks.
- Blendstocks will not be sufficient as SAF production is a significant fraction of 35 BGY.
- Airlines already want 100% SAF options.
- Production capability growth across multiple pathways will be necessary to achieve higher and higher blending limits until 100% SAF can be approved.

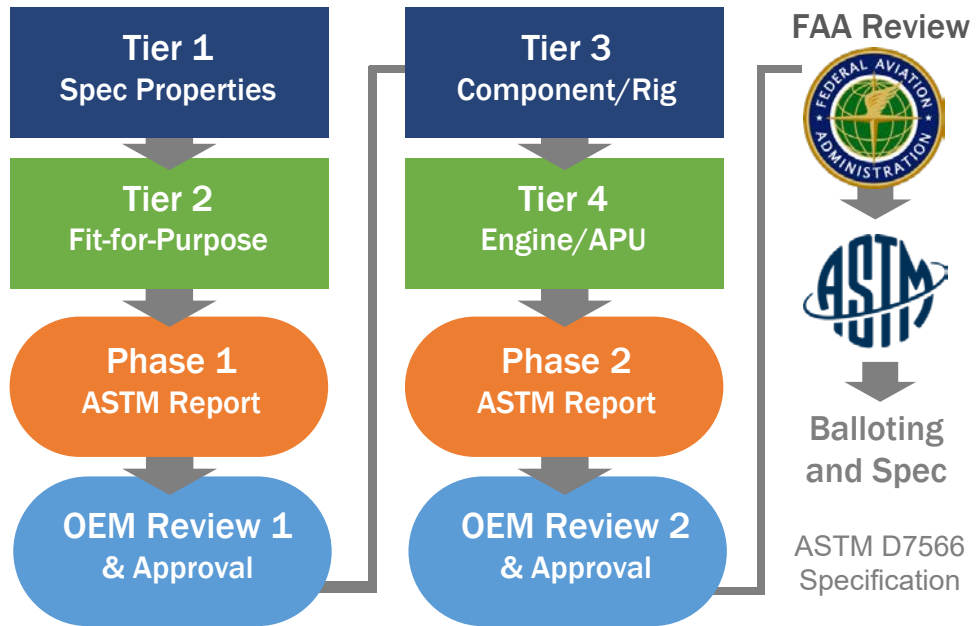
A combination of multiple pathways will enable 100% SAF.



New SAF routes require ASTM evaluation and balloting process

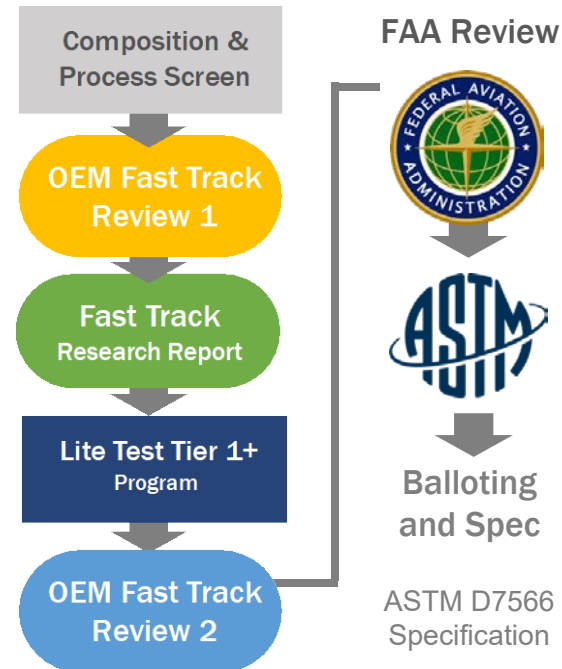
ASTM D4054 for Evaluating New SAF Routes

>100k gal, >\$5M, 3-7 years



Recent "Fast Track" Process

<1k gal, <\$1M, <2 years



- ASTM D4054 requires evaluating new SAF routes through tiered testing, reporting, and balloting
- New Fast Track approval process (2020) that limits SAF to 10 vol% but greatly accelerates evaluation process to < 2 years