NREL
Transforming ENERGY

To 35 Billion Gallons by 2050

Innovative Technologies and Scale-Up Approaches for SAF Production at NREL

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CAAFI Webinar, January 19, 2022

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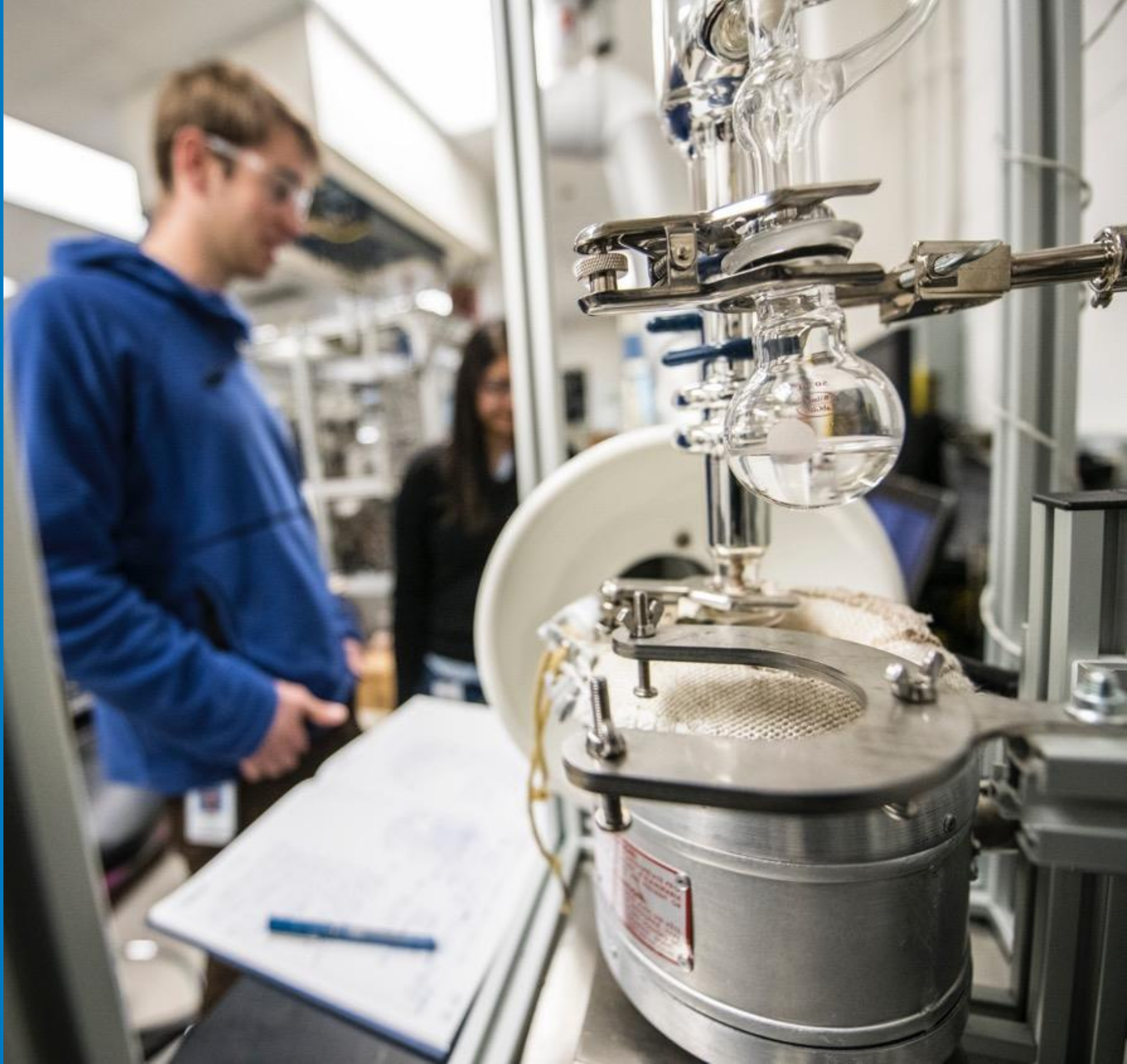
Overview of NREL and its Bioenergy Program



NREL at a Glance

2,400

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

World-class
facilities, renowned technology experts

>820

Partnerships
with industry, academia, and government

Campus
operates as a living laboratory

>$1B annually

National Economic Impact

NREL Science Drives Innovation

Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Bioenergy - SAF

Vehicle Technologies

Hydrogen

Energy Efficiency

Buildings

Advanced Manufacturing

Government Energy Management

Energy Systems Integration

Grid integration & modernization

High-Performance Computing

Data and Visualization

NREL's Bioenergy SAF Program Is Broadly Based and Spans Technology Development From Discovery to Large Pilot Scale

Foundational Science / Science &Technology Focus Areas

- Pretreatment & Biological Conversion
- Lignin to Fuels & Products
- CO_2 & Waste Gas to Fuels & Products
- Catalytic Conversion
- Algal Biofuels & Bioproducts
- Polymers & Bioproducts

Cross Cutting

Techno-Economic Analysis and Life Cycle Analysis

Market Impact via Industry Partners Across SAF Supply Chains

Feedstock Suppliers – Harvesters – Preprocessing – Conversion - SAF

Tech-to-Market Pipeline, Stage-Gate Processes, Piloting Facilities

Pretreatment and Biological Conversion Capabilities

Fundamental Biology Research

- Understanding fundamental biology processes to produce fuels and chemicals
- Genetic and pathway engineering

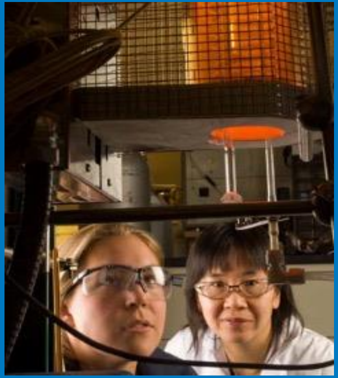
Bench-Scale Fermentation

- 500 mL to 5 L fermentation systems with pH, temperature, and O_2 controls for enzymatic hydrolysis and fermentation testing
- Microorganism evaluation and development with at-line analytics

Pilot-Scale Process Integration

- Extensive pretreatment, enzymatic hydrolysis, 8,000 L fermentation, and product recovery capabilities @ 1 ton/day
- Experienced process engineers with access to world-class scientists and researchers

Catalytic Conversion Capabilities



Catalyst Development and Testing

- Catalyst screening, determination of optimal activation and operating conditions, online analytics, kinetic model support, and simulated recycle
- Up to 1000ºC; 2,000 PSI operating conditions

Catalyst Characterization

- Rapid thermal analysis, elemental composition, surface analysis and characterization, adsorption and chemisorption
- Kinetic studies of catalytic reactions

Pilot-Scale Process Integration

- Extensive gasification, pyrolysis, hydrotreatment, catalyst testing, and recycling; gas cleanup; fuel synthesis; and product recovery capabilities
- Experienced process engineers with access to world-class scientists and researchers

Algae Program Capabilities

Strain Development

- Leverage strain selection for high photosynthetic productivity under simulated environmental conditions (500 mL to 100L)
- Develop genetic engineering toolkits for robust strains with high growth rate and high-quality biomass
- Target high carbohydrate and high lipid biomass that can be readily converted

Deconstruction

- Hybrid biochemical/thermochemical conversion strategy for maximum valorization of bioenergy components
- The saturated fatty acids are used to produce fuels, and the unsaturated free fatty acids are used to produce polyurethanes
- Carbohydrates fermented to high-value products

End Goals

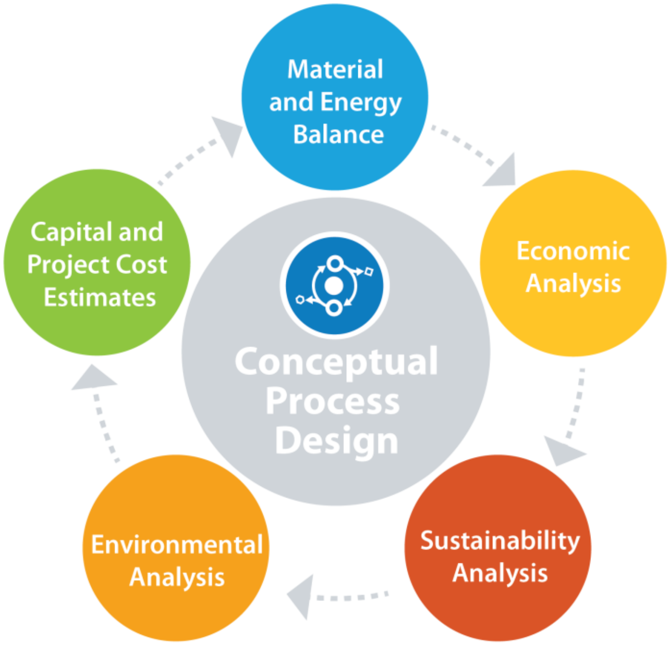
- Emphasis on robust, high growth rate strains on salt water
- Wastewater cleanup, nitrogen fixation
- Producing cost effective SAF blend stock, chemicals, and products

Techno-Economic Analysis Delivers Commercially Compelling Sustainable Processes

Assess technical & economic feasibility of process

- Impact of major cost drivers (sensitivity studies)
- Set research targets & use them as measure of research progress
- Track research progress (economic & sustainability criteria)

Commercially Compelling, Sustainable Processes



Life Cycle Sustainability Analysis Evaluates GHG Emissions, Water Consumption, Water Quality and Social Impact Across Supply Chains

Feedstock Production and Logistics

- Evaluate nutrient and carbon cycling
- Assess impact on land and resource use

Conversion

- Minimize water consumption, air pollution, and carbon footprint
- Utilize coproducts and fully integrate systems
- Maximize efficiency

ethanol
diesel
gasoline
jet fuel
biopower
bioproducts

End Use

- Minimize greenhouse gas (GHG) emissions
- Avoid negative impacts on human health

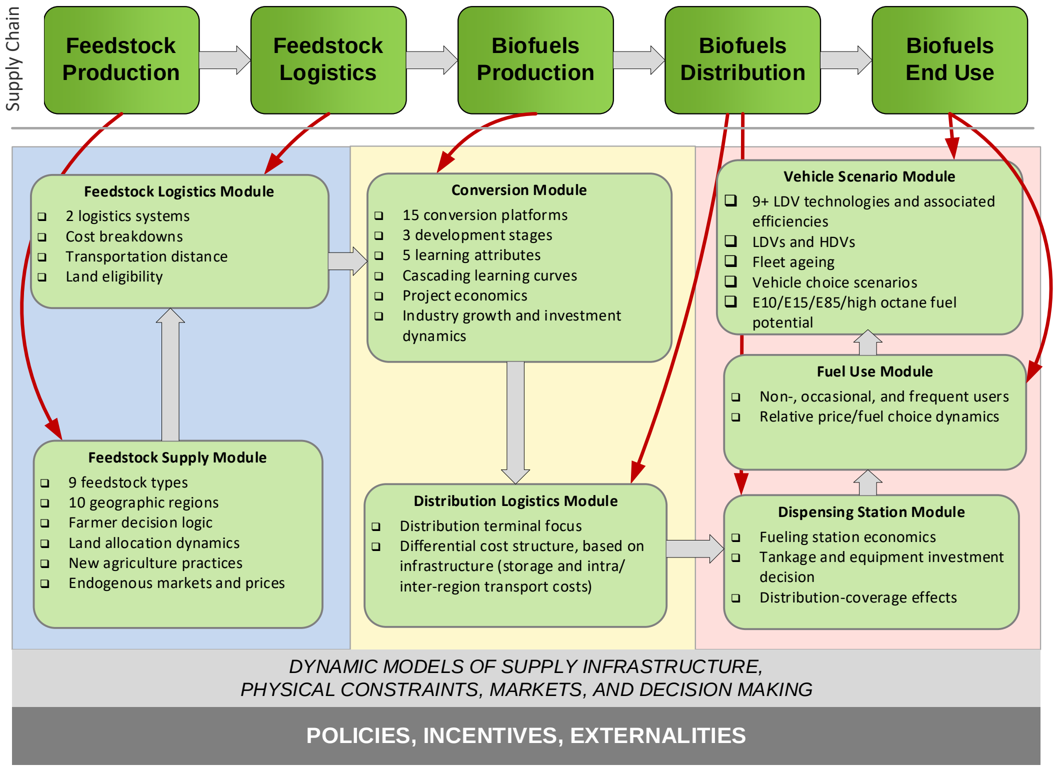
Cross-Cutting

- Life-cycle analysis of water consumption and GHG emissions
- Land-use change modeling
- Water quality analysis
- Environmental, economic, and social factors

Systems Analysis Modeling Can Inform Impact of Policy and Incentives on SAF Production Growth Rates

We use the Biomass Scenario Model (BSM) to simulate the potential implications of different policy scenarios.

In this analysis, we focus on potential SAF production, CO_2 emissions, and policy costs.

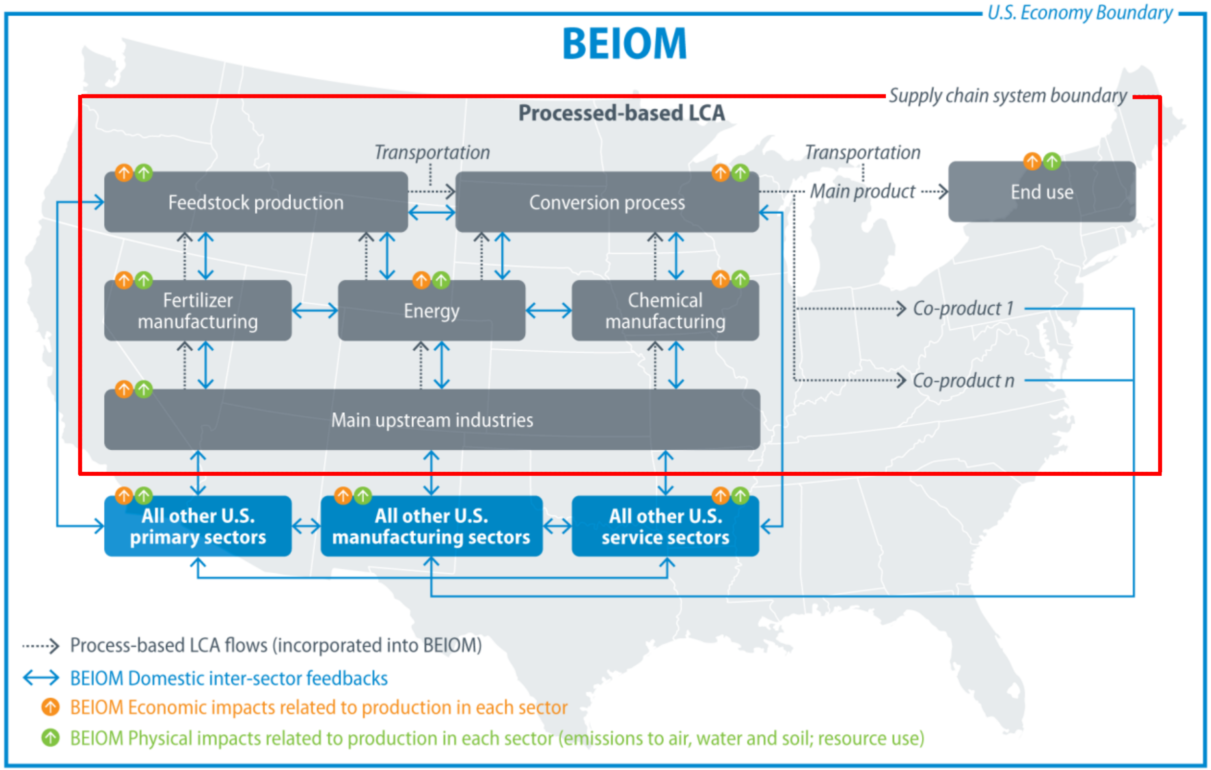


Bio-based Environmentally-extended Input-Output Model (BEIOM) Can Assess Environmental and Socioeconomic Impacts

Macro-economic analyses of the entire bioeconomy to allow evaluation of benefits and tradeoffs of the new SAF industry

- Holistic
- Multi-dimensional
- Consistent method across metrics
- Cross-sectoral

- Feedback effects
- Indirect effects
- Time series



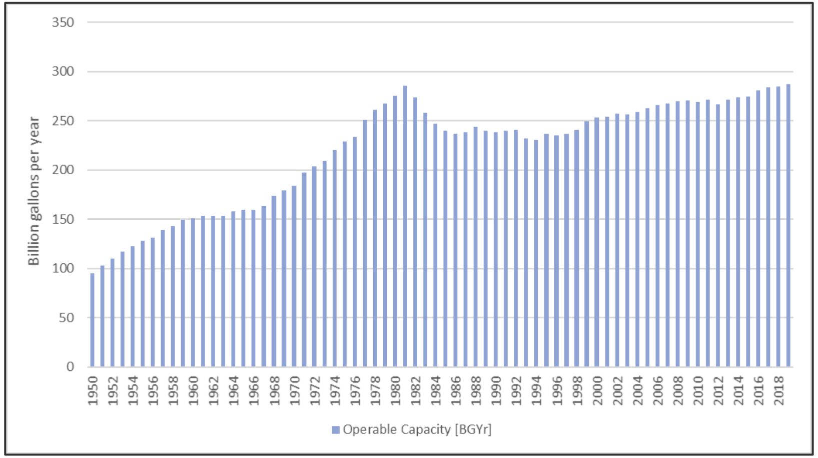
BEIOM: Bio-based circular carbon economy Environmentally-extended Input-Output Model

2

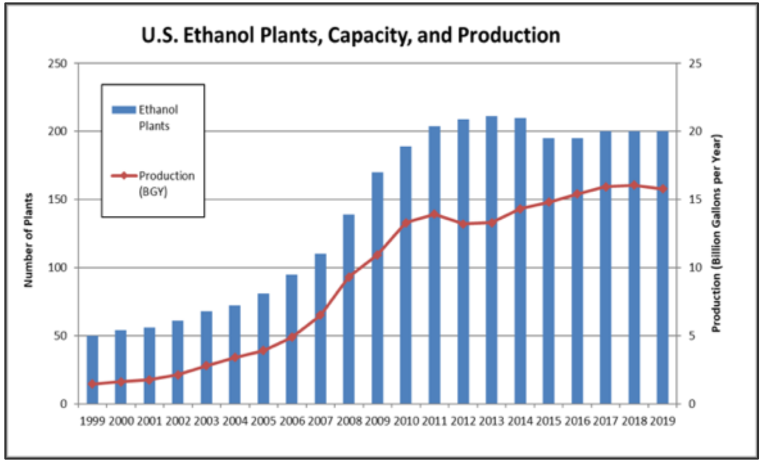
Guiding Principles to Accelerate Deployment and Production of SAF Blend Stock To Achieve the 35 Billion Gallon Goal

Precedent for Scale-Up Rates in the Petroleum and Ethanol Industries Suggests That Scaling SAF Production to 35 BGPY by 2050 Is Achievable

Refinery production increased by 150 BGPY in 30 years



Ethanol production to 15 BGPY took 15 years



Source: U.S. Energy Information Administration (EIA), and Renewable Fuels Association (RFA), Markets & Statistics

Key Questions:

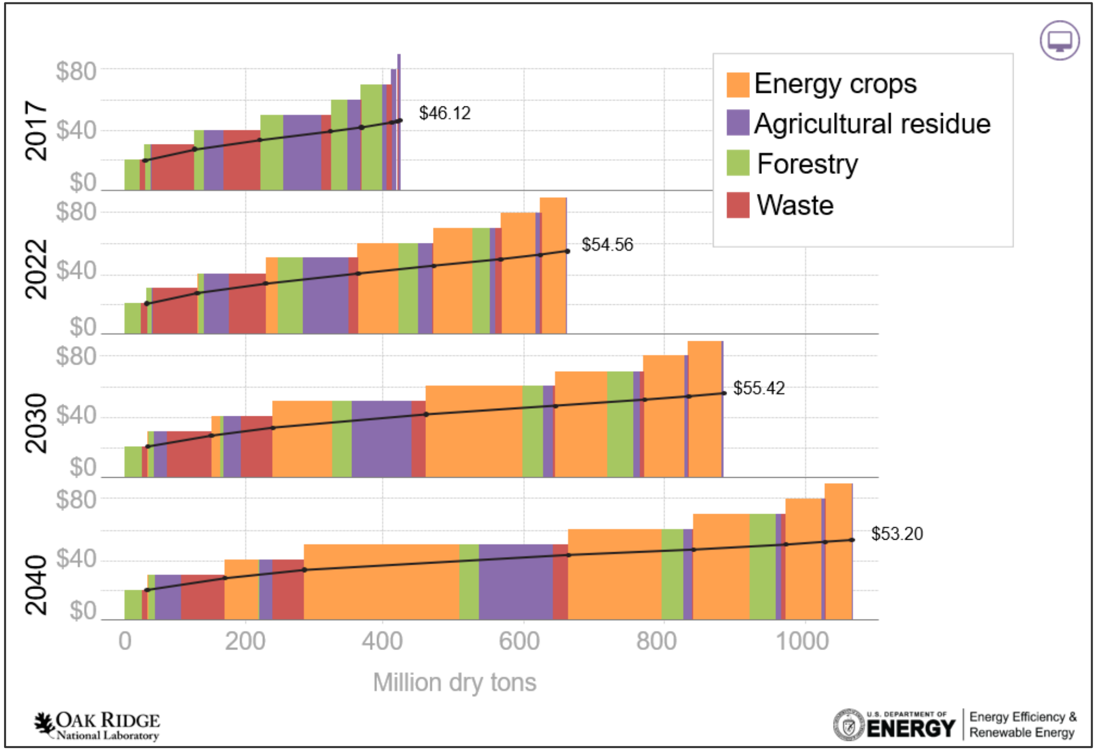
- Is there sufficient feedstock?
- What fuel properties will be acceptable for commercial aviation use?
- What is the quickest path to approval?
- What opportunities are there to reduce risk and cost, and accelerate deployment?

There Is Sufficient Feedstock Available To Produce 35 BGPY of SAF

Some Considerations:

- Other uses, for example renewable diesel and BECCS may compete for feedstock
- Conversion processes may have to be developed for “off spec” feedstock.
- “Waste” is not “free”
- Marginal cost of additional tons to billion tons supply increases by 4X
- Energy crops and conversion technologies chosen to reduce carbon intensity

ORNL Billion-Ton Study Shows Supplies Vary With Price and Time

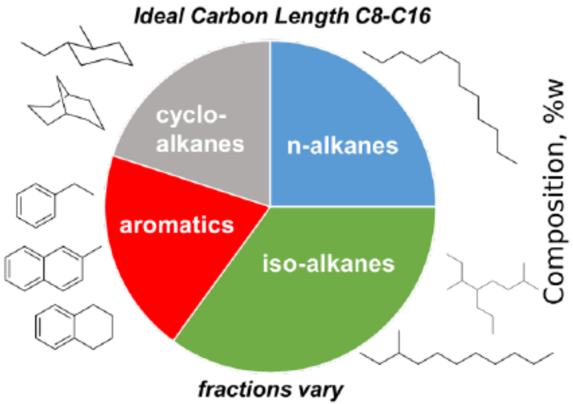


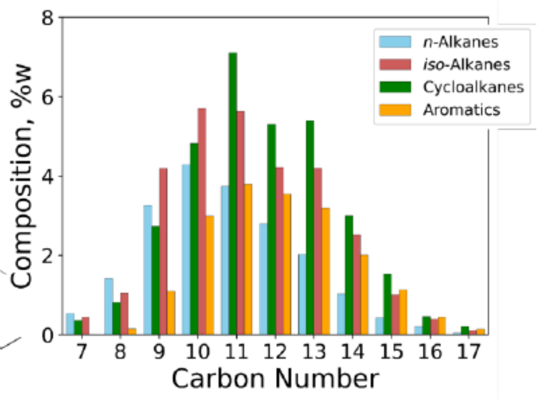
Fuel Properties: SAF Will Require Compatibility With Existing Aircraft and Engines

Drop-In
- Must be fully fungible, and can be used seamlessly with existing operations and handling

Performance
- Specific energy
- Energy density
- Emissions
- Thermal stability

Operability
- National Jet Fuels Combustion Program (NJFCP)
- ASTM D4054
- ASTM D1655





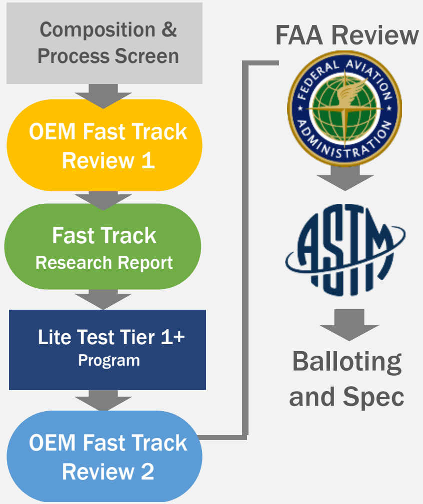
- J. Holladay, Z. Abdullah, J. Heyne, "Sustainable Aviation Fuel: Review of Technical Pathways," DOE EERE, Bioenergy Technologies Office Report, Sep 9, 2020
- Edwards, J.T., "Reference Jet Fuels for Combustion Testing," in 55th AIAA Aerospace Sciences Meeting, Grapevine, Texas, January 9–13, 2017

Quickest Path To Approval: ASTM "Fast Track" Will Enable Earlier Market Entry for New SAF Routes

New ASTM "Fast Track" Approval Process Reduces Barriers and Time to Market

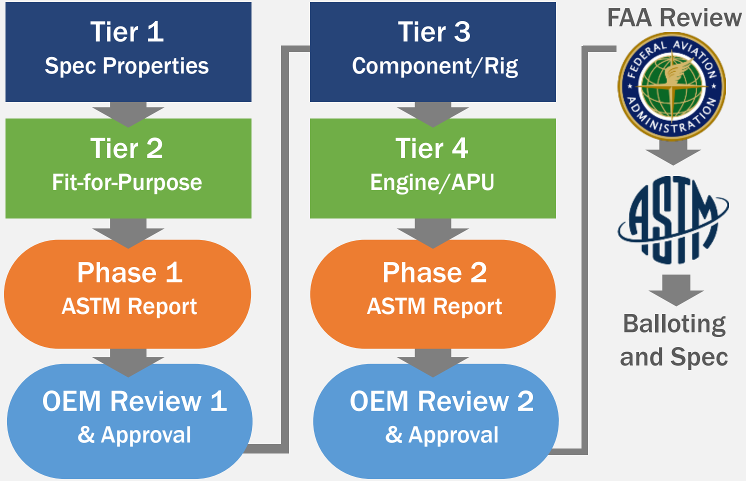
New ASTM "Fast Track" Approval Process in 2020

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



Conventional ASTM D4054 Approval Process

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



Leveraging Petroleum Industry's $10B Investment in Hydrotreating Will Lower Costs and Accelerate Deployment

Opportunities

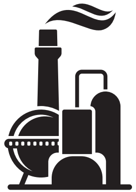
- ~6.6M BBPD (97 BGPY) distillate HT capacity available in the United States
- Leveraging this capacity may save $0.33 of capital/gal SAF
- May allow incremental transition to renewables by blending renewable and fossil streams
- Opportunities where re-permitting may not be required

Challenges

- Large variability of streams
- Match equipment to streams
- Hydrotreater scale too large
- ASTM approval of pathways
- Incompatibility of materials of construction with bio-streams
- Managing exothermic reactions

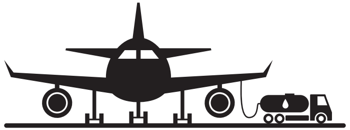
Fats, Oils, Greases | FT Waxes & Oils | Alcohols | Bio-Oils/ Biocrudes | Ketones | Sugars | Algae Oils | Lignin streams

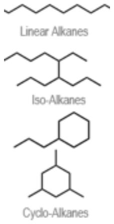
Focus of R&D: Pretreatment of Feeds To Meet Critical Material Attributes (CMA)
These are physical and chemical properties of pretreated renewable streams which can be processed by refinery hydrotreaters with no or minor modifications.



Petroleum Refinery

- Hydrotreatment
- Fuel finishing
- Trained workforce
- Industry know-how





- Fuel QA/QC
- Fuel delivery
- Fuel branding

https://www.eia.gov/dnav/pet/PET_PNP_CAP1_A_(NA)_8CDHD0_BPSD_A.htm

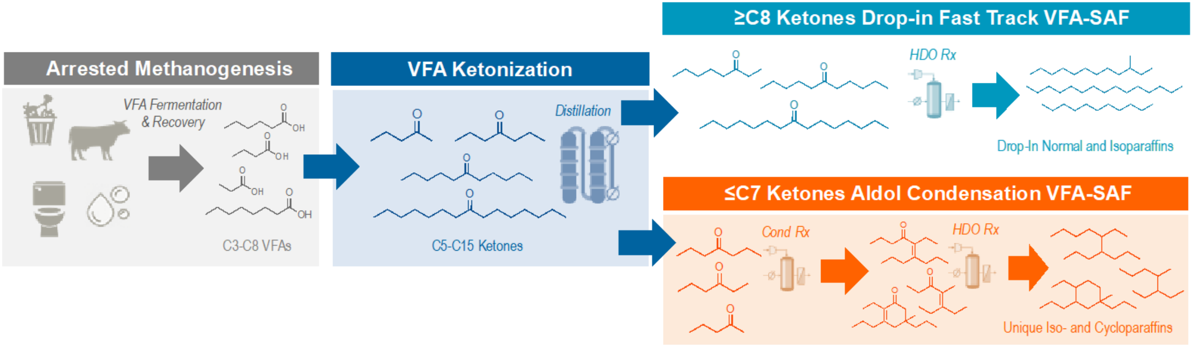
3

Selected Pathways for SAF Blend Stock Production Under Development at NREL

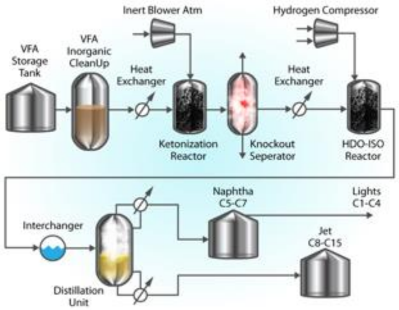
NREL VFA – SAF Catalytic Process Produces Normal and Iso alkane SAF Blendstocks From Wet Waste

- NREL catalytic technology upgrades neat volatile fatty acids from arrested anerobic digestors to ketones, which can then be upgraded to SAF
- Approach enables a bolt-on solution for existing anerobic digestor systems and petroleum refineries
- Technology has been licensed to Alder Fuels

"Fast Track" VFA-SAF 10% Blend



Novel 70% VFA-SAF Blend for Net Zero



For further information contact:
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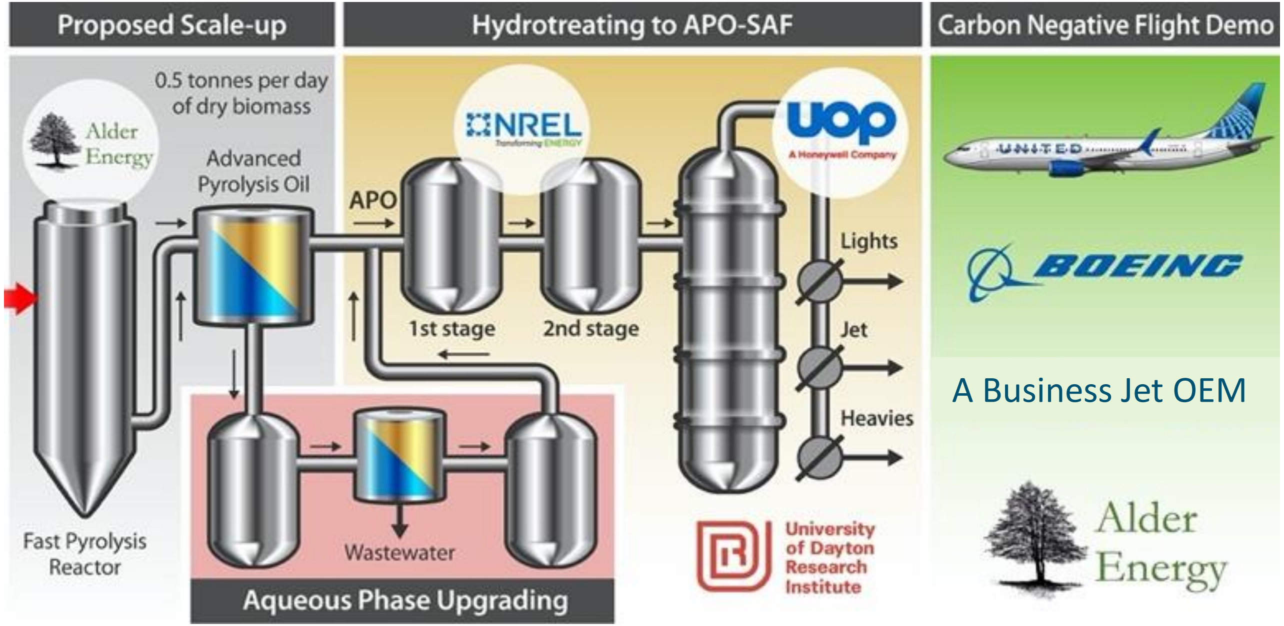
Huq et al., PNAS March 30, 2021, 118 (13) U.S. Patent Application No 17/121,336

Alder Fuel's "Green Biocrude" Pathway Converts Biomass to SAF Blend Stock

- Utilizes woody biomass residues, agricultural residues, and regenerative agricultural crops to enable carbon-negative "green biocrude" oil production
- "Green biocrude" to be hydrotreated within existing refinery infrastructure to minimize capital and time to market
- SAF rich in cycloparaffins and aromatics that meets ASTM fuel properties

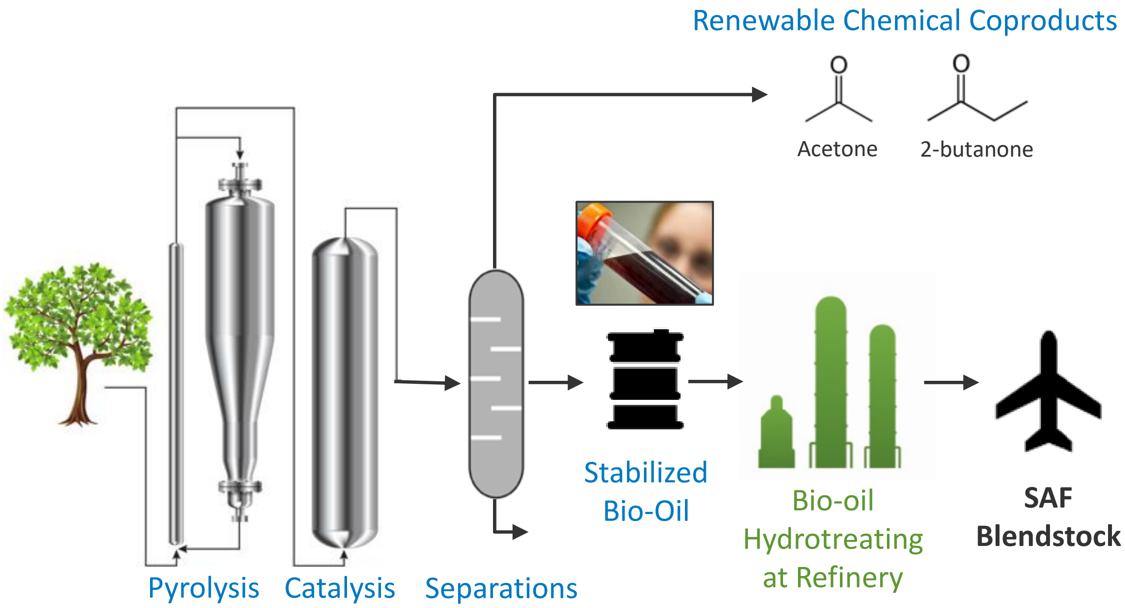


For further information contact:
AlderFuels.com

Catalytic Fast Pyrolysis Produces Stable Bio-Oil Which Can be Hydrotreated to Produce SAF Blend Stock

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

- Utilizes woody and low-cost feedstocks (e.g., forest residues)
- Char can sequester carbon for additional credits
- Refinery integration can save $0.30/gal on capital cost, reduce risk, and provide trained workforce
- Provides cycloparaffins and aromatics—complementary to HEFA
- >70% reduction in modeled GHG emissions relative to petroleum-derived fuel



For further information contact:
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Dutta et al., "Ex Situ Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2020 State of Technology", Technical Report: NREL/TP-5100-80291

FCC Co-Processing (CP) Offers a Near Term Option to Introduce Biogenic Carbon into Aviation Fuels

Our CP SAF technology uses bio-oils, biogenic waxes, and FOGs with petroleum feedstocks and zeolite catalysts to produce biogenic carbon containing aviation fuel fractions in existing refinery FCC units.

Feedstock

Bio Oil, Wax, FOGs

Production

Bio Oils

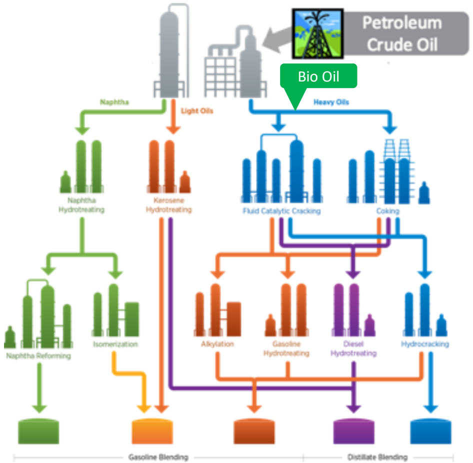
Petroleum Feeds (VGO)

Biogenic Waxes & FOGs

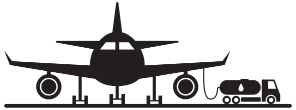
Co-Feed, Miscible Feedstocks

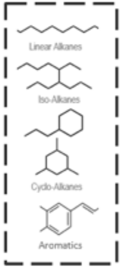
FCC Co-Processing to SAF

Fuel Property Analysis (ASTM)



Product





SAF product contains > 80% of biogenic carbon in the feed

For further information contact:
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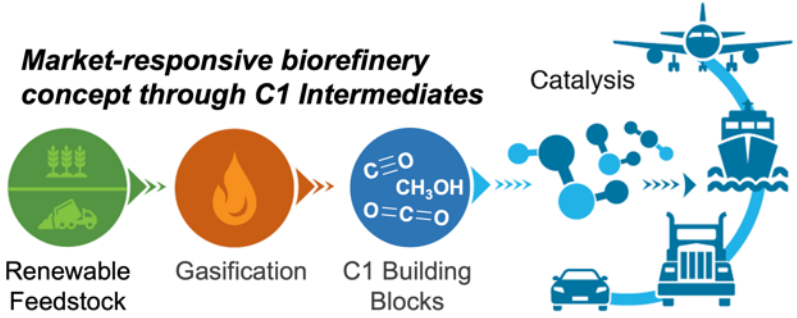
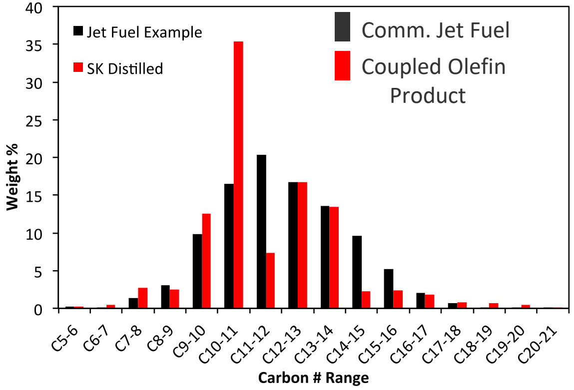
Methanol - Olefins – SAF Offers a Novel Pathway to Upgrade Syngas to SAF Blend Stock

NREL developed the centerpiece technology for the **conversion of renewable C1 intermediates** to produce a suite of fuels with **improved carbon efficiency, reduced capital expense, and control of the product distribution to SAF**.



Developed a mild-condition route for coupling syngas-derived olefins to jet-range hydrocarbons

C_4-C_8 Branched **OLEFINS** → C_8-C_{20} Branched **SAF Blend Stock**



Product meets 5 key ASTM International jet fuel property specifications

- ✓ Density
- ✓ Freeze Point
- ✓ Viscosity
- ✓ Heating Value
- ✓ Boiling Curve

For further information contact:
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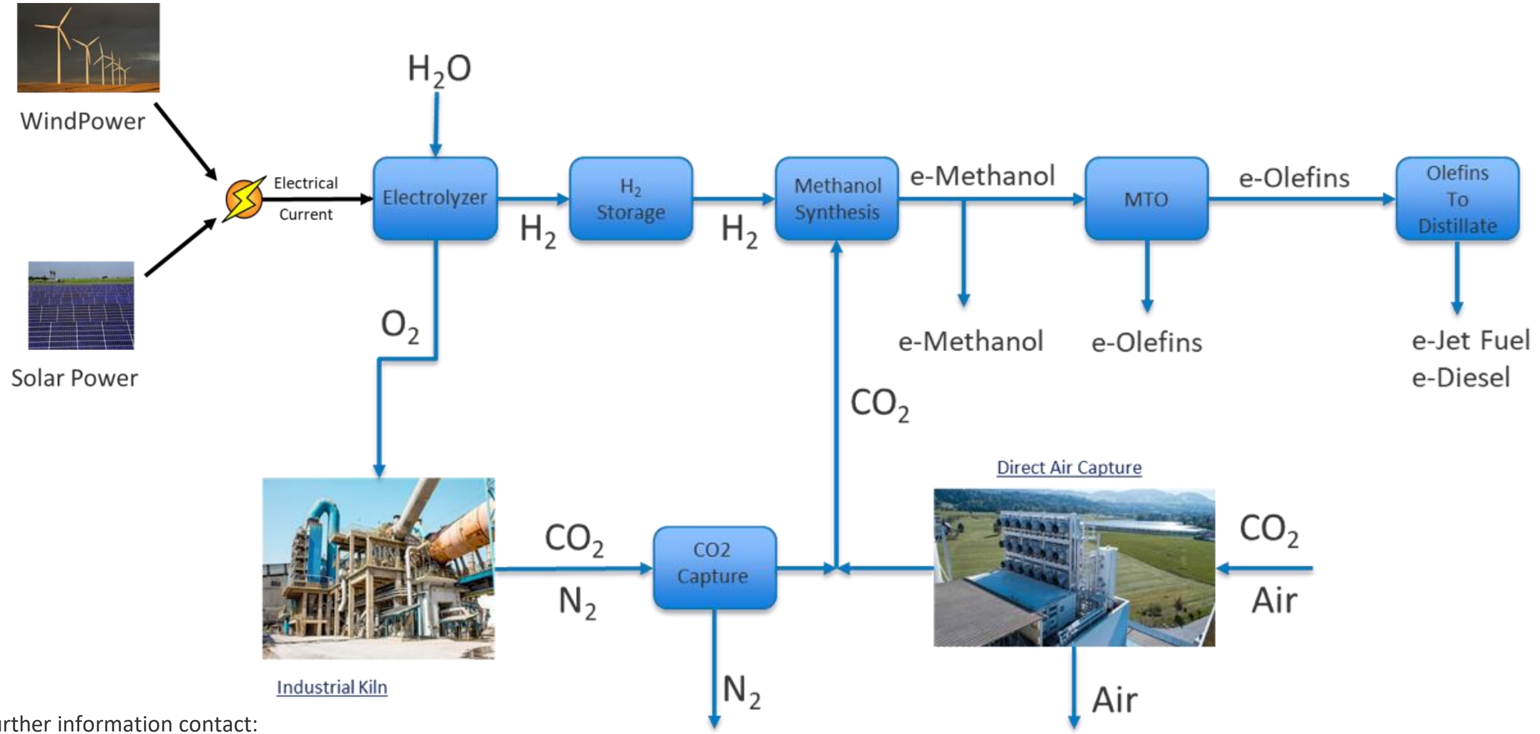
e-Methanol to Olefins Pathway Offers an Approach to Upgrade CO_2 to SAF Blend Stocks Using Renewable Electricity



For further information contact:
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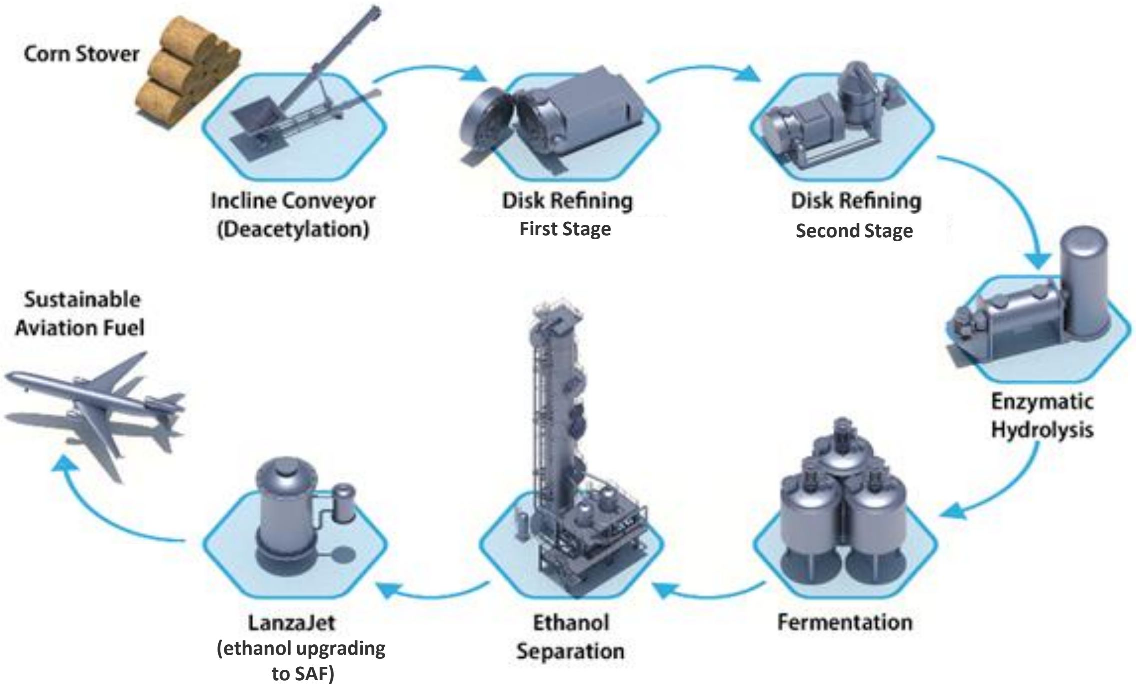
Ethanol From Corn Stover 2nd Generation Sugar Can be Upgraded via the D3MAX / LanzaJet Corn Stover to SAF Process

- NREL provides DMR technology and enzymatic hydrolysis to produce 2nd generation sugar

- In a 3.5-year DOE project, demonstrate reliable, low-GHG production of an intermediate ethanol product from corn stover in a fully integrated, 10 ton per day pilot-scale facility



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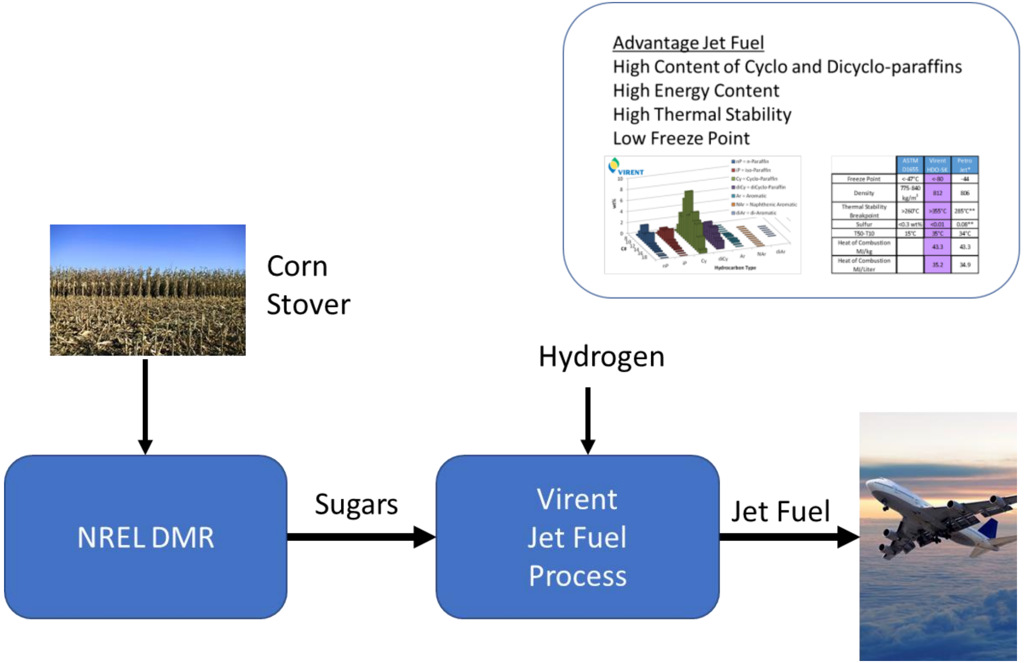
Virent's Bioforming Distillate Process Along With NREL's DMR Technology Offers A Direct Approach to Upgrade Cellulosic Sugars to SAF Blend Stock

- Integrate NREL's DMR and Virent's Catalytic Conversion processes.
- Combined expertise from CU-Boulder, NREL, Shell, and Virent
- De-risking and Continued Development of Virent's Catalytic Conversion of Sugars to Advantage Jet Fuel
- Construction and operation of an integrated process



For further information contact:
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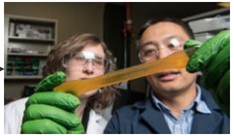
(DE-EE0008921 Funded Project Lead: University of Colorado)

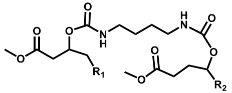
NREL's CAP Process Offers Attractive Economics For SAF Blend Stocks And Non-Isocyanate Polyurethane From Algae

Algae Biomass Production → Pretreatment & Extraction

Lipids → Fractionation → Distillation

Unsaturated fatty acids → Polyurethane Polymers





Saturated Fatty Acids (ASTM D7566)

Hydrotreating proprietary catalysis → SAF

Carbohydrates → Fermentation → Ethanol → SAF

Residue → Anaerobic Digestion → Renewable Fertilizers Nutrient Recovery

Residue → Feed/Aquaculture Opportunities

Innovative agriculture
Proprietary cultivars

Current olefins from algae 20% jet range, 70% diesel range, catalytically tunable

- $2.50/GGE (with NIPU, no credits)
- $8-10/GGE (no NIPU)
- $5-7/GGE
  - **D5 RIN credit @ $3/GGE**
  - **LCFS credit: 55% CO_2 reduction (no coproduct)**

Energy Fuels 2017, 31, 10, 10946−10953

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Integration of Electrochemistry With Fermentation: Formate as an Energy Source To allow Sugar Fermentation with no net CO_2 Generation

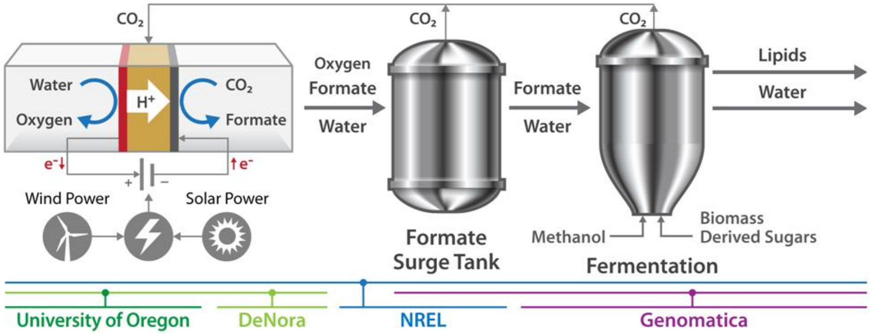
Technology Summary

- Develop and demonstrate an integrated process that electrochemically generates formate from CO_2 and use the formate as an energy source for the fermentation of sugars to fatty acid methyl esters (FAME) without net CO_2 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 CO_2-Free Fermentation



- CI for the generated FAME of this process is 35 gCO_2e/MJ
- Utilizing enhanced farming technologies would allow the **generated FAME to have a CI of 23 gCO_2e/MJ**, (similar to tallow feedstocks)

For further information contact:
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Summary: Strategy To Achieve 35 BGPY by 2050

- Use lowest cost feedstock first
- Be mindful of tradeoff between carbon intensity and cost
- Co-develop conversion processes with feedstock
- Target “drop-in” fuel molecules that are already in aviation fuel
- Get SAF approved though ASTM D4054 “fast track” to get to market quickly
- Then apply for conventional ASTM D4054 approval for higher blending ratio
- Focus on risk reduction to survive scaleup difficulties
- Focus on preprocessing feed to make it compatible with existing brownfield sites

Thank you

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ASTM Approved Pathways Address A Broad Range of Feedstock

Feedstock	Pathway	Approved Name	Blending Limitation
Municipal solid waste, agricultural and forest wastes, energy crops	**Fischer-Tropsch Synthetic Paraffinic Kerosene**	FT-SPK, ASTM D7566 Annex **A1**, 2009	50%
Oil-based feedstocks (e.g., jatropha, algae, camelina, and yellow grease)	**Hydroprocessed Esters and Fatty Acids**	HEFA-SPK, ASTM D7566 Annex **A2**, 2011	50%
Sugars	**Hydroprocessed Fermented Sugars to Synthetic Isoparaffins**	HFS-SIP, ASTM D7566 Annex **A3**, 2014	10%
Municipal solid waste, agricultural and forest wastes, energy crops	**FT-SPK with Aromatics**	FT-SPK/A, ASTM D7566 Annex **A4,** 2015	50%
Cellulosic biomass	**Alcohol-to-Jet Synthetic Paraffinic Kerosene**	ATJ-SPK, ASTM D7566 Annex **A5**, 2016	30%
Fatty acids or fatty acid esters or lipids from fat oil greases	**Catalytic Hydrothermolysis Synthesized Kerosene**	CH-SK or CHJ, ASTM D7566 Annex **A6,** 2020	50%
Algal oil	**Hydrocarbon-Hydroprocessed Esters and Fatty Acids**	HC-HEFA-SPK, ASTM D7566 Annex **A7**, 2020	10%