Beyond 2030 Technologies and Scale-Up Approaches for SAF Production at NREL

Zia Abdullah
Laboratory Program Manager

CAAFI Biennial General Meeting, June 3, 2022

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

Broad Variety of Feedstock Necessary to Achieve SAF Production of 35 BGY

Feedstock Production

Lignocellulosic Biomass (Wood, MSW, agri-waste, grasses, etc.)

Energy crops,
ag residues,
Stover, bagasse

Sugar/Starch Crops (corn, sugarcane etc.

Oils, FOG, Algae lipids, Volatile Fatty Acids from wet waste

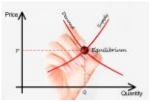
CO_2 (point source & DAC), Waste gas, e-

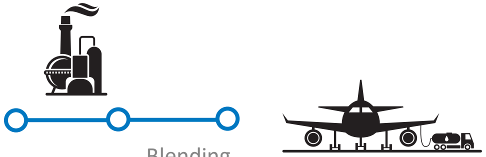
Selected 'Beyond 2030' Conversion Technologies Under Development at NREL

- Catalytic Fast Pyrolysis
- Ketonization
- Gasification - C_1 to olefins
- Lignin to SAF
- CO_2 reduction and upgrading to intermediates
- Algae deconstruction to carbohydrates, lipids and proteins
- Low CI Hydrogen production

Commoditized drop-in for refineries

SAF Blend stock





Blending

Product Specifications

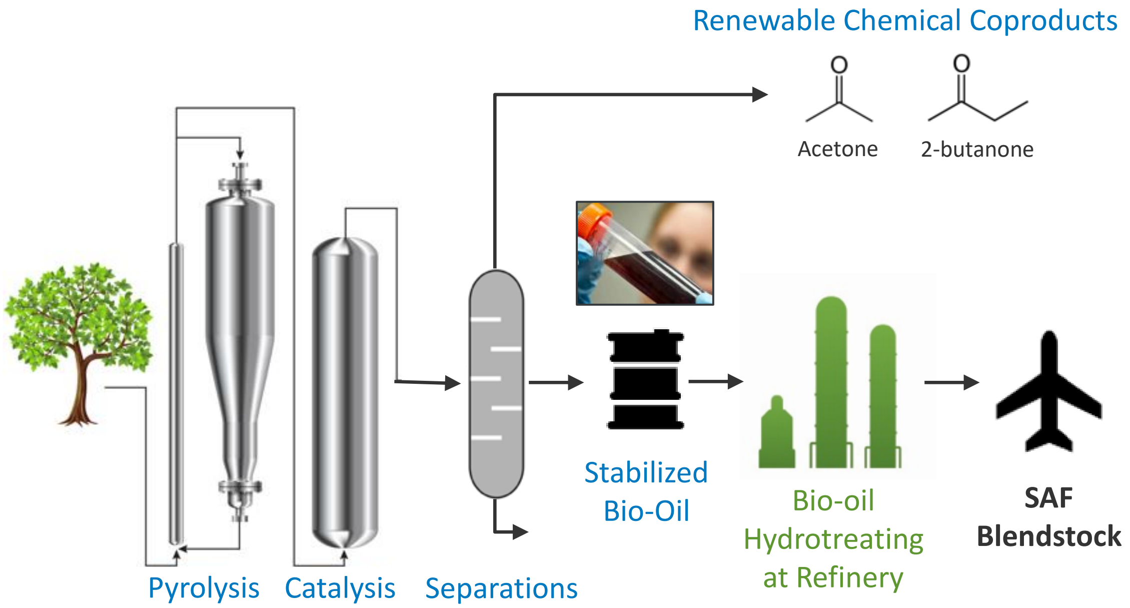
ASTM D4054

ASTM D7566 (Jet-A)

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

NREL, in collaboration with PNNL and INL developed a **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

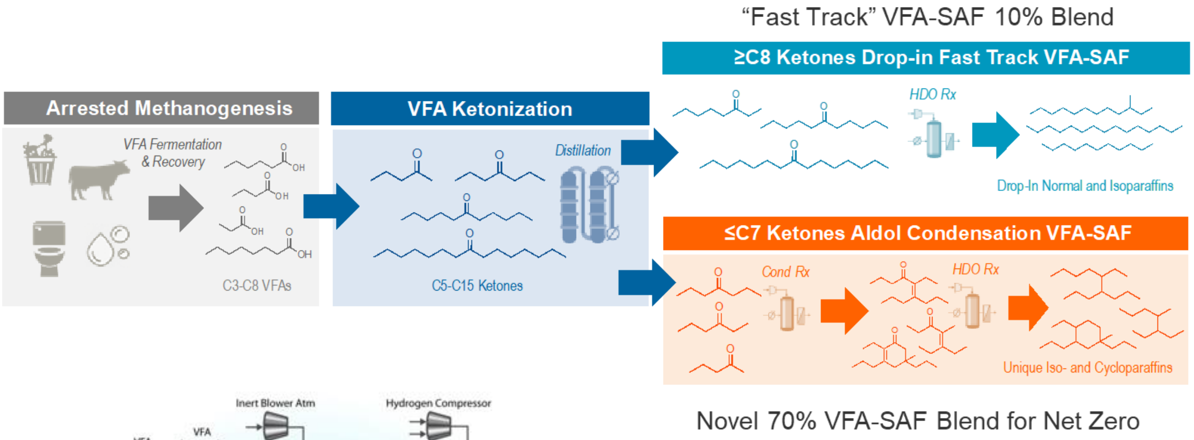


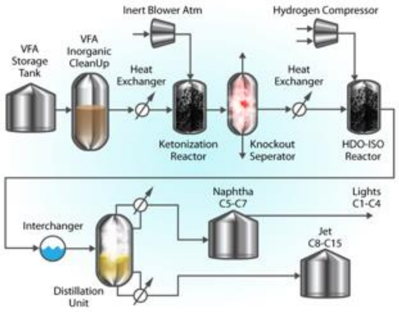
For further information contact:
Josh Schaidle
Joshua.Schaidle@nrel.gov

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

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



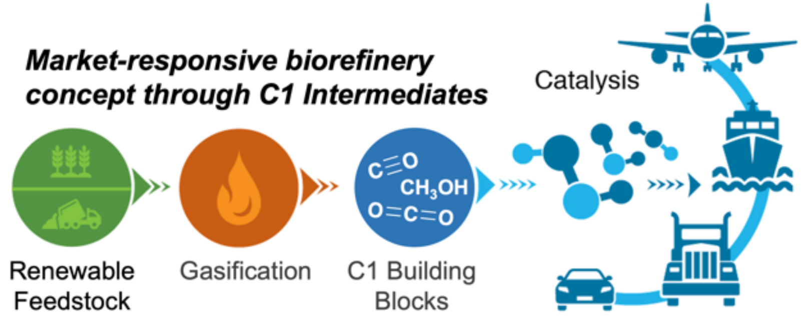


For further information contact:
Jacob Miller
jacob.miller@nrel.gov

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

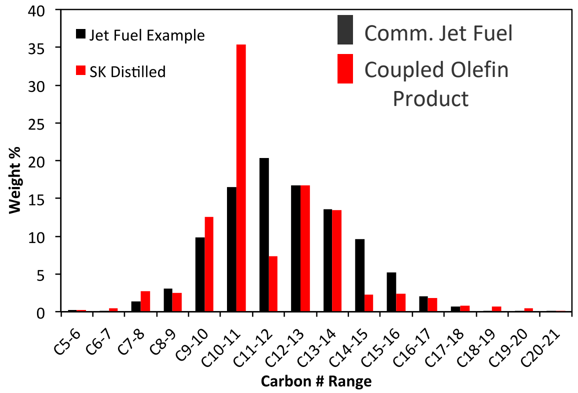
Methanol - Olefins – SAF Offers a Novel Pathway to Upgrade Syngas to SAF Blend Stock

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**

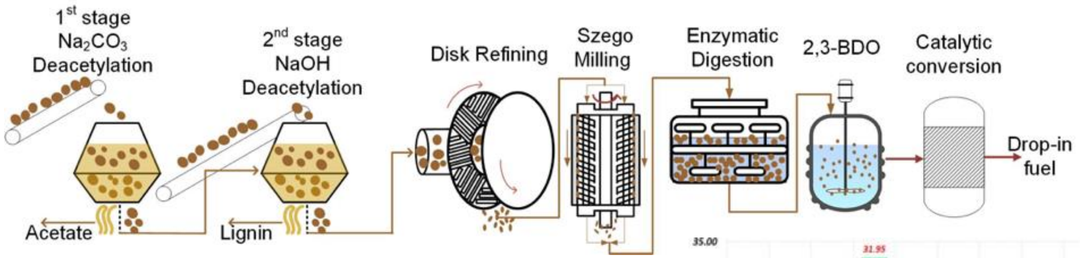


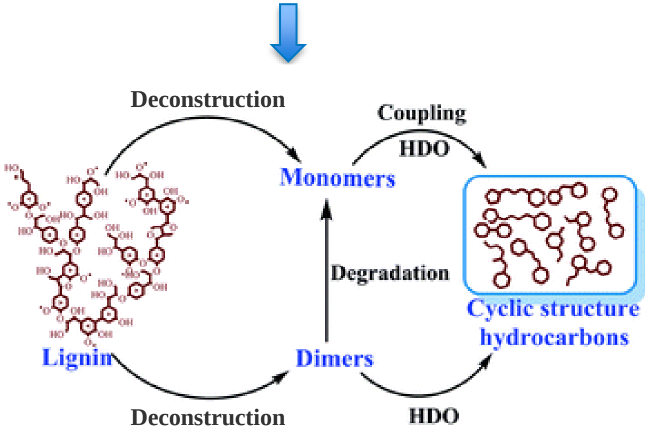
Product meets 5 key ASTM International jet fuel property specifications

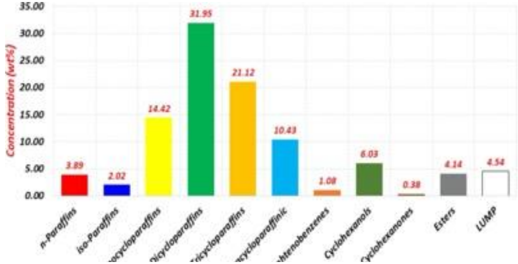
- ✓ Density
- ✓ Freeze Point
- ✓ Viscosity
- ✓ Heating Value
- ✓ Boiling Curve

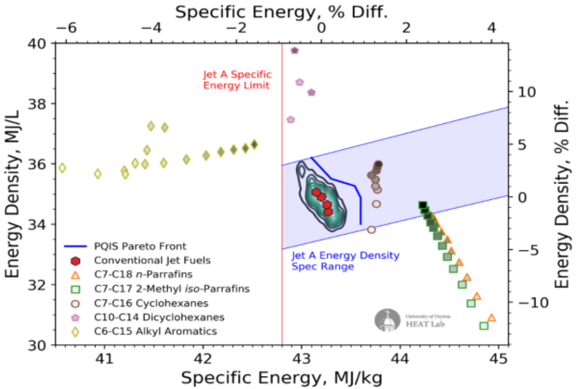
For further information contact:
Dan Ruddy
Dan.Ruddy@nrel.gov

DMR - Lignin Conversion to SAF Blendstocks









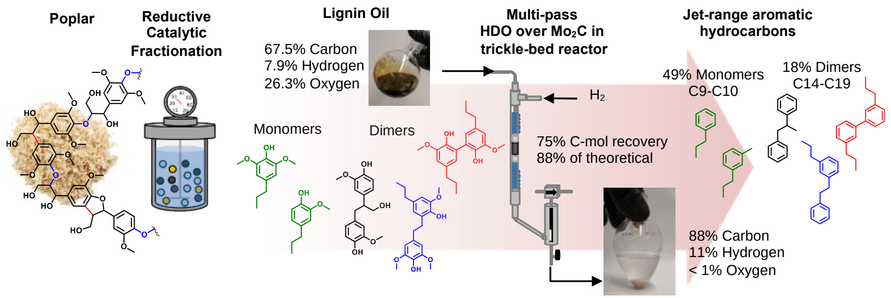
Wang, Chen, Tucker and Yang et al. , Green Chemistry, 2015
Ruan, Heyne, Yang et al. , Fuel, 2019

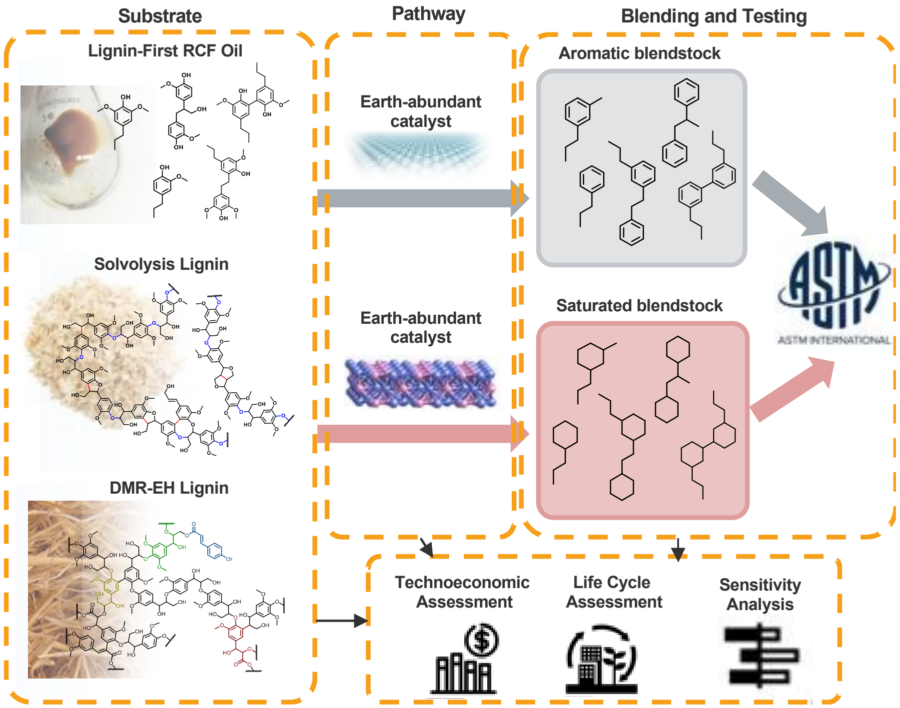
- Using lignin waste from deacetylation and mechanical refining (DMR) process (a low temperature atmospheric biomass deconstruction process)
- Producing high energy density dicycloparaffins that could be a potential candidate for high energy fuel additive
- Mimicking the swelling characteristics of aromatics

NREL
NATIONAL RENEWABLE ENERGY LABORATORY
WASHINGTON STATE UNIVERSITY
UND UNIVERSITY OF NORTH DAKOTA
UNIVERSITY of DAYTON
UNIVERSITY of DAYTON

RCF - Lignin Conversion to SAF Blendstocks

- DOE-funded project focused on converting lignin from woody feedstocks, grasses, and agricultural residues to aromatic and cycloalkane blendstocks
- Collaboration with MIT, Argonne National Lab, and University of Dayton Research Institute
- Have demonstrated this work to date on lignin substrates from Reductive Catalytic Fractionation
- Able to achieve >90% mass balance and < 1 wt% oxygen from poplar feedstocks
- Can control selectivity to aromatic or saturated products
- TEA, LCA, and blendstock property testing ongoing





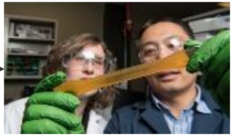
Work funded by DOE BER Center for Bioenergy Innovation and the DOE EERE Bioenergy Technologies Office

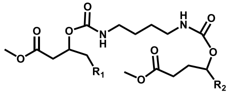
NREL's CAP Process Offers Attractive Economics For SAF Blend Stocks And Non-Isocyanate Polyurethane From Algae

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

PATENTED

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

For further information contact:
Lieve Laurens
Lieve.Laurens@nrel.gov

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

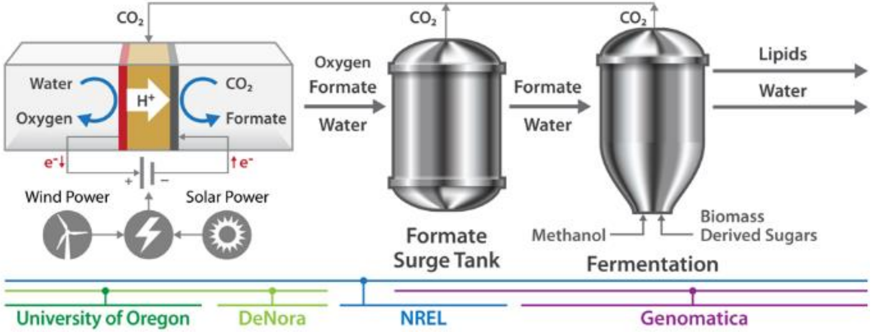
Technology Summary

- 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

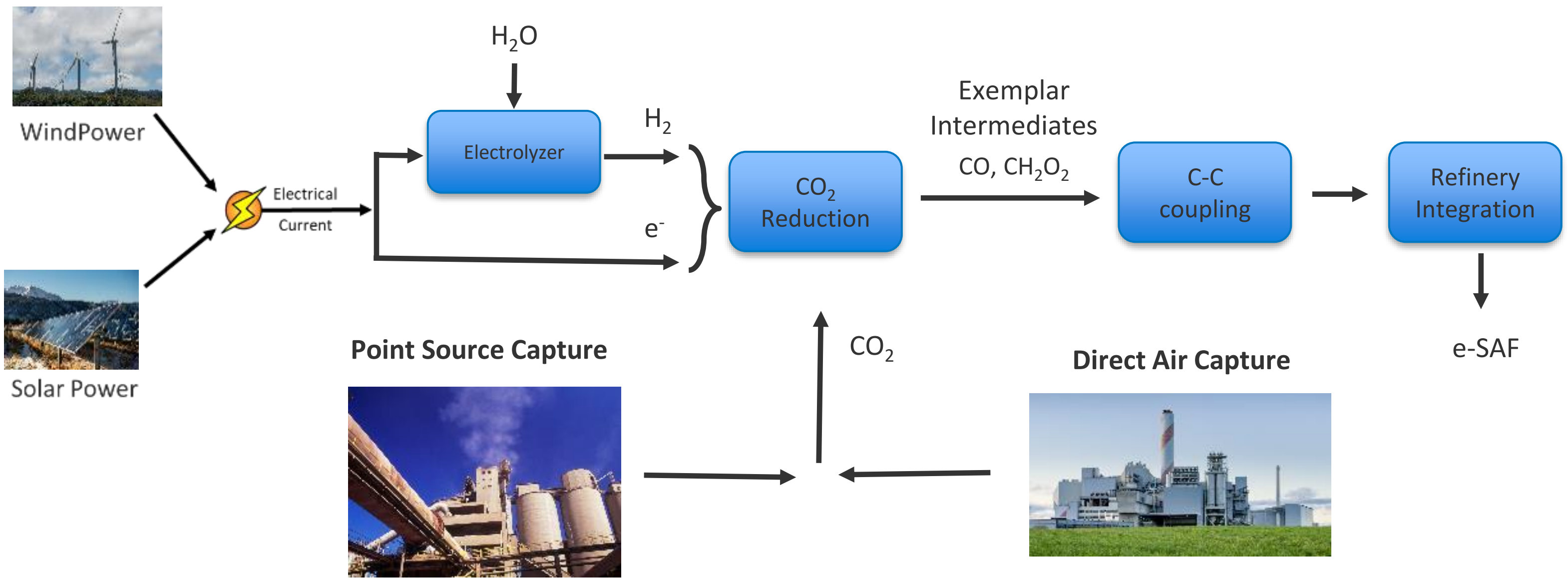
Integrated Process That Allows CO_2-Free Fermentation



- 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:
Randy Cortright
Randy.Cortright@nrel.gov

NREL's e-M Program is Developing Pathways to Upgrade CO_2 to SAF Blend-stocks Using Renewable Electricity



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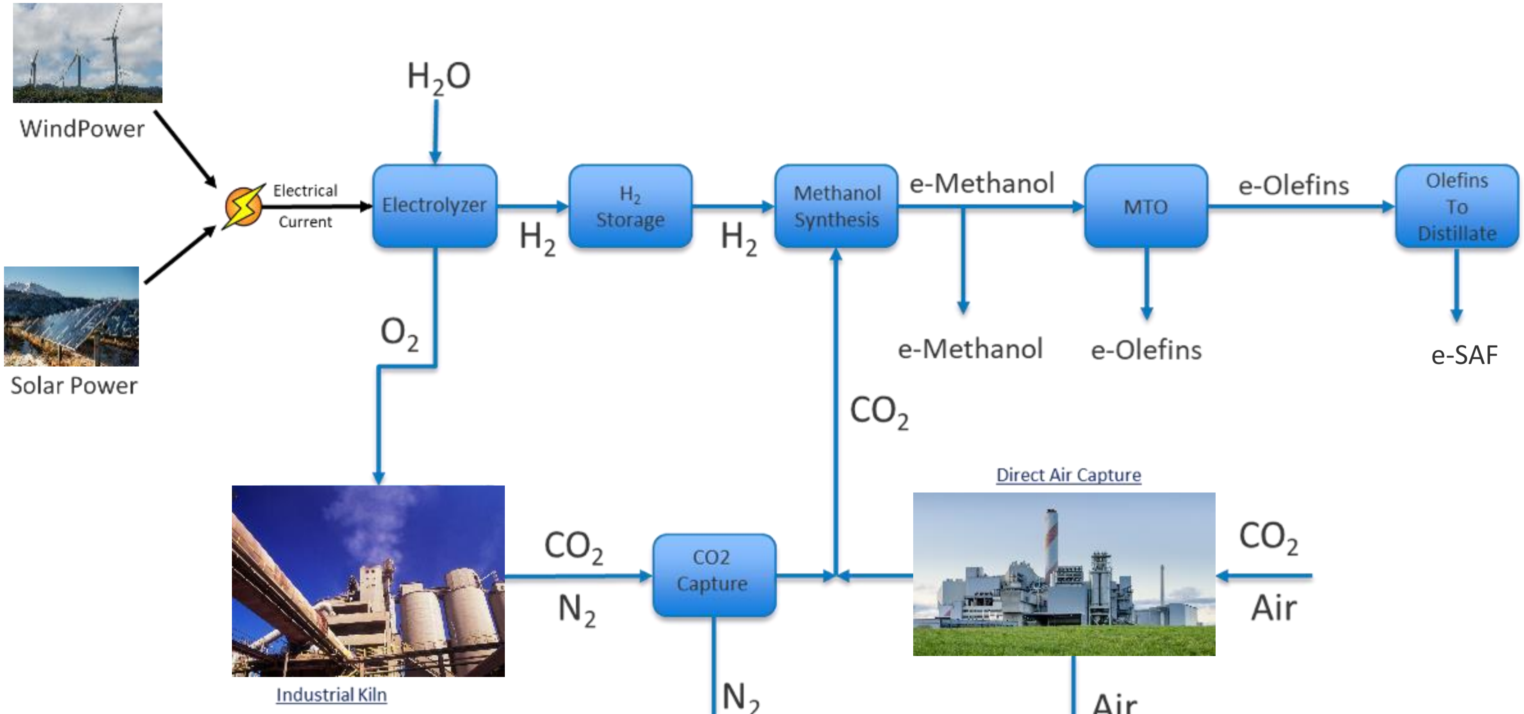
e-Methanol to Olefins Pathway Offers a Nearer Term Option to Upgrade CO_2 to SAF Blend Stocks Using Renewable Electricity



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Randy Cortright
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Refinery Integration: Refineries Can Be Customers For Biofuels Intermediate Stream Producers

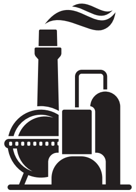
Opportunities

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

Challenges

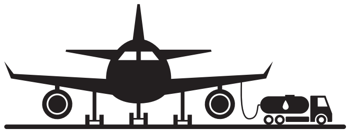
- Large variability of streams
- Match equipment to streams
- Hydrotreater scale too large
- ASTM approval of pathways
- Incompatibility of materials of construction with bio-streams
- Managing exothermic reactions

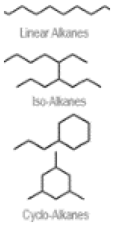
Fats, Oils, Greases



Petroleum Refinery

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





- Fuel QA/QC
- Fuel blending
- Fuel branding

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

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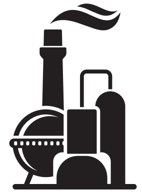
FT Waxes & Oils | Alcohols | Bio-Oils/ Biocrudes | Acids/ Ketones | Sugars | Algae Oils | Lignin streams

Focus of R&D: Conversion of Intermediates 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.

Blend stock

Fats, Oils, Greases



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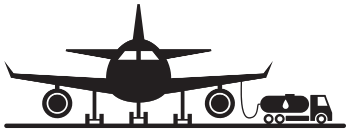

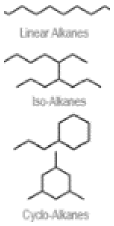

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Thank you

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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 by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Bioenergy Technologies Office. The views expressed in the article 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.

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