The future of biofuels and bioproducts towards achieving carbon neutrality by 2050

Thomas D. Foust – NREL Bioenergy Director

2022 North American Biochar and Bioenergy Conference


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

Science Drives Innovation

Renewable Power

Solar
Wind
Water
Geothermal

Sustainable Transportation

Bioenergy - SAF
Vehicle Technologies
Hydrogen

Energy Efficiency

Buildings
Advanced Manufacturing
Government Energy Management

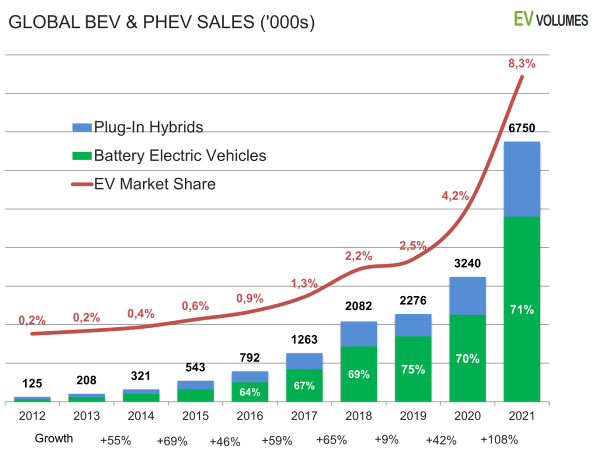
Energy Systems Integration

Grid integration & modernization
High-Performance Computing
Data and Visualization

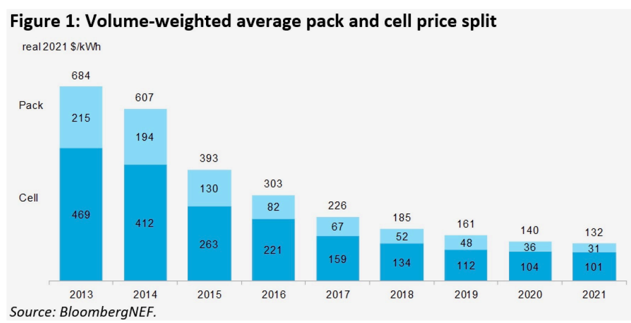
Sustainable, low carbon and low-cost electricity are central to electricity generation

MACRO TRENDS: Battery Electric Vehicles are a Major Disruptor to Light Duty Transportation

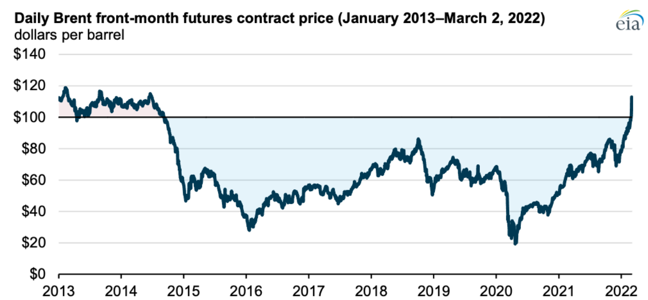
Many Countries Have Plans to Ban Gasoline Vehicles. Manufacturers Making Major Bets on BEVs



Battery Cost Reduction trending towards $100 kwh



Crude oil prices are highly volatile



Electric cars and autonomous drive probably are the future of light duty transportation

- Electric cars (with battery improvements) could be very long lasting - >1M miles
- Provides excellent opportunities for fleet ride sharing
  - Typical POV driven at 15k miles/year – 5% utilization factor
  - Fleet ride sharing vehicles could be 50% utilization factor or above ~ 150k miles/year
  - Electric plus autonomous can brings down cost per mile traveled to less than POV ownership
  - Decrease commuting time – less traffic jams
- If vehicles connected to electric grid they can provide storage capacity and further reduce costs

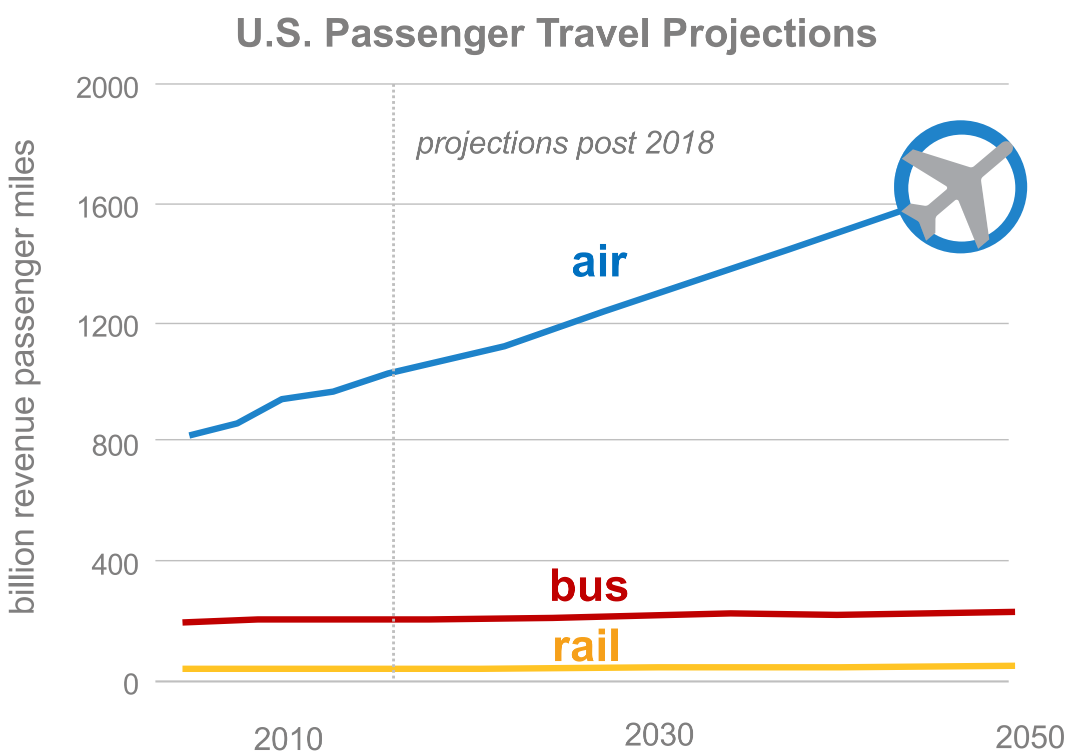
Low carbon biofuels will be required for air, marine and rail transport

1. Motivation to decarbonize with 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; current state-of-the-art batteries store 2.5% energy per mass as jet fuel



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

Powering Boeing 737-800 with Batteries or H_2

Hybrid Powertrains May Be Possible But Full Electrification Is Unlikely With Current State of Technology

Boeing 737-800
Specifications:

- Jet A Fuel capacity: 6,875 gals
- Jet A Fuel weight: 21.37 tons
- Max takeoff weight: 87 tons

Option 1: Battery Power and electric turbofan:

- Motor efficiency 90% vs turbine eff 55%
- Battery weight: 600 tons (28 X Jet A)
- Charging current at 480V is 192 KA (65% to full charge)
- Charging power 368 X Tesla V3 charger

Option 2: H_2 displaces Jet A with same turbofan engine:

- H_2 storage pressure: 10,290 PSI (same as Toyota Mirai)
- H_2 tank volume: 43,713 gals (6.4 X Jet A vol, 50% fuselage volume)
- H_2 storage temperature: -253 C (cryogenic storage)
- H_2 tank volume: 27,530 gals (4.0 X Jet A vol, 28% fuselage volume)

Option 3: H_2 with fuel cell & electric turbofan

- H_2 storage pressure: 10,290 PSI (same as Toyota Mirai)
- H_2 tank volume: 44,523 gals (6.5 X Jet A vol , 51% fuselage volume)
- H_2 storage temperature: -253 C (cryogenic storage)
- H_2 tank volume: 28,040 gals (4.1 X Jet A vol, 29% fuselage volume)

Multiple feedstocks needed to 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. has the potential capacity to produce a billion tons of biomass which can be converted to ~ 60 BGPY of biofuels
- SAF provides links to agriculture, food security, and waste management with opportunities for cross-sector benefits at the intersection of energy and environment

Jet Fuel (Kerosene) Compared to Gasoline and Diesel Fuels

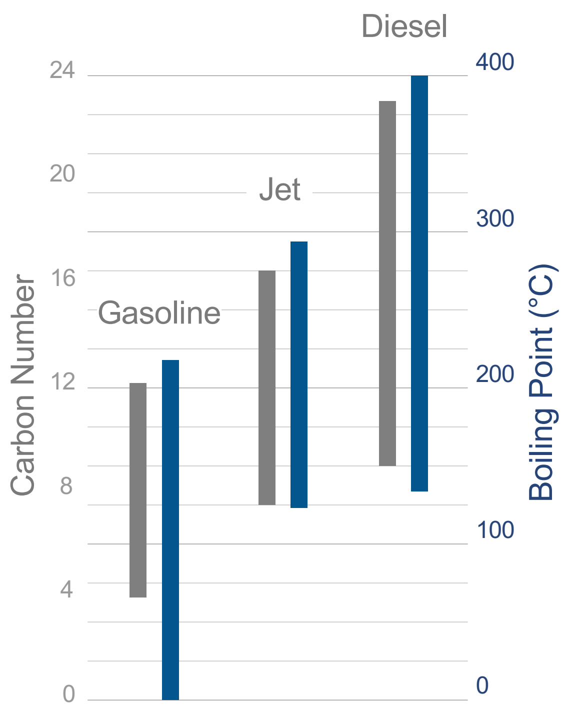
Jet Hydrocarbon Classes

- Normal Alkanes
- Iso Alkanes
- Cyclo Alkanes
- Aromatics

Gasoline / Diesel Oxygenates

- Alcohols (ethanol)
- Esters (biodiesel)

Carbon & Boiling Point Range

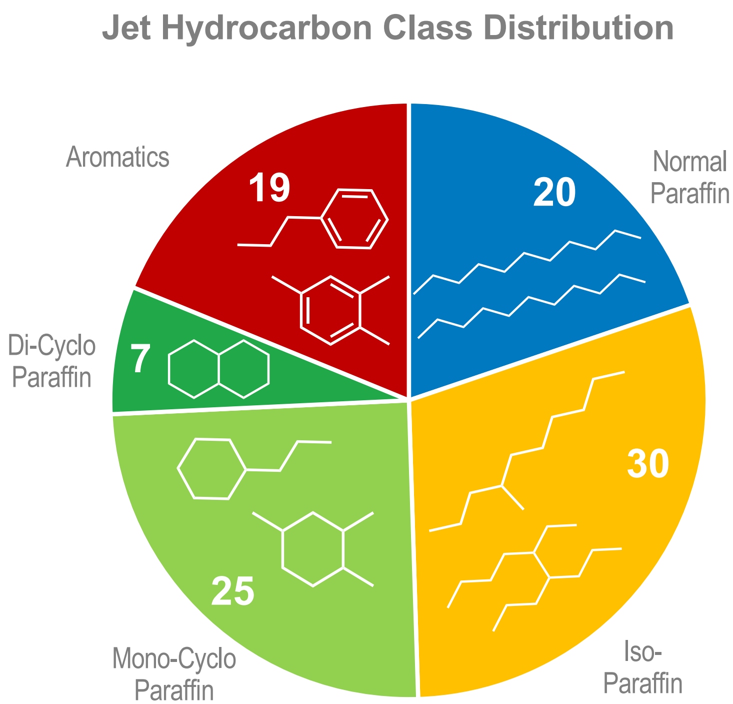


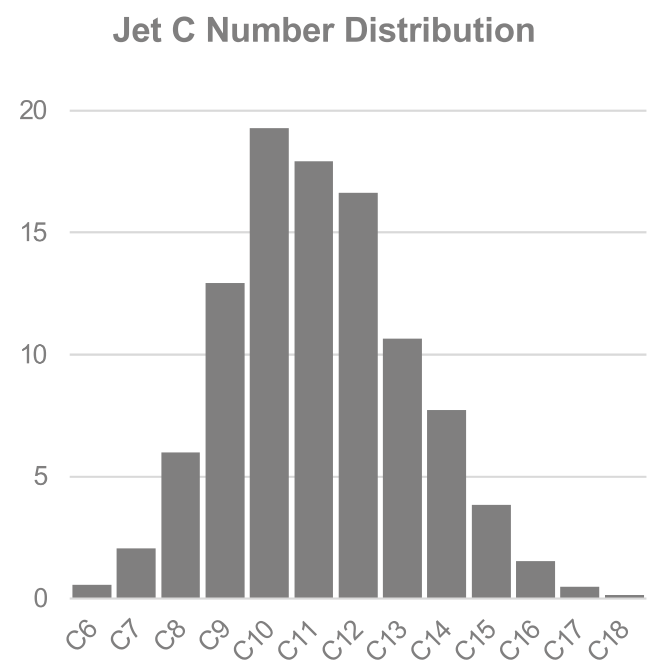
Source: ASTM D1655; ASTM D7566; ASTM D4054; Holladay et al. (2020) DOE/EE-2041 8292

- Safety, operability, and performance are core criteria for aviation fuel as an engineered liquid energy carrier
- Jet fuel unique from gasoline and diesel fuel based on fuel property requirements – no oxygen or olefins, among other specifications
- ASTM qualification ensures SAF meets same standard of jet fuel performance, regardless of fossil or renewable origin

Jet Fuel Composition as it Relates to Functions and Properties

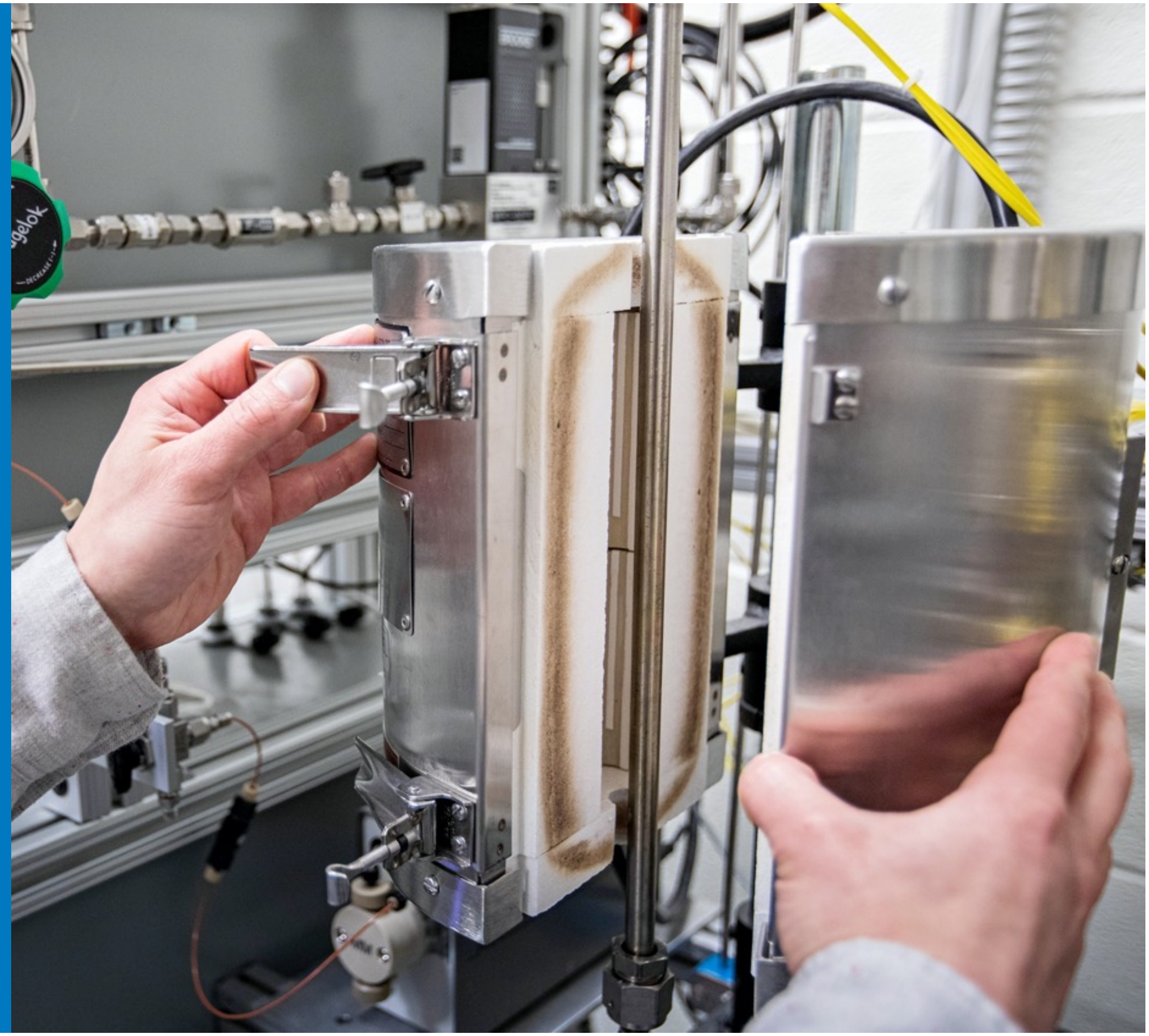
- Jet fuel Has Multiple Functions:
  - coolant (heat transfer media)
  - lubricant
  - hydraulic fluid
  - ballast fluid,
  - swelling agent,
  - capacitance agent
  - energy source
- Key properties:
  - low temp fluidity, thermal stability, energy content
  - Lightly branched alkanes
  - Cyclic alkanes
  - No heteroatoms or alkenes
  - No metals or water





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

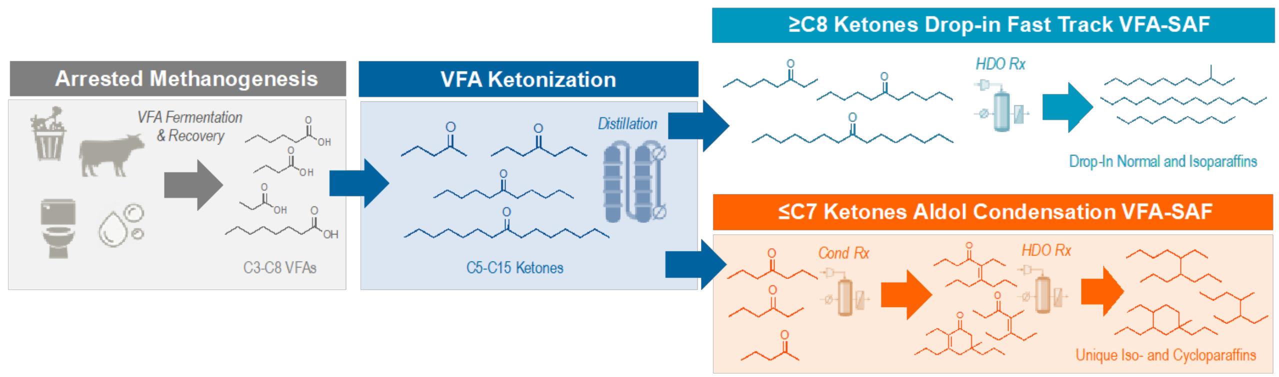
Selected Pathways for SAF Blend Stock Production Under Development



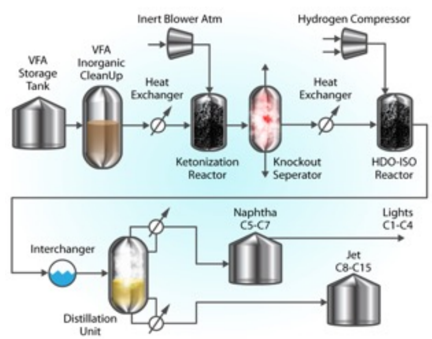
Wet Waste– SAF Catalytic Process Produces Normal and Iso alkane SAF Blendstocks From Wet Waste

- 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

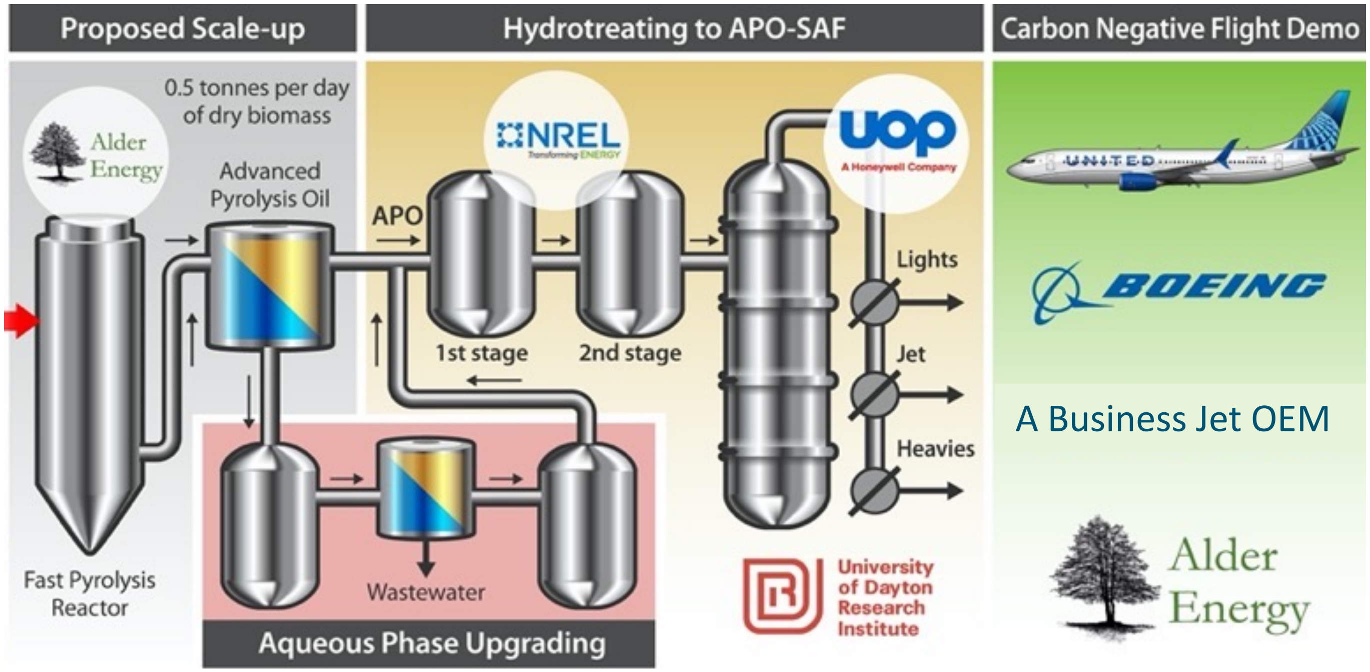


For further information contact:
Jacob Miller
jacob.miller@nrel.gov

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

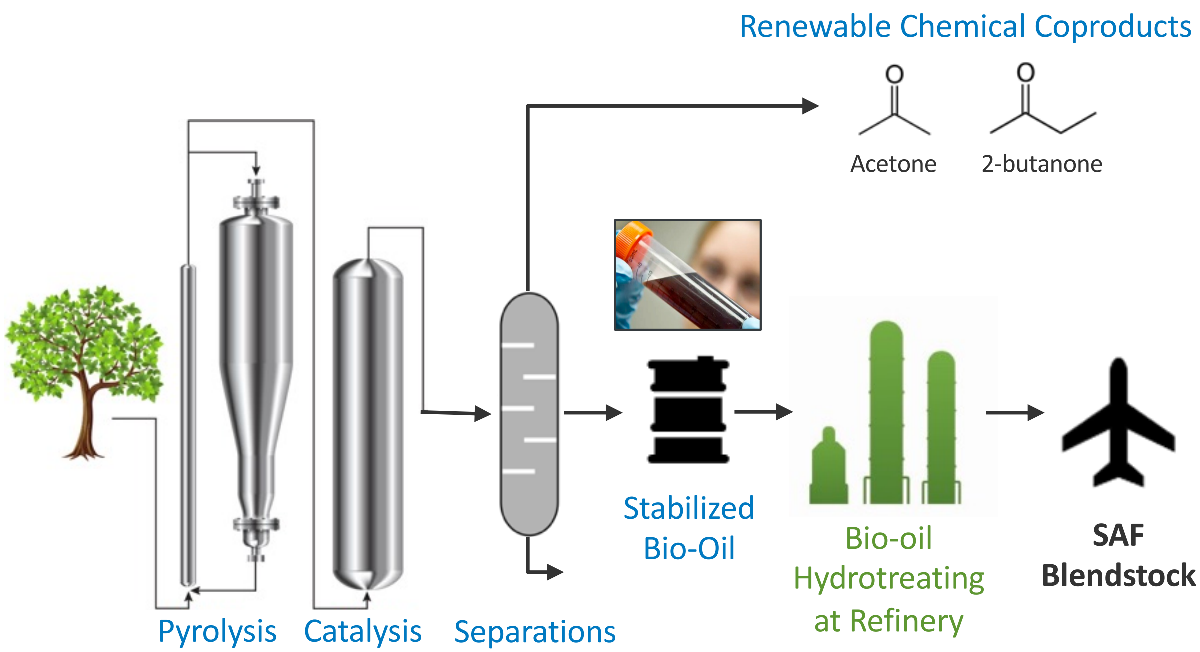


For further information contact:
AlderFuels.com

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



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

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

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

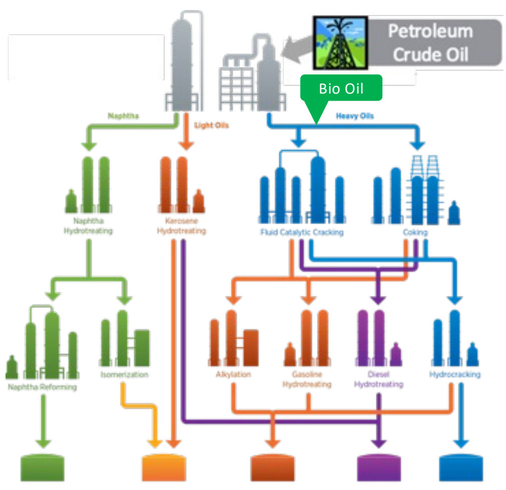
Production

Bio Oils

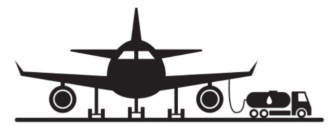
Petroleum Feeds (VGO)

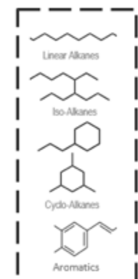
Biogenic Waxes & FOGs

Co-Feed, Miscible Feedstocks → FCC Co-Processing to SAF → Fuel Property Analysis (ASTM)



Product

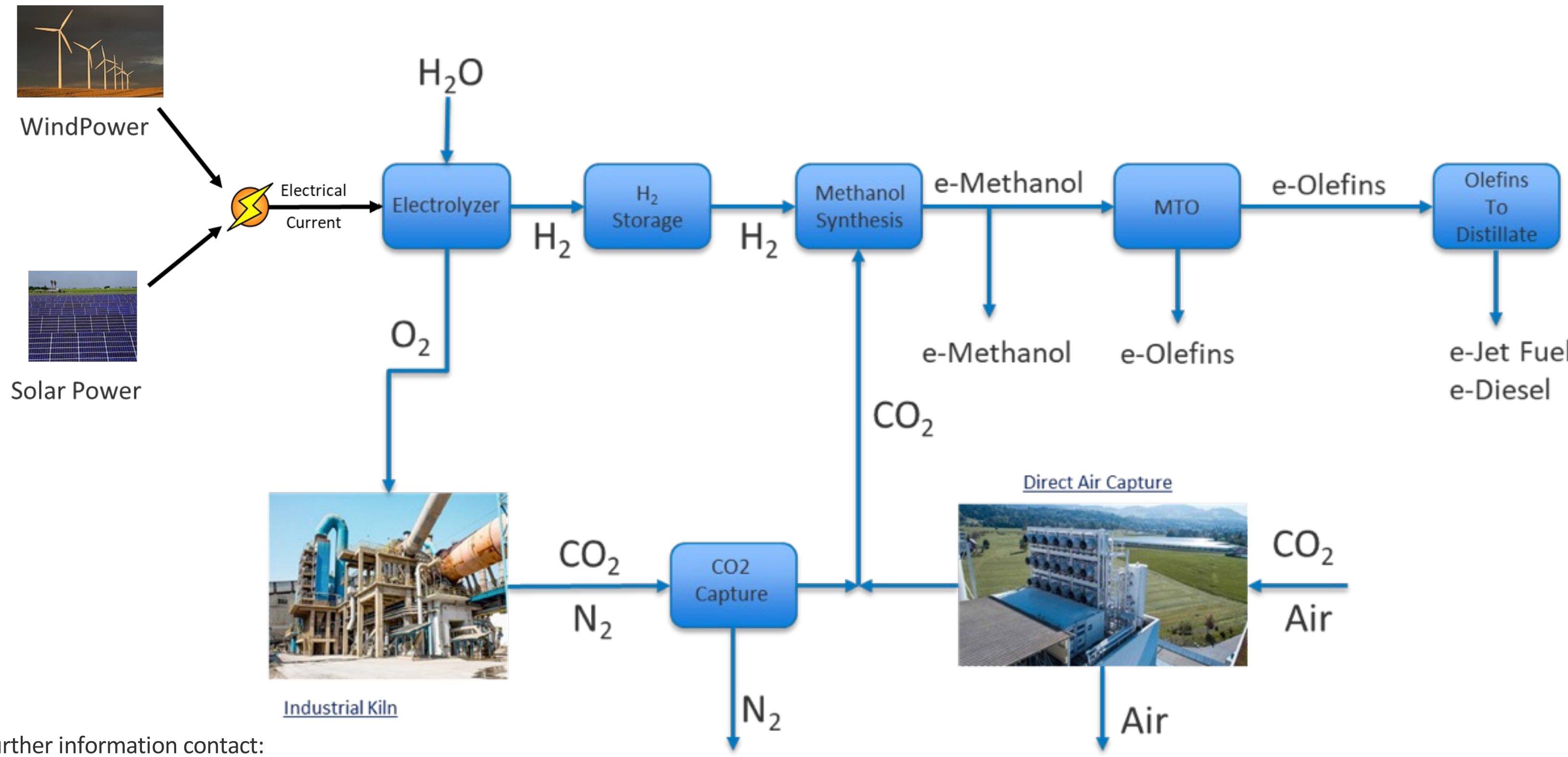




SAF product contains > 80% of biogenic carbon in the feed

For further information contact:
Kim Magrini
Kim.Magrini@nrel.gov

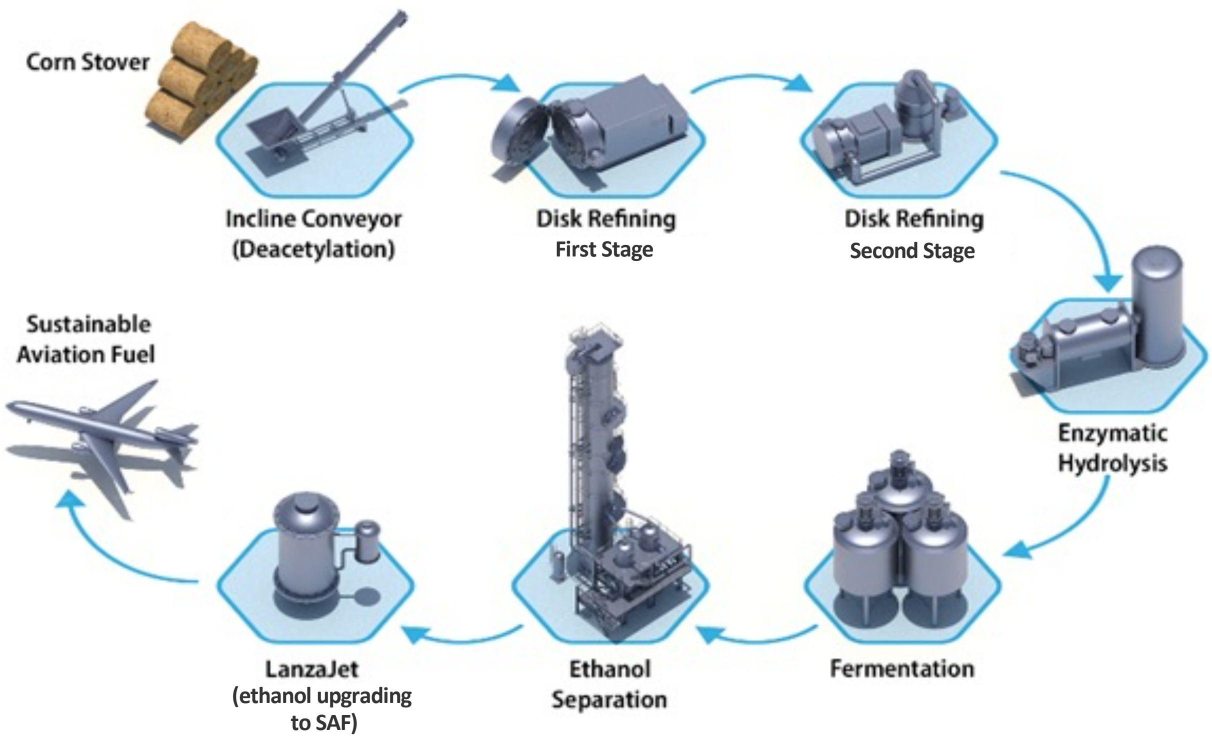
e-Methanol to Olefins Pathway Offers an Approach to Upgrade CO_2 to SAF Blend Stocks Using Renewable Electricity



For further information contact:
Randy Cortright
Randy.Cortright@nrel.gov

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



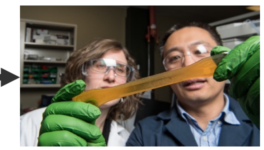
For further information contact:
Mike Himmel
Mike.Himmel@nrel.gov

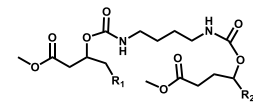
SAF Blend Stocks And Non-Isocyanate Polyurethane From Algae

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

Polyurethane Polymers





SAF

Innovative agriculture
Proprietary cultivars

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

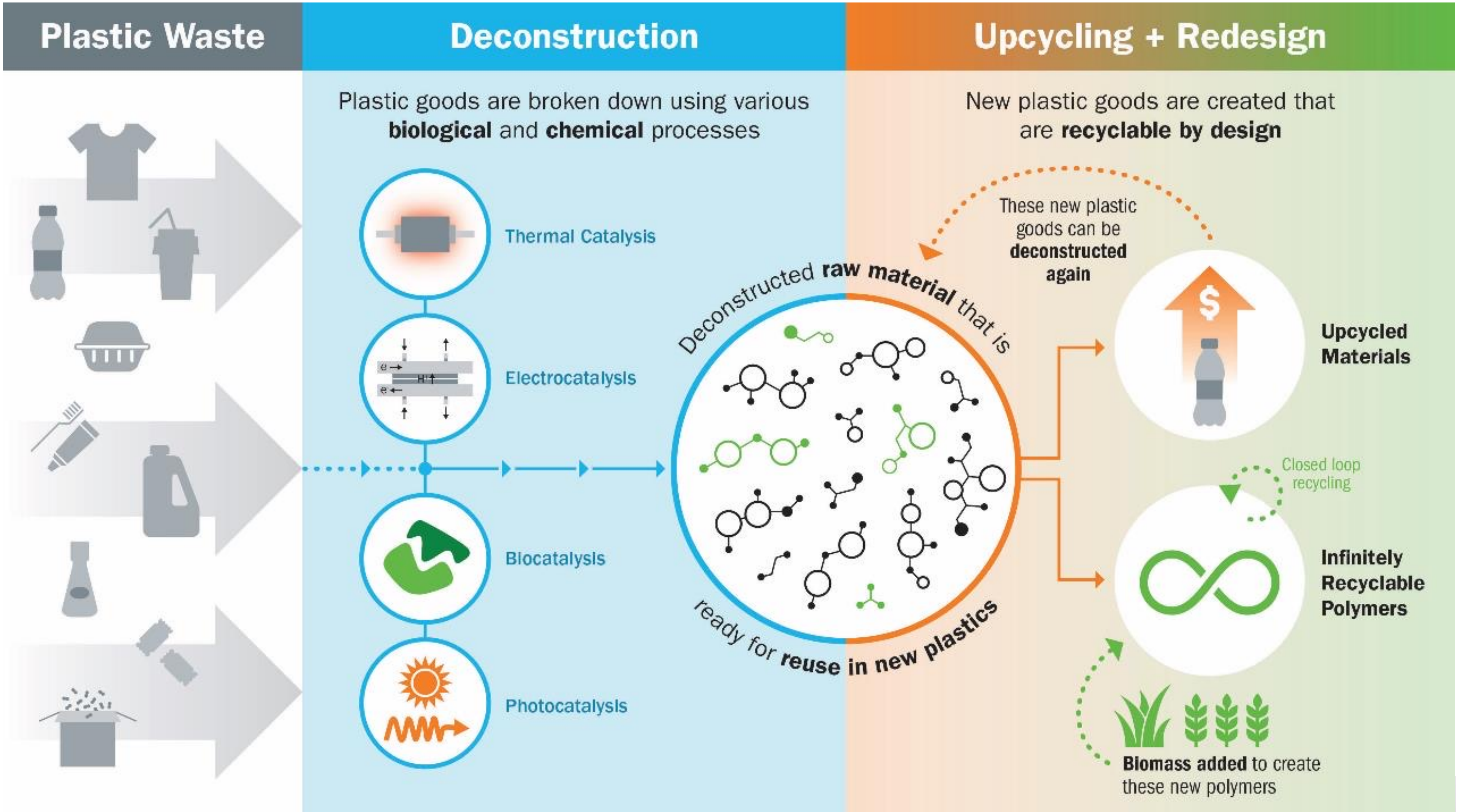
- $2.50/GGE (with NIPU, no credits)
- $8-10/GGE (no NIPU)
- $5-7/GGE
  - **D5 RIN credit @ $3/GGE**
  - **LCFS credit: 55% CO_2 reduction (no coproduct)**

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

Energy Fuels 2017, 31, 10, 10946−10953

ASTM Approved Pathways Address A Broad Range of Feedstock, And If Hurdles Can Be Lowered, Can Offer Rapid Market Impact

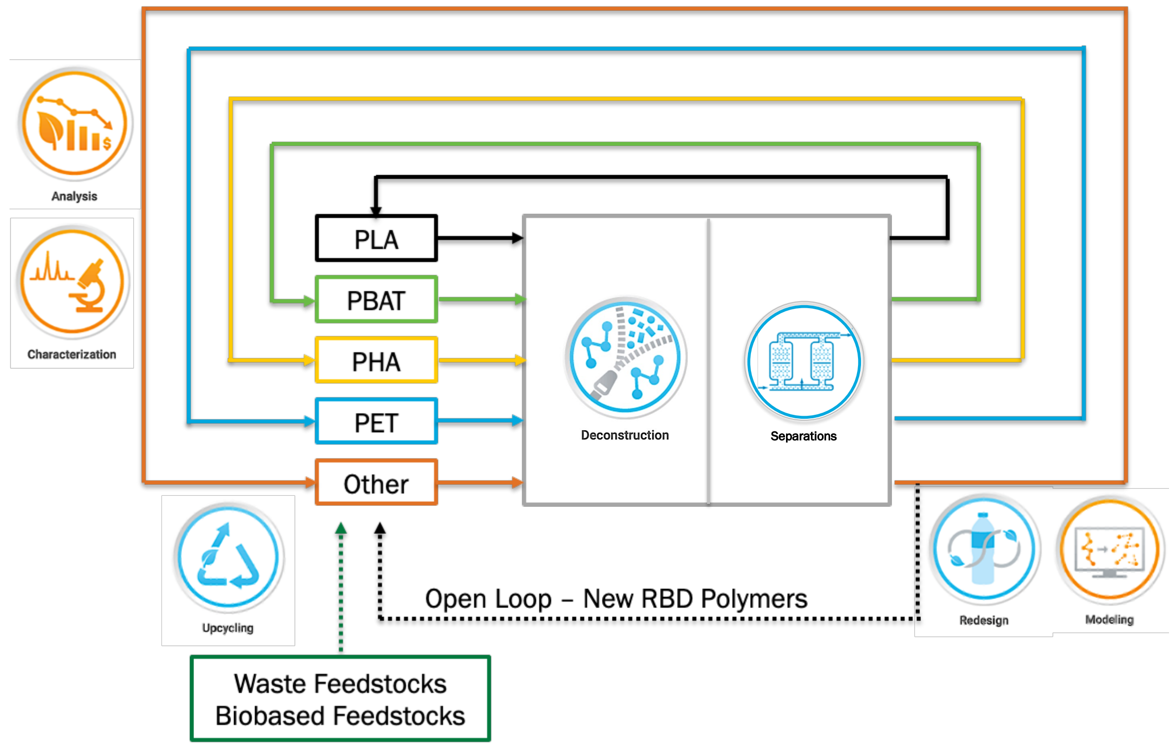
Feedstock	Pathway	Approved Name	Blending Limitation
Municipal solid waste, agricultural and forest wastes, energy crops	**Fischer-Tropsch Synthetic Paraffinic Kerosene**	FT-SPK, ASTM D7566 Annex **A1**, 2009	50%
Oil-based feedstocks (e.g., jatropha, algae, camelina, and yellow grease)	**Hydroprocessed 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%


Plastic Waste
Deconstruction
Upcycling + Redesign
Plastic goods are broken down using various biological and chemical processes
Thermal Catalysis
Electrocatalysis
Biocatalysis
Photocatalysis
Deconstructed raw material that is ready for reuse in new plastics
New plastic goods are created that are recyclable by design
These new plastic goods can be deconstructed again
Upcycled Materials
Closed loop recycling
Infinitely Recyclable Polymers
Biomass added to create these new polymers

Deconstruction, upcycling, & redesign of polyesters

Overall Goals:
- Develop recycling solutions for non-sorted polyesters
- Develop new recycle-by-design polyesters from the intermediates from deconstruction

Closed Loop Polyester Recycling Pathways

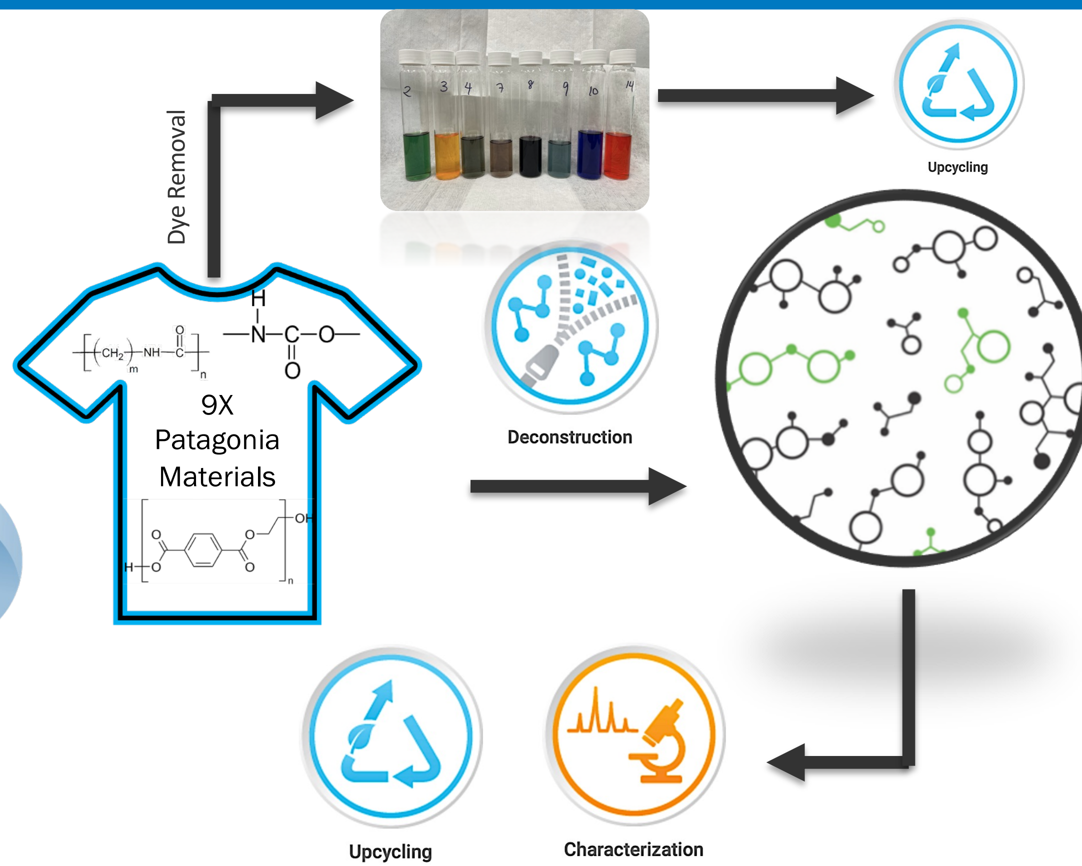


Amazon's investment in the Closed Loop Infrastructure Fund is focused on financing recycling and circular economy infrastructure in North America

patagonia - Textile recycling solutions

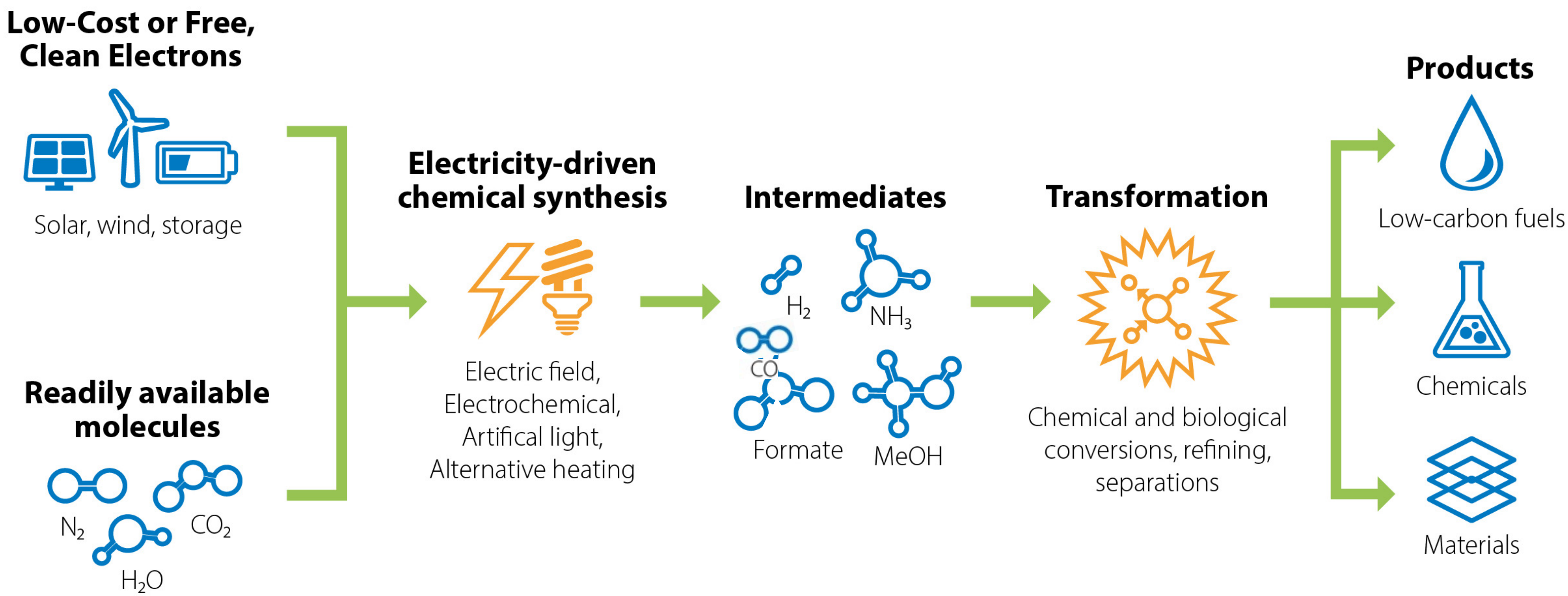
Patagonia is moving toward 100% renewable and recycled raw materials and needs our help!

BOTTLE Project



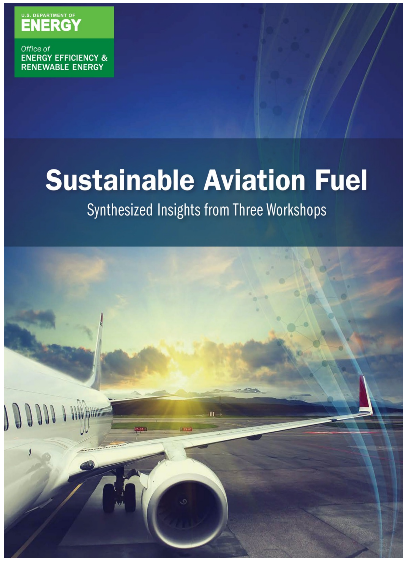
Overall goal: Develop an integrated, streamlined recycling technology for heterogenous textile waste

Electrons to Molecules Overview



Science driven Bioenergy: Better fuels and chemicals

- Use lowest cost feedstock first, and minimize CAPEX/OPEX/Permit Requirements
- Be mindful of tradeoff between carbon intensity and cost
- Co-develop conversion processes with feedstock
- Partner with feedstock suppliers and refiners who know how to process at scale
- Be mindful of bottleneck owners and process guarantors and partner
- Focus on risk reduction to survive scaleup difficulties
- Focus on intermediate streams to make them compatible with existing refineries
- Biomass can revolutionize ability to recycle plastics



Thank you

www.nrel.gov

Sources: https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf

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