Transforming The Renewable Fuels and Chemicals Industry through Innovation

Zia Abdullah

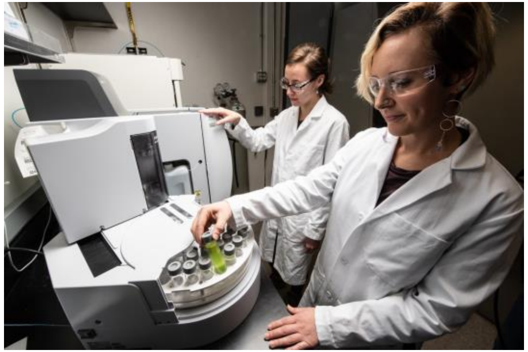
IEA Task 42 Meeting

November 8, 2023

We Are Proactive In Making Our Safety Culture More Inclusive

We Have Open lines of communication to address researcher concerns and needs

- **Leadership:** Visible commitment to safety (Safety Moments in meetings)
- **Reporting:** Tool for anonymous reporting safety concerns
- **Safety Council:** Researcher led; seeks candid feedback from staff
- **Mentoring:** Appointed Mentoring Coordinator to address gaps in mentoring process
- **Safety Coordinator:** Full-time position to strengthen safety culture and improve outcomes
- **Designated Area Representatives:** Responsible for safety in each laboratory
- **JEDI Safety:** Incorporating justice, equity, diversity, and inclusion considerations into safety culture



A Bit of Our History

SERI | Solar Energy Research Institute

SERI was created in response to the Solar Energy Research, Development, and Demonstration Act of 1974, in response to the 1973 oil embargo.

Solar Energy Research Institute (SERI) groundbreaking in 1977

President Carter visited SERI May 3, 1978

And then there were ten

Hats off to NREL — a new national laboratory

Dr. Duane Sunderman takes his place in history as the only director of both SERI and NREL.

On September 16, at a morning press conference in the White House, President George Bush displayed a sporty new cap and jacket bearing the initials and the logo of the tenth DOE national laboratory.

Those initials are *NREL* — for National Renewable Energy Laboratory, SERI's new name. Just after announcing the long-awaited change, President Bush was presented with the two mementos of the occasion. And then the President and Dr. Duane Sunderman, NREL's director, accompanied by Deputy Secretary of Energy W. Henson Moore, shook hands in front of an audience that included members of Congress, MRI officers and trustees, solar industry representatives, corporate executives, and numerous well-wishers in addition to a throng of reporters and photographers.

The announcement moved NREL into a very exclusive group. Only 9 other DOE R&D facilities, out of more than 30, are similarly designated as national laboratories, so the change represents a new status for our lab. NREL now joins an elite group of DOE laboratories: Argonne, Brookhaven, Lawrence Berkeley, Lawrence Livermore, Oak Ridge, Los Alamos, and Sandia National Laboratories as well as Pacific Northwest Laboratory and Idaho National Engineering Laboratory. Employment at these national labs tops 50,000 scientists, engineers, technicians, and support personnel, and annual expenditures are more than $7 billion.

In addition to the prestige of the designation, the establishment of NREL indicates the stability and strength of the

See **NREL** on page three

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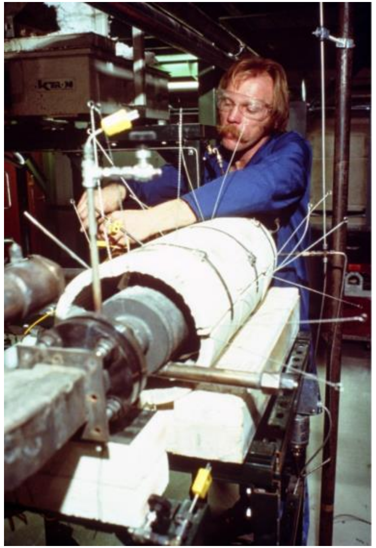
Kickoff — see page 8

In 1991, President George H.W. Bush elevated SERI to a DOE National Laboratory and changed its name to the National Renewable Energy Laboratory (NREL).



NREL's 1 TPD fast pyrolysis vortex reactor ~ 1995

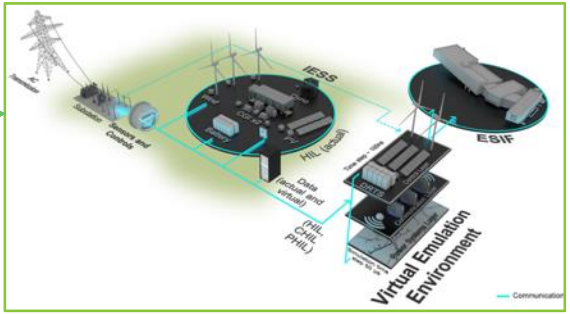
NREL Bridges the Gap Between Foundational Science And Commercial Deployment

Foundational Science | Accelerated Technology Scale-Up | Systems | Markets

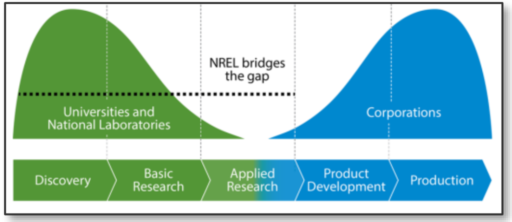
Bench-scale- discovery → Scaling R&D and Process Engineering → R&D with Industry Partners

Solar Energy Research Facility
Science and Technology Facility
Field Test Laboratory Building

- Renewable Fuels and Chemicals
- Carbon-free H_2
- PV, Wind, Water, Power, Geothermal
- Energy storage
- Industrial Materials, Manufacturing and Systems
- Grid and security tech
- Buildings



Advanced Research on Integrated Energy Systems



High-Performance Computing, Simulation, and Visualization

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

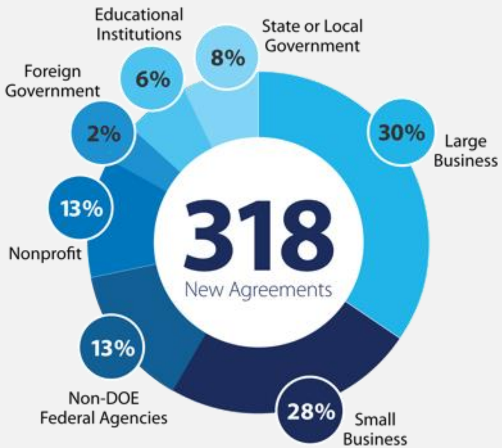
Partnerships with:

- Industry
- Academia
- Government

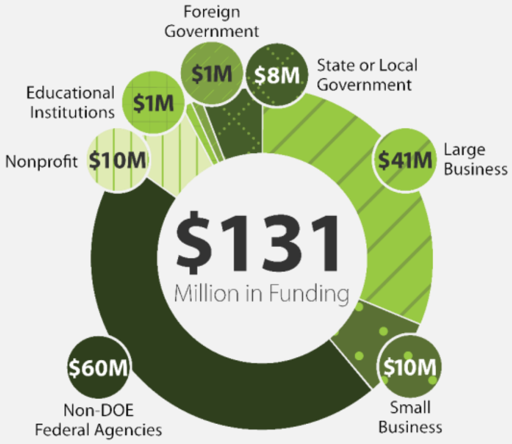
4 campuses operate as living laboratories

Photo by Werner Slocum, NREL 71582

More Than 1,000 Active Partnerships in FY 2022



Agreements by Business Type



Funding by Business Type

Bioenergy

Develop industrially relevant, cost-competitive, and performance-advantaged fuels, materials, and chemicals from renewable and waste carbon sources through foundational science, applied R&D, and industrial partnerships.

Research Challenges

- Produce cost competitive, energy dense biofuels that can enable decarbonization of **heavy-duty truck, marine and aviation sectors.**
- Develop industrially relevant **bio-based materials and chemicals** that provide performance advantages—such as recyclability, multifunctionality, and lower toxicity for chemicals.
- Use electricity to upgrade carbon from diverse "low energy" sources such as CO_2 and other waste gases to produce high-value fuels and chemicals at acceptable cost.
- Use foundational science to design, upcycle, and manufacture energy and carbon-efficient materials and processes.

We Are A Technology Powerhouse in Renewable Energy And Fuels, And Attract Top Talent From Across the World

Patent Awards

- Advanced Adsorption Processes for Separation of Bio-Derived Products
- Bioderived Biphenyl-Containing Compounds and Their Conversion to Polymers and Macromonomers
- Catalysts, Catalyst Supports, and Methods of Making the Same
- Conversion of Biomass to Useful Intermediates
- Conversion of S-Lignin Compounds to Useful Intermediates
- Fuels and Methods of Making the Same
- Microbial Conversion of Methane
- Riboswitch-Mediated Regulatory Control of Gene Expression in Thermophilic Bacteria
- Systems and Methods for Producing Fuel Intermediates
- Systems and Methods for Producing Nitriles
- Valorization of Bio-Oils

Strategic Partnership Projects (SPP): Agreements

Active Intellectual Property Agreements
- 27 active IP agreements in FY22.

Funding Opportunity Announcement (FOA) Partnerships*

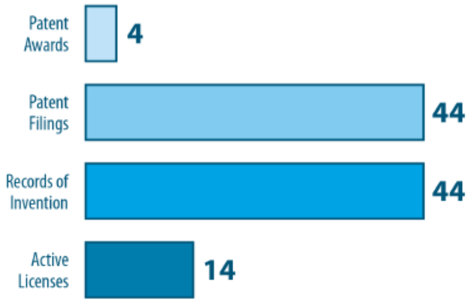
Technology Commercialization Fund (TCF) Partnerships

Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Partnerships

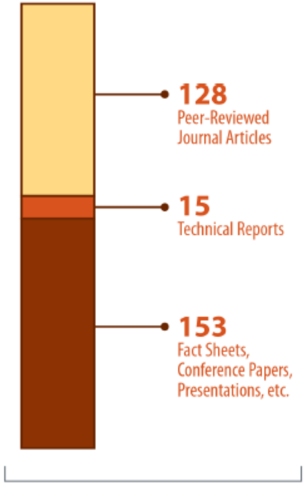
Lab Funding Opportunity (Program Announcement to DOE National Laboratories) Award

FY23 R&D Metrics:

Patents & Records of Invention:



Total FY23 Publications:



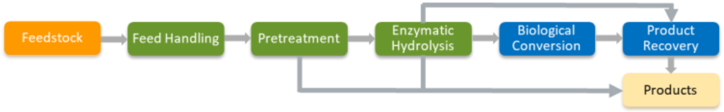
296 Total Publications

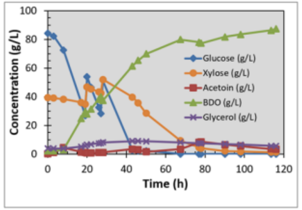
Value-Added Partnerships:

Leveraged **DOE funds** to establish industry and research partnerships

Including Cooperative Research and Development Agreements, Funds-in Agreements, Agreements for Commercializing Technology, Technical Service Agreements, Technology Commercialization Fund Partnerships, and Interagency Agreements.

Pretreatment and Biological Conversion Capabilities





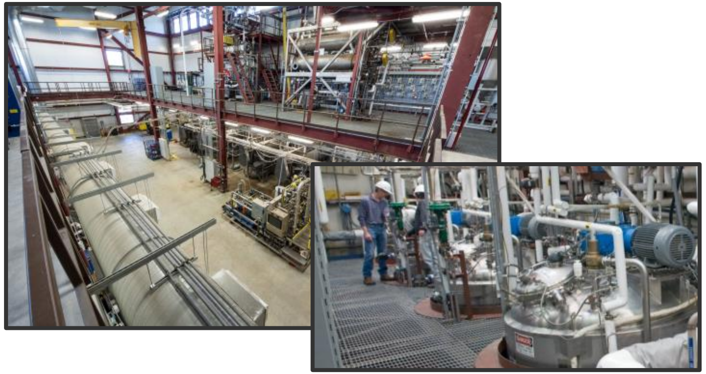
Fundamental Biology Research

- Understanding fundamental biology processes to produce fuels and chemicals
- Genetic and microbial pathway engineering
- Advanced one-of-a kind instrumentation usually not available to industry

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

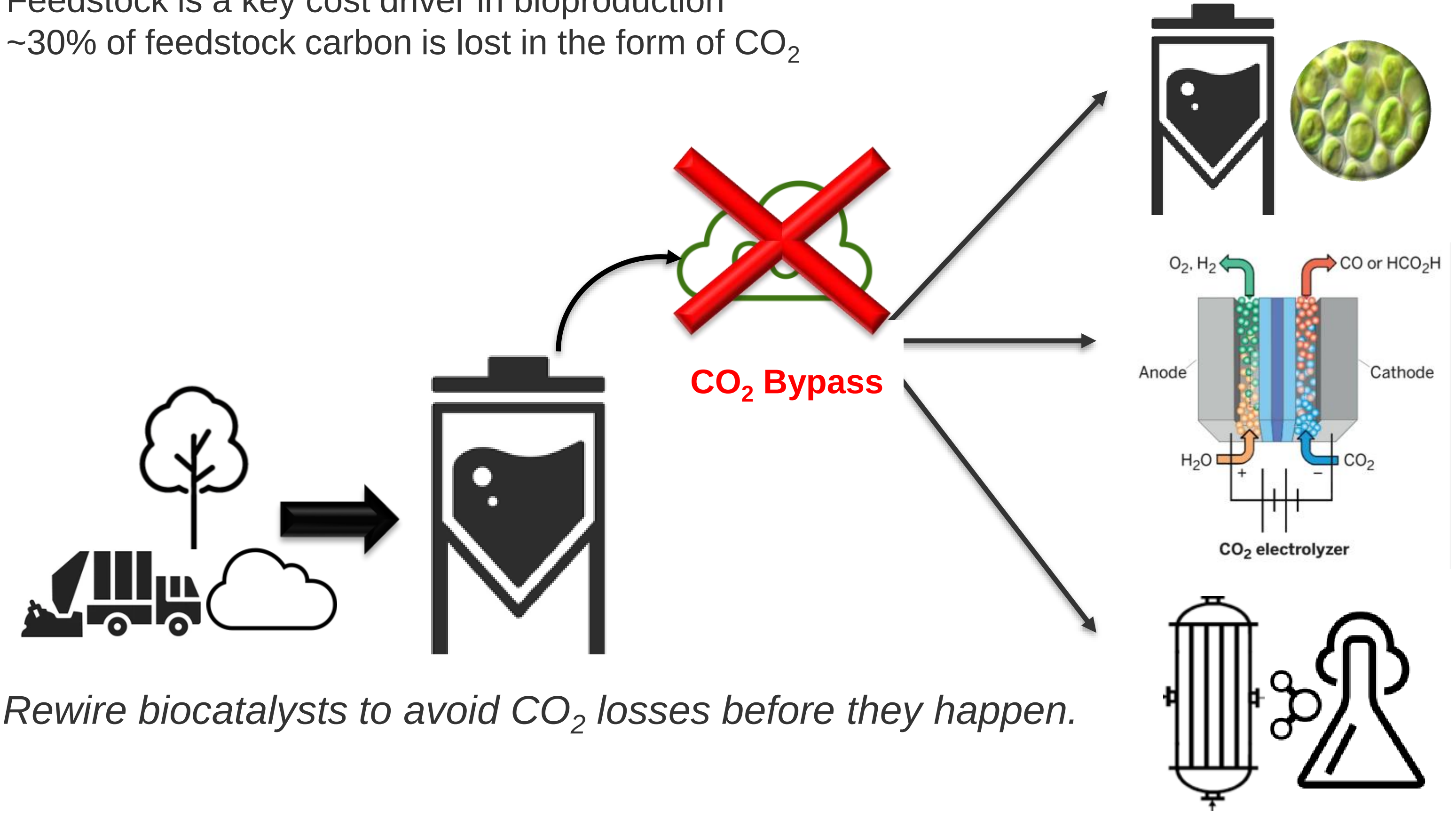
Pilot Plant Facilities



- 2,500 m^2 open floor space
- Integrated 0.5–1.0 t/d process trains
- Feed handling through high-solids, enzymatic hydrolysis and product separation
- Utilities (steam, air, water, etc.) and emission control systems

Low-to-Negative CI Conversion Technologies

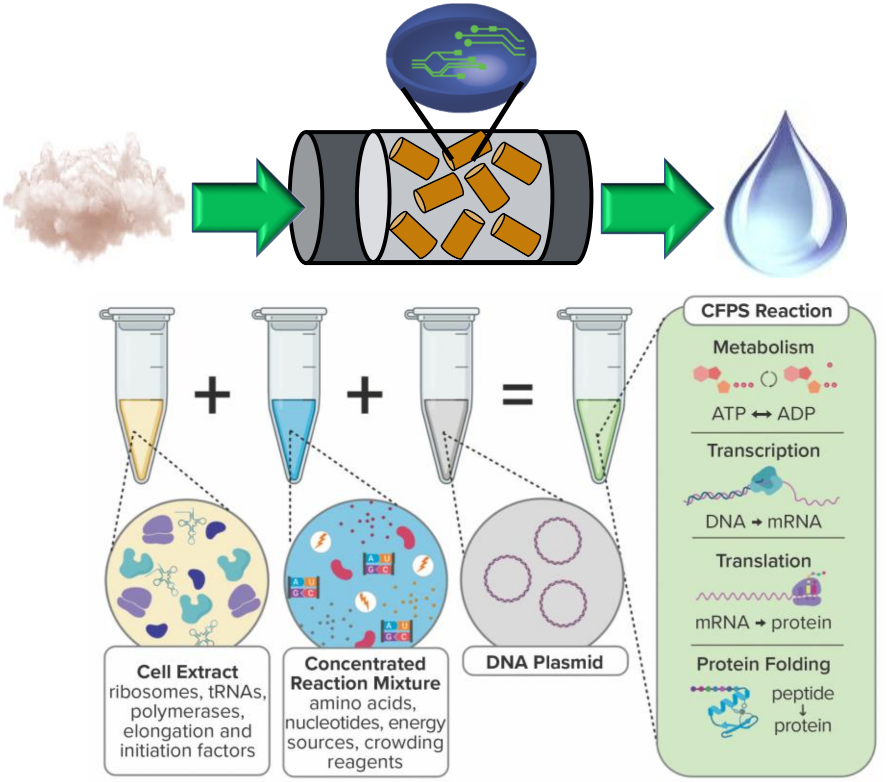
- Feedstock is a key cost driver in bioproduction
- ~30% of feedstock carbon is lost in the form of CO_2

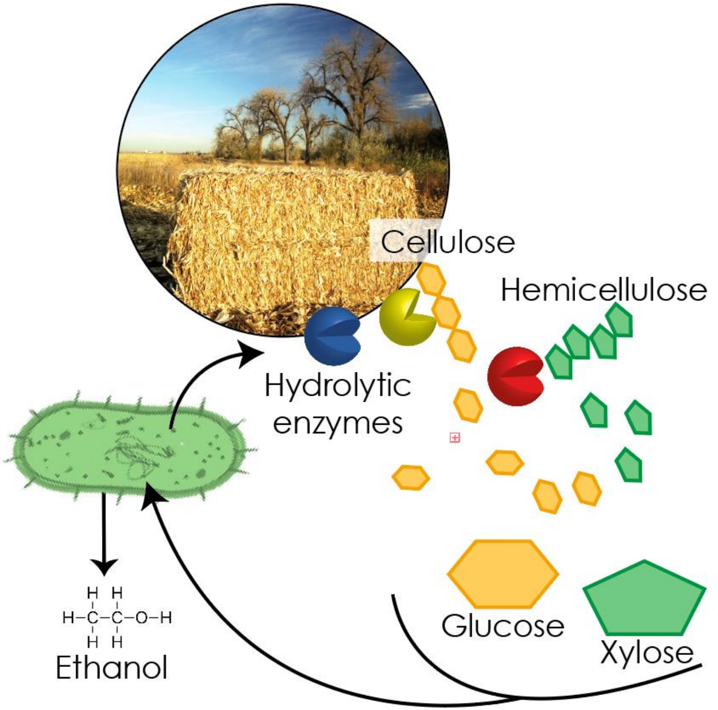


Rewire biocatalysts to avoid CO_2 losses before they happen.

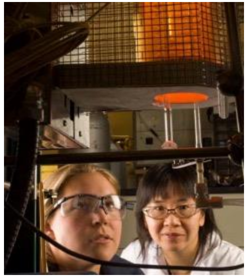
Next Generation Biocatalysts To Enable CFT and CBP

Process Intensification Enables Bypass of Conventional Tech & Cost Barriers to Improve TRY





Catalytic Conversion Capabilities



Catalyst Development, Scaling up and Testing

- Catalyst screening, determination of optimal activation and operating conditions, online analytics, kinetic model support, and simulated recycle
- Up to 1,000^{o}C; 2,000 PSI operating conditions

Catalyst Characterization and pilot scale manufacturing

- Rapid thermal analysis, elemental composition, surface analysis and characterization, adsorption and chemisorption
- Pilot scale catalyst pellet manufacturing
- Kinetic studies of catalytic reactions

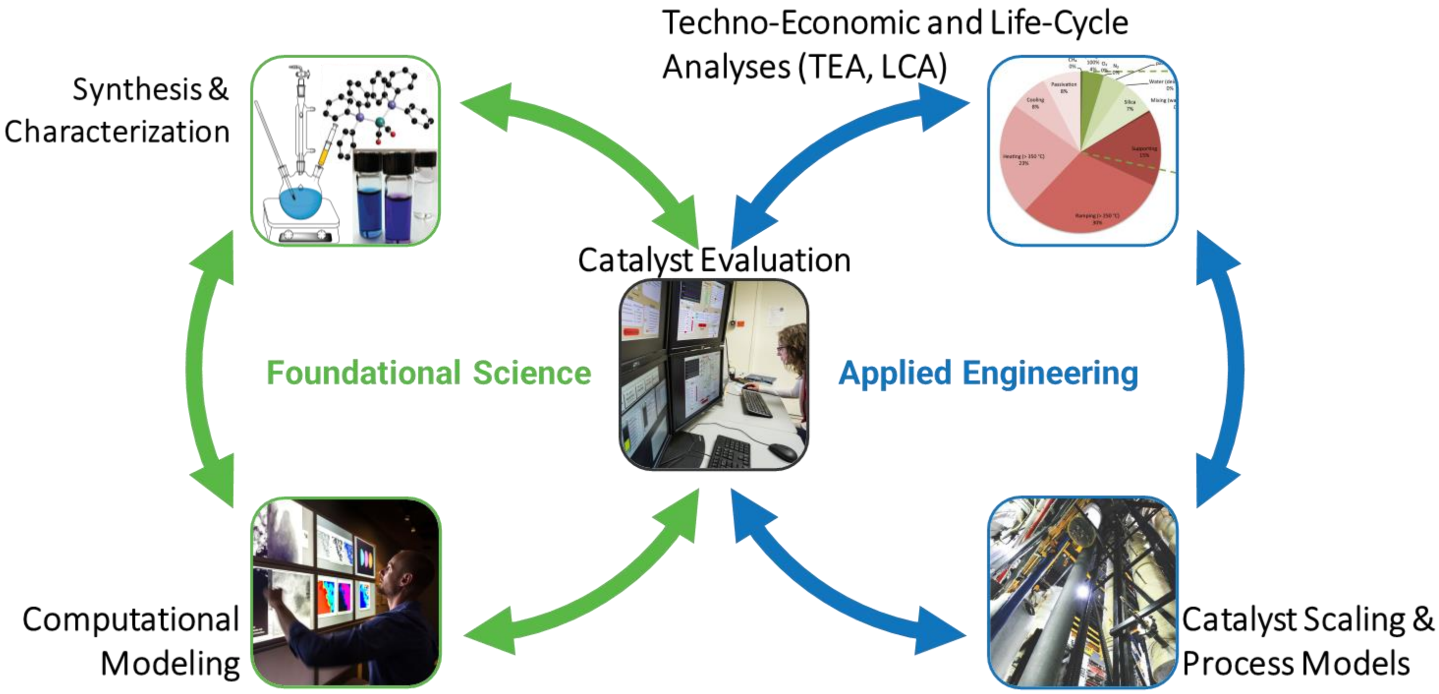
Pilot Plant Facilities

Broad thermochemical technologies

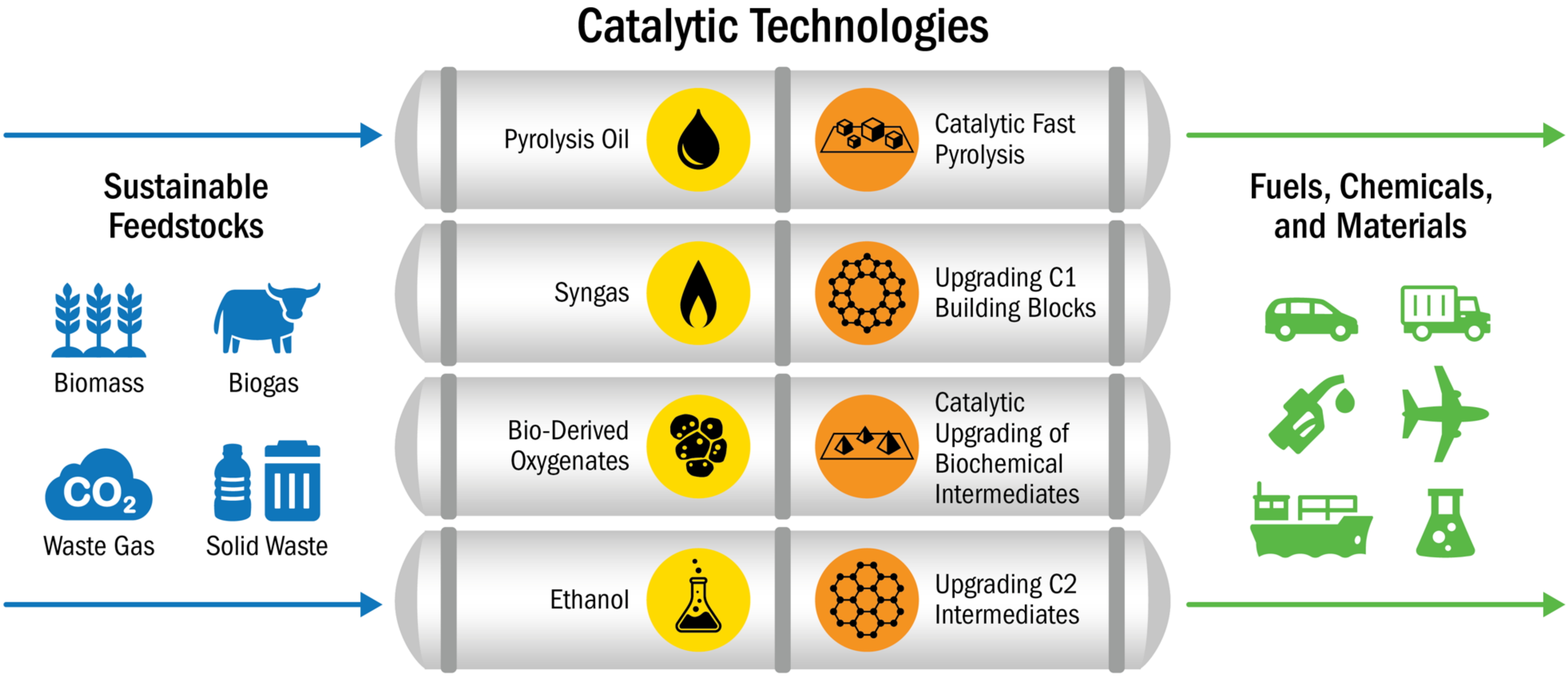
- Pyrolysis
- Catalytic fast pyrolysis
- Riser reactors
- Gasification
- Catalytic upgrading

- Integrated 1 t/d process train
- Feed handling through product separation
- Utilities (steam, air, water, etc.) and emission control systems

Dual Cycle for Catalyst & Process R&D



Pathways Under Development in ChemCatBio



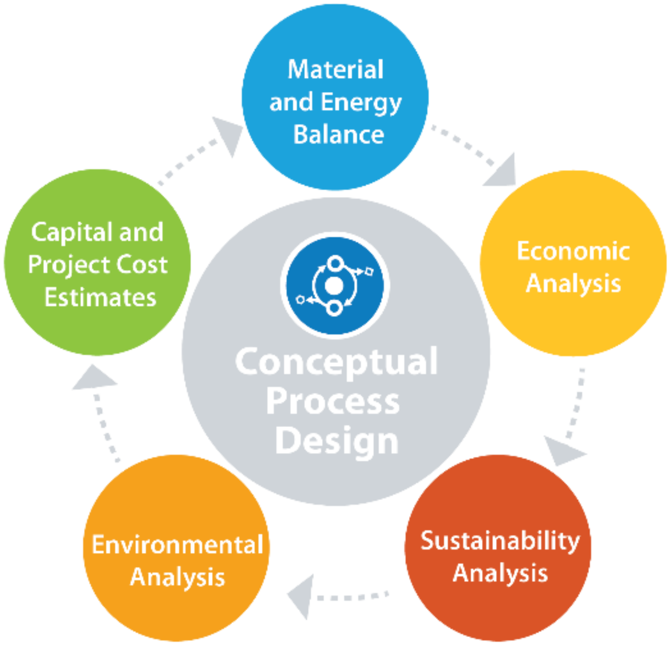
Exploring conversion of multiple feedstocks through multiple processes, targeting SAF as the primary product

Techno-Economic And Sustainability Analyses Deliver 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

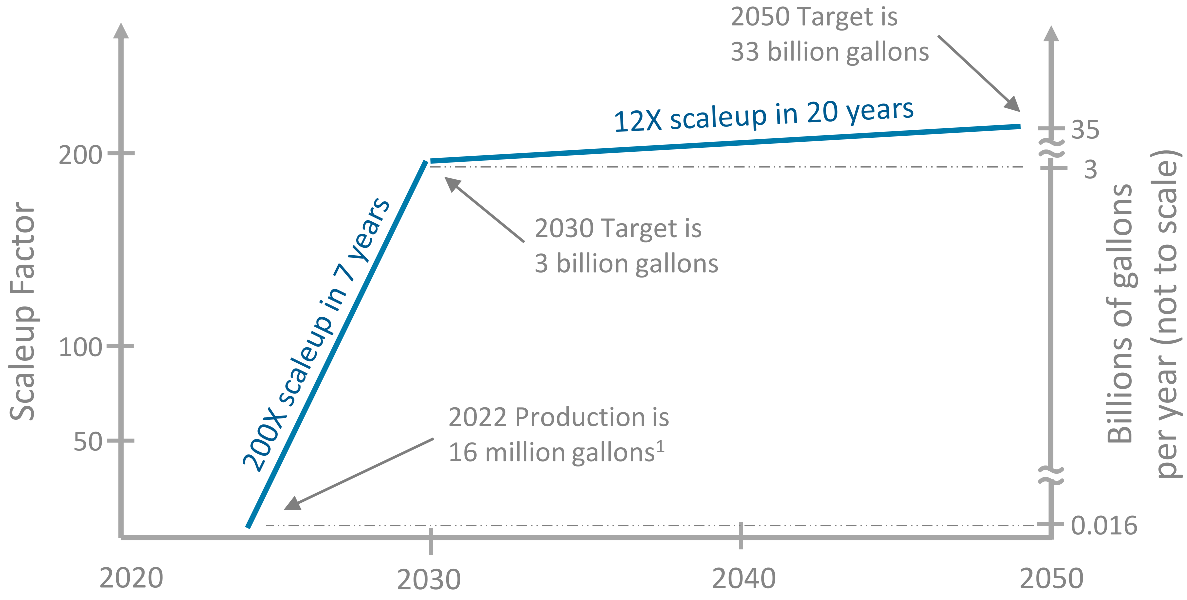


3B
gallons annually by 2030

35B
gallons annually by 2050

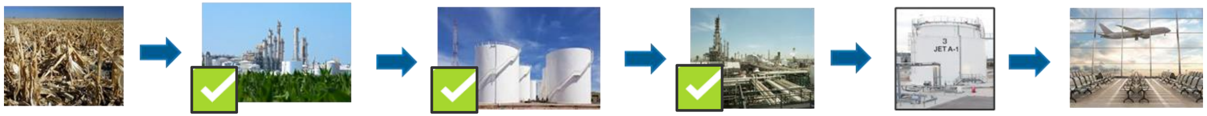
NREL Goals:

- Through S&T, develop new pathways which can be rapidly scaled to achieve 2030 and 2050 goals
- Develop new chemicals and materials technologies to support economics for fuels
- Grow industry partnerships for scaleup
- Support industry scale up their technologies



1: Source US GAO: https://www.gao.gov/products/gao-23-105300#:~:text=SAF%20production%20and%20use%20in,U.S.%20airlines%20(see%20table).

NREL's BETO Program Is Supporting the SAF Grand Challenge By Developing Pathways Across Multiple Feedstocks And Deployment In Partnership With Industry



Market Impact via Industry Partners Across SAF Supply Chains

Feedstock Suppliers – Harvesters – Preprocessing – Conversion - SAF
Tech-to-Market Pipeline, Stage-Gate Processes, Piloting Facilities

Cross Cutting Techno-Economic Analysis and Life Cycle Analysis

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

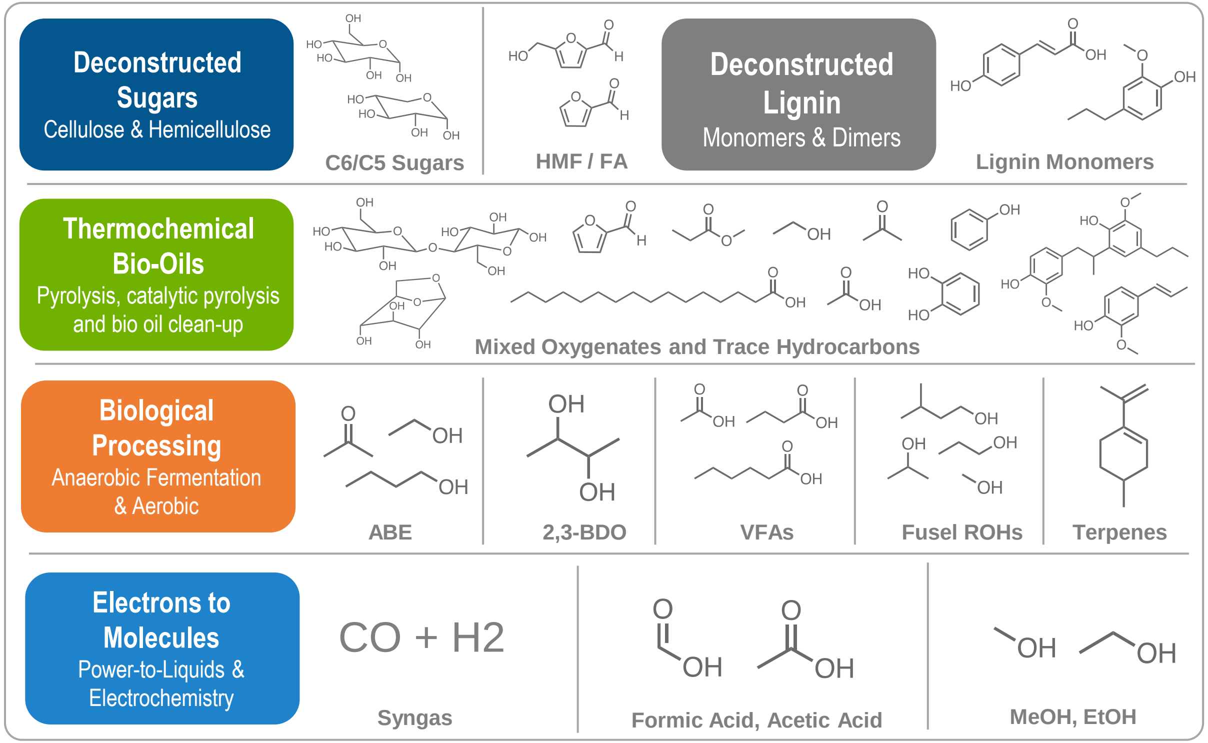
✓ NREL's focus areas along the supply chain.

NREL's S&T Program is Developing Multiple Pathways To Produce SAF From Biomass and Waste Streams

Feedstocks Include Broad Carbon Sources:

Processes include:

- Thermochemical
- Biological
- Hybrid
- Electrochemical



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

Our BETO SAF Program's Approach is to Accelerate Deployment By Producing Intermediates Which Can be Readily Upgraded in Existing Refineries

Opportunities

- ~200 BGPY distillate and FCC capacity .
- May allow incremental transition to renewables by blending renewable and fossil streams.
- Opportunities where re-permitting may not be required.
- ASTM D7566 SAF blendstock can be blended with in-house Jet-A to produce ASTM D1655 approved SAF which can be transported via pipelines.
- Reduces Jet-A price risk relative to greenfield sites.

Renewable feedstocks including forestry waste, herbaceous crops, algae, MSW, wet wastes

R&D Objective # 1: Production of Intermediates from renewable carbon feedstock.

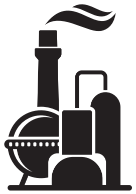
FT Waxes | Alcohols | Bio-Oils/ Biocrudes | Acids/ Ketones | Sugars | Algae Oils | Lignin

R&D Objective # 2: Conversion of Intermediates to refinery processable streams.

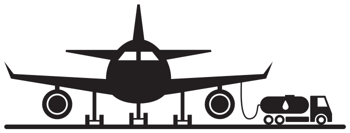
Renewable streams processable in hydrotreaters and FCC units

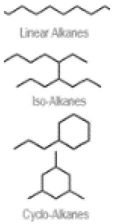
Exemplar Streams
- Ketones
- Lipids
- FT waxes
- Olefins
- Lignin monomers
- Alcohols

Fats, Oils, Greases



Petroleum Refinery
- Safety
- Fuel finishing
- Trained workforce
- Industry know-how





Fuel Property Goals:
- Meet ASTM specs.
- Reduce aromatics
- Increase isoalkanes and cycloalkanes

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

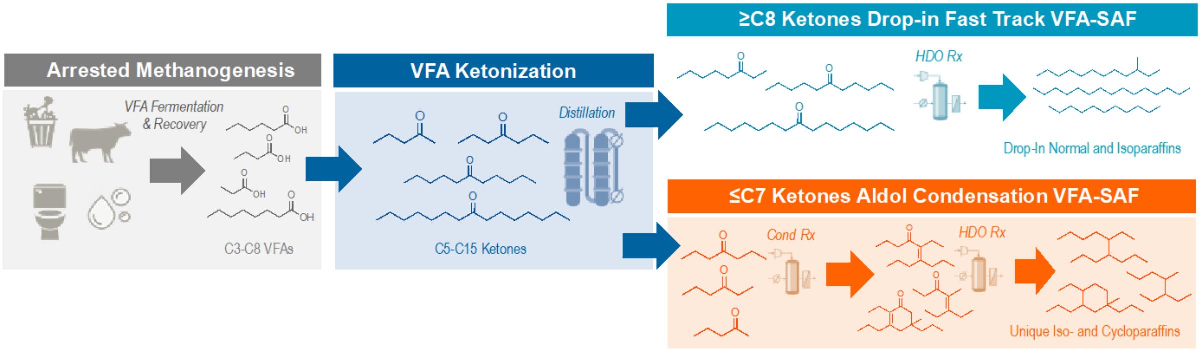
Selected Pathways for SAF Blend Stock Production Under Development at NREL

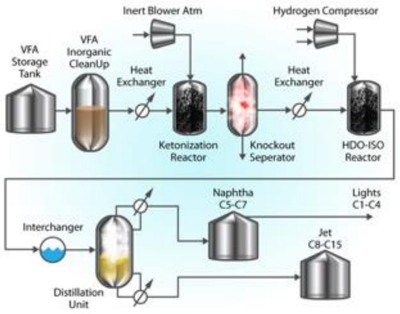
NREL VFA – SAF Catalytic Process Produces Normal and Iso alkane SAF Blendstocks From Wet Waste

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

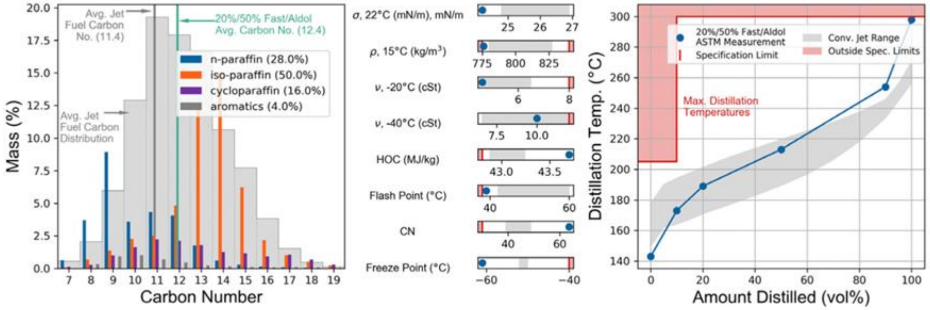
- 70/30 blend of VFA-SAF/Jet A meets critical SAF properties
- Bolt-on solution for existing AD systems and refineries
- Technology has been licensed to Alder Fuels
- SCUBA FOA for Scaleup of started in Q2FY23

"Fast Track" VFA-SAF 10% Blend



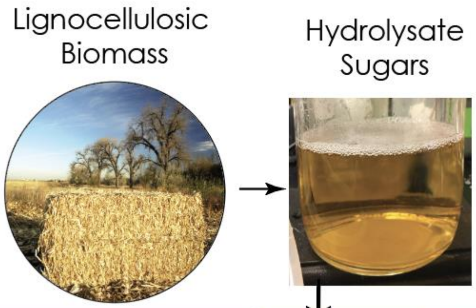


Novel 70% VFA-SAF Blend for Net Zero

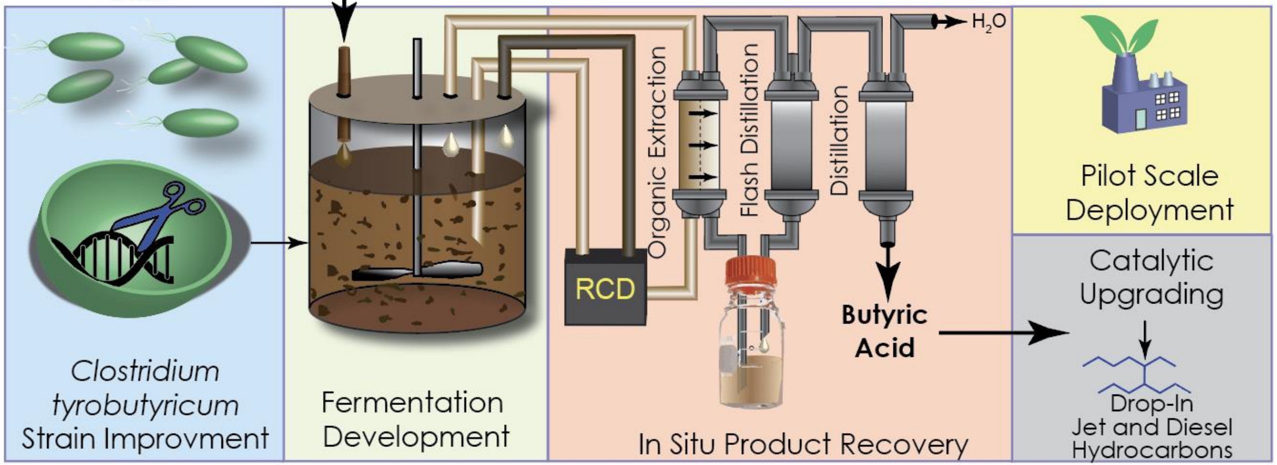


Huq et al., PNAS March 30, 2021, 118 (13) U.S. Patent Application No 17/121,336

Biological Upgrading of Sugars (BUS) to Butyric Acid



- 2 Mols H_2 produced per mol glucose.
- *tyro* has a high protein content and is being developed for human nutrition and animal feeds.



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

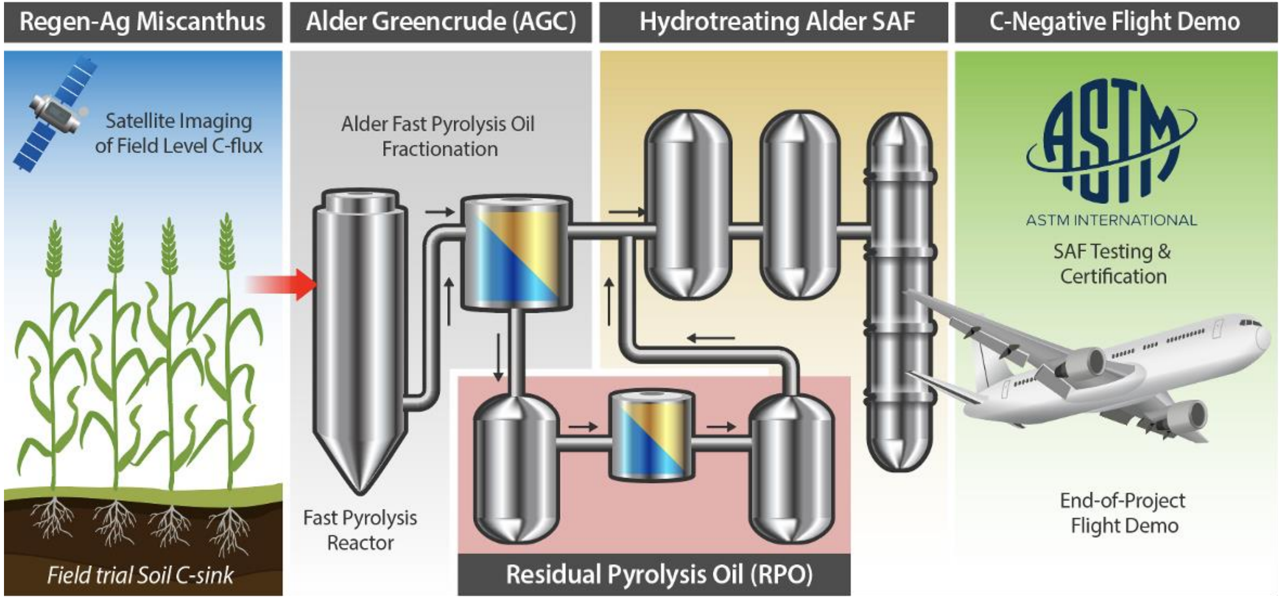
Field-to-Fuel Production of Carbon-Negative Sustainable Aviation Fuel from Regenerative-Agriculture Biomass

Alder Funded

- 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)

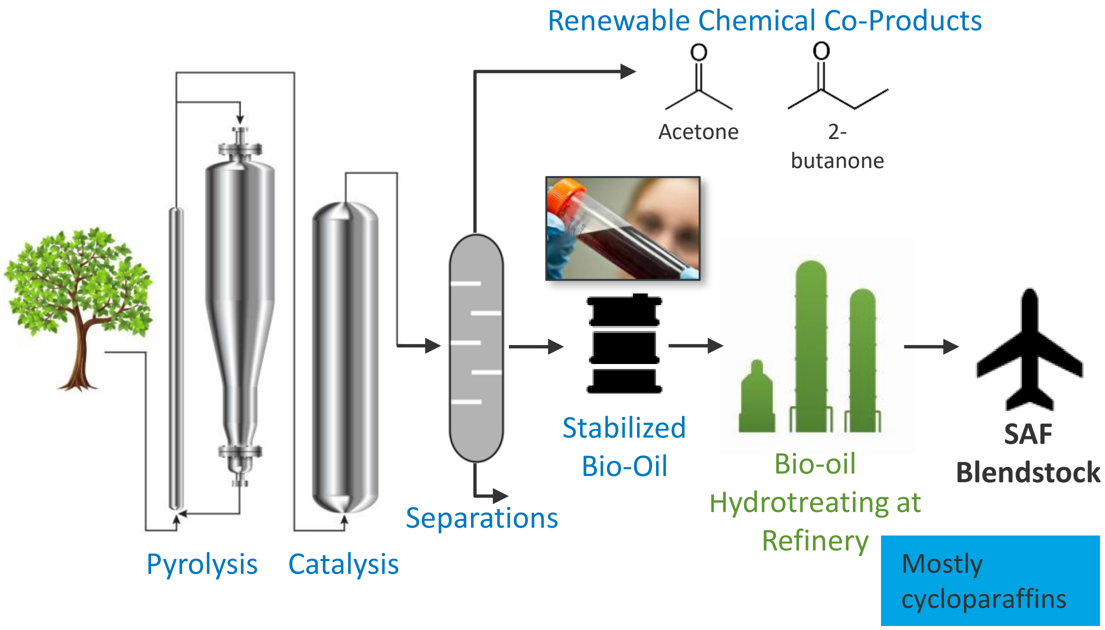
DOE FOAs

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

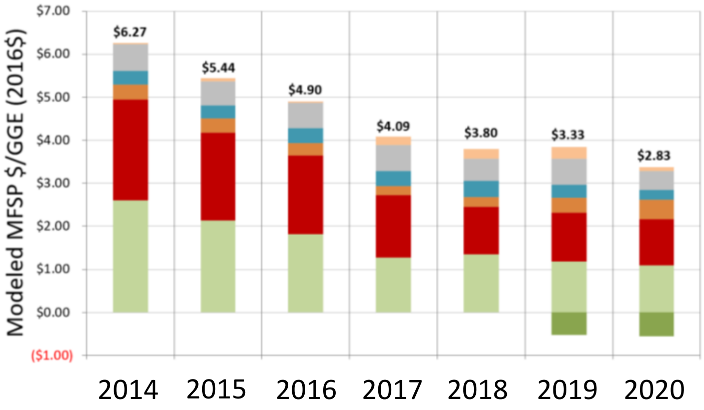


Catalytic Fast Pyrolysis (CFP): SAF via Stabilized Bio-Oil

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



Modeled biofuel production costs below $3/GGE



Product meets key ASTM Int'l jet fuel property specifications

	SAF Fraction	Density @ 15°C, g/cm3	Freeze Point, °C	LHV, MJ/kg	SIMDIS, 10%, °C	SIMDIS, FBP, °C
ASTM D1655	-	775-840	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

NREL Developed bio-oil carbonyl titration method was approved by ASTM. A new accelerated aging protocol was also developed for the bio-oil characterization

Actual Aging (Room Temp; Months to Years) →

Accelerated Aging (80 °C; Hours) →

- Increase in Viscosity
- Decrease in Carbonyl Content

<u>Old Accelerated Aging Protocol:</u>

- 24 hours at 80°C
- Track with viscosity measurement
- *Equivalent to >3 years storage at room temperature*
- Large errors due to viscosity measurement

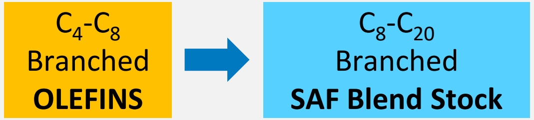
<u>New Accelerated Aging Protocol:</u>

- 2 hours at 80 °C
- Track with carbonyl titration
- *Equivalent to 9 months storage at room temperature*
- Robust aging protocol enabled by small errors in carbonyl titration

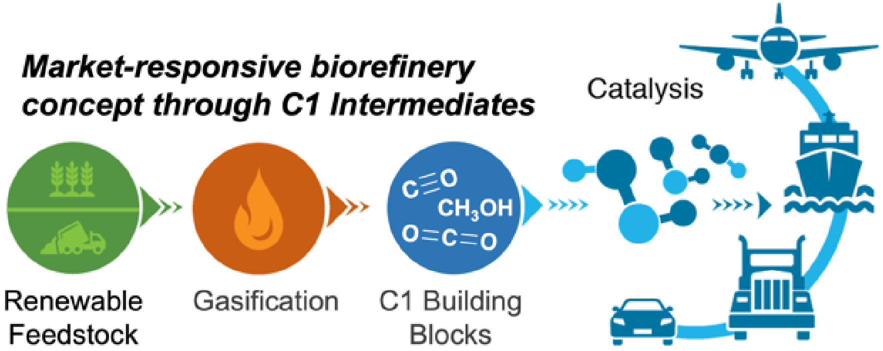
Single Step Syngas-to-Hydrocarbons Pathway Novel Route to SAF Blend Stock

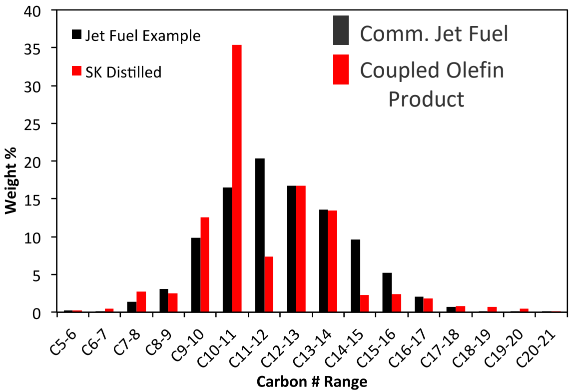
NREL developed the centerpiece technology for the **conversion of renewable C1 intermediates** to produce a suite of fuels with **improved carbon efficiency, reduced capital expense, and control of the product distribution to SAF**.

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



- **Comparable activity and selectivity in 1-step** compared to 3-steps
- Demonstrated co-conversion of CO_2 with syngas to **increase overall carbon efficiency**





Product meets 5 key ASTM International jet fuel property specifications

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

Lignin Conversion to SAF Blendstocks

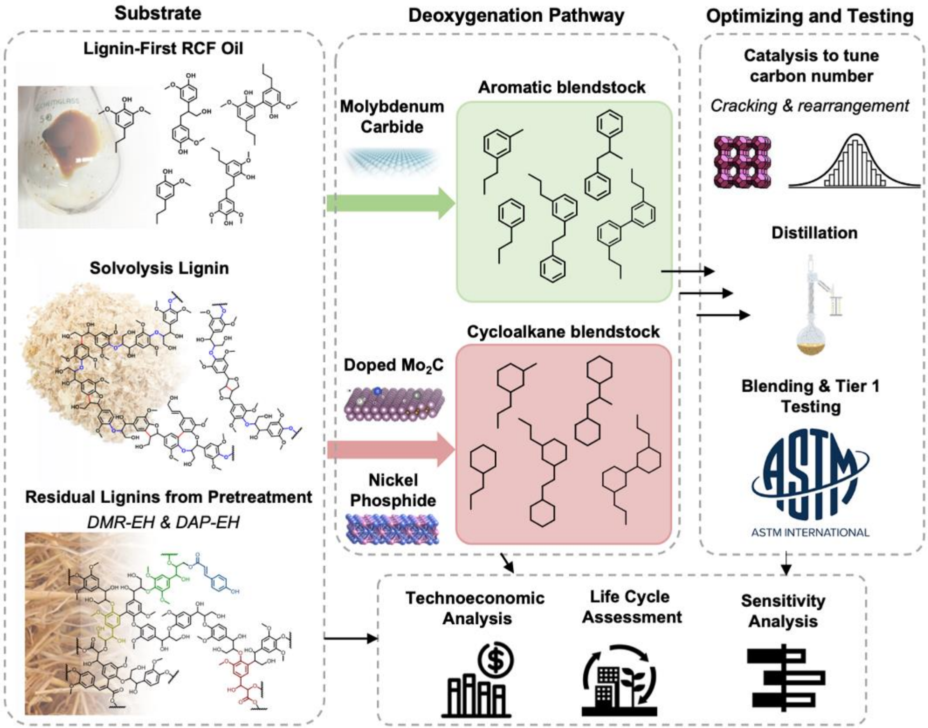
Collaboration with MIT, Argonne National Lab, and University of Washington

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



Stone *et al. Joule* 2022

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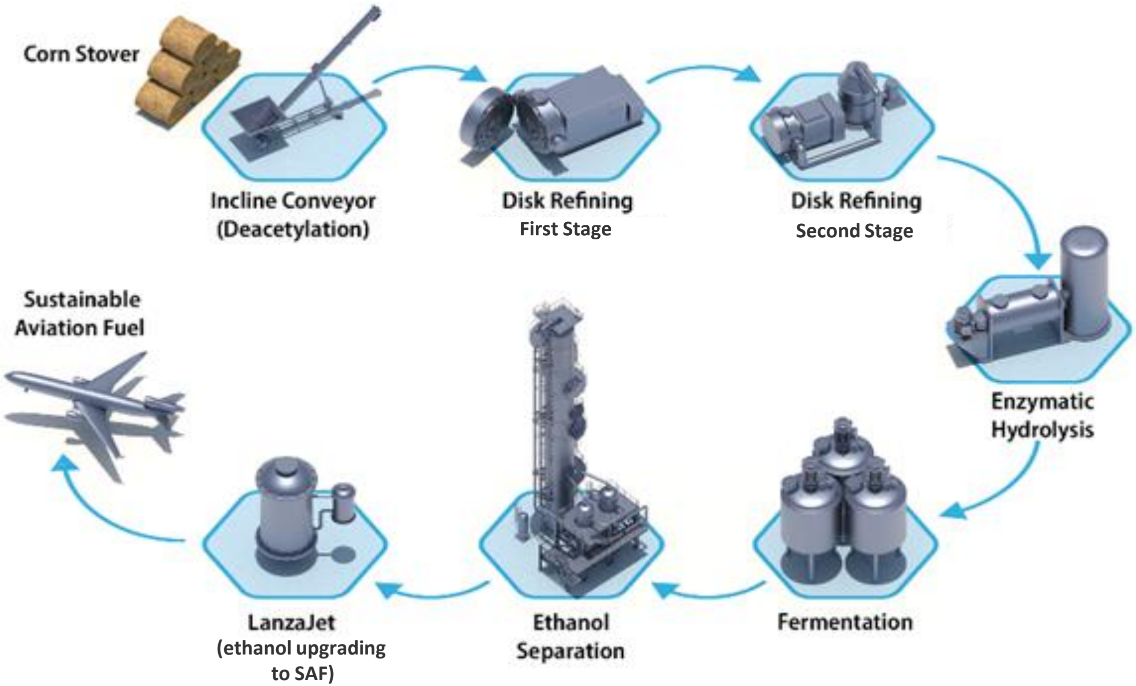
Ethanol From Corn Stover 2nd Generation Sugar Can be Upgraded via the D3MAX / LanzaJet Corn Stover to SAF Process

- 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



For further information contact:
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2,3-Butanediol (BDO): Process and Product Highlights

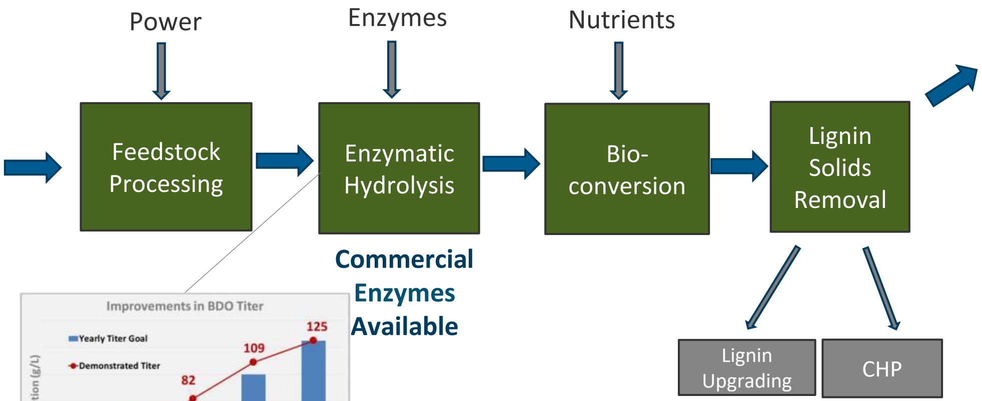
Bio-derived BDO is a flexible chemical feedstock for producing jet fuels, diesel, solvents, chemicals, and fuel additives. It can be produced from cellulosic feedstocks for low carbon fuel credits. Fermentation process is flexible and can be run as a traditional fed-batch on liquid sugars or from corn grain or biomass sources. Biocatalyst is robust and self-replicating; scalable fermentation. Multiple routes to jet fuel.

Feedstocks

Herbaceous and Corn Crops

Corn Stover & Ag. Waste

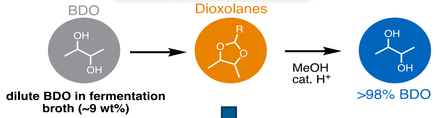
Production



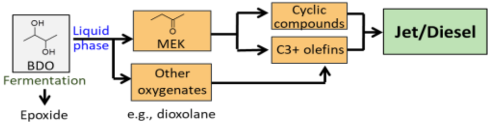
Commercial Enzymes Available

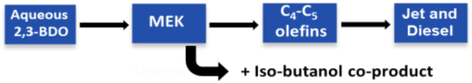
Separations/Upgrading

BDO Purification



BDO Products





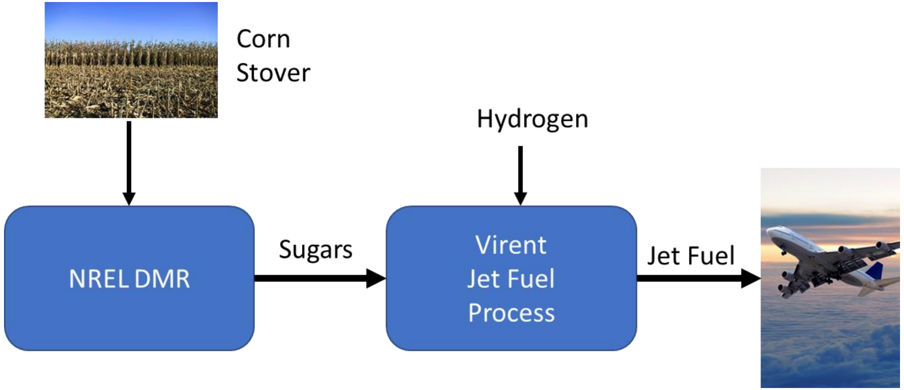
ChemCatBio Chemical Catalysis for Bioenergy

NREL National Renewable Energy Laboratory | Oak Ridge National Laboratory | Los Alamos National Laboratory | Pacific Northwest National Laboratory

Cellulosic-Derived Advantage Jet Fuel (DE-EE0008921)

Project Objectives:

- Direct Catalytic Conversion of NREL DMR Sugars to Advantaged SAF
- Construction and operation of an integrated process
- Generation of at least 2 gallons of SAF for blending studies



Team

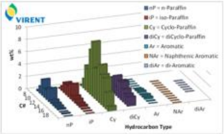
University of Colorado Boulder — Project Lead, Improved Condensation Catalyst

NREL — Biomass Deconstruction, Integrated Processing

Jet Fuel Analysis

VIRENT — Technology Provider

Advantage Jet Fuel
High Content of Cyclo and Dicyclo-paraffins
High Energy Content
High Thermal Stability
Low Freeze Point



	ASTM D1655	Virent HDO-SK	Petro Jet*
Freeze Point	<-47°C	<-80	-44
Density	775-840 kg/m³	812	806
Thermal Stability Breakpoint	>260°C	>355°C	285°C**
Sulfur	<0.3 wt%	<0.01	0.08**
T50-T10	15°C	35°C	34°C
Heat of Combustion MJ/kg		43.3	43.3
Heat of Combustion MJ/Liter		35.2	34.9

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

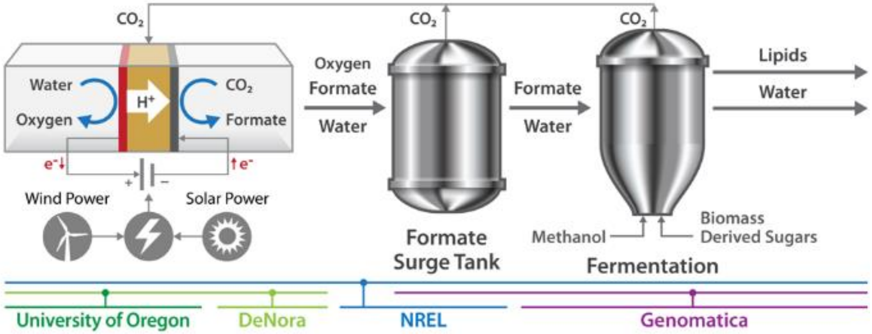
Technology Summary

- 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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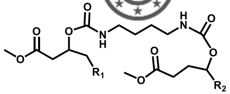
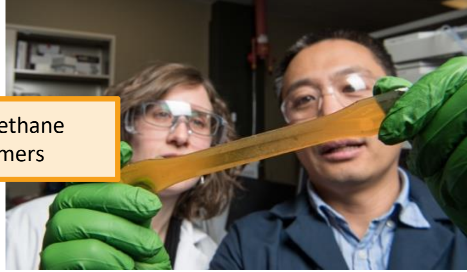
Algae Farm to SAF

Algae Biomass Production → Pretreatment & Extraction

- Lipids → Fractionation (PATENTED)
  - distillation → Unsaturated fatty acids → Polyurethane polymers (PATENTED)
  - Saturated Fatty Acids (ASTM D7566) → Hydrotreating proprietary catalysis → Jet Fuel
- Carbohydrates → Fermentation → Ethanol → Jet Fuel
- Residue → Anaerobic Digestion → Renewable fertilizers Nutrient Recovery
  - Residue → Feed/Aquaculture opportunities

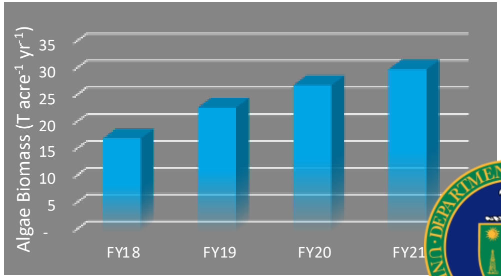




POLARIS RENEWABLES

ASTM INTERNATIONAL

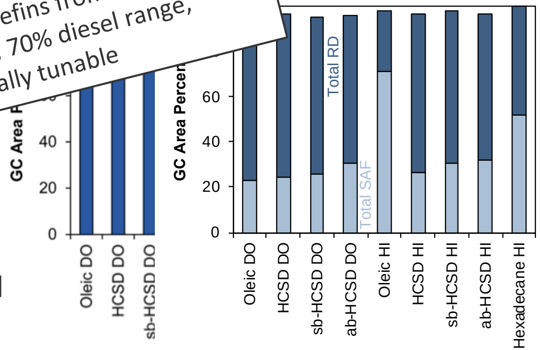
Innovative agriculture
Proprietary cultivars (PATENTED)



- \$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 co-prod**

→ Approved ASTM pathway (HEFA-Jet)

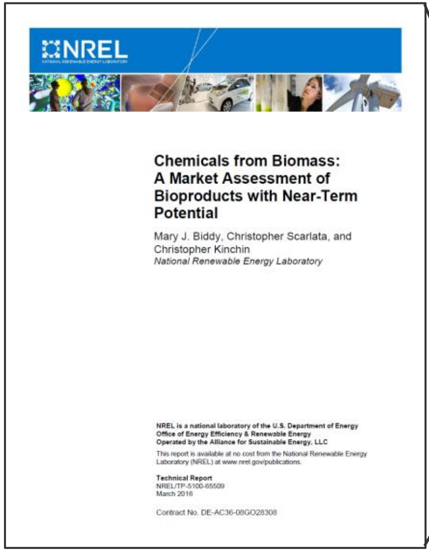
Current olefins from algae 20% jet range, 70% diesel range, catalytically tunable



Energy Fuels 2017, 31, 10, 10946−10953

Business Sensitive: For Chevron's internal use only

Biochemicals & Bioproducts To Support SAF Production and Scaleup Are Encouraged by the DOE and Part of Our Research Strategy



Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin

National Renewable Energy Laboratory

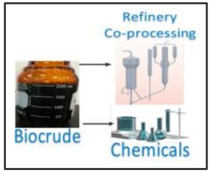
NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Operated by the Alliance for Sustainable Energy, LLC

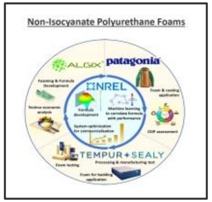
This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

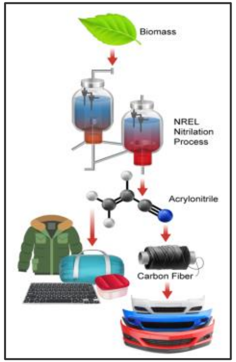
Technical Report NREL/TP-5100-65509 March 2016

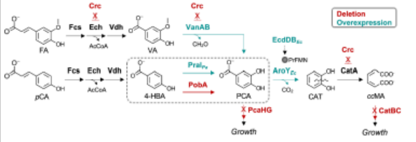
Contract No. DE-AC36-08GO28308

Chemical	Type	Conversion Pathway
Butadiene (1,3-)	Drop-in	BC-Biological TC/BC - Gasification/Fermentation
Butanediol (1,4-)	Drop-in	BC – Biological
Ethyl Lactate	Functional	BC– Biological
Fatty Alcohols	Drop-in	TC – Gasification, BC – Biological, Algae
Furfural	Functional	TC– Pyrolysis, BC – Catalytic
Glycerol	Functional	Algae
Isoprene	Drop-in	BC-Biological
Lactic Acid	Functional	BC-Biological
Propanediol (1,3-)	Functional	BC-Biological
Propylene Glycol	Functional	BC-Biological
Succinic Acid	Functional	BC-Biological
Xylene (para)	Drop-in	BC-Catalytic TC-Pyrolysis

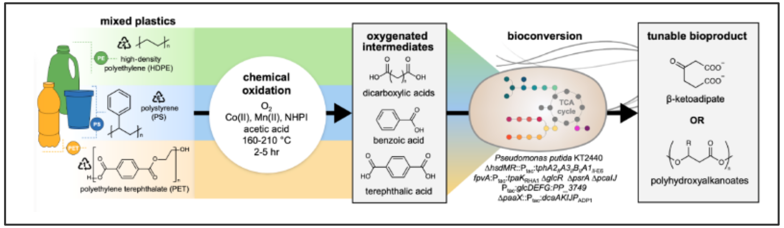








Engineering of the H-lignin and G-lignin pathways in *Pseudomonas putida* KT2440 have resulted in improved muconic acid (ccMA in the figure) production.



Closing Remarks

- Our mission is to take on Grand Challenges associated with decarbonizing ‘difficult to electrify’ sectors of industry
- We attract the best science talent from across the world
- We collaborate with industry, research institutions and academia extensively
- Safety is the top priority at our lab
- We rely on industry partners to deploy technology rapidly
- We believe that success is through a diversity of opinions and perspectives