A U.S. Perspective on Biofuels

Bio4Fuels Days 2020
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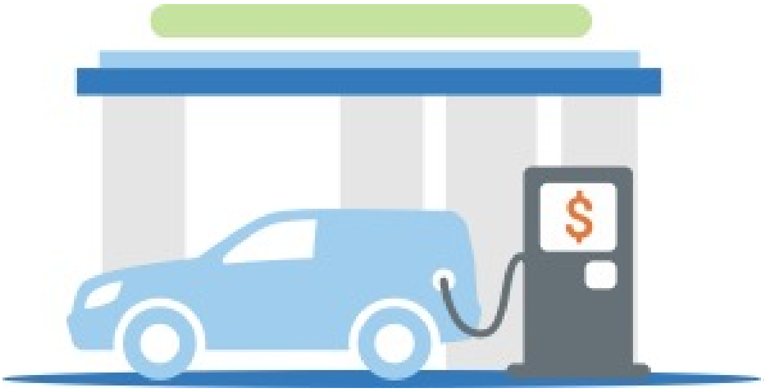
RTI is an independent, nonprofit institute that provides research, development, and technical services to government and commercial clients worldwide.

Our mission is to improve the human condition by turning knowledge into practice.

From Challenge to Opportunity



The Challenge

- More than $215 million/day spent on foreign oil imports ($43/barrel/day in 2016*)
- Dependence on foreign oil
    - Vulnerable to disruptions in supplies
    - Contributes to U.S. trade deficit.
- Transportation accounts for 67% of petroleum consumption.

The Opportunity

- More than 1 billion tons of biomass could be domestically converted into biofuels and products
- Biomass could displace up to 25% of U.S. petroleum use annually by 2030:
    - Revenues stay in the United States; adding jobs
    - Reducing annual CO_2 emissions.

*Annual Energy Outlook 2017 with projections to 2050
Eia.gov/outlooks/aeo/pdf/0383(2017).pdf

**Rogers et al. 2016, An assessment of the potential products and economic and environmental impacts resulting from a billion ton bioeconomy.
Onlinelibrary.wiley.com/doi/10.1002/bbb.1728/full

Key Biofuels Policies

2005 Energy Policy Act

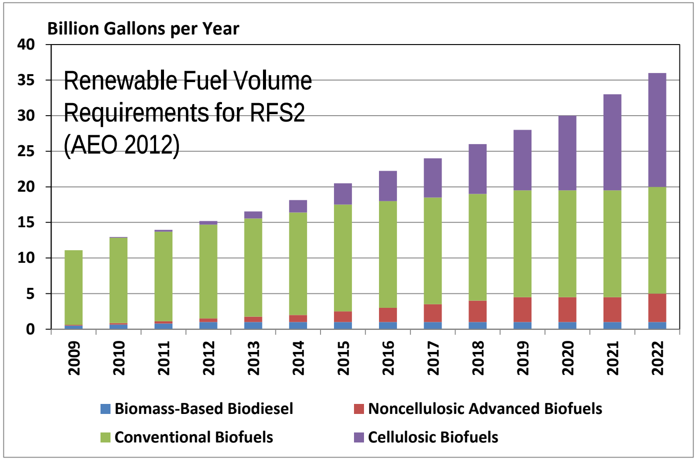
Diversify America's Energy Supply

- 7.5 bill gallons of ethanol and biodiesel by 2012
- 30% tax credit for E85 stations
- Excise tax exemption of $.51 per gallon of ethanol used as motor fuel
- "A recent DOE/USDA study suggests that biofuels could supply some 60 billion gallons per year – 30% of current U.S. gasoline consumption – in an environmentally responsible manner w/o affecting future food production."
- "To achieve greater use of 'homegrown' renewable fuels, we will need advanced technologies that will allow competitively priced ethanol to be made from cellulosic biomass. Advanced technology can break those cellulosic materials down into their component sugars and then ferment them to make fuel ethanol."

2007 Energy Independence and Security Act

Increase the supply of alternative fuel sources by setting a mandatory Renewable Fuel Standard (RFS) requiring transportation fuel sold in the U.S. to contain a minimum of 36 billion gallons of renewable fuels by 2022, including advanced and cellulosic biofuels and biomass-based diesel.

Requires the Corporate Average Fuel Economy (CAFE) standard to reach 35 miles per gallon by the year 2020. The EISA is projected to reduce energy consumption by 7% and greenhouse gas emissions by 9% by 2030.



Current Biofuels Market

Renewable Identification Numbers (RINs) based on RFS2

Corn ethanol industry annual production at capacity - 15 bgy

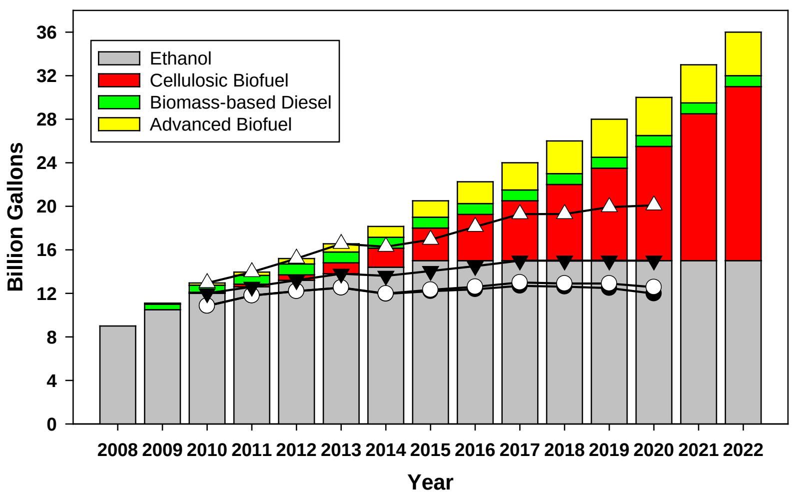
- 10% ethanol blended in gasoline – Blend Wall
- 15% ethanol blends approved by U.S. EPA for model year 2001 and newer vehicles all year
- E85/Flex Fuel Vehicle market is small

Conventional biodiesel – 1.5 – 2 bgy

Advanced Biofuels Production (2018) – 800 MM gallons

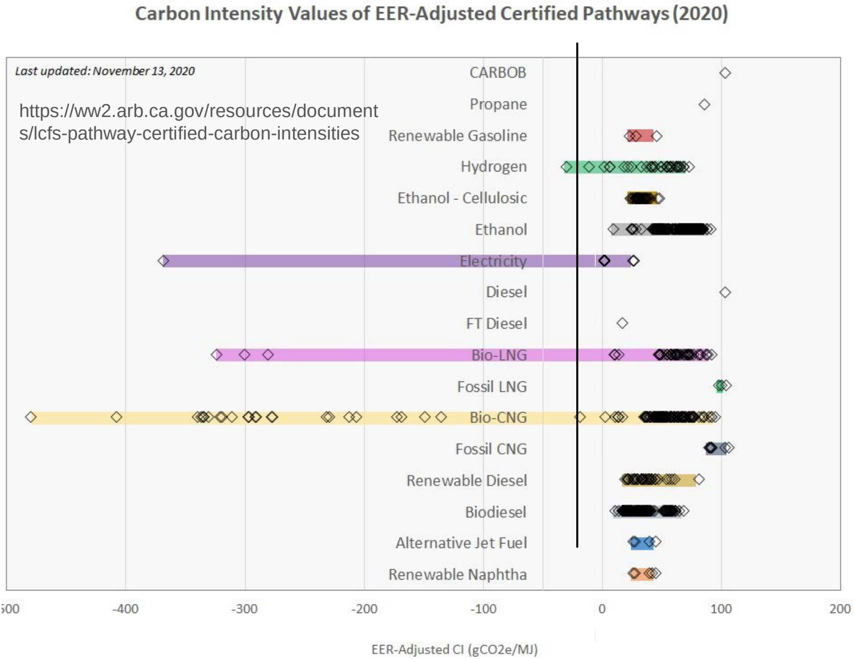
- 418 MM gallons of cellulosic ethanol
- Renewable diesel (hydrotreated waste oils, fats, and greases) production is increasing
- Most of the advanced biofuels are RNG

RFS - Renewable Volume Obligations vs. Actual



California Low Carbon Fuel Standard (LCFS)

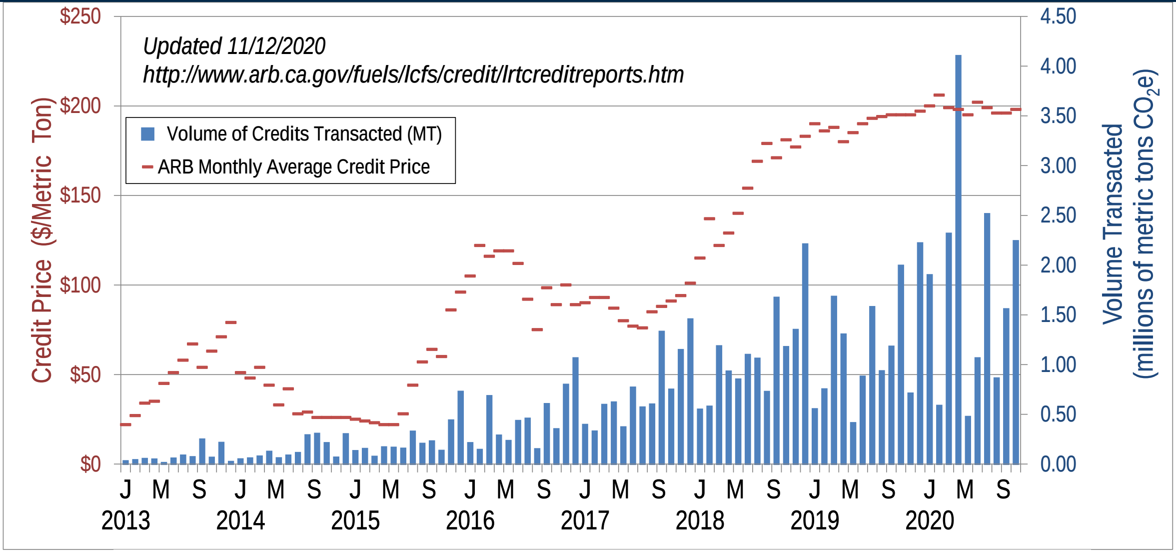
- In 2006, the California legislature enacted the Global Warming Solutions Act (AB 32) leading to the Low Carbon Fuel Standard (LCFS) to reduce greenhouse gas emissions from transportation fuels - gasoline, diesel and alternatives.
- Goal: Reduce the carbon intensity (CI) of the transportation fuel pool by 10% by 2020.
- The LCFS is administered by the California Air Resources Board (CARB)
- Originally adopted in 2009; became effective in 2011; re-adopted in 2015 to remedy the deficiencies and update the program provisions; became effective on January 1, 2016.

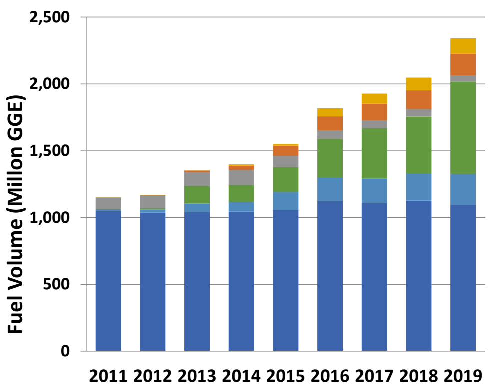


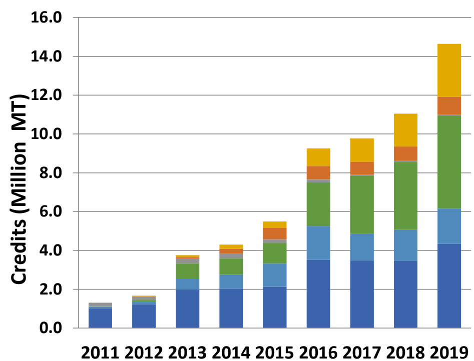
The LCFS credits are based on the Carbon Intensity (CI) of a fuel based on the calculated GHG emissions in the lifecycle or "pathway" of the fuel.

The EER-adjusted CI value (CI divided by the Energy Economy Ratio - EER) represents the GHG emissions from the use of alternative fuel per MJ of conventional fuel displaced.

California Low Carbon Fuel Standard (LCFS) – Carbon Credits







Ethanol Biodiesel Renewable Diesel Fossil Natural Gas Biomethane Electricity

U.S. Government Bioenergy-related Inter- and Intra-agency Groups

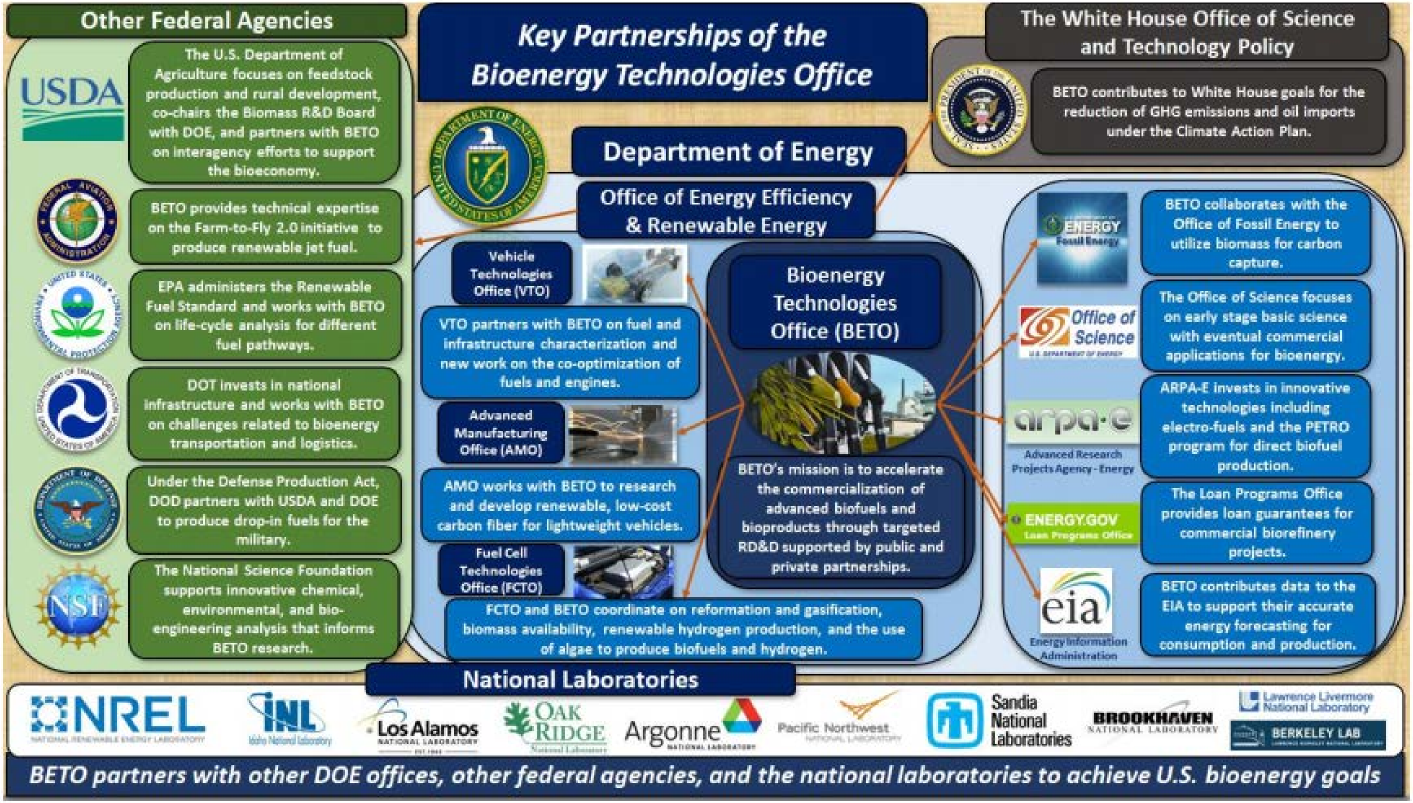


Figure 1-8: Key partnerships with other DOE offices and federal agencies

Bioenergy Technologies Office Multi-Year Program Plan March 2016
https://www.energy.gov/sites/prod/files/2016/07/f33/mypp_march2016.pdf

U.S. Government Interagency Groups – Biomass R&D Board

- The Biomass Research and Development Act of 2000 established the Interagency Biomass R&D Board.
- The BR&D Board facilitates coordination among federal government agencies that affect the research, development, and deployment of biofuels and bioproducts.

Membership

Senate-confirmed sub-cabinet officials from 8 executive branch agencies

Co-chair

Co-chair

U.S. Government Intra-agency Groups within DOE

Bioenergy Technologies Office Collaborations

- Office of Science (BioDesign)
  - Bioenergy Research Centers
  - Agile Biofoundry
  - Algae Genome Science Partnership – Biological and Energy Research, Joint Genome Institute, and LANL
- Fossil Energy
  - Leverage Fossil Energy computational capabilities in the Consortium for Computational Physics and Chemistry in ChemCatBio
- ARPA-E: Specific bioenergy-related programs
  - ECOSynBio (Energy and Carbon Optimized Synthesis for the Bioeconomy)
  - ElectroFuels (Microorganisms for Liquid Transportation Fuel)
  - MARINER (Macroalgae Research Inspiring Novel Energy Resources)
  - PETRO (Plants Engineered to Replace Oil)
  - ROOTS (Rhizosphere Observations Optimizing Terrestrial Sequestration)
  - TERRA (Transportation Energy Resources from Renewable Agriculture)
  - REFUEL (Renewable Energy to Fuels Through Utilization of Energy-Dense Liquids)
- Within Energy Efficiency and Renewable Energy
  - Advance Manufacturing Office - RAPID Institute and Biobased additive Manufacturing Prize
  - Fuel Cell Technologies Office – energy storage in RNG
  - Vehicle Technologies Office – Co-Optima and Electrification and Natural Gas fuel medium- and heavy-duty vehicles

BETO National Laboratory Consortia (energy.gov/eere/bioenergy/bioenergy-consortia)

Agile BioFoundry

U.S. DEPARTMENT OF ENERGY
BIOPROCESSING SEPARATIONS CONSORTIUM

fcic
FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM
U.S. DEPARTMENT OF ENERGY

Co-Optimization of Fuels & Engines

CCPC
Consortium for Computational Physics and Chemistry

ChemCatBio
Chemical Catalysis for Bioenergy

DISCOVR
Development of Integrated Screening, Cultivar Optimization, and Verification Research

bottle
changing the way we recycle™
U.S. DEPARTMENT OF ENERGY
Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment

Bioenergy Technology Office – Critical Program Areas

Production & Harvesting

Feedstock Supply & Logistics

Works to reduce the cost, improve the quality, and increase the volume of sustainable feedstocks available for delivery to a conversion process.

Advanced Algal Systems

Focuses on improving the productivity of algal biomass and enhancing the efficiency of cultivation and harvesting.

Conversion & Refining

Conversion

Develops technologies to convert non-food feedstocks into biofuels, bioproducts, and biopower.

Conducts feedstock blend testing, separations, materials compatibility evaluations, and techno-economic analyses to focus research on highest impacts.

Distribution & End Use

Advanced Development and Optimization

Aims to reduce technology uncertainty in bioenergy by integrating individual technologies into a system/process and provides vital knowledge fed back to research programs.

Crosscutting

Sustainability and Strategic Analysis

Supports program decision-making and develops science-based strategies to understand and enhance the economic and environmental benefits of advanced bioenergy.

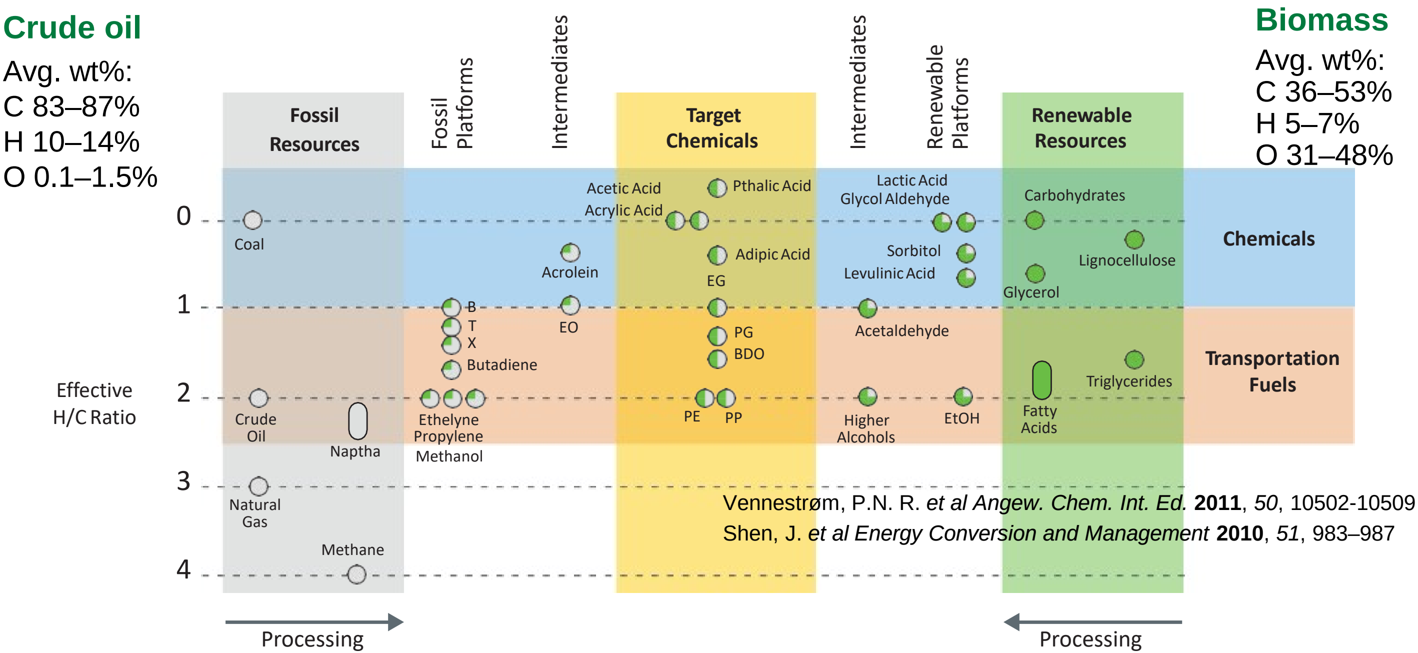
BETO Budget Overview

Feedstock | Algae | Conversion | Systems | Data

$US millions	FY17	FY18	FY19	FY20
Total	**$205MM**	**$221.5MM**	**$226MM**	**$259.5MM**
Feedstock Supply and Logistics	$20MM	$29MM	$30.5MM	$40MM
Advanced Algal Systems	$30MM	$30MM	$32MM	$40MM
Conversion Technologies	$90.2MM	$103MM	$96MM	$110MM
Advanced Demonstration and Optimization	$54MM	$54.5MM	$57.5MM	$60MM
Strategic Analysis and Crosscutting Sustainability	$10.7MM	$5MM	$10MM	$9.5MM

Evolving Trend - Bioproducts to Enable Biofuels

- Fuels makes up 76% of the volume of U.S. oil products
- Chemicals make up 17% of the volume of U.S. oil products and nearly 50% of the revenue



Vennestrøm, P.N. R. *et al Angew. Chem. Int. Ed.* **2011**, *50*, 10502-10509
Shen, J. *et al Energy Conversion and Management* **2010**, *51*, 983–987

Consider the Oxidation State of Chemicals – Retain What Nature Provides

- High value bioproducts can improve the economics of developing advanced biofuels processes
- Near-term technology deployment or performance-advantaged bioproducts and bio-based chemicals
- Technology maturation for biofuels

Potentially Untapped Carbon Resources

Apply expertise in biomass polymer deconstruction to distributed waste carbon resources to recover molecular building blocks for fuels, products, and energy

Wet Wastes:
Biosolids, Food Wastes, Manures

Economically Advantageous Feedstocks

Solid Wastes:
Sorted Municipal Solid Waste including Plastics

Gaseous Wastes:
CO and CO_2

Plastics Innovation Challenge 2030 Goals:

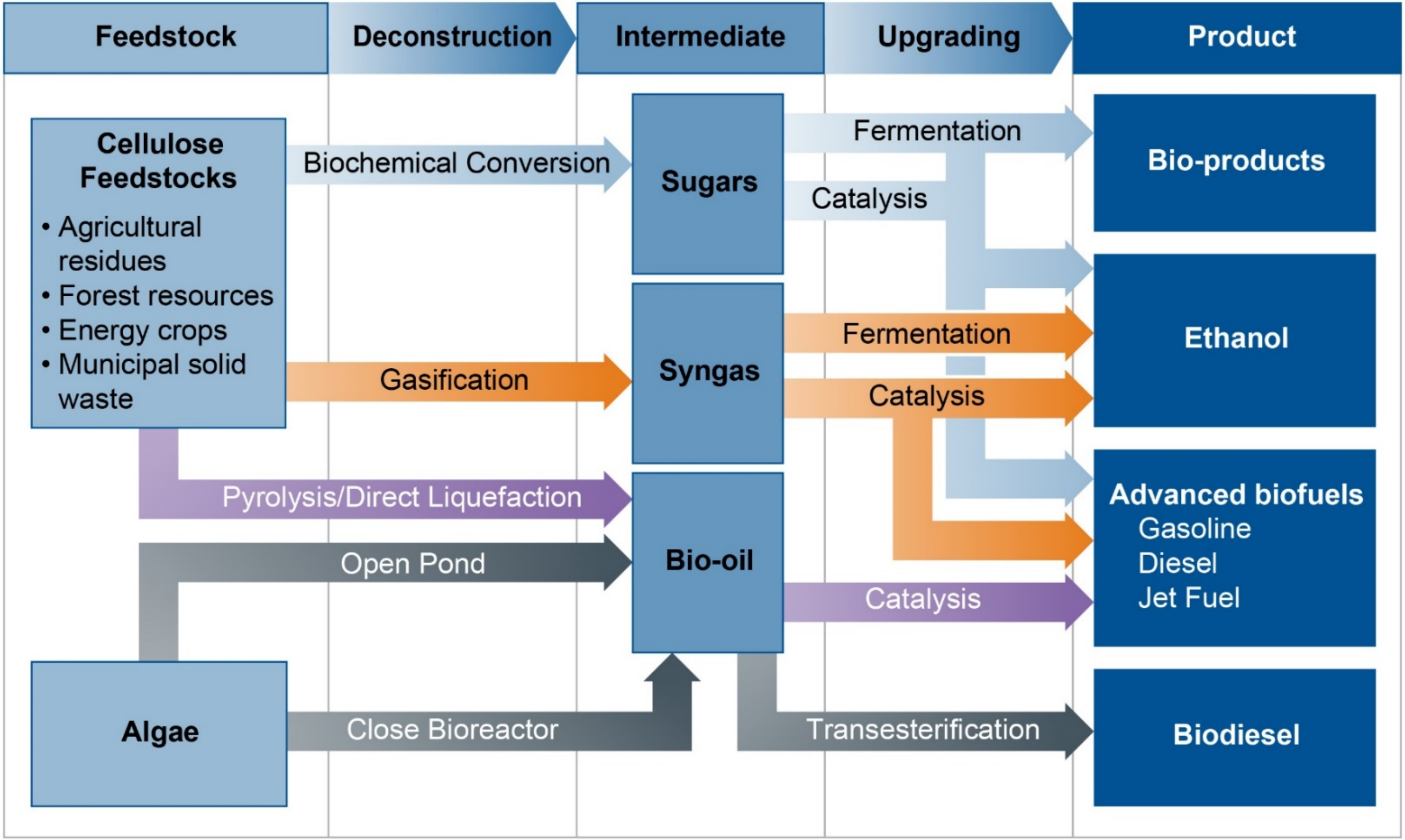
Collection: Develop novel collection technologies to prevent plastics from entering the ocean.
Deconstruction: Develop biological and chemical methods for deconstructing plastic waste, including from rivers and oceans, into useful chemical streams.
Upcycling: Develop technologies to upcycle waste chemical streams into higher-value products, which reduces energy intensity and encourages further recycling.
Design for recyclability: Develop new plastics that are recyclable-by-design and can be scaled for domestic manufacturability.
Commercialization: Support a domestic plastics upcycling supply chain for U.S. companies to scale and deploy new technologies in domestic and global markets.

bottle

Bio-**O**ptimized **T**echnologies to keep **T**hermoplastics out of **L**andfills and the **E**nvironment

U.S. Department of Energy multi-organization consortium focused on developing new chemical upcycling strategies for today's plastics and redesigning tomorrow's plastics to be recyclable-by-design.

Biofuels Technology Options



Technology Development and Demonstration – Biochemical Conversion

Poet/DSM Project Liberty - http://poet-dsm.com/liberty

- Commercial demonstration (25 MM GPY cellulosic ethanol)

Amyris - https://amyris.com/

- Scaled 10 molecules for personal care, health and wellness, and flavors and fragrances industries
- Bioproducts – squalane, cannabinoids

Gevo – https://gevo.com/

- Isobutanol and ethanol in Luverne, MN (~1MM gpy but idled due to COVID-19)
- Isobutanol to SAF in Silsbe, TX (70,000 gpy)

Lygos - https://lygos.com/

- Sustainable organic acid specialty chemicals and bio-monomers.
- Pilot Scale Demonstrations

Bio-organisms/Enzymes/Protein Engineering:

- Novozymes - https://www.novozymes.com/en
- Codexis - https://www.codexis.com/
- Gingko Bioworks - https://www.ginkgobioworks.com/

Technology Development and Demonstration – Thermochemical Conversion

Gasification

Fulcrum – http://fulcrum-bioenergy.com/ (7 MM GPY synthetic crude oil) MSW Gasification/Fischer-Tropsch Synthesis in Reno, NV

Enerkem - https://enerkem.com/ MSW Gasification/Methanol Synthesis

- Commercial facility in Edmonton, Alberta Canada (10 MM GPY ethanol
- New projects in Netherlands (70 MM GPY) and Spain (70 MM GPY)

Red Rock Biofuels - https://www.redrockbio.com/

Woody biomass gasification/Fischer-Tropsch (16 MM GPY diesel and jet fuel) in Oregon

Velocys – https://www.velocys.com/ MSW and Woody Biomass Gasification/Fischer-Tropsch Synthesis

- Demo Plant in Oklahoma (1.6 MM L of finished fuel and wax); Bayou Fuels Reference Project in MS (24 MM GPY + CCS)

Oberon Fuels – Methanol to DME

Syngas/Waste Gaseous Carbon Fermentation

Lanzatech - https://www.lanzatech.com/

- Commercial-scale facilities in China (16MM GPY) and Belgium (21 MM GPY) (Steel Mill off-gases)
- Pilot-scale MSW Gasification to ethanol in Asia and India
- Pilot-scale Alcohol-to-Jet Fuel (3 MM GPY) in Soperton, GA

Biomass Pyrolysis

Envergent - https://uop.honeywell.com/en/industry-solutions/renewable-fuels/rtp-biomass-conversion

- (JV: Honeywell UOP and Ensyn) Commercial facility in Quebec (10.5 MM GPY)

Anellotech - https://www.anellotech.com/ Catalytic Fast pyrolysis for Bioproducts (pilot plant in Texas)

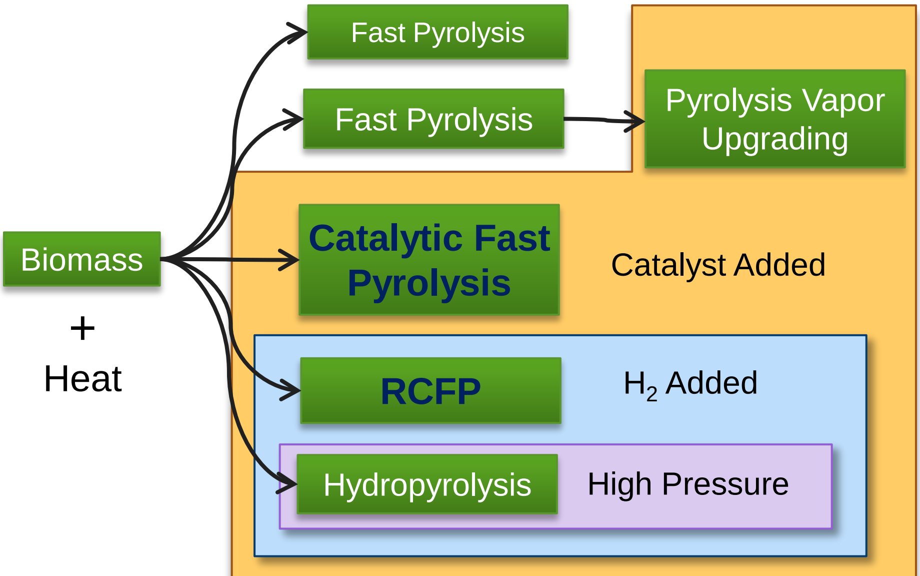
Renewable Energy Group (REG) - https://www.regi.com/

Hydrothermal Liquefaction

GeniFuel/PNNL - https://www.genifuel.com/ Hydrothermal liquefaction of biosolids in Vancouver, Canada and California

Pyrolysis Pathways for Advanced Biofuels

Application of catalysts to maximize yields and improve biocrude ***quality*** (oxygen content, chemical composition, thermal stability)



1. Mante, O. D., Dayton, D. C., Carpenter, J. R., Wang, K., & Peters, J. E. (2018), Pilot-scale catalytic fast pyrolysis of loblolly pine over γ-Al_2O_3 catalyst. *Fuel*, *214*, 569–579.
2. Cross, P.; Wang, K. G.; Weiner, J.; Reid, E.; Peters, J.; Mante, O.; Dayton, D. C., Reactive Catalytic Fast Pyrolysis of Biomass Over Molybdenum Oxide Catalysts: A Parametric Study. Energy & Fuels 2020, 34 (4), 4678-4684.

RTI Projects and Capabilities

Dept. of Energy – ARPA-e
- Catalyst development and testing
- Process design and development
- Process Scale-Up
- RTI Facility Design and Construction
- 1 TPD Process Development, Fabrication, and Installation

ADM ConocoPhillips

Dept. of Energy – EERE – BETO
- Novel catalyst development
- Improved bio-crude quality
- Aqueous phase carbon recovery to maximize carbon efficiency

HALDOR TOPSØE VEOLIA

Dept. of Energy – EERE – BETO
- Process Operation and Optimization
- Bio-crude Upgrading
- Integrated process development

forestconcepts research&development NREL HALDOR TOPSØE INL

Dept. of Energy – EERE – BETO
- Advanced biofuels technology
- Integrates reactive catalytic biomass pyrolysis and hydrotreating
- Renewable diesel blendstock that meets ASTM specifications

HALDOR TOPSØE

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023+

Project	Funding
Catalytic Bio-crude Production in a Novel, Short-Contact Time Reactor	\$4.1MM
Catalytic Upgrading of Thermochemical Intermediates to Hydrocarbons	\$5.4MM
Improved H_2 Utilization and Carbon Recovery for Higher Efficiency Thermochemical Bio-oil Pathways	\$3.9MM
Building Blocks from Biocrude: High Value Methoxyphenols	\$2.2MM
Bio-crude Production and Upgrading to Renewable Diesel	\$3.4MM
Naphthenic Biofuel-Diesel Blend for Optimizing Mixing Controlled Compression Ignition Combustion	\$1.5MM
Integrated Reactive Catalytic Fast Pyrolysis System for Advanced Hydrocarbon Biofuels	\$3MM
Integrated Separations to Improve Biocrude Recovery for Biofuels and Bioproducts	\$4.4MM

HALDOR TOPSØE

- Process Operation and Optimization
- Bio-crude Upgrading
- Integrated process development

Dept. of Energy – EERE - BETO

ARKEMA AECOM

- Develop laboratory-scale separation of methoxyphenols
- Complete product development assessment.
- TEA and LCA demonstrating < \$3/gge and > 50% GHG emissions

Dept. of Energy – EERE - BETO

Stony Brook University

- Produce a naphthenic distillate bio-blendstock to improve cold start properties and reduce soot formation
- Blended fuel will be tested in a single-cylinder research engine

Dept. of Energy – EERE - VTO

ECOSTRAT

- Improve separation of solids from the vapor product stream,
- Enhance rapid quenching and collection of pyrolysis vapors
- Recover highly oxygenated bioproducts
- Upgrade remainder into advanced biofuel.

Dept. of Energy – EERE - BETO

Catalyst Screening

Fixed Bed Model Compound Reactor

Micropyrolyzer

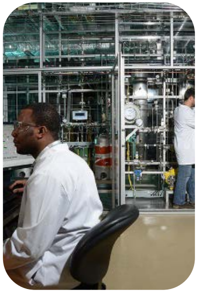
Process Development

Laboratory Catalytic Pyrolysis Unit

Bench-scale Distillation Unit

Process Scale-up

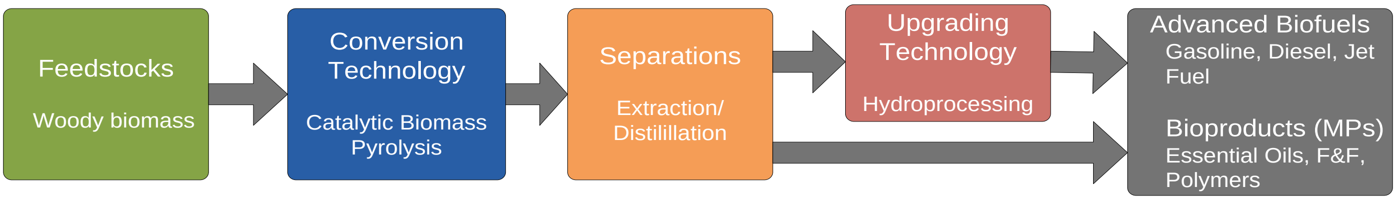
1 Ton/Day Pilot-scale Catalytic Pyrolysis Unit



Pilot-scale Hydroprocessing Unit

Summary of RTI Activities

Demonstrate an advanced biofuels technology that integrates a catalytic biomass pyrolysis step and a hydroprocessing step to produce infrastructure compatible biofuels. Improve the economic viability of this process by recovering high-value bio-products.



Multiple feedstocks

- ***Continuous Process***
- ***Flexible Operating Conditions***
- ***Produce Bio-crude***

- ***Separation Efficiency***
- ***Quality and Purity***

- ***Biocrude quality***
- ***Upgrading severity***

Scale-up CFP process to pilot-scale to validate catalyst performance and bio-crude yields and quality

1) Optimize the catalytic biomass pyrolysis process (1TPD) to maximize high-quality bio-crude production (< 20 wt% O and > 40% carbon recovery)
2) Improve bio-crude thermal stability

Design, build and operate a pilot-scale hydroprocessing unit to upgrade bio-crude intermediates

1) Evaluate the impact of bio-crude quality on the hydroprocessing step
2) Evaluate co-processing opportunities
3) Evaluate hydrogen demand of the integrated process
4) Maximize biofuels yield

Develop and optimize a hybrid separation method to recover high-value methoxyphenols(MPs) from biocrude.

1) Leverage catalytic biomass pyrolysis to produce a thermally stable biocrude with narrow product slate.
2) Tailor separation approach to the physicochemical properties of the biocrude.
3) Adapt a hybrid separation strategy for extraction, concentration and purification of MPs

Technology Development and Demonstration – Other

Renewable Diesel and Sustainable Aviation Fuels

Hydrotreating Used Cooking Oil (UCO)

1.9 MM gallons renewable diesel produced in 2019.

U.S. refiners to increase capacity - HollyFrontier, CVR, P66, Marathon, Global Green Energy

California market driving growth - Neste, Valero, and REG

Alcohol to Jet Fuels

Honeywell UOP, Lanzatech, Gevo, Vertimass (https://www.vertimass.com/)

Renewable Natural Gas

Biogas from animal wastes, wastewater treatment solids, and landfills

Aemetis – http://www.aemetis.com/

- Commercial Ethanol Plant in California (65 MM GPY) and biodiesel plant in India (50 MM GPY)
- Developing Biogas Digesters for dairies near CA ethanol plant)

OptimaBio - http://pig.energy/

- Swine waste to energy – with Duke Energy and Smithfield Foods, Inc.

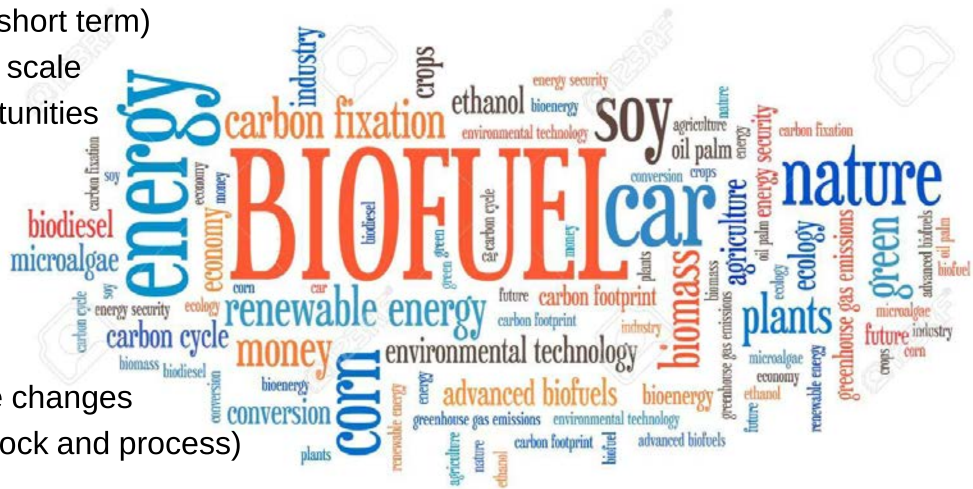
Renewable Natural Gas Databases:

https://www.anl.gov/es/reference/renewable-natural-gas-database

https://www.epa.gov/lmop/renewable-natural-gas#rngmap

Continuing Challenges

- Technical barriers
  - Improve biofuel yields
  - Maximize carbon efficiency
  - Minimize hydrogen consumption
  - Feedstock quality vs. technology robustness
- Economics: How do we become cost competitive? ($3/gge)
  - Tax credits and subsidies (short term)
  - Reduce CAPEX – optimize scale
  - Leverage integration opportunities
  - Reduce feedstock costs
  - High value co-products
- Sustainability
  - GHG emissions reduction
  - Waste-to-energy
  - Direct and indirect land use changes
  - Water consumption (feedstock and process)
- Market acceptance
  - Early adopters: commercial aviation industry and military
  - Blendstocks and fuel properties
  - Infrastructure compatibility



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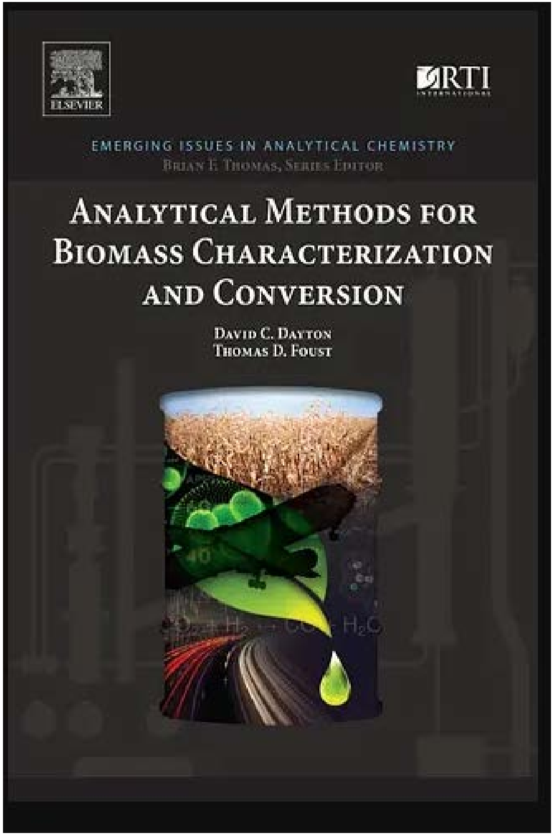

The **Fuel for Thought** Podcast

The world's first podcast about renewables for the refinery industry.

https://renewables.topsoe.com/podcast

https://www.elsevier.com/books/analytical-methods-for-biomass-characterization-and-conversion/dayton/978-0-12-815605-6

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