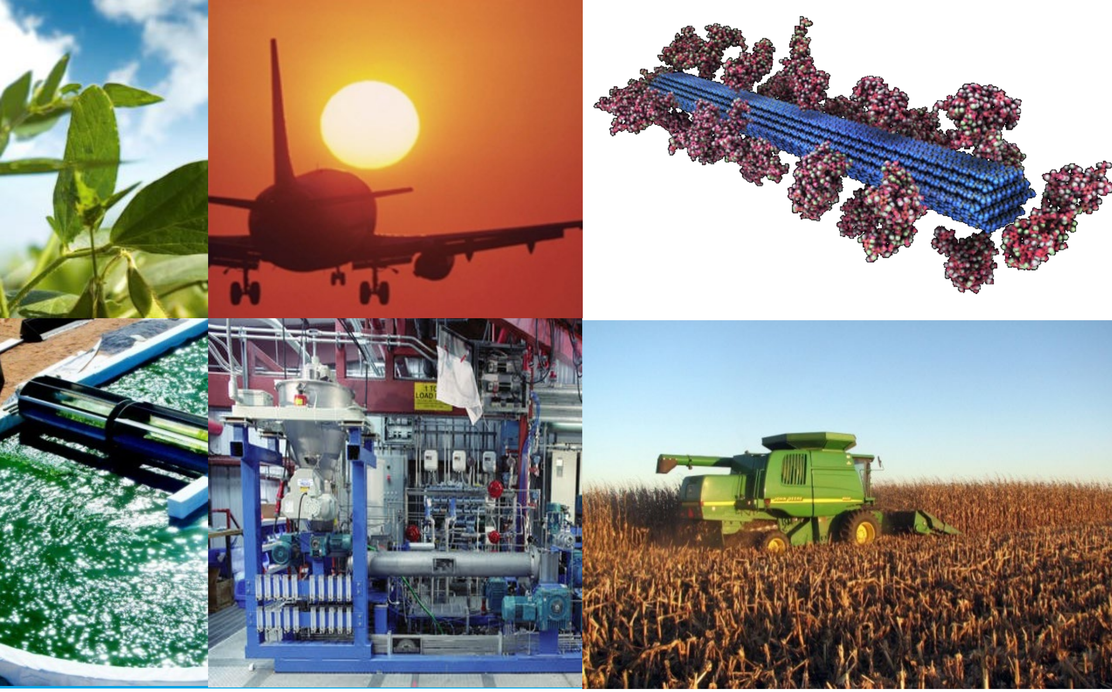

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

2019 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
BIOENERGY TECHNOLOGIES OFFICE

Conversion Technologies Research & Development

Kevin Craig

Program Manager, Conversion R&D

March 4th, 2019

Outline

- Conversion Team Introduction
- Conversion Goals and Approaches
- Portfolio Structure, Challenges, and Budget
- FOA and Other Awards
- Accomplishments and Direction
- New and expanded R&D Areas
- Review Panel Introduction

Conversion R&D Team – DOE and Fellows

Kevin Craig, Program Manager

DOE Staff
David Babson
Jay Fitzgerald
Nichole Fitzgerald
Beau Hoffman
Ian Rowe
Liz Moore*
ORISE Fellows
Andrea Bailey
Jeremy Leong

David

Jay

Nichole

Ian

Beau

Andrea

Jeremy

Liz

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Conversion R&D Team – Support Contractors

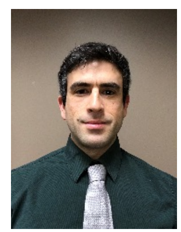
Conversion Support Contractors
Josh Messner - AST, Manager
Mark Philbrick – AST
Jessica Phillips – AST
Clayton Rohman – AST
Trevor Smith – AST
Seth Menter - AST
Robert Natelson – AST
Camryn Sorg – The Building People, LLC


Josh

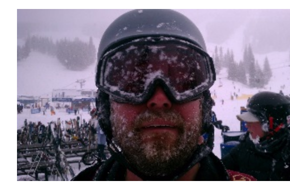

Mark


Trevor


Jessica


Robert


Seth


Clayton


Camryn

- **BETO Strategic Goal:** ***Enable use of America's abundant biomass and waste resources for advanced biofuels, bioproducts, and biopower by:***
  - *Identifying and developing biofuel pathways and innovative end uses;*
  - *Lowering the cost of production through increased efficiency, productivity, and yields; and*
  - *Completing applied research and development on complex, real world systems, and integrating engineering processes for promising new advanced bioenergy technologies*

  while maintaining or enhancing economic, environmental, and social sustainability.

Conversion R&D – Goals and Approaches

- **Conversion R&D Goal:** ***Develop efficient and economical biological and chemical technologies to convert biomass feedstocks into energy-dense liquid transportation fuels, such as renewable gasoline, diesel, and jet fuel, as well as bioproducts, chemical intermediates, and biopower.***

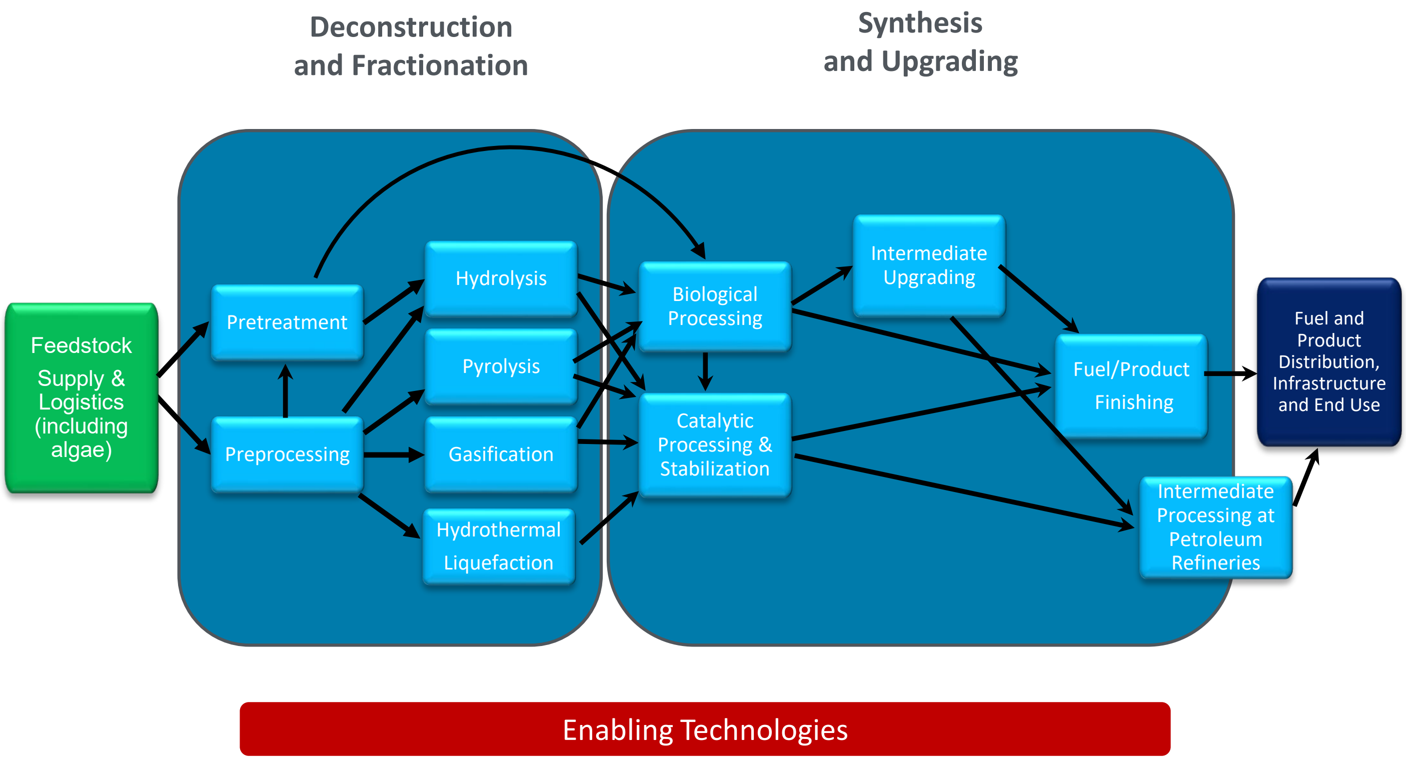
Approaches:

- Enhance U.S. industrial competitiveness by reducing time-to-market, improving yields, and increasing selectivity
- Fund research that supports a diversity of biochemical, thermochemical, and hybrid conversion technologies to match the distributed, diverse, domestic resources
- Leverage biological pathway engineering science
- Develop better catalysts and organisms faster through applied science

Price-competitive technologies for converting biomass into fuels and products

PORTFOLIO STRUCTURE AND BUDGET

Pathways are collections of technologies and interfaces



Program Structure

- **Deconstruction & Fractionation**
  - Feedstock Interface
  - High-Temperature Deconstruction
  - Low-Temperature Deconstruction
  - Fractionation, Cleanup, & Conditioning

Feedstock Conversion Interface Consortium (FCIC)

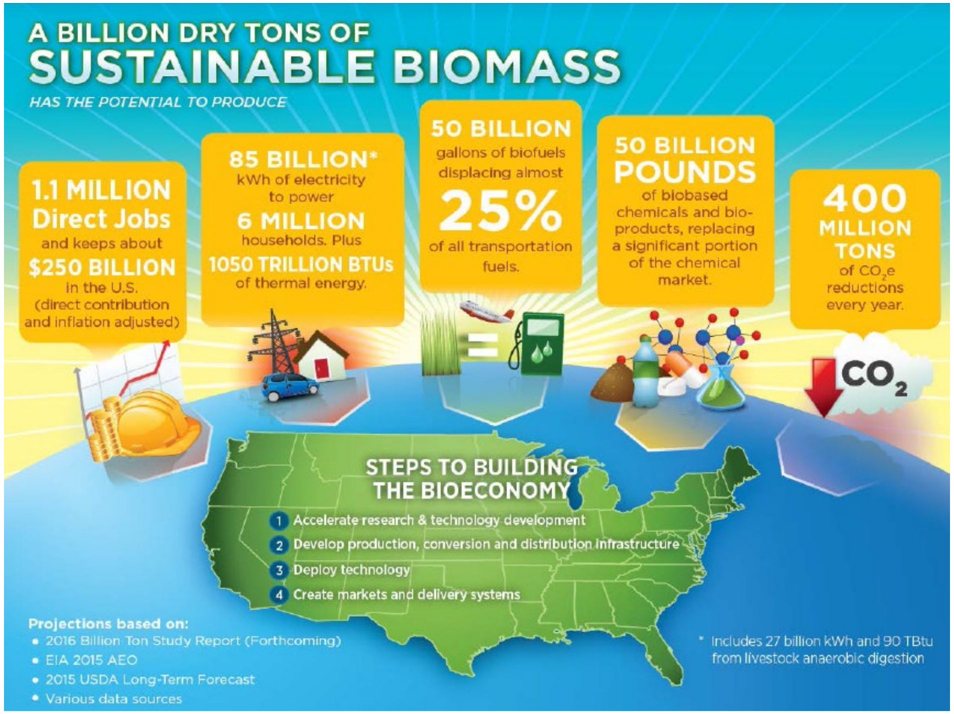
- **Synthesis & Upgrading**
  - Chemical Conversions to Intermediates & Products
  - Biological Conversions to Intermediates & Products
  - Cleanup or Finishing
  - Hybrid Conversions to Intermediates & Products

ChemCatBio
Chemical Catalysis for Bioenergy

Pathway-focused R&D

- **Enabling Technologies**
  - Computational Modeling & Analytical Tools — CCPC
  - Standards & Methods Development
  - Systems Biology — Agile BioFoundry
  - Design & Discovery of New Catalysts/Enzymes — ChemCatBio, Chemical Catalysis for Bioenergy
  - Advanced Separations — Bioprocessing Separations Consortium
  - Novel Technologies

The Challenge: How can BETO enable cost-competitive (<$3/GGE) lignocellulosic biofuels in the near term (~5-10 years)?



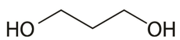
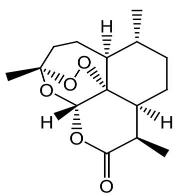
We annually model and periodically verify 6 lignocellulosic biofuel pathways

The average MSFP at nth plant is $3.36/GGE

Can bioproducts be the thin edge of the wedge?

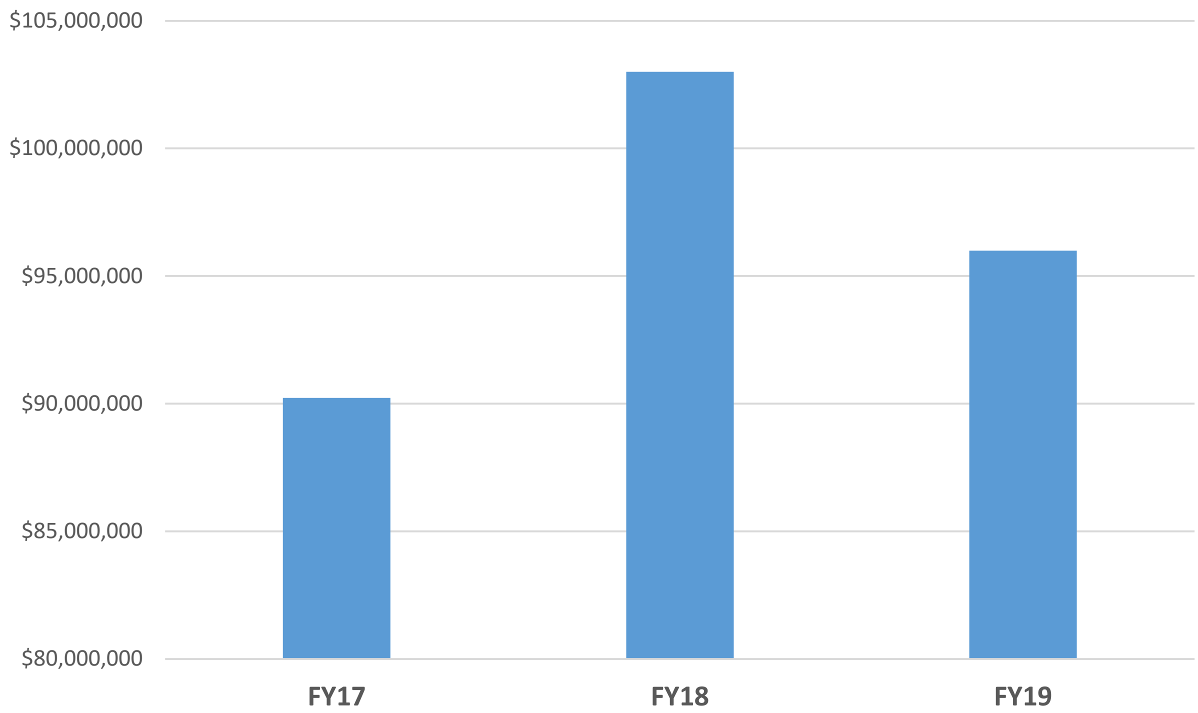
"An assessment of the potential products and economic and environmental impacts resulting from a billion ton bioeconomy"
Biofuels, Bioprod. Bioref. 11:110–128 (2017). Z Haq (BETO) and partners at USDA, Energetics, AST, and ANL

The Challenge: Cost and Time to Market

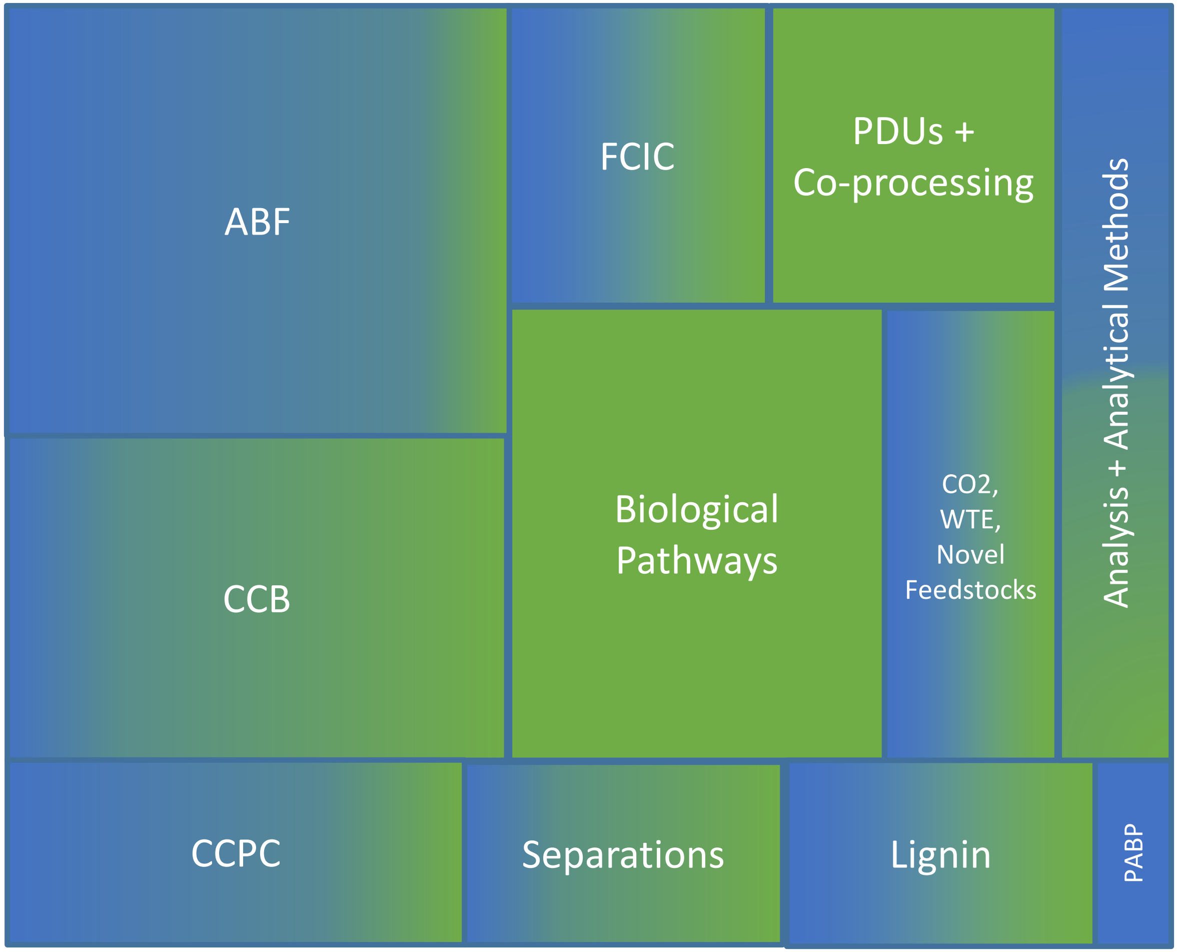
Molecule	Company	Cost	Time
1,3-Propanediol (PDO) 	DuPont - Tate & Lyle	>>$120M	15 years
Artemisinin 	UC Berkeley, Amyris, Sanofi	>$50M	10 years

Possible savings of *billions* of dollars by reducing development time of products, reducing energy intensity and increasing carbon efficiency

Total Conversion Budget by FY for the Review Period

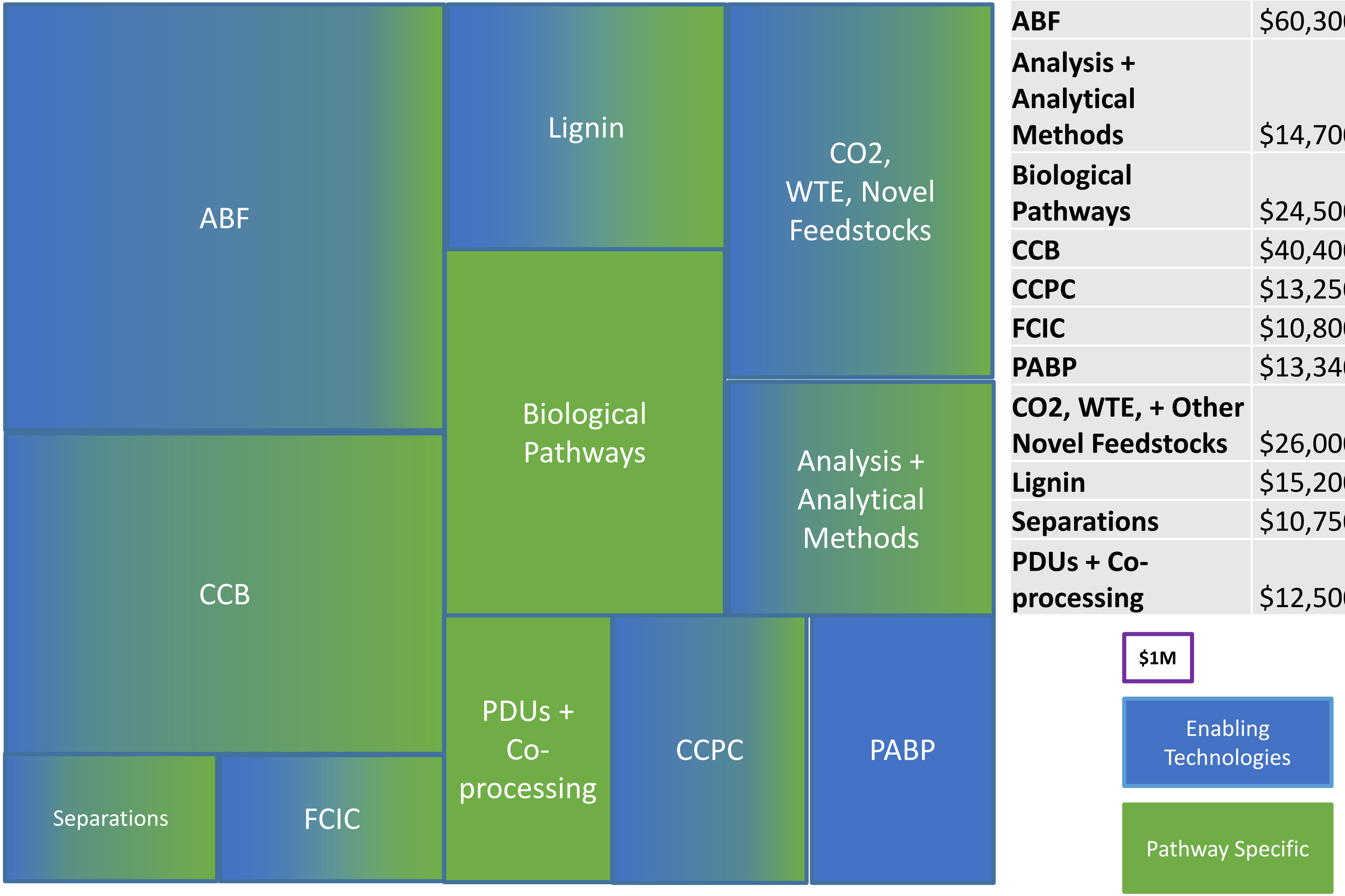


Portfolio Overview – National Lab Work FY17-FY19



ABF	$47,800,000
Analysis + Analytical Methods	$14,700,000
Biological Pathways	$24,500,000
CCB	$32,600,000
CCPC	$13,250,000
FCIC	$10,800,000
PABP	$4,340,000
CO2, WTE, + Other Novel Feedstocks	$15,000,000
Lignin	$10,700,000
Separations	$10,750,000
PDUs + Co-processing	$12,500,000

Portfolio Overview – Including Awarded Competitive Funds FY17-FY19

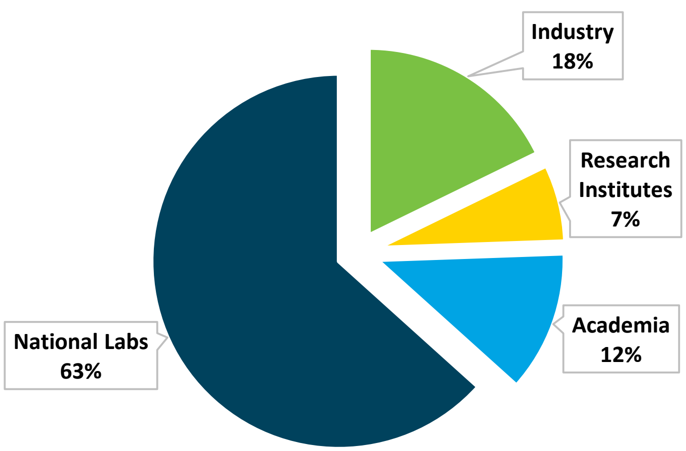


ABF	$60,300,000
Analysis + Analytical Methods	$14,700,000
Biological Pathways	$24,500,000
CCB	$40,400,000
CCPC	$13,250,000
FCIC	$10,800,000
PABP	$13,340,000
CO2, WTE, + Other Novel Feedstocks	$26,000,000
Lignin	$15,200,000
Separations	$10,750,000
PDUs + Co-processing	$12,500,000

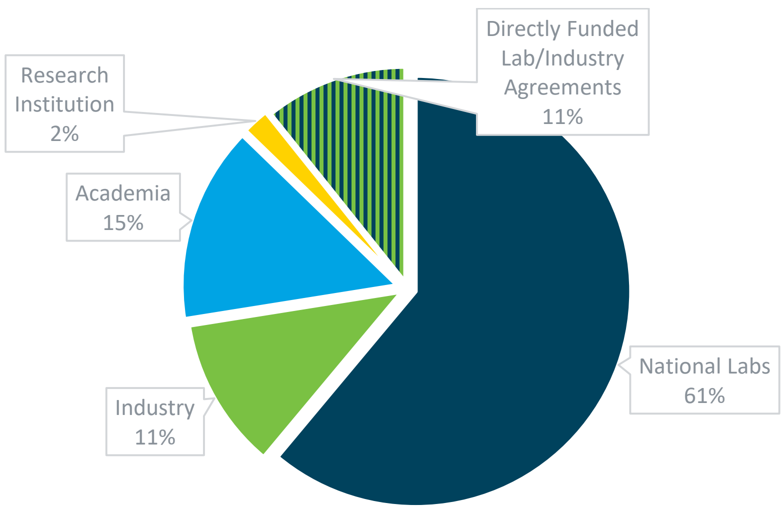
Portfolio Structure

149 total Conversion portfolio projects to be reviewed over the next four days:

– 27 in the Biochemical Review Session
– 10 in the ABF Review Session
– 24 in the Catalysis Review Session
– 11 in the Waste to Energy (WTE) Session
– 14 in the PABP/Seps Review Session
– 11 in the Lignin Review Session
– 7 in the CO2 Review Session
– 32 in the Poster Session
– 12 in additional review sessions from other programs



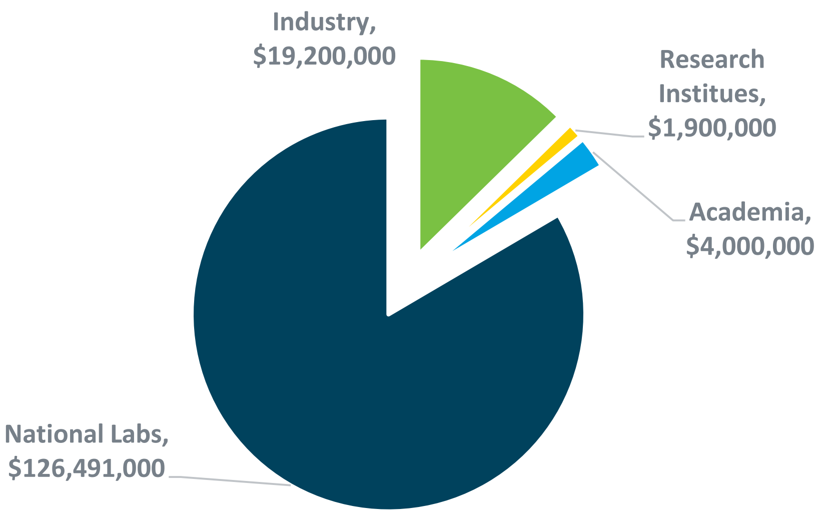
FY15-16



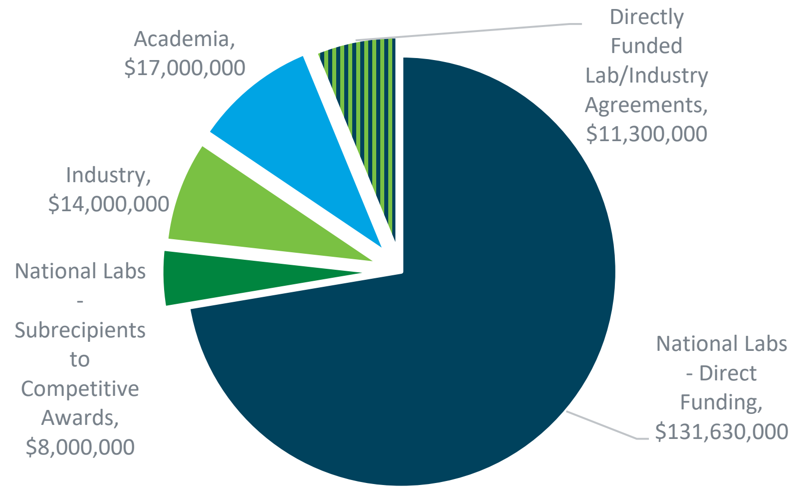
FY17-18

Portfolio Structure and Budget

Amount Appropriated During Review Period by Recipient Type (numbers rounded)



FY15-16



FY17-18

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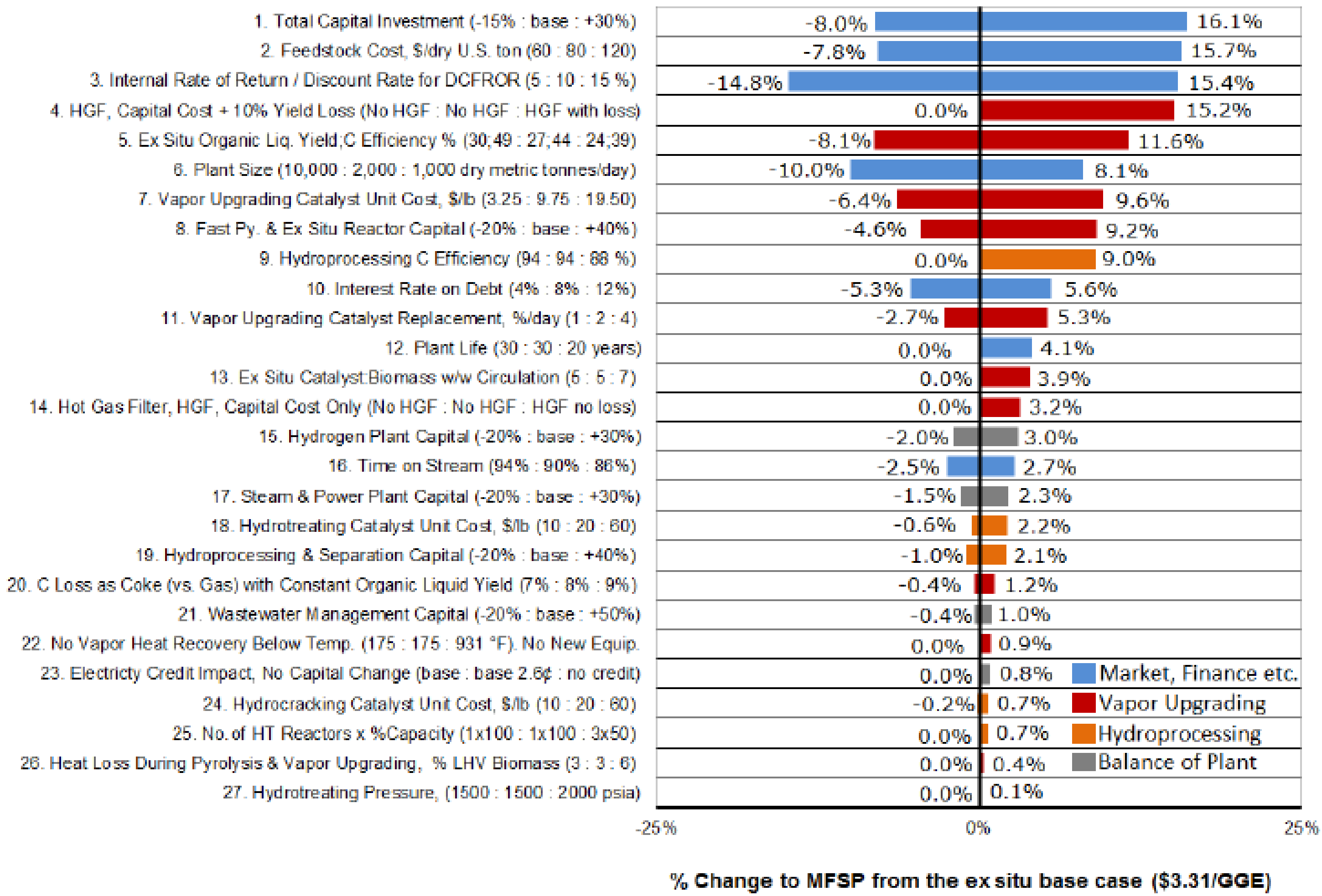
Ex-situ CFP



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Ex-situ CFP

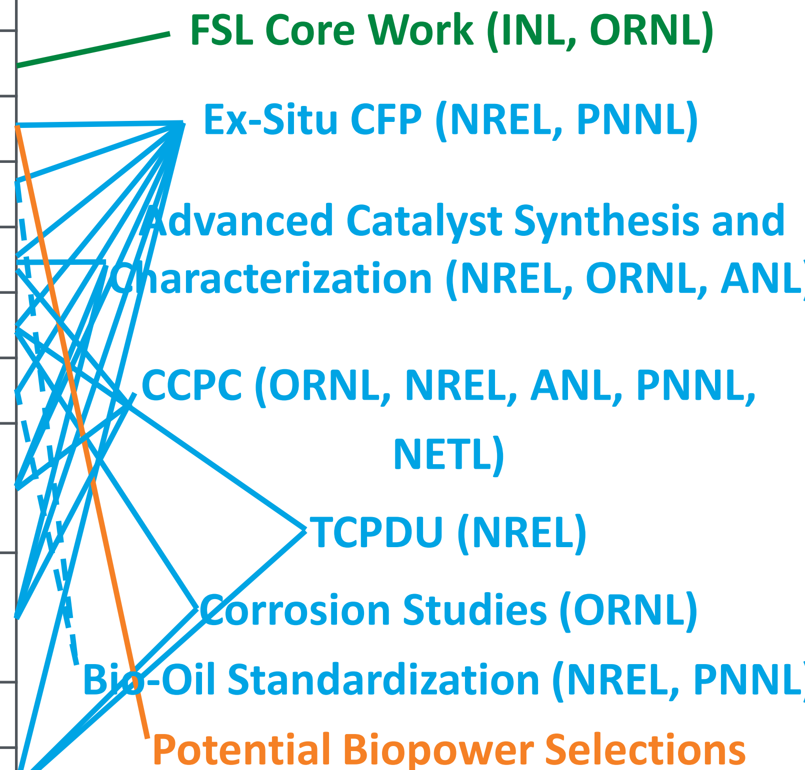
Items either not directly tied to BETO R&D or influenced by progress in the bioenergy industry as a whole were eliminated

Rank	Description	Max Impact (negative)	Max Impact (positive)
1	Total Capital Investment	-8.0%	16.1%
2	Feedstock Cost $/dry US ton	-7.8%	15.7%
3	Internal IRR	-14.8%	15.4%
4	HGF Capital Cost	-0.0%	15.2%
5	Ex-Situ Organic Liq Yield	-8.1%	11.6%
6	Plant Size	-10.0%	8.1%
7	Vapor Upgrading Catalyst Unit Cost	-6.4%	9.6%
8	Fast Py & Ex Situ Reactor Capital	-4.6%	9.2%
9	Hydroprocessing C Efficiency	-0.0%	9.0%
10	Interest Rate on Debt	-5.3%	5.6%
11	Vapor Upgrading Catalyst Replacement	-2.7%	5.3%
12	Plant Life	-0.0%	4.1%
13	Ex Situ Catalyst Biomass with Circulation	-0.0%	3.9%
14	Hot Gas Filter, Capital Cost	-0.0%	3.2%
15	Hydrogen Plant Capital	-2.0%	3.0%
16	Time on Stream	-2.5%	2.7%
17	Steam and Power Plant Capital	-1.5%	2.3%
18	Hydrotreating Catalyst Unit Cost	-0.6%	2.2%
19	Hydroprocessing and Separation Capital	-1.0%	2.1%
20	C Loss as Coke with Constant Organic Liquid Yield	-0.4%	1.2%
21	Wastewater Management Capital	-0.4%	1.0%
22	No Vapor Heat Recovery Below Temp	-0.0%	0.9%
23	Electricity Credit Impact	-0.0%	0.8%
24	Hydroprocessing Catalyst Unit Cost	-0.2%	0.7%
25	Number of HT Reactors x %Capacity	-0.0%	0.7%
26	Heat Loss During Pyrolysis Vapor Upgrading	-0.0%	0.4%
27	Hydrotreating Pressure	-0.0%	0.1%

Ex-situ CFP

Top 10 remaining areas by current active project:

Rank	Description
2	Feedstock Cost $/dry US ton
4	HGF Capital Cost + Yield C Efficiency
5	Ex-Situ Organic Liquid Yield
7	Vapor Upgrading Catalyst Unit Cost
8	Fast Py & Ex Situ Reactor Capital
9	Hydroprocessing C Efficiency
11	Vapor Upgrading Catalyst Replacement
13	Ex Situ Catalyst Biomass with Circulation
15	Hydrogen Plant Capital
16	Time on Stream



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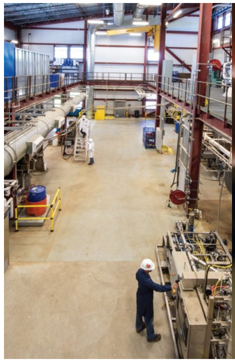
Ex-situ CFP

Top 10 remaining areas by FY17 investment:

Rank	Description	FY17 Investment ($K)
2	Feedstock Cost $/dry US ton	$1,600
4	HGF Capital Cost + Yield C Efficiency	$4,000
5	Ex-Situ Organic Liquid Yield	$4,750
7	Vapor Upgrading Catalyst Unit Cost	$7,925
8	Fast Py & Ex Situ Reactor Capital	$7,550
9	Hydroprocessing C Efficiency	$4,750
11	Vapor Upgrading Catalyst Replacement	$7,925
13	Ex Situ Catalyst Biomass with Circulation	$7,925
15	Hydrogen Plant Capital	$0
16	Time on Stream	$7,550

FOA and Direct Funding Opportunities

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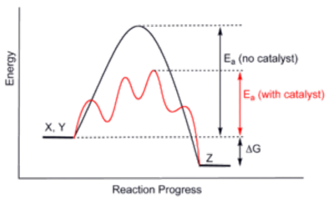
Bioenergy Engineering for Products Synthesis (BEEPS) FOA

On May 5,th 2018 the U.S. Department of Energy (DOE) announced a FOA to support R&D to develop highly efficient conversion processes for improving the affordability of fuels and products from biomass and waste streams.

FOA Topic Areas:

- **Topic Area 1:** ChemCatBio Industrial Partnerships (CCB)
- **Topic Area 2:** Agile BioFoundry Industry Partnership Initiative (ABF)
- **Topic Area 3:** Performance Advantaged Bioproducts (PABP)
- **Topic Area 4:** Biofuels and Bioproducts from Wet Organic Waste Strean
- **Topic Area 5:** Rewiring Carbon Utilization (Rewiring)
- **Topic Area 6:** Lignin Valorization (Lignin)



Catalytic Carbon Reduction

Agile BioFoundry

Funding Amount: Up to $28,000,000

ChemCatBio


U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Moving Beyond Drop-In Replacements: Performance-Advantaged Biobased Chemicals

Workshop Summary Report

June 2018

Contributions to BETO's mission:

- R&D to increase efficiency of conversion to drive down cost of biofuels and bioproducts
- Increases industry access to capabilities to improve biofuel and bioproduct production and management through partnerships with DOE's Agile BioFoundry and ChemCatbio
- R&D in valorizing residual side streams through lignin valorization
- R&D on leveraging waste as an untapped resource with economic advantages

Bioprocessing Separations Consortium CRADA/DFO Partnerships

- Separations for Biochemical Conversion – Developed in situ product recovery system to extract carboxylic acids from fermentation broth utilizing solvent/membrane systems and increased acid product concentration ~6x
- Separations for Thermochemical Conversion – Developed functionalized resins and molecular sieves that exceeded FY18 target of 25% carbonyl reduction in liquid pine bio-oils

- Directed Funding Opportunity

Company w/ Labs	Feedstock	Separations	Product
Visolis w/ ANL & LBNL	Cellulosic Sugar	RW-EDI, wiped film distillation	fatty acid
Kalion w/ ORNL, ANL & NREL	Cellulosic Sugar	pervaporation, RW-EDI, nano-adsorbents	Glucaric acid
Mango Materials w/ LBNL	Biogas	Tangential Flow Filtration	PHAs from methanotrophs
DMC Biotechnologies w/ ANL	Cellulosic Sugar	Nano-adsorbents	Farnesene, liquid hydrocarbons
HelioBioSys w/ LANL & LBNL	Atmospheric CO_2	Ultrasonic Separations	Extracellular polysaccharides from cyanobacterial consortium

Agile BioFoundry CRADA/DFO Partnerships

Company	Labs	Feedstock	Organism	Capabilities	Product
Kiverdi	NREL, LBNL, ORNL	CO_2 and H_2	*Cupriavidus necator*	Design: DIVA, Test: targeted –omics and biocatalyst optimization	Fatty-acid derived molecule
LanzaTech	ANL & NREL	Syngas & Waste Gas	*Clostridium autoethanogenum*	Learn: machine learning and deep learning	Various chemicals and fuels
Lygos	SNL, LBNL, PNNL	Cellulosic Sugar	*Pichia kudriavzevii*	Design: DIVA, Build, Test: Proteomics, Metabolomics, Experiment Data Depot	Organic acid
TeselaGen	LBNL, PNNL, SNL	NA	NA	Design: BOOST, BLiSS; Test: Experiment Data Depot	NA
Visolis	NREL, ORNL	Cellulosic Sugar and Waste Gas	*Clostridium ljungdahlii*	Build: Genetic Transformation and Tool Development	Hydroxyacid intermdiate
University of Georgia	LANL, NREL	Cellulosic Sugar	*Acinetobacter baylyi* ADP1	Test: Biocatalyst Optimization, High Throughput Screening	Terephthalic acid

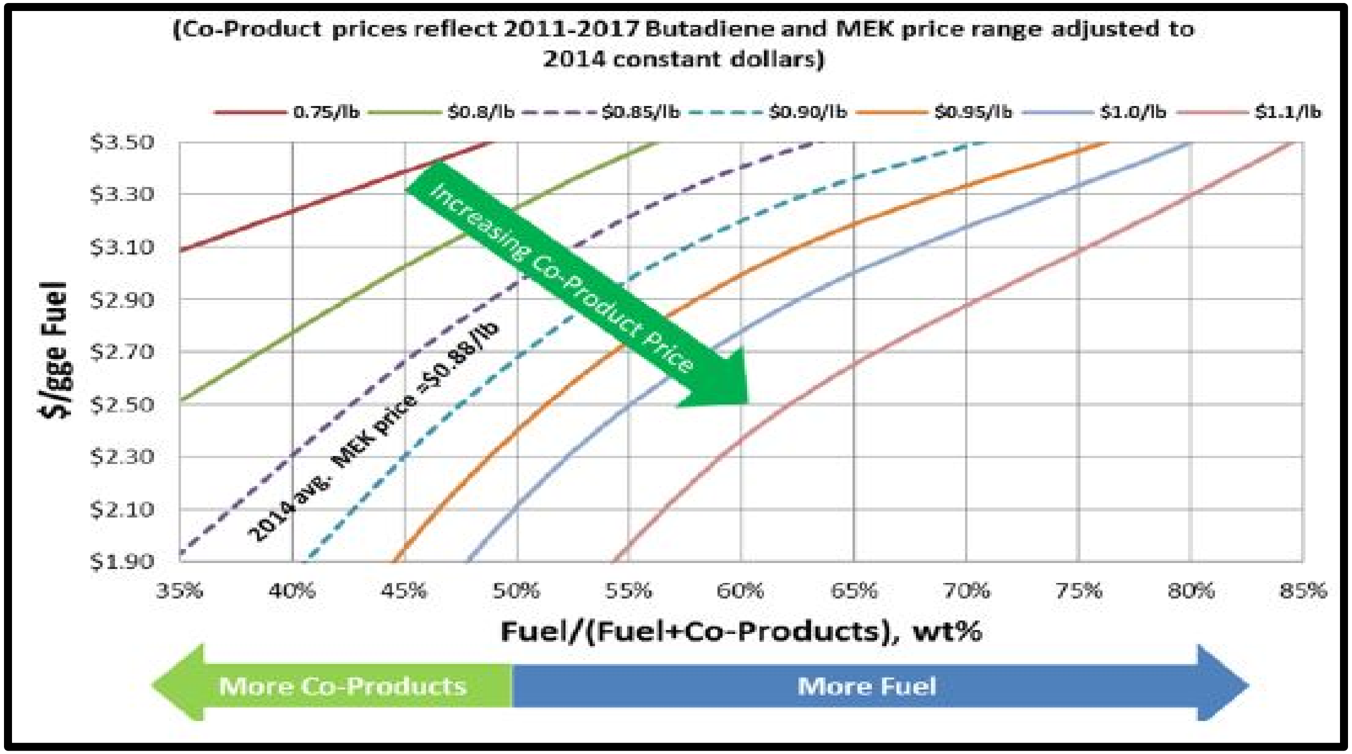
ChemCatBio CRADA/DFO Partnerships

Company	Labs	CCB Capabilities	Product
GEVO (mixed oxide)	NREL, ANL, ORNL	Characterization	C_3-C_4 olefins
Visolis	NREL	Synthesis, Evaluation	diols
Vertimass	NREL, ANL, ORNL	Characterization	Hydrocarbon fuels
Lanzatech (Terephthalic Acid)	PNNL	Synthesis, Characterization, Evaluation, Modeling	Terephtalic acid
GEVO (Tactical Aviation Fuels)	LANL	Synthesis, Characterization, Evaluation, Modeling	cyclobutanes
ALD Nanosolutions and JM	NREL	Synthesis, Characterization, Evaluation, Modeling	Hydrocarbons
Lanzatech (Fuel Fractions)	PNNL	Evaluation, Modeling	Jet fuel
Opus-12	NREL	Synthesis, Characterization, Evaluation	alcohols
Sironix Renewables	LANL	Synthesis, Characterization, Evaluation, Modeling	oleo-furan surfactants

Accomplishments & Direction

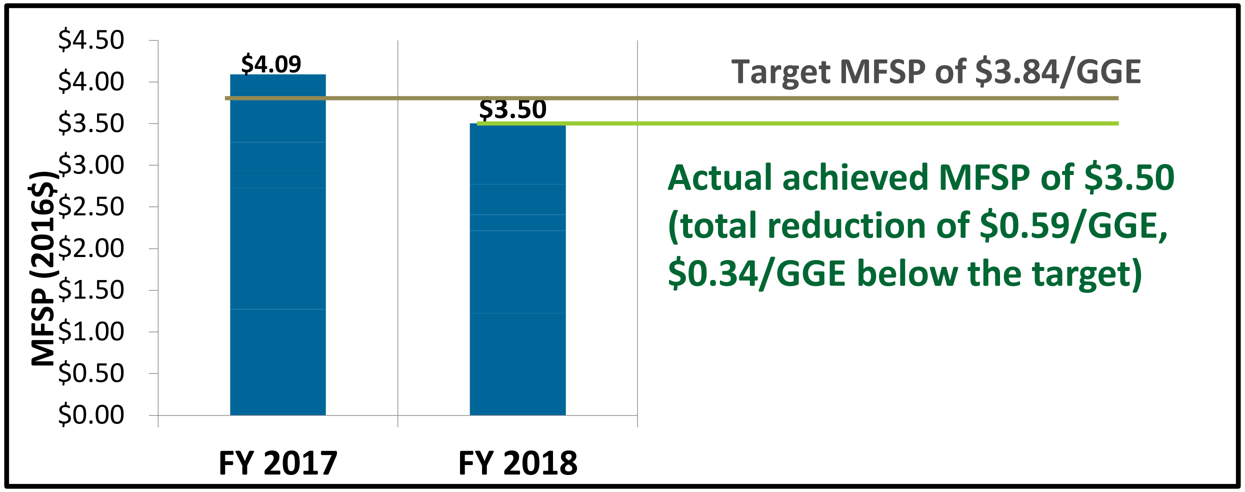
Achieved FY2017 Office Performance Metric

- $3/gge Modeled, Mature-plant Fuel Price (plant gate)
- Unanticipated problems with Fast Pyrolysis & Upgrading
- Pivoted to analysis of Lanzatech alcohol-to-jet process utilizing PNNL catalyst
  - PNNL received “Excellence in Technology Transfer Award” for this work with LanzaTech
- Highlights importance of co-products



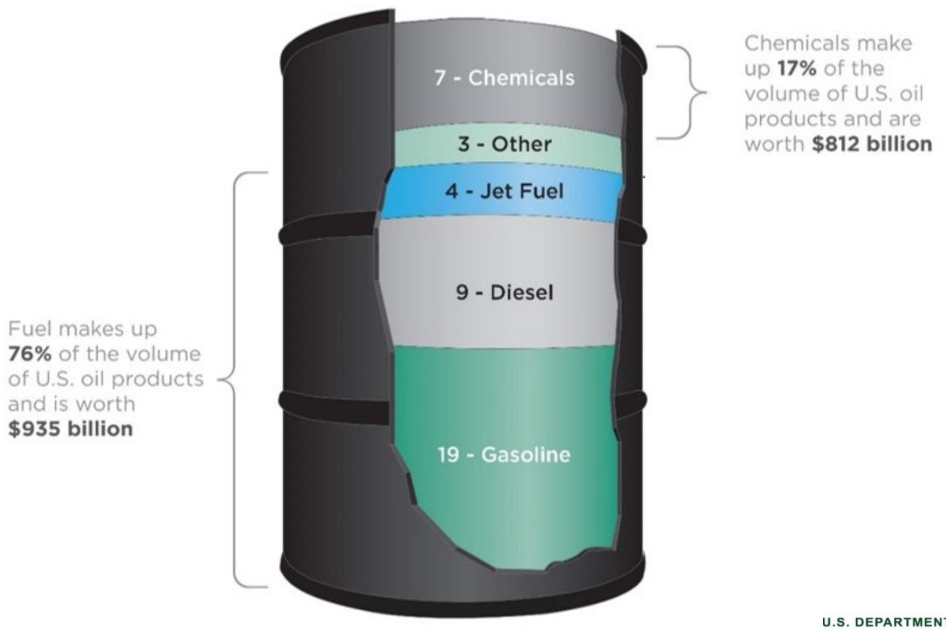
Catalytic Fast Pyrolysis Exceeds FY18 Office Performance Targets

- **FY18 Office GPRA Target:** For at least one approach (e.g., in situ, ex situ, dual bed, co-processing/hydrotreating),
  - Carbon efficiency greater than 36% to fuel blendstocks. **Final result: 39.7%**
  - Reduction in the modeled MFSP by $0.25/GGE compared to the FY17 SOT. **Final result: -$0.59/GGE**



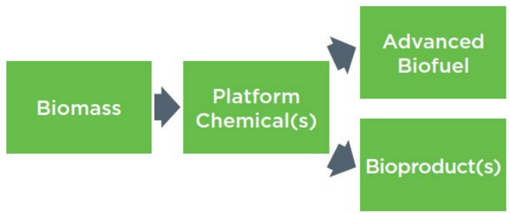
Replacing the Whole Barrel – A Shift Toward Drop-ins and Bioproducts

- Only ~40% of a barrel of crude oil is used to produce petroleum gasoline. Reducing oil dependence requires replacing **diesel, jet fuel, heavy distillates, and other products.**
- EERE successfully achieved modeled mature cost goals for cellulosic ethanol in 2012 and shifted its R&D to focus on **hydrocarbon "drop-in" biofuels, jet fuels, and bio-based products.**
- **Fuel makes up 76% of the** volume of U.S. oil products and is worth **$935B**.
- Products make up 17% of the volume of U.S. oil products and are worth **$812B**.

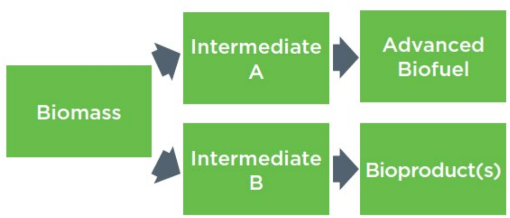


Potential Pathways of Interest to BETO

Fuel alone. Traditional approach which was highly successful for cellulosic ethanol



Platform chemical. (e.g. Vertimass EtOH to jet, levulinic acid)



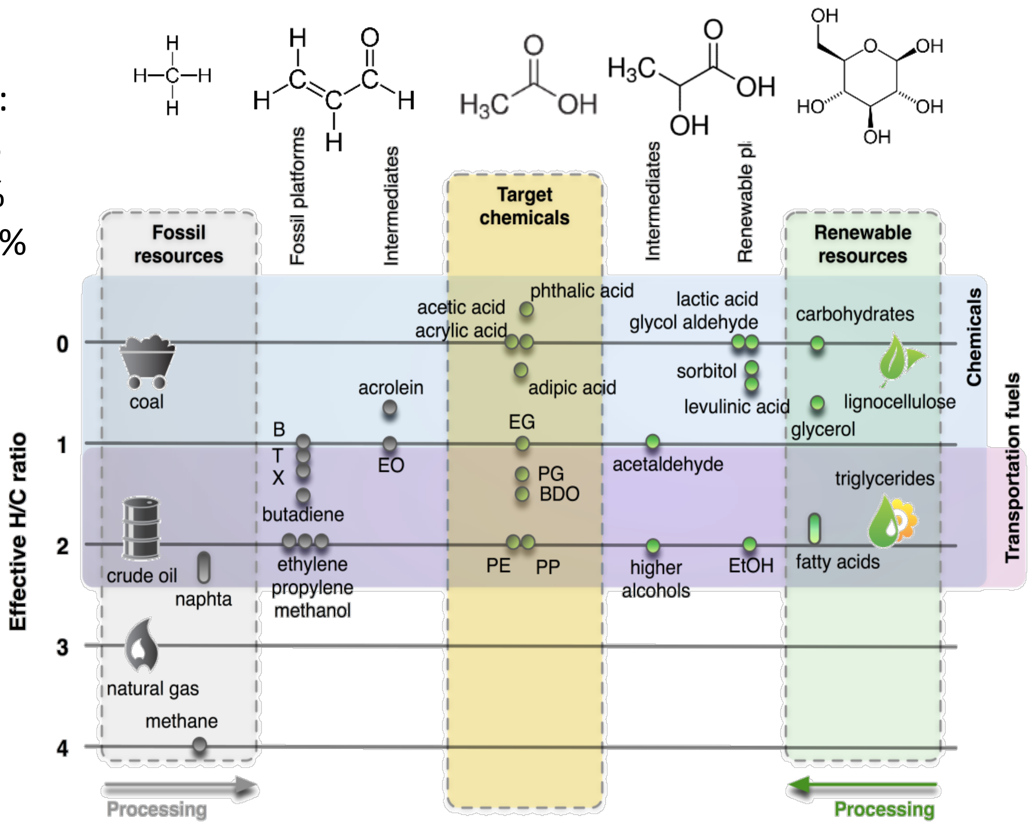
Coproduction. May utilize waste stream/slip stream conversion
(e.g. C5 to succinic, lignin utilization, starch ethanol, etc.)

Product alone. De-risks upstream unit operations, builds supply infrastructure, builds investor confidence

Biobased products contain oxygen… like biomass

Crude oil

Avg. wt%:
C 83-87%
H 10-14%
O 0.1-1.5%



Biomass

Avg. wt%:
C 36-53%,
H 5-7%,
O 31-48%

Consider the oxidation state of chemicals – retain what nature provides

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

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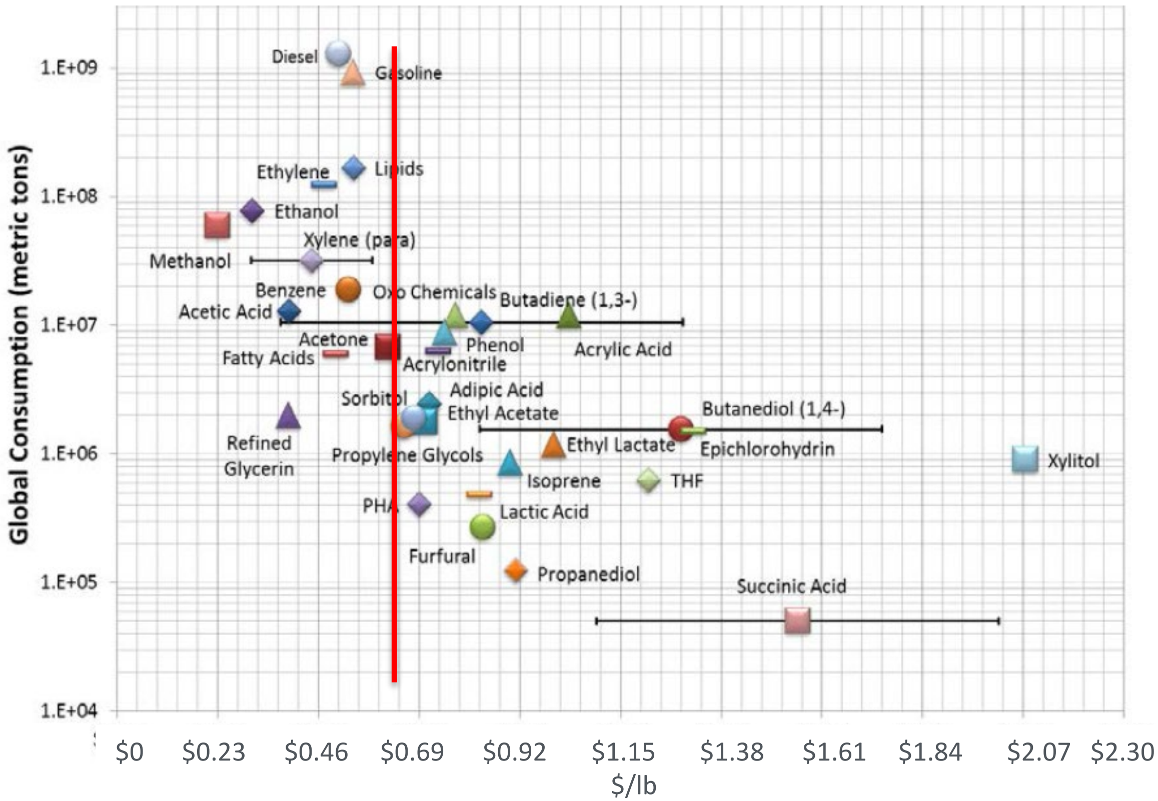
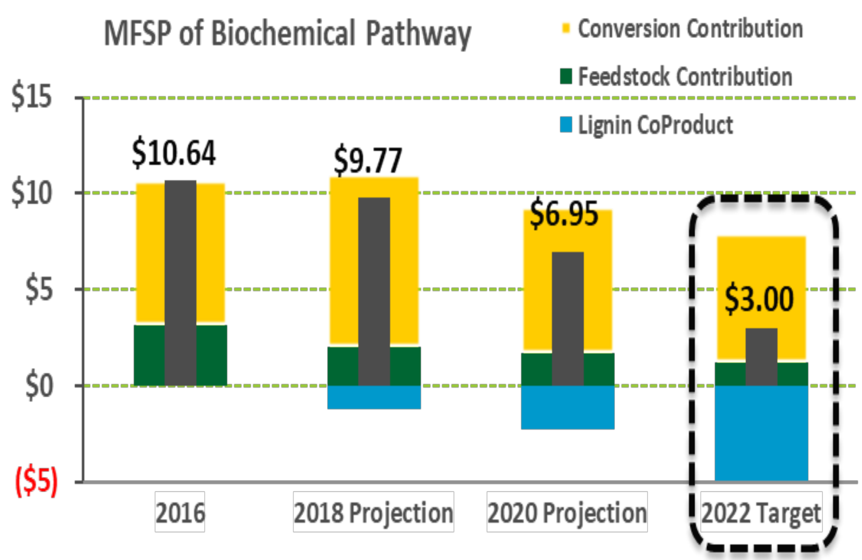
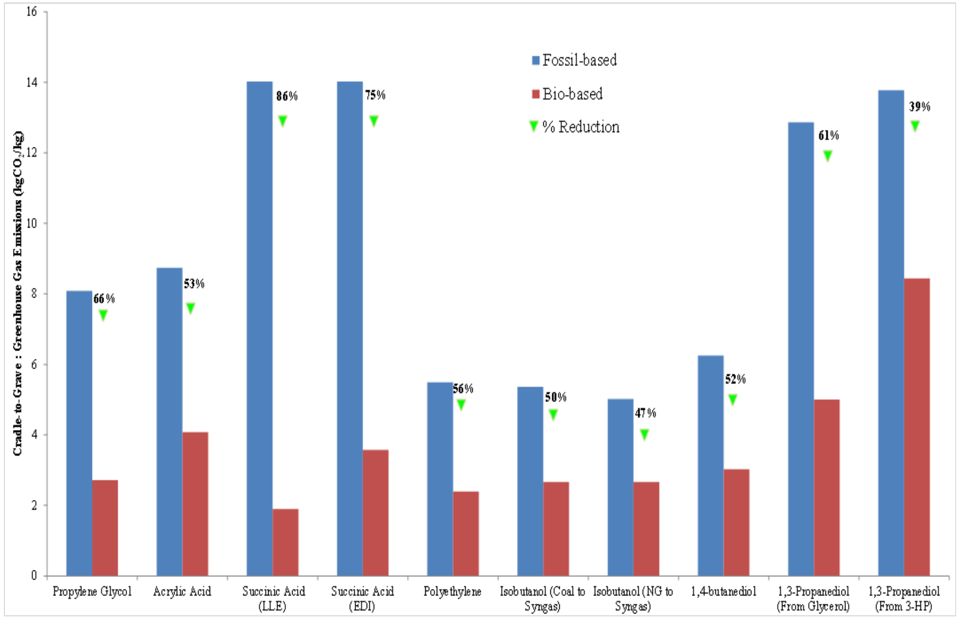
Scalability of Bioproducts



Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential, Mary Biddy (NREL) and colleagues. Available at: http://www.nrel.gov/docs/fy16osti/65509.pdf

Bioproducts uniformly showed emission reductions compared to their fossil-derived counterparts





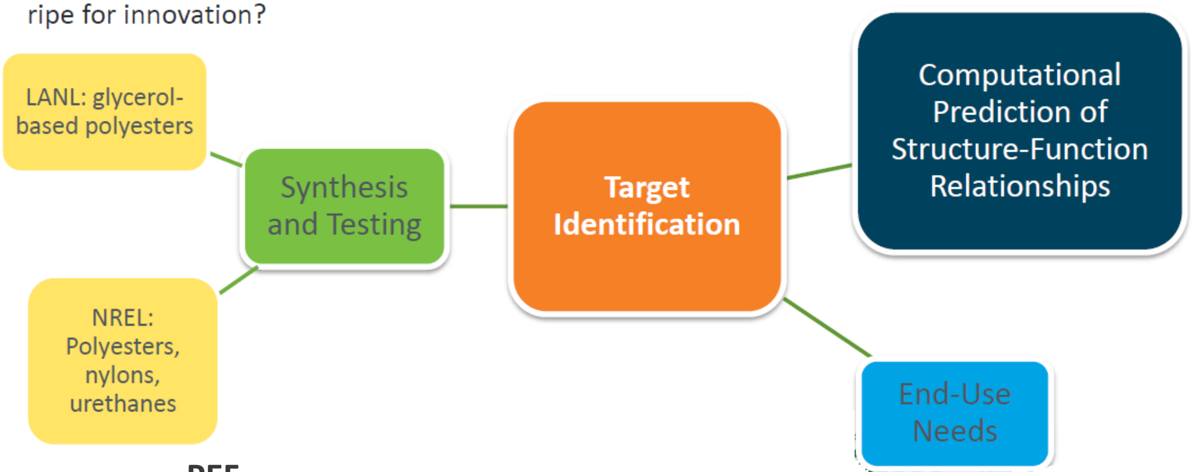
Life-Cycle Fossil Energy Consumption and Greenhouse Gas Emissions of Bioderived Chemicals and Their Conventional Counterparts – Felix Adom, Jennifer Dunn, Jeongwoo Han, and Norm Sather.

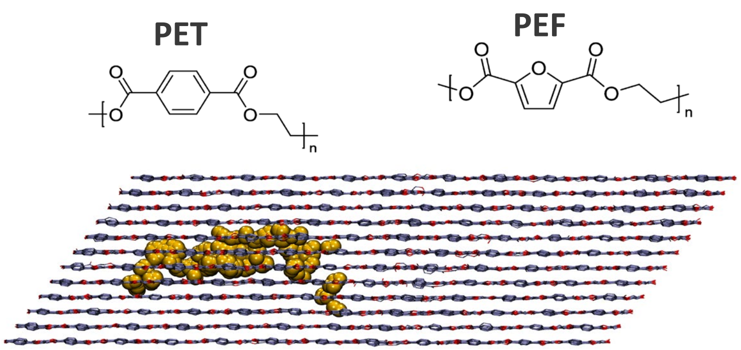
Consortia

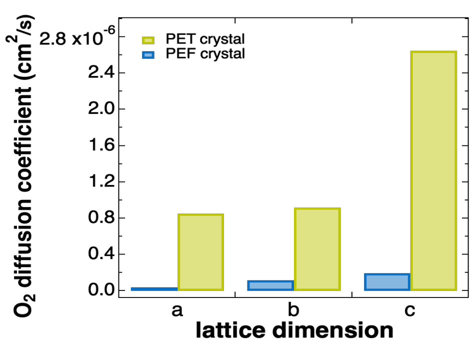
Performance Advantaged BioProducts (PABP) Consortium

- FY18 began $1.9M mini consortium at NREL to identify novel, performance advantaged bioproducts; FY19 introduced LANL + NREL partnership
- Three focus areas that represent workshop stakeholder concerns:
  - Computational modeling to predict how biobased compounds will behave
  - High throughput screening of biobased compounds to understand what can be easily made and what
  - End Use Needs- can we look at existing products and assess what is ripe for innovation?

Workshop in June, 2017; report PUBLISHED (check BETO website)







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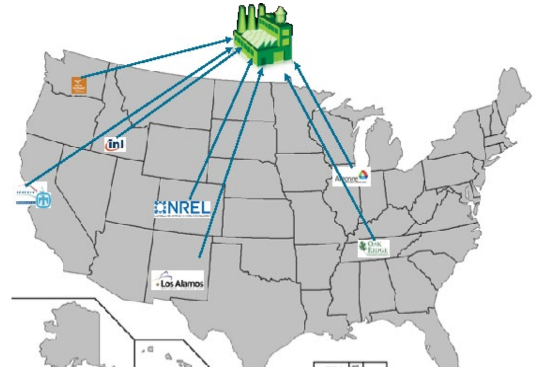
Agile BioFoundry

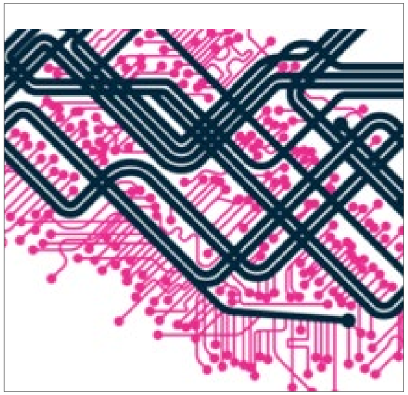
Structure:
- Virtual consortium of 8 national laboratories

Goal:
- Public infrastructure to enable 50% reductions in time and cost to bring a new bio-derived chemical to market through enhance conversion efficiency

Outcomes:
- 10X improvement in Design-Build-Test-Learn cycle efficiency, new host organisms, new IP and manufacturing technologies effectively translated to U.S. industry ensuring market transformation.

Recent Accomplishments:
- Three FY18 FOA selections awarded for Agile BioFoundry Industry Partnerships
- Constructed advanced machine learning models to improve pathway design
- 4X increase in DNA sequence validation speed (384 -> 1536 samples/week)
- PNNL/LBNL designed and built 3-hydroxpropionic acid pathway and transformed it into *Aspergillus pseudoterreus*
  - 1st cycle demonstrated 2-3 g/L titer, and doubled the titer in 2^{nd} cycle
- NREL/ORNL/ANL reached near-theoretical yields of muconate from glucose-fed *Pseudomonas putida* (41.3% mol/mol)
- SNL produced up to ~200 mg/L 1,8-cineole on modified *Rhodosporidium toruloides*





LYGOS

ZYMOCHEM
NEXT-GENERATION MICROBES FOR INDUSTRIAL CHEMICALS

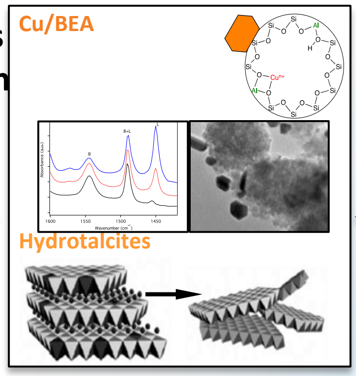
UC San Diego

Chemistry Catalysis For Bioenergy (ChemCatBio) Approach

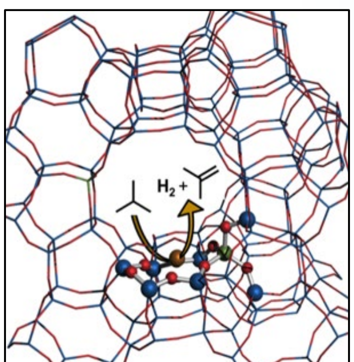
Establish an integrated and collaborative portfolio of catalytic technologies and enabling capabilities

Foundational Science

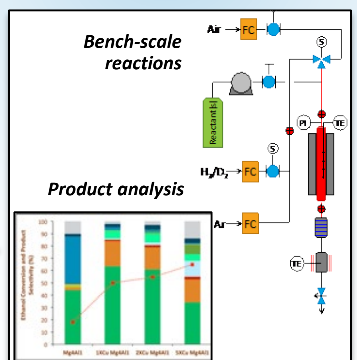
Advanced Synthesis and Characterization



Theory

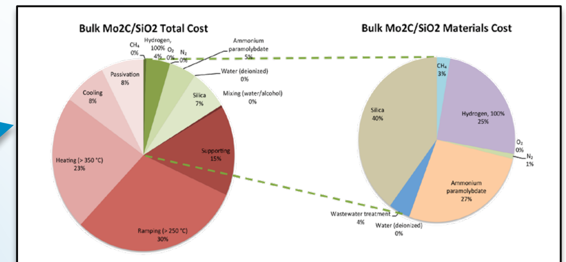


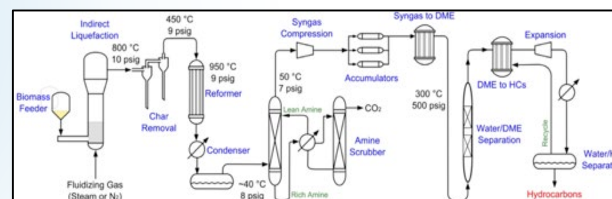
Performance Evaluation



Applied Engineering

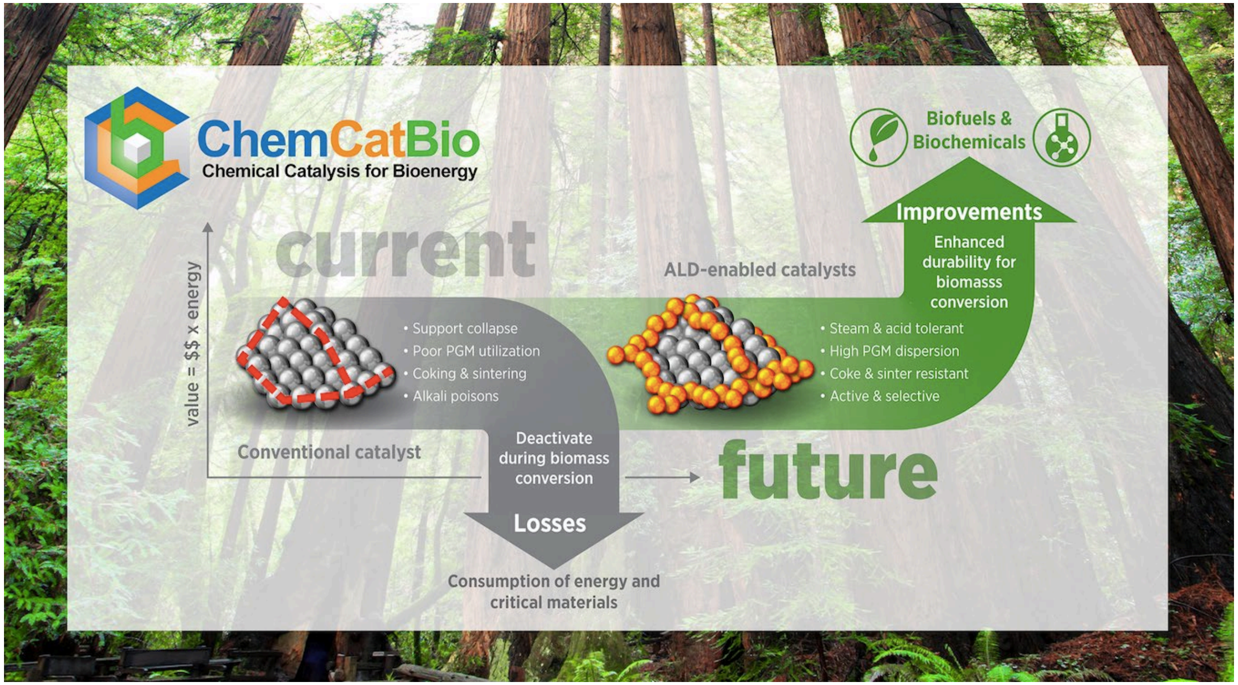
Catalyst Cost Estimation





Catalyst Scaling and Integrated Testing

- NREL has developed atomic layer deposition (ALD) coatings that improve catalyst stability during the production of biobased chemicals, with potential to favorably impact process economics. Through the ChemCatBio DFA, these ALD coatings were recently tailored to improve catalyst performance in the presence of biogenic impurities.



Impact in the words of industry:

"The work being done by the NREL team in the ChemCatBio project is of significant value in being able to understand the potential of ALD coating as a tool for next generation catalysts in biomass processing."
-Mike Watson
Technology Manager at Johnson Matthey

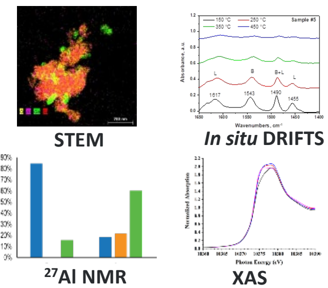
"The collaboration with NREL is an extremely valuable method to get industrial validation to the emerging applications for advanced catalyst thin film coatings."
-Karen Buechler,
CTO of ALD NanoSolutions

Work currently under review for publication. A.E. Settle, N.S. Cleveland, X. Huo, A.M. York, E.J. Kautz, A. Devaraj, K.K. Ramasamy, R.M. Richards, K.A. Unocic, G.T. Beckham, M.B. Griffin, K.E. Hurst, E.C.D. Tan, S.T. Christensen, D.R. Vardon. Atomic layer deposition for improved catalyst durability during the production of biobased adipic acid.

ChemCatBio
Chemical Catalysis for Bioenergy

The project team at ORNL, NREL and ANL utilized unique characterization techniques to study catalysts used in ethanol upgrading process at Vertimass LLC.

Oak Ridge National Laboratory



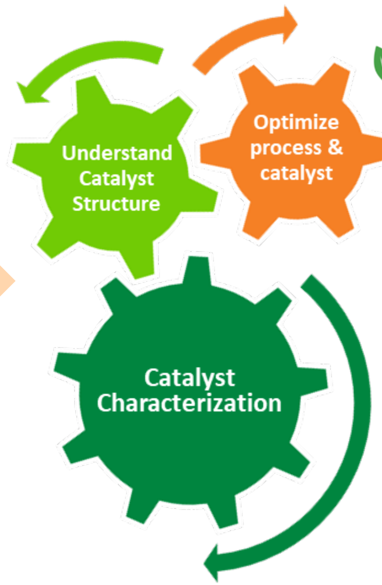
NREL National Renewable Energy Laboratory

Argonne National Laboratory

ChemCatBio
Chemical Catalysis for Bioenergy

Advanced Catalyst Characterizations

Vertimass™
Transformative fungible biofuels.



- **Deep characterization is helping optimize the catalysts and process, lower cost**
  - Identified catalyst changes at various operation conditions
    - Certain operational parameters can effect catalyst performance
    - Characterization provides structure-performance relationship, allowing for process and catalyst optimization

Impact in the words of industry:

"The ChemCatBio program has provided excellent catalyst characterization insights allowing us to optimize performance and lower conversion costs."
-John Hannon, Chief Operating Officer at Vertimass LLC

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- The CCPC has developed coupled particle and reactor scale models that have been extensively validated at NREL.
- Recently, these models were leveraged in a collaboration with Forest Concepts to predict required thermochemical conversion times and expected product yields as a function of specific feedstock attributes.

Impact in the words of industry:

"The work that you are doing has two direct benefits to our company and the industry. First, the simulations and associated graphics help us understand and explain how the 'dials we turn in production' affect feedstock functional performance. Second, we may want to add new 'label information' to our production reports related to functional performance as well as the physical properties measurements that we currently provide our customers and clients."

-Jim Dooley
CTO of Forest Concepts

Methods are reported in: M. Pecha, E. Ramirez, G. Wiggins, D. Carpenter, B. Kappes, S. Daw[2] , and P. Ciesielski, "Integrated Particle- and Reactor-Scale Simulation of Pine Pyrolysis in a Fluidized Bed," *Energy&Fuels, 2018*

CatCost: Better Cost Information for Catalyst R&D

ChemCatBio
Chemical Catalysis for Bioenergy

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

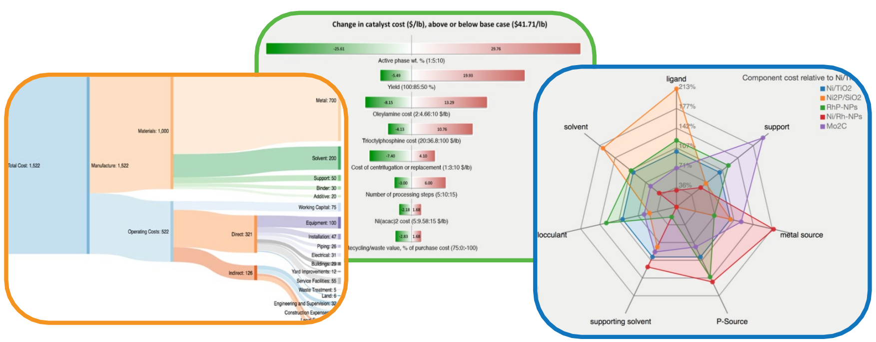
Pacific Northwest
NATIONAL LABORATORY

Problem: High commercialization risk

- Catalyst cost is a major contributor to commercialization risk for catalytic processes
- Up to 10% of capital cost and ±10% uncertainty in MFSP for biomass conversion
- ***No publicly available tools to evaluate cost***

Solution: "CatCost" Catalyst Cost Estimation Tool

- Enables early-stage comprehensive cost analysis
- No process design / TEA experience needed
- Improves cost-responsiveness of catalyst R&D



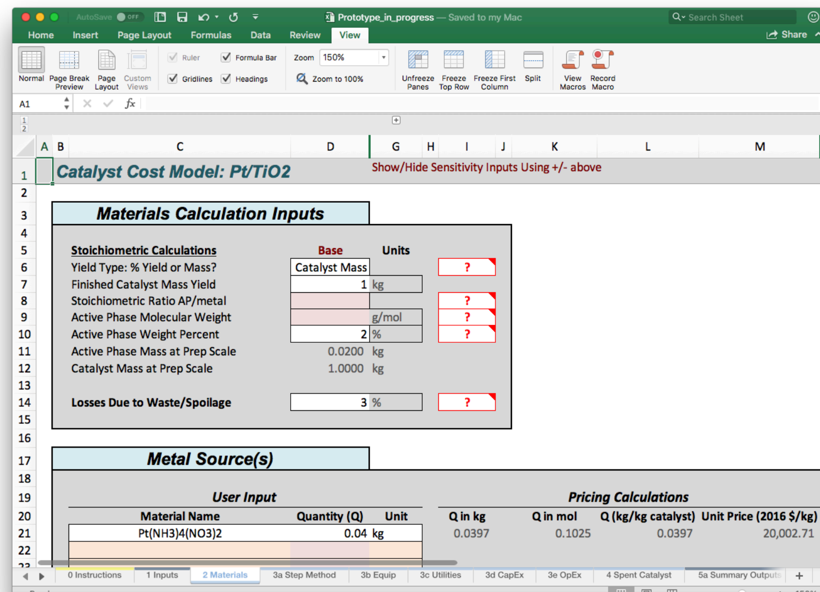
Developed at NREL and PNNL with guidance of industry experts

<u>Free and public</u> release:

01 October 2018 *(debuted at AIChE meeting's dedicated session)*

catcost.chemcatbio.org

Excel- and web-based versions available



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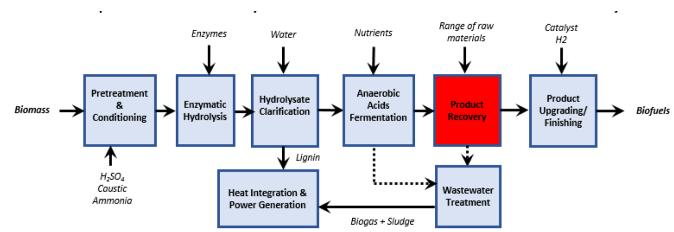
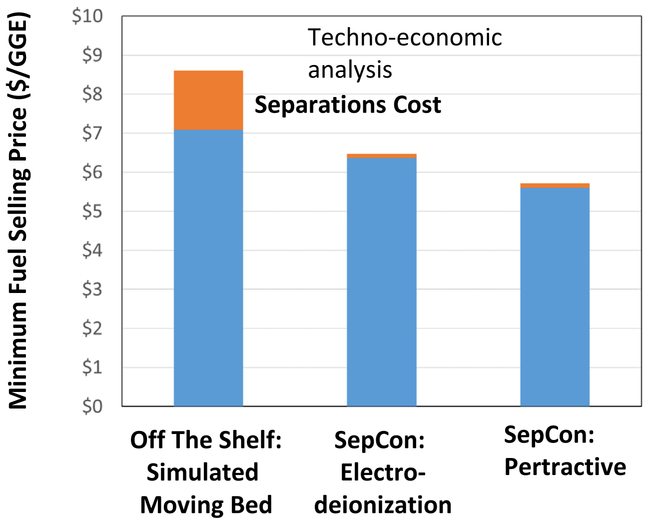
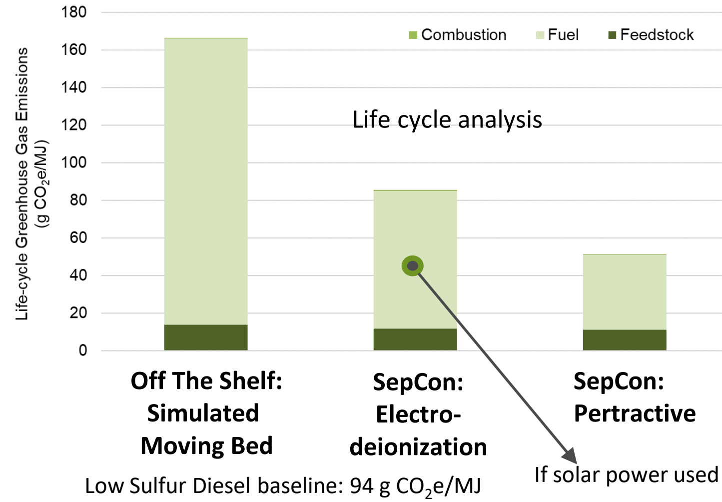
- **Evaluating TEA/LCA for 3 different technologies for acid intermediates extraction (planning for 2022 BC Verifications)**







Strategies being developed under separations consortium lower separations costs and biofuel life-cycle GHG emissions for this pathway

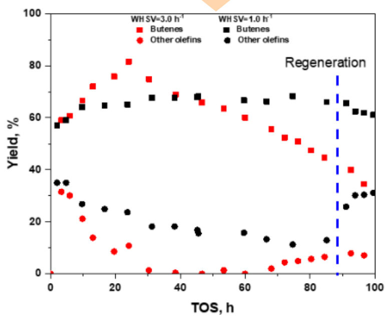
NOTE: Results reflect scenario in which lignin combusted, resulting energy consumed in process.

CUBI and ACSC collaboration: key to identifying catalyst structure and informing better operation for 2,3-BDO Upgrading

ChemCatBio
Chemical Catalysis for Bioenergy

CUBI

Cu/zeolite synthesis (ORNL)

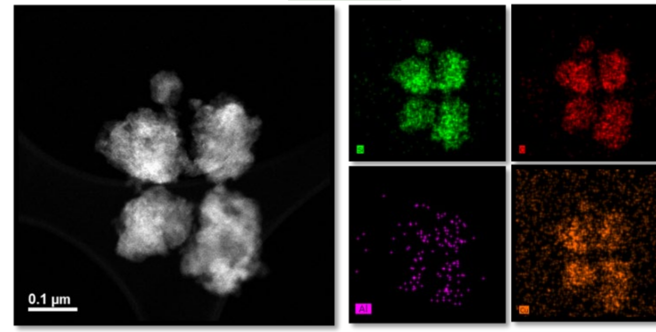


2,3-BDO conversion to butenes (ORNL)

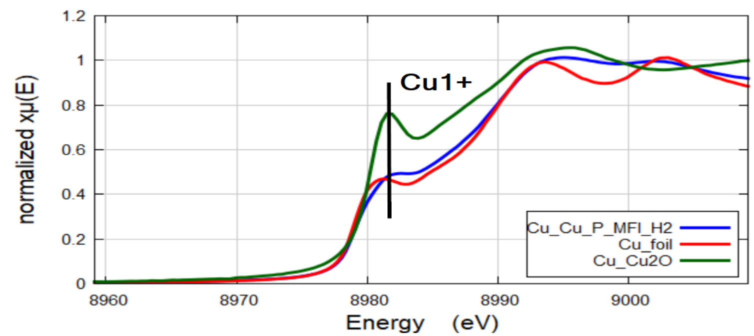
Fresh catalysts

Used catalysts

ACSC



STEM/EDS analysis (ORNL)



X-ray absorption near edge structure (ANL)

- **ACSC helped understand catalyst structure and inform better catalyst operations**
  - STEM/EDS: uniform Cu distribution, no large agglomeration
  - XAS: metallic Cu (majority), particle size ≈ 0.7-1.2 nm
  - Frequent catalyst regeneration (<90 h each cycle): avoid hard coke formation
- **Major impact: better catalyst design to increase higher olefins yield and lower MFSP**

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Biological Deconstruction

- At NREL, moved from batch to continuous countercurrent deacetylation

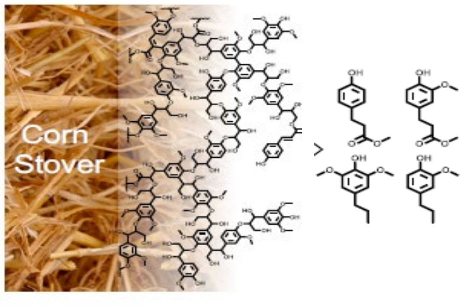
- NREL's Low Temperature Advanced Deconstruction studied how DMR (deacetylation and mechanical refining: the planned pathway for 2022 verification) impacts lignin
  - Used NMR, GPC, and TOF MS to demonstrate that DMR black liquor stream contains large amounts of lignin monomers/dimers along with aryl-ether bonds (β-O-4 linkages intact)
- NREL's Enzyme Engineering and Optimization (EEO) developed an artificial multifunctional cellulase with improved performance over native enzyme mixture
  - NREL has been shifting from DDA to DMR for 2022 cost targets, because DMR's lignin is more readily converted to products
    - But DMR cellulose is more recalcitrant than DDA cellulose
      - So EEO has been developing new cellulases to handle DMR cellulose

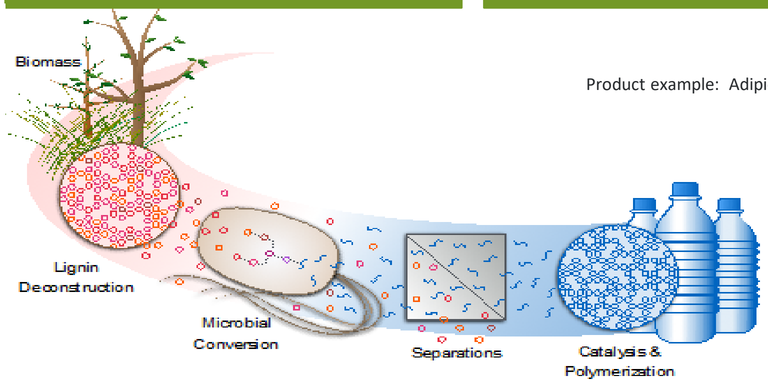
Biological Upgrading

- NREL - Bench Scale Integration's (BSI) end of year SMART milestone goal was to produce 75 g/L of 2,3-butanediol (BDO) from recombinant *Zymomonas mobilis* strain fed biomass sugars. **BSI exceeded this goal, producing an average of 83 g/L BDO from triplicate fermentations, using a combination of concentrated hydrolysate liquor from deacetylated disc refined (DDR) corn stover, using a fed-batch fermentation strategy, and lowering the aeration rate during xylose metabolism to maximize BDO production.**
  - Knockout of pyruvate decarboxylase gene enabled eliminating ethanol pathway
  - Data was produced too late in year to be included in FY18 SOT, but moves BETO closer to the 102 g/L that is targeted in the design case (as a route to $2.5/gge) and nearly a 2X increase from the end of FY17.
  - Yield was ~86% of theoretical (ultimate project goal is 125 g/L @ 85% yield).
  - In Q1, NREL will deliver 100 L of this fermentation broth to the CUBI teams
- NREL's Biological Upgrading of Sugars (BUS) worked with BioESep to develop in situ product recovery of butyric acid produced from Clostridium, as the Clostridium produces the acid but before cytotoxicity kicks in at high titer
  - Fermentation broth continuously pumped to membrane contactors; cells recycled
  - Extractant in contactors extracts acids; acids then distilled and extractant recycled
  - 300-hr continuous run → +22% productivity and +7% yield of butyric acid

Lignin Valorization

Chemical Breakdown | Biological Funneling | Catalytic Upgrading





Product example: Adipic acid (Nylon)

Residual
Biorefinery Lignin

Motivation: Lignin constitutes 15-40% of biomass carbon but it is currently considered a waste-stream in biorefineries, generally burned for heat and power.

Techno-economic modeling at NREL has indicated that lignin valorization to high-value products may reduce lignocellulosic biofuel cost by ~$1-2/gge.

CLEMSON UNIVERSITY — Spero Pioneering a greener future

FY18 FOA Selections on conversion of lignin to higher-value products:

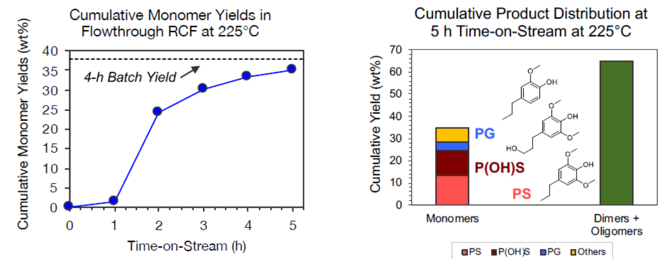
- Two awards, $3.4 million
- Carbon fiber and spray insulation, thermoset polymers used for fiberglass and automotive applications

DOE/USDA Biomass Research and Development Initiative (BRDI) awarded and started to develop a solvent liquefaction process for feedstock deconstruction and lignin upgrading

Recent Wins in Lignin

Chemical Breakdown

New flow system gives >35% yield of upgradable monomers with >90% enzymatic hydrolysis yields for monomers

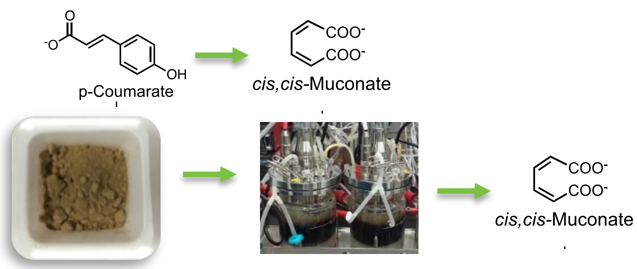


Beckham Lignin First project (unpublished) on poplar

Biological Funneling

Model feed: 50 g/L titer, 100% yield, 0.5g/L/hr productivity

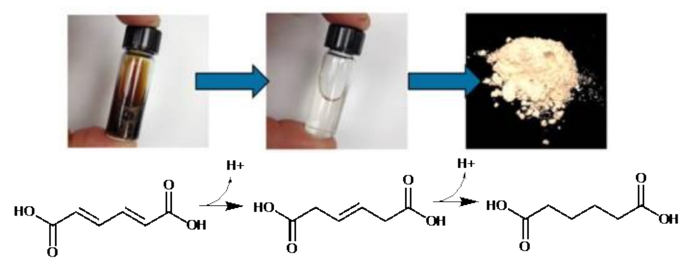
Real Lignin Baseline First Test: 4 g/L, 15% yield by mass (137% yield from 2 major monomers in stream)



Biological Lignin Valorization Davinia Salvachua

Catalytic Upgrading

>99% yield of adipic acid from biologically produced muconic acid in flow system



Derek Vardon

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New/Expanded Areas Since Last Peer Review

Cell-Free Synthetic Biology and Biocatalysis

- Cell-Free Synthetic Biology as an Enabling Tool for the Bioeconomy
  - Utilizing cell-free synthetic biology as a prototyping tool to rapidly discover the most carbon-efficient and energy-efficient routes from biomass to chemicals

- Cell-Free Synthetic Biology as a New Conversion Platform for the Bioeconomy
  - Free Enzyme Biocatalysis
    - Mix of only the needed enzymes in a reactor could allow better titers, rates, and yields, plus easier product separation

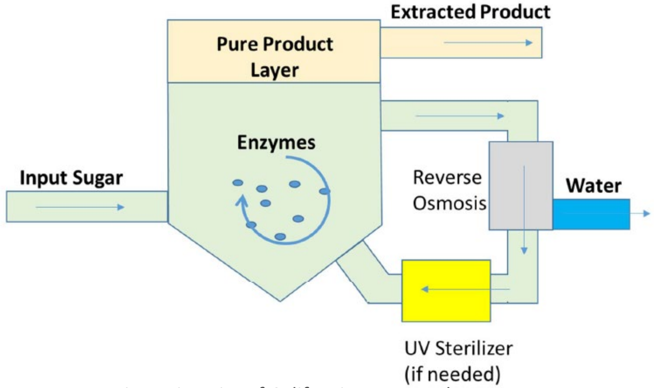

Image courtesy James Bowie, University of California, Los Angeles.

  - Scaffold/Stabilized Biocatalysis
    - Potential novel bioreactor designs such as the "printed tube reactor" (right) for improved mass transfer and heat transfer, compared to traditional designs such as the Continuous Stirred-Tank Reactor

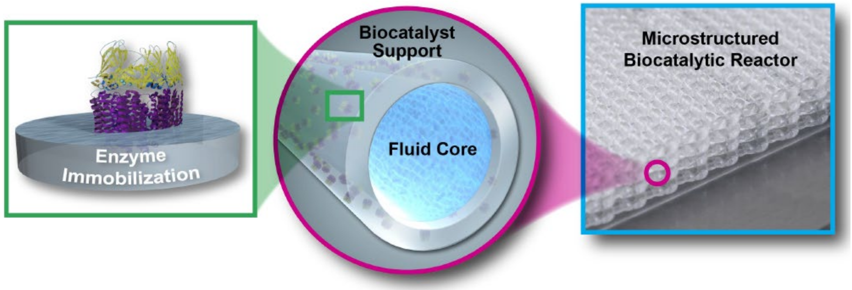

Image courtesy Sarah Baker, Lawrence Livermore National Laboratory.

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Potentially Untapped Carbon Resources

Leveraging DOE's National Laboratories expertise in polymer deconstruction in biomass and applying it to distributed sources of waste carbon to make 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

Re-Evaluating the Value of CO_2 as a Resource

- BETO-supported National Academies of Sciences study on "Developing a research agenda for utilization of gaseous carbon waste streams"

- CO_2 Valorization via Rewiring Carbon Metabolic Network in bacterial cells
  - NREL tailored bacteria as a model for direct biochemical CO_2 utilization, reaching 150 mg/L titer of 3-hydroxybutyrate (3-HB, a polyester precursor) and developing CRISPR-Cas9 gene editing tools

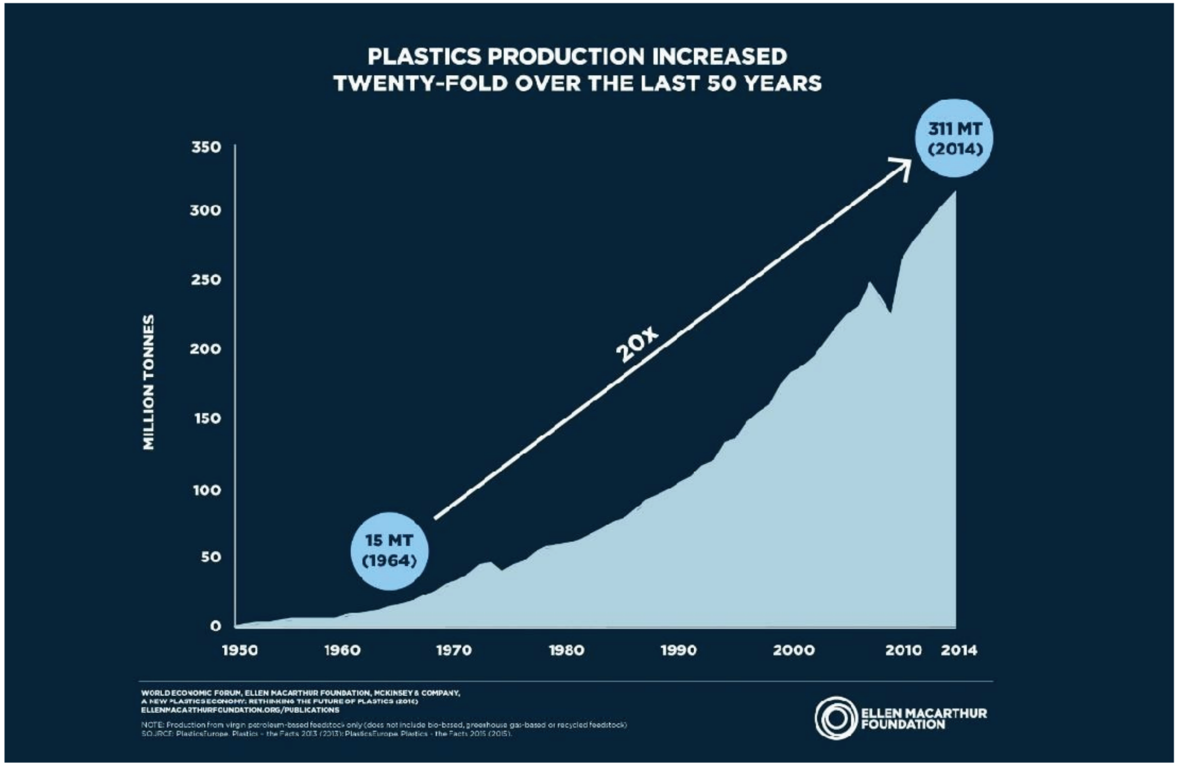
- Three FY18 FOAs awarded in Topic Area 5: Rewiring Carbon Utilization

LanzaTech MONTANA STATE UNIVERSITY JOHNS HOPKINS UNIVERSITY

- Formate Lab Call – new AOPs in early stage R&D for biological platforms capable of upgrading formate, which can be efficiently generated from CO_2
  - NREL – Improving formate upgrading via bacterial conversion
  - NREL – Enhancing CO_2 conversion to value-added products via formate
  - NREL/LBNL – Synthetic cycle for electrosynthesis of products and fuels from formate

Plastics are ubiquitous in modern society

~300 MM tonnes per year produced worldwide

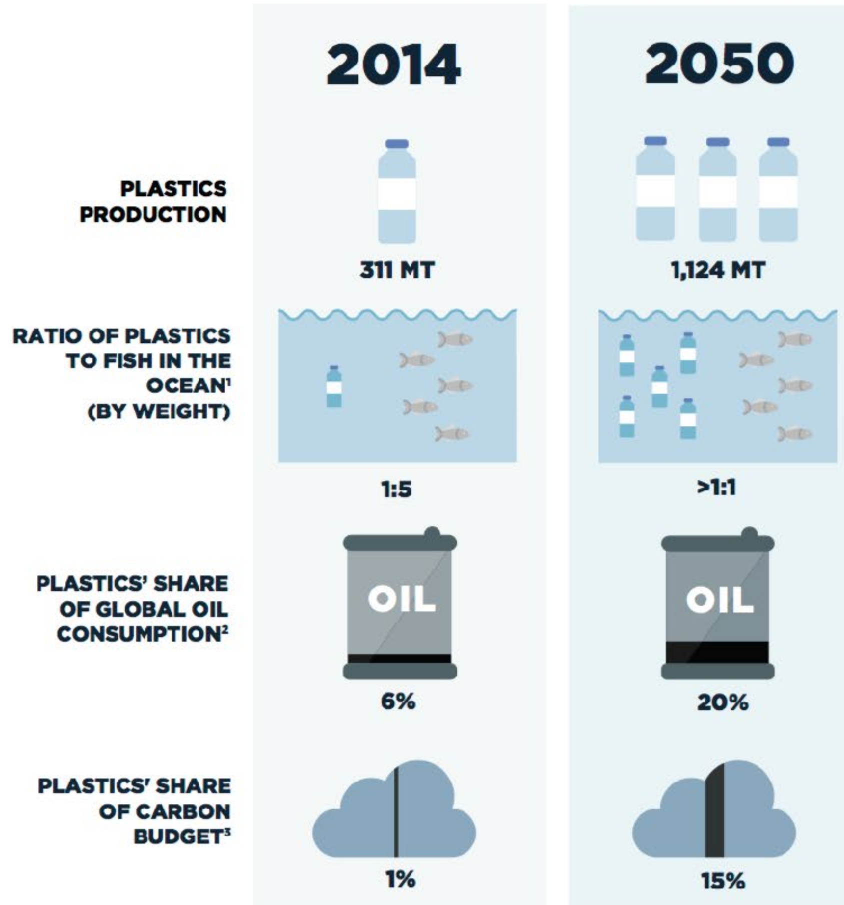


Ellen MacArthur Foundation, 2016

2

Plastics are also creating an environmental catastrophe

~8 MM tonnes per year of plastics enter the ocean



Ellen MacArthur Foundation, 2016

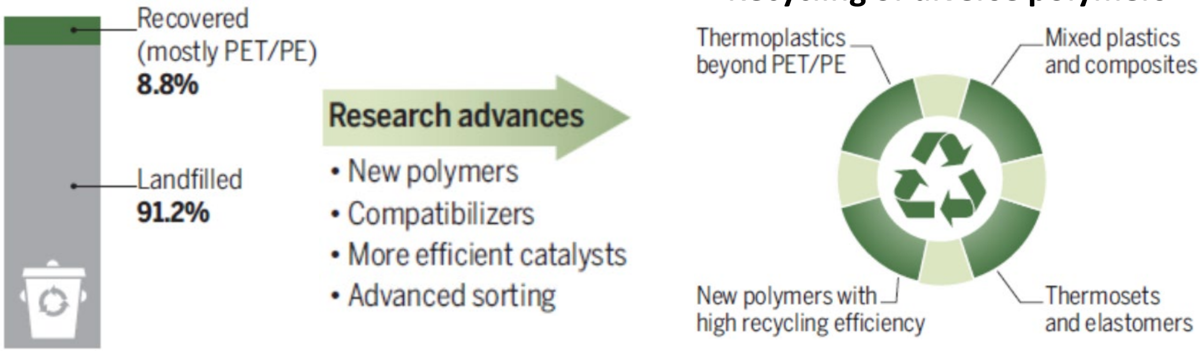
3

What is Needed: Better Plastics, Better Recycling

Moving beyond PET/PE recycling
Most plastic waste is not currently recycled – New methodologies hold promise for recycling a wider range of plastics, including mixtures.

Current plastic waste treatment

BETO Opportunity Areas
Recycling of diverse polymers

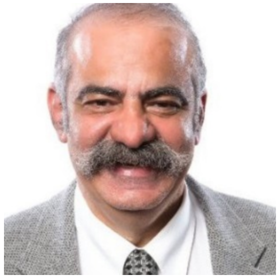


Garcia, J.M., Robertson, M.L. The Future of Plastics Recycling. *Science* 358 (6365), 870-872.

Today's Waste = Tomorrow's Untapped Resources

Introductions – Biochemical Conversion Reviewers

Name	Affiliation	Previous Peer Review Experience
Charles Abbas (Lead Reviewer)	iBiocat	New this year
Steve Van Dien	Persephone Biome, Inc.	Reviewer
Ben Gordon	MIT-Broad Foundry	New this year
Chris Rao	University of Illinois at Urbana-Champaign	New this year
Farzaneh Rezaei	Pivot Bio	New this year



Charles

Steve

Ben

Chris

Farzaneh

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Name	Affiliation	Previous Peer Review Experience
Ben Gordon (Lead Reviewer)	MIT-Broad Foundry	New this year
Matt Tobin	Matthew B. Tobin Consulting	New this year
Farzaneh Rezaei	Pivot Bio	New this year
Chris Rao	University of Illinois at Urbana-Champaign	New this year
Steve Van Dien	Persephone Biome, Inc.	Reviewer

Ben

Matt

Farzaneh

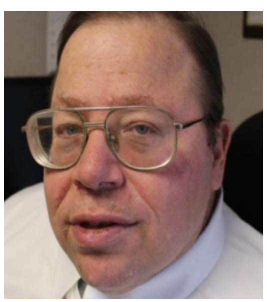
Chris

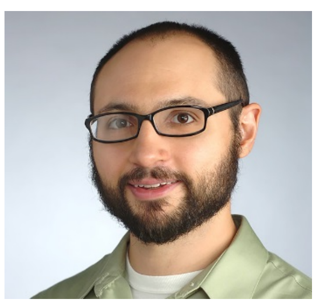
Steve

Introductions – Catalysis Reviewers

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Name	Affiliation	Previous Peer Review Experience
Lorenz (Larry) Bauer	Consultant	TC Reviewer 2017
Jesse Bond	Syracuse University	New, w/MR experience
Chris Bradley Viviane Schwartz	DOE, Office of Science	New, w/MR experience
Cory Phillips	Phillips 66	New
John Regalbuto	University of South Carolina	New, w/MR experience


Larry


Jesse


Chris

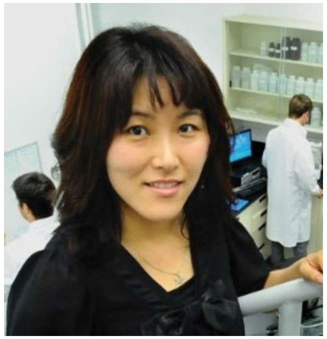

Viviane


John


Cory

Introductions – CO2 Reviewers

Name	Affiliation
Alissa Park	Columbia University (lead reviewer)
Jason Ren	Princeton University
Matthew Lucas	Carbon180
Igor Bogorad	Amyris
Matthew Kanan	Stanford University



Alissa

Igor

Matthew K

Matthew L

Jason

Waste to Energy Reviewers

Name	Affiliation	Previous Peer Review Experience
Phil Marrone	Leidos, Inc.	Reviewer
Tim Olson	California Energy Commission	New to BETO peer review, has reviewed for DOE
Gary Vanzin	Colorado School of Mines	New to peer review, has reviewed for DOE
Luca Zullo	VerdeNero, Inc.	Lead Reviewer


Phil


Tim


Gary


Luca

Introductions – Separations/Performance Advantaged Bioproducts

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Name	Affiliation	Previous Peer Review Experience
Joe Bozell (Lead Reviewer)	University of Tennessee	Reviewer
Peter Keeling	Purdue University	New this year
Melissa Klembara	U.S. Department of Energy – Advanced Manufacturing Office	New to reviewing this year, formerly BETO staff
Jeff Scheibel	formerly of P&G	Reviewer
Matt Tobin	Matthew B. Tobin Consulting	New this year

Joe

Peter

Melissa

Jeff

Matt

Introductions – Lignin

Name	Affiliation	Previous Peer Review Experience
Emma Master (Lead Reviewer)	University of Toronto	New this year
Joe Bozell	University of Tennessee	Reviewer
Mike Sanford	Formerly of DuPont	New this year
Jeff Scheibel	formerly of P&G	Reviewer
Matt Tobin	Matthew B. Tobin Consulting	New this year


Emma


Joe


Mike


Jeff


Matt

Thank you!