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

DOE Peer Review
Conversion R&D

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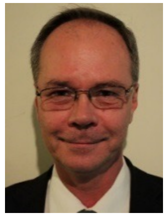
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Seth


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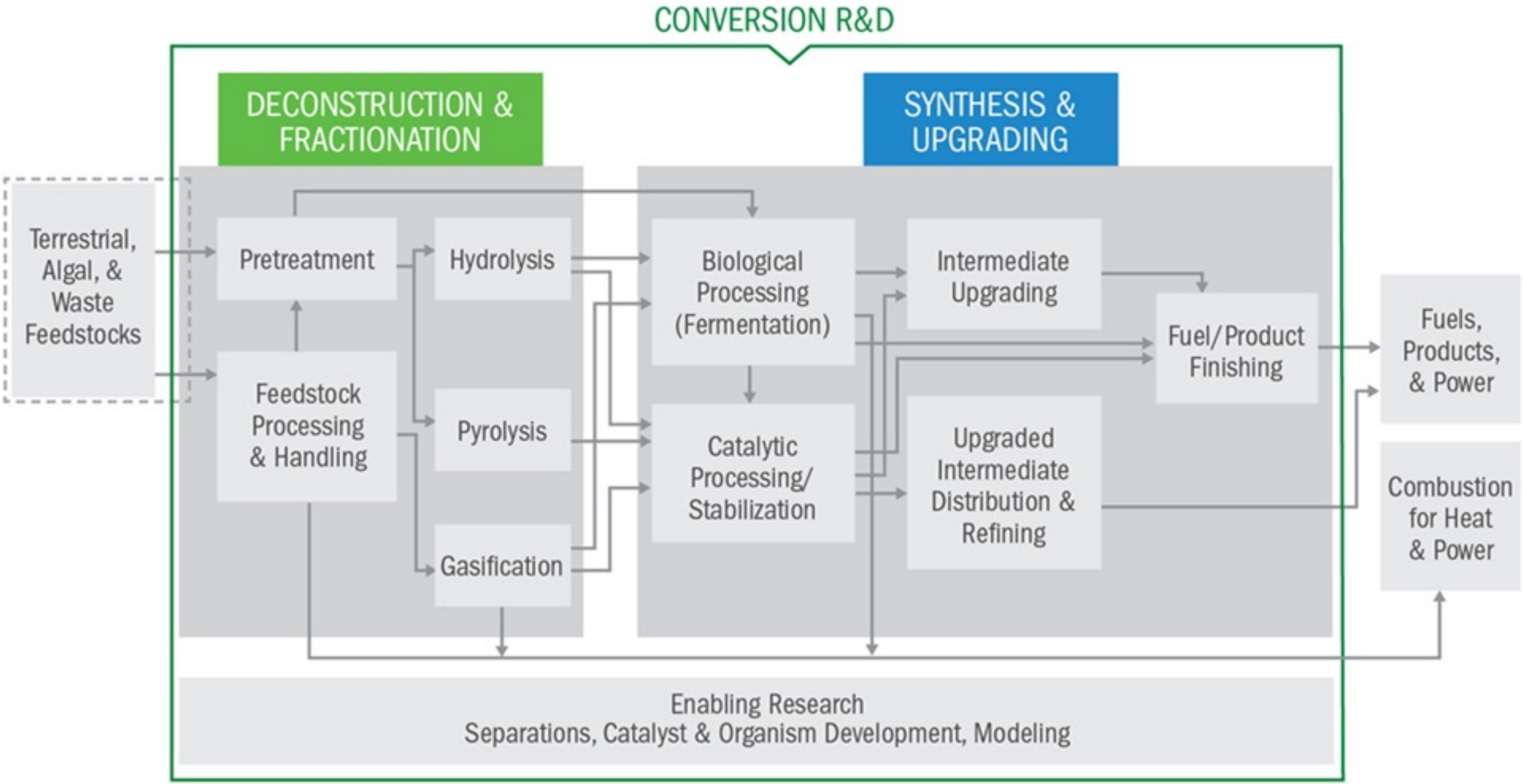
Program Goals – Conversion R&D

- Strategic Goal
  - The strategic goal of the Conversion R&D program is to develop efficient and economical biological and chemical technologies to convert biomass feedstocks into energy-dense liquid transportation fuels, such as renewable gasoline, diesel, and sustainable aviation fuel (SAF), as well as bioproducts, chemical intermediates
- Performance Goal
  - By 2021, complete the research necessary to enable an integrated technology pathway verification at engineering scale in 2022 of a process that yields a mature modeled MFSP of $3/GGE or less for production of a hydrocarbon biofuel and, where appropriate, a coproduct, and which has a minimum 60% reduction in GHG emissions relative to currently predominant fuel.

Conversion R&D Performance Goals (2020 MYP update)

- By 2022, achieve 90% monomeric sugar yield from hydrolysis of deacetylation and mechanical refining (DMR) solids at low (10 milligrams/gram) protein loading using a new DMR-specific enzyme cocktail formulation.
- By 2023, demonstrate an integrated lignin valorization process that achieves 60% carbon valorization of real lignin from a hardwood, grass, or agricultural residue. Instead of being a cost burden from a capital and operating cost perspective, this lignin valorization process will reduce the MFSP by at least $0.25/GGE.
- By 2024, complete the R&D necessary to define a route to a 2030 verification of a mature modeled MFSP of $2.5/GGE or less for biomass through a conversion pathway to hydrocarbon biofuel and coproducts with a GHG emissions reduction of 60% or more compared to currently predominant fuel.
- By 2025, produce bioproducts at needed scales (20–100 kilograms) for product testing to support off-take agreements and end-user/market acceptance.
- By 2026, demonstrate at least three fully integrated bench-scale processes that employ catalysis (biological and/or chemical) that are able to upcycle at least three large-market commodity polymer materials to higher-value materials that meet the 2-times economic incentive, greater than 50% energy savings relative to virgin material production, and retain at least 75% of the carbon present in the original polymer in the upcycled product. Demonstrate these fully integrated processes on both clean and realistic plastics streams, the latter as would be encountered after separations at a materials recovery facility

Program Structure



CONVERSION R&D

DECONSTRUCTION & FRACTIONATION

SYNTHESIS & UPGRADING

Terrestrial, Algal, & Waste Feedstocks

Pretreatment

Feedstock Processing & Handling

Hydrolysis

Pyrolysis

Gasification

Biological Processing (Fermentation)

Catalytic Processing/ Stabilization

Intermediate Upgrading

Upgraded Intermediate Distribution & Refining

Fuel/Product Finishing

Fuels, Products, & Power

Combustion for Heat & Power

Enabling Research
Separations, Catalyst & Organism Development, Modeling

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Program Structure

Deconstruction & Fractionation

- Feedstock Interface

Feedstock Conversion Interface Consortium (FCIC)

- High Temperature Deconstruction
- Low Temperature Deconstruction
- Fractionation, Cleanup, & Conditioning

Synthesis & Upgrading

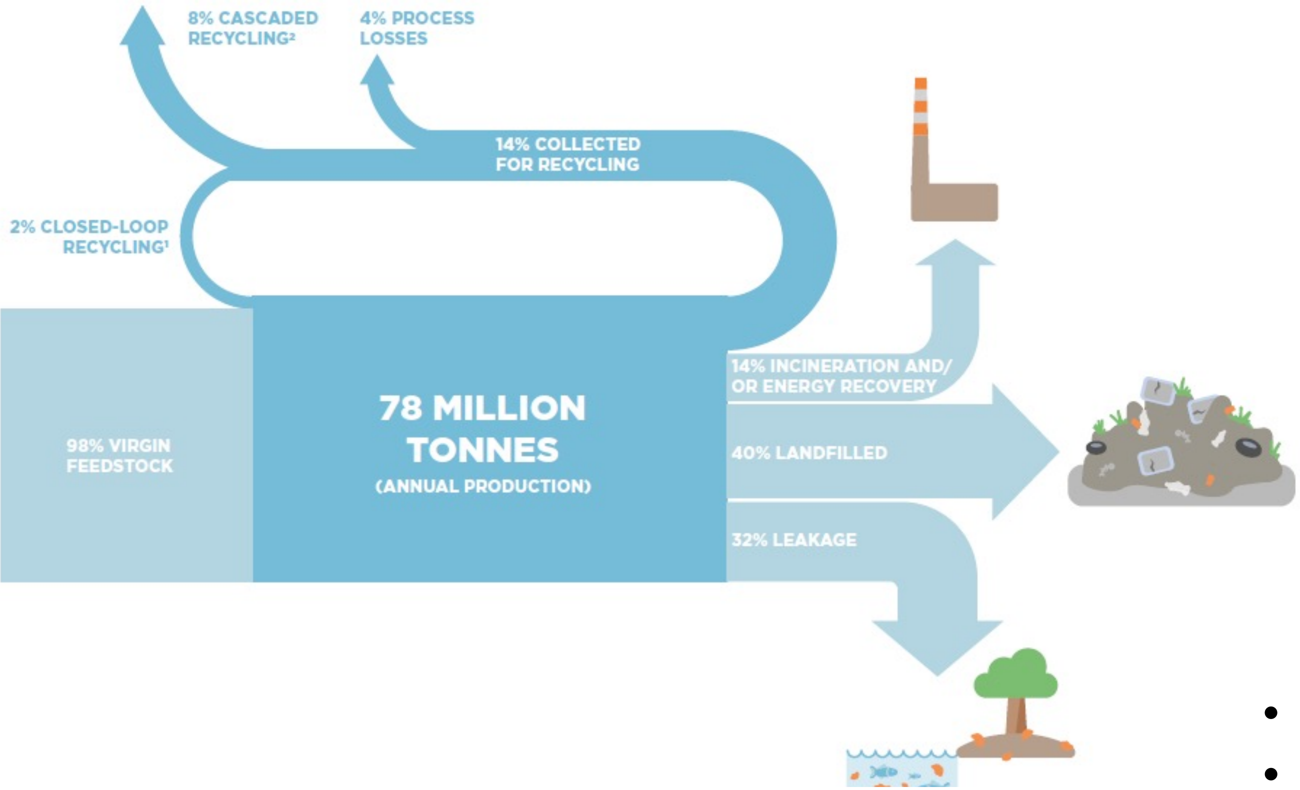
- Chemical Conversions to Intermediates & Products — ChemCatBio Chemical Catalysis for Bioenergy
- Biological Conversions to Intermediates & Products — Agile BioFoundry
- Cleanup or Finishing
- Hybrid Conversions to Intermediates & Products

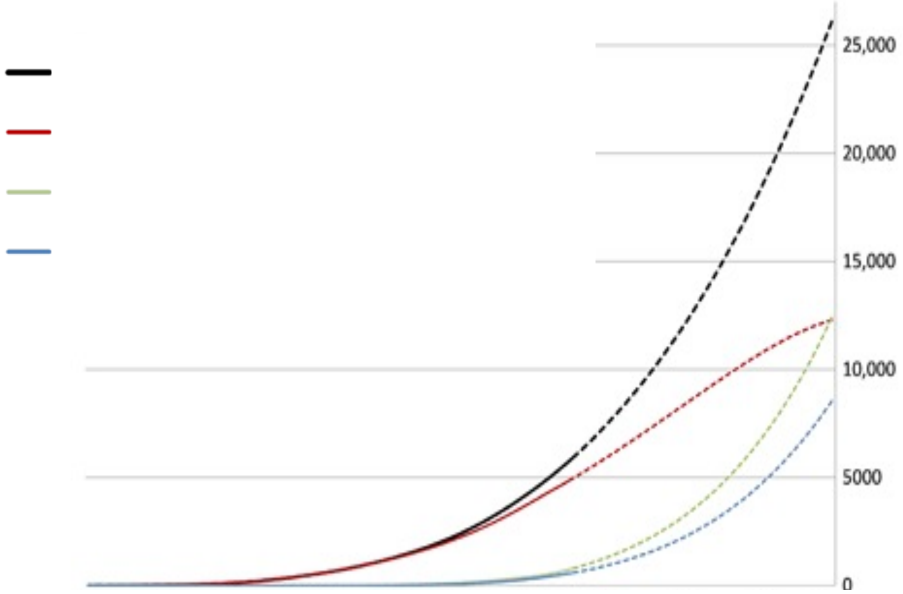
Pathway-focused R&D

Enabling Technologies

- Computational Modeling & Analytical Tools — CCPC Consortium for Computational Physics and Chemistry U.S. DEPARTMENT OF ENERGY BIOENERGY TECHNOLOGIES OFFICE
- 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: A linear carbon economy for plastics





- Plastic is made from non-renewable feedstocks
- Plastic waste is increasingly accumulating[1]
- Most of that plastic waste ends up in landfills and the environment[2]
- Plastic production currently consumes 6% of global oil and is anticipated to increase to 20% of global oil by 2050[3]

[1] Geyer et al. Science Advances 2017

[2] Zheng and Suh. Nature Climate Change 2019

[3] Jambeck et al. Science 2015 and Ellen MacArthur Foundation

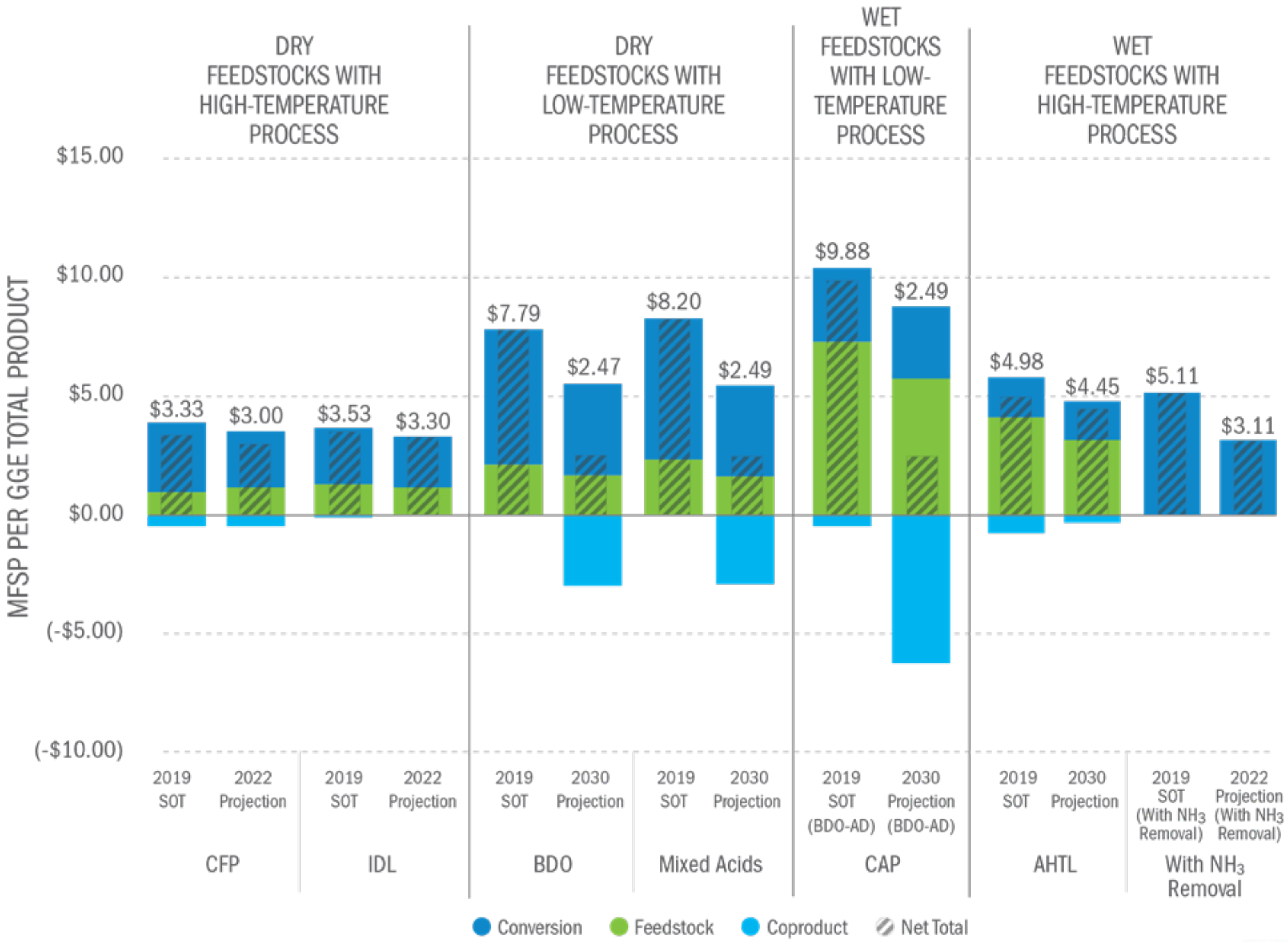
Challenges

- Pathway Specific Barriers
  - Deconstruction and Fractionation
    - Feedstock quality metrics
    - Efficient Preprocessing and Pretreatment
  - Synthesis and Upgrading Barriers
    - Process development for lignin conversion
    - Advanced bioprocess development
    - Increasing catalytic process yield
    - Decreasing catalyst development time
  - Waste Conversion Barriers
    - Gas fermentation
    - High moisture feedstock conversion beyond AD
  - Bioproducts Barriers
    - Identification and evaluation of potential co-products
    - Bio-based production synthesis

Challenges

- Enabling Research Barriers
  - Organism development
  - Reactor materials and analytical methods
  - Multi-scale computational framework for accelerating technology development
  - Separations
    - Selective separation of organic species
    - Selective separation of inorganic contaminants

Technoeconomic Assessments (TEA) for Several Example Pathways



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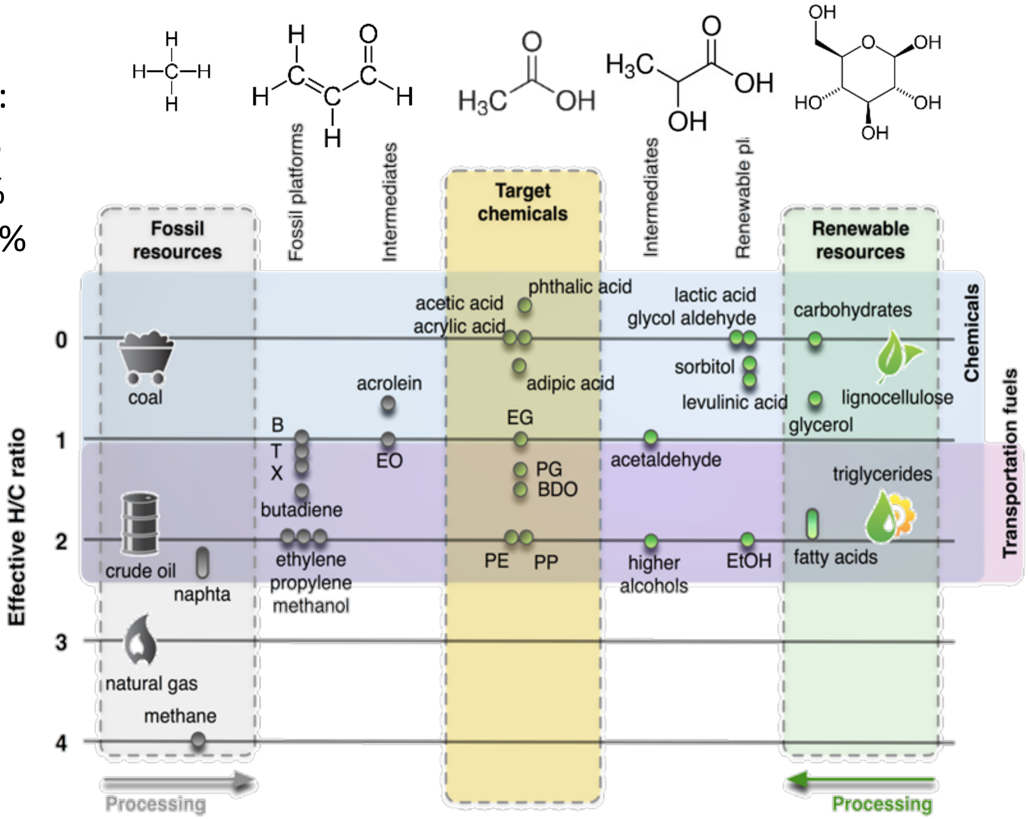
Biobased products contain oxygen… like biomass

Crude oil

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



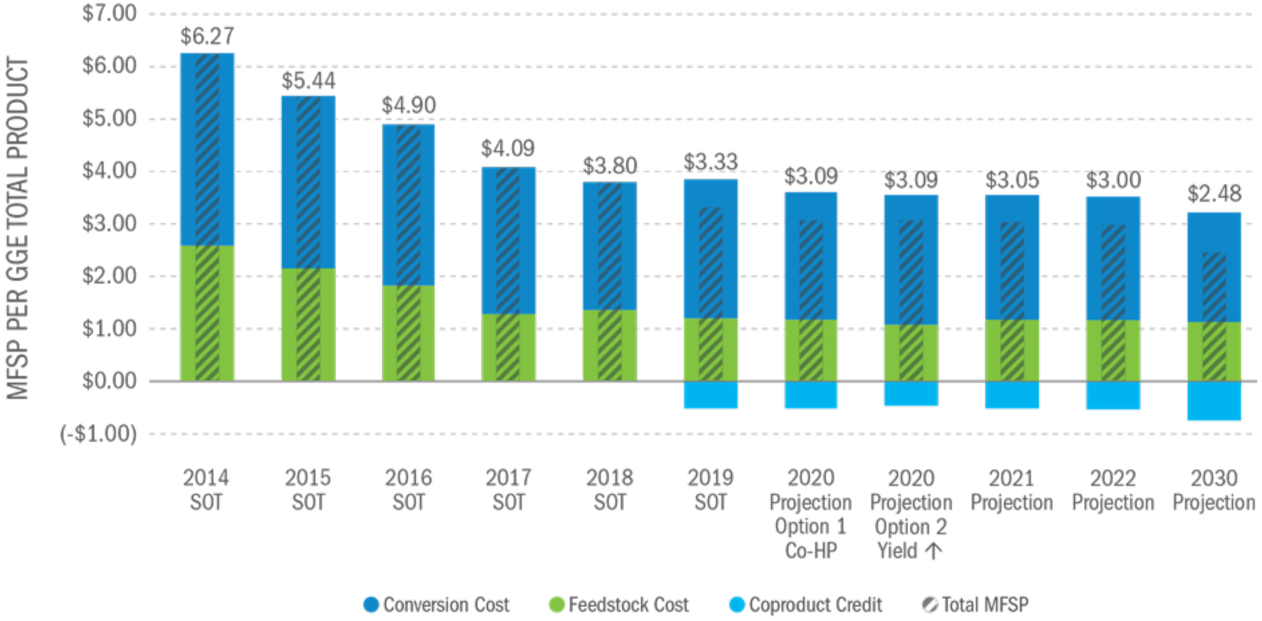
Biomass

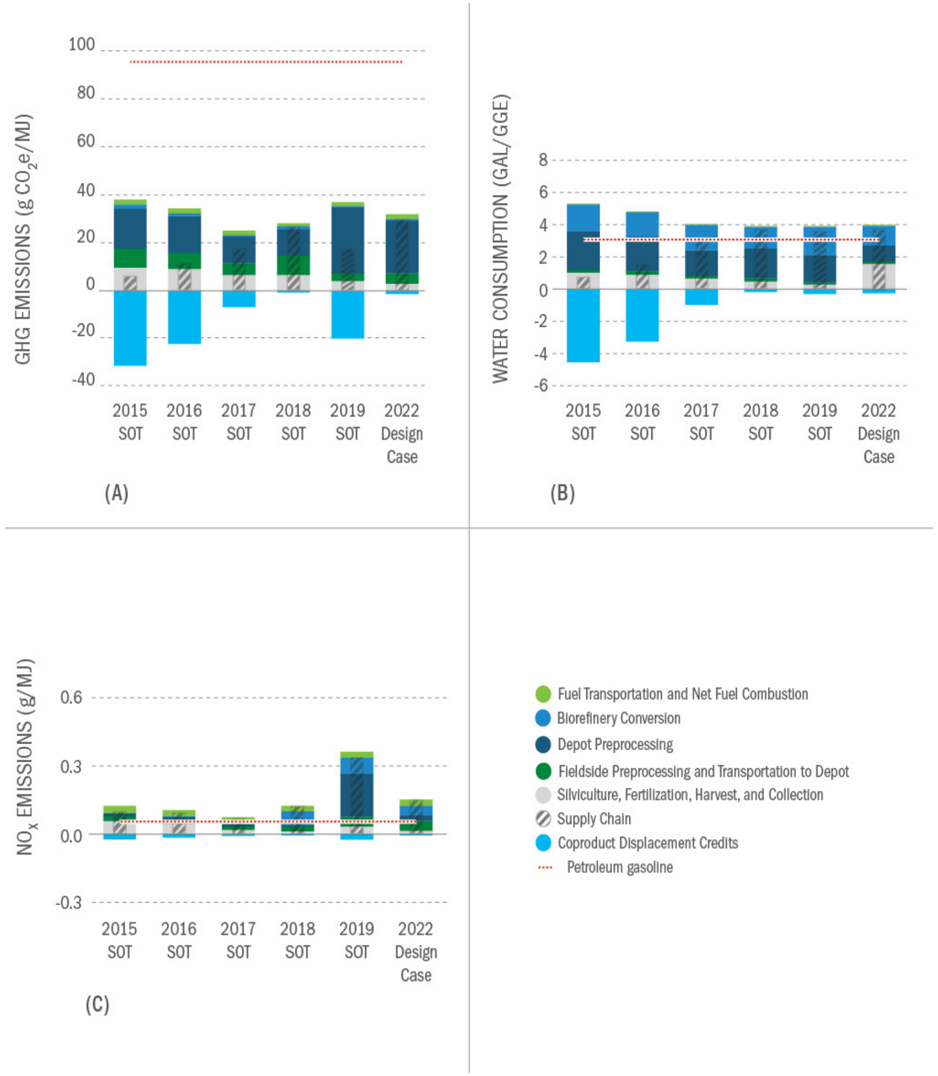
Avg. wt%:
C 36-53%,
H 5-7%,
O 31-48%

Consider the oxidation state of chemicals – retain what nature provides

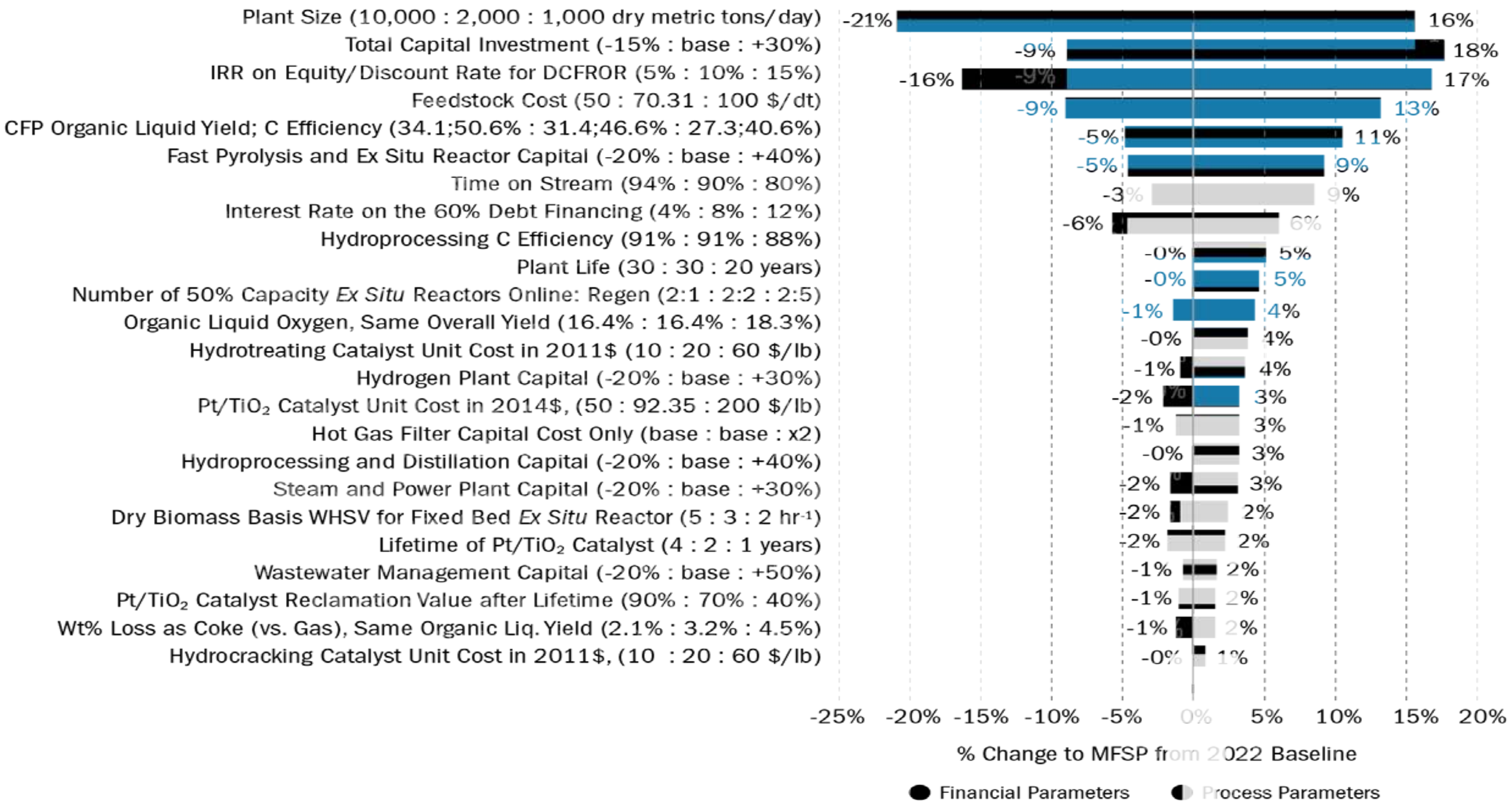
Vennestrøm, P.N. R. *et al Angew. Chem. Int. Ed.* **2011**, *50*, 10502-10509
Shen, J. *et al Energy Conversion and Management* **2010**, *51*, 983–987

Catalytic Fast Pyrolysis – TEA and Sustainability Analysis

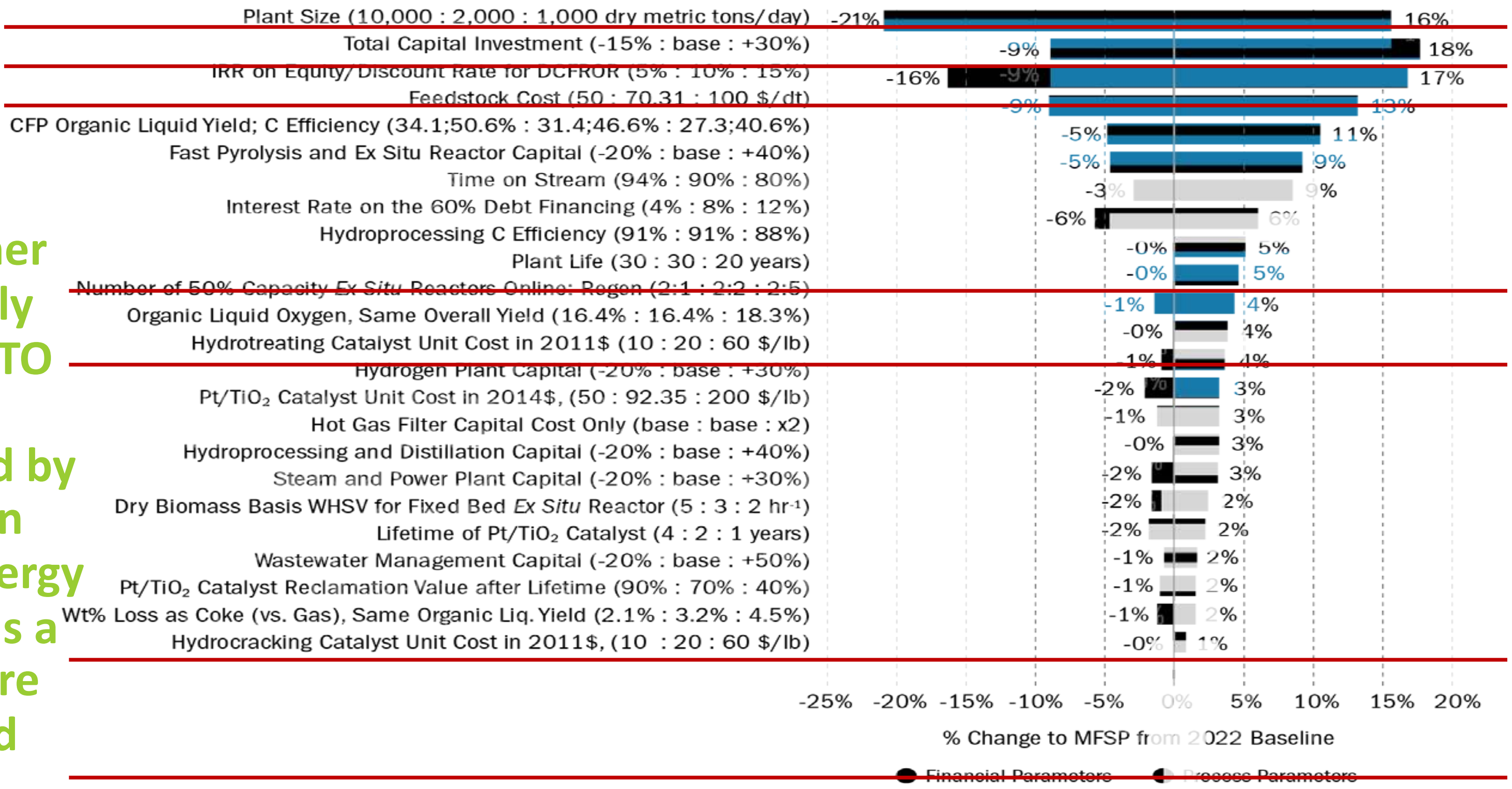




Ex-situ CFP


Plant Size (10,000 : 2,000 : 1,000 dry metric tons/day)
-21%
16%
Total Capital Investment (-15% : base : +30%)
-9%
18%
IRR on Equity/Discount Rate for DCFROR (5% : 10% : 15%)
-16%
-9%
17%
Feedstock Cost (50 : 70.31 : 100 $/dt)
-9%
13%
CFP Organic Liquid Yield; C Efficiency (34.1;50.6% : 31.4;46.6% : 27.3;40.6%)
-5%
11%
Fast Pyrolysis and Ex Situ Reactor Capital (-20% : base : +40%)
-5%
9%
Time on Stream (94% : 90% : 80%)
-3%
9%
Interest Rate on the 60% Debt Financing (4% : 8% : 12%)
-6%
6%
Hydroprocessing C Efficiency (91% : 91% : 88%)
-0%
5%
Plant Life (30 : 30 : 20 years)
-0%
5%
Number of 50% Capacity *Ex Situ* Reactors Online: Regen (2:1 : 2:2 : 2:5)
-1%
4%
Organic Liquid Oxygen, Same Overall Yield (16.4% : 16.4% : 18.3%)
-0%
4%
Hydrotreating Catalyst Unit Cost in 2011$ (10 : 20 : 60 $/lb)
-1%
4%
Hydrogen Plant Capital (-20% : base : +30%)
-2%
3%
Pt/TiO₂ Catalyst Unit Cost in 2014$, (50 : 92.35 : 200 $/lb)
-1%
3%
Hot Gas Filter Capital Cost Only (base : base : x2)
-0%
3%
Hydroprocessing and Distillation Capital (-20% : base : +40%)
-2%
3%
Steam and Power Plant Capital (-20% : base : +30%)
-2%
2%
Dry Biomass Basis WHSV for Fixed Bed *Ex Situ* Reactor (5 : 3 : 2 hr-1)
-2%
2%
Lifetime of Pt/TiO₂ Catalyst (4 : 2 : 1 years)
-1%
2%
Wastewater Management Capital (-20% : base : +50%)
-1%
2%
Pt/TiO₂ Catalyst Reclamation Value after Lifetime (90% : 70% : 40%)
-1%
2%
Wt% Loss as Coke (vs. Gas), Same Organic Liq. Yield (2.1% : 3.2% : 4.5%)
-0%
1%
Hydrocracking Catalyst Unit Cost in 2011$, (10 : 20 : 60 $/lb)
-25%
-20%
-15%
-10%
-5%
0%
5%
10%
15%
20%
% Change to MFSP from 2022 Baseline
● Financial Parameters
◐ Process Parameters

Ex-situ CFP

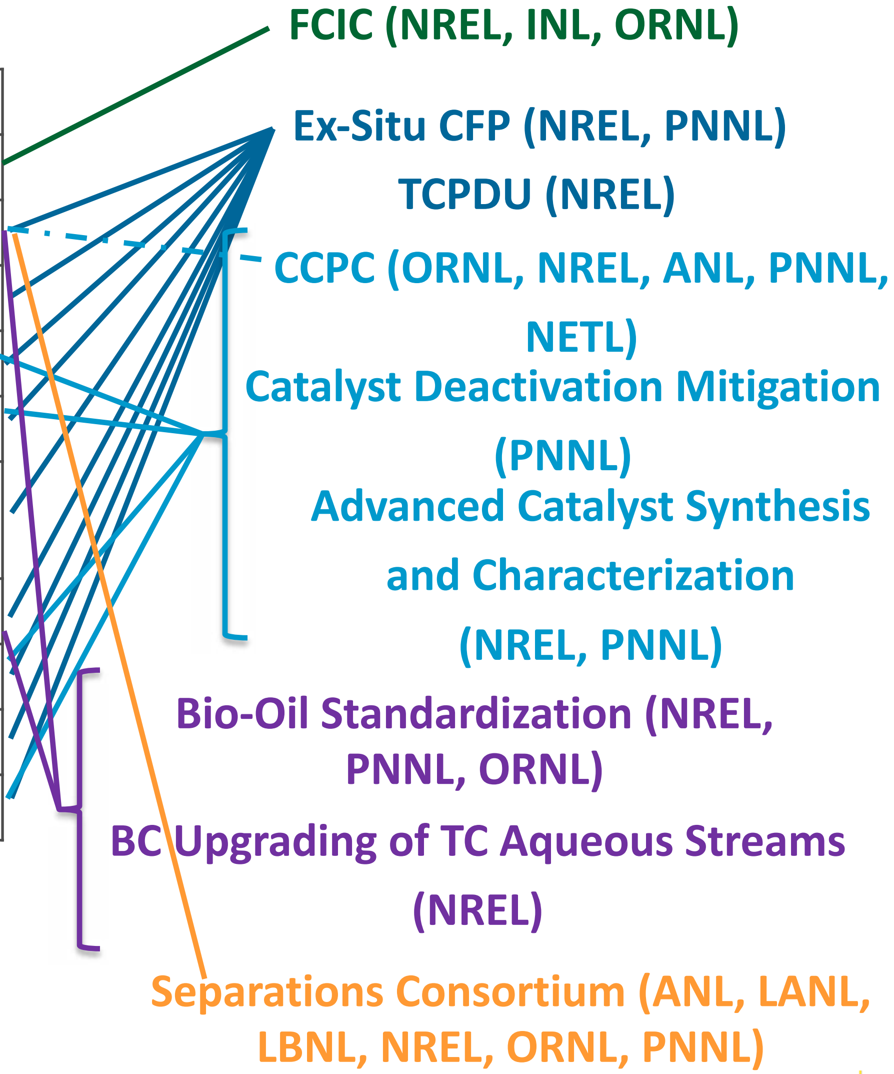


Items either not directly tied to BETO R&D or influenced by progress in the bioenergy industry as a whole were eliminated

Ex-situ CFP

Top 10 remaining areas by current active project:

Rank	Description
1	Feedstock Cost, $/dry U.S. ton
2	CFP Organic Liq. Yield; Carbon Efficiency %
3	Fast Py. & Ex Situ Reactor Capital
4	Time on Stream
5	Hydroprocessing C Efficiency %
6	No. of 50% Capacity Ex Situ Reactors Online:Regen
7	Organic Liq. Oxygen %, Same Overall Yield
8	Hydrotreating Catalyst Unit Cost
9	Hydrogen Plant Capital
10	Pt/TiO2 Catalyst Unit Cost



FCIC (NREL, INL, ORNL)

Ex-Situ CFP (NREL, PNNL)

TCPDU (NREL)

CCPC (ORNL, NREL, ANL, PNNL, NETL)

Catalyst Deactivation Mitigation (PNNL)

Advanced Catalyst Synthesis and Characterization (NREL, PNNL)

Bio-Oil Standardization (NREL, PNNL, ORNL)

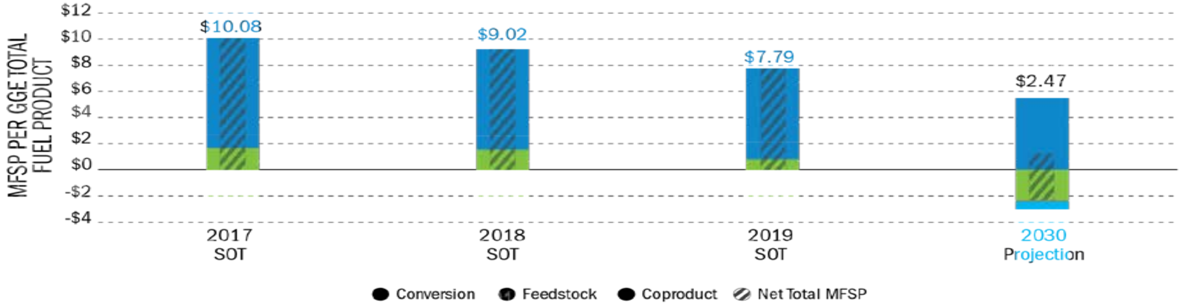
BC Upgrading of TC Aqueous Streams (NREL)

Separations Consortium (ANL, LANL, LBNL, NREL, ORNL, PNNL)

Investments in High Impact Barriers - Ex-situ CFP

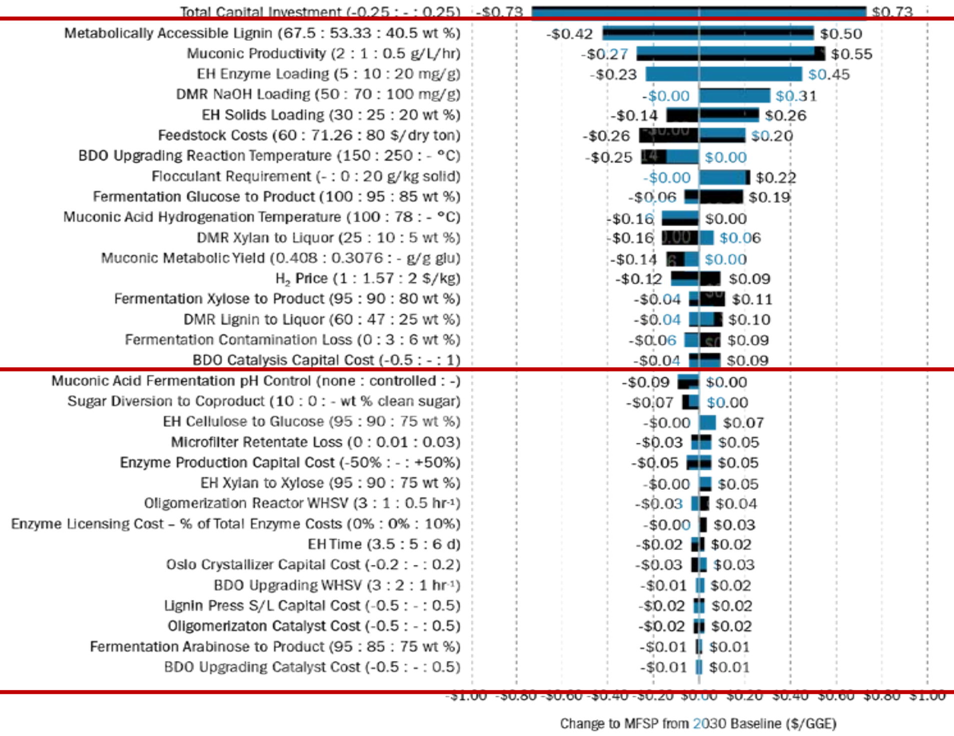
Rank	Description	FY19	FY20	FY21
1	Feedstock Cost, $/dry U.S. ton	$1,500,000	$2,000,000	$2,000,000
2	CFP Organic Liq. Yield; Carbon Efficiency %	$12,330,000	$10,000,000	$8,300,000
3	Fast Py. & Ex Situ Reactor Capital	$4,450,000	$3,400,000	$1,700,000
4	Time on Stream	$9,530,000	$7,200,000	$5,500,000
5	Hydroprocessing C Efficiency %	$9,530,000	$7,200,000	$5,500,000
6	No. of 50% Capacity Ex Situ Reactors Online:Regen	$4,450,000	$3,400,000	$1,700,000
7	Organic Liq. Oxygen %, Same Overall Yield	$5,650,000	$4,600,000	$2,900,000
8	Hydrotreating Catalyst Unit Cost	$9,530,000	$7,200,000	$5,500,000
9	Hydrogen Plant Capital	$4,450,000	$3,400,000	$1,700,000
10	Pt/TiO2 Catalyst Unit Cost	$9,530,000	$7,200,000	$5,500,000

Biochemical Pathways – TEA and Sustainability Analysis

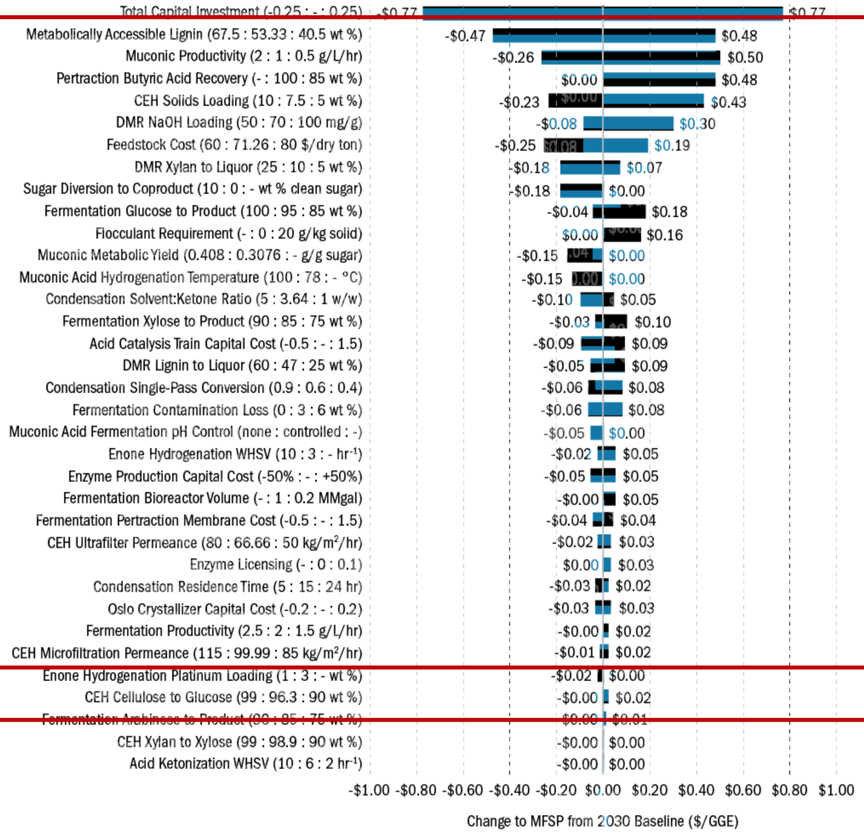


Fuel price sensitivity – Biochemical Conversion Pathways

Biochemical – BDO



Biochemical – Acids



Biochemical – BDO/Acids (Lignin)

1	Metabolically accessible lignin (wt%)
2	Muconic productivity (g/L/hr)
3	EH enzyme loading mg/g
4	DMR NaOH loading (mg/g)
5	EH Solids loading (wt%)
6	BDO upgrading reaction temperature (°C)
7	Fermentation glucose to product (wt%)
8	Muconic acid hydrogenation temperature (°C)
9	DMR xylan to liquor (wt%)
10	Muconic metabolic yield (g/g glu)
11	Fermentation xylose to product (wt%)

Low Temperature Advanced Deconstruction (NREL)

Oxidative Valorization of Lignin* (PNNL)

Electrocatalytic Oxidation of Lignin Oligomers* (NREL)

Gas Phase Selective Partial Oxidation of Lignin* (NREL)

Biological Lignin Valorization (NREL, SNL*)

Lignin Utilization (NREL)

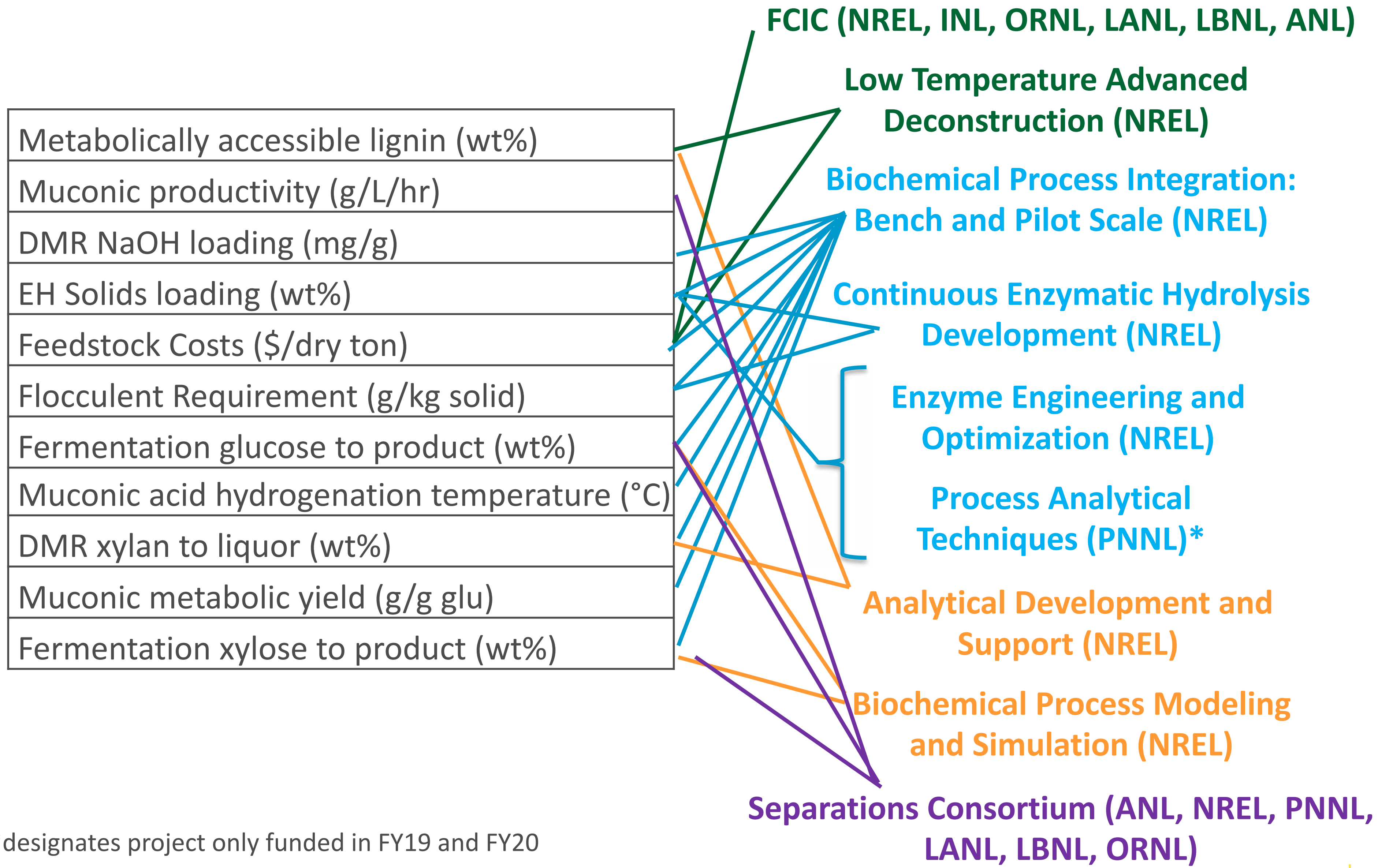
Lignin First Biorefinery Development (NREL)

Synthetic Metabolic Pathways for Bioconversion of Lignin (ORNL)

Multiple competitive selections made in FY19 and FY20

*designates project only funded in FY19 and FY20

Biochemical – BDO/Acids (other overlapping areas)



Metabolically accessible lignin (wt%)
Muconic productivity (g/L/hr)
DMR NaOH loading (mg/g)
EH Solids loading (wt%)
Feedstock Costs ($/dry ton)
Flocculent Requirement (g/kg solid)
Fermentation glucose to product (wt%)
Muconic acid hydrogenation temperature (°C)
DMR xylan to liquor (wt%)
Muconic metabolic yield (g/g glu)
Fermentation xylose to product (wt%)

FCIC (NREL, INL, ORNL, LANL, LBNL, ANL)

Low Temperature Advanced Deconstruction (NREL)

Biochemical Process Integration: Bench and Pilot Scale (NREL)

Continuous Enzymatic Hydrolysis Development (NREL)

Enzyme Engineering and Optimization (NREL)

Process Analytical Techniques (PNNL)*

Analytical Development and Support (NREL)

Biochemical Process Modeling and Simulation (NREL)

Separations Consortium (ANL, NREL, PNNL, LANL, LBNL, ORNL)

*designates project only funded in FY19 and FY20

Investments in High Impact Barriers – Biochemical Pathways

Biochemical – BDO

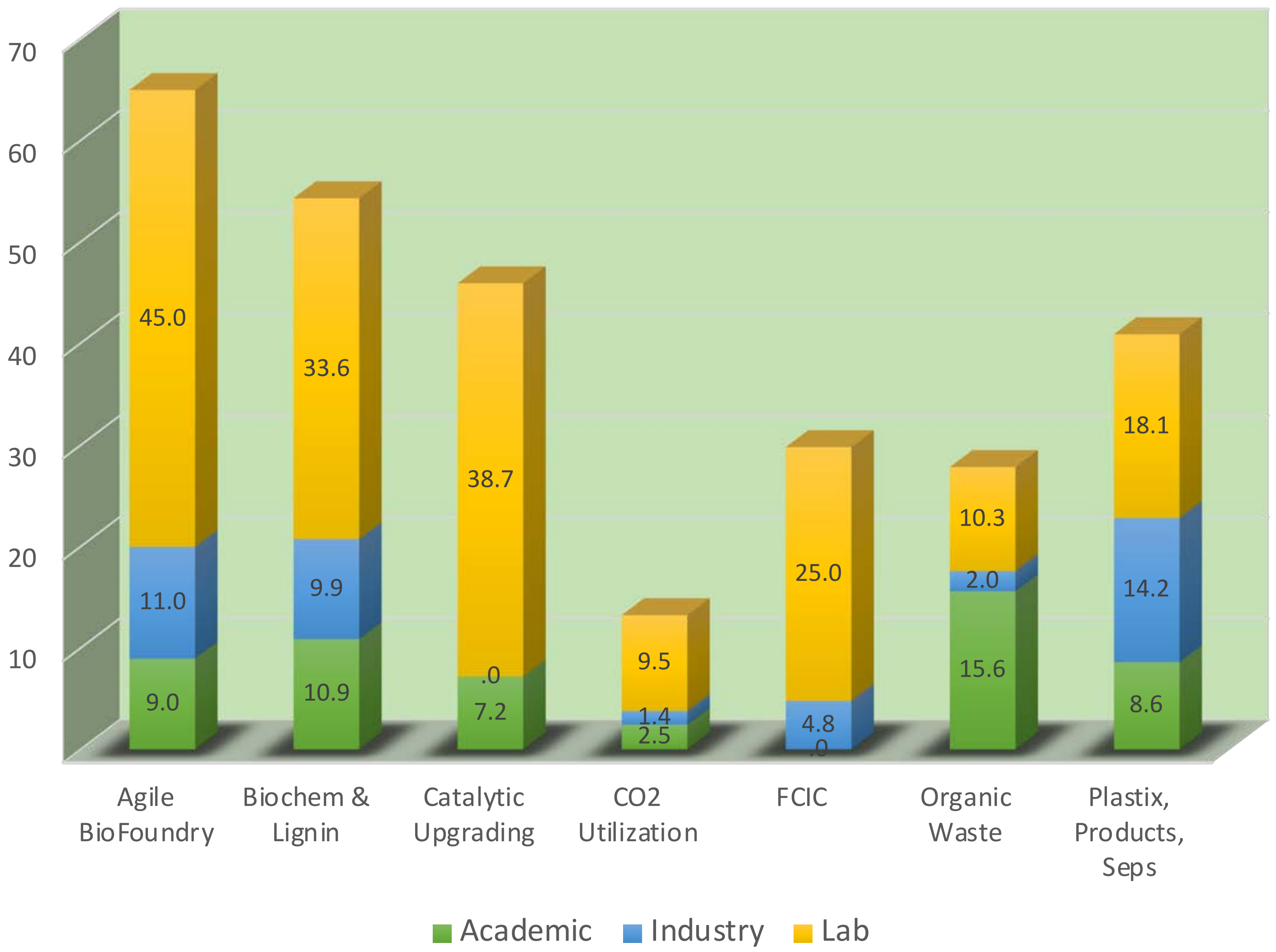
	Description	FY19	FY20	FY21
1	Metabolically accessible lignin (wt%)	$6,500,000	$6,220,000	$5,370,000
2	Muconic productivity (g/L/hr)	$5,650,000	$5,650,000	$5,650,000
3	EH enzyme loading mg/g	$3,950,000	$3,950,000	$3,700,000
4	DMR NaOH loading (mg/g)	$2,250,000	$2,250,000	$2,250,000
5	EH Solids loading (wt%)	$3,400,000	$3,400,000	$3,150,000
6	Feedstock Costs ($/dry ton)	$1,500,000	$2,000,000	$2,000,000
7	Flocculant Requirement (g/kg solid)	$1,300,000	$1,300,000	$1,300,000
8	BDO upgrading reaction temperature (°C)	$4,050,000	$4,050,000	$4,050,000
9	Fermentation glucose to product (wt%)	$8,500,000	$8,500,000	$8,500,000
10	Muconic acid hydrogenation temperature (°C)	$2,250,000	$2,250,000	$2,250,000
11	DMR xylan to liquor (wt%)	$5,700,000	$5,570,000	$5,570,000
12	Muconic metabolic yield (g/g glu)	$2,250,000	$2,250,000	$2,250,000
13	Fermentation xylose to product (wt%)	$8,500,000	$8,500,000	$8,500,000

Biochemical – Acids

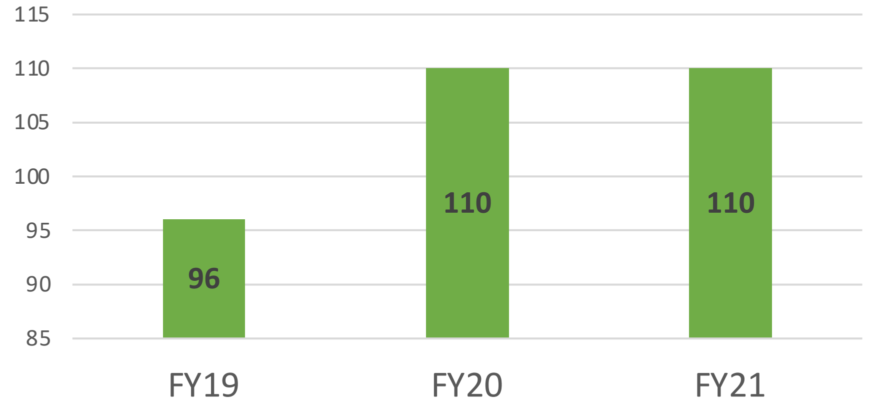
	Description	FY19	FY20	FY21
1	Metabolically accessible lignin (wt%)	$6,500,000	$6,220,000	$5,370,000
2	Muconic productivity (g/L/hr)	$5,650,000	$5,650,000	$5,650,000
3	Pertraction butyric acid recovery (wt%)	$4,150,000	$4,150,000	$4,150,000
4	CEH Solids loading (wt%)	$3,950,000	$3,950,000	$3,700,000
5	DMR NaOH loading (mg/g)	$2,500,000	$2,500,000	$2,250,000
6	Feedstock Cost ($/dry ton)	$1,500,000	$2,000,000	$2,000,000
7	Flocculant Requirement (g/kg solid)	$1,300,000	$1,300,000	$1,300,000
8	DMR xylan to liquor (wt%)	$3,050,000	$2,920,000	$2,920,000
9	Sugar diversion to coproduct (wt% clean sugar)	$750,000	$750,000	$750,000
10	Fermentation glucose to product (wt%)	$8,050,000	$8,050,000	$7,650,000
11	Muconic metabolic yield (g/g sugar)	$4,900,000	$4,900,000	$4,900,000
12	Muconic acid hydrogenation Temperature (°C)	$2,250,000	$2,250,000	$2,250,000
13	Condensation solvent:ketone ratio (w/w)	$2,100,000	$2,100,000	$1,700,000
14	Fermentation xylose to product (wt%)	$5,800,000	$5,800,000	$5,400,000

Budget totals for years under review

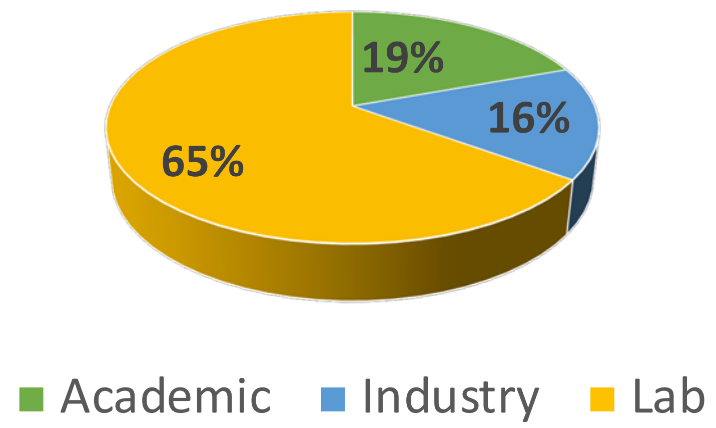
Reviewed Project Budgets ($M)



Annnual Conversion R&D Budget ($M)



Funding Distribution



Recent Conversion R&D Funding Opportunity Announcements

FY19 FOA Topics	Available Funding
Renewable Energy from Urban and Suburban Wastes	$10,000,000
Advanced Bioprocessing	$5,000,000
Agile Biofoundry	$5,000,000
Designing Highly Recyclable Plastics	$5,000,000
Designing Novel Methods for Deconstructing and Upcycling Existing Plastics	$5,000,000
Rethinking Anaerobic Digestion	$5,000,000
Biopower and RNG	$5,000,000

FY20 FOA Topics	Available Funding
Waste to Energy Strategies for the Bioeconomy: 2a: Municipal Solid Waste (MSW) 2b: Optimizing Community Scale Wet Organic Wastes	$2,500,000
Biopower and Products from Urban and Suburban Wastes: North American Multi-University Partnership for Research and Education: 6a: Biopower from Organic Wastes 6b: Waste Plastics to Products	$15,000,000
Scalable CO_2 Electrocatalysis	$8,000,000

Recent Conversion R&D SBIR topics and Directed Funding Opportunities

SBIR Topics	Available Funding
Cell-Free Biochemical Platforms to Optimize Biomass Carbon Conversion Efficiency (FY19 Phase 1, Release 2)	$806,497
Cell-Free Biochemical Platforms to Optimize Biomass Carbon Conversion Efficiency (FY20 Phase 2, Release 2)	$1,098,268
BOTTLE/PIC	$4,500,000

Directed Funding Opportunities	Available Funding
Agile BioFoundry Directed Funding Opportunity (FY20)	$5,700,000
Consortium for Computational Physics & Chemistry	$1,032,000
ChemCatBio (CCB)	$980,000

Key Accomplishments

Technology Area	Key Technical Advance(s)
Biochemical Conversion and Lignin Utilization	Biochemical Conversion: • Developed and published major organism engineering strategies used to optimize the organism at the center of the anaerobic fermentation of sugars to carboxylic acids pathway. This new strain can produce over 85 g/L butyric acid and still maintain cell growth at that high product concentration. • Cell-Free Biosynthesis: Demonstrated Glucose *and* Xylose co-utilization in Cell-free Biosynthesis with near 60% yield on hydrolysate Lignin: • Developed and industrially-relevant process concept for lignin-first processing for the first time Conducted first comprehensive TEA and LCA for reductive catalytic fractionation of lignin Demonstrated stable lignin oil production for the first time Developing continuous RCF with high BP solvents • Improvements in lignin analytics (via the LigninWrangler computational tool) to generate lignin structure libraries as well as lignin-derived molecules resulting from deconstruction chemistries • Biological approaches: Developed *P. putida* strains and bioprocesses able to achieve near industrially-relevant TRY (~49g/L muconate); Discovered novel biological underpinnings of lignin degradation
CCB & CCPC	• Licensing of ORNL's ethanol-to-butadiene-jet (ETBJ) technology to Prometheus Fuel • Sironix Renewables DFA and LANL received the R&D 100 Special Recognition: Green Tech R&D World magazine awarded a bronze special recognition to Sironix and LANL for their work on oleo-furan surfactants made from renewable biomass. • ChemCatBio Consortia continues to improve research efficiency and accelerate catalyst-process development cycle through publicly available tools: The CatCost^{TM} Tool continues to expand, showing high utilization rates by researchers: in 2020 the tool had 1,492 users / 2,077 sessions. https://catcost.chemcatbio.org/. In 2020, the ChemCatBio Data Hub project developed and publicly released the Catalyst Property Database https://cpd.chemcatbio.org/: curation and standardization of 3000+ datasets currently.

Key Accomplishments

Technology Area	Key Technical Advance(s)
ABF	Publications: 250+ citations across 50 publications to date (since FY17 – many are since FY19) 67 citations across 17 publications since FY20 Patents: • 16 patent applications; 6 records of invention; 7 software disclosures; 5 licenses • 18 partnerships with industry & academia (let me know if you want the NASCAR slide below) • Developed Beachhead concept and metabolic map • Exceeded FY20 annual milestone: “Demonstrate at least one representative target of a beachhead at a TRY of 20 g/L, 0.3 g/L/hr, and 50% of theoretical yield” Acontic acid was produced using *Aspergillus pseudoterreus*, exceeding the titer goal of 20 g/L by 130%, exceeding the rate goal of 0.3 g/Lh by 27%, and coming within 96% of the yield goal.
Separations	• Separations applications: product separation and recovery, impurity/foulant removal, new material development. • Separation technologies developed: adsorption, extraction-distillation, membranes, catalytic hot gas filtration, capacitive deionization, electrodeionization, and countercurrent chromatography. • 9 journal publications, 3 patent applications since 2019. • Three year overview published, outlining the progress made over the first three years
CO2 Utilization	• NZTT: Performed TEA and LCA on several renewable fuel pathways to understand the potential and the cost for "efuels" to acheive net-zero carbon intensity. • Completed a three-year study into the overall feasibility of CO2 reduction and to produce technical information to inform an aggressive R&D strategy in the field • Issued and awarded 3 FOA awards to develop scalable CO2 electrolyzers (Dioxide Materials,University of Delaware, Opus 12)

Key Accomplishments

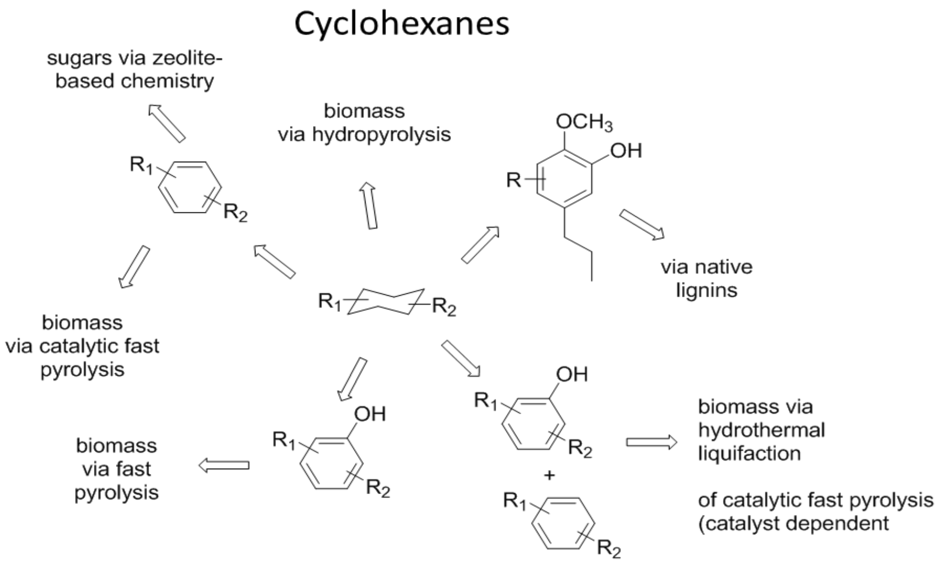
Technology Area	Key Technical Advance(s)
Waste Utilization	• Site-specific organic waste availability survey • Engine testing of HTL fuels • Process for conversion of volatile fatty acids (e.g. from AD) to sustainable aviation fuels • RNG from biogas - SoCalGas/Electochaea project • Improved Anaerobic Digestion technologies and reactor design
Performance advantaged bioproducts	• 100 new polymer formulations and identified 11 new products that can be classified as performance-advantaged relative to a petroleum standard in at least one material property. T_g Flame resistance Biodegradability. • Development of a computational tool for identifying novel polymers Released to the public later this year Forthcoming *Nature* article in late spring 2021 that proposes a standard framework for how to identify and design PABPs.
Plastics	• BOTTLE Consortium kicked off and FOA issued both in partnership with the Advanced Manufacturing Office • Request for information issued for Plastics Innovation Challenge roadmap

Future Directions

- SAF Emphasis
- BOTTLE
- CO2 conversion
- Waste to fuels

Specific SAF R&D Aligned with BETO Portfolio:

Fuel Molecules



Cyclohexanes

sugars via zeolite-based chemistry

biomass via hydropyrolysis

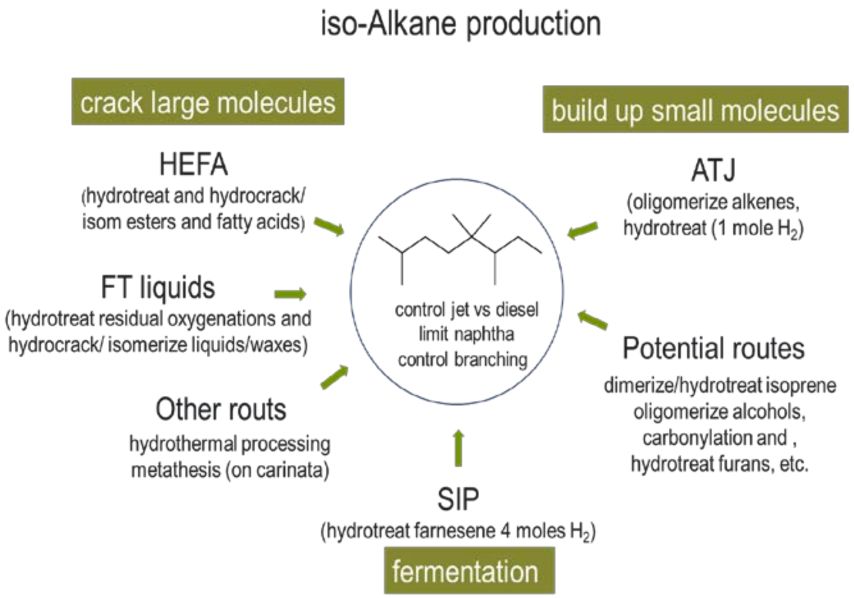
via native lignins

biomass via catalytic fast pyrolysis

biomass via fast pyrolysis

biomass via hydrothermal liquifaction

of catalytic fast pyrolysis (catalyst dependent



iso-Alkane production

crack large molecules

build up small molecules

HEFA

(hydrotreat and hydrocrack/ isom esters and fatty acids)

ATJ

(oligomerize alkenes, hydrotreat (1 mole H_2)

FT liquids

(hydrotreat residual oxygenations and hydrocrack/ isomerize liquids/waxes)

control jet vs diesel
limit naphtha
control branching

Potential routes

dimerize/hydrotreat isoprene oligomerize alcohols, carbonylation and , hydrotreat furans, etc.

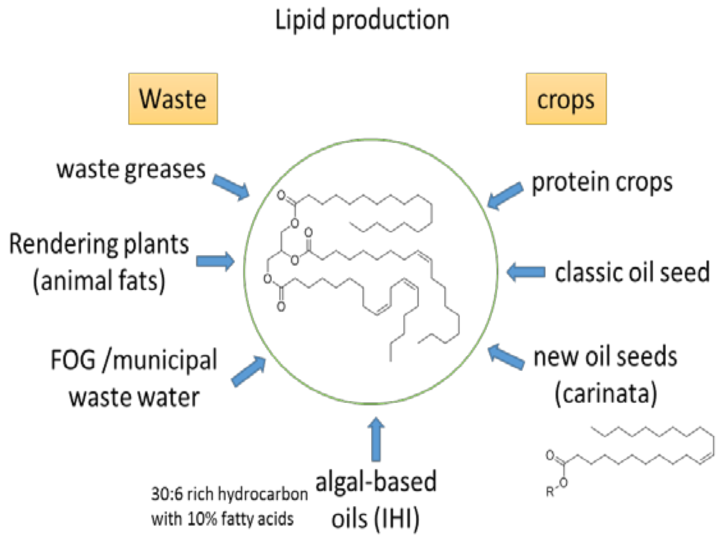
Other routs

hydrothermal processing metathesis (on carinata)

SIP

(hydrotreat farnesene 4 moles H_2)

fermentation



Lipid production

Waste

crops

waste greases

Rendering plants (animal fats)

FOG /municipal waste water

protein crops

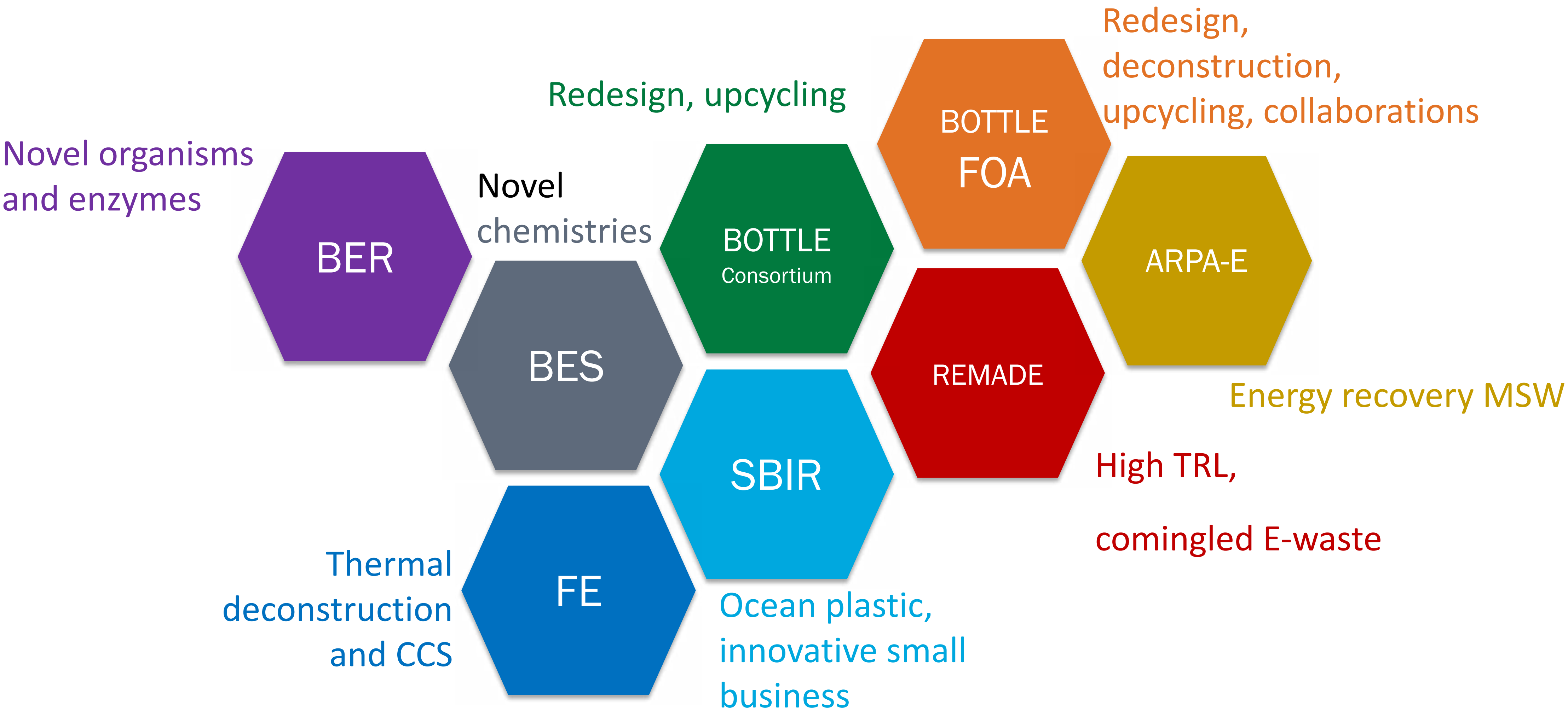
classic oil seed

new oil seeds (carinata)

30:6 rich hydrocarbon with 10% fatty acids

algal-based oils (IHI)

What can DOE do?



Novel organisms and enzymes

BER

Novel chemistries

BES

Redesign, upcycling

BOTTLE Consortium

Redesign, deconstruction, upcycling, collaborations

BOTTLE FOA

ARPA-E

Energy recovery MSW

REMADE

High TRL,

comingled E-waste

SBIR

Ocean plastic, innovative small business

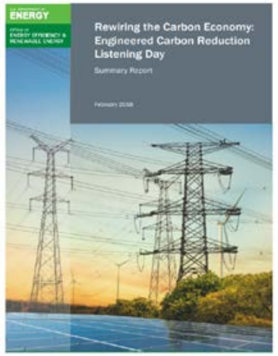
FE

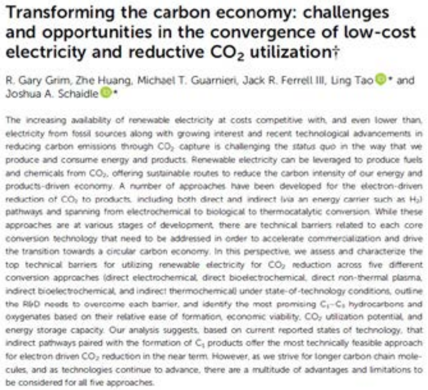
Thermal deconstruction and CCS

DOE’s Plastics Innovation Challenge

Background on CO_2-to-Fuels in BETO

- **<u>FY17</u>: BETO began investigating CO_2 utilization**
    - **Hosted a workshop in July 2017**
    - **Leveraged SBIR program to understand the current state of technology**
    - **Initiated a *Feasibility Study* at NREL to get a firm view on technical barriers**





Transforming the carbon economy: challenges and opportunities in the convergence of low-cost electricity and reductive CO_2 utilization†

R. Gary Grim, Zhe Huang, Michael T. Guarnieri, Jack R. Ferrell III, Ling Tao* and Joshua A. Schaidle*

The increasing availability of renewable electricity at costs competitive with, and even lower than, electricity from fossil sources along with growing interest and recent technological advancements in reducing carbon emissions through CO_2 capture is challenging the status quo in the way that we produce and consume energy and products. Renewable electricity can be leveraged to produce fuels and chemicals from CO_2, offering sustainable routes to reduce the carbon intensity of our energy and products-driven economy. A number of approaches have been developed for the electron-driven reduction of CO_2 to products, including both direct and indirect (via an energy carrier such as H_2) pathways and spanning from electrochemical to biological to thermocatalytic conversion. While these approaches are at various stages of development, there are technical barriers related to each core conversion technology that need to be addressed in order to accelerate commercialization and drive the transition towards a circular carbon economy. In this perspective, we assess and characterize the top technical barriers for utilizing renewable electricity for CO_2 reduction across five different conversion approaches (direct electrochemical, direct bioelectrochemical, direct non-thermal plasma, indirect bioelectrochemical, and indirect thermochemical) under state-of-technology conditions, outline the R&D needs to overcome each barrier, and identify the most promising C_1–C_3 hydrocarbons and oxygenates based on their relative ease of formation, economic viability, CO_2 utilization potential, and energy storage capacity. Our analysis suggests, based on current reported states of technology, that indirect pathways paired with the formation of C_1 products offer the most technically feasible approach for electron driven CO_2 reduction in the near term. However, as we strive for longer carbon chain molecules, and as technologies continue to advance, there are a multitude of advantages and limitations to be considered for all five approaches.

- **Informed a strategy that took advantage of BETO's existing portfolio structure**

Carbon

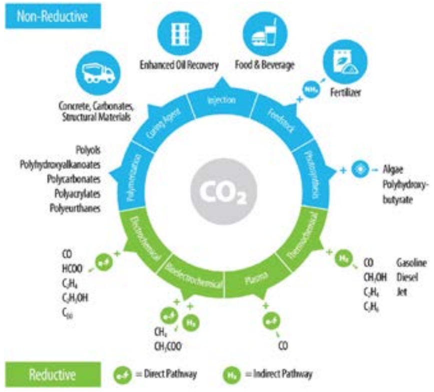
Engineered Carbon Reduction

Reduced Intermediate Conversion & Upgrading

- **<u>FY18 FOA</u>: sought entities that could perform CO_2 reduction to team with those w/expertise in upgrading**

- **<u>FY20 FOA</u>: *Scalable CO_2 Electrocatalysis*, hosted a CO_2 Summit and issued a questionnaire to the labs**

- **Now understand the challenges and barriers, and we wish to address them with a larger targeted effort at the National Labs**



THANK YOU REVIEWERS (and attendees)!