NREL
NATIONAL RENEWABLE ENERGY LABORATORY

DOE Bioenergy Technologies Office (BETO) 2017 Project Peer Review

Biochemical Platform Analysis

Ryan Davis
National Renewable Energy Laboratory

Biochemical Platform Review, March 7, 2017, Denver, CO

Goal Statement

Objective

Provide **process design and economic analysis support** for the biochemical conversion platform, to **guide R&D priorities towards economic viability**

- Translate demonstrated or proposed research advances into economics quantified as $/gal ($/GGE) selling price

Outcomes

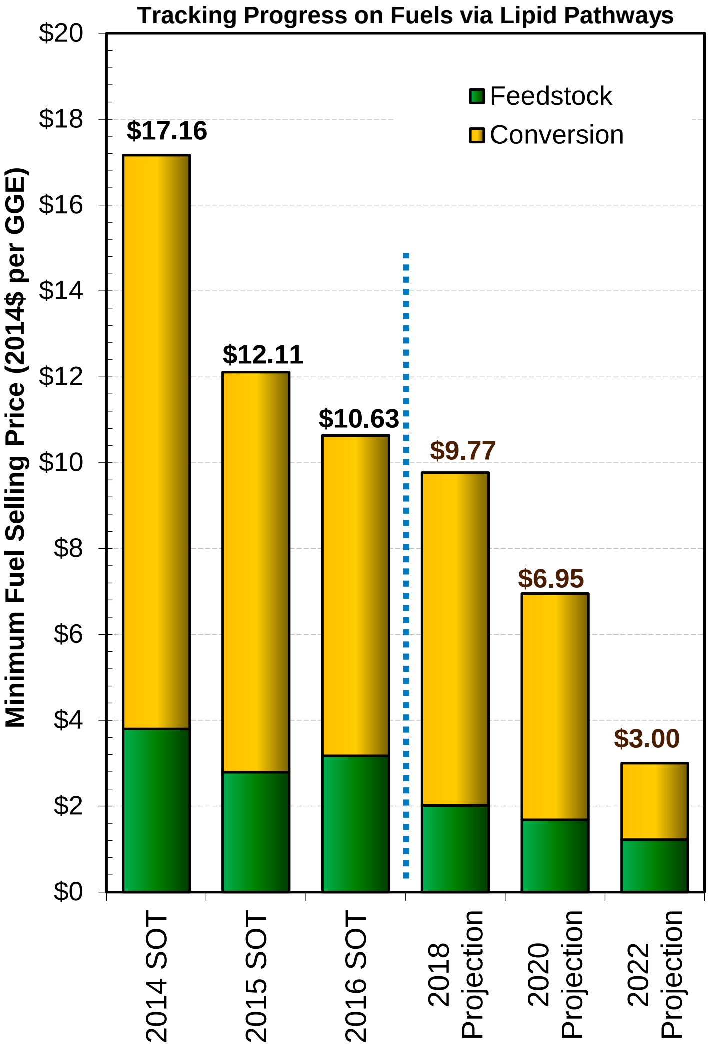
Project develops benchmark process models in Aspen Plus and related economic-analysis tools, used to:

- Assess cost-competitiveness and **establish process/cost targets** for biofuel production pathways
- **Track progress** towards goals through state of technology (SOT) updates
- Quantify **sustainability metrics** associated with modeled biorefinery conversion operations
- **Disseminate** rigorous, objective modeling and analysis work in a transparent way (the "design report" process)

Relevance

This project **directly supports the BETO Program** by providing "bottom-up" TEA to show R&D needs for achieving "top-down" BETO cost goals

- *Guide R&D towards economic viability, eventual adoption of biofuels into U.S. market*



Example of the use of TEA to track historical progress towards goals for hydrocarbon fuels via lipid fermentation pathways

Quad Chart Overview

Timeline

- Started: Oct 2016 (3-year cycle)
- Finish: Sept 2019 (3-year cycle)
- 17% complete (year 1/Q2 of 3-year cycle)

Budget

	Total Costs FY 12 – FY 14	FY 15 Costs	FY 16 Costs	Total Planned Funding (FY 17-Project End Date)
DOE Funded	$2.3 MM	$750k	$750k	$2.35 MM
Project Cost Share (Comp.)	NA	NA	NA	NA

Barriers

MYPP Barriers Addressed

- CT-J: Process Integration
  - *TEA models tie all R&D operations together*
- AT-A: Comparable, Transparent, and Reproducible Analyses
  - *Rigorous models with significant documentation of assumptions*
- AT-C: Data Availability Across the Supply Chain
  - *Design reports and SOTs disseminate R&D/TEA data*

Partners

- No partners with shared funding
- Other interactions/collaborations
  - INL—Feedstock interface activities, supply-chain analysis
  - ANL—GREET modeling team, water-quality assessment team
  - PNNL—Biochemical modeling/report reviews
  - Industrial partners
  - Engineering subcontractors

Project Overview

- NREL has a long history of establishing and maintaining rigorous process models
  - Set objective, transparent benchmarks for a single plausible conversion pathway
  - Quantify economic impact of funded R&D improvements relative to benchmarks
  - Evaluate sensitivities to uncertainties, alternatives
  - “Basic engineering” and process optimization
- Phased Approach:
  - Develop baseline models with best available data
  - Validate and conduct peer review modeling assumptions, publish “design reports”
  - Assist in cost-target development
  - Iterate with researchers and external stakeholders and refine models as new data becomes available
- Types of Analysis:
  - Technoeconomic analysis (TEA)
  - Life-cycle analysis (LCA)/sustainability metrics
- Technology Focus:
  - 2001–2012: cellulosic ethanol
  - 2013+: hydrocarbon biofuels, bioproducts

July 1999 • NREL/TP-580-26157

Technical Report

Lignocellulosic Biomass t
Ethanol Process Design a
Economics Utilizing Co-C
Dilute Acid Prehydrolysis
Enzymatic Hydrolysis Cur
and Futuristic Scenarios

Robert Wooley, Mark Ruth, John Sheehan, K
Biotechnology Center for Fuels and Chemical

Henry Majdeski, Adrian Galvez
Delta-T Corporation

June 2002 • NREL/TP-510-32438

l Report

Lignocellulosic Biomass to
Ethanol Process Design and
Economics Utilizing Co-Current
Dilute Acid Prehydrolysis and
Enzymatic Hydrolysis for
Corn Stover

Ibsen, J. Jechura,
an, and B. Wallace
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n, and J. Lukas

ewable Energy Laboratory

NREL

Process Design and Economics
for Biochemical Conversion of
Lignocellulosic Biomass to
Ethanol

Dilute-Acid Pretreatment and
Enzymatic Hydrolysis of Corn Stover

C. Kinchin,

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NREL

Process Design and Econo
for the Conversion of
Lignocellulosic Biomass to
Hydrocarbons:
Dilute-Acid and Enzymatic
Deconstruction of Biomass to Su
and Biological Conversion of Su
Hydrocarbons

R. Davis, L. Tao, E.C.D. Tan, M.J. Bidd
G.T. Beckham, and C. Scarlata
National Renewable Energy Laboratory

J. Jacobson and K. Cafferty
Idaho National Laboratory

J. Ross, J. Lukas, D. Knorr, and P. Sch
Harris Group Inc.

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Office of Energy Efficiency & Renewable Energy
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Technical Report
NREL/TP-5100-60223
October 2013

Contract No. DE-AC36-08GO28308

NREL

Process Design and Economics
for the Conversion of
Lignocellulosic Biomass to
Hydrocarbons:
Dilute-Acid and Enzymatic
Deconstruction of Biomass to Sugars
and Catalytic Conversion of Sugars to
Hydrocarbons

R. Davis, L. Tao, C. Scarlata, and E.C.D. Tan
National Renewable Energy Laboratory

J. Ross, J. Lukas, and D. Sexton
Harris Group Inc.

Approach (Technical)

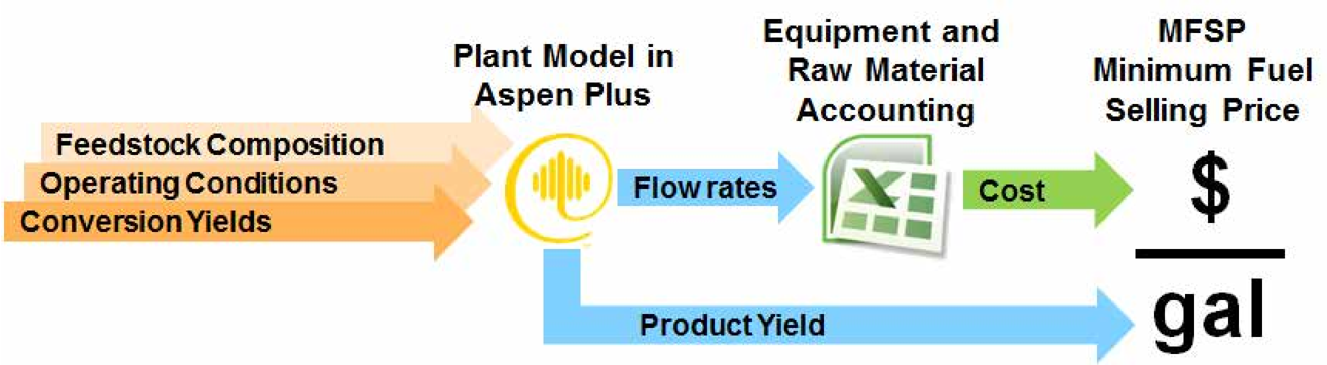
- Aspen Plus modeling for rigorous M&E balances
- Discounted cash-flow ROR calculation determines minimum fuel selling price (MFSP)
- Credibility of analysis supported by vendor cost estimates, thorough vetting with industry and research stakeholders

Critical Success Factors:

- TEA shows that economics are more challenging for long-chain hydrocarbon pathways versus ethanol; requires rigorous process optimization, maximizing carbon yields, pursuing coproduct opportunities → quantify resulting impacts through complex models
- Provide accurate sensitivity analyses to establish research priorities in platform R&D projects
- Critical to maintain credible engineering analyses that are transparent and unbiased—work with engineering subcontractors to reduce uncertainty, subject design reports to thorough external peer review

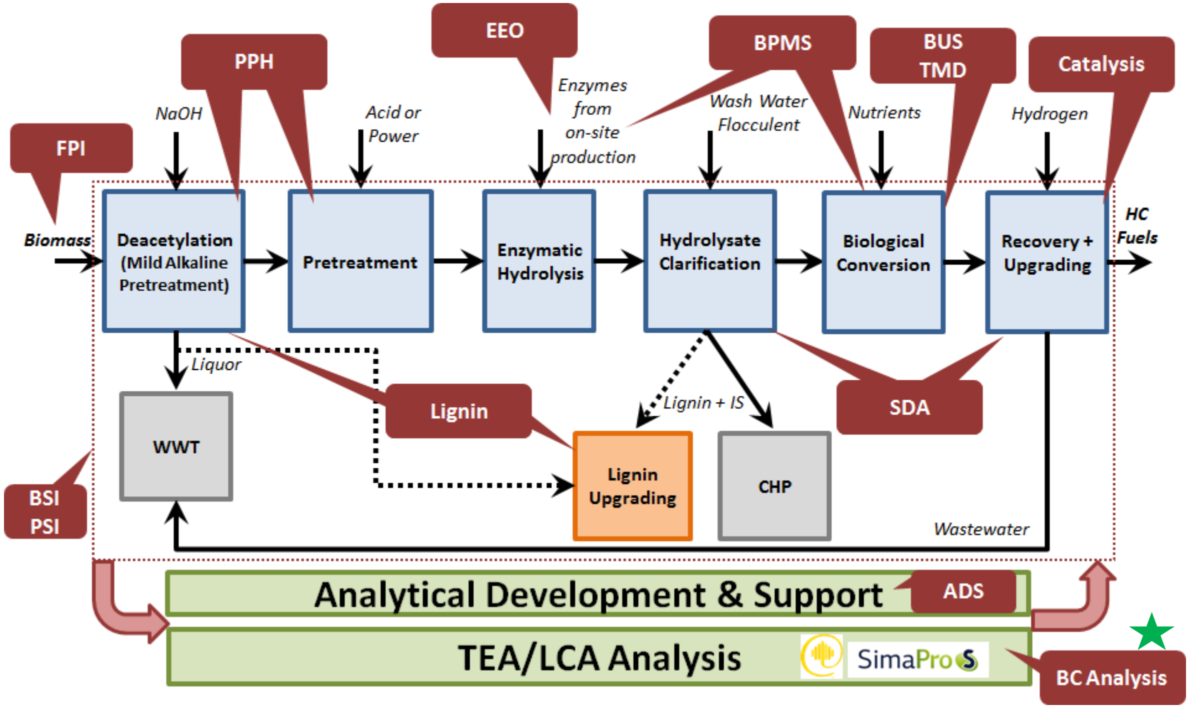
Challenges:

- New technology pathways for hydrocarbon biofuels = lack of public data availability on key process steps, more modeling uncertainty
- Successful outcomes defined by future achievement of $3/GGE in 2022 demonstrations; beyond TEA potential, must weigh technology maturity/risks in selection of “the” 2022 pathway



Approach (Management)

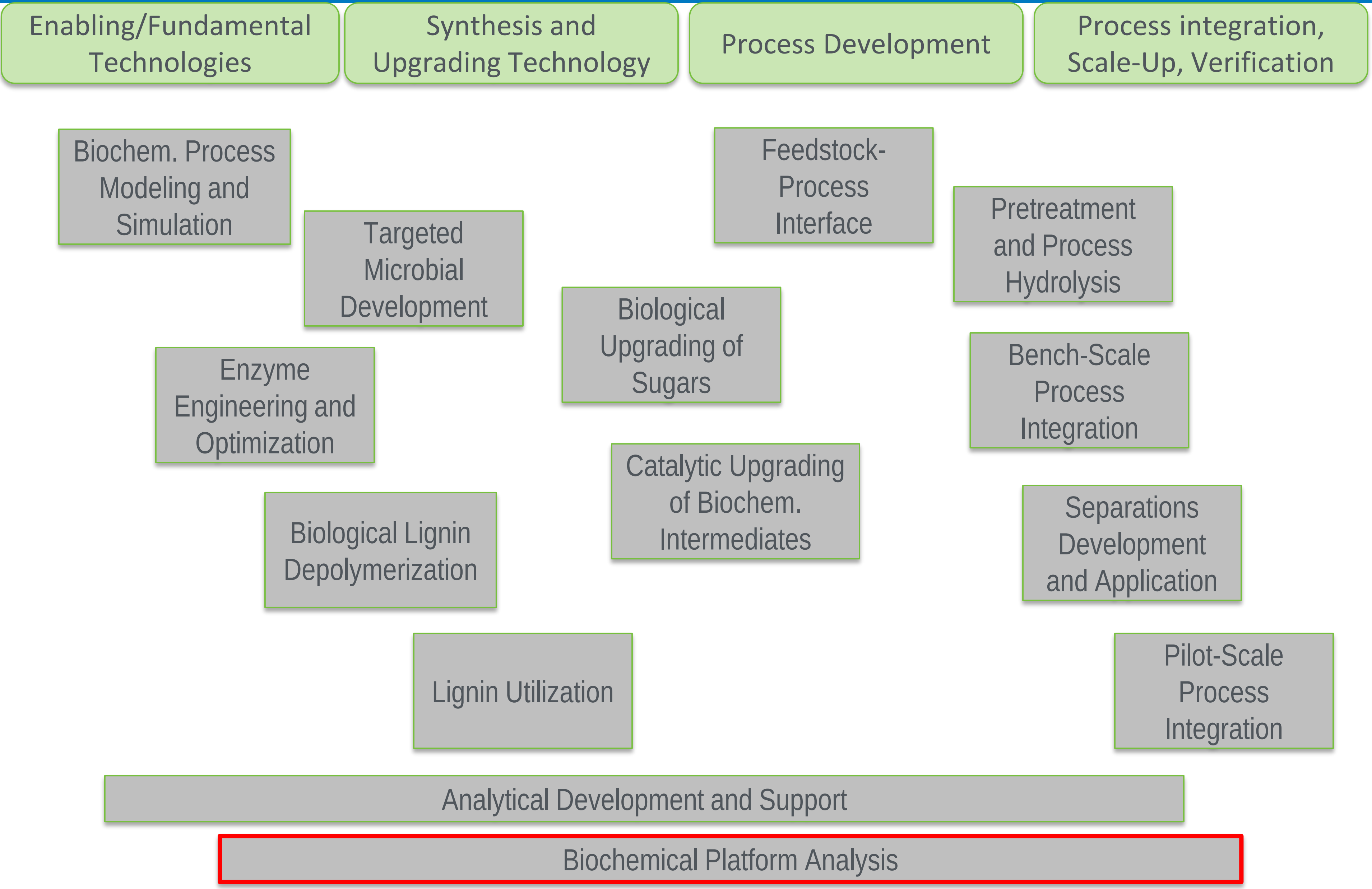
- Project management tracked using milestones
- **Activities are highly integrated with research efforts, assist in go/no-go decisions for R&D**
    - Example—FY16 go/no-go milestone to identify biological pathways to $3/GGE, highlight R&D needs



Project Milestones/Activities	FY16				FY17				FY18 (planned)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
R&D/Platform Support												
TEA analysis for paths to $3/GGE by 2022		●			▼					●	▼	▲
SOT benchmarking				▲				▲				▲
Lignin coproduct modeling						▼			▼			
Feedstock logistics variability—impact on conversion TEA	▲							▼				
Catalytic conversion pathways analysis						▲						▲
Design/Engineering Analysis/TEA Refinement												
Cost of aeration TEA/optimization		▼	▲				▼					
Updated sugar model					▼							
Cost/optimization for separations, lipid extraction/upgrading	▼		▲	▲			▼					

▲= Milestone, ▼= Quarterly progress measure, ● = Go/no-go decision

Approach (Management): Tie-Ins with Other Projects



Enabling/Fundamental Technologies

Synthesis and Upgrading Technology

Process Development

Process integration, Scale-Up, Verification

Biochem. Process Modeling and Simulation

Feedstock-Process Interface

Targeted Microbial Development

Pretreatment and Process Hydrolysis

Biological Upgrading of Sugars

Enzyme Engineering and Optimization

Bench-Scale Process Integration

Catalytic Upgrading of Biochem. Intermediates

Separations Development and Application

Biological Lignin Depolymerization

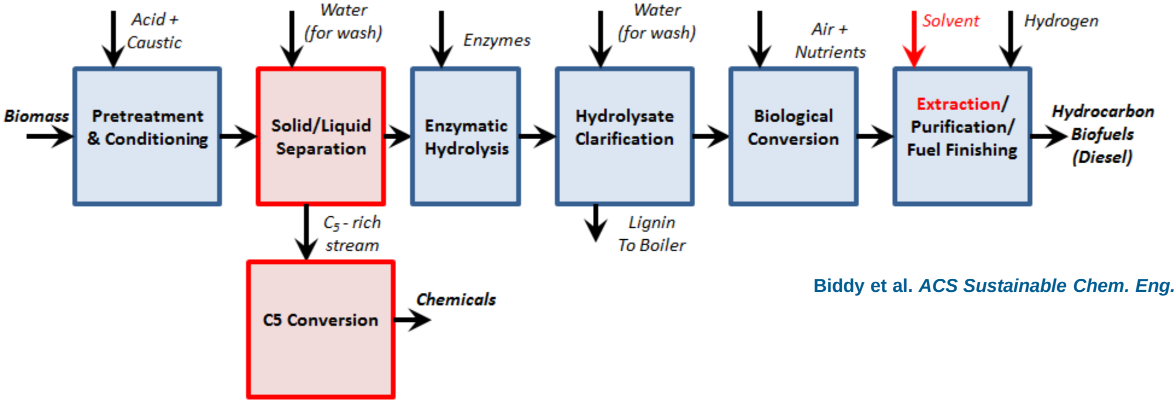
Lignin Utilization

Pilot-Scale Process Integration

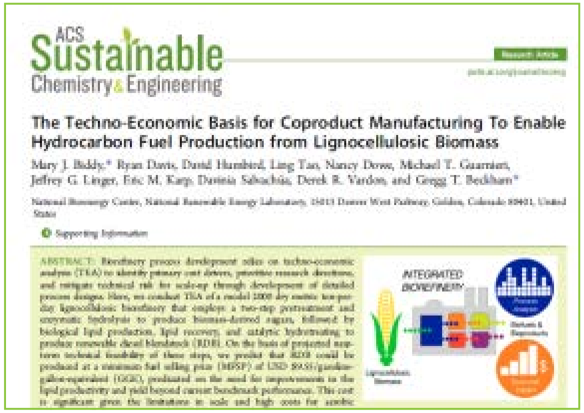
Analytical Development and Support

Biochemical Platform Analysis

Technical Accomplishments/Progress/Results: *Paths to $3/GGE (Go/No-Go)*



Biddy et al. *ACS Sustainable Chem. Eng.* 2016



ACS Sustainable Chemistry & Engineering

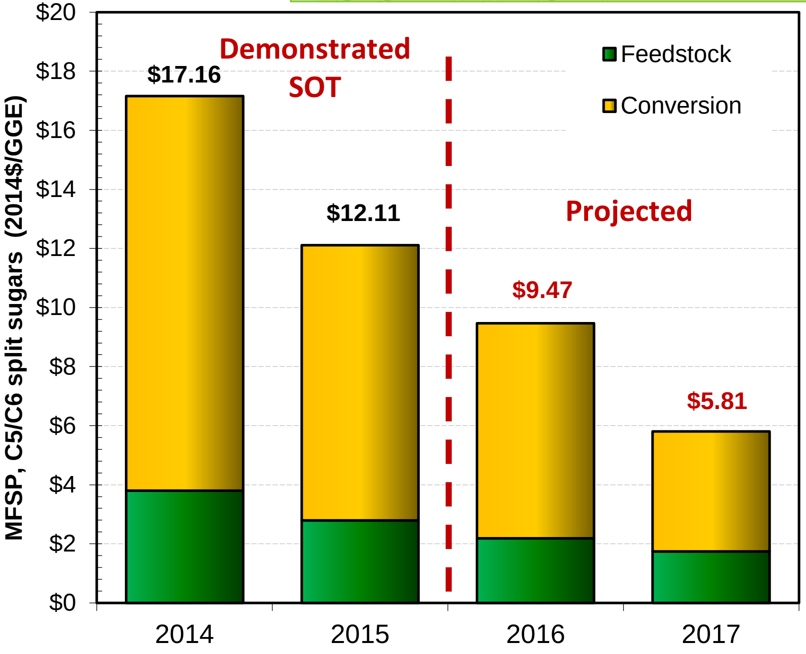
The Techno-Economic Basis for Coproduct Manufacturing To Enable Hydrocarbon Fuel Production from Lignocellulosic Biomass

Mary J. Biddy,* Ryan Davis, David Humbird, Ling Tao, Nancy Dowe, Michael T. Guarnieri, Jeffrey G. Linger, Eric M. Karp, Davinia Salvachúa, Derek R. Vardon, and Gregg T. Beckham*

National Bioenergy Center, National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, Colorado 80401, United States

Supporting Information

- FY14–15 focused on "C5/C6" pathway to **fuels and coproducts (succinic acid) from sugars**
- Previously focused on achieving a $5/GGE "interim" goal by 2017 via diversion of C5 sugars to coproducts
- Demonstrated favorable performance and significant MFSP improvements to 2015
- At BETO's guidance, "interim" demonstration case was de-emphasized to focus on longer-term 2022 strategies

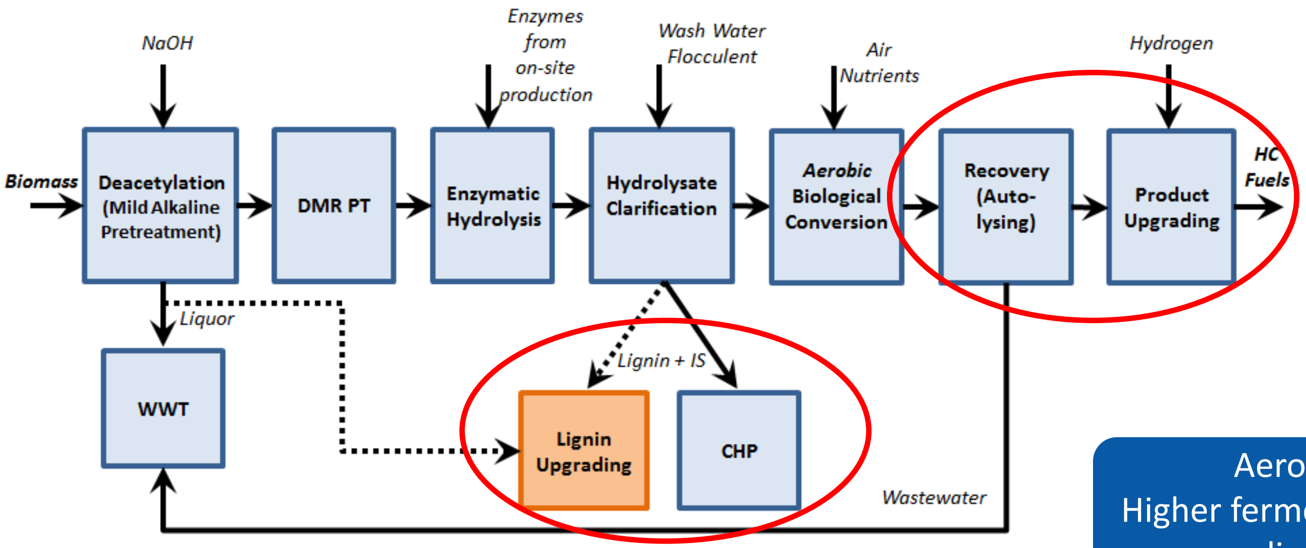


- Initiated by Q2 Go/No-Go milestone to evaluate options for $3/GGE routes
  - Focused on whether a viable route to $3/GGE exists, and if so to identify key process projections/R&D needs
  - NOT intended to down-select to "the" new pathway strategy

Representative Pathways: Aerobic

Lipids

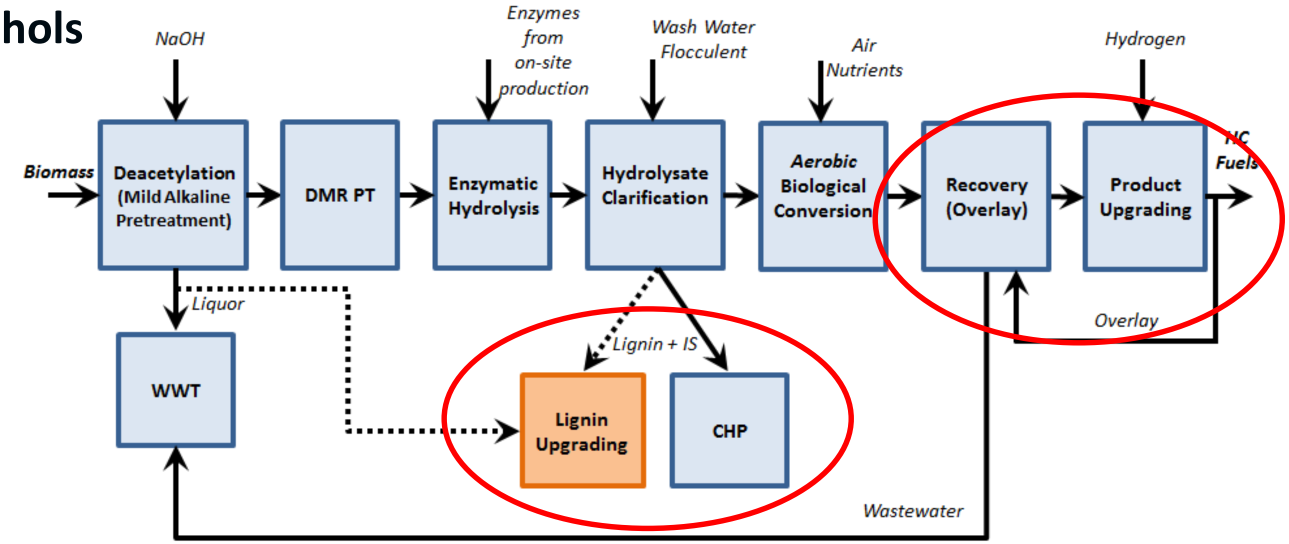
(BSI, PSI, BUS)



Aerobic pathways:
Higher fermentation costs, easier upgrading (long-chain HCs)

Fatty Alcohols

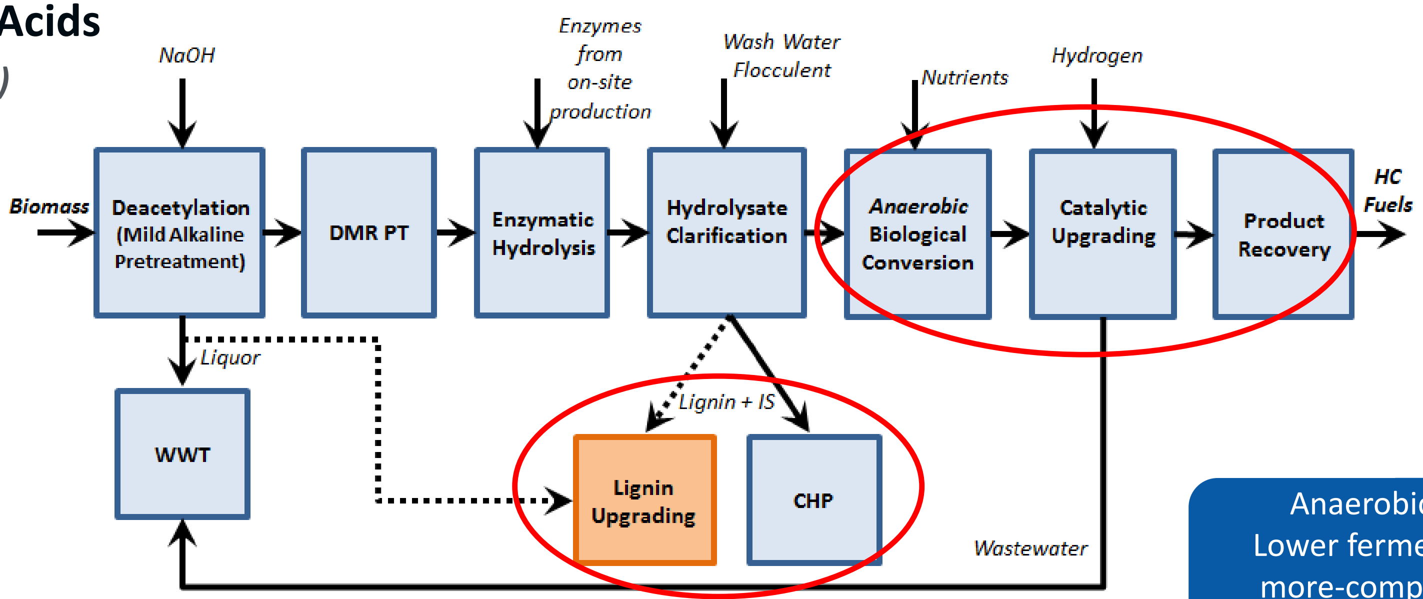
(TMD)



Representative Pathways: Anaerobic

Organic Acids

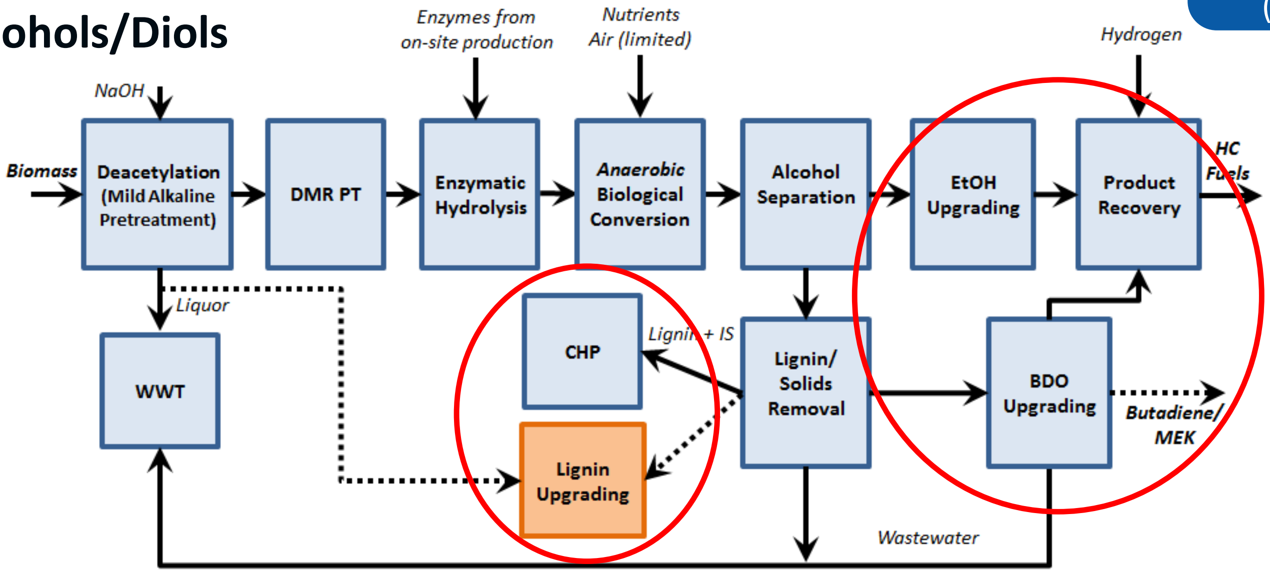
(BUS)


NaOH
Enzymes from on-site production
Wash Water
Flocculent
Nutrients
Hydrogen
Biomass
Deacetylation (Mild Alkaline Pretreatment)
DMR PT
Enzymatic Hydrolysis
Hydrolysate Clarification
Anaerobic Biological Conversion
Catalytic Upgrading
Product Recovery
HC Fuels
Liquor
WWT
Lignin + IS
Lignin Upgrading
CHP
Wastewater

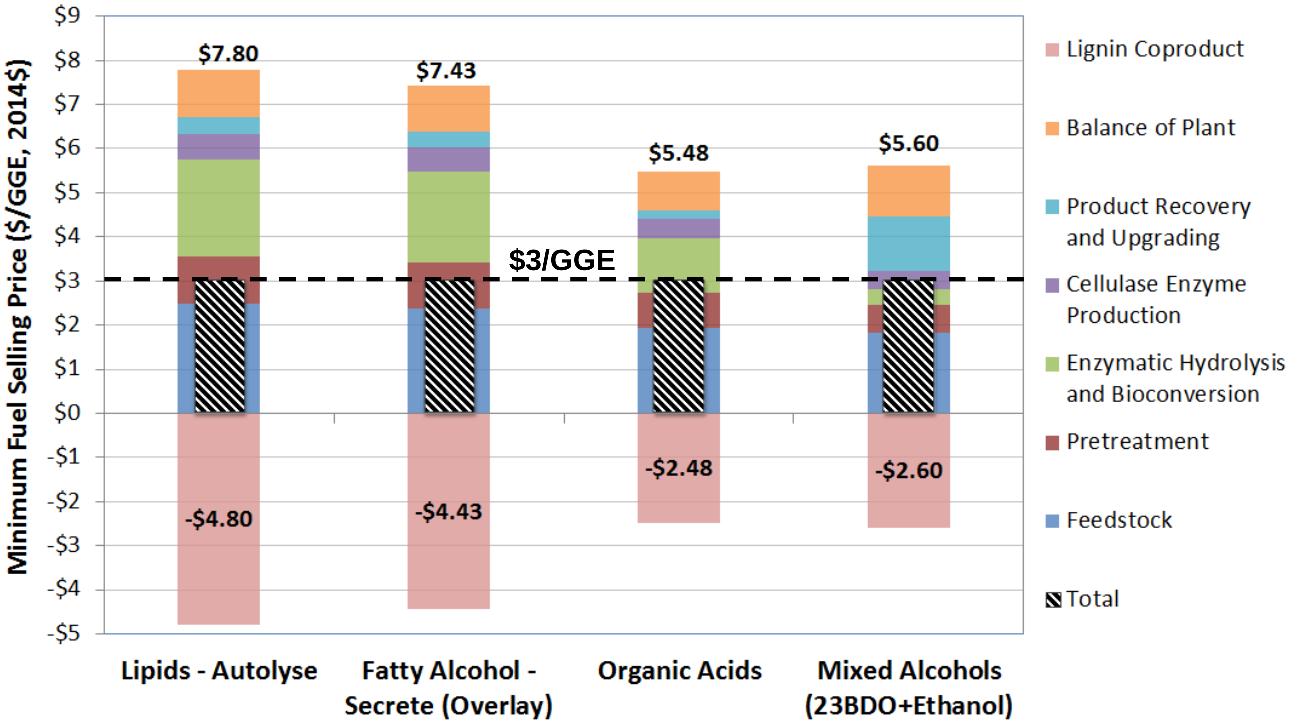
Anaerobic pathways:
Lower fermentation costs,
more-complex upgrading
(short-chain oxygenates)

Mixed Alcohols/Diols

(TMD, BSI)


NaOH
Enzymes from on-site production
Nutrients
Air (limited)
Hydrogen
Biomass
Deacetylation (Mild Alkaline Pretreatment)
DMR PT
Enzymatic Hydrolysis
Anaerobic Biological Conversion
Alcohol Separation
EtOH Upgrading
Product Recovery
HC Fuels
Liquor
WWT
CHP
Lignin + IS
Lignin Upgrading
Lignin/ Solids Removal
BDO Upgrading
Butadiene/ MEK
Wastewater

Paths to $3/GGE: TEA Results Highlight Potential and Drivers

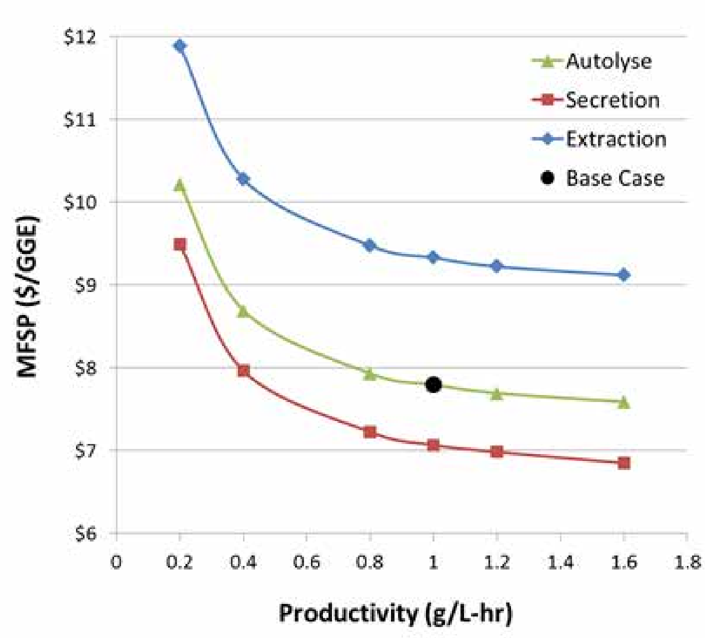


All pathways show potential to achieve $3/GGE, but in all cases require coproducts from lignin

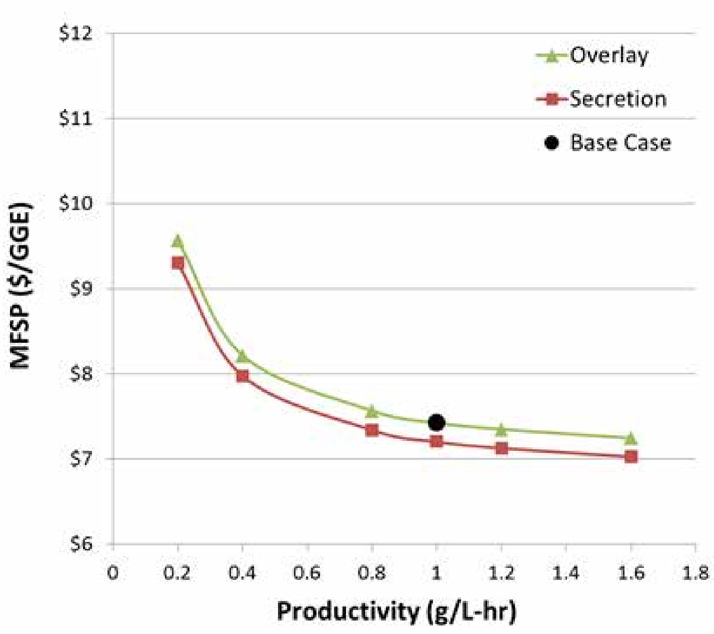
- Aerobic more challenging than anaerobic—higher cost, lower yields
- FaOH shows potential benefits over lipids via product recovery + upgrading, but early TRL
- Anaerobic cases are comparable—trades higher fermentation costs vs higher upgrading costs
- $3/GGE requires 40–60% C efficiency across lignin-to-coproducts train

Metric	Lipids	Fatty Alcohols	Organic Acids	BDO + EtOH
MFSP ($/GGE, 2014$) —Prior to coproducts	$7.80	$7.43	$5.48	$5.60
Fuel C efficiency from biomass (%)	20%	21%	25%	27%
Fuel yield (GGE/ton)	34.2	35.7	43.5	46.5
TCI ($MM) —Prior to coproducts	$640	$628	$520	$527
Fuel-carbon chain length	~9–20	~16–20	11	~8–18
Carbon efficiency through lignin-to-coproduct train required to achieve $3/GGE (C in adipic acid vs C available in residual biomass)	59%	56%	40%	46%

Sensitivity Analysis (Aerobic): Productivity + Lipid Recovery Are Key



Lipids

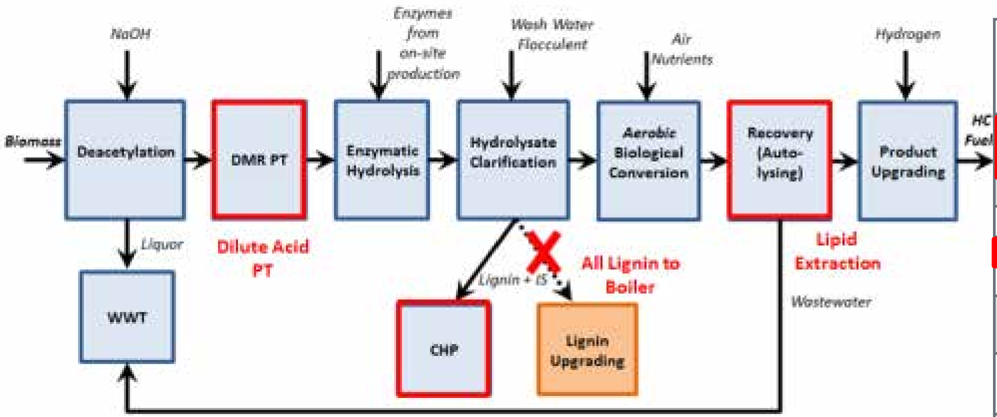


Fatty Alcohols

Sensitivity scans based on routing all lignin to boiler (not including lignin coproducts for $3/GGE goals)

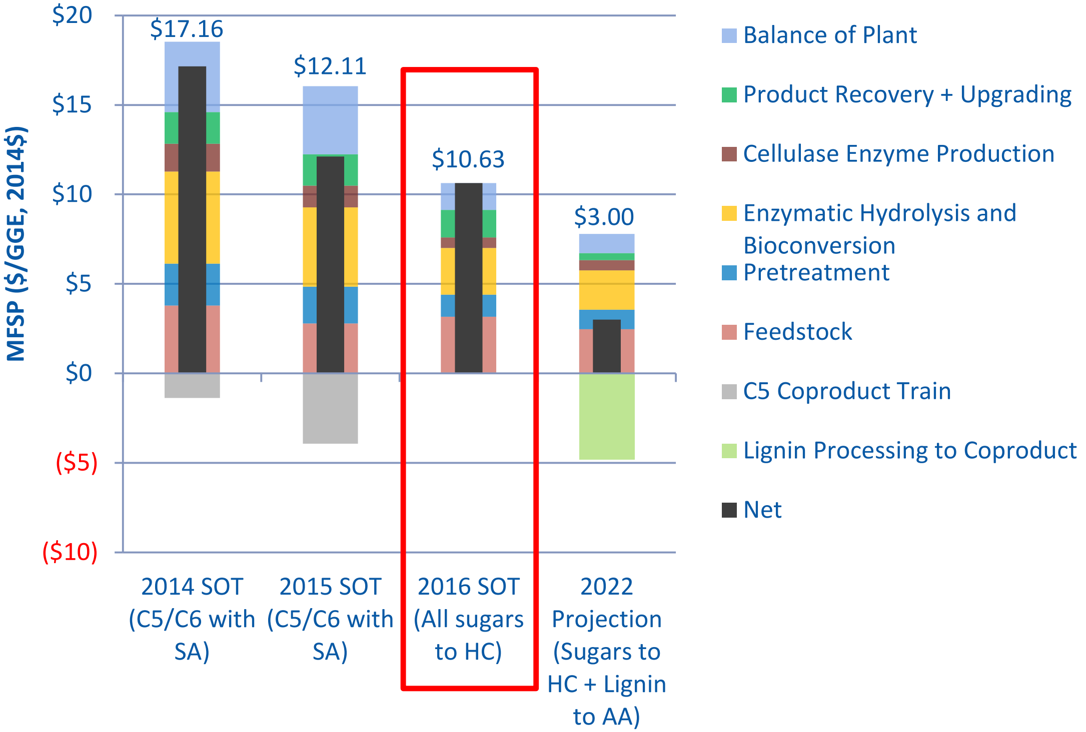
- High costs for aerobic bioconversion require productivity near 1 g/L-hr for reasonable economics
- Key to avoid extraction for lipid case (~$1.5/GGE penalty for extraction vs. auto-lysing)
- Less sensitivity for FaOH case via secretion vs. “overlay”

Technical Accomplishments/Progress/Results:
2016 SOT – NREL TEA Sets Benchmarks

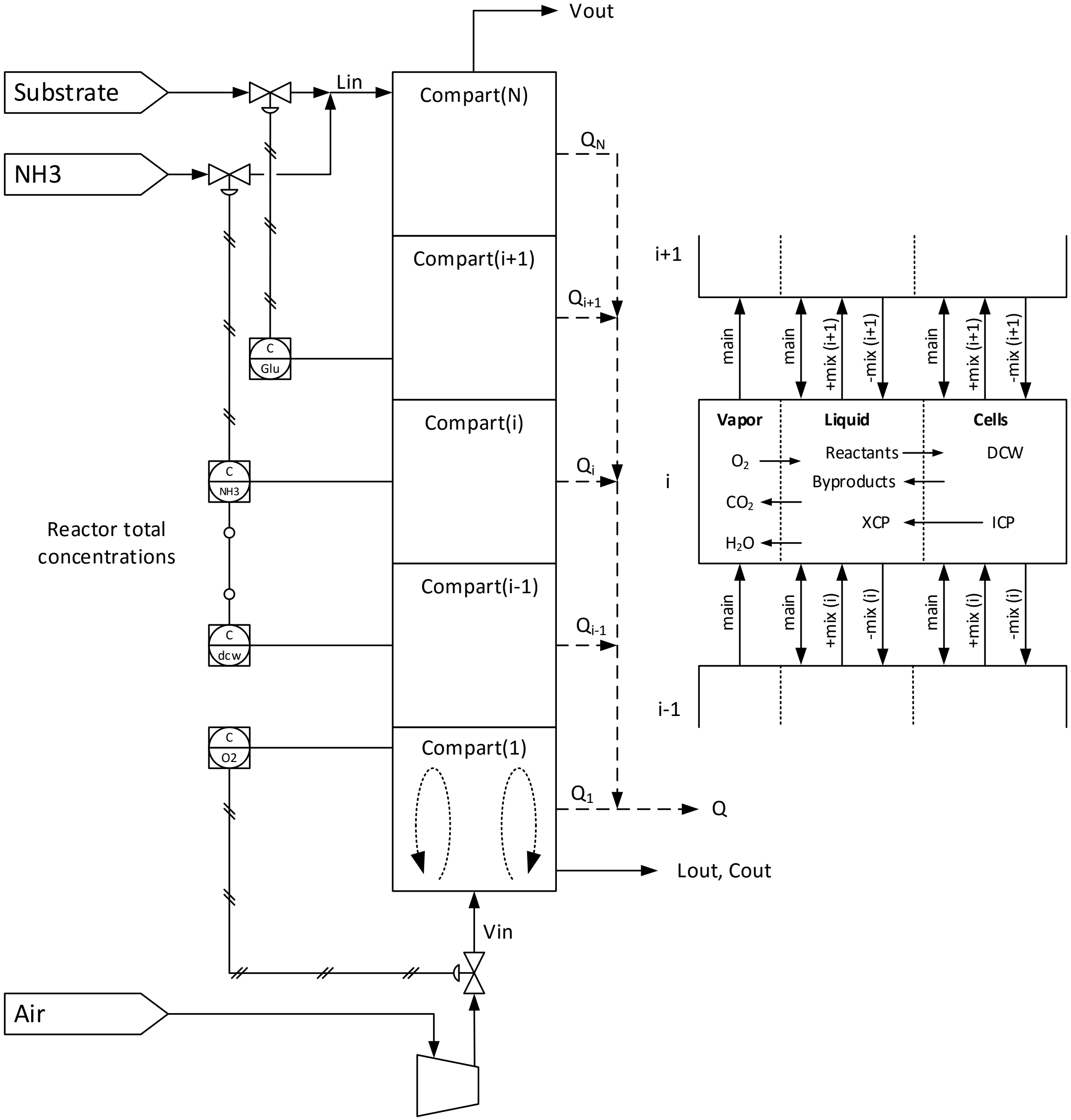


Parameter	FY15 SOT (DDA whole hydrolysate basis)	FY16 SOT	FY22 Goal
Enzyme loading (mg/g cellulose)	20	10	10
Hydrolysis glucan-to-glucose	79%	85%	90%
Hydrolysis residual xylan-to-xylose	26%	26%	90%
Enzymatic hydrolysis time (days)	5	5	3.5
Bioconversion vol productivity (g/L-hr)	0.34	0.68	1.0
Lipid content (wt%)	60%	62%	70%
Glucose to product [total glucose conv]	75% [100%]	78% [100%]	82% [100%]
Xylose to product [total xylose conv]	44% [59%]	77% [100%]	81% [85%]
Intermediate product recovery	Extraction	Extraction	Autolyse

- FY16 SOT based on lipid pathway, given longer R&D history and most available data
- Again, NOT intended to imply a down-select to this pathway
- Some modifications vs. 2022
- Significant improvements observed for enzyme performance and productivity
  - Data will be shown in BSI talk
- **Translated to ~$1.5/GGE improvement vs. FY15 SOT even with loss of valuable coproduct**



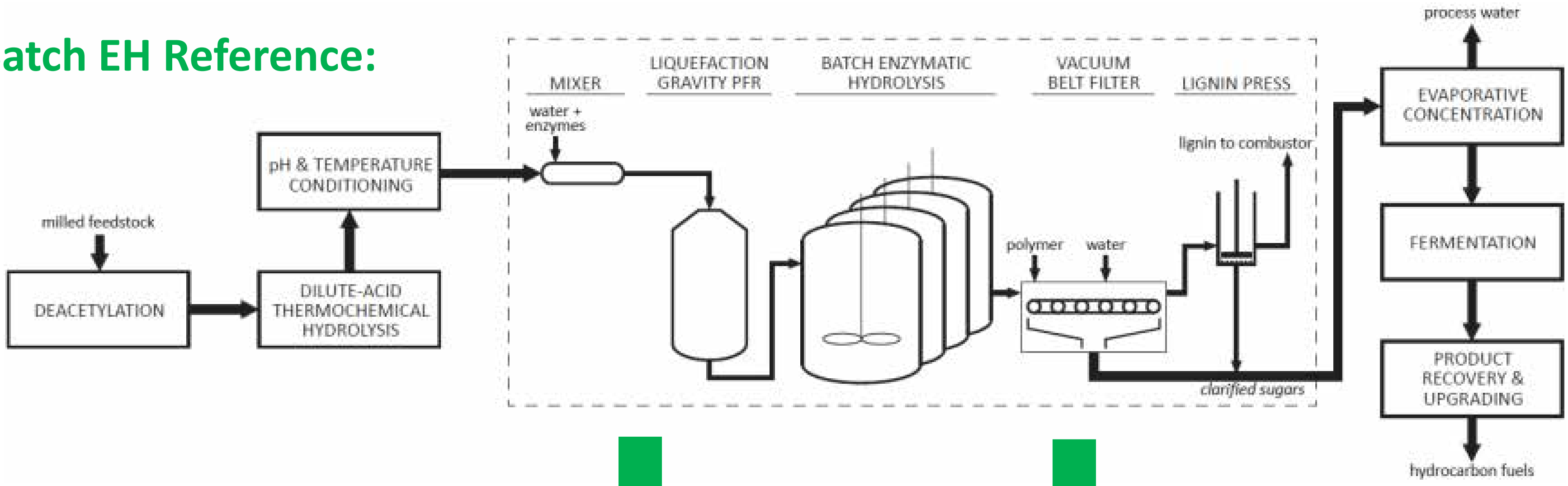
Technical Accomplishments/Progress/Results: *Refining Aeration Cost Estimates*



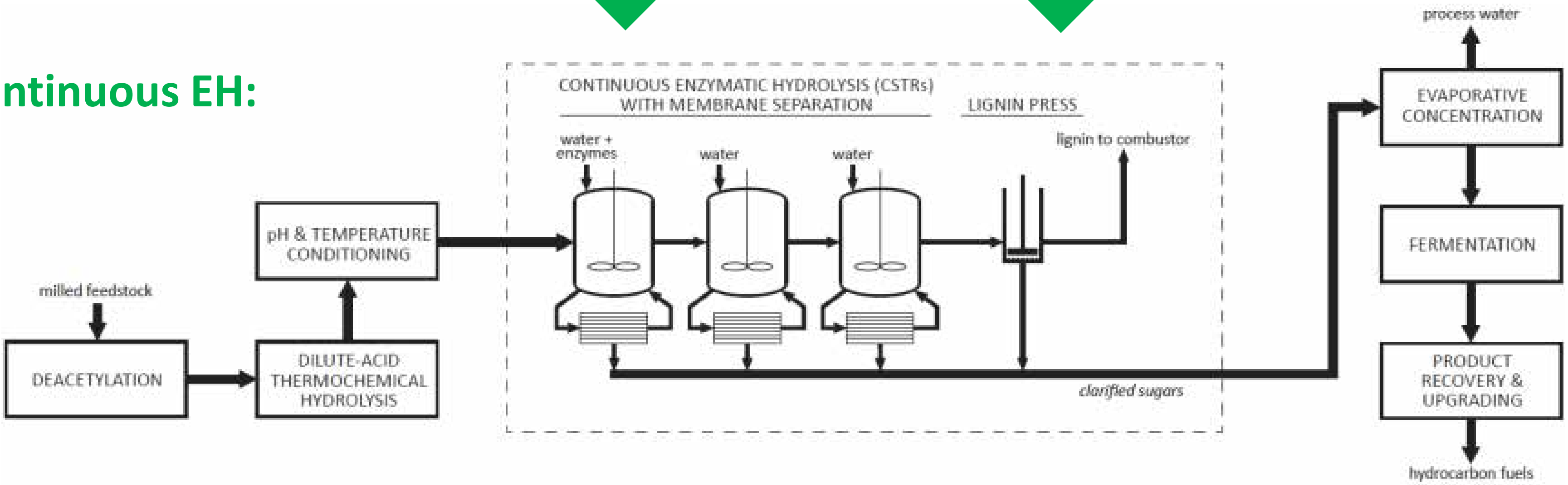
- Aerobic fed-batch bioreactor dynamics are too complex to capture in steady-state Aspen+ model
- Moving to a new advanced-fermentation process model in ACM
- Intended to capture dynamics of cell/product growth vs. OTR and other inputs (e.g., N nutrients) over fermentation cycle
- Developed with inputs from industry experts
- Further work planned in FY17

Technical Accomplishments/Progress/Results: *TEA Evaluation for Novel Hydrolysis Approach*

Batch EH Reference:

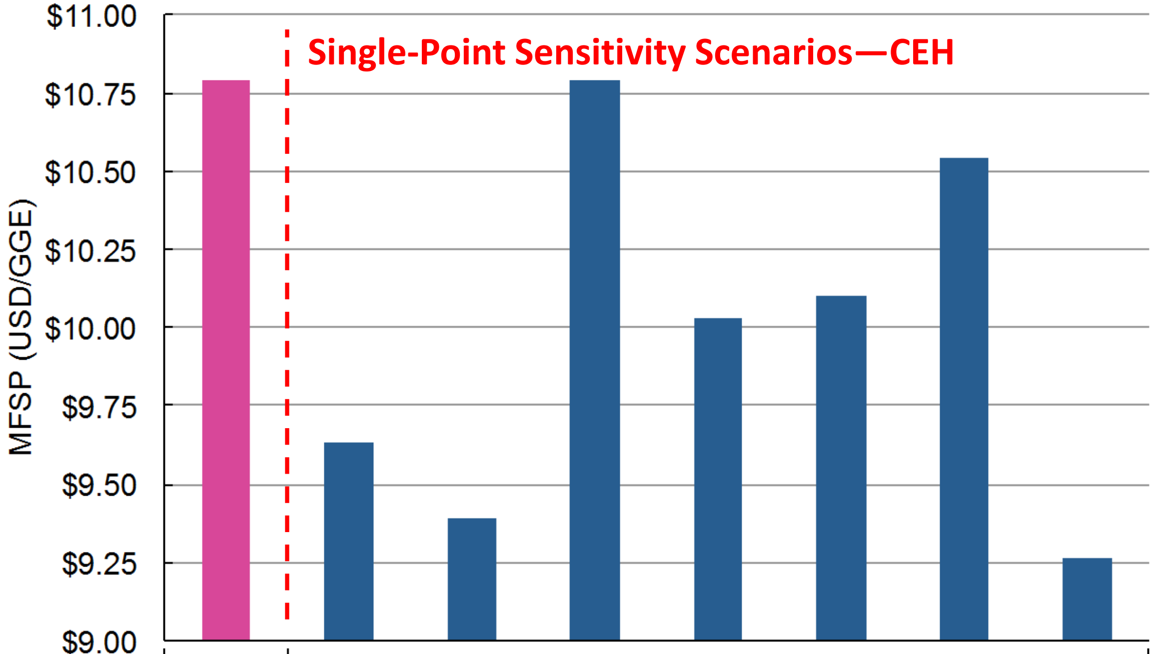


Continuous EH:



CEH concept/research coordinated out of NREL SDA project (included here to show TEA support)

CEH—Results of TEA Show Significant MFSP Promise



	batch	*continuous*						
	reference case	base case	3 CSTRs	5 % IS	7½ % IS	20 mg/g enzyme	74% yield	p/f=0.5
hydrolysis reactor size[1] (kg)	30,400,000	5,710,262	8,039,525	13,262,665	8,160,194	2,855,131	3,678,557	9,223,713
permeate rate[1] (kg/h)	*n/a*	982,001	774,710	1,952,540	1,301,694	982,001	1,166,569	672,768
membrane area[1] (m^2)	*n/a*	19,640	15,494	39,051	26,034	19,640	23,331	13,455
recirc. pump rate[1] (kg/h)	*n/a*	6,579,407	5,190,557	13,082,020	8,721,347	6,579,407	7,816,015	4,507,544
total sugar conc.[2] (g/L)	72.0	45.0	55.0	22.0	34.0	44.0	34.0	63.0

[1] *totals for all hydrolysis units in the system*

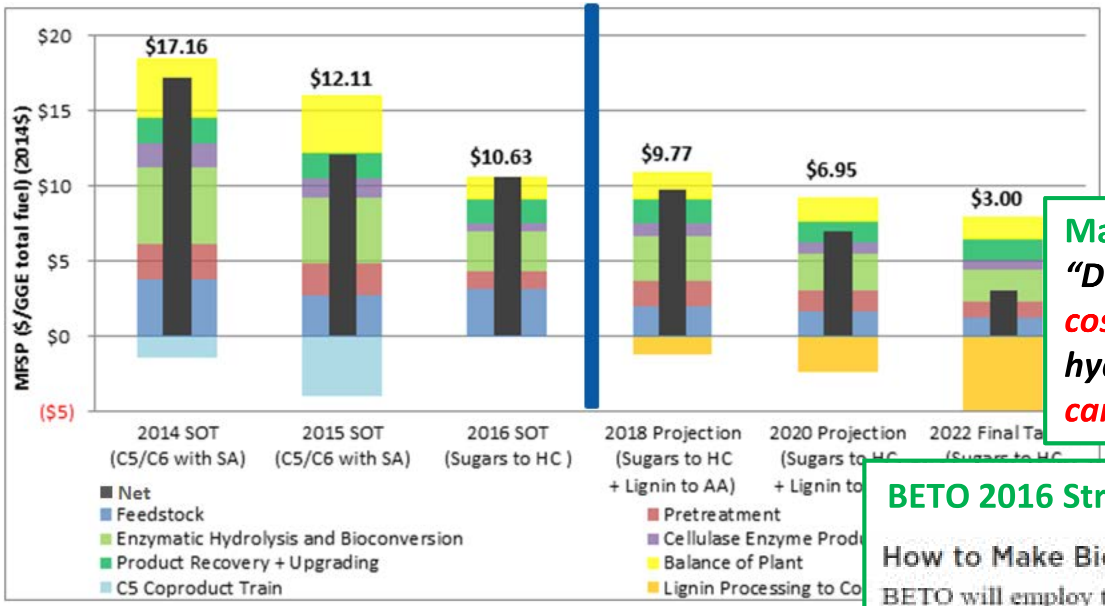
[2] *final concentration of all sugars after lignin press stream added to filtrate/permeates*

Preliminary results indicate significant potential for cost improvement over current approach

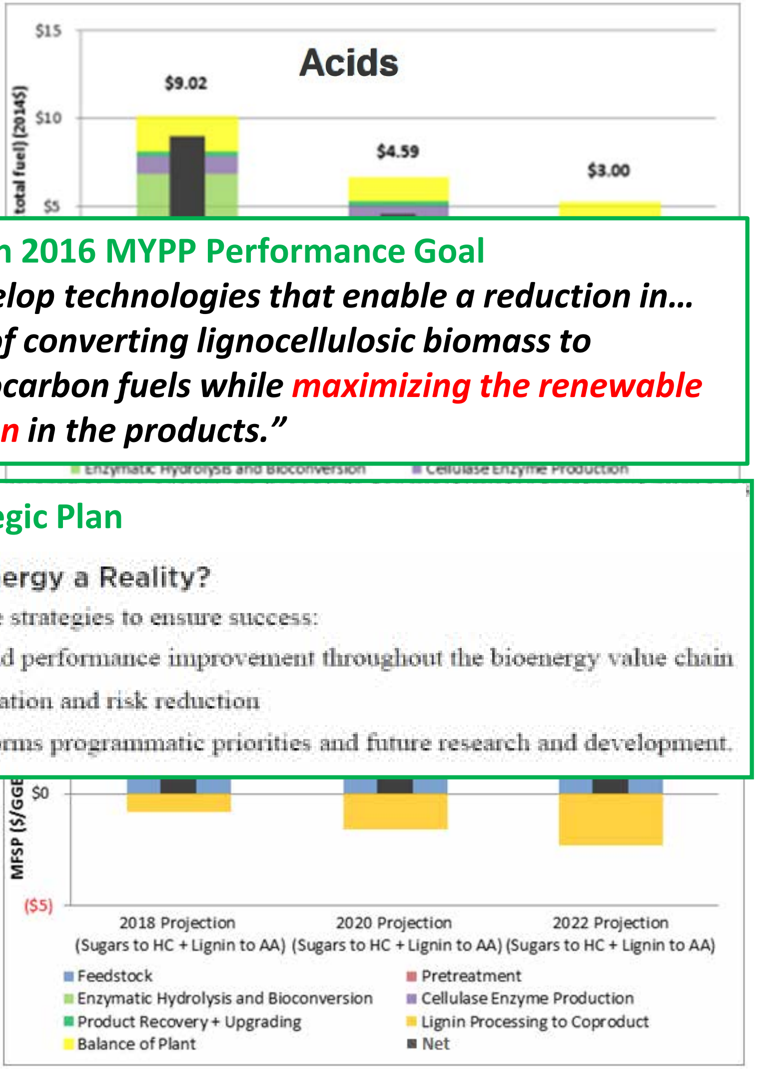
- Reference case based on latest EH SOT results with older enzyme package
- Using same enzyme, "best-case" CEH scenarios could reduce MFSP by up to $1.50/GGE (14%)
- Further R&D should investigate newer enzymes and other upstream pretreatment strategies

Relevance

TEA Progression Goals: Lipids



TEA Progression Goals: Anaerobic Cases



March 2016 MYPP Performance Goal

"Develop technologies that enable a reduction in… cost of converting lignocellulosic biomass to hydrocarbon fuels while maximizing the renewable carbon in the products."

BETO 2016 Strategic Plan

How to Make Bioenergy a Reality?

BETO will employ three strategies to ensure success:

- ★ Cost reduction and performance improvement throughout the bioenergy value chain
- Technology validation and risk reduction
- ★ Analysis that informs programmatic priorities and future research and development.

TEA is highly relevant to industry + BETO goals

- Analysis can serve a wide variety of stakeholders
  - *Industry (facilitate interaction between industry, NREL, DOE)*
  - *Research community, decision makers*
  - *TEA helps to "de-risk" a technology prior to commercialization*
- Identifies key R&D directions (e.g., pathways, coproducts)
- Guides R&D, DOE decisions, sets out year targets
  - *Technical targets (e.g., yields, process performance)*
  - *Cost targets (BETO MYPP goal: $3/GGE MFSP by 2022)*

Future Work

Design/Engineering Assessment:

- Publish updated sugar model (Aspen Plus) to NREL website—*Near future (sugar milestone completed Q1 FY17)*
- Evaluate alternative/reduced-cost separation options for key drivers in 2022 pathways—*Q3*
- Organism management/optimization for aerobic pathways (exercise new ACM model to better quantify TEA for various organism scenarios) —*Q3*

R&D Support/Guidance:

- Lignin-to-alcohols TEA (joint with NREL and ORNL R&D projects)—*Q2*
- Evaluate catalytic pathways investigated within ChemCatBio—*FY17–19*
- Feedstock interface TEA (conversion logistics for feedstock blends) —*Q4*
- TEA analysis for lignin deconstruction options (joint with Lignin Utilization)—*Q1 FY18*
  - Lignin will be key to MFSP targets—frequent interfacing with Lignin R&D

Key Strategic Activities to Guide Platform:

- State of Technology benchmarking—*Q4 FY16, FY17*
- 2022 pathway down-select for FY18 design report—*Go/No-Go, Q2 FY18*
  - Platform-wide decision point, weighing TEA potential, SOT, technology development progress
- FY18 design report—*Q3–Q4 FY18 (multiple milestones)*
  - Develop, review, and deliver a new design report based on the selected pathway from Q2

Summary

- Biochemical Analysis task has seen a tremendous amount of activity and achievements since FY15 peer review
    - Close-out and publication of C5/C6 pathway for parallel conversion of sugars to fuels and chemical coproducts, with significant TEA improvements shown by FY15 SOT
    - Go/no-go milestone serving as the first step towards transitioning to longer-term pathways, highlighting key R&D barriers/focus areas for $3/GGE by 2022
    - FY16 SOT and out-year projections through 2022 to begin guiding near-term R&D goals at NREL, priorities at BETO (including MYPP projections)
    - TEA support to guide R&D decisions for other NREL experimental projects
- TEA work is highly relevant to supporting program directions for BETO, near- and long-term R&D for NREL
- Supports industry and research community via transparent models and design reports, communication with stakeholders
- Further efforts planned moving forward around engineering/design optimizations, model refinements, and TEA support to guide experimental projects and overall BC Platform

Additional Slides

www.nrel.gov

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Responses to Previous Reviewers' Comments from 2015 Review

- It would be useful to develop a more simplified tool for economic analysis to analyze proposed technologies/developments in earlier stages of conceptualization prior to budgeting time and money or warranting a full design report.
- We support the notion of exploring more simplified TEA approaches for less developed concepts, and have acted on this feedback through several mechanisms over the past two years. In terms of "tools" for quicker analysis, within NREL's TEA group (with support and input from this project) we have developed a high-level qualitative method to help guide R&D thinking, planning, and work prioritization for internal research projects, with a simple color-code system to identify potential benefits and challenges for a particular concept with respect to process complexity and expected yields (primary drivers on MFSP), as well as knowns/unknowns that would be required to run a more detailed TEA. Additionally (also with collaboration from this project), NREL's TEA team has begun to develop a "quick turn-around analysis" tool which takes this a step further to provide cash-flow and MFSP estimates for a process of interest, given inputs for processing costs and yields without necessitating the use of a full Aspen Plus process simulation (although we stress the latter is still important in tracking M&E balances to reasonably quantify those metrics for new concepts which have not previously been explored).

- Feedback from private sector would be useful (if they are willing) to get an outside reality check on assumptions and metrics.
- One means of achieving this important step is the design case peer review process, which is undertaken by NREL's design reports that document the details of established models prior to publication and the release of these reports. This process solicits feedback from stakeholders in industry, academia, and other national laboratories with representation that spans all technology areas covered in the given pathway model. In many cases, the models and resulting cost estimates are modified as a direct result of the peer review feedback received prior to publication of the final report. Additionally, NREL maintains working relationships with outside partners, and strives to capitalize on opportunities for additional modeling feedback, validation, and/or improvement through these channels, as we are able to incorporate such inputs in publicly available reports.

Publications, Patents, Presentations, Awards, and Commercialization (Since 2015 Review)

- M. J. Biddy, R. Davis, D. Humbird, L. Tao, N. Dowe, M. T. Guarnieri, J. G. Linger, E. M. Karp, D. Salvachua, D. R. Vardon, G.T. Beckham, “The techno-economic basis for coproduct manufacturing to enable hydrocarbon fuel production from lignocellulosic biomass.” *ACS Sustainable Chem. Eng.*, 4(6): p. 3196-3211, 2016
- A. Bhatt, Y. Zhang, R. Davis, A. Eberle, G. Heath, “Economic implications of incorporating emission controls to mitigate air pollutants emitted from a modeled hydrocarbon-fuel biorefinery in the United States.” *Biofuels, Bioprod. Bioref.* 10: p. 603-622, 2016
- D. W. Templeton, J. B. Sluiter, A. Sluiter, C. Payne, D. P. Crocker, L. Tao, Ed Wolfrum, “Long-term variability in sugarcane bagasse feedstock compositional methods: sources and magnitude of analytical variability.” *Biotechnology for Biofuels*, 9(1): p. 233, 2016
- X. Chen, E. Kuhn, E. Jennings, R. Nelson, M. Zhang, P. Ciesielski, L. Tao, and M. P. Tucker, “DMR (deacetylation and mechanical refining) processing of corn stover achieves high monomeric sugar concentrations (230 g/L) during enzymatic hydrolysis and high ethanol concentration (>10% v/v) during fermentation without hydrolyzate purification or concentration.” *Energy and Environmental Science*, 9(4): p. 1237-1245, 2016
- X. Chen, W. Wang, P. Ciesielski, O. Trass, S. Park, L. Tao, and M. P. Tucker, “Improving sugar yields and reducing enzyme loadings in the deacetylation and mechanical refining (DMR) process through multi-stage disk and Szego Refining and corresponding techno economic analysis.” *ACS Sustainable Chem. Eng.*, 4(1): p. 324-333, 2016
- X. Chen, J. Shekiro, T. Pschorn, M. Sabourin and M. P. Tucker, and L. Tao, “techno-economic analysis of the deacetylation and disk refining process: characterizing the effect of refining energy and enzyme usage on minimum sugar selling price and minimum ethanol selling price.” *Biotechnology for Biofuels*, 8:173, 2015
- H. Chum, F. Nigro, R. McCormick, G. T. Beckham, J. E. A. Seabra, J. Saddler, L. Tao, E. Warner, R. P. Overend, “Chapter 5 - Conversion Technologies for Biofuels and Their Use.” SCOPE, Bioenergy & Sustainability: Bridging the gaps. Paris, 2015
- C. J. Scarlata, R. E. Davis, L. Tao, E. C. D. Tan, and M. Biddy, “Chapter3 - Perspectives on Process Analysis for Advanced Biofuel Production.” Direct Microbial Conversion of Biomass to Advanced Biofuels, M. E. Himmel. Amsterdam, Elsevier: 33-60, 2015
- M.J. Biddy, “Techno-economic motivations for coproduct manufacturing that enable hydrocarbon fuel production from lignocellulosic biomass.” Invited presentation, 2016 SIMB Annual Meeting and Exhibition, New Orleans, LA, July 2016
- D. Humbird, R. Davis, “Aerobic bioreactor scale-up: modeling and economics.” Presented at AspenTech Optimize 2015, Boston, MA, May 2015

Backup Slides

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NATIONAL RENEWABLE ENERGY LABORATORY

Paths to $3/GGE: Key Inputs for Pathways

Lipids

Lipid Pathway: Parameter	*Projection*
Lipid productivity (g/L-hr)	1.0
Lipid content (wt%)	70%
Conversion: Glucose → Lipid [total utilization] (%)	82% [100%]
Conversion: Xylose → Lipid [total utilization] (%)	81% [85%]
Conversion: Arabinose → Lipid [total utilization] (%)	81% [85%]
Modeled metabolic yield [Process yield] (g/g sugar)	0.27 [0.25]
Product recovery method	Autolyse
Product recovery yield	95%
Upgrading yield to fuels (wt% of lipid feed)	81 wt%
C yield across upgrading (C in fuel product/C in feed)	89%

Acids

Organic Acids Pathway: Parameter	*Projection*
Fermentation residence time (days)	1.5
Glucose utilization (%)	95%
Xylose utilization (%)	85%
Arabinose utilization (%)	85%
Modeled metabolic yield [Process yield] (g/g sugar)	0.41 [0.39]
Product recovery method	Low-pH pertractive fermentation
Product recovery yield	>99%
Upgrading yield to fuels (wt% of organic acid intermediate)	66 wt%
C yield across upgrading (C in fuel product/ C in acid)	89%

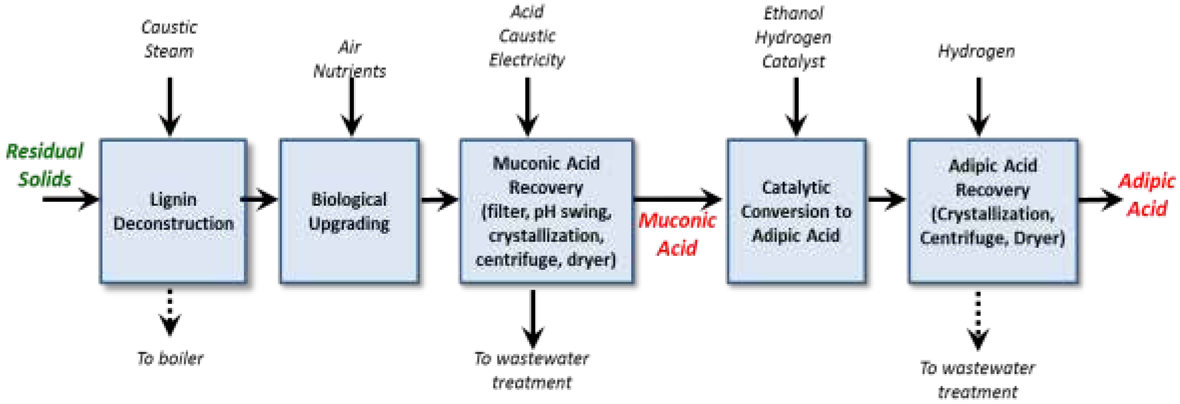
Fatty Alcohols

Fatty Alcohol Pathway: Parameter	*Projection*
FaOH productivity (g/L-hr)	1.0
FaOH theoretical metabolic yield (g/g sugar consumed)	0.28
FaOH modeled metabolic yield (g/g sugar consumed)	0.252
Conversion: Glucose → FaOH [total utilization] (%)	90% [100%]
Conversion: Xylose → FaOH [total utilization] (%)	90% [85%]
Conversion: Arabinose → FaOH [total utilization] (%)	90% [85%]
Product recovery method	Overlay-assisted secretion
Overlay:Broth Volume	1:10
Product recovery yield	95%
Upgrading yield to fuels (wt% of FaOH feed)	92 wt%
C yield across upgrading (C in fuel product/ C in feed)	98.5%

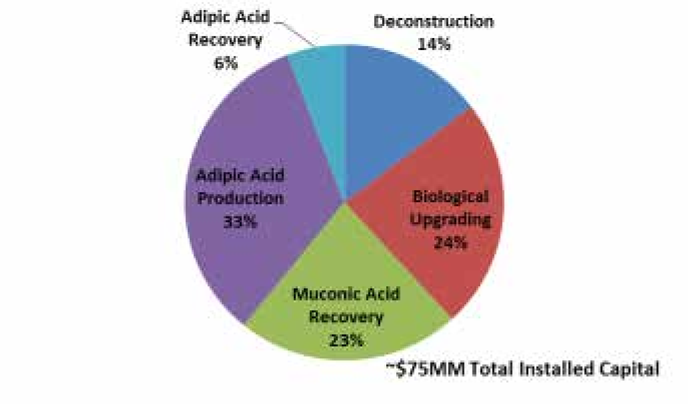
Alcohols/Diols

Alcohols/Diols Pathway: Parameter	*Projection*
Fermentation batch time (days)	1.5
Conversion: Glucose → 2,3-BDO [total utilization] (%)	85% [95%]
Conversion: Xylose → 2,3-BDO [total utilization] (%)	70% [85%]
Conversion: Arabinose → 2,3-BDO [total utilization] (%)	0% [85%]
Conversion: Glucose → Ethanol [total utilization] (%)	10% [95%]
Conversion: Xylose → Ethanol [total utilization] (%)	15% [85%]
Conversion: Arabinose → Ethanol [total utilization] (%)	85% [88%]
Modeled metabolic yield [Process yield] (g/g sugar)	0.51 [0.49]
Product recovery method	Distillation
Ethanol recovery yield	98%
2,3-BDO recovery yield	96%
C yield across upgrading (C in fuel product/C in feed)	91%

Paths to $3/GGE: Lignin-to-Coproducts Train



- Base case utilizes lignin/unconverted C removed via SLS after EH (after fermentation for alcohol/diol case) AND DMR liquor
- Lignin conversion train includes significant refinements beyond 2013 design case estimates for conversion/recovery/upgrading
- All scenarios appear plausible to achieve <60% C yield to product

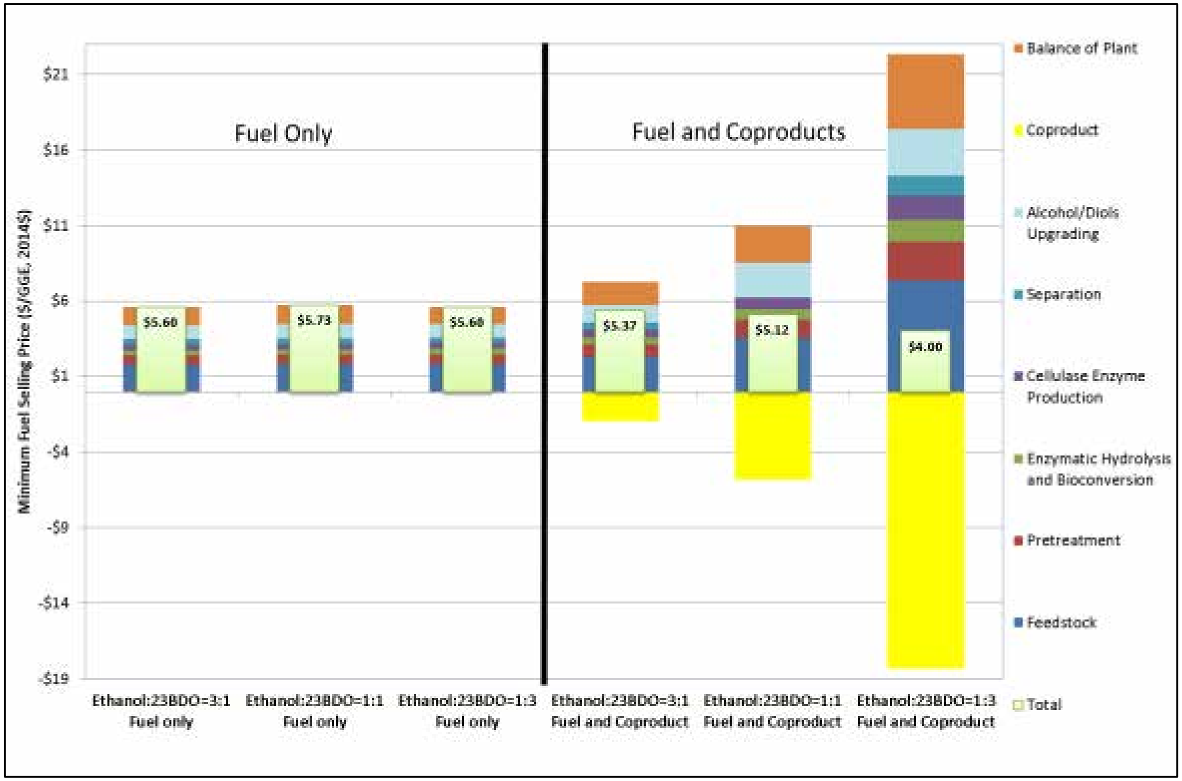


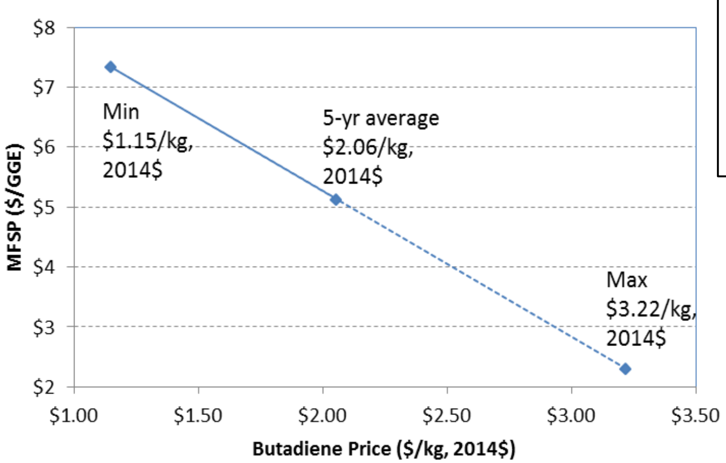
~$75MM Total Installed Capital

Sensitivity Scenarios: Anaerobic Cases (Alcohol/Diol)

Alcohol/diol case:

- MFSP fairly insensitive to EtOH:BDO ratio
- Potential for significant cost reduction if instead BDO is converted to butadiene coproduct (but results in low C yield to fuels)
  - Highly sensitive to coproduct value
- Also potential for better separation strategies

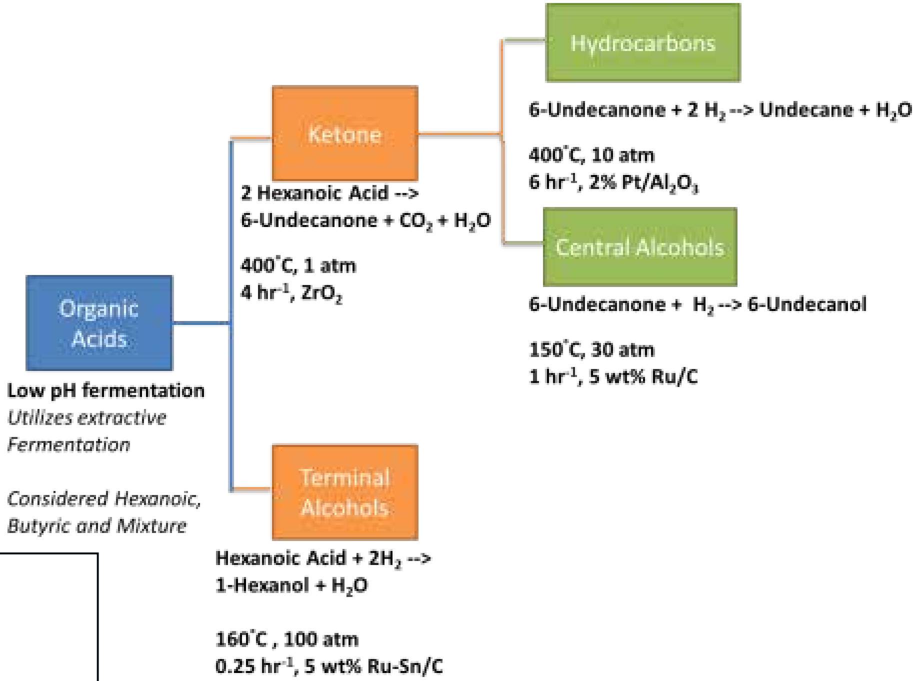




Sensitivity Scenarios: Anaerobic Cases (Acids)

Organic acid case:

- Multiple routes possible from organic acids to products
- Potential for oxygenated blendstocks vs hydrocarbon fuel
- MFSP for HC base case similar to ketone; potential for marginal cost reduction for terminal alcohol product



Organic Acids

Low pH fermentation

Utilizes extractive Fermentation

Considered Hexanoic, Butyric and Mixture

Ketone

2 Hexanoic Acid --> 6-Undecanone + CO_2 + H_2O

400˚C, 1 atm

4 hr^{-1}, ZrO_2

Hydrocarbons

6-Undecanone + 2 H_2 --> Undecane + H_2O

400˚C, 10 atm

6 hr^{-1}, 2% Pt/Al_2O_3

Central Alcohols

6-Undecanone + H_2 --> 6-Undecanol

150˚C, 30 atm

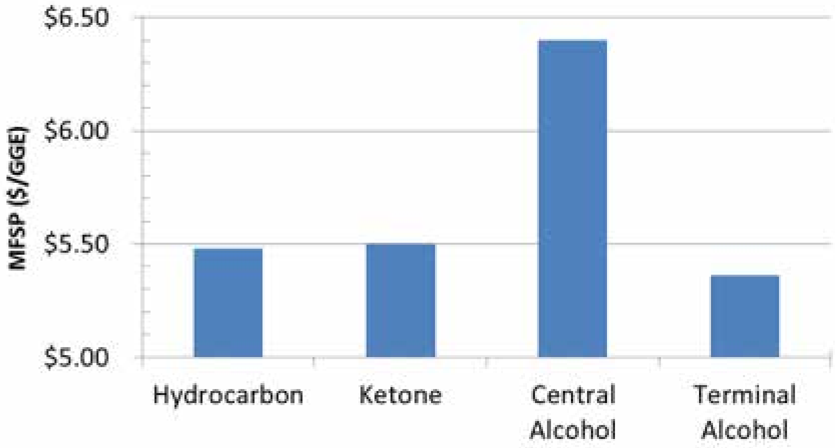
1 hr^{-1}, 5 wt% Ru/C

Terminal Alcohols

Hexanoic Acid + 2H_2 --> 1-Hexanol + H_2O

160˚C , 100 atm

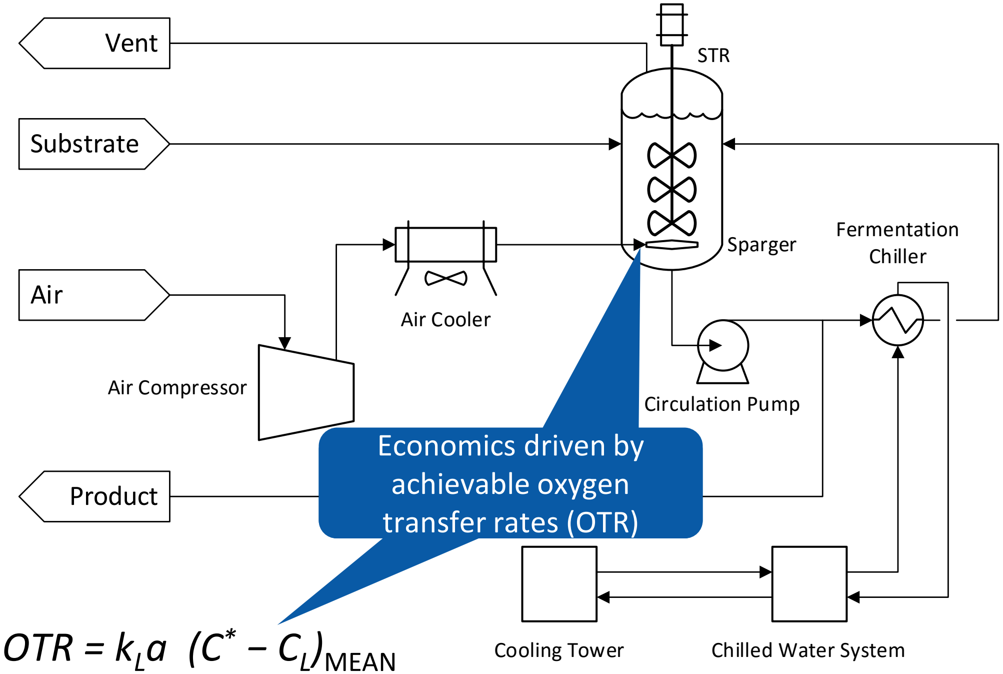
0.25 hr^{-1}, 5 wt% Ru-Sn/C



Metric (Hexanoic Acid Basis)	*Hydrocarbon*	*Ketone*	*Central Alcohol*	*Terminal Alcohol*
MFSP ($/GGE)	$5.48	$5.50	$6.40	$5.36
C efficiency from biomass (%)	25%	25%	25%	27%
Fuel yield (GGE/ton)	43.5	41.2	42.3	46.3
TCI ($MM)	$520	$510	$518	$555
Fuel carbon chain length	11	11	11	6

Technical Accomplishments/Progress/Results: *Refining Aeration Cost Estimates*

- 2013 design report initially assumed aerated CSTRs based on vendor feedback
- We subsequently questioned this choice and conducted several joint activities with PSI project to validate CSTR economics and evaluate other designs
- Joint work culminated in FY16 with PSI Go/No-Go to demonstrate >5% MFSP improvement in switching to BCR vessels
- Conclusion = BCRs are more optimum for large-scale commodity fuel production



Economics driven by achievable oxygen transfer rates (OTR)

$$OTR = k_L a \ (C^* - C_L)_{MEAN}$$

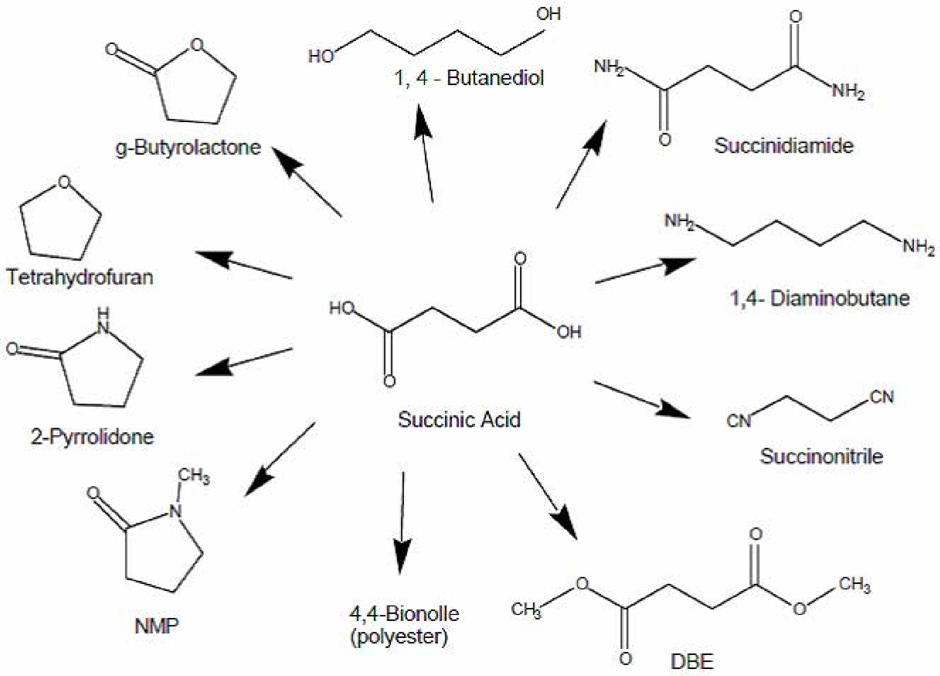
$$STR: k_L a \ [s^{-1}] = 0.002 \ (P / V \ [W/m^3])^{0.7} \ (u_S \ [m/s])^{0.2}$$

$$BCR: k_L a \ [s^{-1}] = 0.32 \ (u_S \ [m/s])^{0.7} \ (\mu_{eff} \ [cP])^{-0.84} \ X \ 1.025^{(T \ [°C] - 20)}$$

BCR vs STR, 500 m^3 reactors		BCR	STR	% reduction BCR vs STR
RDB Production	MMGGE/y	24.7	24.7	
MFSP	$/GGE	$7.80	$9.39	17%
A300	$/GGE	$2.25	$3.84	41%
Aerobic equip only	$/GGE	$0.88	$2.42	64%
Capital charge	*$/GGE*	*$0.56*	*$1.83*	*70%*
Electric power	*$/GGE*	*$0.20*	*$0.21*	*7%*
Fixed costs (maintenance)	*$/GGE*	*$0.13*	*$0.39*	*67%*

BCR vs STR, 1,000 m^3 reactors		BCR	STR	% reduction BCR vs STR
RDB Production	MMGGE/y	24.7	24.7	
MFSP	$/GGE	$7.46	$8.27	10%
A300	$/GGE	$1.90	$2.71	30%
Aerobic equip only	$/GGE	$0.54	$1.33	59%
Capital charge	*$/GGE*	*$0.28*	*$0.92*	*70%*
Electric power	*$/GGE*	*$0.20*	*$0.21*	*6%*
Fixed costs (maintenance)	*$/GGE*	*$0.07*	*$0.20*	*68%*

Succinic Acid



Product	World Production (thousand tons/year)	Price ($/ton)	Projected growth rate	Primary Usage
1,4 Butanediol	>1,000	3170	5%	Tetrahydrofuran, specialty chemicals
Maleic Anhydride	>2,000	1240	5%	Polyster resin, BDO, Fumaric Acid
Tetrahydrofuran	>1,500	2300	5%	Polymers, solvents
Poly-butyl succinate	>10-15			Polymer
Pyrrolidinones	>500			Solvent