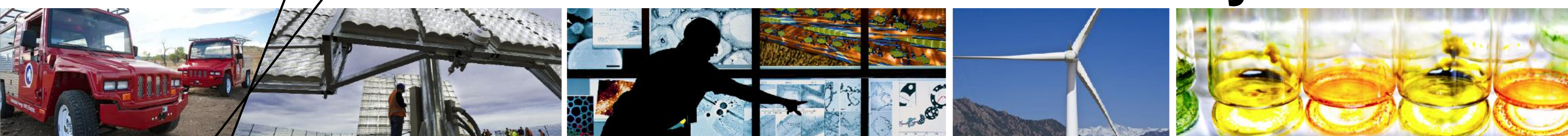
DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

Biochemical Platform Analysis



Biochemical Platform Review
March 23, 2015
Alexandria, VA

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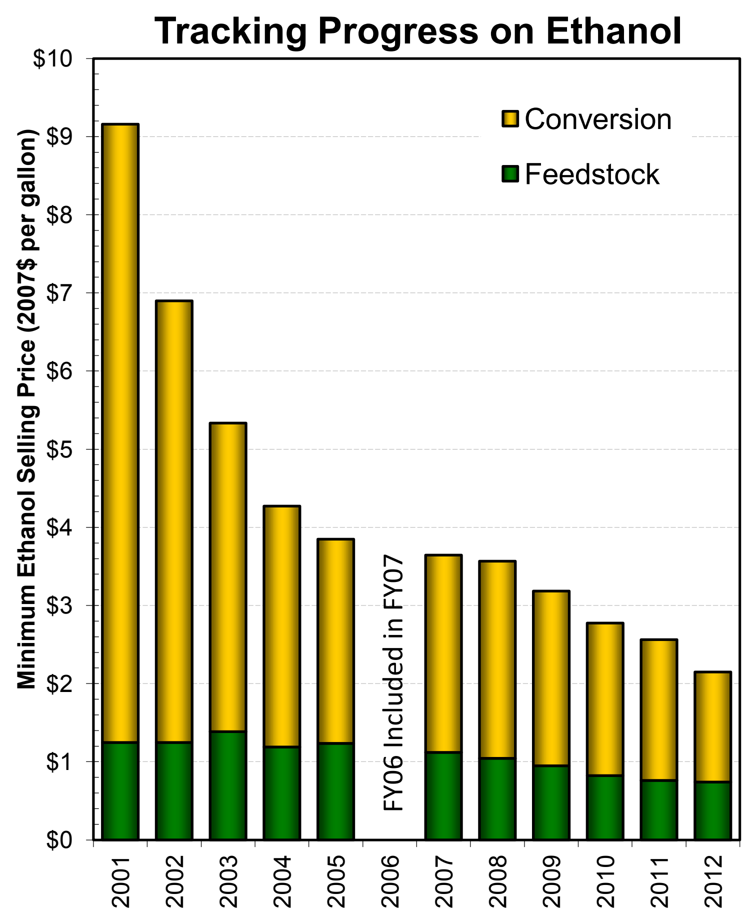
Goal Statement

Biochemical Platform Analysis Objective:

- Provide **process design and economic analysis support** for the biochemical conversion platform, to **guide R&D priorities** for both NREL and BETO
  - Translate demonstrated or proposed research advances into economics quantified as $/gal ($/GGE) selling price

- 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 information in a transparent way (the "design report" process)

- This project **directly supports the BETO Program** by assisting in the development of cost benchmarks and future targets for use in MYPP planning
  - *Guide R&D towards economic viability, eventual adoption of hydrocarbon biofuels into U.S. market*



Example of the use of TEA to track historical progress towards goals under NREL's ethanol program

Quad Chart Overview

Timeline

- Started: 2010
- Finish: 2017
- 75% complete

Barriers

- Barriers addressed
  - BT-H: Cleanup/Separation
  - BT-J: Biochemical Conversion Process Integration
  - BT-K: Product Acceptability and Performance

Budget

	Total Costs FY 10 – FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date
DOE Funded ($MM)	$1.8	$1.1	$0.9	$2.7
Project Cost Share (Comp.)*	NA	NA	NA	NA

Partners

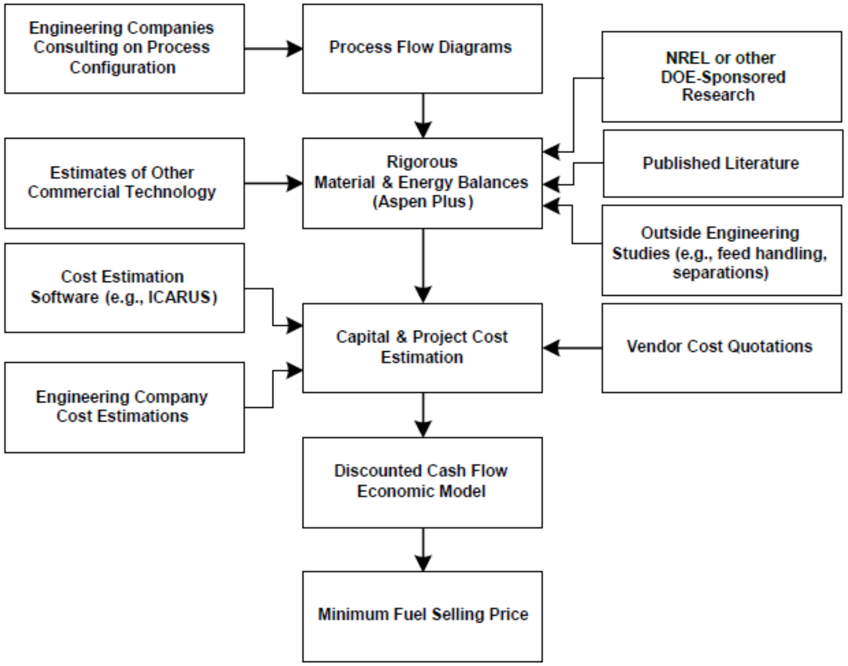
- Partners
  - No partners with shared funding
- Other interactions/collaborations
  - INL – Feedstock interface activities, supply chain analysis
  - ANL – GREET modeling team, water quality assessment team
  - PNNL – Biochemical modeling/report reviews
  - Industrial partners
  - Engineering subcontractors

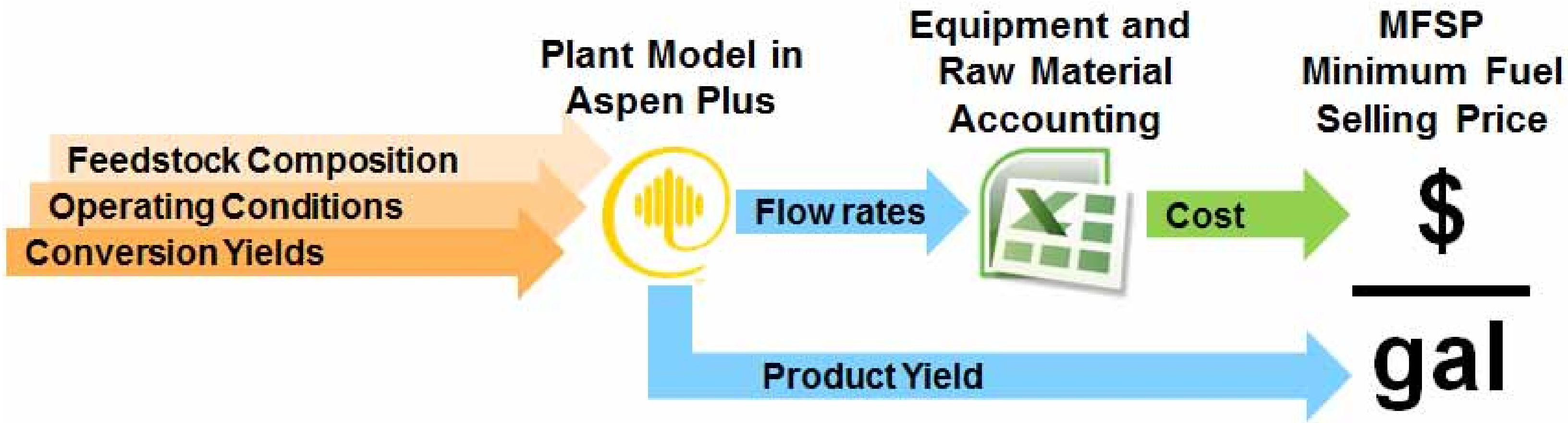
Project Overview

- NREL has a long history of establishing, maintaining, and exercising 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, process alternatives
  - “Basic engineering” and process optimization
- Phased approach:
  1) *Develop baseline models using best available data*
  2) *Validate and peer review modeling assumptions, publish “design reports”*
  3) *Assist in cost target development*
  4) *Iterate with researchers and external stakeholders as new data becomes available to refine models*
- Types of analysis:
  - Techno-economic analysis (TEA)
  - Lifecycle analysis (LCA)/sustainability metrics
- Technology focus:
  - 2001-2012: cellulosic ethanol
  - 2013+: hydrocarbon biofuels, bioproducts

Approach (Technical)

- Process model in Aspen Plus based on NREL research data (where available), published literature (when necessary)
- Assumes n^{th}-plant project cost factors and financing (ignores first-of-a-kind risks)
- Discounted cash-flow ROR calculation determines minimum fuel selling price (MFSP)
- Credibility of analysis supported by vendor-based cost estimates, thorough vetting with industry and research stakeholders
- Research advances → Higher modeled conversion → Lower MFSP





Approach (Management)

- Project management tracked using milestones
- Activities are highly integrated with research efforts, assist in go/no-go decisions for R&D
  - Example – FY14 TEA assessment for PHB catalysis to fuels; no-go decision on the research pathway due to challenging cost potential

- *Critical success factors:*
  - Leverage process design to highlight barriers for scale-up/commercialization in under-researched areas
  - Conduct sensitivity analysis to find biggest “bang for the buck” items for targeted improvement
  - 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
  - TEA shows that economics are more challenging for long-chain hydrocarbon pathways vs ethanol; requires rigorous process optimization, maximizing carbon yields, considering coproduct opportunities

Project Milestones/Activities	FY14				FY15				FY16 (not yet set)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Biological conversion pathway												
Water use/WWT optimization in 2013 design case	▶				▶							
Biological conversion R&D out-year targets		▲										
Lignin co-product modeling			▶									
SOT assessment/out-year targeting updates				▲				▲				
Engineering design/alternative scenario studies						▲	▲	▶		▼		
Catalytic conversion pathway												
Catalytic conversion design report				▶	▲							
SOT assessment/out-year targeting updates					▲							
Alternative catalytic processing scenarios				▲▼				▲				

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

Technical Accomplishments/Progress/Results:
2013 Biological Pathway Design Report

- TEA detailed modeling focused on near-term (“2017”) goal of $5/GGE selling price for renewable diesel blendstock
- Represents intermediate target on path to ultimate 2022 goal of $3/GGE, but allows for high transparency of process/design details
- Vendor quotes provided for all new operations via engineering contractor
- Thoroughly vetted through 15 industry peer reviewers
- Baseline pathway derived from ethanol process: whole-hydrolysate conversion of C5 + C6 sugars to diesel-range fatty acid intermediate
  - Aggressive targets for yield + productivity
  - Assumed generic organism with fatty acid secretion capability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Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons:
Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons

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

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Technical Report
NREL/TP-5100-60223
October 2013

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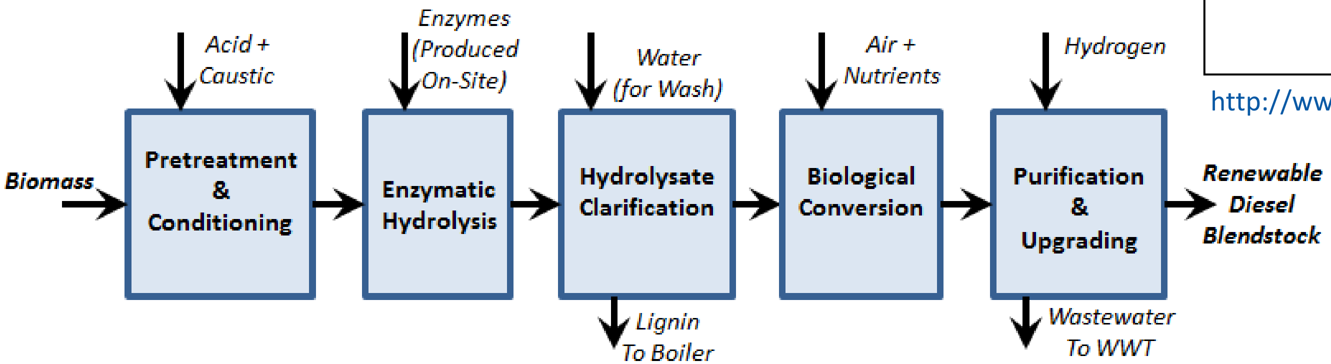
http://www.nrel.gov/docs/fy14osti/60223.pdf



2013 Design Report Results

2013 Hydrocarbon Design Report Results – Contrasted Against 2011 Ethanol Design Report	2012 Ethanol Target	2017 HC Target
Minimum Fuel Selling Price ($/GGE, 2011$)	**$3.61**	**$5.10**
Feedstock Contribution ($/GGE, 2011$)	$1.13	$1.76
Enzyme Contribution ($/GGE, 2011$)	$0.60	$0.37
Non-Enzyme Conversion Contribution ($/GGE, 2011$)	$1.88	$2.96
Yield (GGE/dry ton)	52	45
Feedstock		
Feedstock Cost ($/dry ton)	$58.50	$80.00
Pretreatment		
Solids Loading (wt%)	30%	30%
Xylan to Xylose (including enzymatic)	90%	90%
Xylan to Degradation Products	5%	5%
Conditioning		
Ammonia Loading (g per L hydrolysate liquor)	4.8	1.6
Hydrolysate solid-liquid separation	No	No
Xylose Sugar Loss	1%	0%
Glucose Sugar Loss	0%	0%
Enzymes		
Enzyme Loading (mg/g cellulose)	20	10
Enzymatic Hydrolysis & Bioconversion		
Total Solids Loading (wt%)	20%	20%
Combined Saccharification & Conversion Time (d)	5	6.5
Corn Steep Liquor Loading (wt%)	0.25%	0.25%
Combined *cellulose-to-glucose* x *glucose-to-product**	86%	86%
Xylose to Product	85%	85%
Arabinose to Product	85%	85%
Metabolic Yield (total sugar-to-product)	0.44	0.28

All: 45 vs 52 GGE/ton yield
- Theoretical metabolic energy yield limited to ~91% vs EtOH

Feedstock: $80 vs $58.50/ton
- Cost increase consistent with targets at INL

Enzymes: 10 vs 20 mg/g loading
- Reflects 5 more years of commercial enzyme progress

Conversion: Higher cost/complexity
- TCI = $583 MM vs $471 MM
- Facility on-line time = 90% vs 96%

More information:

2011 Ethanol Design Report:
www.nrel.gov/docs/fy11osti/47764.pdf

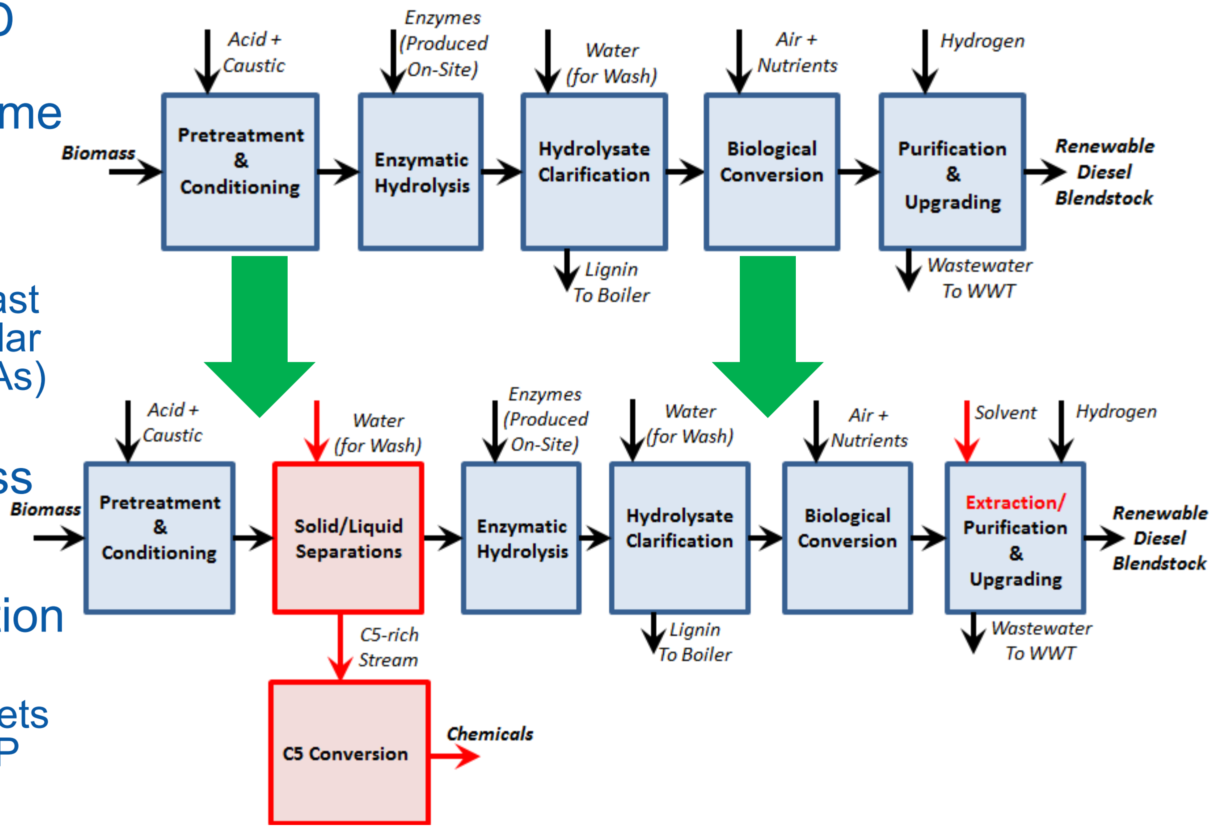
2013 Hydrocarbon Design Report:
www.nrel.gov/docs/fy14osti/60223.pdf

*Does not include losses to contamination or cell growth

Update to Biological Design Case

- While 2013 design case targets are plausible, subsequent R&D benchmark data showed large hurdles to overcome in short time
  - Low C5 conversion with whole hydrolysate
  - Low productivity
  - Best performance seen with yeast (requires extraction of intracellular lipids, not simple secretion of FAs)

- FY14 SOT modifies the process to add C5 sugar separation, conversion to chemical co-product (succinic acid), extraction of lipids from C6 train
  - Allows for more achievable targets by 2017 while maintaining MFSP



Bioconversion Metrics – C6 Train to Fuel	Design Report Basis	New Schematic
Bioconversion Volumetric Productivity (g/L-hr)	1.3	0.4
Glucose to Product [total glucose utilization]	87% [95%]	78% [100%]
Xylose to Product [total xylose utilization]	82% [86%]	76% [98%]
Arabinose to Product [total arabinose utilization]	85% [85%]	-
Intermediate Product Recovery	97%	90%
Carbon Yield to RDB from Biomass	26.2%	12.5%
Carbon Yield to Succinic Acid from Biomass	n/a	12.2%

Overview of NREL Biochem Project Structure

Biochemical Conversion Platform - NREL

- Feed/Process Interface **2.2.1.101**
- Biochemical Platform Analysis **2.1.0.100**
- Pretreatment and Process Hydrolysis **2.2.3.100**
- Analytical Development and Support **2.5.1.101**
- Separations Development and Application **2.4.1.101**
- Targeted Microbial Development **2.4.3.102**
- Enzyme Engineering and Optimization **2.5.4.100**
- BC Process Modeling and Simulation **2.5.1.100**
- Biological Upgrading of Sugars **2.3.2.105**
- Lignin Utilization **2.3.4.100**
- Catalytic Upgrading of Sugars **2.3.1.101**
- Virent Blackbird - NREL **2.4.1.201**
- Process Integration (Bench Scale) **2.4.1.100**
- Process Integration (Pilot Scale) **2.4.1.102**

Seed Projects

- Biological Lignin Depolymerization **2.3.2.100**
- Genetic Engineering of *C. Thermocellum* **2.5.3.100**
- Biogas to Fuels-Methanotrophic Organism **2.3.2.102**
- Waste to Energy TEA **2.1.0.103**

Validation Projects

- SynBio Validation **2.6.1.103**
- BC Hydrocarbon Fuel Validation **2.6.1.102**

Out-Year Targeting for R&D

	Design Report Basis	2014 SOT	2015 Projection	2016 Projection	New 2017 Target
Minimum Fuel Selling Price ($/GGE, 2011$)	***$5.10***	**$12.97**	**$10.14**	**$7.43**	**$5.03**
Feedstock Contribution ($/GGE, 2011$)	*$1.76*	$3.88 [1]	$3.20 [1]	$2.47 [1]	$1.87 [1]
Conversion Contribution ($/GGE, 2011$)	***$3.33***	**$9.09** [1]	**$6.93** [1]	**$4.97** [1]	**$3.16** [1]
RDB Fuel Yield (GGE/dry ton)	*45*	18	20	20	22
Succinic Acid Yield (lb/dry ton)	*NA*	197	206	232	270
Feedstock					
Feedstock Cost ($/dry ton) [2]	*$80*	$130	$115	$95	$80
Feedstock Blend	*Blend*	Stover	Stover	Blend	Blend
Pretreatment/Separation					
Solids Loading (wt%)	*30%*	30%	30%	30%	30%
Xylan to Xylose (including conversion in C5 train)	*>73%*	73%	75%	78%	78%
Hydrolysate solid-liquid separation	*No*	Yes	Yes	Yes	Yes
Xylose Sugar Loss (into C6 stream after acid PT separation)	*NA*	5%	4%	2.5%	1%
Enzymes					
Enzyme Loading (mg/g cellulose)	*10*	14	12	10	10
Enzymatic Hydrolysis & Bioconversion – C6 Train					
Total Solids Loading to Hydrolysis (wt%)	*20%*	15%	15%	17.5%	17.5%
Enzymatic Hydrolysis Time (d)	*3.5*	3.5	3.5	3.5	3.5
Hydrolysis Glucan to Glucose	*90%*	77%	85%	85%	90%
Hydrolysis Residual Xylan to Xylose	*>30%*	30%	30%	30%	30%
Glucose Sugar Loss (into solid lignin stream after EH separation)	*1%*	5%	4%	2.5%	1%
Expt'l bioconversion scale/method	*NA*	Bench scale/ Batch	Bench scale/ Fed-batch	Bench scale/ Fed-batch	Pilot scale/ Fed-batch
Bioconversion Volumetric Productivity (g/L-hr)	*1.3*	0.29	0.3	0.35	0.4
Lipid Content (wt%)	*NA*	57%	57%	60%	60%
Glucose to Product [total glucose utilization] [3]	*87% [95%]*	75% [100%]	75% [100%]	78% [100%]	78% [100%]
Xylose to Product [total xylose utilization] [3]	*82% [86%]*	74% [98%]	74% [98%]	76% [98%]	76% [98%]
C6 Train Bioconversion Metabolic Yield (Process Yield) (g/g sugars)	*0.34 (0.28)*	0.26 (0.26)	0.26 (0.26)	0.27 (0.27)	0.27 (0.27)
Intermediate Product Recovery	*97%*	90%	90%	90%	90%
Carbon Yield to RDB from Biomass	*26.2%*	10.4%	11.4%	11.8%	12.5%
Coproduct Production Performance – C5 Train					
Bioconversion Volumetric Productivity (g/L-hr)	*NA*	0.3	1	1.5	2.0
C5 Train Bioconversion Metabolic Yield (Process Yield) (g/g sugars)	*NA*	0.63 (0.59)	0.64 (0.60)	0.66 (0.65)	0.795 (0.74)
Succinic Acid Recovery Efficiency	*NA*	80%	80%	80%	80%
Carbon Yield to Succinic Acid from Biomass	*NA*	8.9%	9.3%	10.5%	12.2%

SOT demonstrated at NREL; projections based on BETO R&D targets

Recovery yields targeted to be demonstrated by 2017 (2014-2016 fixed constant prior to 2017 demo)

[1] Cost breakdowns to feedstock vs conversion cost contributions are allocated in new target case according to carbon efficiency to RDB fuel vs succinic acid
[2] Feedstock costs based on a 5% "ash equivalent" basis for all years considered, consistent with values provided by INL ash "dockage" costs
[3] First number represents sugar conversion to desired product (FFA), values in parentheses indicate total sugar utilization

Conversion Stage Sustainability Metrics - Biological

Sustainability Metric [1]	2014 SOT	2015 Projection	2016 Projection	2017 Design Case	2022 Projection [2]
GHGs (g CO_2-e/MJ fuel) (fossil emissions)	-63.8	-58.0	-72.0	-78.6	-301
Fossil Energy Consumption (MJ fossil energy/MJ fuel)	-0.9	-0.8	-1.0	-1.1	-1.3
Total Fuel Yield (GGE/dry ton)	18	20	20	22	44
Biomass Carbon-to-Fuel Efficiency (C in fuel/C in biomass)	10%	11%	12%	13%	26%
Biomass Carbon-to-Coproduct Efficiency (C in succinic acid coproduct/C in biomass)	9%	9%	11%	12%	NA [2]
Water Consumption (m^3/day; gal/GGE fuel) [1]	6,294 m^3/day (42 gal/GGE)	6,146 m^3/day (48 gal/GGE)	5,817 m^3/day (45 gal/GGE)	5,773 m^3/day (42 gal/GGE)	4,553 m^3/day (12 gal/GGE)
Net Electricity Import (KWh/GGE)	19.9	19.8	21.1	24.0	0.3

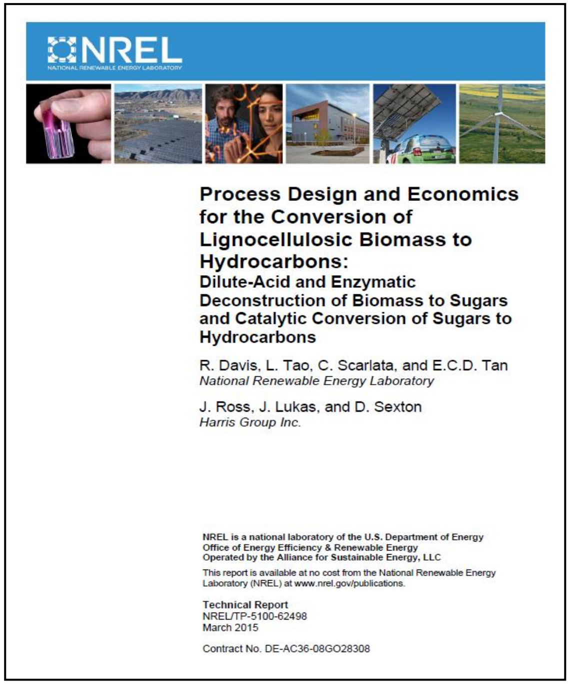
[1] *Note, gal/GGE water metric is fully allocated to fuel product (not distributed to coproduct train), thus appears high in this format*

[2] *2022 projection represents one possible scenario based on converting a fraction of lignin to adipic acid co-product; pathway reverts back to whole-hydrolysate conversion to fuels, thus removes C5 sugars-to-succinic acid process train*

- Project also tracks key sustainability metrics for biorefinery design cases
- Sustainability metrics above only consider conversion stage (not a full Well-to-Wheel LCA)
- Demonstrated improvements in GHG emissions alongside TEA costs when routing lignin to select coproduct options in support of 2022 targets for $3/GGE

Technical Accomplishments/Progress/Results: *2014 Catalytic Pathway Design Report*

- Design pathway based on aqueous phase reforming ("APR") catalysis of hydrolysate
  - Potential for flexibility around conversion of multiple hydrolysate species beyond monomeric sugars, including oligomers, acetate, sugar degradation products, soluble lignin, etc.
  - Catalytic upgrading based on patent literature for commodity sugars with additional guidance from industry (engineering subcontractor, technology vendors, and external industry guidance)
  - Maintains consistent front-end assumptions for biomass deconstruction (deacetylation, PT, EH) as biological conversion pathway
- Followed similar approach as biological design report
  - Vendor/subcontractor inputs
  - Report vetted through 11 external peer reviewers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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

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Technical Report
NREL/TP-5100-62498
March 2015

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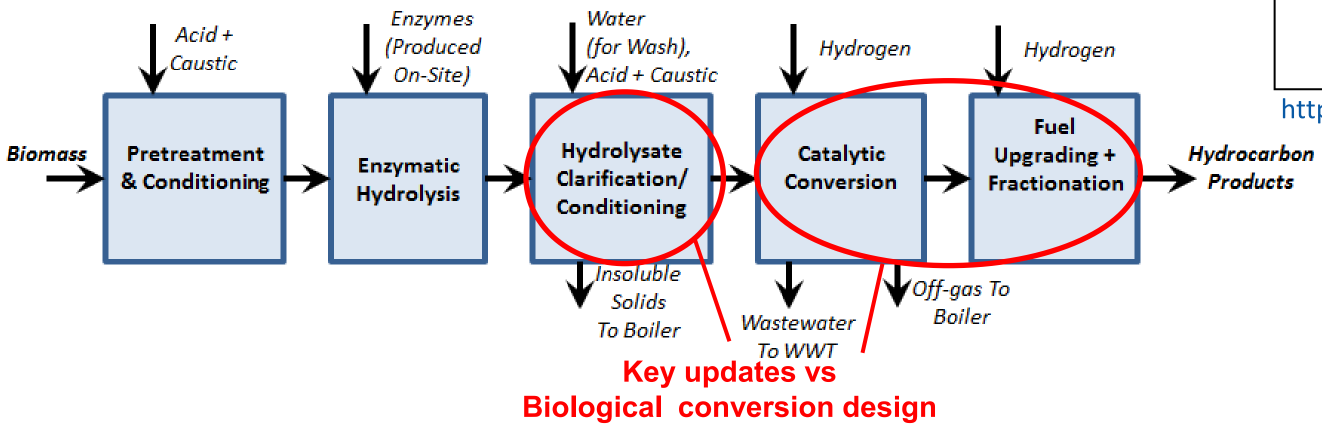
http://www.nrel.gov/docs/fy15osti/62498.pdf



Out-Year Targets: Catalytic Pathway

	2014 SOT Estimate	2015	2016	2017 Design Case Targets
Minimum Fuel Selling Price ($/GGE, 2011$)	**$7.29**	**$5.89**	**$4.83**	**$4.05**
Feedstock Contribution ($/GGE, 2011$)	$2.58	$1.95	$1.41	$1.02
Conversion Contribution ($/GGE, 2011$)	**$4.71**	**$3.94**	**$3.42**	**$3.03**
Yield (GGE/dry ton)	50.3	59.1	67.5	78.3
Feedstock				
Feedstock Cost ($/dry ton) [1]	$130	$115	$95	$80
Feedstock Blend	Stover	Stover	Blend	Blend
Pretreatment				
Solids Loading (wt%)	30%	30%	30%	30%
Xylan to Xylose Conversion (overall) [2]	81%	84%	87%	90%
Enzymatic Hydrolysis				
Solids Loading (wt%)	20%	20%	20%	20%
Enzymatic Hydrolysis Time (d)	3.5	3.5	3.5	3.5
Glucan to Glucose Conversion [2]	77%	85%	85%	90%
Enzyme Loading (mg/g cellulose)	14	12	10	10
Sugar Conditioning				
Sugar Loss in S/L Separation (Belt Filter)	5%	4%	2.5%	1%
Microfiltration Soluble Retention Loss	10%	10%	10%	10%
Catalytic Conversion and Upgrading				
Hydrogen Feed Molar Ratio (H_2 : total APR feed)	9.8	9.8	9.8	9.8
Total Hydrogen Consumption (wt % vs APR feed)	4.6%	5.3%	5.9%	6.5%
Hydrogenation WHSV (h^{-1})	0.7	0.85	1.0	1.2
APR WHSV (h^{-1})	0.7	0.8	0.9	1.0
Condensation WHSV (h^{-1})	0.7	0.85	1.0	1.2
Hydrogenation catalyst lifetime (years)	0.5	0.6	0.8	1
APR catalyst lifetime (years)	1	1.3	1.6	2
Condensation catalyst lifetime (years)	1	1.3	1.6	2
Overall C Yield to Fuels vs APR Feed Components	64%	70%	78%	86%
Overall C Yield to Fuels vs Biomass C (vs Total C) [3]	29% (25%)	34% (28%)	39% (32%)	45% (36%)

*All projections based on external SMR H_2 sourcing

SOT demonstrated at NREL; projections based on BETO R&D targets

SOT:

-Based on patent literature (for corn syrup)

-Catalyst lifetime reduced by 50%, C yield to fuels reduced by 25% (assumptions)

2015/2016:

-Interpolated projections to meet 2017 design case targets

[1] Feedstock costs shown here based on a 5% "ash equivalent" basis for all years considered, per discussion with INL

[2] Values represent glucan/xylan conversion to both monomeric and oligomeric sugars

[3] "Total carbon" includes external natural gas carbon implicit in SMR-derived H_2

Conversion Stage Sustainability Metrics - Catalytic

Sustainability Metric [1]	2014 SOT	2015 Projection	2016 Projection	2017 Design Case	2022 Projection [2]
GHGs (g CO_2-e/MJ fuel) (fossil emissions)	39.8	42.7	45.8	49.2	-69.4
Fossil Energy Consumption (MJ fossil energy/MJ fuel)	0.73	0.75	0.78	0.82	0.3
Total Fuel Yield (GGE/dry ton)	50	59	68	78	76
Biomass Carbon-to-Fuel Efficiency (C in fuel/C in biomass)	29%	34%	39%	45%	41%
Total Carbon-to-Fuel Efficiency (C in fuel/C in biomass + NG)	25%	28%	32%	36%	33%
Water Consumption (m^3/day; gal/GGE fuel)	5,038 m^3/day (12.0 gal/GGE)	4,635 m^3/day (9.4 gal/GGE)	4,269 m^3/day (7.6 gal/GGE)	3,817 m^3/day (5.8 gal/GGE)	3,496 m^3/day (5.3 gal/GGE)
Net Electricity Export (KWh/GGE)	4.9	3.6	2.6	1.7	0.6

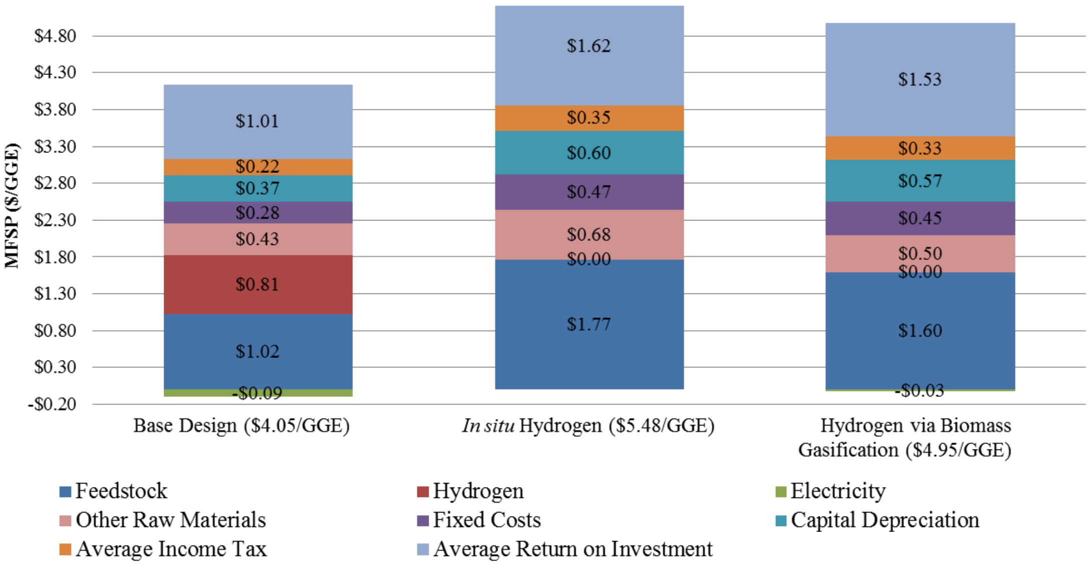
[1] *Note, all cases based on external SMR H_2 sourcing basis*

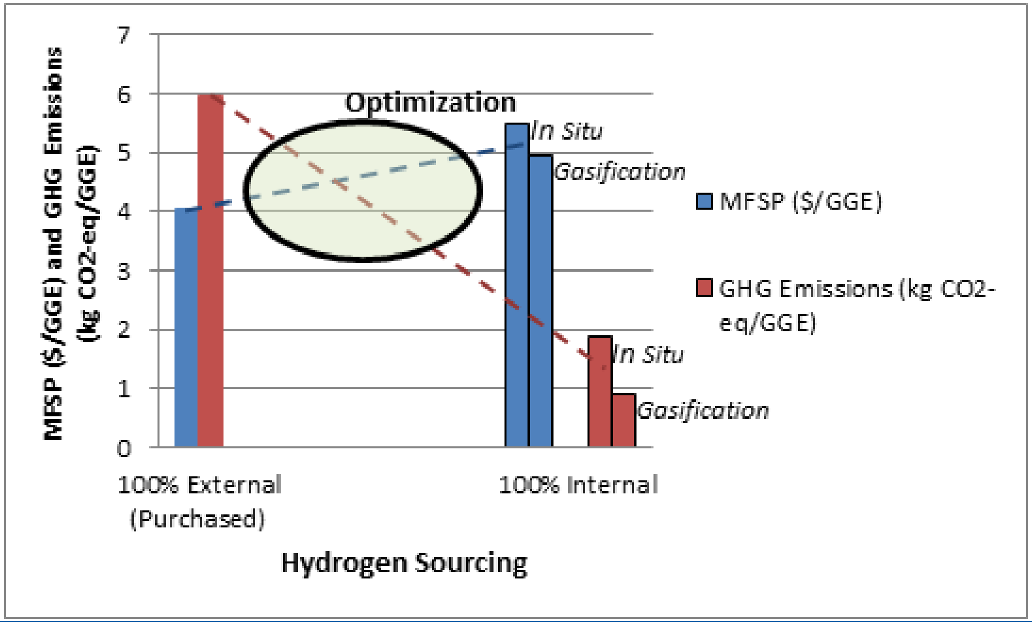
[2] *2022 projection represents one possible scenario based on converting a fraction of lignin to adipic acid co-product*

- Sustainability metrics above only consider conversion stage (not a full WTW LCA)
- Alternative H_2 scenarios in design report proved very useful in quantifying large differences between SMR H_2 sourcing and alternative scenarios via *in situ* reforming of sugars or biomass gasification
  - 3-6X lower GHG emissions from conversion stage for alternative (internal) H_2 scenarios vs SMR basis

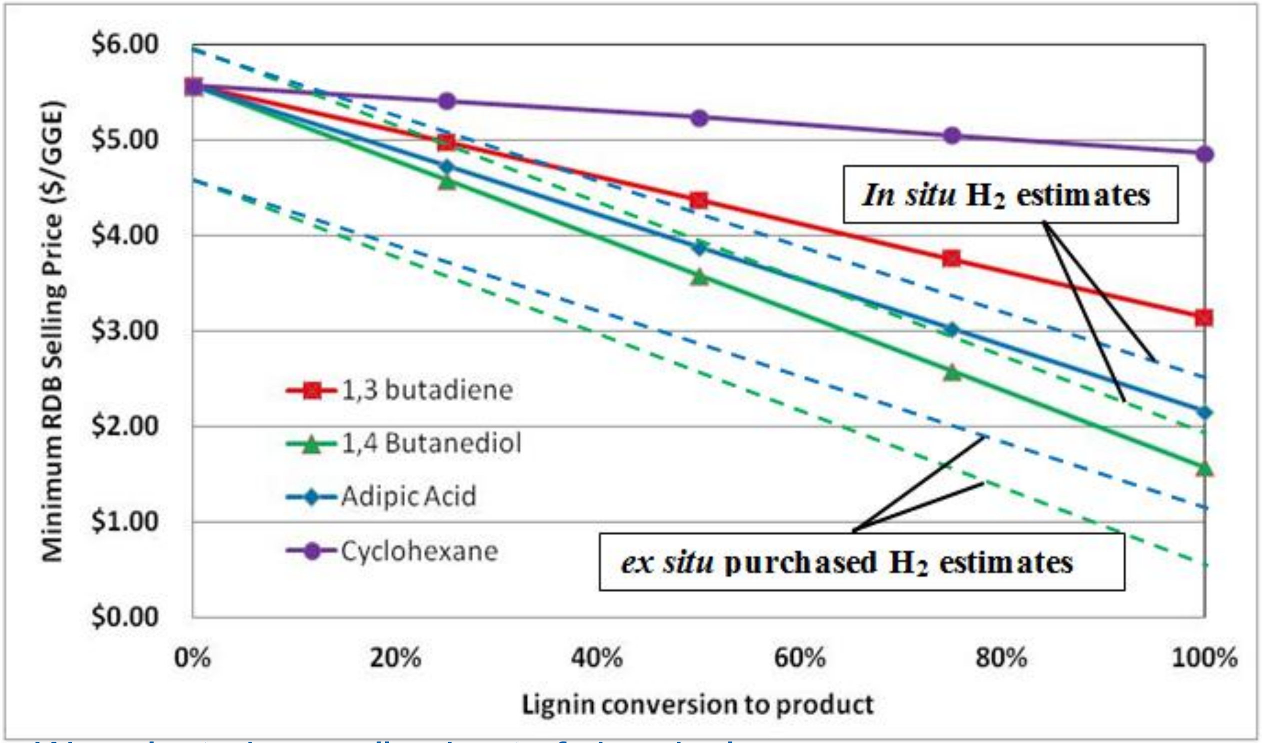
Alternative H_2 Sourcing Scenarios

- Base case assumes large hydrogen import purchased from off-site natural gas SMR production (*ex situ*)
- Alternative case investigates producing hydrogen internally (*in situ*) via reforming reactions from a fraction of hydrolysate, or by diverting a fraction of feedstock biomass to gasification train
  - Increases cost to \$5.48/GGE (*in situ*), \$4.95/GGE (gasification)
  - Requires large fractional diversion of hydrolysate (41%, *in situ*) or biomass (36%, gasification) to generate required H_2 = reduced fuel yield
  - Although lower yield/higher cost, also tradeoffs in sustainability





Biochemical Pathways: Path to $3/GGE



- Solid lines = biological pathway, potential for 2022
- Dashed lines = reference for catalytic pathway scenarios for purchased and *in situ* H_2

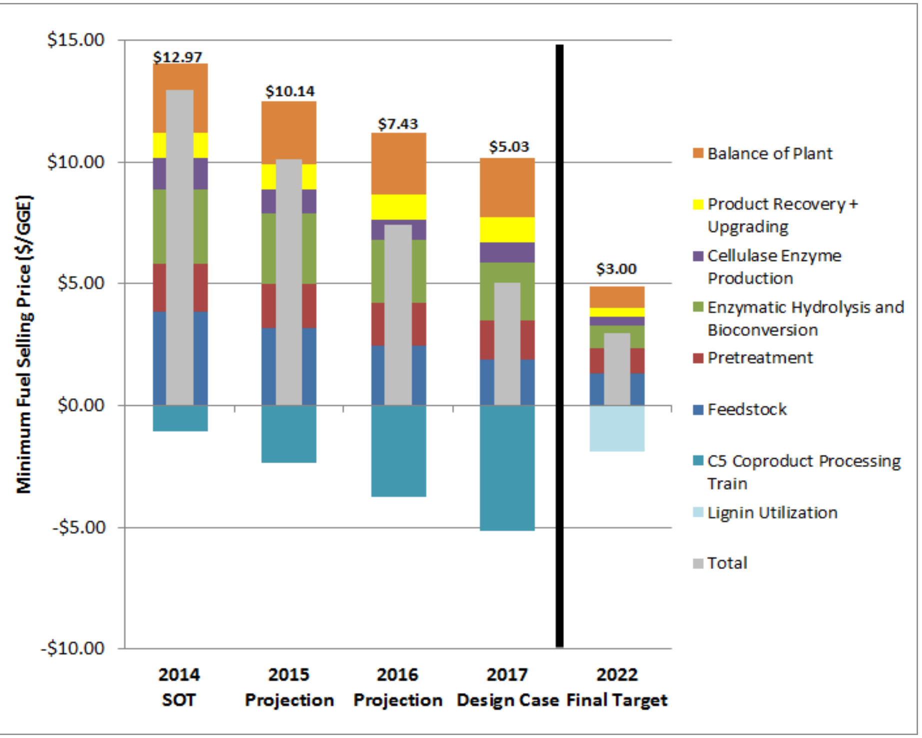
*Plot is based on % lignin conversion, vs 80% solubilized upstream in deconstruction via modified alkaline pretreatment

- We selected a small subset of chemical coproducts among many more possibilities
- Some coproducts show the potential to achieve $3/GGE target, others do not
- Critical to consider market volume capacity for coproducts from a high-volume industry such as biofuels
  - >25k tons/yr world market volume = minimum cutoff applied here
- TEA is currently higher-level for this process, but will be focus for future work in support of 2022 targets

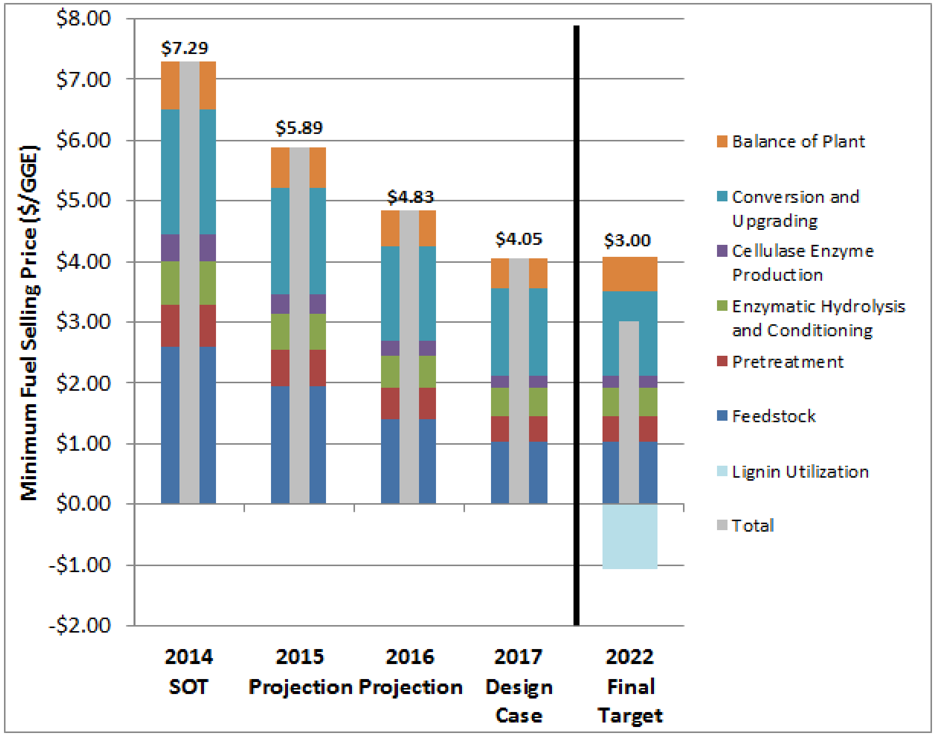
Product	World Production (thousand tons/year)	Price ($/ ton)	Projected growth rate	Primary Usage
1,3 Butadiene	>12,000	3200	5%	Synthetic rubber
1,4 Butanediol	>1,000	3170	5%	Tetrahydrofuran, specialty chemicals
Adipic Acid	>3,000	1700	4-4.5%	Nylon-6,6
Cyclohexane	>5,700	1000	2.5%	Nylon-6,6 precursors

Relevance

TEA Progression Goals: Biological



TEA Progression Goals: Catalytic (*in situ* H2)



NREL TEA modeling is highly relevant to BETO goals:

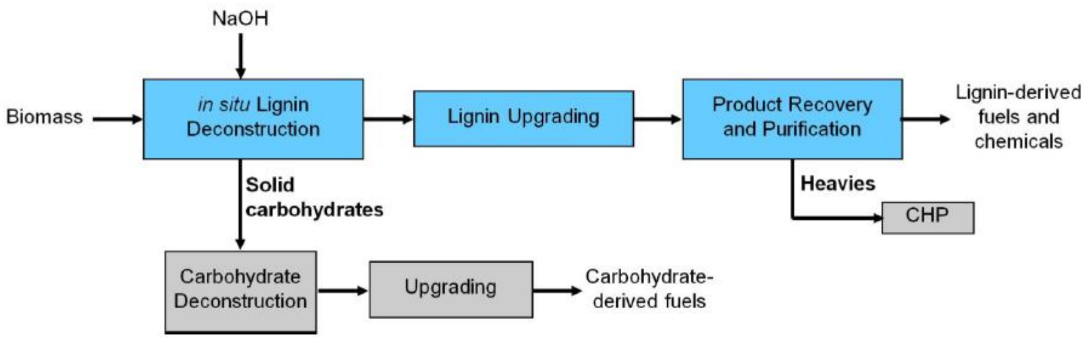
- Helps guide R&D, DOE decisions, out-year target projections
  - *Technical targets (yields, process performance, etc)*
  - *Cost targets (BETO MYPP goal: $3/GGE MFSP by 2022)*
- Identifies key R&D directions (yields, coproduct opportunities, etc)
- Analysis can serve a wide variety of stakeholders
  - *Industry (facilitate interaction between industry, NREL, DOE)*
  - *TEA helps to "de-risk" a technology during research stages, prior to commercialization*
  - *Research community, decision makers*

Nov 2014 MYPP Performance Goal:
"By 2017, achieve an nth plant modeled conversion cost of $3.30/GGE via a biochemical or chemical conversion pathway. This contributes to an MFSP of $5.10/GGE, an interim target on the path to $3/GGE fuels."

Future Work

- Design/engineering assessment:
  - Collaboration with NREL Pilot Scale Integration project to better understand optimal design and cost for commercial-scale aerobic bioreactor systems – *Q2 milestone*
  - Collaboration with NREL LCA team to consider recommendations for strategies to reduce air pollutant emissions from NREL's biological pathway model – *Q4 Quarterly Progress Measure*
- Alternative scenario modeling development:
  - Publication of NREL technical report documenting new C5/C6 parallel conversion strategy (fuels + coproducts); report will incorporate any pertinent updates to refine prior design case model – *Q3 milestone*
  - Preliminary TEA for catalytic conversion of furans-to-hydrocarbons, in collaboration with NREL Catalytic Conversion of Sugars project – *Q4 milestone*
- 2015 State of Technology assessment for FY15 R&D data – *Q4 milestone*

- FY16 and beyond: TEA support for biochem platform in moving to 2022 target ($3/GGE)
  - Go/no go milestone to downselect TEA focus to at least 2 most promising R&D options for achievement of $3/GGE by 2022 – *Q2 FY16 go/no go*
  - Likely to require lignin conversion to coproducts (R&D currently in progress)



Summary

- Biochemical Analysis task has seen a tremendous amount of activity and achievements since FY13 peer review
  - FY13 biological pathway design report published, showing one path to intermediate \$5/GGE target and another to 2022 \$3/GGE target
  - Biological pathway subsequently revised to pursue parallel conversion of C6 sugars to fuels, C5 sugars to chemical coproducts
  - FY14 catalytic pathway design report published showing intermediate paths to \$4-5/GGE dependent on H_2 source, further paths to \$3/GGE
  - Established out-year targets through 2017 to begin guiding near-term R&D goals at NREL, priorities at BETO (including MYPP projections)
  - Quantification of sustainability metrics for both conversion pathways
- 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 to further improve rigor for complex hydrocarbon pathway models

Additional Slides

Responses to Previous Reviewers' Comments from 2013 Review

•This kind of work is worth doing, but it needs independent verification.

•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.

•Very important to be able to track costs and direct R&D efforts. On-site enzyme production is a questionable approach.

•As noted in recent design report documents, the primary intention for inclusion of on-site enzyme production is to improve transparency in determining the true cost of cellulase enzymes for large-scale production of cellulosic biofuels. The intent is not to imply a judgment call about whether or not the industry should align to this mode of enzyme distribution. Further rationale for this approach in the context of NREL's integrated biochemical process models may be found in the pertinent design report documentation.

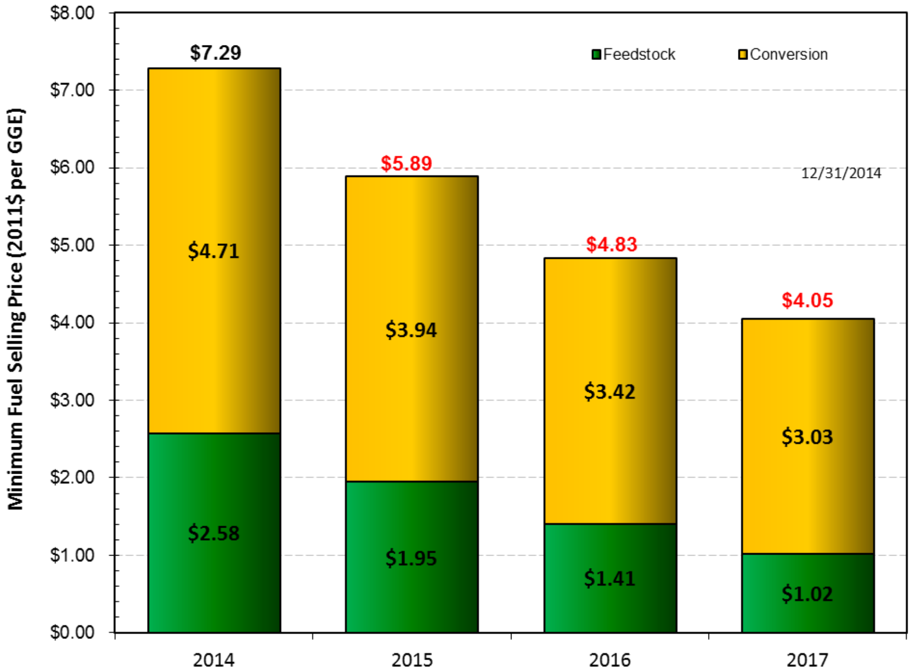
Publications, Patents, Presentations, Awards, and Commercialization

- R. Davis, L. Tao, C. Scarlata, E.C.D. Tan, et al., "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." NREL Technical Report, NREL/TP-5100-62498, March 2015; http://www.nrel.gov/docs/fy15osti/62498.pdf
- R. Davis, L. Tao, E.C.D. Tan, M.J. Biddy, G.T. Beckham, C. Scarlata, et al., "Process design and economics for the conversion of lignocellulosic biomass to hydrocarbons: Dilute-acid and enzymatic deconstruction of biomass to sugars and biological conversion of sugars to hydrocarbons." NREL Technical Report, NREL/TP-5100-60223, October 2013; http://www.nrel.gov/docs/fy14osti/60223.pdf
- L. Tao, D. Schell, R. Davis, E. Tan, R. Elander, A. Bratis, "Achievement of ethanol cost targets: Biochemical ethanol fermentation via dilute-acid pretreatment and enzymatic hydrolysis of corn stover." NREL Technical Report, NREL/TP-5100-61563, April 2014; http://www.nrel.gov/docs/fy14osti/61563.pdf
- R. Brunecky, S. E. Hobdey, L. E. Taylor II, L. Tao, M. P. Tucker, M. E. Himmel, S. R. Decker, "High temperature pre-digestion of corn stover biomass for improved product yields," *Biotechnology for Biofuels*, 7:170, doi:10.1186/s13068-014-0170-2, 2014.
- X. Chen, J. Shekiro, T. Pschorn, M. Sabourin, L. Tao, R. Elander, S. Park, O. Trass, K. Flanegan, E. Nelson, E. Jennings, R. Nelson, D. Johnson, M. P. Tucker, "A highly efficient dilute alkali deacetylation and mechanical (disc) refining process for the conversion of renewable biomass to lower cost sugars," *Biotechnology for Biofuels*, 7(1): p. 98., 2014.
- D. Sievers, L. Tao, D. Schell, "Performance and techno-economic assessment of several solid-liquid separation technologies for processing dilute-acid pretreated corn stover," *Bioresource Technology*, 167: p.291-296, 2014.
- L. Tao, Xin He, Eric C.D. Tan, Min Zhang, A. Aden, "Comparative techno-economic analysis of n-butanol production from corn grain and corn stover," *Biofuels Bioproducts & Biorefining*, 8(3): p. 342-361, 2014.
- C.J. Scarlata, R.E. Davis, L. Tao, E.C.D. Tan, M.J. Biddy, "Perspectives on process analysis for advanced biofuel production." Invited book chapter, *Direct Microbial Conversion of Biomass to Advanced Biofuels*; Edited by M. Himmel; 2015, publication in process.
- L. Tao, E. C. D. Tan, A. Aden, R. T. Elander, "CHAPTER 19: Techno-Economic Analysis and Life-Cycle Assessment of Lignocellulosic Biomass to Sugars Using Various Pretreatment Technologies." Invited book chapter, *Biological Conversion of Biomass for Fuels and Chemicals: Explorations from Natural Utilization Systems*, ed: The Royal Society of Chemistry, DOI:10.1039/9781849734738-003582014, pp. 358-380, 2014.
- R. Davis, L. Tao, E. Tan, M. Biddy, C. Scarlata, "2013 NREL design report: Biochemical conversion of biomass-to-hydrocarbons, process design and economics." Presented at the 2014 AICHE Annual Meeting, November 2014, Atlanta, GA.
- E. Tan and L. Tao, "Sustainability metrics and life-cycle assessment for biochemical conversion of corn stover to cellulosic ethanol, isobutanol, and n-butanol." Presented at the 2013 AIChE Annual Meeting, November 2013, San Francisco, CA.
- X. Chen, N. J. Nagle, L. Tao, M. Tucker, "Furfural production as a by-product of lignocellulosic biofuel process." Presented at the 2013 AIChE Annual Meeting, November 2013, San Francisco, CA.

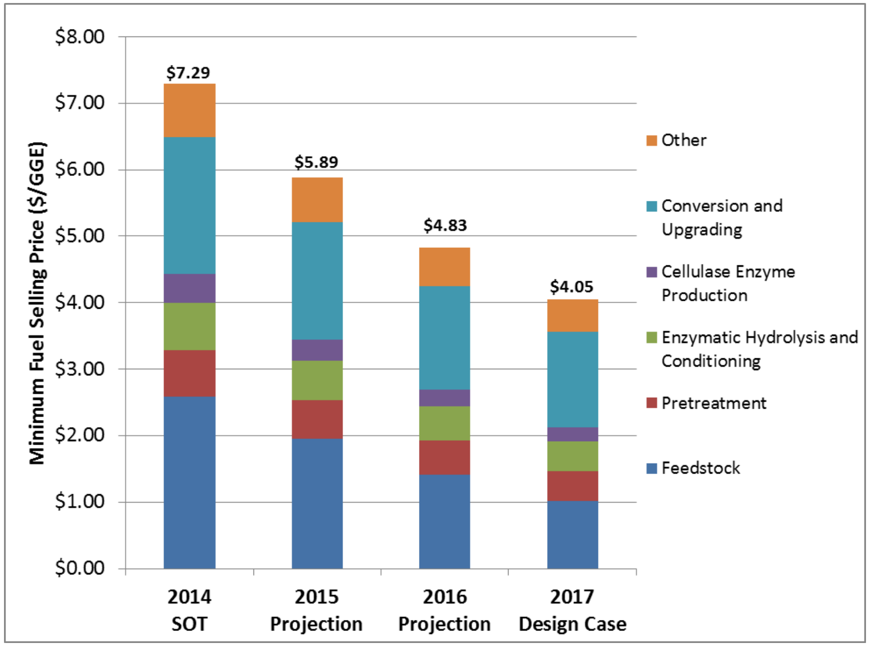
Backup Slides

TEA Cost Projections to 2017 – Catalytic Pathway

With Feedstock Cost Progression



With Feedstock Cost Progression (Detail)



	2014	2015	2016	2017
Feedstock Basis	Corn Stover	Corn Stover	Blend	Blend
Total feedstock cost to biorefinery at 5% ash equivalent ($/dry ton)	$130	$115	$95	$80
Ash dockage vs 5% baseline ($/dry ton) [1]	$11.28	$8.70	$4.40	-

[1] Ash dockage fee is included in the overall "cost to biorefinery" and accounts for variances in ash content above 5% projected by INL prior to 2017 (10.5% in 2014, 9% in 2015, 7% in 2016)

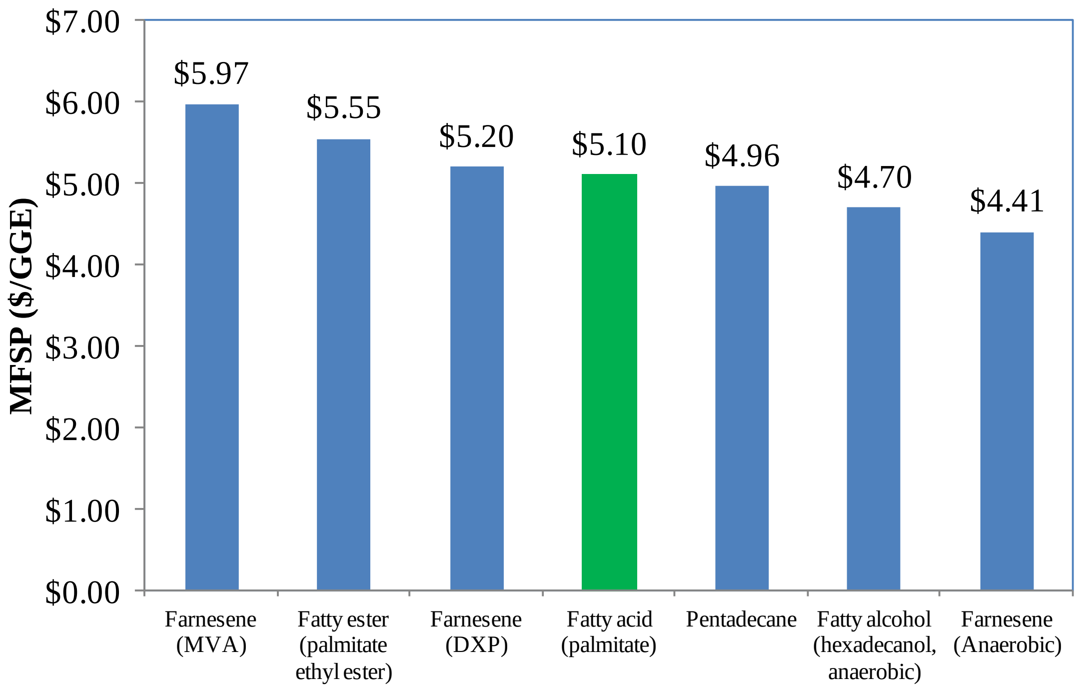
2013 Biological Design Report: Metabolic Product/Pathway Selection

Product	Theoretical yield (metabolic, wt%)	Theoretical carbon yield (metabolic)	Theoretical energy yield (metabolic)
Ethanol	51%	67%	98%
Pentadecane	29%	62%	88%
Farnesene (DXP pathway)	29%	64%	85%
Farnesene (MVA pathway)	25%	56%	74%
Fatty Acid (Palmitic acid)	36%	67%	89%
FAEE (Ethyl palmitate)	35%	67%	90%
Fatty Alcohol (Hexadecanol)	34%	67%	93%

Refs: Rude et al, *Current Opinion in Microbiology* 2009 (12); Huang et al, *Energy Environ. Sci.* 2011 (4); Dugar et al, *Nature Biotechnology* 2011 (29), DOE *CTAB Roadmap* 2012

- Ethanol leverages decades of NREL R&D experience
- HC pathways are much newer given advances in metabolic engineering
- No single best pathway selected by NREL or DOE
- Intention here is to evaluate a *representative* "middle-of-the-road" product for TEA analysis of the general biological conversion technology pathway
- FFA pathway was selected here due to:
    a) Represents median energy yield of all HC pathways (good indicator of economics)
    b) FFA synthesis is a fundamental pathway extensively studied
        - Avoids selection of fuel product(s) targeted by industry

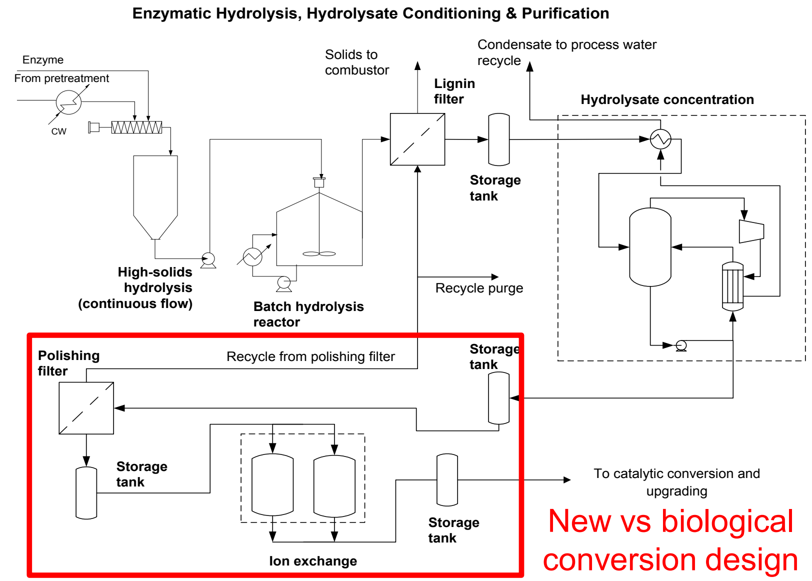
2013 Biological Design Report: Costs for Alternative Biological Pathways



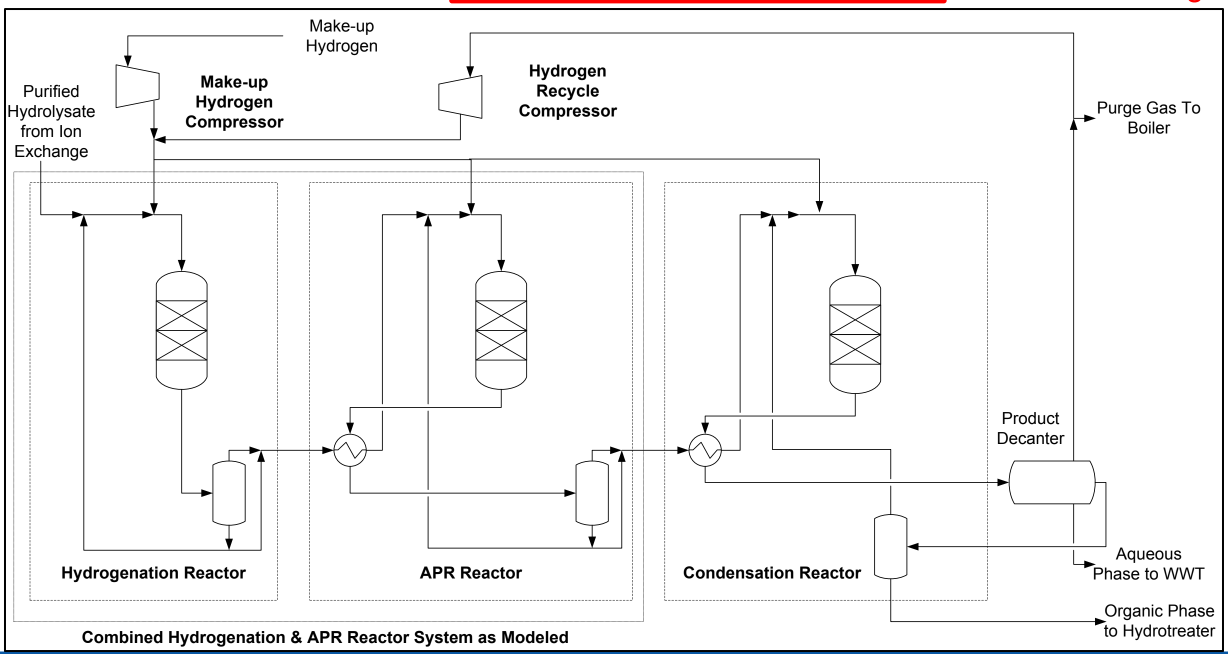
Pathway	Theoretical metabolic mass yield	Theoretical carbon efficiency	MFSP ($/gal)	MFSP ($/GGE)	Production (MMgal/yr)	Production yield (gal/dry ton biomass)
Pentadecane	0.29	0.63	$5.19	$4.96	30.0	41.4
Farnesene (MVA)	0.25	0.56	$6.25	$5.97	27.0	37.3
Farnesene (DXP)	0.29	0.64	$5.44	$5.20	31.1	43.0
Farnesene (Anaerobic)	0.32	0.71	$4.61	$4.41	34.8	48.0
Fatty ester (palmitate ethyl ester)	0.35	0.67	$5.83	$5.55	28.9	40.0
Fatty acid (palmitate, base case)	0.36	0.67	$5.35	$5.10	31.3	43.3
Fatty alcohol (hexadecanol, anaerobic)	0.34	0.67	$4.94	$4.70	32.3	44.5

Overview of Catalytic Conversion Process

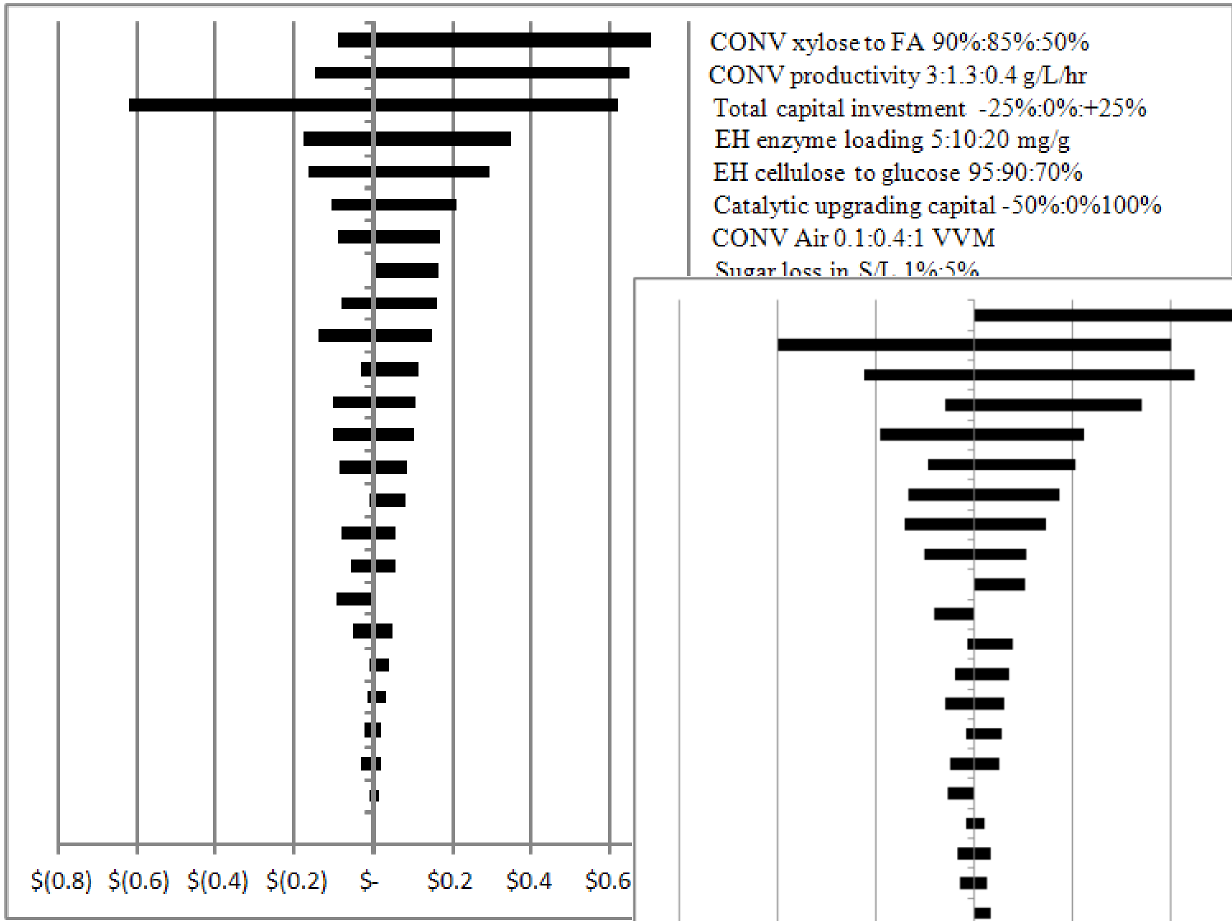
- Whole-hydrolysate conversion pathway, otherwise same targets as biological case for PT + EH
- Requires more extensive hydrolysate cleanup to remove SS fines (microfiltration), ions (IX) for catalyst protection



- Conversion process:
  - Hydrogenation + APR yields oxygenated intermediates <C7
  - Condensation oligomerizes APR products to fuel-range paraffins and mono-oxygenates
  - Mild hydrotreating to complete deoxygenation of condensation organic product phase
  - Conversion yields, operating conditions based on patent literature



Framing the Analysis: Sensitivity Plots



Biological Design Case

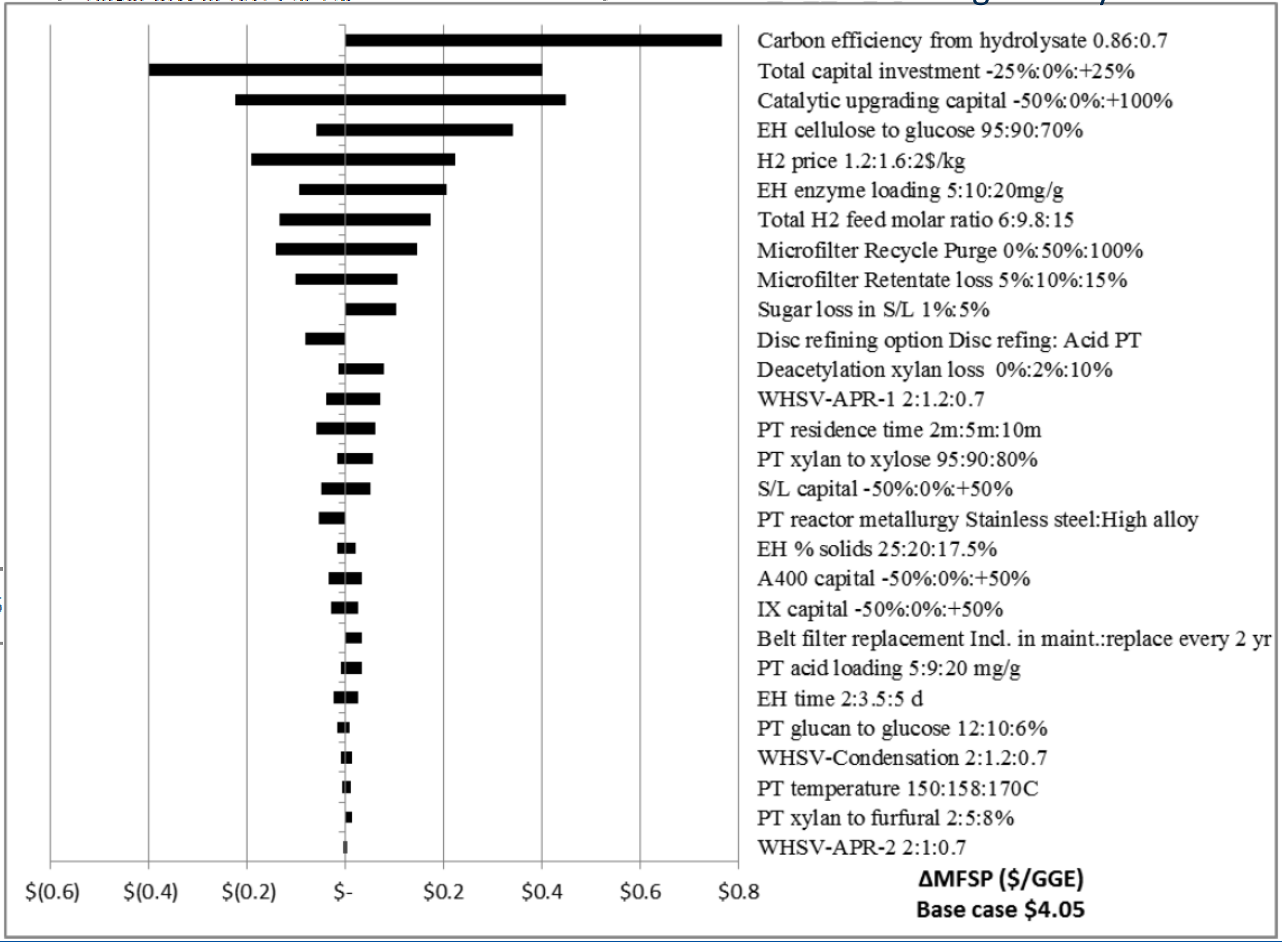
Key drivers:

- Xylose to FA conversion
- Bioconversion productivity
- TCI uncertainty

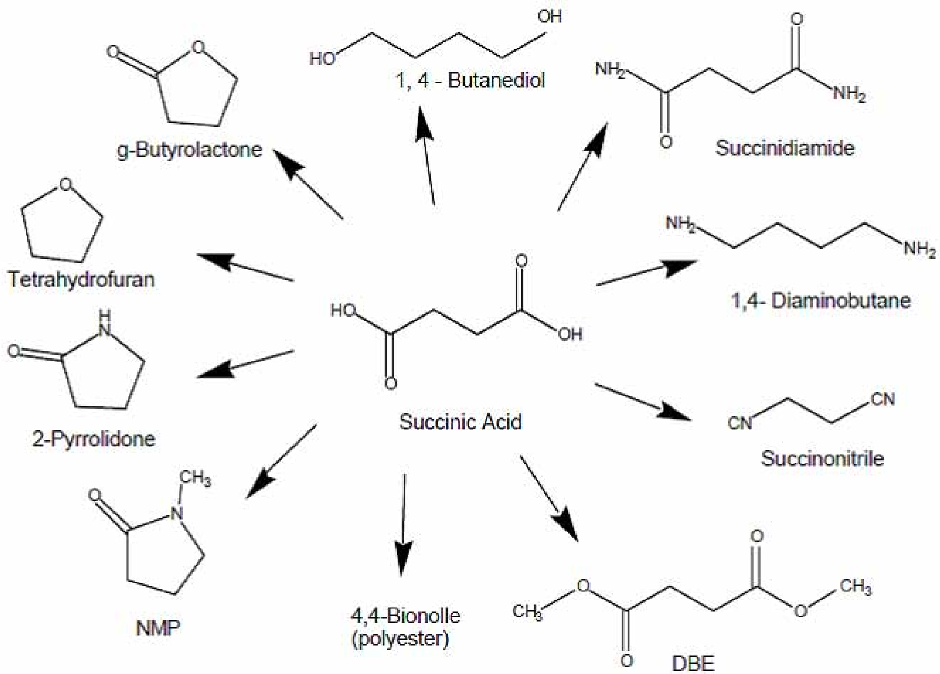
Catalytic Design Case

Key drivers:

- C conversion efficiency
- TCI/ catalytic conversion capex
- Cellulose to glucose yield



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