TEA Perspectives on Biomass Conversion Pathways

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Technology Challenges and Opportunities in Commercializing Industrial Biotechnology

September 28, 2015

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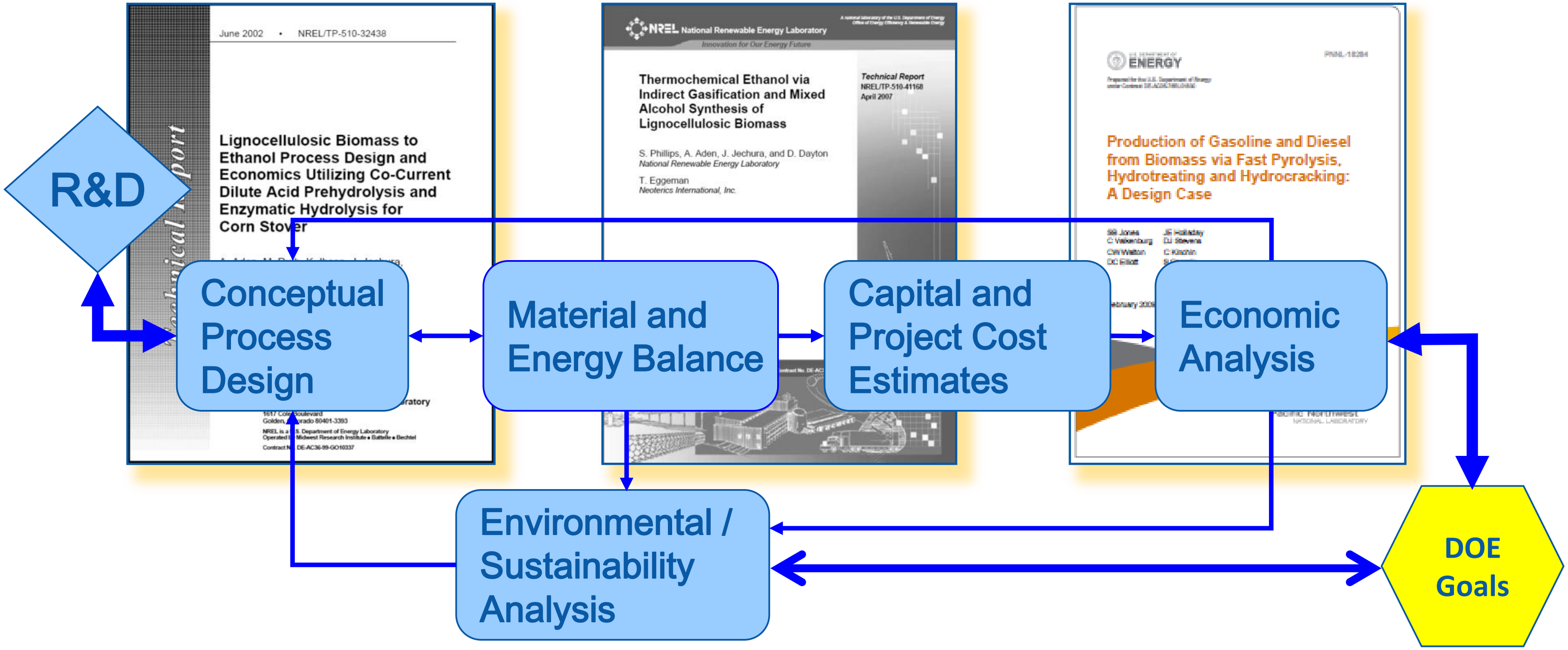
Techno-Economic Analysis: *Approach*



June 2002 • NREL/TP-510-32438

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

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass

Technical Report
NREL/TP-510-41168
April 2007

S. Phillips, A. Aden, J. Jechura, and D. Dayton
National Renewable Energy Laboratory

T. Eggeman
Neoterics International, Inc.

ENERGY

Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case

R&D

Conceptual Process Design

Material and Energy Balance

Capital and Project Cost Estimates

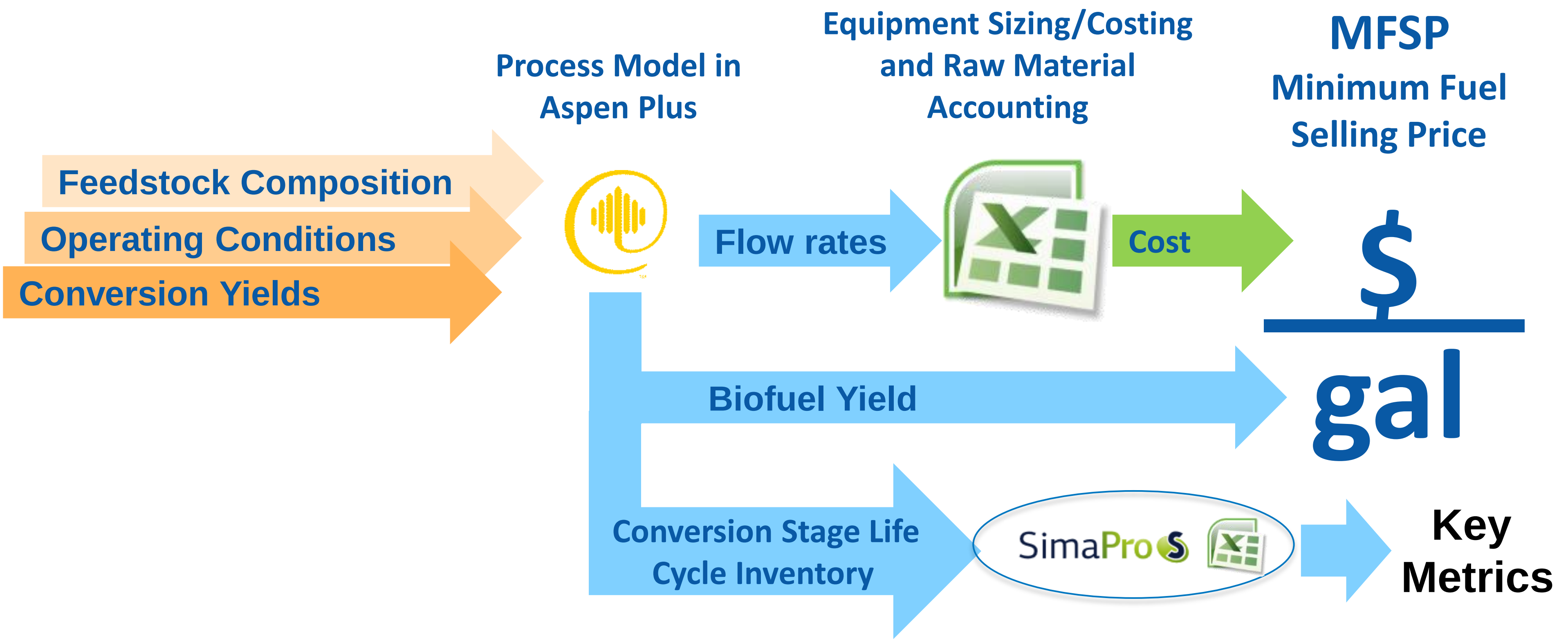
Economic Analysis

Environmental / Sustainability Analysis

DOE Goals

- **TEA: Quantify the impact the R&D improvements and breakthroughs have on the economic viability on a process**
- **Collaboration with engineering and construction firms to enhance credibility and quality**
- **Conceptual design reports are transparent, peer reviewed**
- **Iteration with researchers and experimentalists is crucial**

Techno-Economic Analysis: *Approach*



Feedstock Composition

Operating Conditions

Conversion Yields

Process Model in Aspen Plus

Flow rates

Equipment Sizing/Costing and Raw Material Accounting

Cost

MFSP

Minimum Fuel Selling Price

$ / gal

Biofuel Yield

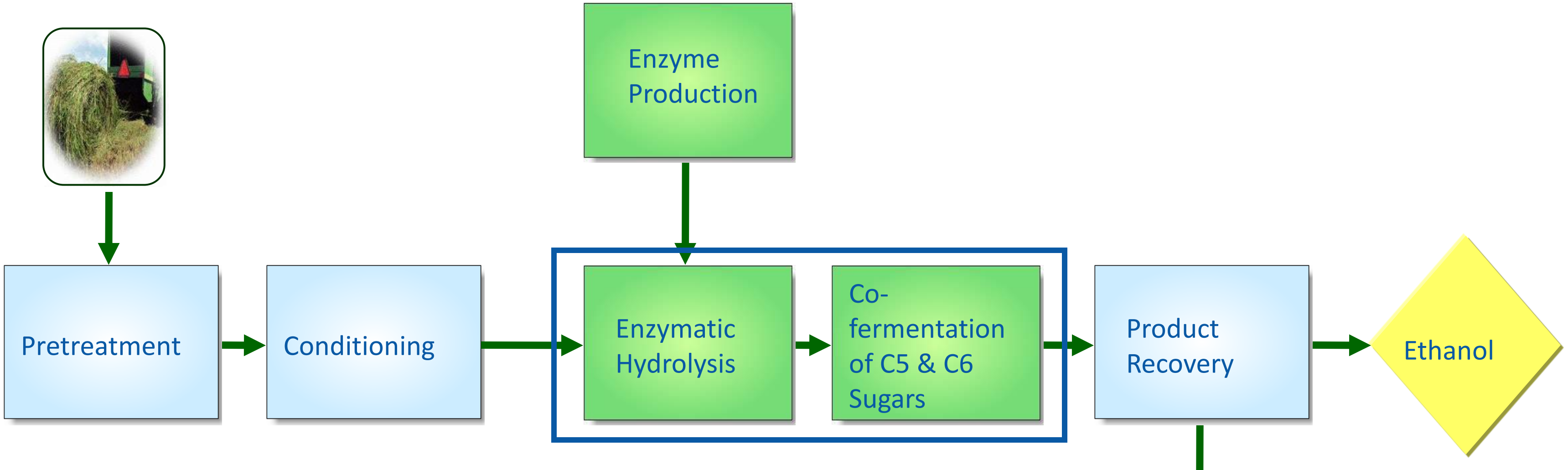
Conversion Stage Life Cycle Inventory

SimaPro

Key Metrics

- Modeling is rigorous and detailed with transparent assumptions
- Assumes nth-plant equipment costs
- Discounted cash-flow ROR calculation includes return on investment, equity payback, and taxes
- Impact of major cost drivers (sensitivity studies)
- Identify research targets and measure research progress

2011 Biochem Design Report for Cellulosic Ethanol


Enzyme Production

Pretreatment

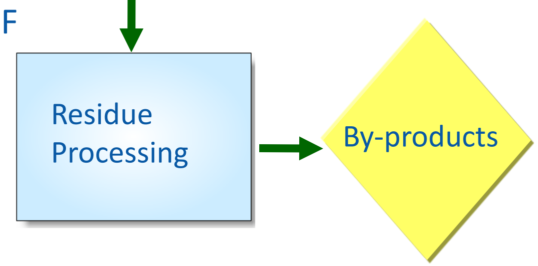
Conditioning

Enzymatic Hydrolysis

Co-fermentation of C5 & C6 Sugars

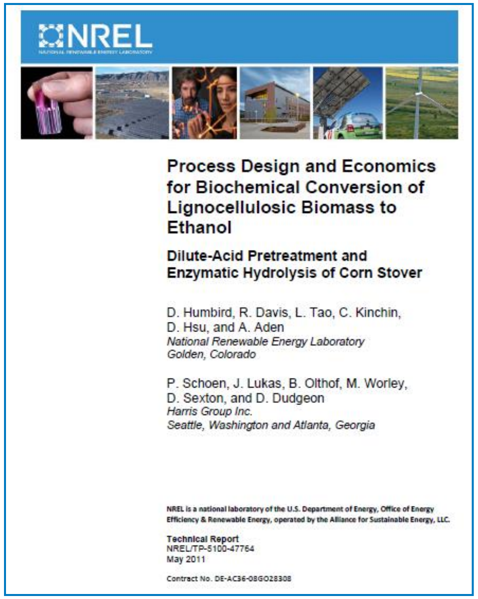
Product Recovery

Ethanol


Residue Processing

By-products

Hybrid Saccharification & Fermentation - HSF


NREL

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

Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover

D. Humbird, R. Davis, L. Tao, C. Kinchin,
D. Hsu, and A. Aden
National Renewable Energy Laboratory
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Harris Group Inc.
Seattle, Washington and Atlanta, Georgia

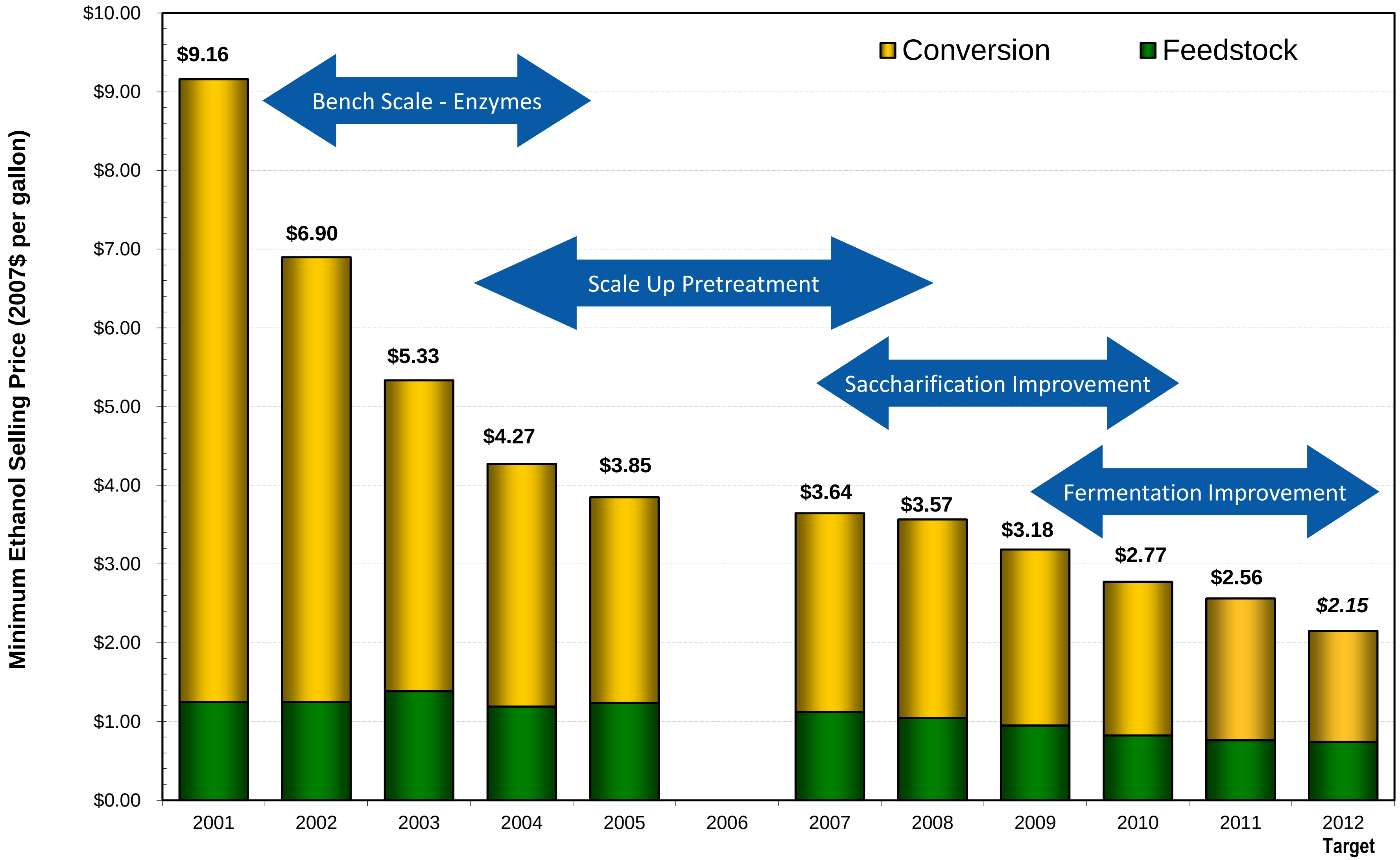
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5100-47764
May 2011

Contract No. DE-AC36-08GO28308

- **Conceptual design of a 2,000 tonnes/day commercial plant – one possible tech package, not optimized**
- **NREL pilot plant based on this process**
- **Basis for connecting R&D targets to cost targets**
- **Has undergone rigorous peer review**
- **Basis for comparison against other technology options**

Historic State of Technology



Bench Scale - Enzymes

Scale Up Pretreatment

Saccharification Improvement

Fermentation Improvement

Technical Target Table

	2007	2008	2009	2010	2011 Targets	2011 Washed Solids	2011 Whole Slurry	2012 Targets
Minimum Ethanol Selling Price ($/gal)	**$3.64**	**$3.56**	**$3.19**	**$2.77**	**$2.62**	**$2.56**	**$2.37**	**$2.15**
Feedstock Contribution ($/gal)	$1.12	$1.04	$0.95	$0.82	$0.76	$0.76	$0.82	$0.74
Conversion Contribution ($/gal)	$2.52	$2.52	$2.24	$1.95	$1.86	$1.80	$1.55	$1.41
Yield (Gallon/dry ton)	69	70	73	75	78	78	71	79
Feedstock								
Feedstock Cost ($/dry ton)	$77.20	$72.90	$69.65	$61.30	$59.60	$59.60	$59.60	$58.50
Pretreatment								
Solids Loading (wt%)	30%	30%	30%	30%	30%	30%	30%	30%
Xylan to Xylose (including enzymatic)	75%	75%	84%	85%	88%	88%	78%	90%
Xylan to Degradation Products	13%	11%	6%	8%	5%	5%	6%	5%
Conditioning								
Ammonia Loading (mL per L Hydrolyzate)	50	50	38	23	25	25	25	25
Hydrolyzate solid-liquid separation	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Xylose Sugar Loss	2%	2%	2%	2%	1%	1%	1%	1%
Glucose Sugar Loss	1%	1%	1%	1%	1%	1%	1%	0%
Enzymes								
Enzyme Contribution ($/gal EtOH)	$0.39	$0.38	$0.36	$0.36	$0.36	$0.34	$0.38	$0.34
Enzymatic Hydrolysis & Fermentation								
Total Solids Loading (wt%)	20%	20%	20%	17.5%	20%	17.5%	17.5%	20%
Combined Saccharification & Fermentation Time (d)	7	7	7	5	5	5	5	5
Corn Steep Liquor Loading (wt%)	1%	1%	1%	1%	0.60%	0.25%	0.25%	0.25%
Overall Cellulose to Ethanol	86%	86%	84%	86%	86%	89%	80%	86%
Xylose to Ethanol	76%	80%	82%	79%	85%	85%	85%	85%
Arabinose to Ethanol	0%	0%	51%	68%	80%	47%	47%	85%

Hydrocarbon Design Reports

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels

Fast Pyrolysis and Hydrotreating Bio-oil Pathway

November 2013

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons via Indirect Liquefaction

Thermochemical Research Pathway to High-Octane Gasoline Blendstock Through Methanol/Dimethyl Ether Intermediates

Eric C.D. Tan, Michael Talmadge, Abhijit Dutta, Jesse Hensley, Josh Schaidle, and Mary Biddy
National Renewable Energy Laboratory

David Humbird
DWH Process Consulting

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels

Thermochemical Research Pathways With *In Situ* and *Ex Situ* Upgrading of Fast Pyrolysis Vapors

Abhijit Dutta, Asad Sahir, Eric Tan
National Renewable Energy Laboratory, Golden,

PNNL-23227

Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading

S Jones
Y Zhu
D Anderson
R Hallen
D Elliott

R Davis
C Kinchin

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

R. Davis, L. Tao, E.C.D. Tan, M.J. Biddy, 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. Schoen
Harris Group Inc.

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Technical Report
NREL/TP-5100-60223
October 2013

Contract No. DE-AC36-08GO28308

Process Design and Economics for the Conversion of Algal Biomass to Biofuels:

Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products

R. Davis, C. Kinchin, J. Markham, E.C.D. Tan, and L.M.L. Laurens
National Renewable Energy Laboratory

D. Sexton, D. Knorr, P. Schoen, and J. Lukas
Harris Group Inc.

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Technical Report
NREL/TP-5100-62368
September 2014

Contract No. DE-AC36-08GO28308

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.

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Technical Report
NREL/TP-5100-62498
March 2015

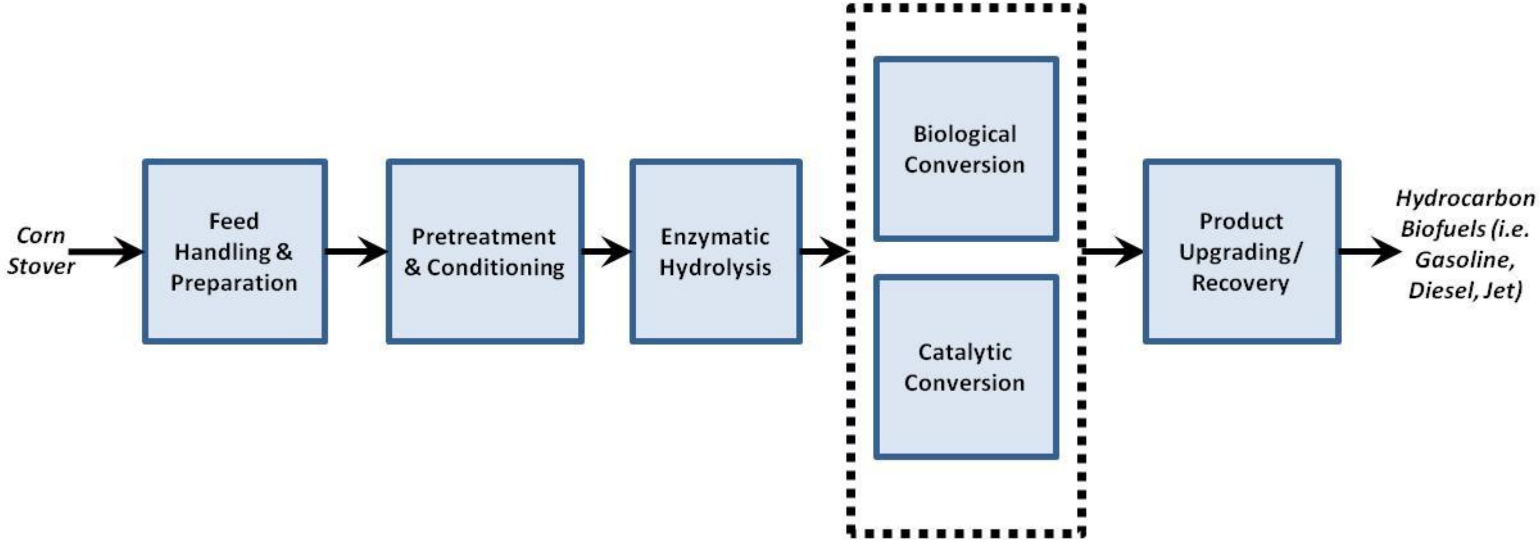
Contract No. DE-AC36-08GO28308

Design reports of 8 representative pathways for the conversion of biomass to hydrocarbon fuels and products.

Biochemical Conversion Pathways

Hydrocarbon Biofuels Technology Pathways

Sugar Conversion to Hydrocarbons



Corn Stover

Feed Handling & Preparation

Pretreatment & Conditioning

Enzymatic Hydrolysis

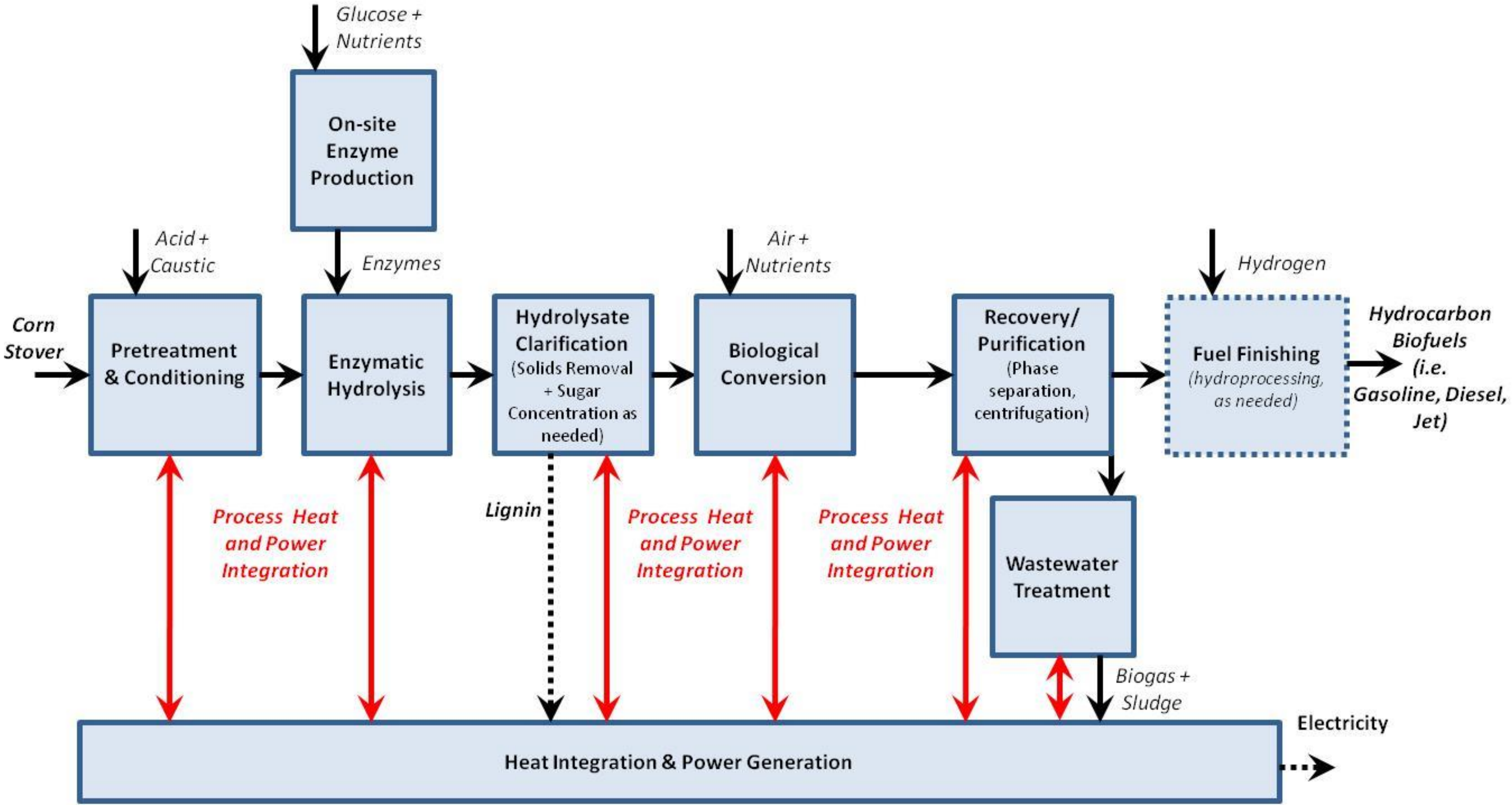
Biological Conversion

Catalytic Conversion

Product Upgrading/ Recovery

Hydrocarbon Biofuels (i.e. Gasoline, Diesel, Jet)

Biological Conversion to Hydrocarbon Fuels



Key to meeting cost target will be maximizing biomass utilization

➔Investigating routes for chemicals production and lignin conversion

$5/GGE Baseline Results

Biological Renewable Diesel Blendstock (RDB) Process Engineering Analysis

Dilute Acid Pretreatment, Enzymatic Hydrolysis, Hydrocarbon (FFA) Bioconversion, Hydrotreating to Paraffins (RDB)
All Values in 2011$

Minimum Fuel Selling Price (MFSP):	**$5.35 /gal**
MFSP (Gasoline-Equivalent Basis):	**$5.10 /GGE**
Contributions: Feedstock	**$1.85 /gal ($1.76/GGE)**
Enzymes	**$0.39 /gal ($0.37/GGE)**
Non-Enzyme Conversion	**$3.11 /gal ($2.96/GGE)**
RDB Production	31.3 MMgal/yr (at 68 °F) (32.9 MM GGE/yr)
RDB Yield	43.3 gal / dry U.S. ton feedstock (45.4 GGE/ton)
Bioconversion Metabolic Yield	0.284 kg FFA/kg total sugars (79% of theoretical)
Feedstock + Handling Cost	$80.00 /dry U.S. ton feedstock
Internal Rate of Return (After-Tax)	10%
Equity Percent of Total Investment	40%

Capital Costs	
Pretreatment	$51,400,000
Neutralization/Conditioning	$2,200,000
Enzymatic Hydrolysis/Conditioning/Bioconversion	$75,400,000
On-site Enzyme Production	$12,400,000
Product Recovery + Upgrading	$26,600,000
Wastewater Treatment	$60,100,000
Storage	$3,400,000
Boiler/Turbogenerator	$76,000,000
Utilities	$8,800,000
Total Installed Equipment Cost	$316,300,000
Added Direct + Indirect Costs	$266,400,000
(% of TCI)	46%
Total Capital Investment (TCI)	$582,700,000
Installed Equipment Cost/Annual Gallon	$10.09
Total Capital Investment/Annual Gallon	$18.59
Loan Rate	8.0%
Term (years)	10
Capital Charge Factor (Computed)	0.135
Carbon Retention Efficiencies:	
From Hydrolysate Sugar (Fuel C / Sugar C)	49.5%
From Biomass (Fuel C / Biomass C)	26.2%
Maximum Yields (100% of Theoretical)[a]	
FFA Production (U.S. ton/yr)	172,465
Current FFA Production (U.S. ton/yr)[b]	117,587
Current Yield (Actual/Theoretical)	68.2%

[a] *Complete conversion of biomass carbohydrates to C16 fatty acid*

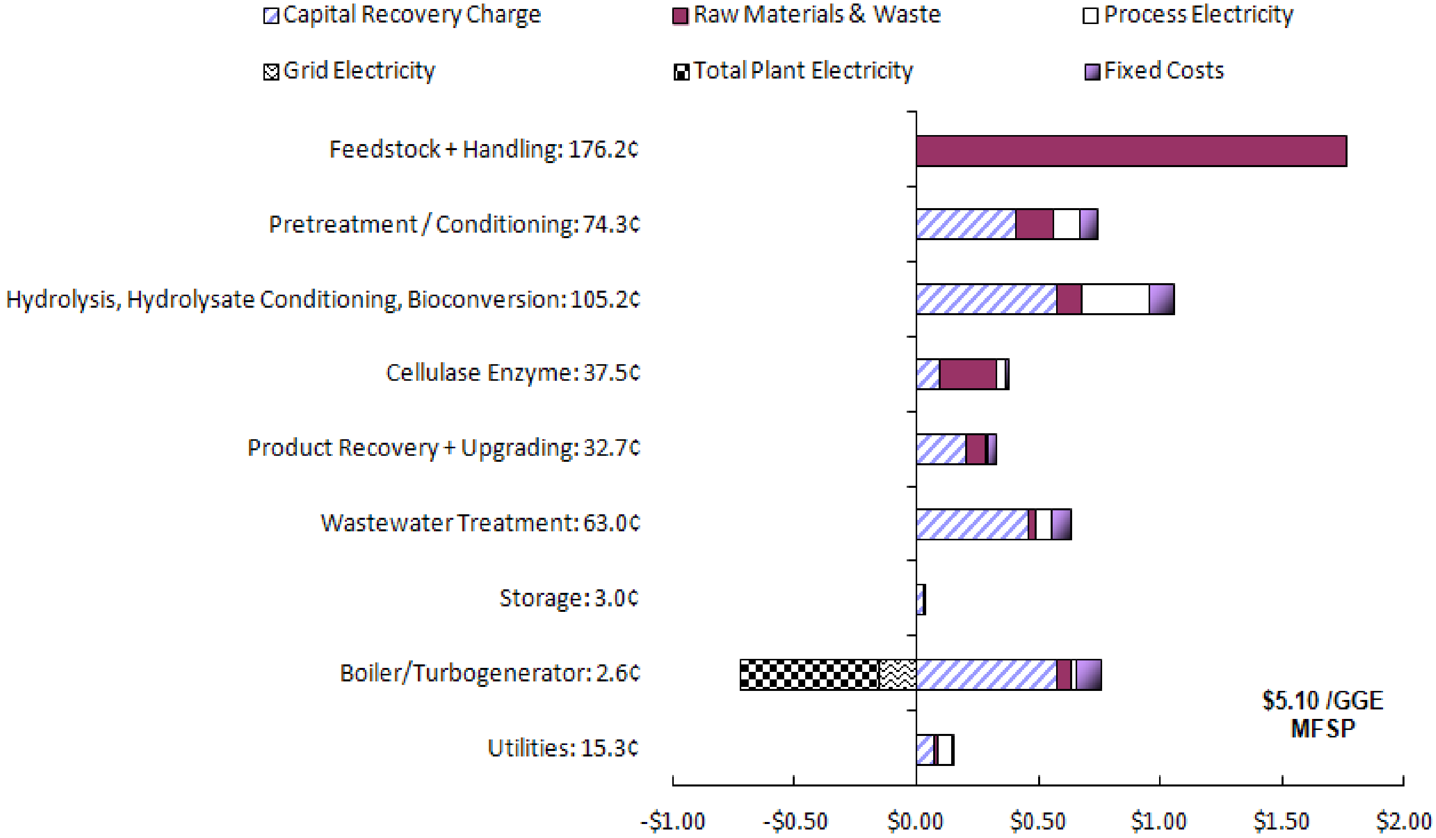
[b] *Recovered FFA yield after concentration, sent to hydrotreating (Theoretical yields above do not consider refining to final RDB product, as refining yield varies with catalyst and conditions)*

Manufacturing Costs (cents/gal RDB product)	
Feedstock + Handling	184.9
Sulfuric Acid	6.2
Ammonia (pretreatment conditioning)	3.6
Caustic	6.5
Glucose (enzyme production)	21.7
Hydrogen	8.4
Other Raw Materials	19.2
Waste Disposal	4.5
Net Electricity	-16.3
Fixed Costs	44.9
Capital Depreciation	58.7
Average Income Tax	34.1
Average Return on Investment	158.5

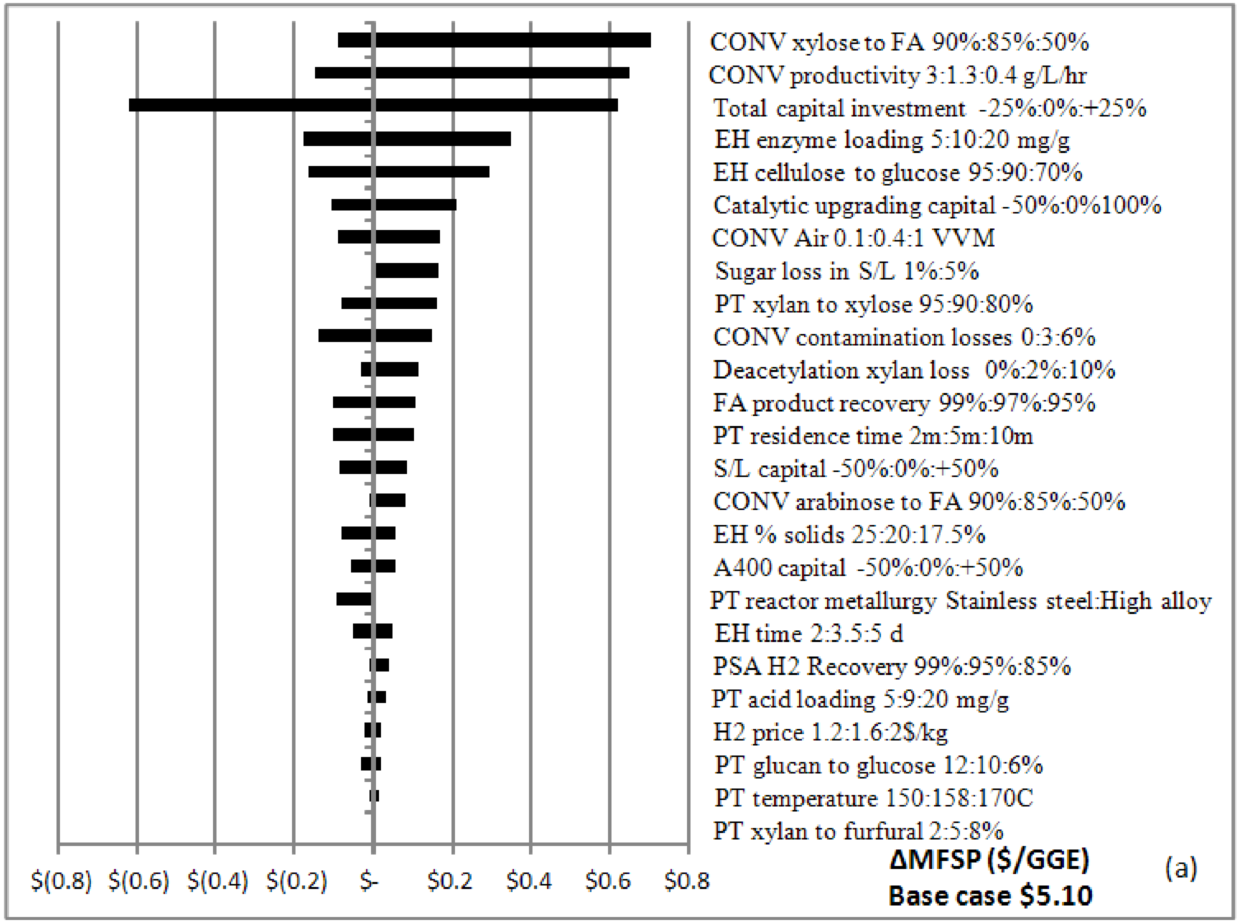
Manufacturing Costs ($/yr)	
Feedstock + Handling	$57,900,000
Sulfuric Acid	$1,900,000
Ammonia (pretreatment conditioning)	$1,100,000
Caustic	$2,000,000
Glucose (enzyme production)	$6,800,000
Hydrogen	$2,600,000
Other Raw Materials	$6,000,000
Waste Disposal	$1,400,000
Net Electricity	-$5,100,000
Fixed Costs	$14,100,000
Capital Depreciation	$18,400,000
Average Income Tax	$10,700,000
Average Return on Investment	$49,600,000

Specific Operating Conditions	
Enzyme Loading (mg/g cellulose)	10
Saccharification Time (days)	3.5
Bioconversion Time (days)	2.9
Bioconversion FFA titer (wt%)	9%
Excess Electricity (kWh/gal)	2.6
Plant Electricity Use (kWh/gal)	11

Cost contributions by area



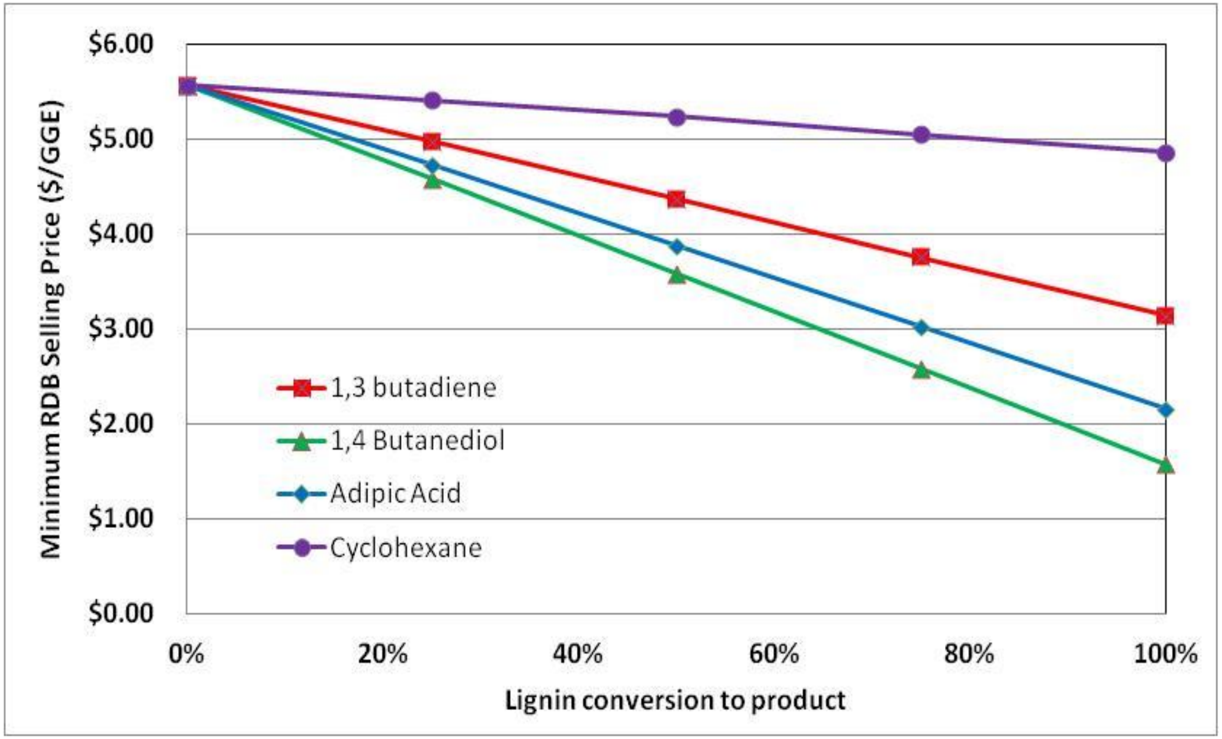
Sensitivity analysis



Primary drivers:

- Xylose conversion
- Volumetric productivity (substantial cost increase for lower productivity values)
- Total Capital Investment
- Enzyme loading

High-level TEA estimate for lignin coproduct pathways



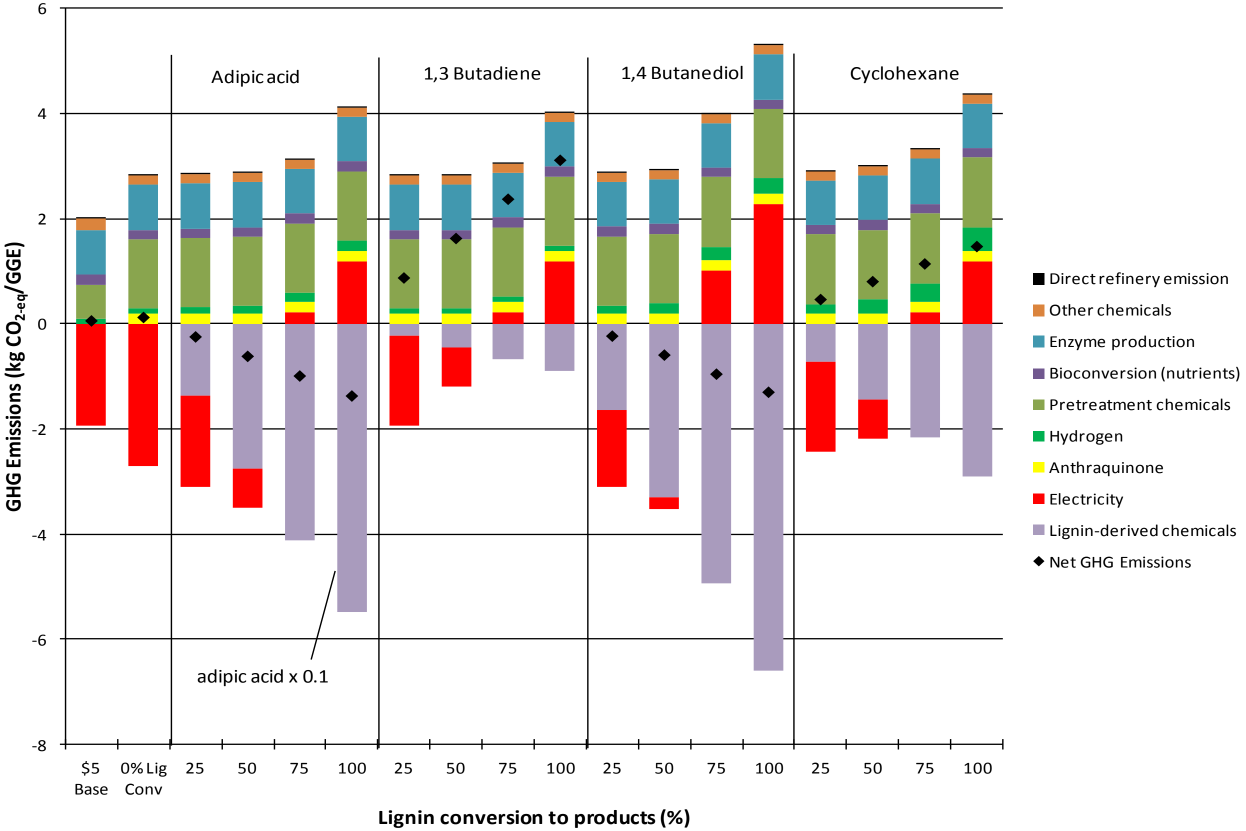
Addition of lignin deconstruction/conversion process equipment increases MFSP

*Plot is based on % lignin conversion, of the 80% solubilized upstream in deconstruction

- 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

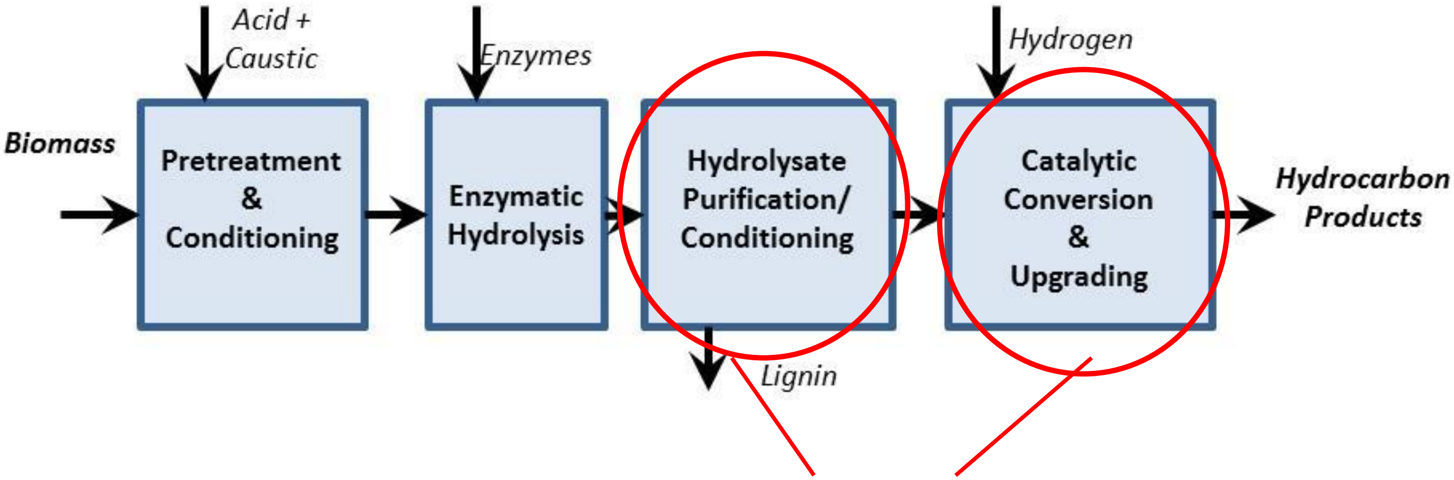
Product	**World Production (thousand tons/year)**	**Price ($/ ton)**	**Projected growth rate**	**Primary Usage**
1,3 Butadiene	>12,000	3200	5%	Synthetic rubber
1,4 Butanediol	>1,000	3170	5%	Tetrahydrofuran, specialty chemicals
Adipic Acid	>3,000	1700	4-4.5%	Nylon-6,6
Cyclohexane	>5,700	1000	2.5%	Nylon-6,6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

High-level GHG estimate for lignin coproduct pathways



- High-level analysis shows that oxygenated products can improve MFSP and GHGs
  - Adipic acid and 1,4 butanediol provide increased GHG offset credit vs lignin combustion to power coproduct
  - Conventional adipic acid production is very carbon-intensive, note x0.1 multiplier on plot (large GHG credit)
  - Minimization and eventual loss of power coproduct, replaced by increasing offsets from chemical coproduct as more lignin diverted away from the boiler

Overall process schematic



Acid + Caustic

Enzymes

Hydrogen

Biomass

Pretreatment & Conditioning

Enzymatic Hydrolysis

Hydrolysate Purification/ Conditioning

Catalytic Conversion & Upgrading

Hydrocarbon Products

Lignin

Key updates vs Biological conversion design

Based on catalysis of lignocellulosic-derived hydrolysate

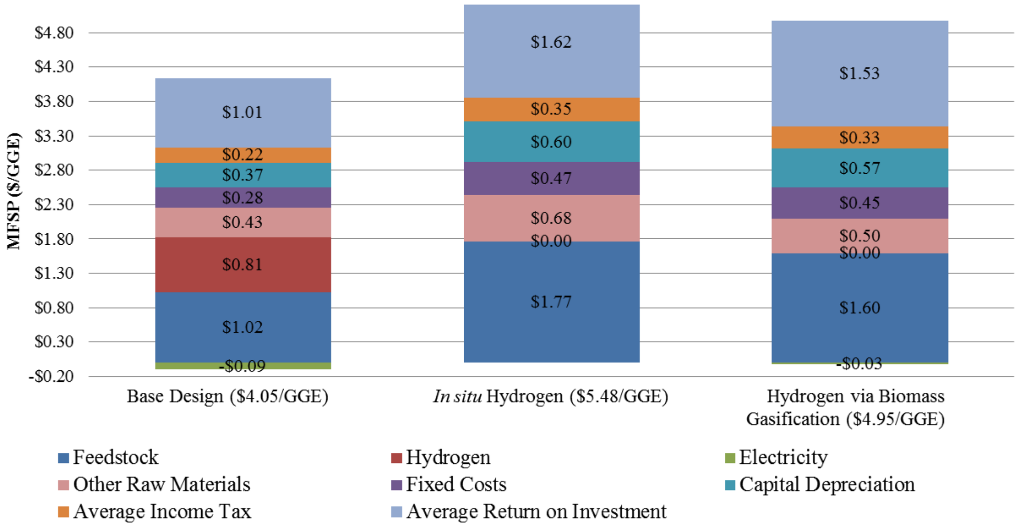
- Potential for flexibility around conversion of multiple hydrolysate species beyond monomeric sugars, including oligomers, acetate, sugar degradation products, soluble lignin, etc.
- Oxygen rejection from sugars-to-fuel intermediates primarily via production of H_2O (vs CO_2) = favorable C yields, but requires high H_2 demand
- Maintains consistent front-end assumptions for biomass deconstruction (deacetylation, PT, EH) as biological conversion pathway

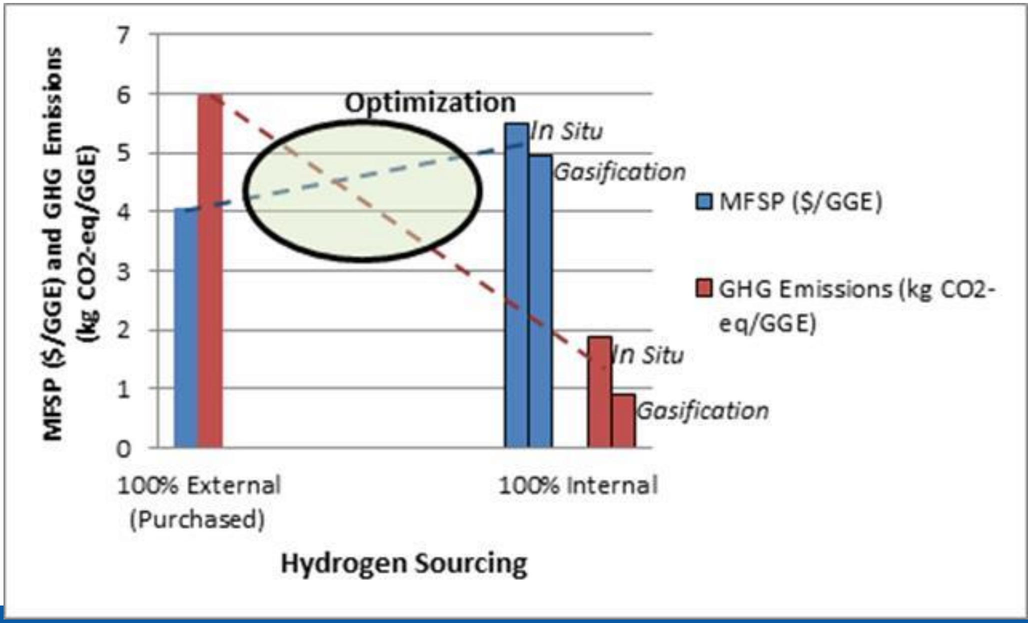
GHG/Cost Trade-Offs & Synergies: Hydrogen Source

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

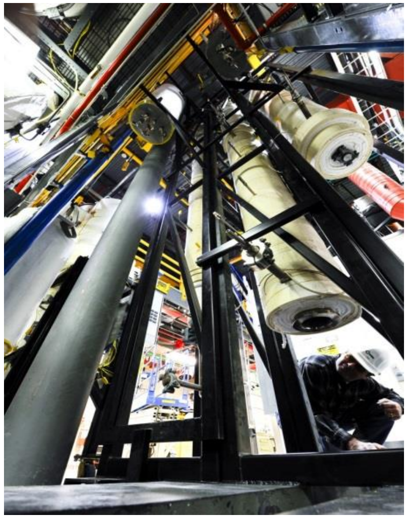
  - Increases cost to $5.48/GGE (in situ), $4.95/GGE (gasification)
  - Requires large fractional diversion of hydrolysate (41%, in situ) or biomass (36%, gasification) to generate required H_2 = reduced fuel yield
  - Although lower yield/higher cost, also tradeoffs in sustainability





Thermochemical Process Development Unit (TCPDU)

Pilot scale system for scaling-up and testing technologies and catalysts developed at the lab scale.



- **Flexible system design - configurable unit operations**
  - Three reformer configuration options for gasification
    - Full stream fluidized bed reformer
    - Full stream FBR + full stream packed bed reformer
    - Circulating fluidized reforming system (R-cubed)
  - Equipment can be used for gasification and pyrolysis with minimal changes
    - R-cubed could be used as vapor-phase upgrading of pyrolysis vapors OR as a catalytic fast pyrolysis system
    - Davison Circulating Reactor (DCR) for upgrading of pyrolysis vapors to fuels and chemicals

Integrated Biorefinery Facility

Pilot scale equipment for integrated biomass processing

- Feed milling and handling
- Three continuous pretreatment process trains
- Two enzymatic hydrolysis process trains
- Fermentation systems (30-L to 9000-L vessels)
- Fermentation labs
- Separation equipment
- Small batch and continuous pretreatment reactors
- Techno-economic and lifecycle modeling
- Compositional analysis laboratories

Horizontal-Tube Pretreatment Reactor

Enzymatic Hydrolysis Reactors

Centrifuge

Fermentors

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- **Thank you to…**
  - Bioenergy Technologies Office:
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    - Kevin Craig, Jay Fitzgerald, Nichole Fitzgerald, Prasad Gupte, Bryna Guriel, Liz Moore (Conversion)
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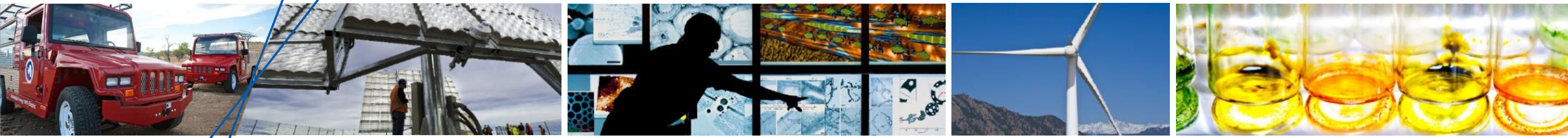
    - Adam Bratis, Gregg Beckham, Ryan Davis, Abhijit Dutta, Daniel Inman, Chris Kinchin, Kim Magrini, Jennifer Markham, Anelia Milbrandt, Asad Sahir, Christopher Scarlata, Michael Talmadge, Eric Tan, Ling Tao, Yimin Zhang, Yanan Zhang, Helena Chum, Mark Davis, Rick Elander, Tom Foust, Philip Pienkos, and NREL researchers
  - National Laboratory Partners (PNNL, INL, ORNL)
  - Industrial and Academic Partners



Back up slides

Questions?

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Design Report Publications

Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A.; Schoen, P.; Lukas, J.; Olthof, B.; Worley, M.; Sexton, D.; Dudgeon, D. (2011). Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover. 147 pp.; NREL Report No. TP-5100-47764. http://www.nrel.gov/docs/fy11osti/47764.pdf

Dutta, A.; Talmadge, M.; Hensley, J.; Worley, M.; Dudgeon, D.; Barton, D.; Groendijk, P.; Ferrari, D.; Stears, B.; Searcy, E. M.; Wright, C. T.; Hess, J. R. (2011). Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol: Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis. 187 pp.; NREL Report No. TP-5100-51400. http://www.nrel.gov/docs/fy11osti/51400.pdf

Link to NREL public TEA models: http://www.nrel.gov/extranet/biorefinery/aspen_models/

Design Report Publications

Biochemical Pathways

Catalytic Conversion of Sugars -- 2015

Davis, R.; Tao, L.; Scarlata, C.; Tan, E. C. D.; Ross, J.; Lukas, J.; Sexton, D. (2015). 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. 133 pp.; NREL Report No. TP-5100-62498.
http://www.nrel.gov/docs/fy15osti/62498.pdf

Biological Conversion of Sugars -- 2013

Davis, R.; Tao, L.; Tan, E. C. D.; Biddy, M. J.; Beckham, G. T.; Scarlata, C.; Jacobson, J.; Cafferty, K.; Ross, J.; Lukas, J.; Knorr, D.; Schoen, P. (2013). 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. 147 pp.; NREL Report No. TP-5100-60223.
http://www.nrel.gov/docs/fy14osti/60223.pdf

Design Report Publications

Thermochemical Pathways

Indirect Liquefaction -- 2015

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