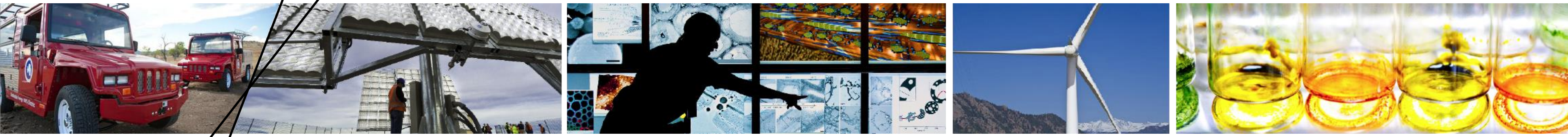
Biochemical Platform Analysis



Biochemical Platform Review
May 20, 2013
Alexandria, VA

Ryan Davis
National Renewable Energy Laboratory

Goals and Objectives

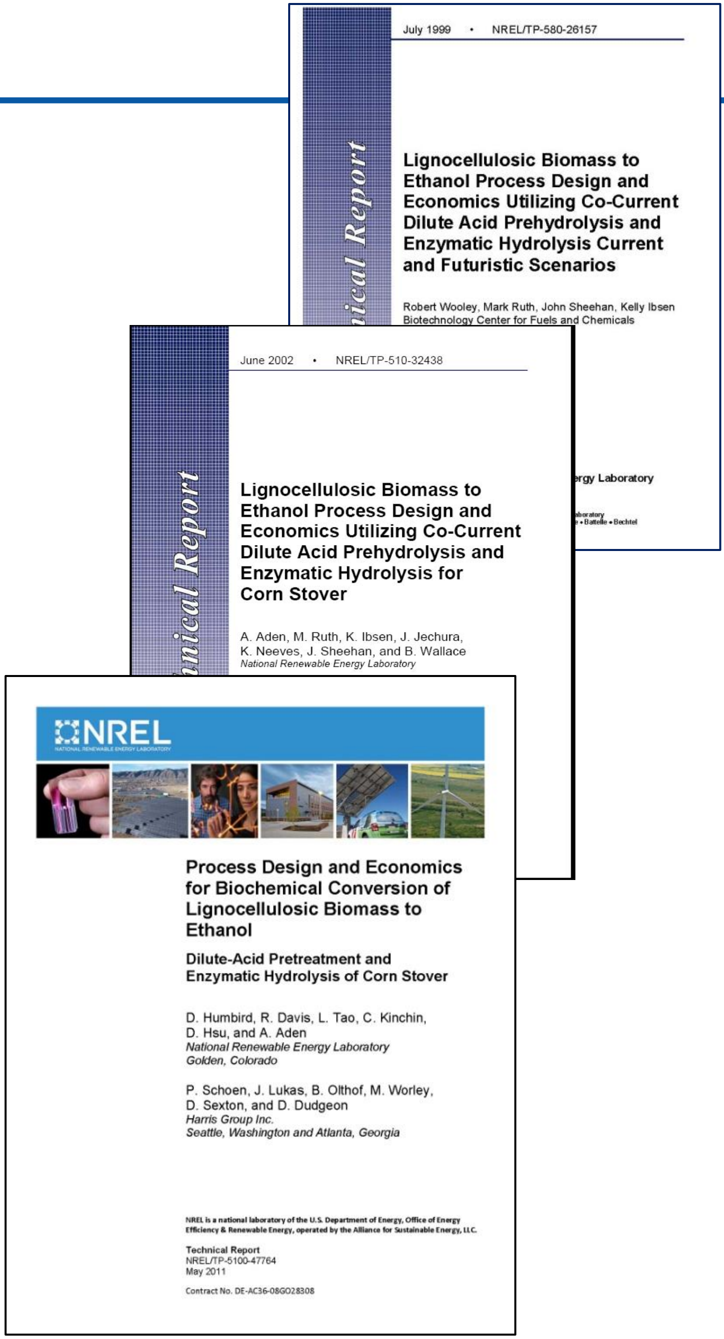
Biochemical Platform Analysis:

- Provides **process design and economic analysis support** for the biochemical conversion platform

- Maintains 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
    - **Disseminate** rigorous, objective modeling and analysis information in a transparent way (the "design report" process)

- Helps to guide future research objectives by translating demonstrated or proposed advances into comparative economic cases

- This task **directly supports the Biomass Program** by assisting in the development of baseline costs and future cost targets
    - *Nov 2012 MYPP goal: "Develop integrated conversion process designs, assess techno-economic feasibility and progress, and evaluate sustainability/life-cycle impacts"*



July 1999 • NREL/TP-580-26157

Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios

Robert Wooley, Mark Ruth, John Sheehan, Kelly Ibsen
Biotechnology Center for Fuels and Chemicals

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

A. Aden, M. Ruth, K. Ibsen, J. Jechura,
K. Neeves, J. Sheehan, and B. Wallace
National Renewable Energy Laboratory

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
Golden, Colorado

P. Schoen, J. Lukas, B. Olthof, M. Worley,
D. Sexton, and D. Dudgeon
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

Quad Chart Overview

Timeline

- Started: 1999
- Finish: 2017
- 75% complete

Barriers

- Bt-E: Pretreatment Costs
- Bt-F: Cellulase Enzyme Production Cost
- Bt-K: Biological Process Integration

Budget

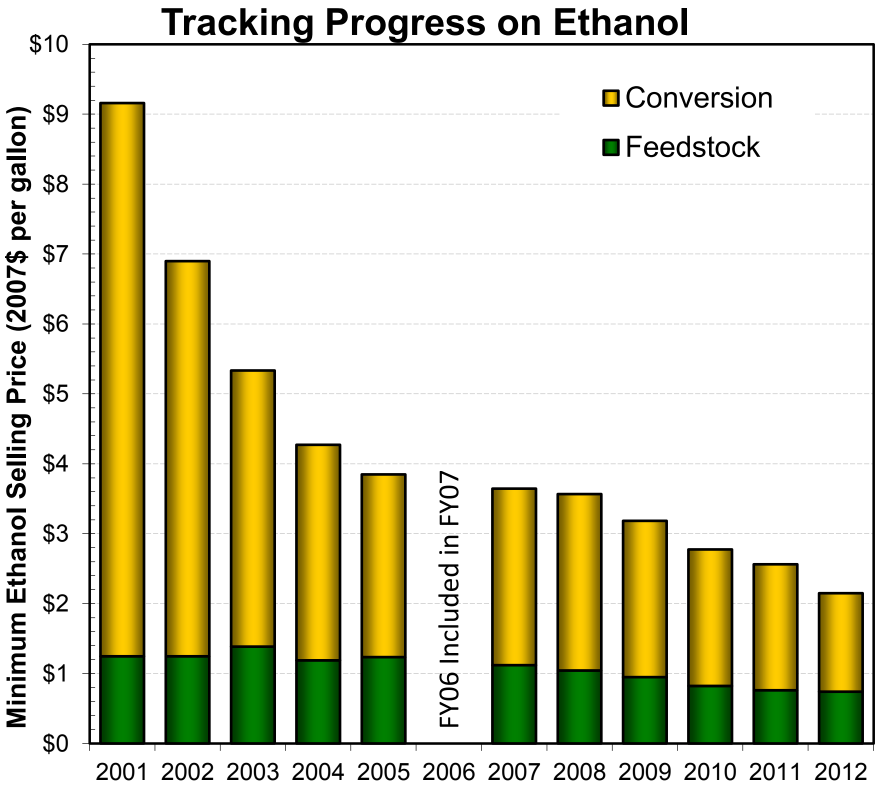
- Funding in FY11: $750,000
- Funding in FY12: $700,000
- Funding for FY13: $850,000
  - 100% DOE funding
- Project has been funded since October 1999; average funding= $429k/yr

Partners

- Idaho National Lab (INL) – Feedstock interface activities
- NREL Biochemical Platform PIs
- Harris Group (Subcontractor)
- Brown and Caldwell (Subcontractor)
- Industrial partners

Project Overview

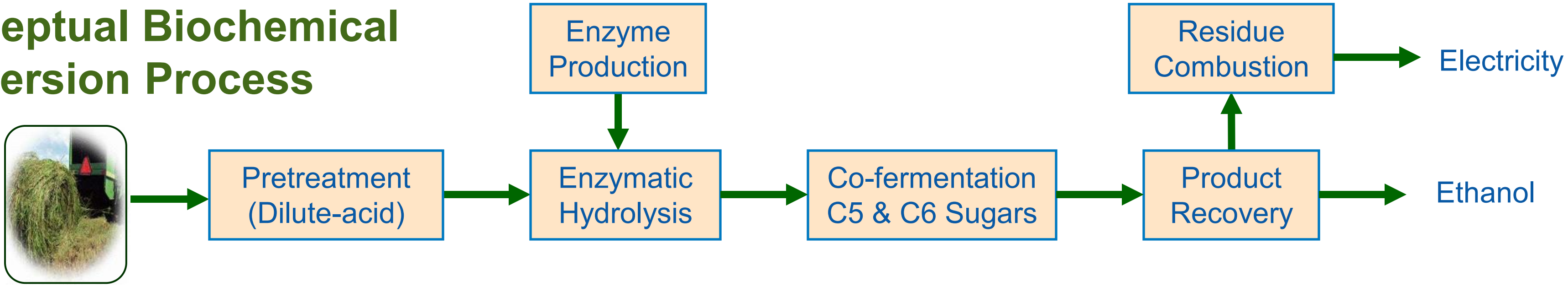
- NREL has a long history of establishing, maintaining, and exercising rigorous process models
  - Set objective, transparent benchmarks for a single plausible conversion pathway
  - Quantify economic impact of funded R&D improvements relative to benchmarks
  - Evaluate sensitivities to uncertainties, process alternatives
  - “Basic engineering” and process optimization
- Phased approach:
  1) *Develop baseline models using best available data*
  2) *Validate and peer review modeling assumptions*
  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
- Focus of biochemical analysis task:
  - 2001-2012: Cellulosic ethanol
  - Beginning 2013: Hydrocarbon fuels/ blend-stocks

Approach to Modeling Conversion Cost

Conceptual Biochemical Conversion Process



Enzyme Production

Residue Combustion

Electricity

Pretreatment (Dilute-acid)

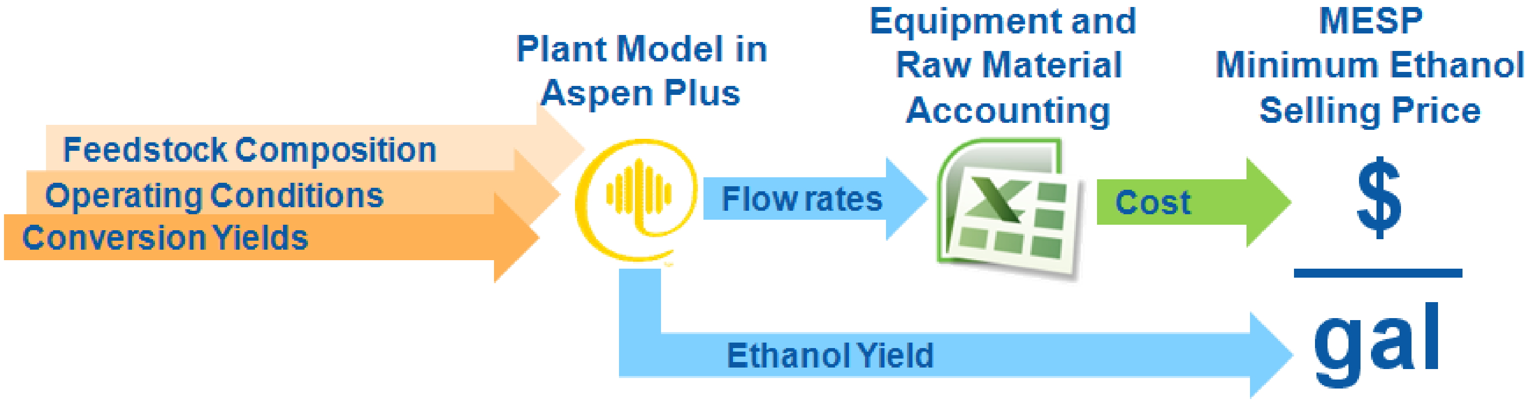
Enzymatic Hydrolysis

Co-fermentation C5 & C6 Sugars

Product Recovery

Ethanol

- Process model in Aspen Plus based on NREL research (TEA modeling is highly integrated with researchers)
- Modeled conversions are based on demonstrated pilot-scale performance in 2012
- Assumes *n*th-plant project cost factors and financing (ignores first-of-a-kind risks)
- Discounted cash-flow ROR calculation determines minimum ethanol selling price (MESP)
- Credibility of analysis supported by vendor-based cost estimates, thorough vetting with industry and research stakeholders
- Research advances → Higher modeled conversion → Lower MESP
- Task management tracked using milestones



Plant Model in Aspen Plus

Equipment and Raw Material Accounting

MESP Minimum Ethanol Selling Price

Feedstock Composition

Operating Conditions

Conversion Yields

Flow rates

Cost

$$\frac{\$}{\text{gal}}$$

Ethanol Yield

Accomplishments

Notable accomplishments (FY11-12):

- Completed biochemical ethanol Design Report update (2011)
  - Revisited all major design/costing assumptions with engineering subcontractor
  - Incorporated R&D learnings from prior years
- Revisited wastewater treatment section design and cost estimates (2011-2012)
  - Worked directly with wastewater vendor to update WWT estimates
- Demonstrated achievement of meeting the 2012 MESP target of $2.15/gal ethanol based on NREL pilot demonstration runs
- Demonstrated reduced GHG emissions for the biorefinery conversion process associated with the 2012 SOT model relative to the 2011 design report case

Current status (FY13):

- Shifting focus from ethanol to hydrocarbon fuels/blend stocks
- Establishing new pathway model for biological conversion of sugars to long-chain hydrocarbons
- Evaluating alternative processing approaches to further optimize integrated process and reduce production costs

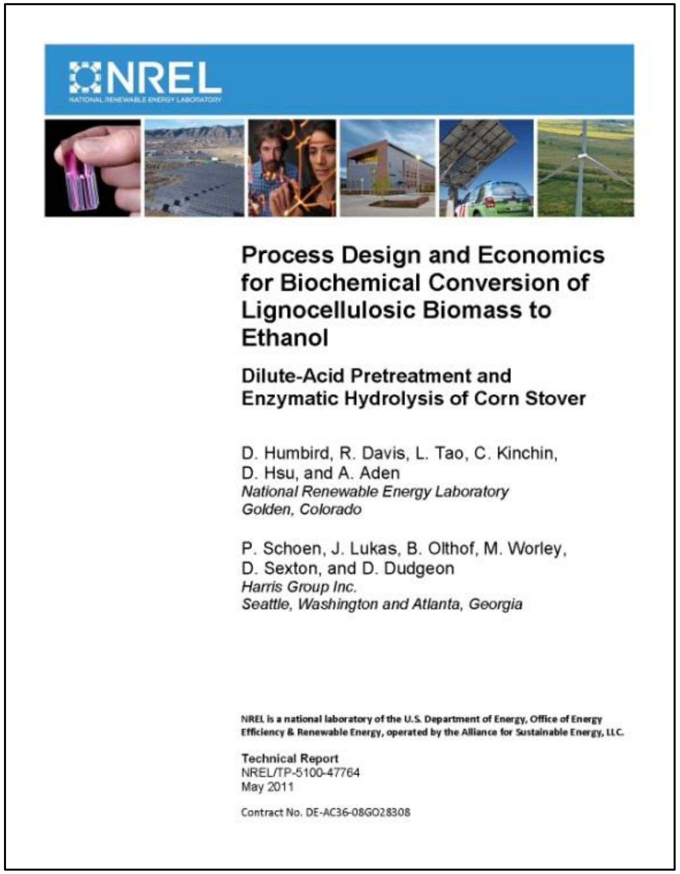
Accomplishments: Ethanol Design Report Update

Motivation for the update

- Incorporate process integration research from the last decade into a 2012-ready design
- Revisit all major assumptions
- Improve model stability and usability
- Update equipment and raw material costs
- Validate model by thorough peer review/vetting

Significant changes

- New feedstock composition and cost
- Detailed pretreatment reactor quote
- Revised other major CAPEX estimates
- On-site enzyme production section
- All-new wastewater treatment section
- Updated direct-cost and financing assumptions
- This update was nearly complete during Feb 2011 Peer Review, but was not yet released



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

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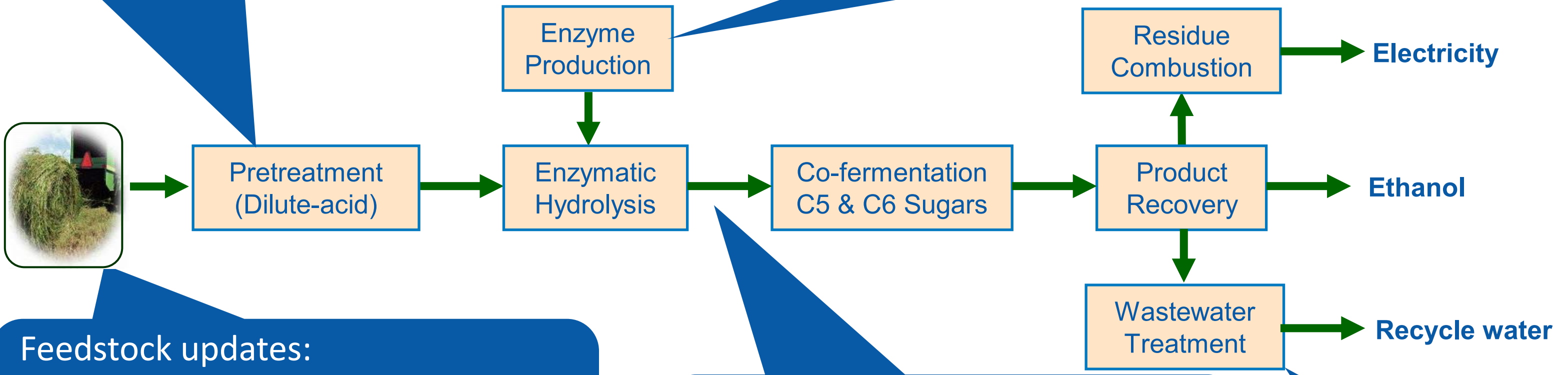
Major Updates in Design Report

Pretreatment updates:

- Whole-slurry NH_3 conditioning replaces S-L separation + liquor-phase conditioning with lime

Enzymes:

- Replace purchased enzymes with on-site enzyme production



DESIGN CASE OUTPUTS:

\$2.15/gal MESP

79.0 gal/dry ton ethanol yield

\$420MM Total Capital Investment

\$76 MM/yr Total Operating Cost

Feedstock updates:

- Composition (lower carbohydrates + lignin)
- Cost (\$50.90 → \$58.50/dry ton)

Hydrolysis/Fermentation:

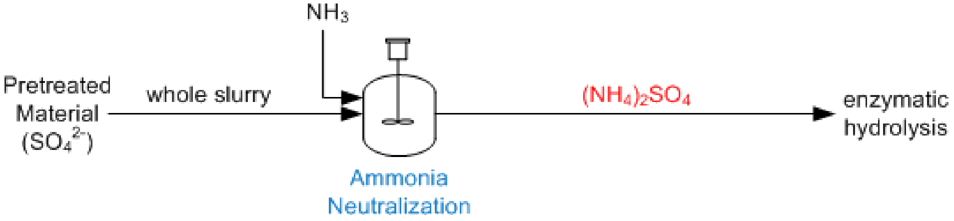
- Replace continuous SSCF mode of operation with batch SHF

Wastewater treatment:

- Re-design WWT system to accommodate elevated levels of nitrogen and sulfur from NH_3 conditioning (produces $(NH_4)_2SO_4$ salts)

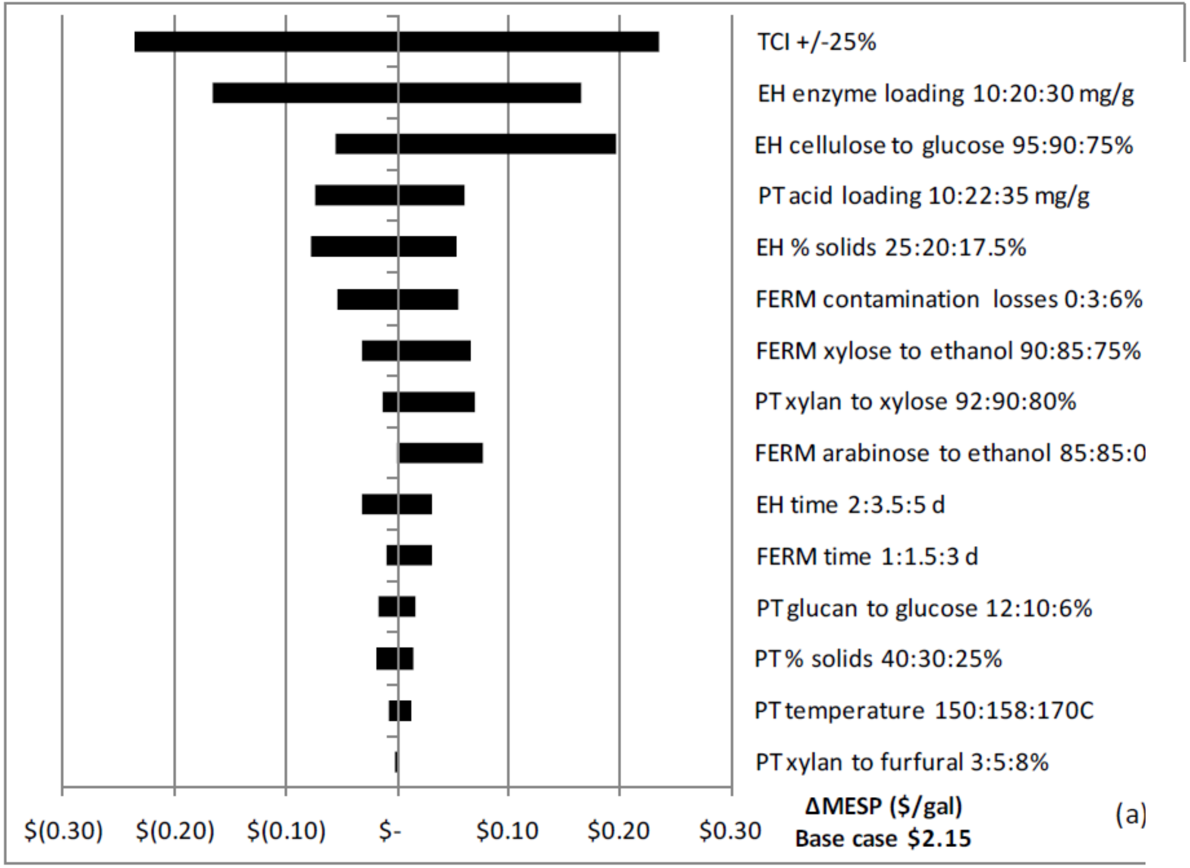
Table 4. Corn Stover Composition from the 2002 Design [2] and the Present Design

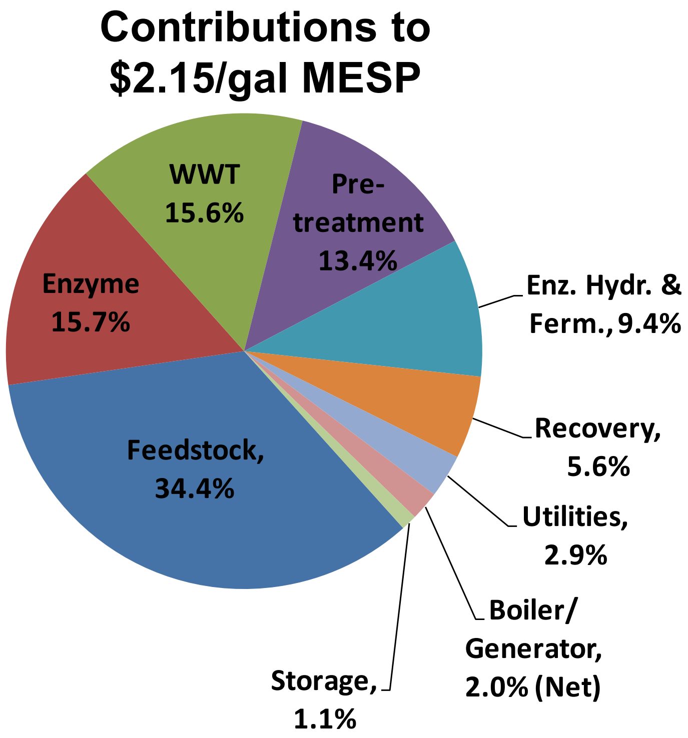
Component	2002 Design (dry wt %)	Present Design (dry wt %)
Glucan	37.40	35.05
Xylan	21.07	19.53
Lignin	17.99	15.76
Ash	5.23	4.93
Acetate[a]	2.93	1.81
Protein	3.10	3.10
Extractives	4.68	14.65
Arabinan	2.92	2.38
Galactan	1.94	1.43
Mannan	1.56	0.60
Sucrose	-	0.77
Unknown soluble solids[b]	1.18	-
Total structural carbohydrate	*64.89*	*58.99*
Total structural carbohydrate + sucrose	*64.89*	*59.76*
Moisture (bulk wt %)	*15.0*	*20.0*



Framing the Analysis

Tornado Plot (2011 Design Report, $2.15/gal baseline)





Sensitivity analysis

- Critical element of TEA modeling
- Quantifies economic impact of uncertainties, risks, and future R&D improvements
- Beyond economic uncertainty associated with underlying analysis methodology, key cost sensitivities include enzyme loading, glucose yield, and acid loading

Accomplishments: FY12 SOT Demonstration - Tracking Progress on Ethanol

	2007	2008	2009	2010	2011	*2012 Target*	*2012 SOT*
Minimum Ethanol Selling Price ($/gal)	**$3.64**	**$3.57**	**$3.18**	**$2.77**	**$2.56**	***$2.15***	***$2.15***
Feedstock Contribution ($/gal)	$1.12	$1.04	$0.95	$0.82	$0.76	*$0.74*	*$0.83*
Conversion Contribution ($/gal)	$2.52	$2.52	$2.24	$1.95	$1.80	$1.41	*$1.32*
Yield (Gallon/dry ton)	69	70	73	75	78	*79*	*71*
Feedstock							
Feedstock Cost ($/dry ton)	$77.20	$72.90	$69.65	$61.30	$59.60	*$58.50*	*$58.50*
Pretreatment							
Solids Loading (wt%)	30%	30%	30%	30%	30%	*30%*	*30%*
Xylan to Xylose (including enzymatic)	75%	75%	84%	85%	88%	*90%*	*81%*
Xylan to Degradation Products	13%	11%	6%	8%	5%	*5%*	*5%*
Conditioning							
Ammonia Loading (g per L hydrolysate liquor)	12.9	12.9	9.8	4.8	3.8	*4.8*	*1.6*
Hydrolysate solid-liquid separation	Yes	Yes	Yes	Yes	Yes	*No*	*No*
Xylose Sugar Loss	2%	2%	2%	2%	1%	*1%*	*0%*
Glucose Sugar Loss	1%	1%	1%	1%	1%	*0%*	*0%*
Enzymes							
Enzyme Contribution ($/gal EtOH)	$0.39	$0.38	$0.36	$0.36	$0.34	*$0.34*	*$0.36*
Enzymatic Hydrolysis & Fermentation							
Total Solids Loading (wt%)	20%	20%	20%	17.5%	17.5%	*20%*	*20%*
Saccharification Mode	Washed-solids	Washed-solids	Washed-solids	Washed-solids	Washed-solids	*Whole-slurry*	*Whole-slurry*
Combined Saccharification & Fermentation Time (d)	7	7	7	5	5	*5*	*5*
Corn Steep Liquor Loading (wt%)	1%	1%	1%	1%	0.25%	*0.25%*	*0.25%*
Overall Cellulose to Ethanol	86%	86%	84%	86%	89%	*86%*	*74%*
Xylose to Ethanol	76%	80%	82%	79%	85%	*85%*	*93%*
Arabinose to Ethanol	0%	0%	51%	68%	47%	*85%*	*54%*

2012 SOT Updates vs 2011 Design Case

Feedstock

Deacetylation:
- Dilute (~0.4%) NaOH, 80 °C, 2 hr
- Removes acetate = improves hydrolysis + fermentation yields
- Reduces portions of non-fermentable components = reduced throughputs by 20-25% = reduced CAPEX

Deacetylation

Deacetylation

Wastewater Treatment

Dilute Acid Impregnation

Dilute Acid and Steam Pretreatment

Conditioning

Enzymatic Hydrolysis

Fermentation

Distillation + Solids Separation

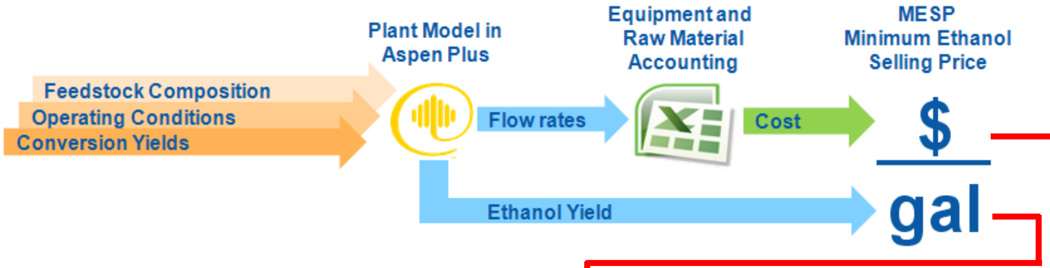
Ethanol

Residue Processing

Pretreatment + Conditioning:
- Lower acid loading in PT reactor + lower acetic acid formation = lower NH_3 neutralization demand = reduced OPEX

Wastewater Treatment:
- Re-costed WWT section with vendor (Brown and Caldwell) = reduced CAPEX and OPEX
  - New WWT feed stream from deacetylation liquor, lower total salts and nitrogen due to pretreatment modifications
  - Reduction in AD retention time from 58 to 40 days
  - Nitrification no longer needed due to large reduction in feed N

Achieving 2012 SOT cost target



Key process results:

Metric	2012 Target	2012 Demonstrated
Enzyme Loading (mg/g cellulose)	20	19
Cellulose to Ethanol	86%	74%
Xylan to Xylose	90%	81%
Xylose to Ethanol	85%	93%
Arabinose to Ethanol	85%	54%
Ethanol Yield (gal/ton)	**79**	**71**

10% decrease in costs ($) balanced by 10% decrease in yield (gal) = $2.15/gal

Key cost results:

Capital Costs ($MM)	2011 Design Report	2012 SOT
Pretreatment	30	25
Neutralization/Conditioning	3	4
Saccharification & Fermentation	31	25
On-site Enzyme Production	18	17
Distillation and Solids Recovery	22	20
Wastewater Treatment	49	41
Storage	5	4
Boiler/Turbogenerator	66	68
Utilities	7	7
Total Installed Equipment Cost	**232**	**210**

Operating Costs ($MM/yr)	2011 Design Report	2012 SOT
Feedstock + Handling	45	45
Sulfuric Acid + Ammonia	5	3
Glucose (Enzyme Production)	12	12
Other Raw Materials	8	6
Waste Disposal	2	1
Net Electricity	-7	-9
Fixed Costs	11	10
Total Operating Cost	**76**	**68**

Accomplishments: Sustainability Metrics Assessment

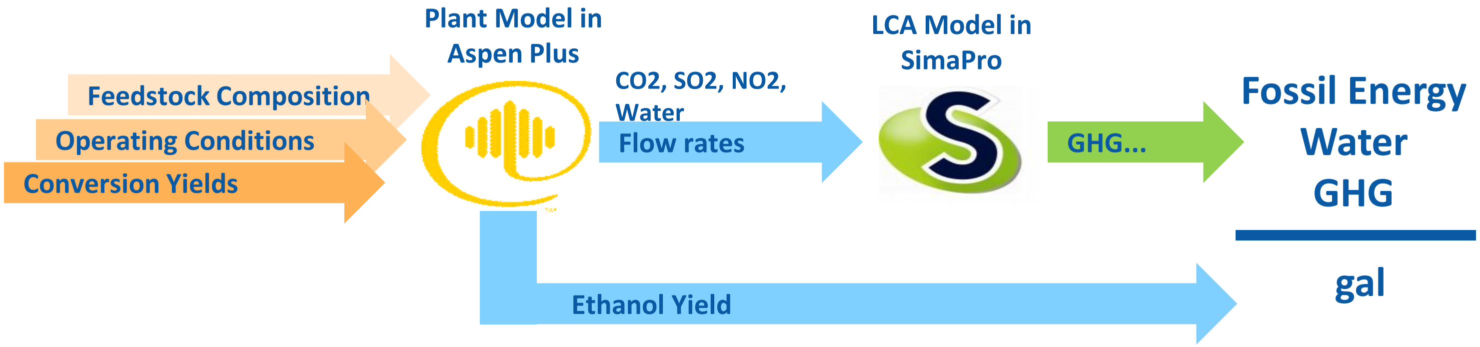
Economic Sustainability
- Profitability
- Efficiency and productivity

Social Sustainability
- Social acceptability
- Social well-being
- Energy security and external trade
- Rural development and workforce training

Environmental Sustainability
- Climate
- Soil quality and agronomics
- Water quality and quantity
- Air quality
- Biological diversity
- Land Use

http://www1.eere.energy.gov/biomass/pdfs/mypp_november_2012.pdf

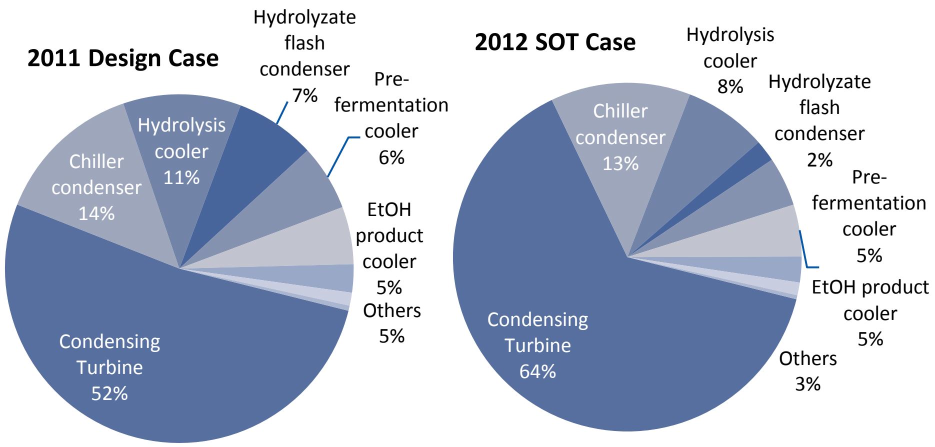
NREL as part of DOE's commitment to sustainability:
- Evaluating sustainability metrics for the biorefinery conversion models
- Assessing life-cycle impact and environmental sustainability scenarios (e.g., tradeoffs between conversion technology options)
- Developing annual state-of-technology (SOT) sustainability assessments for the TC/BC conversion platforms [**milestone reports FY:2009,2010,2011,2012,2013**]



Sustainability Metrics Results: 2012 SOT vs 2011 Design Case

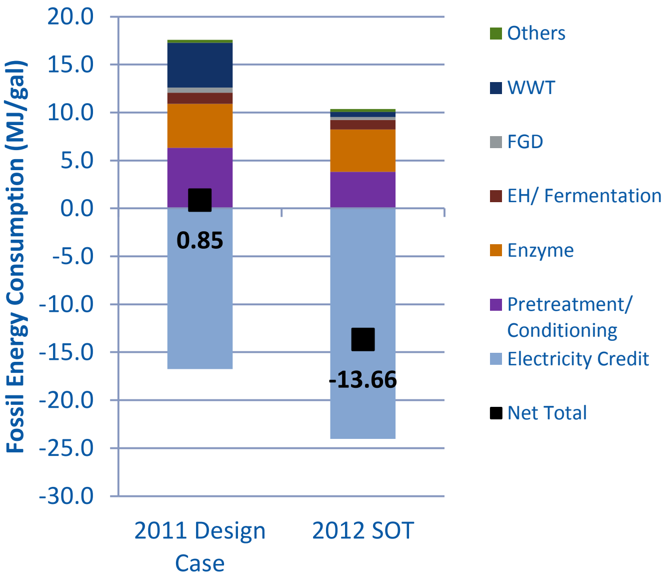
Metric	2011 Design Case	2012 SOT
GHG Emissions (kg CO_{2e}/GJ ethanol)	-0.4	-14.9
GHG Emissions (kg CO_{2e}/gal ethanol)	-0.03	-1.2
Consumptive Water Use (gal/gal ethanol)	5.4	6.6
Net Fossil Energy Consumption (MJ/MJ ethanol)	0.01	-0.17
Net Fossil Energy Consumption (MJ/gal ethanol)	0.9	-13.7
Fuel Yield (gal ethanol/dry ton)	79.0	70.9
Carbon-to-Fuel Efficiency (ethanol/biomass)	30.2%	27.1%

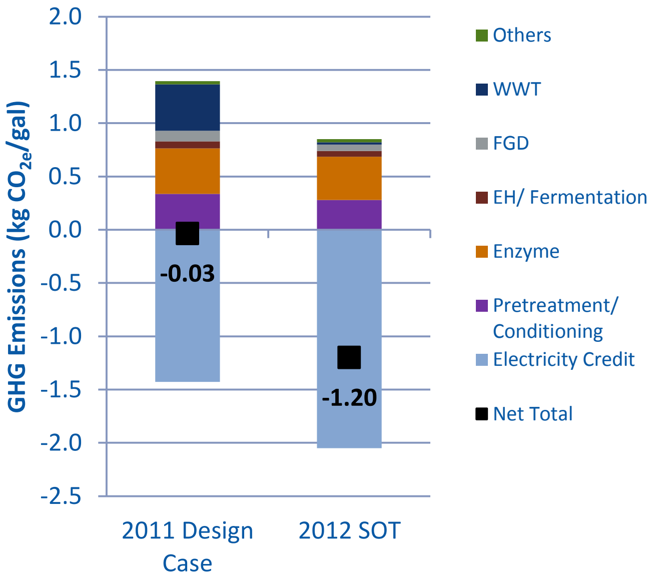
Facility Cooling Water Demands:



***Sustainability metrics for biochemical conversion step are driven largely by power coproduct**

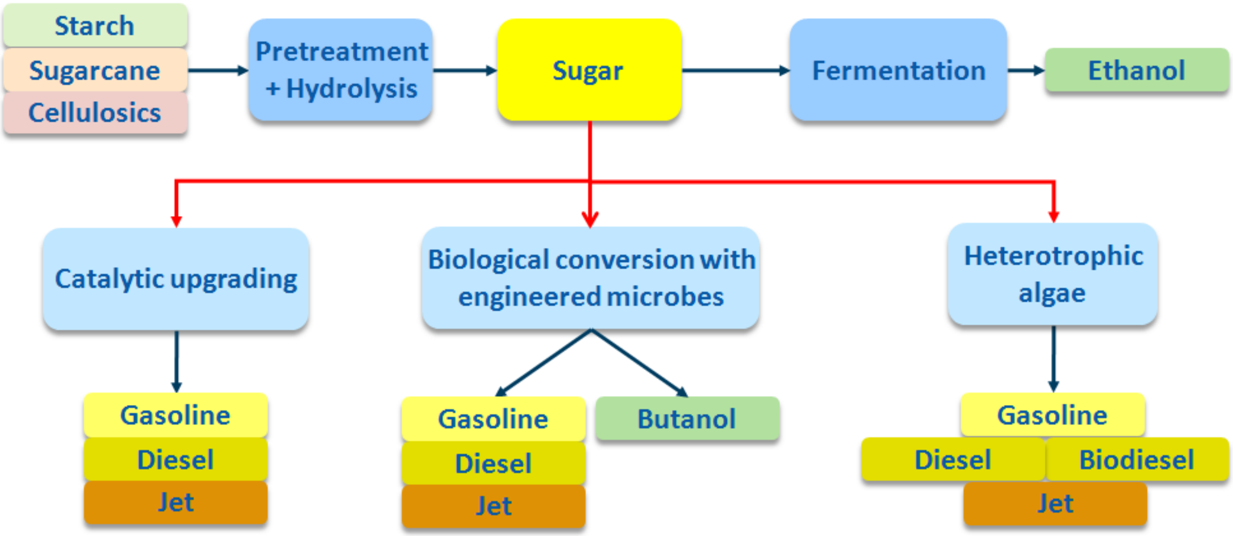
- Lower ethanol yield in SOT case = more unconverted material to boiler = more GHG and fossil energy offsets from increased power coproduct
- More power coproduct = higher cooling water demands for steam turbine = higher net water consumption





Progress on Transition to Hydrocarbon Biofuels

- Moving forward beyond FY12: transitioning to hydrocarbon biofuel pathways
- Biochemical approaches:
  - Catalytic upgrading of sugars (aqueous-phase reforming)
  - Biological upgrading of sugars
    - Intracellular oil production/extraction (e.g., heterotrophic algae)
    - Oil secretion (microbial)
- NREL recently released tech memos highlighting key advantages and research needs for biological + catalytic pathways (March 2013)

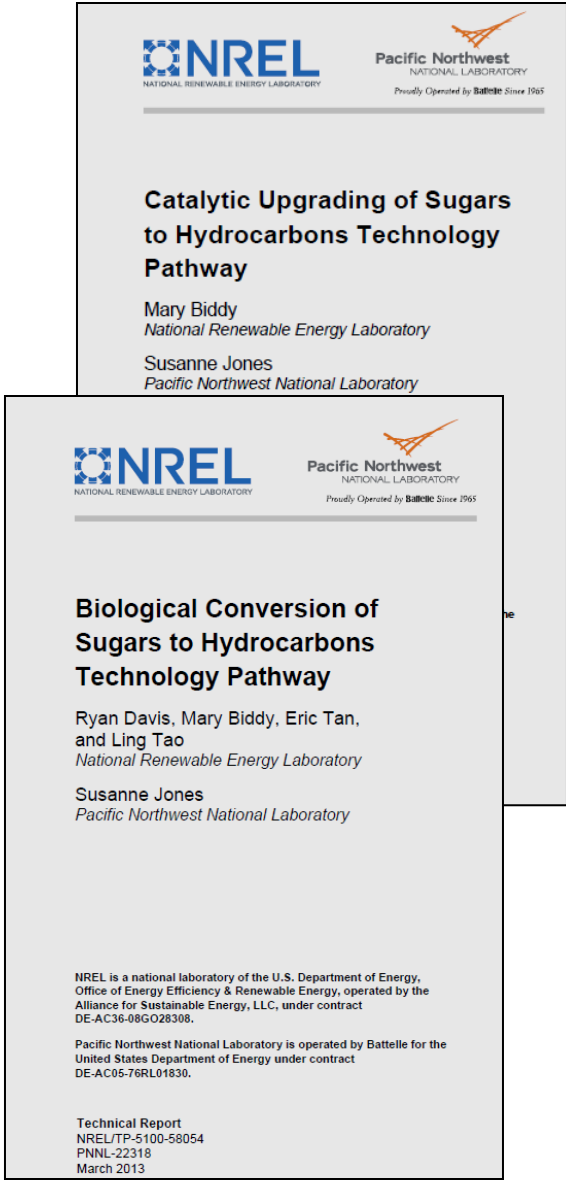


Biological + Catalytic Conversion of Sugars to Hydrocarbons

NREL is beginning to investigate process/economic potential for biological and catalytic hydrocarbon pathways

- Published technical memos March 2013

- Biological conversion: advantages
  - Organisms may be tailored to produce targeted fuel components with high-value or desirable properties
  - Most metabolic pathways will produce a hydrocarbon intermediate requiring mild upgrading at marginal cost
- Catalytic conversion: advantages
  - Flexibility to utilize a wider range of biomass deconstruction products (organic acids, furanics, lignin deconstruction products)
  - Produces drop-in blendstocks and potential for biomass-based chemicals (e.g. para-xylene)
- Key research needs
  - Reduce sugar/hydrolysate production costs and maximize optimization
  - Understand separation/conditioning requirements for hydrolysate, minimize cost of hydrolysate conditioning
  - Optimize design and scale for aerobic fuel production *(biological)*
  - Maximize sugar/carbon utilization and microbe performance *(biological)*
  - Increase catalyst selectivity towards desired fuel products *(catalytic)*
  - Improve catalyst lifetime and durability *(catalytic)*
  - Define product separation and upgrading requirements
  - Evaluate co-product opportunities to utilize additional components, e.g. lignin, acetate



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Catalytic Upgrading of Sugars to Hydrocarbons Technology Pathway

Mary Biddy
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Biological Conversion of Sugars to Hydrocarbons Technology Pathway

Ryan Davis, Mary Biddy, Eric Tan, and Ling Tao
National Renewable Energy Laboratory

Susanne Jones
Pacific Northwest National Laboratory

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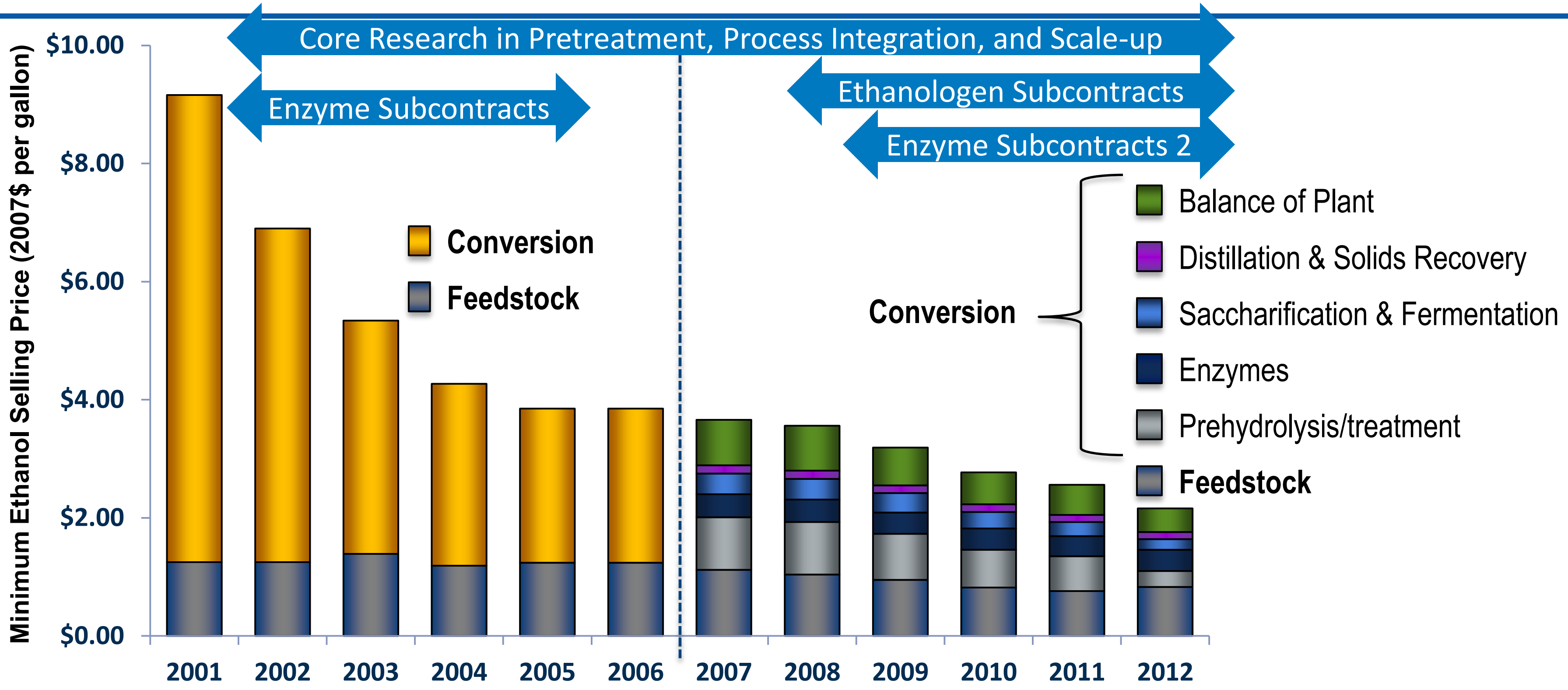
NREL/TP-5100-58054
PNNL-22318
March 2013

http://www.nrel.gov/docs/fy13osti/58054.pdf
http://www.nrel.gov/docs/fy13osti/58055.pdf

Relevance



NREL TEA modeling is highly relevant to DOE goals:

- Helps to guide DOE decisions, out-year target projections
  - *Technical targets (yields, process performance, etc)*
  - *Cost targets (DOE goal: cost-competitive cellulosic ethanol by 2012)*
  - *Validation of modeling assumptions*
- Identifies key R&D directions (yields, coproduct opportunities, etc)
- Analysis can serve a wide variety of stakeholders
  - *Industry (facilitate interaction between industry, NREL, DOE)*
  - *Research community, decision makers*

Nov 2012 MYPP Performance Goal:
"Through R&D, make cellulosic biofuels competitive with petroleum-based fuels at a modeled cost for mature technology of $3 per gallon gasoline equivalent (GGE)"

Success Factors and Challenges

Success Factors

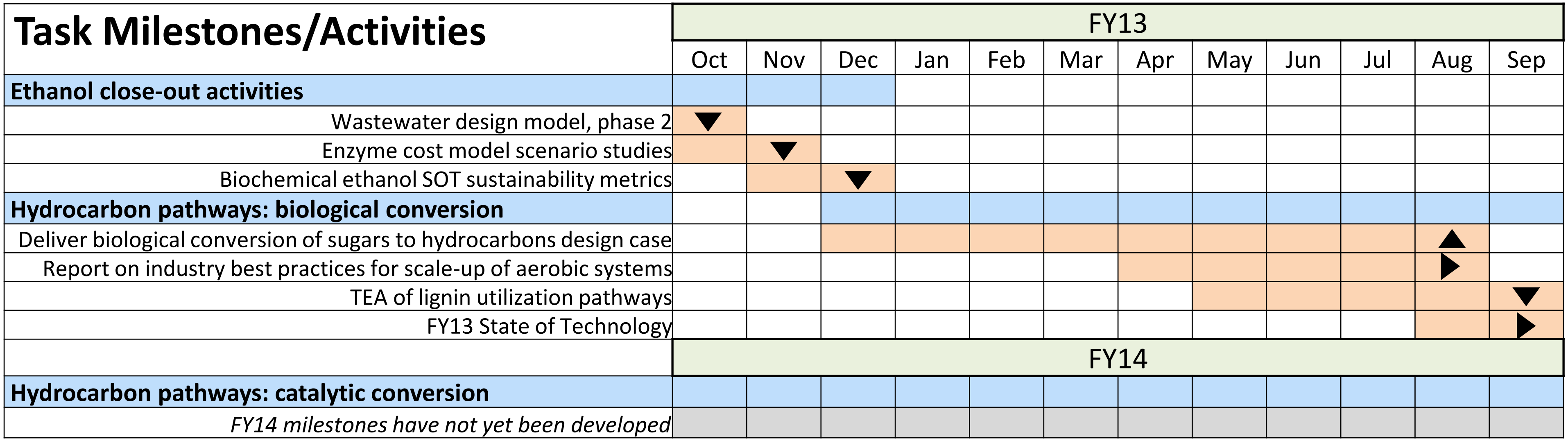
- Maintaining interaction with researchers; serving as interface between researchers, DOE, and broader community
- Critical to maintain credible engineering analyses that are transparent and unbiased
    - These analyses represent a public dissemination of DOE research and a starting point for private industry
- Leverage engineering contractor/vendor estimates for design and cost information
    - Reduce uncertainty in underlying cost estimates
- Through process design, highlight barriers to commercialization in under-researched areas of the process

Challenges

- Transition to hydrocarbon fuels brings new uncertainties on state of technology, future potential
    - Performance for biological production of hydrocarbon fuels, scale-up implications are poorly understood
- Need to increase carbon efficiencies to fuels/co-products, possibly beyond fermentable fraction of biomass
    - Further evaluate co-product opportunities
    - Requires holistic approach to process design, integration, and biomass utilization
- Limited definition of fuel product/blend stock specifications for new hydrocarbon pathways
- Limited sharing of lessons learned by industry

Future Work

- Development of biological conversion of sugars to hydrocarbons technology pathway model (FY13)
    - Working with an engineering subcontractor to establish pertinent design/cost estimates for modeled pathway
    - Document new pathway TEA model and cost targets in a new “design report” technical memo for public dissemination
    - Collaborations under way with NREL Bioprocess Integration (BPI) and Lignin tasks to quantify process/cost implications for aerobic system designs and lignin utilization pathways
    - Establish current State of Technology (SOT) estimates using best available data
- Development of catalytic conversion of sugars to hydrocarbons technology pathway model (FY14)
    - Establish new pathway model for catalytic conversion of cellulosic biomass hydrolysate to hydrocarbons
    - Partners: PNNL, industry stakeholders



Task Milestones/Activities	FY13											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Ethanol close-out activities	🟦	🟦	🟦									
Wastewater design model, phase 2	🟧 ▼											
Enzyme cost model scenario studies	🟧	🟧 ▼										
Biochemical ethanol SOT sustainability metrics		🟧	🟧 ▼									
Hydrocarbon pathways: biological conversion			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Deliver biological conversion of sugars to hydrocarbons design case			🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 ▲	
Report on industry best practices for scale-up of aerobic systems							🟧	🟧	🟧	🟧	🟧 ▶	
TEA of lignin utilization pathways								🟧	🟧	🟧	🟧	🟧 ▼
FY13 State of Technology											🟧	🟧 ▶
	FY14											
Hydrocarbon pathways: catalytic conversion	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
FY14 milestones have not yet been developed	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

▲= Joule milestone, ▶ = D-milestone, ▼ = E-milestone

Summary

- Biochemical Analysis task has made important achievements in FY12-13
  - Ethanol design report completed and published
  - Ethanol SOT complete, demonstrated achieving $2.15/gal MESP target
  - Sustainability Metrics work projects reduced GHG, fossil energy profiles for SOT pathway relative to design case targets
  - Support DOE MYPP efforts (baseline + out-year target projections)
  - Support broader research community (transparent, rigorous models; quantify R&D improvements)
- Currently transitioning to hydrocarbon biofuel pathways
  - FY13 work focusing on biological conversion of sugars
  - Analysis to date suggests important research needs exist to understand microbe metabolic performance on cellulosic substrates, optimize process integration for synergistic benefits, and increase carbon efficiencies
- Considerable activity planned for FY13-14
  - Design report on biological conversion to hydrocarbons
  - Further investigate process and design alternatives
    - Direct microbial conversion, alternative pretreatments, etc.
  - Establish new design model for catalytic sugar conversion
    - Investigate requirements on upstream process modifications (pretreatment, hydrolysis) associated with catalytic processing

Questions?

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- Industrial Partners

Additional Slides

Responses to Reviewers' Comments from 2011

•Does not incorporate technology advancements outside of NREL. If it is to advance the SOT it must look beyond NREL's achievements.

•The models do incorporate technology external to NREL, as they consider improvements in cellulase enzyme preparations and fermenting strains; this type of research is not currently performed to a large extent at NREL. Additionally, the new hydrocarbon models currently being built must rely heavily on published or otherwise publicly-available data, as SOT performance for the associated organisms is not available within NREL.

•The project would like to have more input from industry but this has proven difficult. It advances the SOT "in theory".

•Typically it is difficult to solicit data from industry that can be shared publicly. NREL has a number of collaborations with industry, but many of these are separated from the DOE Platform work. The inputs from industry which may have a better chance of being made public are typically organizations which receive DOE funding, as fully private entities are not likely to provide their best performance results to us, at least to the review standards that we require. While the only SOT models which fully demonstrate the true commercial state of technology would be those which are based on commercial-scale performance, the NREL 2012 SOT models are based on demonstrated values at pilot-scale for all "ISBL" parameters.

•An improvement would be to include sensitivity analyses that show the sensitivity of the model, including how existing variability in data … may affect the model.

•NREL places a high priority on sensitivity analyses in all modeling efforts, as any model is only as good as the inputs that go into it. During the 2011 peer review, sensitivity analysis could not be strongly showcased as the design report numbers had not yet been finalized. This presentation includes sensitivity analysis from the design report; including sensitivity to uncertainties, risks, as well as cost impacts to potential future R&D improvements.

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- R. Davis, M. Biddy, E. Tan, L. Tao, S. Jones, “Biological Conversion of Sugars to Hydrocarbons Technology Pathway,” NREL/PNNL joint technical report NREL/TP-5100-58054, PNNL-22318; http://www.nrel.gov/docs/fy13osti/58054.pdf, http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22318.pdf, March 2013.
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- L. Tao, D. Templeton, D. Humbird and A. Aden, “Effect of Corn Stover Compositional Variability on Minimum Ethanol Selling Price,” *Bioresource Technology*, Accepted April 2013 (in press).
- L .Tao, X. Chen, A. Mohagheghi, H. Smith, W. Wang, C. Dibble S. Park, B.W. Koo and M. Tucker, “Improved overall ethanol yield of corn stover by deacetylation and disc refining with high solids dilute acid pretreatment: Techno-economic analysis,” *Biotechnology for Biofuels*, DOI: 10.1186/1754-6834-5-69, September 2012
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- F. You, L. Tao, D. J. Graziano and S. W. Snyder, “Optimal Design of Sustainable Cellulosic Biofuel Supply Chains: Multiobjective Optimization Coupled with Life Cycle Assessment and Input-Output Analysis,” *AIChE J.*, DOI: 10.1002/aic.12637, March 2011
- L. Tao, E. C. Tan, R. T. Elander and A. Aden, 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 Biomass Utilization Systems; Edited by Jianzhong Sun, Shi-You Ding and Joy Doran Peterson; Accepted, May 2012
- L. Tao, R. T. Elander and A. Aden, Process and Technoeconomic Analysis of Leading Pretreatment Technologies; Invited Book Chapter; Editor Charles Wyman; Accepted, April 2012
- L. Tao and A. Aden, the Economics of Current and Future Biofuels, Biofuels, Global Impact on Renewable Energy, Production Agriculture, and Technological Advancements; invited book chapter, pp37-69; Edited by . D. Tomes, P. Lakshmanan and D. Songstad, Springer New York, 2011
- D. Humbird, “2011 Update of the NREL Biomass-to-Ethanol Process Design Report,” 33rd Symposium on Biotechnology for Fuels and Chemicals, Seattle, WA, May 2011
- L. Tao, R. T. Elander and A. Aden, “Process and Technoeconomic Analysis of Leading Pretreatment Technologies”, AIChE Annual Meeting, Minneapolis, MN, October 2011

Design Report Update: Comparison of Previous Model to New Model

Metric (2012 design case)	2002 Model	2011 Model
MESP, 2007$	**$1.49/gal**	**$2.15/gal**
Ethanol yield, gal/dry ton	89.9	79.0
Total Capital Investment, 2007$	$230MM	$420MM
Variable Operating Cost, 2007$	$54MM/yr	$65MM/yr
Fixed Operating Cost, 2007$	$9MM/yr	$11MM/yr
Direct Cost Factor	51% of purchased cost	91% of purchased cost
Indirect Cost Factor	48% of total direct cost	60% of total direct cost
% Equity	100%	40%; Loan 8% APR, 10 yr

- **2002:** Higher uncertainty in process conversion performance, optimistic project cost assumptions
- **2011:** High confidence in performance assumptions, stronger project cost assumptions due to feedback from Harris, DOE, and peer reviewers
- **New MESP carries considerably lower uncertainty**

Metric Adjustment	$/gal Impact	Comment
Feedstock Cost	$0.10	Increased from $50.90 to $58.50 (new grower payment)
Feedstock Composition	$0.08	Lower ethanol yield using more representative feedstock composition
Enzyme	$0.22	On-site production model predicted $0.34/gal versus $0.12/gal in the purchased model
Electricity Credit	-$0.07	More electricity is generated from biomass but less exported due to higher internal power requirements (e.g., enzyme production and WWT)
Capital	$0.30	Net increase in the cost of required capital equipment and higher direct and indirect cost factors
Financial Assumptions	-$0.06	100% Equity to 40% Equity at 8% interest
Chemicals	$0.06	New chemical costs
Fixed Costs	$0.03	New labor costs
Total	**$0.66**	**($1.49 + $0.66 = $2.15)**