Biochemical Refining of Lignocellulose to Biofuels: Status and Prospects

AIChE Annual Meeting, Salt Lake City, Utah

Sustainable Biorefineries Plenary, Paper 431b

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Outline

Current Situation
– Biofuels progress and drivers
– New initiatives
– RDD&D situation

NREL R&D Progress
– Biochemical cellulosic ethanol
– Improved piloting facilities
– R&D beyond cellulosic ethanol
  • National Advanced Biofuels Consortium (NABC)

Outlook and Final Thoughts
– On-going challenges and unresolved issues
Recent History of Advanced Biofuels

• 1995-2000: Demonstrate technical feasibility
  Focus on cellulosic ethanol

• 2000-2005: Show economic feasibility & scale potential
  Focus remains largely on cellulosic ethanol

• 2005-2010: Increase funding to accelerate biofuels RDD&D
  Expand product portfolio to encompass higher alcohols and hydrocarbons, begin funding new concepts including hybrid BC/TC and algal pathways
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Current Situation

Advanced biofuels R&D booming
- Many potential routes being rigorously studied (BC, TC, hybrid, algae, etc.)
- Major bioenergy research centers formed, actively engaged (BESC, JBEI, GLBRC, EBI, etc.)
- R&D community 100x bigger (more than 50 sessions at this meeting!)

Commercialization starting
- Many dozens of companies pursuing technology development
- Cellulosic and algal biofuels production occurring, albeit at a pace much slower than planned or initially forecasted

Danish fueling station pump dispensing E5 gasoline-ethanol blend containing wheat straw-derived cellulosic ethanol

photo courtesy of Claus Felby (U. Copenhagen)
“Developing the next generation of biofuels is key to our effort to end our dependence on foreign oil and address the climate crisis – while creating millions of new jobs that can't be outsourced. With American investment and ingenuity – and resources grown right here at home – we can lead the way toward a new green energy economy.”

– Secretary of Energy Steven Chu
More Fuels Needed to Displace Fossil Oil

- Advanced biofuels and products are needed to displace the entire barrel (14.7 mbd = 225 bgy = 70% of U.S. petroleum use)

  - Heavy duty/diesel and jet fuel substitutes required to displace several components
    (43 bgy diesel + 25 bgy aviation fuel + 10 bgy fuel oil for shipping = 78 bgy = 36% of transportation fuel)

  - Cellulosic ethanol displaces light duty gasoline fraction
    (140 bgy = 64% of transportation fuel)

DOE Stimulating Progress Across Supply Chain

The USDOE Biomass Program is working to advance biomass technologies in support of its mission to strengthen America’s energy security, environmental quality, and economic vitality through:

- **Feedstocks**: Developing lower cost feedstock logistics systems
- **Conversion technologies**: Improving conversion efficiencies and costs
- **Integrated biorefineries**: Systematically validating and deploying technology at first-of-a-kind facilities
- **Infrastructure**: Evaluating vehicle emissions, performance, and deployment options
- **Biopower**: Providing a clean, domestic, dispatchable renewable source of power
- **Advanced biofuels**: Expanding portfolio beyond cellulosic ethanol to hydrocarbon fuels
Integrated Biorefinery Conversion Platforms

Advanced Biomass R&D

Sugar Platform
- Sugar Feedstocks
- Residues
- Clean Gas

Combined Heat & Power

Thermochemical Platform

Fuels, Chemicals, & Materials

Integrated Industrial Biorefineries

Biomass

Systems Integration
Biomass Conversion to Fuels

**Major Biochemical Conversion Steps**

- Feedstock Prep & Handling
  - Pretreatment & Enzymatic Hydrolysis/Saccharification
    - Hydrolysate Conditioning/Detoxification
      - Biomass Sugar Fermentation
        - Product Recovery/Purification

**Major Thermochemical Conversion Steps**

- Feedstock Prep & Handling
  - Thermochemical Synthesis Gas Production/Gasification
    - Syngas Cleanup & Conditioning/Tar Reforming
      - Syngas Catalytic Upgrading/Product Synthesis
        - Product Recovery/Purification
Biomass Conversion to Fuels

Hybrid Approaches

- Pretreatment & Enzymatic Hydrolysis/Saccharification
- Hydrolysate Conditioning/Detoxification
- Biomass Sugar Fermentation
- Feedstock Prep & Handling
- Thermochemical Synthesis Gas Production/Gasification
- Syngas Cleanup & Conditioning/Tar Reforming
- Syngas Catalytic Upgrading/Product Synthesis
- Product Recovery/Purification

Aqueous Phase Reforming
## Integrated Biorefinery Projects

<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
<th>Feedstocks</th>
<th>Fuel/Product</th>
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</thead>
<tbody>
<tr>
<td><strong>R&amp;D</strong> 2 projects</td>
<td>Includes R&amp;D and a preliminary engineering design</td>
<td>Poultry Fat, Woody Biomass, Ag Residue, Algal Oil</td>
<td>Renewable Fuels, Renewable Gasoline, Renewable Diesel</td>
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<tr>
<td><strong>Pilot Scale</strong> 12 projects</td>
<td>Process a minimum of 1 dry ton per day biomass and verify integrated performance of the given suite of technologies from both a technical and an economic perspective for the first time</td>
<td>Algae, CO₂, Woody Biomass, Sweet Sorghum, Corn Stover, Switchgrass, Energy Sorghum, Ag and Forestry Residue, Hybrid Poplar</td>
<td>Ethanol, Cellulosic Ethanol, Renewable Diesel, Jet Fuel, Renewable Diesel</td>
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<tr>
<td><strong>Demonstration Scale</strong> 9 projects</td>
<td>Validate process technology performance from both technical and an economic perspectives at a scale predictive of a commercial facility</td>
<td>Wheat Straw, Corn Stover, Poplar Residues, Woody Biomass, Algae, Mill Residues, MSW, Ag and Forestry Residue</td>
<td>Cellulosic Ethanol, Renewable Sulfur-free Diesel Fuel, Renewable Hydrocarbon-based Fuel, Renewable Gasoline, Renewable Diesel, Jet Fuel, Succinic Acid</td>
</tr>
<tr>
<td><strong>Commercial Scale</strong> 6 projects</td>
<td>Process a minimum of 700 dry tons per day biomass in a a first-of-a-kind or “beta” commercial facility</td>
<td>Lignocellulosic Biomass, Corn Cobs, Woody Biomass, Mill Waste, Sorted MSW</td>
<td>Cellulosic Ethanol, Ethanol, Methanol</td>
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</tbody>
</table>
DOE’s Integrated Biorefinery Project Map

For more information visit: http://www.eere.energy.gov/biomass/integrated_biorefineries.htm
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Integrated Biorefinery Projects, cont’d.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Conversion</th>
<th>Intermediate Conversion</th>
<th>Product</th>
<th>Performer</th>
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<tr>
<td>Agricultural Residues</td>
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<td>pyrolysis</td>
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<td>Forest Resources</td>
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<td>Energy Crops / Grasses/</td>
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NREL R&D Highlights

Biochemical Cellulosic Ethanol Progressing

New Facilities Coming On-line (TCPDU and IBRF)

New Initiatives Underway (BESC and NABC)
Achieving Economic Feasibility

Process cost drivers

- **Yield > Conc > Rate**
  - Feedstock
  - Capital equipment
    - Pretreatment
    - Enzyme Production
    - Distillation
    - Boiler/CHP
  - Operating cost
  - Coproduct value

- **Reduce CAPEX through co-location and process intensification**

### Table:

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<th>2008 SOT</th>
<th>2012 Target</th>
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<tbody>
<tr>
<td>Feedstock</td>
<td>$0.90</td>
<td>$0.57</td>
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<tr>
<td>Pretreat &amp; Condition</td>
<td>$0.53</td>
<td>$0.26</td>
</tr>
<tr>
<td>Enzymatic Hyd. &amp; Ferm.</td>
<td>$0.33</td>
<td>$0.43</td>
</tr>
<tr>
<td>Cellulase</td>
<td>$0.35</td>
<td>$0.12</td>
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</table>

**Cost savings:**

- $0.90 - $0.57 = $0.33
- $0.53 - $0.26 = $0.27
- $0.33 - $0.43 = -$0.10
- $0.35 - $0.12 = $0.23
- $0.12 - $0.43 = -$0.31
Economic Sugar Production Remains Biggest Challenge

Lignocellulose Feedstock Collection and Delivery

Pre-processing

Pretreatment / Prehydrolysis (make accessible to enzymes)

Conditioning

Pretreatment and Enzymatic Hydrolysis = Sugar Production (Saccharification)

Cellulases
Hemicellulases

Enzymatic cellulose hydrolysis

Biomass sugar fermentation

Hexose/Pentose Utilizing Microbe

Beer Slurry to Biofuel (Ethanol or Another Fuel) and Solids Recovery
Increasing Monomeric Xylose Yields

Source: Rick Elander (NREL)
Intensifying Enzymatic Hydrolysis

Substrate: Dilute acid pretreated corn stover
Enzyme loading: 40 mg cellulase/g cellulose

Source: Dan Schell (NREL)
Biochemical Technology Progress (2007$)


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Integrated Biorefinery Research Facility (IBRF)
NREL’s (DOE’s) Expanded Pilot Plant (IBRF)

- State of the art cellulosic biofuels piloting facility
- Two (2) parallel processing trains for pretreatment and primary enzymatic liquefaction
- Accelerate cost reduction focused R&D for 2012 and beyond
- Provide multiple biomass pretreatment/feedstock options for RD&D support (unparalleled flexibility)
- Greatly improve industry partnering capabilities to speed scale up and commercial deployment
- DOE’S prime facility for future pilot scale pretreatment and enzymatic saccharification R&D

Early March 2010
Integrated Biorefinery Research Facility

June 2010
Inside View of IBRF Operations Level
National Advanced Biofuels Consortium (NABC)
Project Objective – Develop cost-effective technologies to supplement petroleum-derived fuels with sustainable advanced “drop-in” biofuels compatible with today’s transportation infrastructure.

ARRA Funded:  
- 3 year effort  
- DOE Funding $35.0M  
- Cost Share $15.1M  
Total $50.1M

Consortium Leads  
National Renewable Energy Laboratory  
Pacific Northwest National Laboratory

Consortium Partners  
Albemarle Corporation  
Amyris Biotechnologies  
Argonne National Laboratory  
BP Products North America Inc.  
Catchlight Energy, LLC  
Colorado School of Mines  
Iowa State University  
Los Alamos National Laboratory  
Pall Corporation  
RTI International  
TesoRo Companies Inc.  
University of California, Davis  
UOP, LLC  
Virent Energy Systems  
Washington State University
Outlook and Final Thoughts
Outlook for 2011-2015

• 1990-2000: Demonstrate technical feasibility
  Focus on cellulosic ethanol

• 2001-2005: Show economic feasibility & scale potential
  Focus remains largely on cellulosic ethanol

• 2006-2010: Increase funding to accelerate biofuels RDD&D
  Expand RDD&D portfolio to higher alcohols and hydrocarbons, begin funding new concepts including hybrid BC/TC and algal pathways

• 2011-2015: Prove out & winnow advanced biofuels options
  Bring first large scale demonstrations on line
Leverage Past Learnings to Succeed in Commercialization Efforts

Key to success at scale is accurately estimating cost and performance at smaller scales!

Plant cost growth strongly correlated with:
- Process understanding (integration issues)
- Project definition (estimate inclusiveness)

Plant performance strongly correlated with:
- Number of new steps
- % of heat and mass balances based on data
- Waste handling difficulties
- Plant processes primarily solid feedstock

These issues all apply to lignocellulose processing using new technologies. We must directly tackle them!

Energy Density vs. Mass and Enthalpy Yield

Anabolic vs. Catabolic Product Pathways

Final Thoughts

Lots of progress happening. Many process and product options being advanced and scaled up to pilot and demonstration scales. Commercialization beginning.

Solids handling issues and compositional analysis throughput are still challenging technical issues that hinder the pace of biomass to biofuels RDD&D

Factors in play for cellulosic biofuels include:

• What pretreatment and enzymatic hydrolysis (saccharification) schemes will prove out?
• How much and how quickly will hydrolytic enzymes and biofuels production strains be improved?
• How quickly will higher alcohols and hydrocarbons be proven at scale?

Potential game changers include:

• Price on (net) carbon, GHG emissions mitigation
• Competition for feedstocks (biopower, bioproducts)
• Production of higher value coproducts
• Price of petroleum & ethanol blend limit for non-FFVs
Acknowledgments

• USDOE’s EERE’s Office of the Biomass Program – Funding and selected slides on USDOE’s strategy and investments

• NREL’s Rick Elander, Steve Decker, Erik Kuhn, Nick Nagle and Joe Shekiro
  – Data on xylan to xylose yield improvement

• NREL’s Dan Schell, Alex Chapeaux, Nancy Dowe Farmer and Andrew Lowell
  – Data on enzymatic hydrolysis glucose yields = f[insoluble solids]
Thanks for Your Attention!
Questions?
More Information

National Renewable Energy Laboratory
www.nrel.gov

DOE’s Biomass Program
www.eere.energy.gov/biomass/

DOE-USDA Biomass R&D Initiative
www.brdisolutions.com

Alternative Fuels
www.afdc.doe.gov