Cellulosic Ethanol Technology

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Outline

• Context – the U.S. Department of Energy’s Biomass Program activities to grow a robust biofuels economy
• Overview of bioethanol technology
• Technical barriers to economic large volume cellulosic ethanol production
Develop and transform our renewable and abundant biomass resources into cost competitive, high performance biofuels, bioproducts, and biopower.

Core activities accelerate the technological advances needed to support a domestic bioindustry producing cellulosic ethanol and other biofuels in integrated biorefineries.
Cellulosic Ethanol Growth

**U.S. Ethanol Production**

- **Cellulosic Ethanol estimated cost** (US$/gal, at plant gate, untaxed)

**U.S. DOE Biomass Program RD&D Activities & Timeline**

- Biorefinery Demos
- 10% Scale Validation
- Integrated Biorefineries
- IBRF
- Commercial Ethanologen
- 1st Generation Feedstock, Biochemical, Thermochemical Core R&D
- Adv. Feedstocks & Conversion Technology R&D

**2002 Dollars per Gallon/Ethanol**

- $6.0
- $5.0
- $4.0
- $3.0
- $2.0
- $1.0

**Billion Gallons of Ethanol**

- Corn
- Cellulosic

**Years**

- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
- 2012
- 2014
- 2016
Announced competitive selections on Feb 28 for up to $385 million over four years for six cost-shared integrated biorefineries (~700 ton/day feedstock)

- **Abengoa Bioenergy Biomass of Kansas**
  Capacity to produce 11.4 million gallons of ethanol annually using ~700 tons per day of corn stover, wheat straw, milo stubble, switchgrass, and other feedstock (bio and thermo)

- **ALICO, Inc.**
  Capacity to produce 13.9 million gallons of ethanol annually using ~770 tons per day of yard, wood, and vegetative wastes and eventually energy cane (thermo/bio)

- **BlueFire Ethanol, Inc.**
  Sited on an existing landfill, with capacity to produce 19 million gallons of ethanol annually using ~700 tons per day of sorted green waste and wood waste from landfills (chem/bio)
U.S. DOE Biomass Program
Cellulosic Biorefinery Investments

• **Poet (formerly Broin Inc.)**
  Capacity to produce 125 million gallons of ethanol annually. About 25 million gallons will be cellulosic ethanol derived from ~850 tons per day of corn fiber, cobs, and stalks (bio)

• **Iogen Biorefinery Partners, LLC**
  Capacity to produce 18 million gallons of ethanol annually using ~700 tons per day of agricultural residues including wheat straw, barley straw, corn stover, switchgrass, and rice straw (bio)

• **Range Fuels (formerly Kergy Inc.)**
  Capacity to produce 40 million gallons of ethanol annually and 9 million gallons per year of methanol, using ~1,200 tons per day of wood residues and wood based energy crops (thermo)
Achieving the U.S. DOE Biomass Program Goals

Three-pronged approach:

• Effective RD&D Program
• Effective policies
• Private sector investments

Jacques Beaudry-Losique
U.S. Department of Energy Biomass Program Manager
Putting U.S. Ethanol Technology in Context

Feedstock Pathways
- **Today & Near Term**: Corn Ethanol
- **2012 and Beyond**: Cellulosic Ethanol
  - Agricultural residues, energy crops, natural oils, wood/forestry resources

Conversion Processes
- Biochemical Conversion (e.g., fermentation)
- Thermochemical Conversion (e.g., gasification, pyrolysis oils)
  - Integrated Bio/Thermal Processing

Biofuels Distribution
- Existing Distribution Infrastructure
- Expanded, Advanced Distribution Infrastructure

Distributors & Consumers

➢ *Today’s focus is on cellulosic ethanol via biochemical route*
Corn Grain vs. Cellulosics
Corn Stover and Beyond

Corn Grain

Corn Stover

Switchgrass

Husk

Grain

Cob

Ear

Stalk

Leaf

Silk

Tassel

Ear enclosed by husks

Prop roots

Roots
## Composition: Grain vs. Cellulosics

<table>
<thead>
<tr>
<th>Component</th>
<th>Corn Grain</th>
<th>Corn Stover</th>
<th>Switch-Grass</th>
<th>Poplar (Wood)</th>
<th>Bagasse (Cane)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Starch</strong></td>
<td>72-73</td>
<td>Trace</td>
<td>Trace</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Cellulose/ Hemicellulose</strong></td>
<td>10-12</td>
<td>63-74</td>
<td>60</td>
<td>73</td>
<td>67</td>
</tr>
<tr>
<td><strong>Lignin</strong></td>
<td>0</td>
<td>14-18</td>
<td>10</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td><strong>Other Sugars</strong></td>
<td>1-2</td>
<td>3-5</td>
<td>6</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td><strong>Protein</strong></td>
<td>8-10</td>
<td>1-3</td>
<td>5</td>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td><strong>Oil/Other Extractives</strong></td>
<td>4-5</td>
<td>2</td>
<td>13</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Ash</strong></td>
<td>1-2</td>
<td>6-8</td>
<td>6</td>
<td>0.5</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>96-104</td>
<td>90-110</td>
<td>100</td>
<td>100</td>
<td>97</td>
</tr>
</tbody>
</table>

Constituent levels can vary by roughly ± 5% dry weight due to environmental and genetic factors.
Carbohydrate Conversion Steps

Feedstock Collection and Delivery

Pre-processing

Thermochemical Pretreatment (e.g., Heat and Acid or Alkali)

Conditioning

Amylases

Grain Mashing Using Acid, Jet Cooking, and Enzymes

Glucose Sugar Fermentation

STARCH “FUEL & FEED” PROCESS

Cellulases

Cellulose Hydrolysis Using Enzymes

Mixed Biomass Sugar Fermentation

Ethanol and Solids Recovery, Water Recycle

STOVER “FUEL & ENERGY” PROCESS
Coarsely milled corn stover

100 g raw solids (dry)

Pretreated solids

60 g (dry)

Process intermediate

Residue solids

27 g (dry)

Conversion is Technically Feasible…

…the Challenge is Making it Economical!
DOE Biomass Program Goal: Market Competitiveness

Costs driven by:
- Feedstock
- Coproduct value
- Utilities prices
- Capital equipment
  - Pretreatment
  - Enzyme Production
  - Distillation
  - Boiler/Combined Heat and Power

Relative Production Cost

- Cap. Depr.
- Fixed
- Enzymes
- Chemicals
- Feedstock
- Coproduct

Corn Dry Mill
Enzymatic Stover
Total Cost
Technical Barriers/Challenges

1. Sustainable agronomic base
   - Low cost bioenergy crops with high fuel/land efficiencies (GJ/ha-y, L/ha-y)
   - Proven cultivation and supply systems – likely includes both dry and wet storage – that support environmental sustainability goals (e.g., low greenhouse gas emissions, low inputs, low water use, maintain water, soil and air quality, retain biodiversity, etc.)

2. Plant cell wall recalcitrance
   - Deconstruct secondary cell wall polysaccharides to fermentable sugars at high yield and low cost (low energy input)

3. Carbohydrate heterogeneity
   - Ferment all biomass sugars to ethanol at high yield, i.e., the hexoses glucose, galactose, fructose and mannose; and the pentoses arabinose and xylose

4. Process development/integration/qualification
   - Test various process options rapidly and cost effectively, producing high quality data (backed up by high mass balance closures!)

5. Integrated biorefinery scenario assessment
   - Technoeconomic analyses, life cycle assessments and multi-parameter sensitivities
     - A multitude of scenarios and sensitivities remain to be evaluated
1st Challenge: Sustainable Agronomic Base

Consensus Emerging on Lignocellulosics:
Net Energy Positive, Low Net CO2, and Displace Petroleum

2nd Challenge: Cell Wall Recalcitrance

- Lignocellulose cell walls contain *intermeshed* carbohydrate and lignin polymers and other minor constituents
  - The major structural polymers are cellulose, hemicellulose, and lignin
  - These polymers exhibit differential reactivity to thermal, chemical, and biological processing
  - By natural design, cell wall polysaccharides are more difficult to breakdown than storage carbohydrates like starch

➢ Longer term, cell wall and enzyme engineering hold the key
Biotech Toolkit Reducing Enzyme Cost

- DOE Subcontracts to Genencor and Novozymes (cost-shared)
  Focus: lower production cost, increase enzyme system efficacy
  - Enzyme cost ($/gallon EtOH) = Prod. Cost ($/kg) x Usage Req. (kg/gallon EtOH)

> **Cellulase cost reduced over 20-fold! (over 4 years)**

E1 from *A. cellulotiticus*  
Y82  
W42  
Y245  
Cellodextrin

CBH1 from *T. reesei*
3rd Challenge: Polysaccharide Heterogeneity

Carbohydrate Fraction

- Acetate & Uronics
- Galactan/Mannan
- Xylan/Arabinan
- beta-Glucan
- alpha-Glucan

* Bagasse

Corn Grain
Corn Stover
Switchgrass
Poplar

* *
4th Challenge: Process Development

Lignocellulose Feedstock Collection and Delivery

Pre-processing

Pretreatment

Conditioning

Many options to consider, i.e., multiple feedstocks, pretreatments, enzymes, fermentative microbes, and processing configurations.

Cellulases
Hemicellulases

Enzymatic cellulose saccharification

Biomass sugar fermentation

Hexose and Pentose
Utilizing Microbe

Beer Slurry to Ethanol and Solids Recovery

Many options to consider, i.e., multiple feedstocks, pretreatments, enzymes, fermentative microbes, and processing configurations.
Scientific & Engineering Foci

1. Overcoming recalcitrance of plant cell walls to biochemical (and thermochemical) deconstruction

2. Fermenting hexose-pentose mixtures at high rate, yield and titer (>10% ethanol on real hydrolysates)

3. Processing high solids slurries with low energy input, i.e., for effective heat, mass and/or momentum transfer

4. Developing more accurate, comprehensive and rapid analytical methods, i.e., to cost effectively determine the composition and structure of biomass samples and processing intermediates
Conclusions

• Biofuels field growing rapidly, especially cellulosic ethanol
  – Societal/environmental benefits being embraced (must be validated!)
  – Investment in RD&D is increasing markedly

• Bioethanol technology becoming economically feasible
  – Cost of conversion continuing to fall (but high petroleum costs help!)
  – Engineering of improved enzymes and microbes progressing
  – Process intensification decreasing conversion plant capital cost

• Deployment risk being reduced
  – Many commercial projects underway around the world, with plans to build
    many demonstration plants over the next several years

• Additional R&D needed
  – Develop a sustainable feedstock supply infrastructure
  – Achieve compelling conversion economics for higher cost feedstocks
  – Consensus standards for assessing biofuels process performance

➤ The rate of progress depends on policy, investment and the
  nature of scientific and technological advances
Resources and Contacts

Web Sites:
http://www1.eere.energy.gov/biomass/
http://www.nrel.gov/biomass/

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Questions?