The National Bioenergy Center and Biomass R&D Overview

Dr. Michael A. Pacheco
Director of National Bioenergy Center
National Renewable Energy Laboratory

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Why Bioenergy?

• Greenhouse warming  
  Natural CO$_2$ cycle is 10X fossil fuels
• National security  
  60% of our petroleum is imported
• Sustainability  
  Potential to replace petroleum-derived fuels and chemicals
• Rural economic benefit
### U.S. Dependence on Foreign Oil

<table>
<thead>
<tr>
<th>Have Oil</th>
<th>Use Oil</th>
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<tbody>
<tr>
<td>Saudi Arabia</td>
<td>26%</td>
</tr>
<tr>
<td>Iraq</td>
<td>11%</td>
</tr>
<tr>
<td>Kuwait</td>
<td>10%</td>
</tr>
<tr>
<td>Iran</td>
<td>9%</td>
</tr>
<tr>
<td>UAE</td>
<td>8%</td>
</tr>
<tr>
<td>Venezuela</td>
<td>6%</td>
</tr>
<tr>
<td>Russia</td>
<td>5%</td>
</tr>
<tr>
<td>Libya</td>
<td>3%</td>
</tr>
<tr>
<td>Mexico</td>
<td>3%</td>
</tr>
<tr>
<td>China</td>
<td>3%</td>
</tr>
<tr>
<td>Nigeria</td>
<td>2%</td>
</tr>
<tr>
<td>U.S.</td>
<td>2%</td>
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</tbody>
</table>

The U.S. uses more than the next 5 highest consuming nations combined.

While the growing need for sustainable electric power can be met by other renewables...

Biomass is our only renewable source of carbon-based fuels and chemicals
Biomass Share of U.S. Energy Supply
(data for 2002)

Source: AEO 2004 tables (released in December 2003) based on US energy consumption. Overall breakdown Table A1 (Total Energy Supply and Disposition), and Renewable breakdown Table A18 (Renewable Energy, Consumption by Section and Source).
National Bioenergy Center

Announced by Dept of Energy Secretary Bill Richardson at the Kansas City Board of Trade on October 31, 2000

NREL Role: Research Leadership and Coordination of research at DOE labs
Bioenergy Strategic Goals

U.S Dept of Energy

Protect national and economic security by promoting a diverse supply of reliable, affordable, and environmentally sound energy

- Reduce our dependence on foreign oil
- Create the new domestic bioindustry

National Bioenergy Center

Develop biomass-based technologies that will be used by the U.S. transportation fuel, chemical and power industry

Specific Goal

Help establish technology for large-scale biorefineries based on agricultural residues by 2010
**Concern: Energy Balance of Corn Ethanol**
(Btu in EtOH Minus Btu Used)

![Graph showing energy balance of corn ethanol from 1988 to 2004. The graph includes data points from various sources:
- Marland and Turhollow
- Ho
- Keeney and DeLuca
- Lorenz and Morris
- Agri. Canada
- Shapouri et al.
- Wang et al.
- Kim and Dale
- Graboski
- Wang

**Sources of Variation**
- Corn yields per acre
- Energy required to produce ethanol
- Fertilizer usage
- Irrigation practices
- Accounting for byproducts, e.g. DDG

*Source: M. Wang (2003)*
Renewable energy - More energy in than out?

Critics of renewable energy contend it takes more energy to make.

This ignores the question of renewable sources.
Fossil Energy Replacement Ratio

\[
\text{Fossil Energy Ratio (FER)} = \frac{\text{Energy Delivered to Customer}}{\text{Fossil Energy Used}}
\]

The road to petroleum displacement is paved with Cellulosic Biomass.

NREL’s R&D Focuses on:

Lignin: 15-25%
- Complex aromatic structure
- Resists biochemical conversion
- Requires high temperatures to convert

Hemicellulose: 23-32%
- Polymer of 5- and 6-carbon sugars
- Easily depolymerization
- 5-carbon sugars hard to metabolize

Cellulose: 38-50%
- Polymer of glucose
- Susceptible to enzymatic attack
- Glucose easy to metabolize
NREL NBC FY05 Budget ( $ 31.4 Million )

- Sugar Platform R&D: 24%
- Biorefineries & Products R&D: 10%
- Contract Research: 7%
- ThermoChem R&D: 8%
- Subcontracts: 23%
- Capital Equipment: 6%
- Economics & Analysis: 6%
- Other DOE Program R&D: 6%
- NBC & Biomass Program Mngt: 10%
Over 20 Years of Process Development Activities at NREL on Various Cellulosic Feed Stocks for Biomass Ethanol

- 1980: Basic process development on various hardwoods
- 1985: Amoco CRADA—Paper fraction of MSW
- 1990: Integrated process dev./scale-up on hardwood sawdust
- 1995: Collaborative process development on softwood thinnings and residues (Quincy, CA and Sealaska)
- 2000: Advanced pretreatment R&D on hardwood sawdust
- 2005: CAFI pretreatment collaboration on poplar

WOODY BIOMASS AND RESIDUES

- 1980: Basic process development on various residues (straws, stover)
- 1985: New Energy CRADA (corn fiber from dry mill)
- 1990: Amoco CRADA (corn fiber from wet mill)
- 1995: Integrated process dev./scale-up on corn stover
- 2000: Collaborative process dev./scale-up on rice straw (Gridley, CA)

AGRICULTURAL RESIDUES
Rapid Analysis Methods for Biomass

Fiber Optic Probes
DC light
NIR
Sample

Predicts biomass feed performance in biorefinery
Feed quality measurement in the field

Near Infrared combined with multivariate methods
NREL led research

Measured Composition (wt%)
Composition Predicted with NIR

- Glucose
- Xylose
- Galactose
- Arabinose
- Mannose
- Lignin
- Protein
- Ash
- Soil
- Acetyl
- Uronic Acid

Predicts biomass feed performance in biorefinery
“Conversion Platforms”
Drive Biomass R&D Priorities at NREL

Biomass

“Bio-chemical” Conversion
- Residues
  - Combined Heat & Power
    - By-products

“Thermo-chemical” Conversion

Biochemical Intermediates
- Fuels
  - Chemicals & Materials
  - Chemical Intermediates
An integrated biorefinery will make use of:

- Thermochemical conversion technology
- Biochemical conversion technology
- Existing technology
NREL’s Thermochemical User Facility

• Simulates thermochemical conversion processes
  – Pyrolysis
  – Combustion
  – Gasification
• Fully integrated
• Accommodates testing of close-coupled biomass conversion with upgrading
• Various size scales
  – 0.1 kg/h bench-scale reactors to 20 kg/h
Thermochemical Conversion Projects

Example: Gasification to Power

3 Small Modular Power Systems installed in 2003

Example: North Park High School
Walden Colorado

Power & Heat for Greenhouse
Fuel: forest thinning residues
Load: 8 kW
Maintenance: 30 minutes per week

Strong Community Support

Operated by Students
Thermochemical Conversion Projects

Example: *Pyrolysis to Phenolic Resins*

- Multi-year $2.4 million DOE project
- Builds on 15+ years of R&D at NREL
- Commercial pyrolysis partner - Ensyn
- Cost share by resin manufacturers
- CRADA with Wood Product companies LP, Weyerhaeuser, Tembec

- Successful “mill trial” at OSB mill
- Product certification complete
An integrated biorefinery will make use of:

- Thermochemical conversion technology
- Biochemical conversion technology
- Existing technology *Available today*
NREL’s Alternative Fuels User Facility

- Laboratory scale fermentation
- 1 ton/day bioethanol PDU
- Extensive pre-treatment research
- Flexible integration & configuration
- Frequent industry utilization
Biomass Pretreatment & Enzyme Fundamentals at NREL

- Biomass Pretreatment & Enzymology
- Utilization of latest surface science techniques
- Target fundamental breakthroughs in biomass conversion technology
Dilute Acid Pretreatment Of Lignocellulosic Biomass

1 ton/day Sunds Continuous Pretreatment Reactor

Untreated Corn Stover

Pretreated Corn Stover at 35% solids loading
NREL’s Enzymatic Hydrolysis Research

• 3-year Partnerships with Genencor & Novozymes
  – Focus on enzyme biochemistry, cost, and specific activity
  – Investigate enzyme - substrate surface interaction
  – 10-fold reduction in cost of enzyme production

CBH1 from T. reesei

E1 from A. cellulotiticus

2004 R&D 100 Award
Biomass Surface Characterization Laboratory

Planned for
November 2004
Start-up

• NSOM
• AFM
• SEM
• STEM
Genomics, Proteomics & Bioinformatics

- Essential to improve organisms for biofuels and bioproducts
- Critical to understand and optimize:
  - yield, rate, and titer
- Miniature sugar biorefineries of the future
NBC Biobased Products Research

• Critical to Biorefinery Economics
• Continued Leadership in:
  – Pyrolysis oil to products
  – Sugars to fuels and chemicals
  – Lignin to aromatics and octane enhancers

6 billion lb/yr PF Resin Market

Pilot demo at LP Mill Trial at Tembec

Green Chemicals, Plastics, and Fibers

Research at all NBC labs in area of bio-based products
Combined Biorefinery Elements

Starch → Starch Hydrolysis → Fermentation of Sugars

Fermentable Sugars

Cellulose Hydrolysis

Pre-treatment → Lignocellulosic Biomass → Thermo-chemical Conversion

Lignin Residue → Product Recovery

- Ethanol
- Liquid Fuels
- Chemicals

- Heat & Power
- Fuels & Chemicals
  - Pyrolysis Oil
  - Syn Gas

• Ethanol
• Liquid Fuels
• Chemicals

• Heat & Power
• Fuels & Chemicals
  - Pyrolysis Oil
  - Syn Gas
NREL’s Role: Support the Development of New Industrial Biorefinery Concepts

Biomass Feedstock
- Trees
- Grasses
- Agricultural Crops
- Agricultural Residues
- Animal Wastes
- Municipal Solid Waste

Conversion Processes
- Enzymatic Fermentation
- Gas/liquid Fermentation
- Acid Hydrolysis/Fermentation
- Gasification
- Combustion
- Co-firing

USES
Fuels:
- Ethanol
- Renewable Diesel

Power:
- Electricity
- Heat

Chemicals
- Plastics
- Solvents
- Chemical Intermediates
- Phenolics
- Adhesives
- Furfural
- Fatty acids
- Acetic Acid
- Carbon black
- Paints
- Dyes, Pigments, and Ink
- Detergents
- Etc.

Food and Feed
Potential Benefits of Cellulosic Ethanol

Petroleum Use (kg per mile)

<table>
<thead>
<tr>
<th></th>
<th>Total Ethanol Fuel</th>
<th>Total Gasoline</th>
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<tbody>
<tr>
<td>0.00</td>
<td>0.006</td>
<td>0.122</td>
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Greenhouse Gas Emissions (grams CO₂ equiv per mile)

<table>
<thead>
<tr>
<th></th>
<th>Total Ethanol Fuel</th>
<th>Total Gasoline</th>
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<tbody>
<tr>
<td>-24.3</td>
<td></td>
<td>384.7</td>
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J. Sheehan, 2003
Agricultural Residue Opportunity

- Candidate for commercialization of biorefinery in 5-10 year horizon
  - Corn stover: 100 million tons per year of available feedstock
  - Suitable for lignocellulosic biorefinery demonstration

- Synergy with fuel industry issues
  - MTBE phase-out
  - Impending Renewable Fuel Standard
Partnership Example

Dupont-NREL: Integrated Corn Biorefinery

- $38 million (50% from DOE)
- $8 million to NREL
- Goal:
  - develop a Process Design Package for farmers to produce fuels, chemicals and power from entire corn plant
- License to use NREL organism
- 4-yr timeline

building block for Sorona™ polyester

Sorona™

400% AAGR

corn → chemicals

bioethanol

corn stover → power
Pulp & Paper Mill Diversification Opportunity

• Source of dilute xylose upstream of pulping
  – Simplify pulping step & reduce use of pulping chemicals
  – Large year-round source of fuels and/or chemicals

• Black liquor gasification
  – More efficient use of forestry resources
  – Produce Synthesis Gas from biomass
  – Products options: MeOH, DME, FTL, and chemicals

• Diversification of revenue to pulp mill
  – Provides U.S. mills with competitive advantage in international markets
NBC Expertise Applied to a Forest Biorefinery

NBC Technology Expertise
- Syngas Clean-up
- Power production
- Catalytic synthesis of Fuels and Chemicals
- BL Gasification
- Wood Residual Gasification
- Tar Formation & Destruction

Syngas

Pulp & Paper Products

Black Liquor & Residuals

NBC Technology Expertise
- Extract Hemicellulose
- Oligomer hydrolysis
- Conversion to Ethanol and Chemicals
Summarizing The Biomass and Biorefinery Value Proposition

- Only sustainable source of hydrocarbon-based fuels, petrochemicals, and plastics
- Large U.S. and worldwide potential biomass resource base
- Reduction of greenhouse gas emissions
- Reinvigorate and diversify rural economy
- Near-term biorefineries will utilize residues from existing industries & high value products
The National Bioenergy Center
is led by NREL for the
Office of Biomass Program
within the
U.S. Department of Energy