Forest Biomass to Biofuels Research at the Forest Products Laboratory

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USDA Forest Service
Forest Products Laboratory
Madison, WI
September 8, 2010
Presentation Overview

- Brief FPL overview
- Forest Biomass to Bioenergy
  - Liquid Transportation fuels
    - Biomass availability, economic modeling, and LCA
    - Biochemical conversion
    - Thermo-conversion
    - Catalytic conversion
    - Co-production with current forest products (VPP)
  - Direct combustion
USDA Forest Service Research Facilities

- Pacific Northwest Research Station
- Pacific Southwest Research Station
- Rocky Mountain Research Station
- Northern Research Station
- Southern Research Station
- International Institute of Tropical Forestry

Map of research stations across the United States, including Alaska and Hawaii.
FPL Statistics

- Established 1910
- 176 Permanent Employees (48 Scientists)
- Funding $29 million
  - Appropriated Research Funding $19 million
  - Biomass Grants Programs $5 million
  - Program Leverage ~$4 - $5 million
  - Partnerships--Active cooperative R&D agreements 100 - 150
Mission
To promote healthy forests and forest-based economies through the efficient, sustainable use of wood resources
FPL Research Program Capabilities

- Solid Sawn Wood
- Composites
- Pulp & Paper
- Biotechnology
- Timber Demand/Economics/Statistics
- Support Groups
  - Analytical Chemistry & Microscopy
  - Paper Testing
  - Engineering Mechanics & Remote Sensing Laboratory
  - Engineering--Design & Fabrication, Electrical, Electronics
Forest Products Utilization
R&D Focus Areas

- Healthy & Sustainable Forests
- Advanced Structures
- Advanced Composites
- Bioenergy/Biorefinery
- Nanomaterials
- Defense/Homeland Security
Biomass to Liquid Transportation Fuels

Products Made from a Barrel of Crude Oil (Gallons)

- Gasoline - 18.56
- Jet Fuel - 4.07
- Other Products - 7.01
- Liquefied Petroleum Gases (LPG) - 1.72
- Heavy Fuel Oil (Residual) - 1.68
- Other Distillates (heating oil) - 1.38
- Diesel - 10.31
Recent Federal Biofuels Guidance

- Energy Independence and Security Act of 2007 (EISA)
- Food, Conservation and Energy Act of 2008 - Public Law 110-246 (Farm Bill)
EISA defines **Cellulosic Biofuel** as “renewable fuel derived from any cellulose, hemicellulose, or lignin that is derived from renewable biomass and that has lifecycle greenhouse gas emissions...that are at least 60 percent less than baseline lifecycle greenhouse gas emissions.”

EISA defines **Advanced Biofuel** as “renewable fuel, other than ethanol derived from corn starch, that has lifecycle greenhouse gas emissions...that are at least 50 percent less than baseline lifecycle greenhouse gas emissions.”
Biomass Can Substitute for Petroleum in Many Applications

Substitutability of bio-based materials for petroleum-based materials with current technology

<table>
<thead>
<tr>
<th>% of petroleum use</th>
<th>Petroleum-based product</th>
<th>Bio-based substitute</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>Asphalt etc.</td>
<td>Not replaceable</td>
</tr>
<tr>
<td></td>
<td>Propane</td>
<td>Biopropane</td>
</tr>
<tr>
<td></td>
<td>Jet fuel</td>
<td>Biokerosene</td>
</tr>
<tr>
<td></td>
<td>Chemicals</td>
<td>Bio-n-butanol</td>
</tr>
<tr>
<td>80%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gasoline

Source: Lux Research, Inc.

Biofuels' and Biomaterials' Path to Petroleum Parity, December 2009
Major Biomass Pathways

Million dry ton/yr

Feedstock Production and Logistics

Biomass Conversion

End Uses

Agricultural Residues

Energy Crops Processing (Woody energy crops and perennial herbaceous crops)

Biofuels
- Cellulosic ethanol
- Green gasoline
- Green diesel
- Green jet fuel

Energy Crops

Forest Resources Processing (Includes existing and repurposed pulp and paper and forest product mills)

Biopower

Forest Resources

Waste Processing

Bioproducts

Industrial and Other Wastes

Existing Corn Wet Mills

Chemical Intermediates:
- Organic acids
- 1,4-diacids
- Glycerol
- Sorbitol
- Xylitol

Oilseeds and Plants

Existing Corn Dry Mills

(Top Value Added Chemicals From Biomass, PNNL, NREL, DOE-OBP Analytical Study, 2004)

Existing Oil Seed Mills

Yield assumptions:
- Corn: 207 bushels/acre by 2043, Energy crops: 8 dry tons/yr by 2030
- Fuel Yield Assumption:
  1.366 billion dry tons biomass at 100 gallons/ton = 136.6 billions gallons/year
U.S. ETHANOL BIOREFINERY LOCATIONS

- Biorefineries (200)
- Biorefineries under construction (11)

Source: Renewable Fuels Association, January 2010
EPA assigns GHG reductions based upon:
- Renewable fuel type (e.g. ethanol, butanol, biodiesel, cellulosic diesel, etc.)
- Feedstock type (e.g. corn starch, cellulosic biomass, algal oil, animal fats, etc.)
- Conversion process type (e.g. corn wet milling, corn dry milling, fermentation, Fischer-Tropsch, etc.)

In comparison to gasoline, ethanol made from cellulose and produced with power generated from biomass byproducts can result in an 86 percent reduction in greenhouse gas emissions.
Source: America’s Energy Future: Technology and Transformation, National Academy of Sciences, 2009
Feedstock & Logistics Cost Reductions Contribute to Cellulosic Liquid Biofuels Cost Targets*

The 2008 Farm Bill offers a $1.01 subsidy/gallon for cellulosic ethanol and $45/ton to producers/entities that deliver eligible biomass to biomass/biofuels conversion facilities.

*Biomass Multi-Year Program Plan (March 2008) DOE Office of the Biomass Program, EE&RE
Forest Biomass to Energy Program

Forest Biomass Feedstock
- Pulpwood
- Slash
- Short rotation woody crops
- Thinnings

Conversion Processes
- Co-firing/Combustion
- Gasification/Pyrolysis
  - F-T Liquids
  - Gas/liquid fermentation
- Bioconversion
  - Hydrolysis/fermentation
- Catalytic Conversion

USES
- Fuels
  - Ethanol
  - Advanced biofuels
  - Renewable diesel
- Electricity and Heat
- Biobased Products
  - Composites
  - Specialty products
  - New products
  - Chemicals
  - Traditional products
Biofuels Research

- Sustainable forest bioenergy production systems and new wood energy crops
- Efficient and environmentally friendly woody biomass harvesting systems
- Competitive biofuels conversion technologies that reduce fossil fuel use greenhouse gas emissions
- Life-Cycle and sustainability analysis for wood bioenergy systems
2022 Projected Forest Biomass to Liquid Biofuels*

- EPA expects the following feedstock and the associated number of gallons
  - Woody biomass (forestry residue) 0.1 billion gallons (data does not include short-term woody crops)

- USDA estimates the following feedstock and the associated gallons
  - Woody biomass (logging residues only) 2.8 billion gallons

*USDA Biofuels Strategic Production Report June 23, 2010
America’s Forest Resource*

749 million acres (300 million hectares)

About 3/4 of America’s forests in the East are privately owned.

60% of America’s forests are in the Eastern half of the (lower 48 States).

*Forestland > 10% tree cover

Data sources:
- Forest: National Land Cover Data (1992)
- Ownership: Protected Areas Database (2001)
## Timberland*, Contiguous US

<table>
<thead>
<tr>
<th>Region</th>
<th>Standing Biomass</th>
<th>Net Annual Timber Growth</th>
<th>Annual Timber Removals</th>
<th>Annual Timber Mortality</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>4082</td>
<td>49</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>NC</td>
<td>3376</td>
<td>50</td>
<td>25</td>
<td>16</td>
</tr>
<tr>
<td>SE</td>
<td>3745</td>
<td>92</td>
<td>65</td>
<td>18</td>
</tr>
<tr>
<td>SC</td>
<td>4928</td>
<td>107</td>
<td>81</td>
<td>25</td>
</tr>
<tr>
<td>Great Plains</td>
<td>157</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Intermountain</td>
<td>2857</td>
<td>25</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>OR &amp; WA</td>
<td>3122</td>
<td>50</td>
<td>29</td>
<td>14</td>
</tr>
<tr>
<td>CA</td>
<td>1381</td>
<td>23</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>23648</strong></td>
<td><strong>397</strong></td>
<td><strong>232</strong></td>
<td><strong>114</strong></td>
</tr>
</tbody>
</table>

|               | **~1%**          |

*Growing >20 cubic feet of timber/acre/year (data exclude Alaska & Hawaii)

http://nrs.fs.fed.us/pubs/gtr/gtr_wo78.pdf
Forestland Distribution in the United States 2005

- Alaska: 17%
- North: 23%
- Pacific Coast: 12%
- Rocky Mountains: 20%
- South: 28%

Forestland Ownership in the US‡

‡Renewable Fuel Standard
• Woody biomass from federal land is not allowed—except from certain wildfire areas
• Non-slash/non pre-commercial thinnings is not allowed from most natural forested landscapes
• Agricultural land must have been cleared or cultivated prior to Dec 19, 2007 and actively managed or fallow, and non-forested
Impacts of Eligible Forestland Criteria Under EISA are Great

79% reduction in US South
Area of Timberland Qualifying Under the 2007 Energy Act

Forest Inventory and Analysis
USDA Forest Service
Northern Research Station

Sources: USDA Forest Service, 2009
Visit: http://www.ncrs2.fs.fed.us/4801/fiadbl/
Produced April 9, 2009, Author: Barry Wilson
US has Significant Plantations

Countries with the Largest Area of Productive Forest Plantations 2005

- United States: 16%
- Russia: 11%
- Brazil: 5%
- China: 26%
- Turkey: 2%
- France: 2%
- Thailand: 2%
- Chile: 2%
- Indonesia: 3%
- Sudan: 4%
- Other Countries: 27%

Forest Biomass for Biofuels Production

- Longer storage life and lower storage costs
- Higher bulk density (lower transportation costs)
- Less intensive use of water and fertilizers
- Established collection system
- Can be left to grow for longer periods of time
- Can be used for a variety of value-added products
- Compared to many agricultural materials
  - Higher lignin content
  - Lower ash content
Forest Biomass to Biofuels Issues

- Challenging goal to economically make biofuels from wood (High lignin content)
- Huge amounts of wood exist (as standing timber), but not all is available (economically, socially, politically)
- EISA restrictions on forest biomass sources make plantation and short rotation woody crops important
- Several types of technologies exist to make biofuels from forest biomass -- with varying raw material input requirements
- Impacts on existing wood use markets
- Forest managers and land owners have just begun to contemplate biofuel wood supply issues
- When will biofuels from forest biomass become economical without subsidy? (Currently requires >$100 - $130 per barrel oil)
Wood Composition*

* Plus ash content (low)
Composition of Various Forms of Biomass

Starch & Cellulose Yield Six Carbon Sugars
Hemicellulose Yields Five & Six Carbon Sugars
Lignin is a cross-linked aromatic compound
Other includes ash content
Wood Structure
Lignocellulosic Constituents

Lignin: 15-25%
- Complex aromatic structure
- Very high energy content
- Resists biochemical conversion

Hemicellulose: 23-32%
- Xylose is the 2nd most abundant sugar in biosphere
- Polymer of 5- and 6-carbon sugars, marginal biochemical feed

Cellulose: 38-50%
- Most abundant form of carbon in biosphere
- Polymer of glucose, good biochemical feedstock

~43% Oxygen!

Credit: Steve Kelley NREL/NCSU
Forest Products Industry Biorefinery Value Map

- SAW LOGS
- PULP WOOD
- SLAB WOOD
- LUMBER
- BARK
- BIOMASS

Value

- CHEMICALS
- PULP & PAPER
- POWER
- Liquid Fuels
- Black Liquor Gasifier

EXTRACTOR/HOG BOILER/GASIFIER/F-T
Forest Biomass For Biofuels

- **Source**
  - Natural Stands (slash)
  - Plantation
  - SRWC

- **Form**
  - Pulpwood
  - Slash (with bark & foliage)
  - Thinnings (with bark and foliage)
  - Whole tree chips (with bark and foliage)

- **Species Used**
  - Hardwoods & Softwoods
  - Purpose Grown Biofuel Trees (e.g. poplar, willow, eucalyptus, loblolly pine)

*Biochemical Conversion processes require bark and foliage free wood*
Technologies to make biofuels from wood

**Thermochemical conversion**
- **Input:** chips with bark (mill residue, tops/branches/whole tree chips, short rotation hardwood crops or pulping liquor)
- **Processes/outputs**
  - Gasification
    - gasification to syngas – mix of CO, CO$_2$, H$_2$
    - catalytically convert syngas to biofuels & chemicals
  - Pyrolysis
    - Bio oil – refine bio oil into transport fuels and chemicals

**Biochemical conversion**
- **Input:** clean chips (pulpwood, short rotation hardwood crops)
- **Processes/outputs**
  - Extraction of sugars from wood (+ chemical byproducts)
  - Fermentation of sugars to ethanol; use lignin for energy
  - Extract hemicellulose from wood prior to pulping
  - Extract and process sugars from clean chips
    - Catalytic conversion
    - SSF technologies
  - Catalytic conversion to polyols
Forest Biomass to Bioenergy Research at FPL

- Public-Private Partnerships
- Research, Development & Deployment
- Feedstock Types and Supply
- Second (ethanol) & Third Generation Liquid Biofuels (hydrocarbons; butanol and higher alcohols)
  - Conversion Processes
  - Life Cycle Assessment/GHGs
- Chemical Feedstocks
- Business Case & Economic Modeling
FPL Forest Biomass to Biofuels Research

Biochemical conversion
- Integration with existing forest products facilities
  - Value Prior to Pulping
  - Improved separations of wood constituents
    - Chip pretreatments (SPORL)
    - Fundamental mechanisms by which fungi metabolize wood
    - Hemicellulose
    - Recalcitrant cellulose (nanocrystalline cellulose)
- Fermentation of C-5 sugars and mixed streams of C-5/C-6 sugars (rate, EtOH tolerance, monomers vs. oligimers, & inhibitor tolerance)

Thermoconversion
- Novel gasification & pyrolysis technologies

Process modeling & engineering studies
- LCA/LCI (CORRIM)
- Sorting through the many options and configurations for gasifiers and pyrolysis units and feedstock options (mixed biomass, MSW, coal, etc.)
FS/FPL Research Development and Deployment Focus

Stage Gate Process

Concept Generation

Risk Assessment

Proof of Concept

Proof of Process

Demonstration Approach

Transfer

Deployment Decisions

Stage 1

Gate 1

Stage 2

Gate 2

Stage 3

Gate 3

Stage 4

Gate 4

Stage 5

Gate 5

Gate 1

Gate 2

Gate 3

Gate 4

Gate 5

Stage Gate Process
Roundwood
- Natural Stands
- Plantations

Slash

Forms of Forest Biomass

Short Rotation Woody Crops

Thinnings
SPORL (Sulfite) Technology

SPORL pretreatment

Separation

Size reduction

Spent liquor

XAD column detoxification

Hydrolysate fermentation

Filtration

Press

Substrate SSF

Ethanol

Filtration water
Agenda 2020: Integrated Forest Products Biorefinery (IFPB) Concept

Value Prior to Pulping (VPP)

Optimized Plantations

Forest Products

Boards, Paneling, Etc.

Biomass

Boards, Paneling, Etc.

Ethanol, Polymers, Etc.

Hemi Extraction and Conversion

Pulp Mill

Energy

Black Liquor

Pulp

Energy

Paper, Board, Other Mills

Paper, Boxes/Cartons, Tissue/Diapers, Specialties

Ethanol, Others

Gasifier

Fuels/Chemicals

Fuels/Chemicals

Energy
The base case is the same pulp mill with a steaming system replacing the extraction.
## Biofuel Production and Economic Summary

(in a 1,580 tpd mill + total PPI capacity)

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Product</th>
<th>Annual Production</th>
<th>Price ($ per gallon)</th>
<th>Net Revenue (MM dollars)</th>
<th>Capital Cost (MM dollars)</th>
<th>Simple Payback</th>
<th>Industry Prod Billion gpy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biomass Biorefinery</strong></td>
<td>FT liquids Steam Power</td>
<td>20 MM Gal. 1.2 T BTU 8 MW</td>
<td>3.00 7.00/MM BTU $60/MW</td>
<td>40  8  4</td>
<td>250</td>
<td>4.8 years</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Value prior to pulping</strong></td>
<td>Ethanol Acetic acid</td>
<td>10 MM gal 6 MM gal</td>
<td>2.00 3.00</td>
<td>10  18</td>
<td>80</td>
<td>2.9 years</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>New value from BL</strong></td>
<td>FT liquids</td>
<td>46 MM gal</td>
<td>3.00</td>
<td>120</td>
<td>260 full 180 increm.</td>
<td>2.2 years 1.5 years</td>
<td>4.1</td>
</tr>
<tr>
<td><strong>Diesel from tall oil</strong></td>
<td>Biodiesel LK fuel</td>
<td>1.4 MM gal</td>
<td>2.50</td>
<td>TBD</td>
<td>4</td>
<td>TBD</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Reference Mill or Industry Total</strong></td>
<td>Various 83.4 MM gal Liquids</td>
<td>Various</td>
<td>200</td>
<td>594 full</td>
<td>3 years</td>
<td>~7.0</td>
<td></td>
</tr>
</tbody>
</table>

Credit: Ben Thorp and Masood Akhtar Bioenergy Deployment Consortium
Molten Liquid Metal-Based Gasification

Integrated BioRefinery II

Char Gasification/Process Gas Reforming

Bio-oil Process

Fast Pyrolysis - Char, Tar, & Gas

Liquid Metal at 350 Celsius

Air to Combustor

Moisture to Water Tank

Steam/Air Evaporation

Liquid Metal at 150 Celsius

Char Crusher

Process Gas Development at 1000 Celsius and 25 bars

Combustor within 1000 Celsius Liquid Metal

Gas Pump

Flue Exhaust & Condenser

Air

CO

H2

Ethanol, Butanol, Gasoline, or Diesel

Fischer Tropsch Synthesis

CO2, H2O, CO, H2, CH4

Natural Gas

Cyclone

Syngas

Ash Box

High BTU Syngas to IGCC

Biomass feedstock

Ethanol, Butanol, Gasoline, or Diesel

Integrated BioRefinery II

Liquid Metal at 350 Celsius

Char

Crusher

Biomass

feedstock

Process Gas Mix

To Process

Gas Mix

Air to

Combustor

Moisture to

Water Tank

Auger

Device

Process Gas Mix

Co2, H2O, CO, H2, CH4

Natural Gas

Water Tank
CORRIM LCA/LCI Processes Being Evaluated

- **Phase I**
  - Biomass supply
  - Biofuels
    - Thermochemical and biochemical stand alone
    - Pyrolysis
  - Combined heat and power plants
  - Pellets (separate funding)

- **Phase II (if funded)**
  - Biofuels
    - Thermochemical and biochemical add on to pulp mills
RPA* Wood Uses Projections

* Haynes, et. al. -- US Forest Service 2007 Resources Planning Act Timber Assessment Update
Builds on WGA Western Assessment Model to conduct a supply chain analysis on biofuels production in the entire US

Provides county level resource availability data for a variety of biomass feedstocks

GIS-based model provides an optimized network of biorefineries based on cost and demand

Creates a platform for biofuels policy analysis (U.S. renewable fuel standard, carbon price, etc.)

Released in late spring 2010

Project Funded by DOE Office of Biomass
Procurement (at roadside) cost of modeled cellulosic biomass resources
Locations of Biorefineries at $2.50*/gge

gge = gallon gasoline equivalent @ fuel terminal
FAME = fatty acids to methyl esters
LCE = lignocellulosic ethanol
Fischer Tropsch = lignocellulosic F-T diesel

* @ fuel terminal
Biomass harvesting and transportation to conversion facilities are underdeveloped

- The ability to economically harvest and transport feedstock needs to be developed and understood.

Metrics to compare the performance of various feedstocks and conversion technologies are not available.

- Key metrics of raw materials like physical/chemical composition and conversion efficiency are not sufficiently available.
BioREFINERY Innovation Platform
A Multifeedstock, Modular, Integrated System
Research to Markets: Scale, Time, and Capital

10+ years

- Laboratory Bench
- Pilot Plant
- Field Demonstration at Scale
- Full-scale Production Infrastructure

|$ Millions
R&D

|$10’s Millions
Validate Systems Integration

|$100’s Millions
Validate scale-up and continuous operations

|$Billions

© Chevron 2005

DOC ID
FS R&D-FPL Pilot Plant Facility

- One of five hub USDA Regional Biomass Research Centers (FS R&D/ARS-Madison, WI)
- Multi feedstock capable/ARS
- Modular design
- Three conversion pathways
  - Thermochemical
  - Biochemical
  - Chemical
- Focused on forest products industry interactions
- Rentable
Cost

- $5.1 million – Design and engineering
- $34 million – Building construction
- $28 million – Pilot-scale equipment
- $9.2 million – Lab equipment, computers, furnishings
- $76.3 million – Total
Questions
Renewable Biomass Under the Farm Bill

The term renewable biomass means:

(A) materials, pre-commercial thinnings, or invasive species from National Forest System land and public lands (as defined in section 1702 of title 43) that
   (i) are byproducts of preventive treatments that are removed
      (I) to reduce hazardous fuels;
      (II) to reduce or contain disease or insect infestation; or
      (III) to restore ecosystem health;
   (ii) would not otherwise be used for higher-value products; and
   (iii) are harvested in accordance with
      (I) applicable law and land management plans; and
      (II) the requirements for
         (aa) old-growth maintenance, restoration, and management direction of paragraphs (2), (3), and (4) of subsection (e) of section 6512 of title 16; and
         (bb) large-tree retention of subsection (f) of that section;
   or

(B) any organic matter that is available on a renewable or recurring basis from non-Federal land or land belonging to an Indian or Indian tribe that is held in trust by the United States or subject to a restriction against alienation imposed by the United States