Ethanol and Fiber Co-Production from a Forest Biorefinery

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Jyvaskyla – July 31, 2006
Average Bulk Fuel-grade Ethanol Prices
U.S., by State: July 12, 2006

Iowa: 3.57
Illinois: 3.36
Kansas: 3.55
Michigan: 3.52
Minnesota: 3.62
Missouri: 3.66
North Dakota: 3.63
Nebraska: 3.61
South Dakota: 3.60
Wisconsin: 3.76

http://www.axxispetro.com/ace.shtml
Introduction

• Ethanol prices are high and market is expected to increase

• Ethanol from starch will not meet demand

• Can ethanol be made economically from lignocellulosic biomass?

• How best to integrate into the forest products industry?
Objectives:

Overall: to provide a preliminary design and economic analysis methodology for forest- and ag residue-based biorefineries

Current work: To evaluate the profitability of producing ethanol from southern pine

- from hemicellulose and cellulose in a stand-alone ethanol plant
- from hemicellulose extracted from wood prior to pulping in an ethanol plant integrated with a kraft pulp mill
Ethanol Only
Scenario
**Ethanol Only**

- Wood species: Southern Pine
- Hemicellulose + cellulose hydrolyzed: 55-95%
- Ethanol plant wastes concentrated by evaporation and burned in biomass boiler
- Steam and power supplied by biomass boiler and steam turbine
- Energy integration between extraction plant, ethanol distillation columns, and the waste evaporator train
Ethanol from Southern Pine Carbohydrates

WOOD HANDLING

HYDROLYSIS OF HEMICELLULOSE

WOOD

H₂SO₄

Lime

Gypsum

Acetic Acid

CO₂

SIMULTANEOUS SACCHARIFICATION & FERMENTATION

Enzyme

Seed

Nutrients

CHP PLANT

Power

DISTILLATION/DEHYDRATION/EVAPORATION

Ethanol

Excess Biofuel

Process

Biofuel

Steam

Power
Procedure

• Detailed process calculations for each unit operation
• Capital and operating costs estimated for each scenario
• Break-even ethanol price calculated
• Capacity utilization estimated for each unit operation
• Software: *BioRefOpt™*, a detailed spreadsheet program developed and refined over the past six years by Jim Frederick and Steve Lien
Distribution of Wood Among Products

Wood
1,007,400 t/a

Ethanol
252,204 t/a

Biofuel Exported
470,410 t/a

CO₂
241,238 t/a
Distribution of Energy Among Products

- Wood: 629.9 MW\text{th}
- Biofuel Exported: 318.3 MW\text{th} (50.2%)
- Ethanol: 258.2 MW\text{th} (40.7%)
- Other: 57.6 MW\text{th} (9.1%)
- Power: 4.1 MW\text{e}
Annual Cash Flow ($million)

- Wood: $63.69
- Ethanol ($1.14/gal): $96.14
- Other: $0.84
- Biofuel Exported: $14.10
- Chemicals: $3.98
- Power: $2.01

Total Installed Capital: $190
Fixed operating costs: $12.86
EtOH from Hydrolysis of Southern Pine

Break-even cost of EtOH, $/gal

Relative Cost or Value

-50% Base Case +50% +100%

Wood
Capital Recovery
Power
Biofuel

-$0.00 $0.40 $0.80 $1.20 $1.60 $2.00

$0.00 $0.40 $0.80 $1.20 $1.60 $2.00
## Impact of Hydrolysis Yield

<table>
<thead>
<tr>
<th>Carbohydrates converted to ethanol</th>
<th>Break-even price, $/gal</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>$1.14</td>
</tr>
<tr>
<td>75%</td>
<td>$1.36</td>
</tr>
<tr>
<td>55%</td>
<td>$1.74</td>
</tr>
</tbody>
</table>
Ethanol + Fiber Scenario
Ethanol + Fiber from Southern Pine Carbohydrates

Wood → WOOD HANDLING → PARTIAL EXTRACTION → HYDROLYZATE CLEANUP

H₂SO₄ → Lime

Gypsum, Acetic Acid

CO₂ → FERMENTATION

CO₂ → Ethanol

WOOD HANDLING → KRAFT PULP MILL

KRAFT PULP MILL → DISTILLATION/DEHYDRATION/EVAPORATION

Ethanol, Fiber, Excess Biofuel, Excess Power

Process, Biofuel, Steam, Power

Diagram indicates the flow of materials and processes involved in the production of ethanol and fiber from southern pine carbohydrates.
Ethanol Plus Fiber

- Wood species: Southern Pine
- Hemicellulose extracted: 6-18% of dry wood mass
- Wood chips pulped to 30 Kappa after extraction
- Steam and power supplied by pulp mill to hemicellulose extraction and ethanol plants
- Energy integration between extraction plant, ethanol distillation columns, and the waste evaporator train
- **Constraint:** no additional capital for pulp mill operations
Distribution of Cellulose after Extraction and Pulping

- **In Fiber**
- **In Black Liquor**
- **In Hydrolyzate**

**Wood mass extracted, wt-%**

**H-factor for 30 Kappa**
Basis for Analysis

• Pulp production constrained: digesters utilized 100% for extraction and pulping

• Evaporation capacity
  – Capacity added when shortage of evaporation capacity
  – When excess evaporation capacity, utilized to concentrate ethanol waste

• Recovery boiler capacity
  – When excess recovery boiler capacity, utilized to concentrate ethanol waste
Capacity Utilization of Pulp Mill Operations

- Capacity utilization, % of base case
- Wood extracted, wt-% (dry basis)

- Evaporators
- Recovery Boiler
- Brownstock washers
- Recaust, Lime Kiln
- Digesters
- Extractors
Break-even Ethanol Prices:

- $2.05
- $2.16
- $2.31
- $2.64

Value $million/yr

Wood extracted, wt-%

Revenue - Costs

- Fiber
- Ethanol
- Excess Power
- Excess Biomass Fuel
- Gypsum
### Comparison of Cost Study Results

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Ethanol Yield 10^6 gal/yr</th>
<th>Ethanol Yield gal/t biomass</th>
<th>Breakeven Price, $/gal</th>
<th>Total Installed Cost, $10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Milled Corn^1</td>
<td>25</td>
<td>114</td>
<td>$0.88</td>
<td>$31.4</td>
</tr>
<tr>
<td>Corn Stover^1-3</td>
<td>25-69</td>
<td>72-90</td>
<td>$1.07-1.50</td>
<td>$42-218</td>
</tr>
<tr>
<td>Yellow Poplar^4</td>
<td>52</td>
<td>68.0</td>
<td>$1.44</td>
<td>$273</td>
</tr>
<tr>
<td>So. Pine^5</td>
<td>84</td>
<td>93</td>
<td>$1.07-1.30</td>
<td>$190</td>
</tr>
<tr>
<td>Hemicellulose from So. Pine^5</td>
<td>6-16</td>
<td></td>
<td>$2.05-2.64</td>
<td>$66-28</td>
</tr>
</tbody>
</table>

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1. McAloon et al., USDA/NREL (2000)
2. English et al., U. Tenn. (2006)
3. Aden et al., NREL (2000)
5. This study
Conclusions

• Stand-alone ethanol from southern pine will be profitable

• It may be more profitable than co-production of ethanol and fiber
Conclusions

• High hydrolysis conversion of cellulose to sugars is needed to improve profitability of stand-alone ethanol plant

• More rapid/efficient hemicellulose extraction methods are needed to improve profitability of co-production of ethanol and fiber

• Rapid and efficient conversion of pentose sugars is required in both cases
Data and Design Information Sources

Data for Pre-extraction and Pulping Conditions, Yields, and Kappa for So. Pine:

- Rydholm, Pulping Processes (1965)
- Ragauskas, A.J., unpublished research results

Ethanol Plant Configuration and Capital Costs

Conversion of Southern Pine Carbohydrates to Ethanol

- Cellulose consumed in cellulase production: 5%
- Cellulose => glucose: 88%
- Sugars consumed in Z Mobilis production: 4% of glucose, 3% of xylose
- Conversion to ethanol:
  - Glucose: 92%
  - Xylose: 85%
  - Mannose, galactose, arabinose: 90%

- Net conversion of Southern Pine Carbohydrates to ethanol: 25.8%
Basis

• Ethanol product 250,204 t/a

• Product values
  Ethanol (base case: $1.14/gal) $381/t
  Biomass fuel $30/t
  Gypsum $10/t

• Raw material costs
  Southern pine $64/t
  Power $60/MWh
**Base Case Costs**

- Total Installed Capital: $190 million
- Product values (millions)
  - Ethanol (base case: $1.14/gal): $96.14
  - Biomass fuel: $14.10
  - Gypsum: $0.84
- Raw material costs (millions)
  - Southern pine: $63.69
  - Chemicals: $3.98
  - Power: $2.01
- Fixed operating costs (millions): $12.86
### Cost/Value of Wood, Pulp, Energy & Chemicals

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulpwood</td>
<td>$58.00/ODT wood</td>
</tr>
<tr>
<td>Pulping chemicals (makeup)</td>
<td>$0.20/ODT pulp</td>
</tr>
<tr>
<td>Bleaching Chemicals</td>
<td></td>
</tr>
<tr>
<td>$\text{O}_2$</td>
<td>$0.04/\text{lb}$</td>
</tr>
<tr>
<td>$\text{ClO}_2$</td>
<td>$0.45/\text{lb}$</td>
</tr>
<tr>
<td>$\text{H}_2\text{SO}_4$</td>
<td>$0.04/\text{lb}$</td>
</tr>
<tr>
<td>NaOH</td>
<td>$0.20/\text{lb}$</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}_2$</td>
<td>$0.35/\text{lb}$</td>
</tr>
<tr>
<td>MgSO$_4$</td>
<td>$0.17/\text{lb}$</td>
</tr>
<tr>
<td>Net Power Value</td>
<td>$0.06/\text{kWhr}$</td>
</tr>
<tr>
<td>Fossil Fuel Cost</td>
<td>$0.155/\text{lb}$</td>
</tr>
<tr>
<td>(Fossil Fuel Cost</td>
<td>($65/\text{bbl}$)</td>
</tr>
<tr>
<td>Hog Fuel Cost</td>
<td>$27/\text{ODT}$</td>
</tr>
</tbody>
</table>
Critical Input Data

- Process configuration and conditions for a “typical” US kraft pulp mill
- Wood species & composition for both unextracted and pre-extracted chips
- Yield and kappa versus pulping conditions for wood species investigated for both unextracted and pre-extracted chips
- Bleaching response and chemical consumption for pulps from both unextracted and pre-extracted chips
- Exchange of chemicals, energy, and wastes between the pulp mill and ethanol plant
- Amount, composition, and heating value of waste from extraction and ethanol plants that is returned to the pulp mill