Bioethanol Production using Enzymatic Processes: 20 Year Economic Outlook

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Purpose of 20 Year Outlook

- Link Minimum Ethanol Selling Price Improvements to Potential Research Achievements and Process Improvements
- Predict Minimum Ethanol Selling Prices for Industry Models and DOE Purposes
  - Minimum Ethanol Selling Price is the Minimum Price the Ethanol Product can be Sold for to Achieve Required DCFROR

Cases Investigated

- Co-current Dilute Acid Prehydrolysis with Enzymatic Hydrolysis Only

- Update of Wooley, et al Base Case
- Conversion to Corn Stover Feedstock
- Technology Demonstrated at Bench Scale by 2005
  - Commercialization in 2009
- Technology Demonstrated at Bench Scale by 2010
  - Commercialization in 2014
- Multiple 2020 Cases

Updated Base Case

- Upgraded Model from ASPEN v9.2 to ASPEN v 10.1
- Upgraded Physical Properties and Added Soluble Lignin, Protein, and Extractives
- Added Denatured Fuel Cost Calculation
- Slight Process Modifications from Bridge-to-Corn Ethanol Subcontract Input
- Distillation Columns Recosted After USDA Input
- Year End Financial Losses “Carried-Over” for Tax Purposes

Updated Base Case (Continued)

- No Change to Process Parameters
- Parameters are Best Scale-up Estimations of Potential Near Term Research
- Not all Design Parameters Have Been Experimentally Verified

Experimental Data/Design Parameter Comparison

- Prehydrolysis

	Design	Experiment
Solids Concentration	31%	20%
Temperature	190°C	175°C
Monomeric Xylose Yield	75%	66%

Experimental Data/Design Parameter Comparison

- Enzyme Production

	Design	Experiment
Enzyme Loading to SSCF	15 FPU/g	14.19 FPU/g
Enzyme Substrate	Pret. Sol.	Solka Floc
Specific Activity (FPU/g prot)	600	600-assumed
Yield (g prot/g carbo)	0.333	0.183
Productivity (g prot / L hr)	0.125	0.0546
Aeration (OTR in mmol / L hr)	80	40

Experimental Data/Design Parameter Comparison

- SSCF

	Design	Experiment
Effective Solids Conc.	20%	12.6%
Cellulose to Glucose Yield	80%	84%
Glucose to Ethanol Yield	92%	96%
Xylose to Ethanol Yield	85%	91%

Updated Case

- Minimum Ethanol Sales Price dropped from $1.44/gal to $1.42/gal
- Total Project Investment Increased from $234 Million ($4.48/annual gallon) to $237 Million ($4.52/annual gallon)
- 68 gal / dry ton Yield

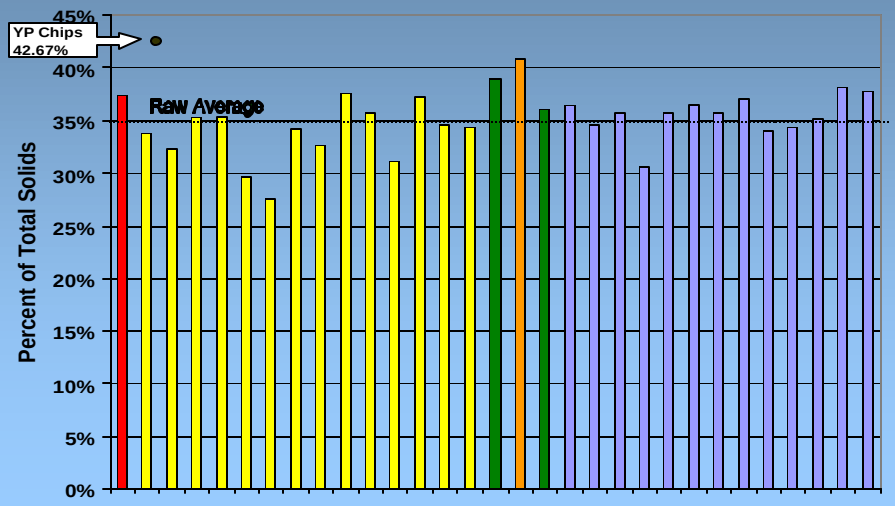
Updated Base Case

- Enzyme Cost: $0.31 / gal Ethanol (22% of Total) (11% of Total Project Investment)
- For Enzymes Achieving the Same Performance
  - If the Enzyme can be Purchased for $0.05 / gal Ethanol the Minimum Ethanol Sales Price would be $1.16 / gal
  - If the Enzyme can be Purchased for $0.50 / gal Ethanol the Minimum Ethanol Sales Price would be $1.61 / gal

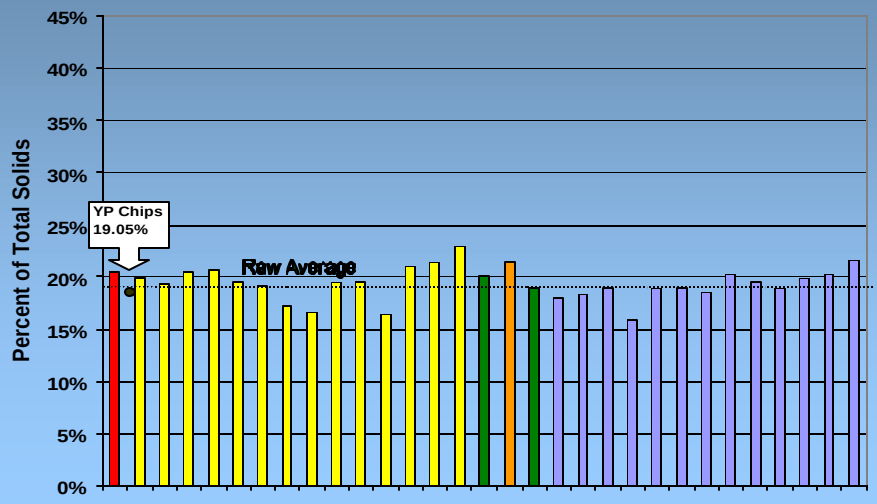
Conversion to Corn Stover

- Average Corn Stover Composition Used for Model
  - EPD, April 2000 Milestone Work
  - Torget, Walter, Himmel, and Grohmann 1991 Publication
- Composition Varies due to Bale Mixture, Weather, and Regional Variations
- Carbohydrate Level (Dry Basis) Always Lower than in Clean Hardwood Sawdust

Percent Glucan in Stover



Percent Xylan in Stover



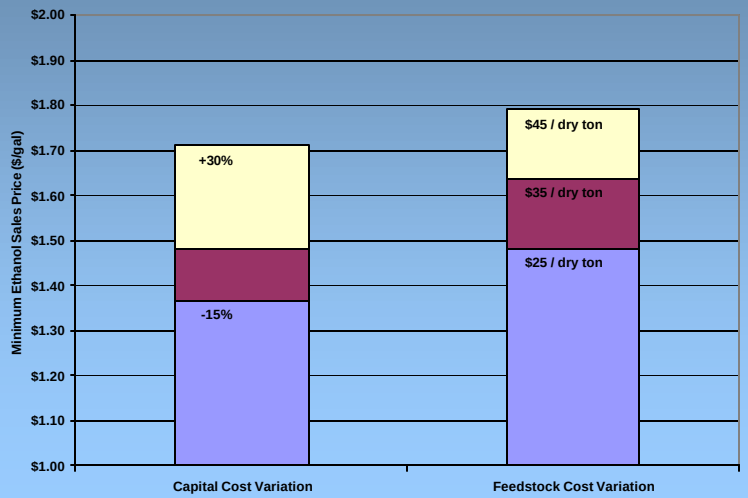
Conversion to Corn Stover

- Extractives (3.3%) and Protein (4.0%) were Included
- 5.6% of Solids Unknown
- Kept Feedstock Cost at $25/dry ton
  - Stover can Currently be Collected for $34-$45 / dry ton but Improvements are Considered Feasible
  - Feedstock Cost Curves from ORNL will be Integrated Once Available

Corn Stover Design Case

- Minimum Ethanol Sales Price of $1.48/gal
- $227 Million Total Project Investment ($4.64 / Annual Gallon)
- 63 gal / dry ton Yield
- Enzyme Cost: $0.30 / gal Ethanol (20% of Total)
  - 11% of Total Project Investment

Capital and Feedstock Cost Variations



Year 2005 Case

- Improved Dilute Acid Pretreatment
- Conditioning: Overliming Only
- SSCF with Staged Biocatalyst Addition
  - 2 Days at 65°C and 2 Days at 41°C
  - Fermentation of Glucose, Xylose, and Arabinose
- Three-fold Increase of Cellulase Activity

Year 2005 Case

- Minimum Ethanol Sales Price: $1.05/gal
  - Previous Study: $0.94/gal
- $165 Million Total Project Investment
  - $2.94 / Annual Gallon
- 73 gal / dry ton Yield
  - 75 gal / dry ton Yield Possible if Mannose and Galactose are Fermented
- Enzyme Cost: $0.08 / gal Ethanol (8% of Total)
  - 7% of Total Project Investment

Year 2010 Case

- Ten-fold Increase in Cellulase Specific Activity from Base Case
- Cellulase Loading Increased to 20 FPU/g
- SSCF with Staged Biocatalyst Addition
  - 1.5 days at 65°C and 1.5 days at 41°C
- 90% Glucose Yield from Cellulose
- 95% Fermentation Yield on all 5 Sugars

Year 2010 Case

- Minimum Ethanol Sales Price: $0.88/gal
  - Previous Study: $0.82/gal
- $155 Million Total Project Investment
  - $2.32 / Annual Gallon
- 86 gal / dry ton Yield
- Enzyme Cost: $0.04 / gal Ethanol (5% of Total)
  - 6% of Total Project Investment

2020 Cases

- Case A: Increased Capacity, Increased On-Line Time, Reduced WWT Capital Cost
- Case B: Case A + Increased Carbo-hydrate in Feedstock
- Case C: Case A + Pre-pretreatment and No Enzyme Production

2020 Case A

- Increased Capacity from 2000 dry tonne / day to 10,000 dry tonne / day
- Increased On-Line time from 8406 hr / yr to 8478 hr / yr
- Assumed Improved WWT Process -- Reduced Capital by 33%

2020 Case A

- Minimum Ethanol Sales Price: $0.69/gal
- $493 Million Total Project Investment
  - $1.47 / Annual Gallon
- 86 gal / dry ton Yield

2020 Case B

- Includes All Changes in 2020-A
- Increased Feedstock's Carbohydrate by 20%
  - Reduced Feedstock's Lignin by 50%
  - Reduced Feedstock's "Soluble Solids" by 64%
- No Turbogenerator
- 632 dry tonne / day Additional Feedstock Required for Steam Production

2020 Case B

- Minimum Ethanol Sales Price: $0.65/gal
- $434 Million Total Project Investment
  - $1.07 / Annual Gallon
- 104 gal / dry ton Yield on Biomass to Ethanol Process
  - 98 gal/dry ton Yield on All Biomass to Facility

2020 Case B

- Kept Turbogenerator
  - 1,775 dry tonne / day Additional Biomass
  - Minimum Ethanol Sales Price: $0.60/gal
  - $520 Million Total Project Investment
    - $1.29 / Annual Gallon
  - 104 gal / dry ton Yield on Biomass to Ethanol Process
    - 88 gal/dry ton Yield on All Biomass to Facility

2020 Case C

- Includes All Changes in 2020-A
- Assumes Pre-Pretreatment to Reduce Pretreatment Severity and Produce / Release Cellulase Enzyme
  - Liquid Hot Water Pretreatment at 125°C for 20 minutes
  - No Additional Cellulase Enzyme Produced / Purchased
- No Hydrolysate Conditioning Required

2020 Case C

- No Carbohydrate Loss in Pre-pretreatment
- No Costs Added for Pre-pretreatment

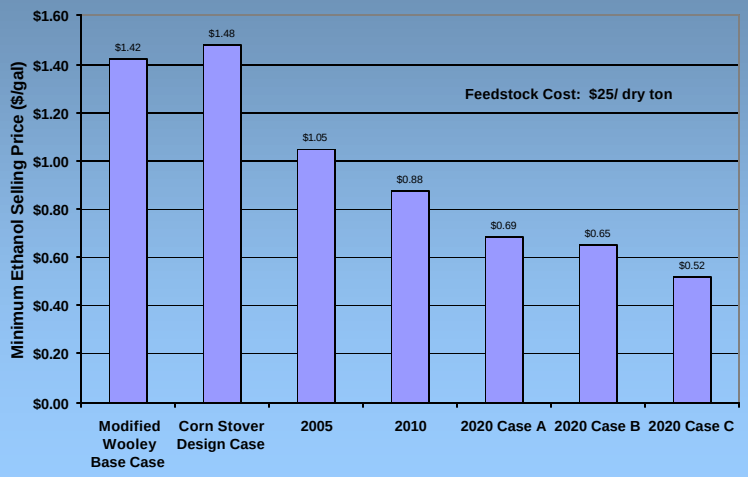
- Minimum Ethanol Sales Price: $0.52/gal
- $451 Million Total Project Investment ($1.33 / Annual Gallon)
- 87 gal / dry ton Yield

2020 Case C

- 3% Carbohydrate Loss in Pre-pretreatment
- $5 Million Added for Pre-pretreatment

- Minimum Ethanol Sales Price: $0.55/gal
- $441 Million Total Project Investment ($1.36 / Annual Gallon)
- 83 gal / dry ton Yield

Projection of Future Minimum Selling Prices



Other Process Ideas

- Many Other Process Changes may Improve the Economics
- Most Have Not been Modeled Yet

Other Process Ideas

- Feedstock Engineering
  - Increase Carbohydrate Levels
  - Improved Digestibility or Pretreatability
- Enzymatic Hemicellulose Hydrolysis
- Advanced Pretreatments

Other Process Ideas

- Cellulase
  - Surface-Culture (Solid-State) Cultivation
  - Fungal Pretreatment
  - Ethanologen Cellulase Production
  - Transgenic Cellulase in Feedstock or Other Crop
  - Enzyme Recycle

Other Process Ideas

- Lignin Utilization
  - Higher Value Co-products
  - Improved Power Cycle
  - Increased Cost of Burner Emission Control
  - High Solids Anaerobic Digestion
  - Solubilize and Separate Lignin from Sugars Early
    - Solubilize Sugars and Separate from Lignin Early
  - Transgenic Ligninases for Pre-pretreatment

Other Process Ideas

- Increased Facility Size
- Biorefineries
  - Split Sugar Stream for Higher Value Coproducts
  - Variable Feedstock Facilities
- Use of Feedstock Cost Projections from ORNL
- Fuel Cells for Power
- Cell Mass Co-Product Possibilities

Conclusions

- Corn Stover has Less Carbohydrate than Hardwood Sawdust
- Corn Stover has Other Potentially Problematic Components
- Enzymatic Process Not Ready for Industry Wide Use Today
- Significant Process / Economic Improvements are Achievable
- Many More Process Improvements Need to be Considered