Techno-economic and Market Analysis of Pathways from Syngas to Fuels and Chemicals

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Objective

Assess the economics of producing fuels and chemicals from biomass-derived synthesis gas.

• Process economics based on literature (consistent TEA assumptions)
• Perform more rigorous TEA on promising pathways
  o Biochemical conversion of syngas to ethanol and higher alcohols
  o Ethanol and higher alcohols to infrastructure-compatible hydrocarbons
• Simple product market analyses

What can we do with syngas?
Analysis Approach

• Simplified TEA model

• Inputs from literature sources
  o Feedstock rate and properties (heating value)
  o Product yields
  o Operating costs (variable & fixed)
  o Capital costs

• Common scaling assumptions
  o Capital scaling exponents
  o Economies of scale for fixed operating costs

• Operating and financing assumptions for n\textsuperscript{th} plant and pioneer plant

• Minimum Product Selling Price
  literature values ➔ average, standard deviation & 90% confidence intervals
## nth Plant Assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis year for analysis</td>
<td>2011</td>
</tr>
<tr>
<td>Feedstock processing capacity</td>
<td>2,000 Dry Tonnes / SD</td>
</tr>
<tr>
<td>Feedstock cost (woody biomass)</td>
<td>$75 / Dry Tonne</td>
</tr>
<tr>
<td>Debt / equity for plant financing</td>
<td>60% / 40%</td>
</tr>
<tr>
<td>Internal rate of return (after-tax) for equity financing</td>
<td>10%</td>
</tr>
<tr>
<td>Annual interest rate and term for debt financing</td>
<td>8% / 10 years</td>
</tr>
<tr>
<td>Total income tax rate</td>
<td>35%</td>
</tr>
<tr>
<td>Plant life</td>
<td>30 years</td>
</tr>
<tr>
<td>Plant depreciation schedule</td>
<td>7-year IRS MACRS</td>
</tr>
<tr>
<td>MACRS = Modified Accelerated Cost Recovery System</td>
<td></td>
</tr>
<tr>
<td>Reliability of operations / on-stream factor</td>
<td>0.90</td>
</tr>
<tr>
<td>Site development costs</td>
<td>4% of ISBL Installed Capital</td>
</tr>
<tr>
<td>Working capital</td>
<td>5% of Fixed Capital Investment</td>
</tr>
<tr>
<td>Indirect costs for capital project</td>
<td>60% of Total Direct Costs</td>
</tr>
<tr>
<td>Capital equipment capacity scaling exponent</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Pioneer Plant Assumptions

- **Internal Rate of Return (IRR):** 10% – 25%

- **Capital Costs:**
  Pioneer Plant Escalation ~ 210% of n$^\text{th}$ Plant Estimates *(Merrow et al, Rand, 1981)*

- **Reliability of Operations / On-Stream Factor:**
  Initial value of 0.5 *(Merrow et al, Rand, 1981)*
  Increasing to 0.9 per experience curve *(Heinen, SRI Consulting, 2001)*
Fuel Pathways Explored

Hydrocarbons (FT Gasoline, Diesel, Jet, Lubricants)

Ethanol & C3+ Alcohols

Synthetic Natural Gas

Syngas

Syngas Fermentation

Methanol

Dimethyl Ether (DME)

Triptyls

Gasoline (MTG)

Olefins (MTO)

Ethanol

Butanol

2,3-Butanediol
Chemical Pathways Explored

- Urea
- Ammonia
- Hydrogen
- DME
- Methyl-Amines
- Methyl Formate
- Formaldehyde
- Acetic Anhydride
- Ethyl Acetate
- Acetic Acid
- Ethylene Glycol
- Formic Acid
- Propylene (MTO)
- Ethylene (MTO)
- Acetic Acid
- Syngas Fermentation
- Syngas
- Hydrocarbons (FT Lubes, Waxes)
- PHA (Polyhydroxyalkanoates)
- Acetic Acid
- Aldehydes (Oxosynthesis)

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NATIONAL RENEWABLE ENERGY LABORATORY
Major Pathway Categories Explored

- **Synthetic Natural Gas** via Methanation of Syngas
- **Ethanol**
  - Catalytic Mixed Alcohol Synthesis
  - Syngas Fermentation *
- **Hydrocarbons**
  - Fischer-Tropsch
  - Methanol to Naphtha Hydrocarbons
  - Ethanol & Higher Alcohols to Hydrocarbons *
- **Hydrogen** via Steam Reforming, WGS & Purification
- **Methanol** via Catalytic Methanol Synthesis

*Pathways explored by NREL through Aspen modeling and rigorous TEA.*
Synthetic Natural Gas

• Methanation of Syngas
Synthetic Natural Gas

Process | Sources | Min. Selling Price Range ($ / MScf)
--- | --- | ---
Syngas to SNG via methanation | McKeough & Kurkela, 2007 Mozaffarian et al, 2004 van der Drift et al, 2005 | n\text{th} Plant 16.52 – 19.13
| | Pioneer 10% IRR 28.50 – 31.05
| | Pioneer 25% IRR 50.00 – 56.93

**Synthetic Natural Gas**

### Techno-economic Analysis

![Chart showing market prices and costs for synthetic natural gas]

- **Market Price (5-Yr)**: 5.50
- **nth-Plant MSP**: 17.62 ± 2.23
- **Pioneer Plant MSP**: 29.80 ± 2.10
- **IRR = 10%**: 53.50 ± 5.70
- **IRR = 25%**: 29.80 ± 2.10

### Market Analysis

- **Average Product per Ton Biomass**: 11,440 Scf / Ton
- **U.S. Consumption (EIA, 2012)**: 25.5T Scf / Year
- **10% of U.S. Natural Gas Market**: 2.55T Scf / Year
- **Equivalent Biomass Consumption**: 223 MMTon / Year
- **Equivalent Biorefineries**: 310 2,000 Tonne / Day Facilities
Ethanol

- Catalytic Mixed Alcohol Synthesis
- Syngas Fermentation

* Pathways explored by NREL through Aspen modeling and rigorous TEA.
### Ethanol via Mixed Alcohol Synthesis

<table>
<thead>
<tr>
<th>Process</th>
<th>Sources</th>
<th>Min. Selling Price Range ($ / Gal GE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pioneer 10% IRR 5.67 – 9.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pioneer 25% IRR 11.27 – 19.20</td>
</tr>
</tbody>
</table>

**Historical Pricing Data Source:** U.S. Energy Information Administration. U.S. Total Gasoline Rack Sales Price by Refiners (Dollars per Gallon), EIA Table 5.22 (2011 AEO) and Table 112 (2009 AEO).
## Ethanol via Syngas Fermentation

<table>
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<tr>
<th>Process</th>
<th>Sources</th>
<th>Min. Selling Price Range ($ / Gal GE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol via syngas fermentation</td>
<td>Putsche, 1999</td>
<td>3.67 – 5.08</td>
</tr>
<tr>
<td></td>
<td>van Kasteren &amp; Verbene, 2005</td>
<td>6.11 – 8.99</td>
</tr>
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<td></td>
<td>Piccolo &amp; Bezzo, 2007</td>
<td>11.07 – 17.02</td>
</tr>
</tbody>
</table>

### Historical Pricing Data

- **Pricing History**
  - **nth Plant**: $4.32 ± 0.83
  - **Pioneer 10% IRR**: $7.14 ± 1.82

**Historical Pricing Data Source:** U.S. Energy Information Administration. U.S. Total Gasoline Rack Sales Price by Refiners (Dollars per Gallon), EIA Table 5.22 (2011 AEO) and Table 112 (2009 AEO).
Ethanol via Syngas Fermentation

NREL TEA Model

- Design Report NREL/TP-5100-51400 utilized as basis through clean compressed syngas from biomass.
- Yield structures based on publications from LanzaTech & INEOS Bio.
- Capital costs for fermenters, seed train and cell recovery developed by Harris Group Inc.
Ethanol

Techno-economic Analysis

Market Analysis

Average Product per Ton Biomass
U.S. Consumption (EIA, 2013)

50% of U.S. Fuel Ethanol Market
Equivalent Biomass Consumption
Equivalent Biorefineries

85 Gallons / Ton
13.0B Gallons / Year
6.5B Gallons / Year
76 MMTon / Year
100 2,000 Tonne / Day Facilities
Hydrocarbons

• Fischer-Tropsch
• Methanol to Naphtha Hydrocarbons
• Ethanol & Higher Alcohols to Hydrocarbons *

* Pathways explored by NREL through Aspen modeling and rigorous TEA.
### Fischer-Tropsch Hydrocarbons

<table>
<thead>
<tr>
<th>Process</th>
<th>Sources</th>
<th>Min. Selling Price Range ($/Gal GE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pioneer 10% IRR 4.75 – 7.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pioneer 25% IRR 9.08 – 13.52</td>
</tr>
</tbody>
</table>

**Historical Pricing Data Source:** U.S. Energy Information Administration. U.S. Total Gasoline Rack Sales Price by Refiners (Dollars per Gallon), EIA Table 5.22 (2011 AEO) and Table 112 (2009 AEO).
# Methanol to Hydrocarbons

## Process

<table>
<thead>
<tr>
<th>Hydrocarbons via methanol synthesis and methanol conversion</th>
</tr>
</thead>
</table>

## Sources

<table>
<thead>
<tr>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phillips et al, 2011</td>
</tr>
<tr>
<td>Hindman, 2010</td>
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<tr>
<td>SRI PEP Report 191A, 1999</td>
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<tr>
<td>Udengaard, 2011</td>
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<tr>
<td>Jones &amp; Zhu, 2009</td>
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<td>Ahn et al, 2009</td>
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## Min. Selling Price Range ($ / Gal GE)

<table>
<thead>
<tr>
<th>Process</th>
<th>Min. Selling Price Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>nth Plant</td>
<td>2.61 – 3.84</td>
</tr>
<tr>
<td>Pioneer 10% IRR</td>
<td>4.67 – 6.47</td>
</tr>
<tr>
<td>Pioneer 25% IRR</td>
<td>8.61 – 11.38</td>
</tr>
</tbody>
</table>

## Pricing History

Historical Pricing Data Source: U.S. Energy Information Administration. U.S. Total Gasoline Rack Sales Price by Refiners (Dollars per Gallon), EIA Table 5.22 (2011 AEO) and Table 112 (2009 AEO).
Ethanol & Higher Alcohols to Hydrocarbons

NREL TEA Model

- Ethanol (and higher alcohol) intermediates for hydrocarbon fuel production.
- Eliminates constraints of renewable ethanol blend limits.
- Technology development taking place in academia, national labs and industry.
Hydrocarbon Fuels

Techno-economic Analysis

- Market Price (4-Yr)
- Price Projection (4-Yr)
- nth-Plant MSP
- Pioneer Plant MSP

Fischer-Tropsch
(Literature)

- 10.66 ± 2.56
- 5.63 ± 1.53

MeOH to Hydrocarbons
(Literature)

- 9.54 ± 1.87
- 5.37 ± 1.09

EtOH to Hydrocarbons
(NREL TEA)

Market Analysis

Average Product per Ton Biomass
U.S. Consumption (EIA, 2013)

- 65 Gallons / Ton
- 220B Gallons / Year

10% of U.S. Hydrocarbon Fuels Market
Equivalent Biomass Consumption

- 22B Gallons / Year
- 338 MMTon / Year

Equivalent Biorefineries

- 440 2,000 Tonne / Day Facilities
Hydrogen

- Steam reforming, water-gas shift & purification
Hydrogen

<table>
<thead>
<tr>
<th>Process</th>
<th>Sources</th>
<th>Min. Selling Price Range ($ / MScf)</th>
</tr>
</thead>
</table>
| Syngas to H₂ via steam reforming, water-gas shift & purification       | Spath et al, 2005  
McKeough & Kurkela, 2003  
Williams et al, 1995  
Hamelinck & Faaïj, 2001 | nth Plant | 5.33 – 8.84 |
|                                                                        |         | Pioneer 10% IRR                      | 10.46 – 15.63 |
|                                                                        |         | Pioneer 25% IRR                      | 20.93 – 29.07 |

Pricing History

2011 $ / MScf

- **Pioneer 10% IRR**: 12.52 ± 3.62
- **nth Plant**: 6.67 ± 2.48

Historical Pricing Data Source: SRI CEH Marketing Research Report, July, 2010  
Projected values based on ratios to EIA natural gas projections.
Hydrogen

Techno-economic Analysis

Market Analysis

Average Product per Ton Biomass 37,300 Scf / Ton
U.S. Consumption (EIA, 2013) 4.1T Scf / Year
10% of U.S. Hydrogen Market 0.41T Scf / Year
Equivalent Biomass Consumption 11 MMTon / Year
Equivalent Biorefineries 14 2,000 Tonne / Day Facilities
Methanol

• Catalytic Methanol Synthesis
Methanol

<table>
<thead>
<tr>
<th>Process</th>
<th>Sources</th>
<th>Min. Selling Price Range ($ / Gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syngas to methanol via catalytic synthesis</td>
<td>Tarud &amp; Phillips, 2011&lt;br&gt;McKeough &amp; Kurkela, 2007&lt;br&gt;SRI PEP Yearbook, 2009&lt;br&gt;Williams et al, 1995&lt;br&gt;Hamelinck &amp; Faaij, 2001</td>
<td>n\textsuperscript{th} Plant 0.96 – 1.32&lt;br&gt;Pioneer 10% IRR 1.63 – 2.13&lt;br&gt;Pioneer 25% IRR 2.97 – 3.91</td>
</tr>
</tbody>
</table>

Methanol as Chemical Intermediate

Techno-economic Analysis

- Market Price (5-Yr): $1.16
- nth-Plant MSP: $1.15 ± 0.26
- Pioneer Plant MSP: $3.41 ± 0.64

IRR = 10% 25%

Market Analysis

- Average Product per Ton Biomass: 170 Gallons / Ton
- U.S. Consumption (SRI / IHS, 2010): 1.9B Gallons / Year
- 10% of U.S. Methanol Market: 0.19B Gallons / Year
- Equivalent Biomass Consumption: 1.1 MMTon / Year
- Equivalent Biorefineries: 1.4 2,000 Tonne / Day Facilities
Methanol as Fuel Intermediate

Techno-economic Analysis

- Average Product per Ton Biomass: 65 Gallons / Ton
- U.S. Consumption (EIA, 2013): 220B Gallons / Year
- 10% of U.S. Hydrocarbon Fuels Market: 22B Gallons / Year
- Equivalent Biomass Consumption: 338 MMTon / Year
- Equivalent Biorefineries: 440 2,000 Tonne / Day Facilities

Market Analysis

- IRR = 10% 25%
- Market Price (5-Yr) 2011 $ / MScf
  - Market Price (5-Yr) 1.16
  - nth-Plant MSP 1.15 ± 0.26
  - Pioneer Plant MSP 1.93 ± 0.39 3.41 ± 0.64

*Image from National Renewable Energy Laboratory*
Conclusions

• Hydrocarbon, ethanol and methanol economics can be competitive for $n^{\text{th}}$-plant.

• Pioneer plant economics are challenged overall.

• Market capacities do not constrain bio-product pathways in major hydrocarbon fuel markets (natural gas, petroleum fuels).

• With fixed ethanol blend limit, cellulosic pathways and grain-derived product will compete for limited market.

• Market capacities for methanol-derived chemicals are constraining.

• Syngas fermentation is potentially competitive, depending on CO / $H_2$ conversion to product(s).

• Methanol and ethanol are attractive intermediates for production of infrastructure-compatible hydrocarbons.
Future Work

• Develop design reports for selected biomass-to-hydrocarbon fuel pathways under DOE-BETO directed efforts.

• Apply simplified TEA and market analysis on emerging pathways to identify economic feasibility in early stages of development.

• Explore opportunities to improve Pioneer Plant economics
  o Biomass co-feeding opportunities (NG-Biomass to Liquids)
  o Utilizing inexpensive feedstocks
  o High-value co-products
  o RIN credits
Acknowledgements

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• NREL Biorefinery Analysis and Thermochemical Platform Teams
References

For a complete list of references utilized in this analysis, please contact Mike Talmadge (michael.talmadge@nrel.gov / 303-275-4632)