Technoeconomic Analysis of Bio-Jet Fuel Production

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• SPONSORS:
  – DOE EERE
  – Boeing
  – IOR Energy
  – MacKay Sugar Factory
  – Virgin Blue Airlines Group
  – Queensland Government
  – GE
Petroleum resources are limited

Source: The Association for the Study of Peak Oil and Gas, C.J. Campbell, 2004
... but demand is increasing...

![Bar chart showing historical and projected energy demand in quadrillion Btu from 1980 to 2030.](chart.png)
… leading to high and volatile oil prices
Jet fuels present a challenge

From WEF, Repowering Transport, 2011
People like flying

> Figure 2: Aviation passenger movements in Australia and New Zealand to 2008. Source: BITRE (2009) and; Statistics New Zealand (2010a)

From CSIRO, Sustainable Aviation Fuel Road Map, 2011
How expensive is it?

Source: IEA BIOENERGY: ExCo: 2009.06

Figure 3: Schematic view of the wide variety of bioenergy routes. Source: E4tech, 2009.
Selling you drop-in biofuels

Adapted from http://www.biofuelsdigest.com/bdigest/2012/11/12/
<table>
<thead>
<tr>
<th>Feedstock/Process</th>
<th>MESP ($/gal)</th>
<th>In 2009$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwood (spruce), steam pretreatment, SSF</td>
<td>$2.16</td>
<td>$2.54</td>
<td>(Wingren et al. 2003)</td>
</tr>
<tr>
<td>Softwood (spruce), steam pretreatment</td>
<td>$2.39</td>
<td>$2.81</td>
<td>(Wingren et al. 2003)</td>
</tr>
<tr>
<td>Corn stover, dilute acid, SSF</td>
<td>$1.34</td>
<td>$1.48</td>
<td>(Eggeman &amp; Elander 2005)</td>
</tr>
<tr>
<td>Corn stover, AFEX, SSF</td>
<td>$1.43</td>
<td>$1.58</td>
<td>(Eggeman &amp; Elander 2005)</td>
</tr>
<tr>
<td>Corn stover, dilute acid</td>
<td>$2.43</td>
<td>$2.43</td>
<td>(Aden &amp; Foust 2009)</td>
</tr>
<tr>
<td>Poplar, dilute acid</td>
<td>$2.37</td>
<td>$2.71</td>
<td>(Hamelinck et al. 2005)</td>
</tr>
<tr>
<td>Corn stover, dilute acid, SSF</td>
<td>$3.30</td>
<td>$3.30</td>
<td>(Dutta et al. 2009)</td>
</tr>
<tr>
<td>Wood, dilute acid, SSF</td>
<td>$1.28</td>
<td>$1.66</td>
<td>(So &amp; Brown 1999)</td>
</tr>
</tbody>
</table>

Results depend on assumptions.
Community-updatable tool

Wiki-based Models
A Biofuels Wiki

Turning corn sugar into ethanol involves well-established technology, but if the goal is to replace a substantial fraction of the world's petroleum with biofuel, alternative feedstocks that now in ne'er-a-soil and don't compete with food...
Renewable Jet-Fuels

- Pongamia Seeds
- Sugarcane
- Algae

Hydrocarbon Intermediate (triacylglyceride or farnesene)

- Naphtha (C$_5$-C$_{10}$)
- Jet Fuel (C$_{10}$-C$_{16}$)
- Diesel (>C$_{16}$)
Methodology

Experimental data

Literature data

Industry best practices

Process Parameters

Material Balances

Energy Balances

Cost Estimation

Preliminary design, Material Flows, Energy Use, Cash Flows

Minimum Selling Price (MSP)

Primary Inputs

Calculations

Primary outputs

Derived outputs

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Minimum selling price

Pongamia Seeds

Sugarcane

Algae

Hydrocarbon Intermediate
(triacylglyceride or farnesene)

Jet Fuel
(C_{10}-C_{16})

Naphtha
(C_{5}-C_{10})

Diesel
(>C_{16})

NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} = \sum_{i=1}^{n} \frac{(MSP \cdot V - C)_i}{(1+r)^i} = 0
Bio-Jet Fuel Processes

1. Pongamia oil extraction and refining
2. Sugarcane juice fermentation to hydrocarbons and refining
3. Algae growth, oil extraction, and refining


**Pongamia oil process**

- *Pongamia pinnata* is a leguminous tree and produces seeds with up to ~40% oil.
- The oil can be extracted and used for biodiesel, or can be refined to compounds that can replace jet fuel.
Pongamia oil process

Seed crushing → Seeds

Oil Extraction → Anaerobic Digestion

Oil cleaning / degumming → UOP Refining

Steam/Electricity → Biofuels
Sugarcane is a perennial grass with high sucrose content

Sugar content in cane may be 100-150 kg/MT

Sugar can be fermented to a variety of molecules, including compounds that can replace jet fuel use.
Sugarcane molasses process

Crushing → Sugarcane

Clarification/Evaporation → Steam/Electricity

Clarification/Evaporation → "A" Sugar

Molasses Fermentation → Farnesene separation

Farnesene separation → UOP Refining

UOP Refining → Biofuels
Microalgae are photosynthetic microorganisms, some are capable of high lipid accumulation.

- Oil content in microalgae may be 20-50% (or more).
- The oil can be extracted and used for biodiesel, or can be refined to compounds that can replace jet fuel.
Algae oil process

(Nannochloropsis sp.)

- Algae Ponds
- Algae Harvesting
- Oil extraction
- Anaerobic digestion
- CO₂, N, P, Light
- Water recycle
- Oil Cleaning
- Steam/Electricity
- Biofuels
- UOP Refining

Nutrient recycle
Summary of the Results
### Likely current economics

<table>
<thead>
<tr>
<th></th>
<th>Pongamia</th>
<th>Sugarcane</th>
<th>Algae</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Capital Investment ($M)</strong></td>
<td>$506</td>
<td>$259</td>
<td>$3,451</td>
</tr>
<tr>
<td><strong>Annual Operating Cost ($M)</strong></td>
<td>$303</td>
<td>$253</td>
<td>$984</td>
</tr>
<tr>
<td>Facility-dependent Costs(^1,2)</td>
<td>31.93%</td>
<td>18.84%</td>
<td>84.17%</td>
</tr>
<tr>
<td>Raw Materials(^1)</td>
<td>57.86%</td>
<td>70.89%</td>
<td>10.11%</td>
</tr>
<tr>
<td>Utilities(^1)</td>
<td>5.56%</td>
<td>8.13%</td>
<td>4.43%</td>
</tr>
<tr>
<td>Labor Cost(^1)</td>
<td>4.53%</td>
<td>2.14%</td>
<td>1.25%</td>
</tr>
<tr>
<td>Consumables(^1)</td>
<td>0.12%</td>
<td>0.01%</td>
<td>0.04%</td>
</tr>
<tr>
<td><strong>Minimum Selling Price ($/barrel eqv.)</strong></td>
<td>$373.68</td>
<td>$301.35</td>
<td>$1,343.18</td>
</tr>
</tbody>
</table>

1. As percentage of annual operating cost
2. Facility-dependent costs include depreciation, maintenance, insurance and overhead
Capex breakdown

The diagram shows the capex breakdown for Pongamia, Sugarcane, and Algae. Each category is represented by different colors:
- Fermentation
- Amine Scrubber
- Digestion & Cogeneration
- Hydrocracking
- UOP Refining
- Degumming
- Hexane Extraction
- Seed Processing
- Harvesting
- Algae Ponds

The percentage of capital expenditure for each category is indicated by the height of the bars within each category.
Microalgae dewatering is a major obstruction to industrial-scale processing of microalgae for biofuel production. The dilute nature of harvested microalgal cultures creates a huge operational cost during dewatering, thereby, rendering algae-based fuels less economically attractive. Currently there is no superior method of dewatering medium is an essential and important step. The efficient separation dewatering and drying of microalgae is probably the most essential factor in the economic feasibility of any microalgae production system.

Source: Shelef, SA, Green M. Microalgae Harvesting and Processing. Carbon Dioxide Information Analysis Center (1990)
Sensitivity analysis

P - Oil Content (50% : 40% : 30%)
P - Feed ($450: AD : AD)
P - Seed Cost ($500 : $590 : $1000)
S - Feed ($450 : $0 : $0)
S - Yield (95% : 55% : 40%)
S - Sep. Efficiency (98% : 96% : 90%)
S - Molasses Cost (10c : 15.5c : 40c)
A - Carbon Dioxide (-$40 : $0 : $40)
A - Feed ($450 : AD : AD)
A - Productivity (15g : 20g : 30g)
A - Nutrient Recycle (100% : 90% : 20%)
A - Harvesting Cost (35% : 100% : 130%)

Change to production cost ($ / barrel equiv.)
Sensitivity analysis

- Oil Content (50% : 40% : 30%)
- Feed ($450 : $0 : $0)
- Seed Cost ($500 : $590 : $1000)
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Change to production cost ($ / barrel eqv.)
Likely current and future economics

- Pongamia
- Sugarcane
- Algae

MSP ($/bbl oil equivalent)
Community-updatable tool

http://qsafi.aibn.uq.edu.au
Questions?

Daniel Klein-Marcuschamer

Email: dklein@lbl.gov
Pongamia model validation

Raw Materials

$590/MT

~20% more expensive than soybean

Capex

$54.4M for oil extraction

Range for soybean oil extraction is $56-78M*

Overall process

MSP of $440/MT for meal and $1150/MT for oil

Similar to market prices for soybean meal and oil

* Source: Soares et al., FEASIBILITY STUDY & PRELIMINARY BUSINESS PLAN FOR A MICHIGAN SOYBEAN CRUSH PLANT, 2006
Sugarcane model validation

Raw Materials

$190/MT molasses

Validated by Mackay Sugar Ltd.

Capex

Not publicly available

Overall process

MSP of the farnesene intermediate $4.30-$7.10/gal

Farnesene for non-fuel target markets start at ~$6.40/gal*

* Source: http://www.biofuelsdigest.com/bdigest/2011/05/03/amyris-the-owners-manual/
Algae model validation

Raw Materials
Unimportant

Overall process
MSP $1340/bbl ($32/gal oil)
IHI Japan reported current fuel price at $48/gal*

Capex**

<table>
<thead>
<tr>
<th>CAPITAL COSTS ($/ha):</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponds (earthworks, CO₂ sumps, mixing)</td>
<td>27,500</td>
</tr>
<tr>
<td>Harvesting (settling ponds, centrifuges)</td>
<td>12,500</td>
</tr>
<tr>
<td>System-wide Costs (water, CO₂ supply, etc.)</td>
<td>30,000</td>
</tr>
<tr>
<td>Processing (oil extraction, digestion)</td>
<td>10,000</td>
</tr>
<tr>
<td>Engineering, Contingencies (25% of above)</td>
<td>20,000</td>
</tr>
<tr>
<td>TOTAL CAPITAL COSTS ($/ha)</td>
<td>100,000</td>
</tr>
</tbody>
</table>

Sources: * [http://www.yomiuri.co.jp/dy/business/T121108003031.htm](http://www.yomiuri.co.jp/dy/business/T121108003031.htm)
** Benemann, J.R. & Oswald, W.J. Final Report to the Pittsburgh Energy Technology Center (1996).
Need for R&D

assumption. This cost estimate (based on Benemann et al., 1978, 1982; and Weissman and Goebel, 1987), made numerous favorable assumptions about the engineering and biological aspects of such a system. For example, the growth ponds economy, the ponds would be earthwork construction with a clay sealer. Many aspects of this process require further analysis and R&D. Harvesting involves

culture medium is an essential and important step. The efficient separation, dewatering, and drying of microalgae is probably the most essential factor in the economic feasibility of any microalgae production system.


Source: Shelef, SA, Green M. Microalgae Harvesting and Processing. Carbon Dioxide Information Analysis Center (1990)
QSAFI: Building a Biorefinery

www.biocore-europe.org
Economic Estimates

- CAPEX based on data from various NREL and ORNL reports, vendor quotes, and Aspen calculators
- Refining equipment numbers were validated by IOR
- Minimum selling prices (MSP) included a discount rate (i.e. a WACC) of 10% for 25 years, a debt-equity split of 60/40, with an interest rate of 8% (admittedly optimistic, under the assumption of government support. These can be changed)
• Analysis includes annual operating costs (AOC), breakdown of CAPEX by section, and minimum selling prices (MSP)
• MSP analysis was carried out by varying the prices of naphtha, aviation fuel, and diesel simultaneously.
  – This analysis gives the equivalent price of oil that would make the biorefinery competitive with an oil refinery
TEA: Value proposition

• For Government agencies (DOE, USDA, etc.)
  – Assess the potential impact of a grant or program, advise policy, provide independent evaluation on technology

• For researchers at early stages
  – Evaluate different research directions, prioritize efforts, apply for grants

• For start-ups and researchers with technologies close to commercialization
  – Attract capital, make informed decisions, apply for grants

• For venture capital and industry
  – Due diligence, valuate intellectual property, analyze competitive advantage of proprietary technologies