Process design and evaluation of butanol production from lignocellulosic biomass

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C.M. Daza Montaño
PROCESS DESIGN AND EVALUATION OF BUTANOL PRODUCTION FROM LIGNOCELLULOSIC BIOMASS

Claudia Daza Montaño
Presentation Outline

• Why Butanol?

• ABE (acetone, butanol, ethanol) fermentation background and state of the art

• Developed conceptual process design

• Economic evaluation

• Environmental Impact assessment (LCA)

• Conclusions
BUTANOL ($C_4H_9OH$): Bulk chemical and fuel

Butanol is better biofuel than ethanol due to its more favorable chemical/physical properties. But even more valuable as chemical

<table>
<thead>
<tr>
<th>Properties</th>
<th>1-Butanol $C_4H_9OH$</th>
<th>Ethanol $C_2H_5OH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHV (MJ/kg)</td>
<td>33</td>
<td>27</td>
</tr>
<tr>
<td>Solubility (ml/100 ml H$_2$O)</td>
<td>9 miscible</td>
<td></td>
</tr>
<tr>
<td>Vapor pressure (mmHg)</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>37</td>
<td>15</td>
</tr>
</tbody>
</table>

- Butanol can be shipped and distributed through existing pipelines and filling stations
- Butanol can be blended with diesel and with gasoline
- Butanol is a widely used solvent in industry
Acetone-butanol-ethanol (ABE) fermentation

Sugars and starch

Biofuels

- USA
- Canada
- South Africa
- China
- Japan
- URSS
- Others

Chemicals

- DuPont & BP in UK
- USA
- China
- Brazil
- Others

Traditional fermentation

Petrochemicals

ABE revival

1920
1950
2008
2015

[Image: Pict. source: Jones, D; Clostridia X Workshop]
Challenges and research on butanol fermentation

- High cost of raw material
- Butanol toxicity (10 gr/l)
  - Low solvent yields
  - Low productivity
  - Dilute product streams
  - Expensive DSP

Metabolic and Genetic engineering
- Broad substrate range – agricultural and food industry residues
- Solvent tolerant strains
- Thermophilic strains
- Selective product formation

Process technology
- Upstream: Pre-treatment and hydrolysis
- Fermentation configuration
- In Situ Product Removal (ISPR)
- DSP and process integration
Definition of process designed

• **Plant capacity** ➔ 100 kton/year bio-butanol (167 kton/year ABE)

• **Lignocellulosic feedstock** ➔ Wheat straw

  Input 1416 kton/year (d.m)

  Cost: 31€/ton (d.m.)

• **Mode of operation** ➔ Continuous

• **In situ product removal technique** ➔ Gas stripping
ABE fermentation parameters

Solvent-producing *Clostridia beijerinckii* NACIMB 8052

- Wild type - Anaerobic bacteria
- Saccharolytic: C6 (glucose) and C5 (xylose) and sugar polymers (starch, xylan)
- Typical yield: 0.3 kg A.B.E/kg_{sugar} with 3:6:1 mass ratio

<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
<th>wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugars</td>
<td>CH$_2$O</td>
<td>-</td>
</tr>
<tr>
<td>Acetone</td>
<td>C$_3$H$_6$O</td>
<td>9</td>
</tr>
<tr>
<td>Butanol</td>
<td>C$_4$H$_9$OH</td>
<td>18</td>
</tr>
<tr>
<td>Ethanol</td>
<td>C$_2$H$_5$OH</td>
<td>3</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>CH$_3$COOH</td>
<td>1.5</td>
</tr>
<tr>
<td>Butyric acid</td>
<td>C$_4$H$_8$O$_2$</td>
<td>1.5</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H$_2$</td>
<td>1.6</td>
</tr>
<tr>
<td>Microbial cells</td>
<td>CH$<em>{1.8}$O$</em>{0.5}$N$_{0.2}$</td>
<td>12.7</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO$_2$</td>
<td>49.7</td>
</tr>
</tbody>
</table>
Product recovery

Product Removal (ISPR) required to optimize fermentation productivity

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency</th>
<th>State of development</th>
<th>Scale</th>
<th>Capital cost</th>
<th>Operating cost</th>
<th>Technology status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distillation</td>
<td>High</td>
<td>Complete</td>
<td>Commercial</td>
<td>Med</td>
<td>High</td>
<td>Commercial</td>
</tr>
<tr>
<td>Gas Stripping</td>
<td>Medium</td>
<td>Research</td>
<td>Lab</td>
<td>High</td>
<td>High</td>
<td>Research</td>
</tr>
<tr>
<td>Solvent Extraction</td>
<td>High</td>
<td>Research</td>
<td>Lab</td>
<td>Med</td>
<td>Med</td>
<td>Research</td>
</tr>
<tr>
<td>Pervaporation</td>
<td>High</td>
<td>Development</td>
<td>Pilot</td>
<td>High</td>
<td>High</td>
<td>Research</td>
</tr>
<tr>
<td>Adsorption</td>
<td>High</td>
<td>Research</td>
<td>Commercial</td>
<td>High</td>
<td>Low</td>
<td>Research</td>
</tr>
</tbody>
</table>

Gas stripping advantages:

- Simple technology
- Selective removal of volatile compounds
- Use of fermentation off gas (CO₂)
- No toxicity to cells
## Overall mass & energy balance

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Kton/year</th>
<th>Value MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat straw (d.w., 9 wt% ash)</td>
<td>1416</td>
<td>835*</td>
</tr>
<tr>
<td>Heat demand</td>
<td></td>
<td>196</td>
</tr>
<tr>
<td>Electricity demand</td>
<td></td>
<td>61</td>
</tr>
<tr>
<td><strong>Total input</strong></td>
<td></td>
<td>1091</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetone</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Butanol</td>
<td>100</td>
<td>181 *</td>
</tr>
<tr>
<td>Ethanol</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Heat generation in CHP’s</td>
<td></td>
<td>431</td>
</tr>
<tr>
<td>Electricity generation in CHP’s</td>
<td></td>
<td>196</td>
</tr>
<tr>
<td><strong>Total output</strong></td>
<td></td>
<td>808</td>
</tr>
<tr>
<td><strong>Net heat surplus</strong></td>
<td></td>
<td>235</td>
</tr>
<tr>
<td><strong>Net electricity surplus</strong></td>
<td></td>
<td>136</td>
</tr>
</tbody>
</table>

*(LHV basis)*

- Process energy demand (steam and electricity) fully covered + large electricity export
- Room for improvement via heat integration
- Surplus heat could be used for sterilization or for cooling generation via Absorption Refrigeration Plant

\[
\text{Energy efficiency} = \frac{\text{Energy content in ABE} + \text{Electricity output}}{\text{Energy input (feedstock)}} = 38\%
\]
## Total production cost

<table>
<thead>
<tr>
<th>Costs</th>
<th>€/TonABE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw materials</td>
<td>421</td>
</tr>
<tr>
<td>Utilities</td>
<td>5</td>
</tr>
<tr>
<td>Labor</td>
<td>21</td>
</tr>
<tr>
<td>Maintenance</td>
<td>110</td>
</tr>
<tr>
<td>Others</td>
<td>71</td>
</tr>
<tr>
<td>Taxes</td>
<td>30</td>
</tr>
<tr>
<td>Capital charge</td>
<td>204</td>
</tr>
<tr>
<td><strong>Total gross</strong></td>
<td>862</td>
</tr>
<tr>
<td><em><em>Total-electricity</em> sales</em>*</td>
<td>408</td>
</tr>
</tbody>
</table>

* 0.07 €/kWh

### Production cost distribution

- Raw materials: 30%
- Straw: 30%
- Enzymes: 16%
- Others: 8%
- Taxes: 4%
- Capital charge: 24%
- Maintenance: 13%
- Labour: 2%
- Utilities: 1%
- Sulphuric acid: 0%
- Nutrients: 0%
- Lime: 0%
- Water: 1%
# Product sales revenues

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>CHEMICALS</th>
<th>PRODUCTION</th>
<th>ANNUAL SALES</th>
<th>PRODUCT VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Selling Price €/Ton</td>
<td>Kton/year</td>
<td>M€/year</td>
<td>%</td>
</tr>
<tr>
<td>Acetone</td>
<td>571</td>
<td>50</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td>Butanol</td>
<td>929</td>
<td>100</td>
<td>93</td>
<td>68</td>
</tr>
<tr>
<td>Ethanol</td>
<td>857</td>
<td>17</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Total ABE (3:6:1 wt)</td>
<td>814</td>
<td>167</td>
<td>136</td>
<td>100</td>
</tr>
</tbody>
</table>

Internal Rate of Return (IRR) = 9.6%
Sensitivity analysis on Internal Rate of Return (IRR)

Total ABE sales as chemicals: 136 M€/year
IRR=9,6%

<table>
<thead>
<tr>
<th>PRODUCTS</th>
<th>LHV (MJth/kg)</th>
<th>FUELS</th>
<th>CHEMICALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total ABE (3:6:1 wt)</td>
<td>31</td>
<td>440</td>
<td>814</td>
</tr>
</tbody>
</table>

*0.015 €/MJth
The goals of the screening LCA are to assess the environmental impacts of ABE production from straw, in a “cradle to gate” analysis and to compare these impacts with those of ABE petrol-based production and with those of gasoline production.

Software: SimaPro (version 7) [www.pre.nl](http://www.pre.nl)
Inventory analysis and impact assessment

Ecoinvent database
Functional unit 1 MJ ABE = 0.032 kg ABE

CML method
(Centrum voor Milieukunde Leiden (CML))

Impact categories
• Abiotic depletion
• Global warming
• Ozone layer depletion
• Human toxicity
• Fresh water aquatic ecotoxicity
• Marine aquatic ecotoxicity
• Terrestrial ecotoxicity
• Photochemical oxidation
• Acidification
• Eutrophication
Comparison ABE from wheat straw with gasoline and with petrochemical ABE

Normalization set: West Europe, 1995

Functional unit: 1 MJ

Normalization set: West Europe, 1995

Functional unit: 1 MJ
Overall conclusions and recommendations

- Wheat Straw to ABE as chemicals = CLOSE TO be economically competitive.
  - Raw materials are the major cost driver

- Increase of butanol ratio to A:E produced improves energy efficiency and economics

- Environmental performance: straw-ABE better than petrol-based ABE
  - Residues conversion into heat and electricity are a key parameter
  - Major environmental impacts: eutrophication
  - Recovery of nutrients and production of useful by-products would improve LCA

- OPTION: Retrofit existing ethanol plants for butanol production
Thank for your attention

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Wageningen University & Research Centre WUR

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