3rd Pan American Congress
On Plants and Bioenergy

Virtual Sugarcane Biorefinery
A Systems Approach to Sustainability

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Champaign, IL – USA
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Virtual Sugarcane Biorefinery

Concept and methodology
Technological Assessment Program: Virtual Sugarcane Biorefinery

Objectives

- Assess different Biorefinery routes and technologies
- Assess stage of development of new technologies
- Optimize concepts and operations in the Biorefinery
VSB – Virtual Sugarcane Biorefinery

- Pre planting operations
- Soil preparation
- Planting
- Cultivation
- Harvesting
- Sugarcane transport

- Biorefinery 1G
- Biorefinery 2G
- Biorefinery “n”
- Transport logistics

- AspenPlus®
- Cana Soft
- Economic Engineering
- Input-Output Matrix
- SimaPro®

Economic Analysis
- Production cost
- IRR
- ...

Social Analysis
- Manpower
- Wages
- ...

Environmental Analysis (Life Cycle Assessment)
- Global warming
- Acidification
- Eutrophication
- Ecotoxicity
- Ozone layer depletion
- Energy balance
- Water use
- Land use
- ...

Usage Spreadsheet
Cana Soft

Standard parameter of main operations

Pre planting operations  Soil preparation  Planting  Cultivation  Harvesting  Transport

Cana Soft

Economic Inventory
✓ CapEx
✓ OpEx

Social Inventory
✓ Manpower
✓ Wages

Life Cycle Inventory
✓ Diesel
✓ Fertilizers
✓ Machinery
✓ Industrial inputs
✓ Equipments
✓ Local emissions, e.g. $N_2O$, $CO_2$
✓ Other inputs and outputs...

User input data for scenario definition

Sugarcane yield
Other general information

Calculation modules

Emission factors
Transport
Agrochemicals
Vinasse spreading
Biorefinery simulation

Evaluated scenarios:
- Autonomous Distillery
- Annexed plant
- Integrated 1G2G process
- Stand-alone 2G process
- Harvest extension with sorghum
- Sucrochemistry route (butanol)

Input data (user):
- Components
- Process Flow Diagram
- Composition, flows and conditions of streams
- Operational data for equipments

Process steps (depending on each scenario):
- Cleaning of sugarcane and sugar extraction
- Juice treatment and concentration
- Fermentation
- Distillation and dehydration
- Combined heat and power generation

Aspen Plus®

Economic, social and enviromental inventory:
- Raw material and inputs
- Production data (ethanol, electricity, sugar, etc)
- Sub-products and residues
- Emission information
- Inputs for investment calculation
- Other information

Report
Usage spreadsheet

Standard parameters of main operations

- Emission factors
- Transportation efficiency
- Load capacity
- Inputs

Modal
Distances
Use of products
Other info

User input data for scenario definition

Logistics and usage

- Lorries
- Train
- Pipes
- Grid

Calculation modules

Economic Inventory
- CapEx
- OpEx

Social Inventory
- Manpower
- Wages
- Others

Life Cycle Inventory
- Diesel
- Machinery
- Local emissions: e.g. N₂O, CO₂
- Other inputs and outputs

Output reports

Under construction
Evaluation of Agricultural Process

Scenarios and results
Manual planting and harvesting

Mechanical planting and harvesting
Agricultural Scenario on Canasoft®

<table>
<thead>
<tr>
<th>Manual planting and manual harvesting</th>
<th>Mechanized planting and mechanized harvesting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-planting</strong></td>
<td><strong>Pre-planting</strong></td>
</tr>
<tr>
<td>Reform</td>
<td>Reform</td>
</tr>
<tr>
<td>88.0 %</td>
<td>88.0 %</td>
</tr>
<tr>
<td>Expantion</td>
<td>12.0 %</td>
</tr>
<tr>
<td><strong>Planting</strong></td>
<td><strong>Planting</strong></td>
</tr>
<tr>
<td>Semi-mechanized</td>
<td>Semi-mechanized</td>
</tr>
<tr>
<td>100.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>Mechanized</td>
<td>Mechanized</td>
</tr>
<tr>
<td>0.0 %</td>
<td>100.0 %</td>
</tr>
<tr>
<td>Sugarcane planting</td>
<td>Sugarcane planting</td>
</tr>
<tr>
<td>85.4 %</td>
<td>77.9 %</td>
</tr>
<tr>
<td>Setts planting</td>
<td>Setts planting</td>
</tr>
<tr>
<td>14.6 %</td>
<td>22.1 %</td>
</tr>
<tr>
<td>Filter cake application</td>
<td>Filter cake application</td>
</tr>
<tr>
<td>58.0 %</td>
<td>58.0 %</td>
</tr>
<tr>
<td>Ash application</td>
<td>Ash application</td>
</tr>
<tr>
<td>43.5 %</td>
<td>43.5 %</td>
</tr>
<tr>
<td><strong>Cultivation</strong></td>
<td><strong>Cultivation</strong></td>
</tr>
<tr>
<td>Plant cane</td>
<td>Plant cane</td>
</tr>
<tr>
<td>19.3 %</td>
<td>18.9 %</td>
</tr>
<tr>
<td>Ratoon</td>
<td>Ratoon</td>
</tr>
<tr>
<td>77.4 %</td>
<td>75.7 %</td>
</tr>
<tr>
<td>Setts growing</td>
<td>Setts growing</td>
</tr>
<tr>
<td>3.3 %</td>
<td>5.4 %</td>
</tr>
<tr>
<td>Vinassee application</td>
<td>Vinassee application</td>
</tr>
<tr>
<td>51.8 %</td>
<td>51.8 %</td>
</tr>
</tbody>
</table>
# Agricultural Scenario on Canasoft®

## Manual planting and manual harvesting

<table>
<thead>
<tr>
<th>Harvesting</th>
<th>100 %</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>100.0 %</td>
<td>Mechanized</td>
</tr>
<tr>
<td>Burned</td>
<td>100.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>Setts harvesting</td>
<td>3.3 %</td>
<td>Sugarcane harvesting</td>
</tr>
</tbody>
</table>

## Mechanized planting and mechanized harvesting

<table>
<thead>
<tr>
<th>Harvesting</th>
<th>100 %</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>0.0 %</td>
<td>100.0 %</td>
</tr>
<tr>
<td>Burned</td>
<td>0.0 %</td>
<td>100.0 %</td>
</tr>
<tr>
<td>Setts harvesting</td>
<td>5.4 %</td>
<td>Sugarcane harvesting</td>
</tr>
</tbody>
</table>

## Transport

<table>
<thead>
<tr>
<th>Mode</th>
<th>100 %</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodotrem</td>
<td>65.0 %</td>
<td>Romeu e Julieta</td>
</tr>
<tr>
<td>Distance</td>
<td>32.3 km</td>
<td>Distance</td>
</tr>
</tbody>
</table>
Total Cost

- Manual planting and harvesting: $32.0/TC
- Mechanized planting and harvesting: $28.0/TC
Fraction of total cost

Mechanical planting and harvesting

- Reform area: 26%
- Land transformation: 3%
- Planting: 3%
- Cultivation - ratoon: 2%
- Cultivation - plant cane: 2%
- Soil preparation: 1%
- Harvesting: 40%

Manual planting and harvesting

- Reform area: 27%
- Land transformation: 19%
- Planting: 2%
- Cultivation - ratoon: 2%
- Cultivation - plant cane: 3%
- Soil preparation: 1%
- Harvesting: 46%
Environmental Impacts

1st Generation Ethanol Production from Sugarcane in Brazil

Simulation and technical parameters
1G Ethanol, Sugar and Electricity Production from Sugarcane (Annexed Distillery)
Simulation

- Autonomous distillery
- Aspen Plus
Simulation

- Annexed distillery – sugar mill
- Aspen Plus
# Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant operation – sugarcane processed (TC/h)</td>
<td>500</td>
</tr>
<tr>
<td>– operation (days/year)</td>
<td>167</td>
</tr>
<tr>
<td>Sugarcane quality - fibers content (%)</td>
<td>13</td>
</tr>
<tr>
<td>- TRS content (%)</td>
<td>15.3</td>
</tr>
<tr>
<td>- trash produced in the fields (kg/TC, dry basis)</td>
<td>140</td>
</tr>
<tr>
<td>– bagasse/trash moisture (%)</td>
<td>50/15</td>
</tr>
<tr>
<td>Efficiency – sugar extraction in the mills (%)</td>
<td>96</td>
</tr>
<tr>
<td>– fermentation (%)</td>
<td>90</td>
</tr>
<tr>
<td>– boiler 22/90 bar (LHV basis) (%)</td>
<td>75/87</td>
</tr>
<tr>
<td>– turbine – high/intermediate pressure/condensing (%)</td>
<td>72 / 81 / 70</td>
</tr>
<tr>
<td>LHV – bagasse (50% moisture)/trash (15% moisture) (MJ/kg)</td>
<td>7.5/14.9</td>
</tr>
<tr>
<td>Energy demand of the process - electricity (direct/electric drivers) (kWh/TC)</td>
<td>12/30</td>
</tr>
<tr>
<td>Steam – process/molecular sieves – pressure (bar)</td>
<td>2.5 / 6</td>
</tr>
<tr>
<td>– demand in azeotropic distillation/ molecular sieves (kg/L EtOH)</td>
<td>2.0 / 0.6</td>
</tr>
<tr>
<td>Anhydrous ethanol purity (wt%)</td>
<td>99.6</td>
</tr>
<tr>
<td>VVHP sugar specification: purity/moisture (%)</td>
<td>99.6/0.1</td>
</tr>
</tbody>
</table>
Validation

Data from process

Process Flow Diagram description

Mass and Energy Balances (Excel)

Simulation using Aspen Plus

Results comparison

Final analysis

New calculations using Aspen Plus

Adjustment of simulations

Validation’s report

Results

<table>
<thead>
<tr>
<th>Product</th>
<th>Unit</th>
<th>Bulletin</th>
<th>Aspen</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar</td>
<td>t/h</td>
<td>64.44</td>
<td>66.15</td>
<td>2.6%</td>
</tr>
<tr>
<td>Hydrated ethanol</td>
<td>m³/h</td>
<td>15.46</td>
<td>15.59</td>
<td>0.88%</td>
</tr>
<tr>
<td>Anhydrous ethanol</td>
<td>m³/h</td>
<td>25.03</td>
<td>24.88</td>
<td>-0.63%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Yield (TRS based)</th>
<th>Bulletin</th>
<th>Aspen</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>89.9%</td>
<td>91.3%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Sugar House</td>
<td>91.5%</td>
<td>93.8%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Distillery</td>
<td>86.6%</td>
<td>87.1%</td>
<td>0.62%</td>
</tr>
</tbody>
</table>
1\textsuperscript{st} Generation Ethanol Production from Sugarcane in Brazil

Investment and economic parameters
1G Investment data


- 2,000,000 TC/year
- 22 bar boiler
- Azeotropic distillation

Transmission lines – electricity credit

- Costs (R$/km): R$ 480,000/km
- Length: 40 km
- R$ 19.2 million for transmission lines

Technological improvements (optimized 1G):

- + 40% on distillation sector (molecular sieves)
- + 40% on cogeneration sector (90 bar boilers)
- + 10% on distillation sector (heat exchanger network)

Investment fraction by sector:

<table>
<thead>
<tr>
<th>Process step</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reception, cleaning, extraction</td>
<td>15</td>
</tr>
<tr>
<td>Juice treatment, fermentation, distillation</td>
<td>17</td>
</tr>
<tr>
<td>Production of steam and electricity</td>
<td>30</td>
</tr>
<tr>
<td>Buildings, laboratories, etc</td>
<td>5</td>
</tr>
<tr>
<td>Control system, etc</td>
<td>7</td>
</tr>
<tr>
<td>Packing, transportation</td>
<td>3</td>
</tr>
<tr>
<td>Set up, etc</td>
<td>20</td>
</tr>
<tr>
<td>Engineering, services, etc</td>
<td>3</td>
</tr>
</tbody>
</table>
### 1G Investment data

Annexed distillery: US$ 85/TC - UNICA (Sousa and Macedo, 2010)

For a distillery processing 2 MTC/year:

<table>
<thead>
<tr>
<th>Process step</th>
<th>Investment (mi US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reception, cleaning, extraction</td>
<td>21</td>
</tr>
<tr>
<td>Juice treatment, fermentation, distillation</td>
<td>16</td>
</tr>
<tr>
<td>Sugar production</td>
<td>16</td>
</tr>
<tr>
<td>Production of steam and electricity</td>
<td>36</td>
</tr>
<tr>
<td>Others</td>
<td>16</td>
</tr>
<tr>
<td>Buildings</td>
<td>22</td>
</tr>
<tr>
<td>Control system, etc</td>
<td>3</td>
</tr>
<tr>
<td>Set up, etc</td>
<td>26</td>
</tr>
<tr>
<td>Engineering, services, etc</td>
<td>17</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>170</strong></td>
</tr>
</tbody>
</table>

Source: Elaborated by Markestrat from data provided by Procknor Engenharia
## Economic Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarcane price (US$/TC) (^{(a)})</td>
<td>23.25</td>
</tr>
<tr>
<td>Sugarcane trash price (US$/t) (^{(b)})</td>
<td>17.05</td>
</tr>
<tr>
<td>Electricity price (US$/MWh) (^{(c)})</td>
<td>84.88</td>
</tr>
<tr>
<td>Anhydrous ethanol price (US$/L) (^{(a)})</td>
<td>0.60</td>
</tr>
<tr>
<td>Hydrated ethanol price (US$/L) (^{(a)})</td>
<td>0.54</td>
</tr>
<tr>
<td>Sugar price (US$/kg) (^{(a)})</td>
<td>0.43</td>
</tr>
</tbody>
</table>

\(^{(a)}\) Averages prices 2001-2010 (São Paulo) updated to 2010  
\(^{(b)}\) Estimated by CTBE specialists  
\(^{(c)}\) Average prices in energy auctions (2004-2010), updated to 2010

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project lifetime (years)</td>
<td>25</td>
</tr>
<tr>
<td>Salvage value of equipment</td>
<td>-</td>
</tr>
<tr>
<td>Construction and start-up (years)</td>
<td>2</td>
</tr>
<tr>
<td>Linear depreciation (years)</td>
<td>10</td>
</tr>
<tr>
<td>Tax rate (%)</td>
<td>34</td>
</tr>
</tbody>
</table>
1st Generation Ethanol Production from Sugarcane in Brazil

Technical-economic results
## Results: 1G Basic X Optimized

<table>
<thead>
<tr>
<th>Parameter</th>
<th>“Basic” plant</th>
<th>Optimized plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler pressure</td>
<td>22 bar</td>
<td>90 bar</td>
</tr>
<tr>
<td>Destination of surplus bagasse</td>
<td>Sold</td>
<td>Burnt</td>
</tr>
<tr>
<td>Surplus electricity sell</td>
<td>None</td>
<td>Sold</td>
</tr>
<tr>
<td>Drivers</td>
<td>Direct</td>
<td>Electrified</td>
</tr>
<tr>
<td>Use of 50% of the trash</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Graph
- **Hydrated ethanol production (L/TC)**
- **Sugar production (kg/TC)**
- **Surplus electricity (kWh/TC)**
- **Bagasse sold (kg/TC)**
Results: 1G Basic X Optimized
2nd Generation Ethanol Production

Simulation and technical parameters
Block Flow Diagram: integrated 1st and 2nd generation bioethanol production from sugarcane

1. Sugarcane
   - Cleaning
   - Extraction of sugars
   - Juice treatment
     - Sugarcane juice
   - Bagasse

2. Sugarcane Trash
   - Lignocellulose
     - Combined Heat and Power generation
     - Biogas
     - Unreacted solids
     - Enzymes
     - Cellulignin

3. Pretreatment
   - Filtration
     - Glucose liquor
     - Pentoses
     - Yeast

4. Juice concentration
   - Fermentation
     - Yeast Treatment
     - Centrifugation

5. Distillation and Rectification
   - Dehydration
     - Anhydrous Ethanol

6. Biodigestion
   - Alternatives for pentose use
Simulation

- Integrated 1G2G
- Aspen Plus
Integrated 1G2G - convergence

1G Process

2G Process

Cogeneration

Solid residues

Surplus bagasse and trash

Bagasse

Trash

Steam

Sugars

Concentration, Fermentation e Purification

Ethanol

Steam demand of the process

Calculation of the available LM

Calculation of the generated steam

Iterative calculation until generated energy = process demand
## Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarcane bagasse/trash – cellulose content (dry basis) (%)</td>
<td>40.7</td>
</tr>
<tr>
<td>– hemicellulose content (dry basis) (%)</td>
<td>26.5</td>
</tr>
<tr>
<td>– lignin content (dry basis) (%)</td>
<td>21.9</td>
</tr>
<tr>
<td>Steam explosion – hemicellulose conversion (%)</td>
<td>70</td>
</tr>
<tr>
<td>– cellulose conversion (%)</td>
<td>2</td>
</tr>
<tr>
<td>Enzymatic hydrolysis – cellulose conversion (%)</td>
<td>70</td>
</tr>
<tr>
<td>– solids loading</td>
<td>15</td>
</tr>
<tr>
<td>Pentoses biodigestion – COD removal (%)</td>
<td>70</td>
</tr>
<tr>
<td>Pentoses fermentation to ethanol conversion (%)</td>
<td>80</td>
</tr>
</tbody>
</table>
2nd Generation Ethanol Production

Investment and technical-economic results
Investment - 2G plant

- US$ 76 million – 462,451\(^{(1)}\) t bagasse/year (US$ 326/t dry bagasse)
- Pentoses biodigestion\(^{(2)}\): US$ 13 million for processing 76,000 Nm\(^3\) biogas/day

Enzyme Costs:
- Future technology: US$ 0.05/L cellulosic ethanol (CTBE estimate)

Investment calculation as a function of equipment capacity (steam flow, bagasse processed on hydrolysis, biogas produced, etc):

\[
Cost_2 = Cost_1 \left( \frac{Capacity_2}{Capacity_1} \right)^{0.6}
\]

\(^{(1)}\) Bioetanol combustível: uma oportunidade para o Brasil, CGEE, 2009
\(^{(2)}\) Dedini – turn key stillage biodigestion unit
Results: 1G 2G

1. Optimized 1G
2. 1G + 2G, pentose biodigestion
3. 1G + 2G, pentose fermentation

Production

- Ethanol
- Electricity

Investment (mi US$)

- Surplus electricity (KWh/TC)

IRR (per year)

Ethanol production cost (US$/L)
2\textsuperscript{nd} Generation Ethanol Production

Comparison between integrated 1G2G and stand-alone 2G
Comparison Between 1G, Integrated 1G+2G and Stand-alone 2G

1G: optimized with electricity maximization

1G2G: integrated process with future hydrolysis technology and pentose fermentation

1G-LM: 1G unit producing surplus Lignocellulosic material

2G: stand-alone 2G with future hydrolysis technology and pentose fermentation
Environmental impacts in ethanol production using CML method

ADP: Abiotic depletion; AP: Acidification; EP: Eutrophication; GWP: Global warming; ODP: Ozone layer depletion; HTP: Human toxicity; FWAET: Fresh water aquatic ecotoxicity; MAET: Marine aquatic ecotoxicity; TET: Terrestrial ecotoxicity; POP: Photochemical oxidation
Single Score

### Characterization
- Express all flows in the inventory related to an impact category in terms of indicators.

### Normalization
- The results of each category are divided by a reference (for a region, country, etc).
- Support to results interpretation.

### Weighting
- Impact category results are multiplied by weighting factors, and are added to create a total or single score.
Environmental impacts in ethanol production using ReCiPe method (Single Score)
Harvest Extension Using Sweet Sorghum

Technical-economic results
Harvest Extension Using Sweet Sorghum

1G scenarios with harvest extension (60 days operating with sweet sorghum\(^a\)):

1. 125 kg TRS/t sorghum, overall yield of 78\(^b\)
2. 137 kg TRS/t sorghum, overall yield of 81\(^b\)
3. 150 kg TRS/t sorghum, overall yield of 83\(^b\)

\(^a\) Sorghum price proportional to sugarcane on a TRS basis (152 kg TRS/TC)
\(^b\) Ethanol from sugarcane processing yield (extraction, juice treatment, fermentation and distillation): 83%
Conclusions:
Why is Brazil a Favorable Environment for 2\textsuperscript{nd} Generation Ethanol Production?

- Country presents a successful experience for ethanol production;
- Flexibility of the sugarcane biorefinery;
- Possibility of increasing revenues through harvest extension using sweet sorghum;
- Lignocellulosic material available at the plant site;
- Technology improvement will make 2\textsuperscript{nd} generation ethanol more profitable than bioelectricity;
- Possibility of integrating 1\textsuperscript{st} and 2\textsuperscript{nd} generation ethanol production – lower investment;
- Possibility of producing ethanol with the same sugar production (kg sugar/TC) through integration of 2\textsuperscript{nd} generation ethanol in the sugar mill.
Looking for the Right Scenarios

“How do you want it – the crystal mumbo-jumbo or statistical probability model?”

“Careful Joe, it could be a computer simulation.”

Better to have a Good Guess than no information!!!
THANK YOU!
(antonio.bonomi@bioetanol.org.br)

VSB Team:

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Rubens Maciel Filho
Tassia L. Junqueira
Terezinha F. Cardoso

Edvaldo R. Morais
Elmer C. Rivera
Isabelle L. M. Sampaio
Marcelo Zaiat
Nathalie Sanghikian
Mylene C. A. F. Rezende
Vera L. R. Gouveia