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Abstract

Biomass Refinery is a sequential of eleven thermochemical processes and one biological process with two initial basic treatments: prehydrolysis for lignocellulosics and low temperature conversion for biomass with medium-to-high content of lipids and proteins. The other ten processes are: effluent treatment plant, furfural plant, biodiesel plant, cellulignin dryer, calcination, fluidized bed boiler, autothermal reforming of cellulignin for syngas production, combined cycle of two-stroke low-speed engine or syngas turbine with fluidized bed boiler heat recovery, GTL technologies and ethanol from cellulose, prehydrolysate and syngas. Any kind of biomass such as wood, agricultural residues, municipal solid waste, seeds, cakes, sludges, excrements and used tires can be processed at the Biomass Refinery. Twelve basic products are generated such as cellulignin, animal feed, electric energy, fuels (ethanol, crude oil, biodiesel, char), petrochemical substitutes, some materials (ash, gypsum, fertilizers, silica, carbon black) and hydrogen. The technology is clean with recovery of energy and reuse of water, acid and effluents. Based on a holistic integration of various disciplines Biomass Refinery maximizes the simultaneous production of food, electric energy, liquid fuels and chemical products and some materials, achieving a competitive position with conventional and fossil fuel technologies, as well as payment capacity for biomass production. Biomass Refinery has a technical economical capability to complement the depletion of the conventional petroleum sources and to capture its GHGs resulting a biomass + petroleum “green” combination.

KEYWORDS: biomass refinery, acidic prehydrolysis, low temperature conversion, autothermal reforming, thermoelectric power plant
INTRODUCTION

Biomass can be grouped in two types each one treated by a specific process: lignocellulosic with polymeric nature treated by a diluted acidic prehydrolysis process (PH) generating a solid (cellulignin) and a sugar solution (prehydrolysate). Biomass with medium-to-high content of lipids and proteins with oleaginous nature is treated by low-temperature conversion (LTC) technology generating oil, char, non-condensable gases and water. Those processes form the basis for a new concept of biomass processing facility called Biomass Refinery (BR), which is a sequence of eleven thermochemical and one biological process generating fuels, electric energy, synthetic and inorganic products.

This paper will show that BR has technical, economical and political capabilities to complement the future petroleum shortage and to capture its Greenhouse Gases (GHGs) into a combination of biomass + petroleum ‘green’. Extension of this concept for CO₂ sequestration from mineral coal is more complex than for petroleum.

BIOMASS REFINERY MATRIX

The BR concept is shown in Fig.1. It comprises biomass production and processing technologies generating basic products. The main lignocellulosic biomasses are wood and its residues, sugarcane bagasse and trash, agricultural residues, grass, municipal solid waste, and macro algae. The main oleaginous biomasses are swine/poultry/cattle excrement, grease and sludge from slaughter houses, bran and cakes from seeds, nuts and coconuts, used tires, organic sludge and micro algae. BR stimulates polycultures, food and feed production. The natural biomass production is a minimum of 10% oleaginous and a maximum of 90% of lignocellulosics.

Lignocellulosic biomass is prehydrolyzed in acidic conditions under moderate pressure and temperature originating a prehydrolysate (C₅ + C₆ sugars solution) and a solid called cellulignin. Prehydrolysate (Ph) is dehydrated to furfural or fermented to ethanol. Cellulignin (CL) is the main product with several applications: (a) in granules, pellets, briquettes or powder, it is a commodity that replaces coal, fuel oil, natural gas; (b) as animal feed additive due to its 58% digestibility (as total digestive nutrient); (c) as silica obtained from CL calcination of hydrolyzed rice rusk and bamboo; (d) as treated biomass for enzymatic hydrolysis for second generation ethanol; (e) as treated biomass for syngas production by autothermal reforming. Syngas has many applications, for example, as a fuel for internal engine combustion or gas turbine; for H₂ extraction with or without water shift; for production of ammonia, urea, methanol and synthetic...
products by gas-to-liquid (GTL) Fischer-Tropsch technology; for production of the third generation ethanol by syngas fermentation with Clostridium species.

Oleaginous biomass is converted by LTC into oil, char, non-condensable gases (NCG) and water. LTC-oil is used as a fuel or is hydroesterified to biodiesel. Char is used as a fuel or as medium aggregated value products (metallurgical coal, molecular sieves or recovered carbon black from used tires), and NCG are burned for process thermal energy.

Overall, BR generates seven types of fuels or chemical products (CL, furfural, ethanol, oils, chars, synthetic fuels and chemicals), electric energy and four inorganic products (gypsum with P + K, ash from boiler with P + K, silica, silicates and silicon in the future). Each BR will optimize the number and amount of products to be generated.

**BATCH-TYPE PREHYDROLYSIS REACTOR**

The first cracking of lignocellulosic biomass is carried out by the PH generating CL with molecular porosity and Ph (C5 + C6 sugars syrup) used for furfural or ethanol production. The discharge of the Ph is by depressurization into a flash tank that separates the furfural fraction formed during PH.

Two sizes of PH reactor were developed 30m$^3$ (90 TDB$^1$/d) and 180 m$^3$ (540 TDB/d) (Fig. 2a). Optimization of biomass collection, operation and cost reduction recommend installation of BR in three sizes, i.e., small (270TDB/d–25 MW), medium (810TDB/d–75 MW) and large (1,620 TDB/d–150 MW); 2/3 of the biomass is prehydrolyzed and 1/3 is burned in the recovery boiler as supplemental fuel aiming radiant heat transference.

PH reactors are made of carbon steel lined with titanium sheet by a fail safety patented technology (Pinatti et al,2005a)(Pinatti,2005b)(Pinatti,2007). Reactors are batch-type operating at 2% H$_2$SO$_4$, 0.8 MPa, 170°C, lasting 1.5 h per reaction yielding up to 16 batches/day.

The operation of PH is coupled with a set of tanks, pipes, pumps and valves (called Reuse) that recycle water, acid solution and Ph resulting a process with low liquid-to-solid ratio (L/S = 2). The effluent of Ph utilization and water from the CL washing are sent to an effluent treatment station for neutralization with Ca(OH)$_2$, flocculation, precipitation, flotation and dewatering of the gypsum that contains K + P, which is recycled to the biomass production. Treated water is recycled to the PH process.

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$^1$ TDB = metric ton of dry biomass
Figure 1. PROBEM™ Biomass – Energy – Materials Program Matrix – Biomass Refinery
Figure 2. (a) Prehydrolysis reactor and (b) LTC reactor (Pinatti et al., 2005a) (Pinatti, 2005b) (Pinatti, 2007) (Pinatti et al, 2008).
SYNGAS PRODUCTION: AUTOTHERMAL REFORMING OF CELLULIGNIN

After washing CL is rotary dried, milled down to a particle size of 150 \( \mu \text{m} \) and syngas is produced in a flame of a simple CL powder torch (Fig. 2a) using 95%-purity \( \text{O}_2 \) as oxidant in a proportion of 0.41 \( t\text{O}_2/t\text{CL} \) and at a temperature of 420\(^\circ\)C in the reaction chamber (outside the flame). After reaction syngas is cooled in a flametubular boiler and cleaned in a sequence of multi-cyclone, sleeve filter, washing tower, and compressed at 25 MPa for injection into a two-stroke low-speed engine (TSLSE). The energy of formed gas is 93%, and the total recovered energy is 98%. The main data for autothermal reforming (ATR) of CL such as chemical equation, mass balance, combustion equation and equivalence ratio are given below. Syngas composition and impurity limits for typical applications are given in Table 1.

Autothermal reforming equation

\[
C_{4.49}H_{6.12}O_{2.35} + 1.3393 \text{O}_2 + 0.3850 \text{H}_2\text{O} \Rightarrow 2.6789 \text{H}_2 + 2.9582 \text{CO} + 1.1510 \text{CO}_2 + 0.2922 \text{CH}_4 + 0.00072 \text{C}_2\text{H}_6 + 0.0553 \text{C}_3\text{H}_8
\]  

(1)

Mass balance

\[
\text{O}_2/\text{CL}: \ 1.00 \ t \text{CL} + 0.41 \ t\text{O}_2 \Rightarrow 1.41 \ t \text{syngas}
\]  

(2)

Consumption of \( \text{O}_2 \): 315.3846 Nm\(^3\)/t CL

Combustion equation

\[
C_{4.49}H_{6.12}O_{2.35} + 0.3850 \text{H}_2\text{O} + 4.845 \text{O}_2 \Rightarrow 4.49 \text{CO}_2 + 6.12/2 \text{H}_2\text{O} + 0.385 \text{H}_2\text{O}
\]  

(3)

Equivalence ratio: \( 1.3393/4.845 = 0.2764 = 27.64\% \)  

(4)
Table 1. Syngas characteristics and specifications for some applications

<table>
<thead>
<tr>
<th>Syngas Characteristics</th>
<th>H₂</th>
<th>CO</th>
<th>CO₂</th>
<th>CH₄</th>
<th>C₂H₆</th>
<th>C₃H₈</th>
<th>N₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Volume, m³/kg</td>
<td>12.297</td>
<td>0.884</td>
<td>0.563</td>
<td>1.542</td>
<td>0.808</td>
<td>0.556</td>
<td>0.885</td>
</tr>
<tr>
<td>HHV*, kcal/kg</td>
<td>34,187</td>
<td>2,418</td>
<td>0.00</td>
<td>13,319</td>
<td>12,446</td>
<td>12,066</td>
<td>0.00</td>
</tr>
<tr>
<td>Syngas O₂/CL</td>
<td>100.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conc. (%v/v)</td>
<td>37.31</td>
<td>41.20</td>
<td>16.03</td>
<td>4.07</td>
<td>0.01</td>
<td>0.77</td>
<td>0.61</td>
</tr>
<tr>
<td>Specific Mass</td>
<td>0.8284kg/Nm³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HHV 2,684 kcal/Nm³ (11.2 MJ/Nm³)</td>
<td>1,037</td>
<td>1,127</td>
<td>0.00</td>
<td>352</td>
<td>1.5</td>
<td>167.1</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Specifications for Syngas Applications (Gurgel, 2008)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unity</th>
<th>Motors</th>
<th>Gas Turbine</th>
<th>Methanol Synthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Value</td>
<td>MJ/Nm³</td>
<td>4 - 6¹</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>°C</td>
<td>low</td>
<td>450 – 600</td>
<td></td>
</tr>
<tr>
<td>Particles</td>
<td>mg/Nm³</td>
<td>&lt; 50</td>
<td>&lt; 30</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>Particle Size</td>
<td>μm</td>
<td>&lt; 10</td>
<td>&lt; 5</td>
<td></td>
</tr>
<tr>
<td>Tar</td>
<td>mg/Nm³</td>
<td>&lt; 100</td>
<td>0 or steam</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Alkaline Metals</td>
<td>ppb</td>
<td>n.a.</td>
<td>20 – 1000</td>
<td></td>
</tr>
<tr>
<td>NH₃</td>
<td>mg/Nm³</td>
<td>n.l.</td>
<td>n.l.</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>HCl</td>
<td>mg/Nm³</td>
<td>&lt; 1</td>
<td>&lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>Sulfonated Compounds (H₂S; COS)</td>
<td>mg/Nm³</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>% vol</td>
<td>n.l.</td>
<td>n.l.</td>
<td>&lt; 12 (n.l.)</td>
</tr>
</tbody>
</table>

HHV = High Heating Value
n.a = not applied
¹For HHV = 11.2 MJ/Nm³ limit of impurities is 2 to 3 times larger
n.l. = not limiting

Data on K, Na, Cl and ash content for *Eucalyptus grandis* and its CL show a reduction factor of 12.7 on the K + Na content (Table 2). Further reduction will take place in the syngas generation (factor of 1.41), multi-cyclone (factor of 5), sleeve filter (factor of 10) and washing tower (factor of 5). Final content of K + Na in the syngas would be 128 ppb.² That content is lower than the requirements for motors and close to the ones for gas turbines. CL syngas has negligible amount of tar because resinous precursors, such as furfural, are cleaned during prehydrolysis and the equivalence ratio is above the tar formation range (Reed, 1998).

Table 2. K, Na, S, Cl and ash content of raw biomass and its cellulignin

<table>
<thead>
<tr>
<th></th>
<th>K</th>
<th>Na</th>
<th>S</th>
<th>Cl</th>
<th>% Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw biomass</td>
<td>490</td>
<td>80</td>
<td>200</td>
<td>80</td>
<td>0.34</td>
</tr>
<tr>
<td>Non washed CL</td>
<td>220</td>
<td>50</td>
<td>1,400</td>
<td>40</td>
<td>0.25</td>
</tr>
<tr>
<td>After first hammered</td>
<td>30</td>
<td>15</td>
<td>600</td>
<td>20</td>
<td>0.23</td>
</tr>
</tbody>
</table>

² Final (K+Na) in syngas: (490 + 80)/(12.7 x 1.41 x 5 x 10 x 5) = 128 x 10⁻³ mg/kg = 128 ppb
Syngas has four applications: electric energy generation by combined cycle using a dual-fuel TSLSE (MAN, 2008) or gas turbine (GE Energy, 2010); synthesis of fuels and chemical products by GTL after H₂ enrichment for H₂/CO ratio=2 (NETL, 2007a); H₂ generation by extraction or water shift reaction (Miller, 2004)(NETL, 2007b); ethanol production by fermentation of syngas with *Clostridium carboxidivorans* (Coskata, 2010) or with *Clostridium ljungdahlii* (Ineos Bio, 2010). Besides ethanol production from Ph and syngas, there is a third route through enzymatic hydrolysis of CL plus fermentation (Verenium, 2010).

BR has the choice to adjust syngas application among electric energy, hydrogen and ethanol production as a function of the market demands and to add GTL when oil price increases. The last option is the only one that demands further syngas purification and use of catalysts.

Hydrogen extraction is carried out by pressure swing adsorption (PSA), with or without selective surface flow membrane (Sircar et al, 1999). Table 3 shows an example of calculation for the possible maximum H₂ extraction of syngas. Up to 22% v/v extraction there is a compensation of the energy and volume reductions in such a way that the HHV remains practically constant. The final content of H₂ is 19.63% v/v. This value coincides with the fact that, by PSA, it is very difficult to achieve contents lower than 20% v/v in the waste syngas. For the large BR capacity, the maximum H₂ extraction represents 26.3 tH₂/d (8,679 t H₂/y) and preliminary studies indicate that the H₂ market in the area of influence of the BR is much lower than the above volume. In practice, the extraction will be lower than 22% v/v and H₂ content will be higher than 20% in the waste syngas.

<table>
<thead>
<tr>
<th>Components</th>
<th>H₂</th>
<th>CO</th>
<th>CO₂</th>
<th>CH₄</th>
<th>C₂H₆</th>
<th>C₃H₈</th>
<th>N₂</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial syngas, % v/v</td>
<td>37.31</td>
<td>41.20</td>
<td>16.03</td>
<td>4.07</td>
<td>0.01</td>
<td>0.77</td>
<td>0.61</td>
<td>100</td>
</tr>
<tr>
<td>22% v/v H₂ extraction, % v/v</td>
<td>15.31</td>
<td>41.20</td>
<td>16.03</td>
<td>4.07</td>
<td>0.01</td>
<td>0.77</td>
<td>0.61</td>
<td>78%</td>
</tr>
<tr>
<td>Renormalization of final syngas, % v/v</td>
<td>19.63</td>
<td>52.82</td>
<td>20.55</td>
<td>5.22</td>
<td>0.01</td>
<td>0.99</td>
<td>0.78</td>
<td>100%</td>
</tr>
<tr>
<td>Final syngas HHV, kcal/Nm³ (MJ/Nm³)</td>
<td>545.74</td>
<td>1,444.78</td>
<td>0.00</td>
<td>450.88</td>
<td>1.54</td>
<td>214.84</td>
<td>0.00</td>
<td>2,658 (11.11)</td>
</tr>
</tbody>
</table>

**LOW TEMPERATURE CONVERSION REACTOR**

LTC batch-type reactor is manufactured in five sizes (40 TDB/d to 200 TBD/d), in multiples of 24 up to 120 tubes made of stainless steel 310 (Fig. 2b). It is composed of a thermally isolated body that contains the tubes, a support allowing
tilting for discharge of char, hot gas inlet and outlet for heating and cold gas cooling, outlet of oil vapor and NCG, top lid with rails for opening the reactor and mill hopper for raw material feeding (Pinatti et al, 2008). The reactions are hermetic in the absence of oxygen and raw materials are dried below 10% humidity using as fuel the hot gas generated in the process. The entire cycle lasts 8 hours (3 batches/d) and follows the sequence: charging, heating, reaction (2.5-hour period), cooling and discharging. After condensation, the oil is stored in tanks, and NCG are burned in the fluidized bed boiler (FBB) of the combined cycle thermoelectric unit (CCTEU), and in the future, in the TSLSE.

The oil has a large fraction of olefinic compounds (≈90%) and can be hydroesterified to biodiesel (Sales, 2007). Char is similar to wood charcoal but with a medium-to-high content of ash recommended being burned in FBB at 850 °C, recovering K + P in the ash for fertilizer application. Together with K + P in the gypsum of PH effluent neutralization, 90% of these nutrients are recycled to biomass growth.

Research is under way in synthetic ammonia production with plasma torch using N₂ from O₂ production and H₂ from syngas extraction aiming to give sustainability of NPK fertilizer to the biomass growth.

**TWO-STROKE LOW-SPEED ENGINE**

Gas turbine and TSLSE are used to drive electric energy generators. The first is fueled by purified syngas from lignocellulosic biomass. The TSLSE used in marine propulsion is ideal to drive electric energy generators using fuels derived from biomass for the following reasons: (a) it operates with dual fuel with a minimum of 8% of oil of the total power and a maximum of 92% of syngas of HHV as low as 11.2 MJ/Nm³ (this combination can be provided by the LTC-oil and the CL-syngas); conventional gasification of biomass (HHV from 3 to 5 MJ/Nm³) can not be used in TSLSE; (b) it does not demand extensive syngas and oil purification; (c) it has higher single cycle efficiency (47%) than steam and gas turbine (27% to 40%), although, for the first generation of BR, a lower efficiency (36%) is admitted; (d) the low oil/syngas proportion of dual fuel matches the low oleaginous/lignocellulosic biomass ratio generated in nature. The use of oleaginous contributes for cleaning of various pollutants as described in the Biomass Refinery Matrix item.

TSLSE has piston diameters from 350 to 980 mm with corresponding powers from 3.5 MW to 80 MW in single cycle. Dual-fuel operation is possible for diameters above 500 mm. It is always possible to design combined cycle with modular sizes of PH reactor, LTC, TSLSE and FBB to cover powers from 25 to 150 MW per set. Examples of liquid and gaseous fuels burned by LSTSE are shown in Table 4.
Gas turbine will be used in a second generation of BR when the economics of syngas purification is improved and for larger power CCTEU. The fact that CL, oil and char can be produced close to biomass production sites and transported to a centralized CCTEU allows gigawatt biomass power plants. In Brazil, those plants should be located close to hydroelectric power plants to optimize generation, transmission and also reversible hydro, not yet explored in the Brazilian electric system.

Table 4. Examples of liquid and gaseous fuels burned by LSTSE

<table>
<thead>
<tr>
<th>Characteristics and Composition</th>
<th>Liquid</th>
<th>Gaseous</th>
<th>Fuel Types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diesel</td>
<td>ISO RMF</td>
<td>ISO RMH</td>
</tr>
<tr>
<td>Viscosity, cSt/50°C</td>
<td>2.27</td>
<td>198</td>
<td>700</td>
</tr>
<tr>
<td>Density at 15°C, kg/m³</td>
<td>843</td>
<td>938</td>
<td>991</td>
</tr>
<tr>
<td>Flash Point, °C</td>
<td>65</td>
<td>100</td>
<td>≥60</td>
</tr>
<tr>
<td>Pour Point, °C</td>
<td>-</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>Conradson Carbon, wt %</td>
<td>0.01</td>
<td>9.4</td>
<td>22</td>
</tr>
<tr>
<td>Carbon Residue, % m/m</td>
<td>-</td>
<td>-</td>
<td>22</td>
</tr>
<tr>
<td>Asphalt, wt %</td>
<td>0</td>
<td>3.7</td>
<td>14</td>
</tr>
<tr>
<td>S, wt %</td>
<td>0.22</td>
<td>0.83</td>
<td>5</td>
</tr>
<tr>
<td>Water, wt %</td>
<td>0</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>Total Sediment after Aging, % m/m</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Ash, wt %</td>
<td>0</td>
<td>0.03</td>
<td>0.2</td>
</tr>
<tr>
<td>Al, mg/kg</td>
<td>-</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>Al + Si, mg/kg</td>
<td>-</td>
<td>-</td>
<td>80</td>
</tr>
<tr>
<td>V, mg/kg</td>
<td>0</td>
<td>12</td>
<td>600</td>
</tr>
<tr>
<td>Na, mg/kg</td>
<td>0</td>
<td>25</td>
<td>30% of V</td>
</tr>
<tr>
<td>CCAI</td>
<td>805</td>
<td>807</td>
<td>-</td>
</tr>
<tr>
<td>LHV, kcal/kg</td>
<td>8.620</td>
<td>8,890</td>
<td>9,550</td>
</tr>
</tbody>
</table>

* Designation types according to ISO 8217/CI MAC (ISO, 2005)

Fig. 3 shows the flow chart, mass and energy balance for a large BR (143.78 MW) dedicated to electric energy generation and processing organic matter of municipal solid waste and sewage sludge of a city of 2.5 million inhabitants. The total biomass consumption is 721.83 TDB/reaction
(90.23 TDB/h) resulting a biomass energy rate of 0.63 TDB/MWh\(^3\) equivalent to 1.26 t/MWh of biomass with 50% humidity. Considering an equivalent HHV = 1,800 kcal/kg for wet biomass, the combined cycle efficiency is 38% (2.62 MW\(_i\)/MW\(_e\))\(^4\) including all the heat for drying the sludge and CL. For wood and animal excrement efficiencies are higher than 44% and if 47% efficiency is admitted for LSTSE, combined cycle efficiency will be 55%.

The investment cost for BR of figure 3 is USD 200 million (USD 1,400.00/kW); annual capital and operational cost are USD 74 million, and annual income is USD 80 million (USD 70/MWh, 7,920h/y) resulting an internal rate of return of 15% including all Brazilian taxes. If intermediate products are chosen they are competitive with commercial commodities, such as (a) USD 3.00/MBTU for CL resulting a USD 3.50/MBTU for syngas, compared with USD 7.50/MBTU for natural gas; (b) USD 12.30/MBTU for LTC-oil (HHV=9,060 kcal/kg) compared with USD 14.20/MBTU for petroleum fuel oil (HHV=9,750 kcal/kg); (c) USD 2.00/MBTU for LTC-char (HHV=6,700 kcal/kg) compared with USD 4.60/MBTU for Brazilian steam grade mineral coal (HHV=4,500 kcal/kg); (d) USD 2.00/kg of H\(_2\) similar to H\(_2\) from mineral coal; (e) USD 70.00/MWh for both electric energy generated by BR and hydroelectricity; (f) USD 350.00/t for both NPK fertilizer generated by BR and mineral sources. Municipal solid waste and sewage sludge are the only biomasses that pay a disposition fee of USD 20.00/t (wet) and BR has a payment capacity of USD 30.00/TDB for all other biomasses.

COMPLEMENTARITIES OF BIOMASS AND PETROLEUM REFINERIES

It is instructive to compare both refineries identifying their complementarities instead of a substitutional competition approach.

(1) BR has 12 unit operations generating 12 types of products (Fig. 1). For petroleum refinery (PR), the unitary operations are also 12: atmospheric column; saturate gas plant; isomerization; hydrotreating (nafta, light distillate, heavy distillate, gas oil); nafta reforming; catalytic cracking and alkylation; vacuum column; delayed coking; visbreaking; solvent; hydrocraking and thermoelectric energy generation unit (TEU). The PR twelve products are sulfur, fuel gas, liquefied petroleum gas, gasoline to aromatics, kerosene, jet fuels, diesel and heating oils, lube oils, coke, heavy fuel oil #6, asphalt and electric energy (Self et al, 2000). Materials are generated in the petrochemical factory.

\(^3\) Biomass energy rate: 90.23 TDB per h / 143.78 MW = 0.63 TDB/MWh

\(^4\) Efficiency = (2 x 90.23 TDB/h x 1,800 kcal/kg)/143.78 MW\(_e\) = 377.16/143.78 = 2.62MW\(_i\)/MW\(_e\)
Figure 3. Flow chart, mass and energy balance of the Biomass Refinery using organic municipal solid waste and sewage sludge maximized for electric energy generation (reactions over 8-hour period).
(2) Similar to PR, BR will be developed in several generations. In the first, topping cycle in the TEU will be a LSTSE (lower cost, higher efficiency) with a desired dependence on oleaginous biomass production (pollution cleaning by LTC and incentive to food and feed production). The second generation demands syngas purification; the topping cycle will be a gas turbine and GTL will generate substitutives for petrochemical products. The first generation will prevail in tropical countries (underdeveloped and developing), and the second generation will prevail in temperate countries (developed).

(3) Both refineries generate three classes of products (fuels, chemicals and materials) but BR generates also inorganic products. With the increase of oil price, the tendency is the PR to shift from fuels to materials products opening space for BR fuels (ethanol and H₃ replacing gasoline, biodiesel and H₂ replacing diesel and cellulignin replacing fuel oil).

(4) In tropical countries, biomass grows 10 times faster than in temperate countries. The two reactors, PH and LTC of BR, with small size electric cogeneration, are installed close to the biomass production and the products (CL, oil, char and ethanol) are transported to medium-to-large distances including overseas exportation. The remainder of BR can be installed in the final consumption sites. CL from PH has LHV = 18.4 MJ/kg. Specific mass of pellets and briquettes is 1,250 kg/m³ (easy to be compressed due to the low mechanical strength given by the CL molecular porosity). Its energetic density of 23 GJ/m³ equals to the mineral coal (average of 22 GJ/m³, LHV=28 MJ/kg, 790 kg/m³), and is 62% of the petroleum (37 GJ/m³, LHV=42.5 MJ/kg, 877 kg/m³). It can be shipped worldwide using the same infrastructure of agricultural grains during the off-crop season; it is clean and ready to be burned, ground and converted into syngas at the consumption sites.

(5) World emission of CO₂ in billions of t/y is: 49 (in 2009), 61 (in 2020 if nothing is done) and 44 (in 2020 if a reduction of 17 is achieved in order to avoid two degrees Celsius heating) (McKinsey, 2009). That reduction represents in billions of t/y: 4.64 of carbon, 8.4 of CL (55.2% C), 10.5 DB (80% CL), which are produced in 262.5 million ha (40 TDB/ha.y in short rotation eucalyptus species, elephant grass, etc.). This represents an area of 2,625,000 km² easily available in tropical countries. Even if the productivity is lower, the resulting area is considered small. The energy of the CL is 8.4 x 10⁹ tCL/y (154.6 x 10⁹ GJ/y)⁵ that is 84% of the energy of the present consumption of petroleum of

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⁵ Energy of the CL: 8.4 x 10^9 ton CL/y x 18.4 MJ/kg = 154.6 x 10^9 GJ/y
85 million barrel (mb)/d (183.9 x 10^9 GJ/y). In 2030, the expected world demand will be of 106 mb/d. Production of the existing fields will be of 31 mb/d (IEA, 2008). The supplying of the difference (75 mb/d) depends on the incorporation of new reserves at higher costs and higher emission of GHGs. The energy difference of 162.3 x 10^9 GJ/y\(^7\) is practically identical to the energy figures generated by CL, which is cheaper than the new petroleum reserves, does not contribute to GHGs and will fix CO\(_2\) in the forest cover of the area indicated above.

(6) Obviously the CO\(_2\) sequestration and the future energy shortage of petroleum will not be covered just by CL of BR; other forms of energy will give their contribution (other forms of biomass, eolic and photovoltaic energy). The above figures show that CL of BR offers a real and immediate technical economic solution to GHG emissions and to petroleum energy world problems. Furthermore, it respects the political interests of tropical (large producers) and temperate (large consumers) countries as well as the integration with and completion of PR.

(7) Compensation of total CO\(_2\) emissions (44 billion t/y) is technically and economically possible but more difficult because of the following reasons: the volume involved is 2.6 larger;\(^8\) coal reserves are large without possibility of reduction of consumption up to 2030; the largest reserves of coal situate in USA, China and India where substitution and sequestration (photovoltaic energy, CO\(_2\) burial in exhausted natural gas and oil wells, for example) are more complex than biomass technology. Costs of biomass energy are of the same order as petroleum, but costs of mineral coal are much lower than both.

(8) Today’s world production of H\(_2\) is 50 million t/y to meet the following industrial applications: metallurgical and thermal treatment, refining and petrochemical industry, chemical and pharmaceutical industry, lubricating oil, fat and oil production, food technology, hydrogen peroxide production, glass and flat glass manufacturing, electronic industry and polysilicon process in the photovoltaic industry (Mahler, 2010). That amount is enough to fuel 250 million fuel cell cars (200 kg H\(_2\)/car.y, 72 km/kg H\(_2\), 14,400 km/car.y). Those 10.5x10^9 TDB/y of item 5 above would demand 29,742 large BRs.\(^9\) Extraction of only 5.1 tH\(_2\)/d per large BR is enough to produce the above 50 million tH\(_2\)/y, a

\(^6\) Present consumption of petroleum: 85 million barrel/d x 365 d x 159 L/barrel x 0.877 kg/L x x 42.5 MJ/kg = 183.9 x 10^9 GJ/y
\(^7\) Energy difference: (75/85) x 183.9 x 10^9 GJ/y = 162.3 x 10^9 GJ/y
\(^8\) 44/17 = 2.6
\(^9\) (10.5 x 10^9 TDB/y) / (1,080 TDB/d x 330 d/y) = 29,742 large BRs
feasible task for the present PSA H₂ extraction technology from syngas since H₂ represents just 4.3% v/v of the initial syngas.¹⁰ This shows that BR has a large capacity to generate H₂ with the advantage of the distributed generation avoiding complex logistic of the centralized production of H₂ by PR + natural gas.

CONCLUSION

Most technologies employed by the BR are thermochemical, electrical, materials science processes, and just for ethanol a biological process is applied. Optimization of processes, equipments, biomass and food production are the key issues to pay the cost of biomass production and make renewable resources competitive with fossil resources. BR is a holistic integration of various technologies and follows the path of the PR that is the most successful holistic approach ever developed in the world. The first two technologies of BR (PH and LTC) and ethanol production are specific for biomass; the others are common to petroleum or coal technologies but with less pollution and zero contribution to GHG. In fact, BR has the capability to solve major world problems, such as to stimulate food and feed production and polycultures instead of the present practice of monoculture; to create payment capacity to establish massive reforestation and certified exploration of native forest in tropical countries owing to the growth rate 10 times faster than in temperate countries; to promote large capacity of GHGs abatement by carbon fixation in the forest cover in tropical areas and to accomplish partial replacement of electric energy, fuels, chemical products and hydrogen presently produced from petroleum and natural gas; to promote pollution cleaning by LTC technology; to recycle NPK and micronutrients for fertilizers; to promote employment generation and growth of the world economy.

Some initiatives are under way in different countries complementing the petroleum and coal activities such as ethanol from corn/lignocellulose and H₂/electric energy from coal with CO₂ sequestration, in USA; ethanol from sugarcane, biodiesel from oleaginous and hydroelectricity, in Brazil; eolic and photovoltaic energy and biodiesel from rape seed (colza), in Europe; petroleum substitutes from coal in South Africa; materials from petroleum and coal in China.

In biomass, a tiny activity in wood pellets and briquettes is starting in some countries (Canada, Argentina, Brazil). The real big step in biomass use is going to take place when CL pellets and briquettes begin to be exported from tropical countries to temperate countries, and the first generation of BR is established in various countries. PR was developed during one century, and BR is going to take at least two decades to reach a significant complement to petroleum.

¹⁰ H₂ extraction from syngas = (5.1 / 26.3) x 22% v/v = 4.3% v/v
This period synchronizes with the decline of half of the production of existing fields because unconventional petroleum (sand oil, emulsion, deepwater) is more expensive than BR products and because there is an increasing pressure to avoid the GHG disaster if nothing is done.

If government, technical and company people separate the energy and GHG problems of petroleum from those of the mineral coal it will be technically and economically possible to solve the problem of the first and to plan the solution of the much larger problem of the last.

NOMENCLATURE

**Acronyms**

ATR    autothermal reforming  
BR     biomass refinery  
CCTEU combined cycle thermoelectric unit  
CL   cellulignin  
DB dry biomass  
FBB fluidized bed boiler  
GHG greenhouse gas  
GTL gas-to-liquid  
HHV high heating value  
LHV low heating value  
LTC low temperature conversion  
mb million barrels  
NCG non-condensable gases  
Ph prehydrolysate  
PH prehydrolysis reaction  
PR petroleum refinery  
PSA pressure swing adsorption  
TDB/d (or y) metric ton of dry biomass per day (or year)  
TEU thermoelectric unit  
TSLSE two-stroke low-speed engine  
USD U.S. dollar
REFERENCES

GE Energy,
Miller C. L., “Converting Coal into Gas is Key”, Dec. 2, 2004, presented to Gas Technologies Institute, Chicago,.