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Cogeneration and Bio-Oil Production Starting from Sugarcane Biomass Residues: Barriers, Challenges and Opportunities

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Abstract: There are more than 70 sugar producer countries around the world. Most of them are underdeveloped and poor. Especially for the underdeveloped, 3rd world, the sugarcane residues disposal has first order priority. The lack of an alternative energy carrier to electricity with storage capability for use in off-season has to date been an unsolvable question for the sugar agro-industry. The improvement of cogeneration capacity *via* implementation of more efficient cogeneration systems and the barriers for their implementation were analyzed. A techno-economic assessment was carried out regarding the three most probable scenarios of sugar producer countries today. The biomass availability and high investment costs continue to be the main barriers to overcome in order to produce Bio-oil starting from sugarcane biomass solid residues.

Keywords: Sugarcane residues, pyrolysis, bio-oil.

1. INTRODUCTION

There are more than 70 sugarcane producer countries around the world. Most of them are undeveloped and poor. Since past 20th Century, world's sugarcane production has experimented an increasing growth. The oil prices soaring in the oil world market and the relatively low bioethanol production cost, mainly in Brazil, are the main reasons what explain current growing investors interest on sugarcane industry. Last decade world's sugarcane production trend is showed in the Fig. (**1**).

The introduction of sugarcane mechanized harvesting combined with power cogeneration technological improvements that took place at sugar factories and ethanol distilleries during last two decades of 20th Century have radically changed the viewpoints on sugarcane residues use in the sugarcane agro-industry. Among the main residues from sugar and ethanol production are sugarcane bagasse and sugarcane trash, also named sugarcane agriculture residues (SCAR). Sugarcane bagasse is the fibrous waste that remains after recovery of sugar juice *via* crushing and extraction. It also has been the principal fuel used around the world in the sugarcane agro-industry because of its well-known energy properties [1], [2]. A ton of bagasse (on a 50% mill-wet basis) is equal to 1.6 barrels of fuel oil on energy basis.

The world sugarcane agro-industry processed more than 1.56E+09 tons of sugarcane in 2007. The mentioned amount of sugarcane generated 4.361E+07 tons of bagasse and 3.894E+07 tons of SCAR and this amount of residues could mean about 2.871E+07 tons of oil equivalent. In other words, sugarcane agro-industry produces around of 530 kg of solid residues for each milled ton of cane.

Regrettably, although the SCAR energy content is similar to bagasse [4], [5] in many places it is burned-off just before harvest to facilitate easier harvesting of the cane stalks. In the sugarcane agro-industry is a common practice the energy use of bagasse for cogeneration in season.

A negligible amount of SCAR is currently used for cogeneration. At first glance the solution seems to be the bagasse and SCAR storage, but bagasse storage and handling on a large scale is a very expensive, difficult and risky operation because of the low density and self-combustion properties of both bagasse and SCAR (Fig. **2**). The lack of an alternative energy carrier to electricity with storage capability for use in off-season has to date been an unsolvable question.

The goal of the present work is to review the challenges and barrier that should be overcome to introduce a Bio-oil as an alternative energy carrier to electricity for its use during off-season, and the real possibilities that exist to do this change.

2. BARRIER TO PLANT COGENERATION IMPROVEMENT IMPLEMENTATION (CEST AND BIG/GTCC)

The existing steam supply and power generation at the most of sugar mills produce, as rule, an average of 20-30 kWh per ton of sugarcane in low-efficiency back pressure steam turbines (BPST) that operate at an average pressure of 1.9-2.2 MPa and a temperature of 593 K. In the BPST case, the typical small boiler burns all bagasse that is produced per ton of produced sugar. As a general rule, the most sugar

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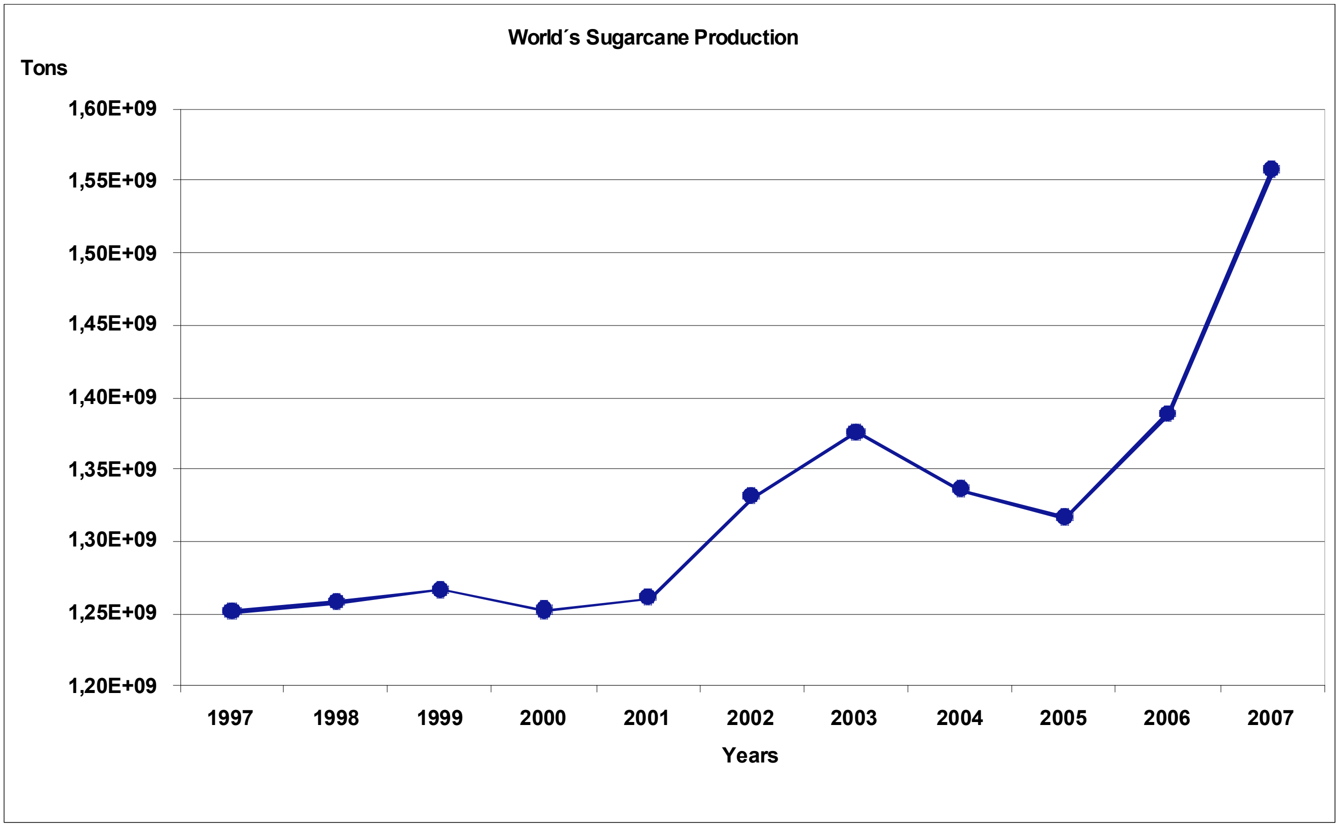

Fig. (1). World's sugarcane production (last decade) [3].

Fig. (2). Sugarcane agricultural residues (SCAR) at sugarcane storage and cleaning center. Photo from Source [15].

mills meet their energy demand, but do not export electricity to the grid.

The co-generated electricity and potential electricity surplus cogeneration per ton of milled sugarcane for a typical mill of 7000 tons of cane/day capacity with BPST, for more efficient standard high pressure and high temperature boilers and Condensing Extraction Steam Turbine cogeneration system (CEST) (Fig. **3**) and for Biomass Integrated-Gasifier /Gas Turbine Combined Cycle

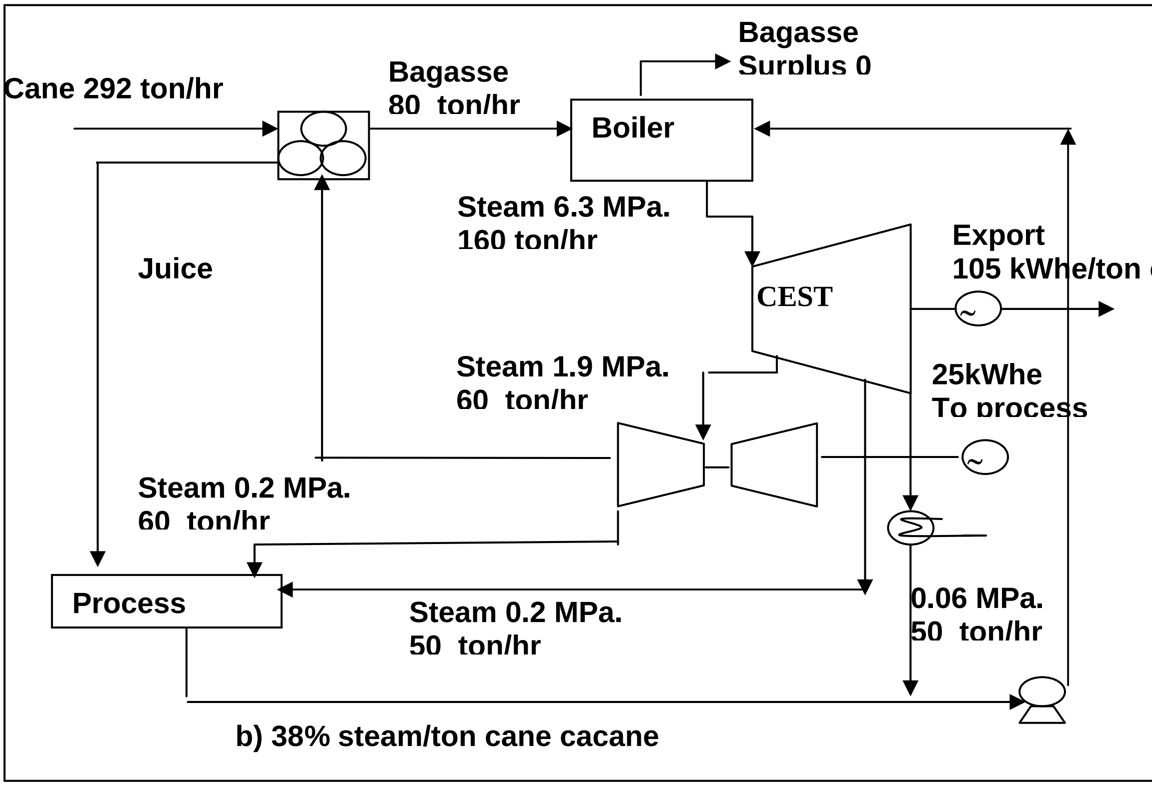

Fig. (3). Sugar mill condensing extraction steam turbine cogeneration system. (380 kg of steam/ton of milled cane).

(BIG/GTCC) were calculated and compared with the energy requirements for milling 1 ton of sugarcane (Table **1**). The results show that the smaller the steam consumption in the process, the bigger the amount of surplus bagasse would be. Nowadays, the average steam consumption figure is 50% of the cane weight and in the immediate future the most probable value of steam savings should reduce this figure to 38%. Corresponding to the last mentioned figure of steam consumption, the BPST could co-generate 29 kWh_e/ton cane and meet the milling electricity requirement; instead a CEST technology at 6.3 MPa could co-generate 130 kWh_e/ton cane to meet the milling energy requirement and export 105 kWh_e/ton cane to the public grid (Table **1**) [6].

The main barrier for the implementation of the above-mentioned advanced cogeneration system remains the cost.

Table 1. Electricity Surplus Cogeneration and Energy Requirement In-Season (1 Ton of Cane) (Milling Capacity 7000 Ton Cane/Day, Milling Season 3800 hr/yr)

Turbogenerator System	BPST 1.9 MPa, 593K (7 Mw)	CEST 4.2 MPa, 693K (38 Mw)	CEST 6.3MPa, 793K (30 Mw)	BIG/GTCC[e] 8.2MPa,793K (52 Mw)
Steam by cane weight[a]	52%	45%	40%	28%
Electric and mechanical consumption kWh_e/ton cane	25			29
Process heat consumption Raw sugar[b] MJ/ton cane	1596	1488	1387	946
Total energy requirement MJ/ton cane	2046	1938	1837	1415
Milling energy requirement to sugarcane energy content ratio[c] %	97	92	87	70
Electricity cogenerate kWh_e/ton cane	22.79[d]	110[d]	130[d]	177
Electricity surplus kWh_e/ton cane	-	85	105	148

Data used:
[a]Process steam pressure at 0.2MPa.
[b]Process heat consumption raw sugar MJ/ton cane=%Steam* Steam Enthalpy.
[c] Milling energy requirement to sugarcane energy content ratio = row 3 + row 4. Overall process efficiency 0.2. Bagasse $_{50\%moisture}$=270 kg/ton cane. Bagasse 50% moisture content, LHV=7.8 MJ/kg.
[c]Sugarcane energy content 2106 MJ/tone cane.
[d]See Fig. (**1**).
[e] Based on the source [8].

For an advanced cogeneration system:

- the investment costs are higher than those for a conventional fossil fuel plant, which are 800-1000 USD/kW$_e$. For a CEST (41 MW) cogeneration system, investment costs are 1109 USD/kW$_e$ [7]; for a BIG/GTCC (60 MW) cogeneration system, costs are estimated at 1400 USD/kW$_e$ [8].
- the pay back period is longer than for conventional fossil fuel plants and the rate of return on investment costs is lower than for conventional fossil fuel plants too.

Even if these barriers could be overcome by external financial support and joint investment, it would be necessary to face other barriers related to the *milling capacity of existing sugarcane factories* and the *seasonal character of sugarcane biomass availability*, because the best efficiency figures for both systems can be achieved only on the basis of year-round operation and there is no certainty of alternative biomass supply to bagasse during the off-season.

3. BIO-OIL PRODUCTION AT SUGAR MILL: THE CHALLENGES

3.1. Bio-Oil Production at Sugar Mills: Advantages and Disadvantages

The bagasse and SCAR conversion into Bio-oil *via* fast pyrolysis could be a solution to the problem of its energy storage, allowing it to be used locally as the need arises. Among the main advantages of sugarcane biomass conversion into a liquid fuel in the sugar industry are the following:

- A sugarcane mill factory has an appropriate energy infrastructure to assimilate technologies like fast pyrolysis.
- The pyrolysis oil may be considered innocuous in terms of CO_2 emissions.
- The infrastructure for transportation and distribution of conventional fossil liquid fuels can also be used for Bio-oil.
- Bio-oil can be transported to remote, isolated towns and used for pumping water, cooking food, heating water, and other small domestic tasks.
- Bio-oil stores 11 times more energy in the same unit of volume and has three times less moisture content.
- Because Bio-oil can be stored, the pyrolysis process can be decoupled from the power generation cycle, increasing the flexibility of its use so it can be used when it is really necessary, at the needed site, in the precise quantity needed.
- Storable Bio-oil provides an alternative to the total conversion of sugarcane biomass into electricity.
- Hydrogen production from biomass *via* fast pyrolysis at the medium plant size has lower cost than *via* gasification
- On the basis of the pyrolysis infrastructure it is possible to introduce gasification technology without a large additional investment.

The more important disadvantages are:

- The conversion process is endothermic.
- Bio-oil is not a stable fuel.
- Bio-oil upgrading is very expensive.
- There are no reported fast pyrolysis facilities with a capacity beyond 3.5 tons/hr.
- There is not Bio-oil properties standard or a Bio-oil market.

3.2. Energy Requirement for Bagasse and SCAR Fast Pyrolysis Module (FPM) at Sugar Mills

Assuming the conditions shown in Fig. (**3**) and including the use of SCAR in-season, the introduction, of fast pyrolysis at a sugar mill was calculated according the thermodynamic laws and regarding the results obtained during projection and construction of pilot plant for residues thermoconversion into energy carriers alternatives to electricity (Fig. **4**) [6].

The SCAR flow rate of 15 tons/hr is too large (assuming a reactor figure charge 300-500 kg/hr m^2 of biomass the reactor diameter corresponds to this quantity would be 6 m or more). In order to estimate the energy requirement, a module biomass feedstock rate of 3 tons/hr was introduced, FPM, for calculation. Under conditions: reactor work pressure up to 0.15 MPa; work temperature 723 K; using dry air as fluidizing gas and olivine sand as inert; regarding stiochiometric combustion of 10% of biomass feedstock, and fast pyrolysis of 90% of biomass feedstock, fluidized bed reactor size for FPM was preliminarily calculated.

4. BIO-OIL PRODUCTION AT SUGAR MILL: THE OPPORTUNITIES

4.1. The Technical and Economical Assessment

The principal costs of Bio-oil production from sugarcane biomass residues are estimated as follows. As it is known, 1.42 tons/hr of SCAR or bagasse will produce 1 ton of Bio-oil. The cost of Bio-oil production depends on several factors, the most important among them are: feedstock cost, feedstock pretreatment, plant scale, and type of technology used [10].

In order to estimate FPM capital cost production, it is very important to determine equipment cost. The engineering capital cost estimate for FPM equipment components (FOB Gulf Coast USA) were estimated to be 0.94E+10^6 USD [11], [12]14]. Production costs and costs for operation, maintenance, interest and other expenses for 1 ton of bio-oil produced *via* FPM were estimated to be 87 USD/ton, 79 USD/ton, 2.5 USD/ton, 12.5 USD/ton, 6.6 USD/ton respectively.

4.2. Added Production Cost and Added Value Analysis

An Added Value analysis was carried out on three scenarios (none of which included the sale of molasses or ethanol derivates):

- Scenario 1 analyzes raw sugar production with no bagasse surplus (current situation).
- Scenario 2 analyzes electricity cogeneration with sales of surplus electricity.

Fig. (4). Pilot plant for residues thermoconversion into hydrogen enriched gas [16].

- Scenario 3 analyzes the previous scenarios when FPM for Bio-oil production is introduced.

The basis of the analysis was 100 tons of milled sugarcane. The results are shown in Table **2**.

Of the three scenarios studied, Scenario 3 has the highest added value: $1866 USD, compared to $834 USD for Scenario 2. Scenario 3 also has an Added Value/Added Cost rate of 1.91, the best among the examined scenarios. Because of the energy requirements for Bio-oil production, the co-generated electricity surplus decreases from 105 to 93 kWhe/ton in Scenario 3, but the value of the loss of electricity is more than made up for by the added value achieved through the introduction of SCAR and the production of Bio-oil. As shown in Table **2** the highest added value figure for a ton of sugarcane ($40 USD) is achieved in Scenario 3; that is 13 USD/ton higher than the added value in Scenario 2.

CONCLUSIONS

The introduction of medium-sized pyrolysis modules in a sugar mill would be one of the first steps toward the feasible implementation of new thermoconversion technologies.

The seasonal characteristics of the sugar agro industry and the lack of alternative biomass supply feedstock during the off-season seem to be the main barriers from a technological point of view in countries where a feasible alternative supply of biomass is not available.

Table 2. Added Cost/Added Value Analysis Bagasse and SCAR (100 Tons of Cane)

	Scenario 1 50% Steam/Cane Weight		**Scenario 2 CEST 6.3MPa,793K; 38% Steam/Cane Weight**		**Scenario 3 CEST 6.3MPa,793K; 38% Steam/Cane Weight +SCAR + Bio-oil**			
	Raw Sugar	**Bagasse Surplus**	**Bagasse Surplus**	**Electricity**	**Bagasse Surplus**	**SCAR**	**Electricity**	**Bio-Oil**
Production	11 Mt	0	8Mt	10500 kwh	8Mt	25 Mt	9300 kwh	15 Mt
Production Cost	1100 USD		80 USD	630 USD	80 USD	375	558 USD	1350 USD
Price	1650 USD		216 USD	1050 USD	216 USD	675 USD	930 USD	2325 USD
Added Production Cost	--------	--------	----------	550 USD	---------	295 USD	478 USD	975 USD
Added Value	---------	---------	216 USD	834 USD	216 USD	459 USD	714 USD	1866 USD
Added Value/ Added Production Cost	--------	--------	-------	1.51	----------	1.55	1.5	1.91
Total value USD/ton of cane	16.5		18.66	27	18.66	23	25	40

Data Used: Cost of investment 1500 USD/kW; Instaled Capacity 30 MW; Electricity cogenerate 3000 kWh / kW/yr Production cost 0.06USD/kWh$_e$ [9]; Electricity Price 0.10 USD/kWh; Bagasse surplus cost 10 USD/ton; SCAR production cost 15 USD/ton; Bio-oil price 155 USD/ton.

Developing the energy potential of the sugar industry would be feasible considering the maturity of boiler technologies (up to 6.3 MPa, 793K), and that in a sugar mill with an improved cogeneration system, all of the conditions for the introduction of pyrolysis and gasification technologies would exist. As a rule, the implementation of any modern system for energy recovery from sugarcane biomass residues in developing countries could be carried out only under condition of subsidies and government support. However, the increase in the price of oil beyond 50 USD/bbl in the world market could provide an incentive for the participation of private capital in joint-venture projects to develop the energy potential of the sugar industry.

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ABBREVATIONS

FPM	=	Fast Pyrolysis Module (3 ton/hr)
SCAR	=	Sugarcane Agriculture Residues
BPST	=	Back Pressure Steam Turbines
CEST	=	Condensing Extraction Steam Turbine cogeneration system.
BIG/GTCC	=	Biomass Integrated-Gasifier/Gas Turbine Combined Cycle
LHV	=	Low Heating Value

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