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Evaluation of the Environmental Performance of Syngas Production from Sugarcane Bagasse and Straw

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A Life Cycle Assessment study was conducted to investigate the environmental performance of syngas production from sugarcane bagasse via Bubbling Fluidized Bed and Entrained Flow gasifiers, as well as the cogasification of sugarcane bagasse and straw using Bubbling Fluidized Bed. The CSFMB® computational tool was used to simulate the gasification process along all the different scenarios performed on this analysis.

1. Introduction

In the search for cleaner energy from renewable sources, biomass has now been consolidated as a qualified alternative to fossil fuels. This need for solutions is mainly due to the increase in atmospheric CO_2 emissions from the burning of non-renewable assets, which can be considered one of the largest problems of modern society (Couto et al., 2017). Evaluating the possibilities of biomass conversion to fuels, gasification is the most promising in this regard, since it can convert the intrinsic energy of different types of biomass into valuable intermediates that find applications as heat and electricity providers in industrial processes (Ruoppolo et al., 2013).

Gasification converts solid fuels into a gaseous mixture whose characteristics [$(H_2/CO)_{mol}$ ratio and moisture] and properties [Low Heat Value (LHV) and outlet temperature] depend on aspects inherent to the synthesis process, such as biomass source, gasifying agent, process temperature, and gasifier requirements (Hossain and Charpentier, 2015; Al-Zareer et al., 2016; Pérez et al., 2012). Among these specificities, the gasifier type is considered a determining factor. The Fluidized Bed Gasifier is a recurring option for syngas production, due to its flexibility regarding diversity of input biomass, and because it provides uniformity in terms of heat and mass transfer, promotes a suitable mixture between the biomass and the gasification agent, and is highly efficient in converting carbonaceous material into products (Jaimes Figueroa et al., 2014). Another type of widely used technology is the Entrained Flow Gasifier, that operates with small particles and high temperatures (1,200–1,500 °C) achieving conversion rates over 90 %, with low residence time, and producing tar-free syngas (Qin et al., 2012). Brazil is known for its potential to produce energy from renewable sources. The country's domestic energy supply in 2016 was of 288 million toes. Of this total, 44 % came from renewable sources, with sugarcane products accounting for 18 % of that amount (EPE, 2017). This productive potential can be further increased with the use of lignocellulosic sugarcane rejects, since they contain about 60 % of carbonaceous materials. To Moutta et al. (2014), the most adequate and efficient way to perform this expansion is the application of gasification technologies.

Although the origin of the raw materials used to produce syngas via gasification suggests the generation of insignificant environmental impacts, the topic has not been profoundly explored in the technical literature. The most recent research carried out in this regard refers to the application of Life Cycle Assessment (LCA) technique to evaluate the environmental performance of syngas synthesis via gasification routes. Burmistrz et al. (2016) used LCA to study the environmental effects of the gasification of two fossil fuels (subbituminous coal and lignite) by GE Energy Texaco and Shell entrained flow gasifiers technologies. Another study, carried out by Kalinci et al. (2012) evaluated the gasification of pinewood using a Downdraft Gasifier and Circulating Fluidized Bed Gasifier through LCA.

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However, to the best of our knowledge, there are no records of investigations that sought to relate the specificities of the gasification process of biomass rejects to possible environmental effects. Thus, this study proposes to contribute to the theme by comparing the environmental performance of syngas production via two distinct gasification systems: Bubbling Fluidized Bed Gasifier (BFBG) and Entrained Flow Rate Gasifier (EFG). In addition, the study also discusses the environmental effects generated from the cogasification of two types of biomass, bagasse and sugar cane straw, in the BFBG. As well as the fact that no reference regarding analyses of this genus are available in the literature, the decision to evaluate the environmental behavior of the use of straw as an input for syngas synthesis dues to the fact that this initiative is a recovery practice under the Cleaner Production view, since biomass is a waste from sugar cane processing.

Diagnoses were also elaborated via LCA, since the technique addresses environmental loads (consumption of natural resources and reject material and energy emissions) and their potential impacts (environmental extraction and release consequences) throughout a product life-cycle (anthropic transformations related to raw material acquisition, the manufacture chain, use, end-of-life treatment, recycling and final disposal) (ISO, 2006a). LCA is based on systems analysis, treating the life cycle of a product as a sequence of sub-systems that exchange material and energy flows. LCA studies take into account four phases: i) Goal and scope definition; ii) Inventory analysis (LCI); iii) Impact assessment (LCI); and iv) Interpretation (ISO, 2006b).

2. Methodology

The method established to perform this study encompasses five steps: (i) description of syngas synthesis through gasification by BFBG and EFG technologies in terms of operational conditions just as resource and emission consumption; (ii) design of mathematical models able to represent process routing, from the data and information collected in the previous step; (iii) exercise of LCA to constitute environmental performance diagnoses for the two alternatives regarding Climate Changes (CC) and Primary Energy Demand (PED); (iv) application of LCA to investigate impacts related to successive replacements of bagasse by straw in the BFBG feed; and (v) a critical investigation of the obtained results for both analyses.

2.1 Description of the evaluated technologies

Sugarcane arrives at the industrial plant by road. Two products originate from its milling: sugar juice and bagasse. The sugar juice will be transformed into ethanol at the distillery, while the bagasse will be divided into two other usages: (i) for use in the syngas production and cogeneration process; and (ii) for marketing. The cogeneration provides electricity and heat for the distillery, in addition to triggering the gasification grinders. The modeling of the EFG technology was initiated by drying 129.6 t/h of bagasse in order to reduce its moisture content from 50 %wt. to 10 %wt. The bagasse is then roasted to reach 0.0 % moisture, ground, and heated to 800 K, thus being able to be dosed in the gasifier. The CSFMB® computational tool was used to simulate the gasification process. In the simulations of EFG, 64.8 t/h of dry bagasse are placed in the gasifier (Table 1) in the presence of air (108 t/h; 929 K) as the gaseous agent and a mixture of (N_2 + CO_2) [60:40] %wt (36.0 t/h), whose process temperature (2,000 K) will be reached only by burning natural gas (NG) at 2,198 m^3/h. Crude syngas currents (202 t/h; 1,792 K), and ash (7.77 t/h) are emitted from the gasifier.

Table 1: Characterization of sugarcane bagasse and straw

Proximate analysis (%wt)			Ultimate Analysis (%wt)		
Component	Bagasse[1]	Straw[2]	Element	Bagasse[1]	Straw[2]
Moisture	0.00	0.00	C	49.66	42.94
Fixed carbon	81.55	86.64	H	5.71	6.26
Volatile matter	15.14	9.41	N	0.21	0.31
Ash	3.31	3.85	O	41.08	46.65
			S	0.03	0.00
			Ash[3]	3.31	3.84

[1] CSFMB®; [2] Rueda-Ordóñez and Tannous, 2015; [3] Complementary part of the total

Before finishing, the syngas is cooled by indirect contact with atmospheric air, which, in addition to being used in the gasifier, will also feed the dryer and the roaster. The syngas circulates by cyclones to remove particulates, and is led to a ZnO reactor to remove H_2S, which poisons the catalysts in the next step. Finally, the syngas reaches the shift reactor, where its constituents, CO and water vapor (fed to the system at 673 K), are transformed into H_2 and CO, until (H_2/CO) mol = 2.00.

The syngas synthesis in a BFBG system is similar to that of EFG until the biomass is ground. In this case however, the bagasse temperature is reduced to 290 K in a cooler to meet the gasifier specifications. The gasifier is fed 64.8 t/h bagasse, with air as the gasifying agent (43.2 t/h, 766 K). Gasification in the BFBG was also simulated using the CSFMB® computational tool. The other operations that occur in the BFBG system are also identical to those previously described for the EFG. However, since, in this case, the heat supplied by the syngas to the air does not meet the drying and roasting thermal demands, a flow of exactly 5,436 m^3 NG/h are transformed into heat, in order to definitely meet those demands.

The simulation of the gasification processes has been based on the following assumptions: (i) all process phenomena are in steady state; (ii) the gasifier bed is divided into two phases: the emulsion phase consists exclusively of solid particles percolated by upward gas, while the bubble phase is completely free of solids, (iii) the velocity profile model is unidirectional and type plug flow; and finally, (iv) the composition of solids is homogeneous throughout the bed.

2.1 Life Cycle modeling

The diagnoses were elaborated by attributional LCA with a 'cradle-to-gate' approach, and according to the ISO 14044 methodological framework (ISO, 2006b). The Reference Flow (RF) for the analyses carried out in this first step of the study were established as “to generate 42.8 m^3 of ethanol in an autonomous distillery coupled to a syngas producing unit”. This decision eliminates the influence of distortions resulting from the simultaneous generation of two products in the system (syngas and ethanol). Figure 1a depicts the Product System for which the diagnoses were performed and Figure 1b and 1c detail the analyzed syngas processing routes.

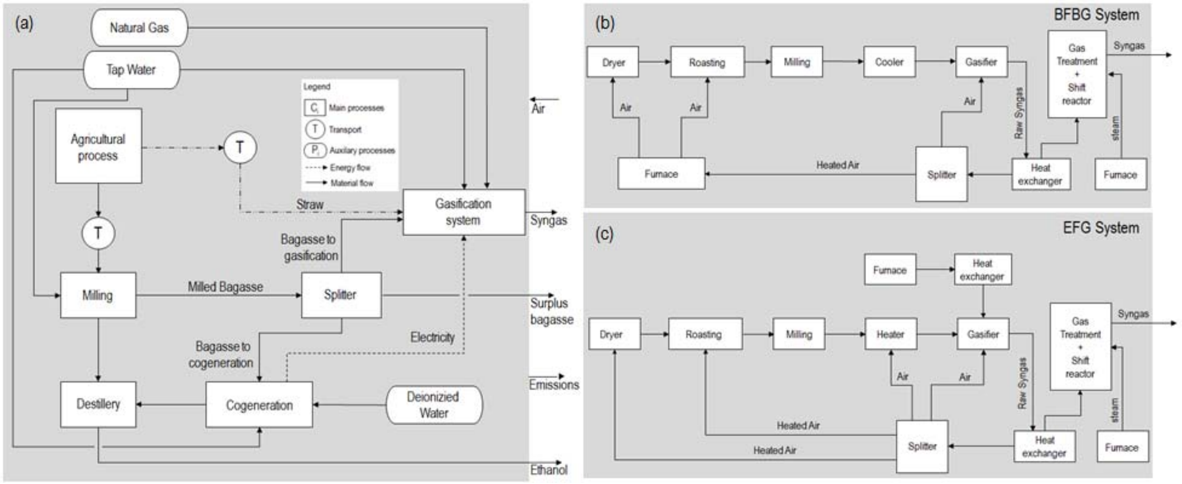

Figure 1. (a) Overview of the product system and detailing of the technologies that comprise the (b) BFBG system and (c) EFG system

The agricultural model was based on the procedures and technical conditions practiced in the State of São Paulo, Brazil’s main producers. Chemical fertilizers – urea, simple superphosphate and potassium chloride – as well as industrial by-products (vinasse and ashes) are dosed to supply macronutrient needs (N, P and K). The application of agrochemicals to control plagues and soil liming are also required actions. The use of agricultural machinery is assumed, with consequential consumption of diesel oil in soil preparation, sowing, treatment and harvesting (Moore et al., 2016). Environmental performance was determined from impacts in terms of Climate Change (CC) and Primary Energy Demand (PED). The contributions to CC were estimated by the method proposed by the Intergovernmental Panel on Climate Change (IPCC, 2006), while the PED consumptions of syngas production were described using the Cumulative Energy Demand (CED) method, v. 1.09. CED method expresses PED contributions of different non-renewable (fossil: NRF; nuclear: NRN; biomass: NRB) and renewable (biomass: RB; wind + solar + geothermal: RWSG; water: RW) sources of energy (Frischknecht et al., 2007).

3. Results and discussion

3.1 Environmental performance: EFG vs BFBG

Table 2 presents the environmental performance values of syngas production by the EFG and BFBG technologies. A comparison based on absolute values and considering only the reference flow established for the study (42.8 m^3 hydrated C_2H_6O) indicates a slightly higher benefit (~ 2.1 %) of EFG over BFBG in terms of

CC. However, when comparing technologies with respect to PED, BFBG consumes 12 % less primary energy than its counterpart. On the other hand, when the same analysis is performed in relative values, per ton of syngas produced (t_{sy}), the EFG performance exceeds that of BFBG in both analyzed dimensions. In the case of PED, the advantage is of 27 %, while for CC the difference reaches 38 %.

The main CC sources associated with EFG are methane and fossil carbon dioxide ($CH_{4,f}$ and $CO_{2,f}$) emissions, which represent, respectively, 52 % and 35 % of the impacts for the category. $CH_{4,f}$ is emitted throughout the NG life cycle used by the system for power generation in extraction operations carried out off the coast of São Paulo (312 kg/RF) and at the onshore fields of Sabalo, Margarita and San Alberto, Bolivia (76.9 kg/RF). NG refining is also the focus of $CH_{4,f}$ generation (São Paulo: 181 kg/RF, Bolivia: 243 kg/RF).

Table 2: Comparison between BFBG and EFG performances in terms of CC and PED

Impact	Unit	Technology	
		BFBG	EFG
CC	kg $CO_{2eq/RF}$	62,903	61,581
CC_e	kg CO_{2eq}/t_{sy}	406	253
PED	GJ/RF	593	676
PED_e	GJ/t_{sy}	3.83	2.77
Syngas Production	t_{sy}	155	244

Offshore extraction results in higher $CH_{4,f}$ releases than onshore processes, due to the operating conditions of each system. Conversely, Brazilian refining units are more efficient than Bolivian ones. $CO_{2,f}$ emissions totaled 21.5 t/RF and are due to NG burning for: (i) production of liquid CO_2 that makes up the current (N_2 + CO_2) and heating of this flow up to 2,000 K before introducing it into the gasifier (58 %); (ii) supply of thermal energy for the bagasse drying and roasting stages (16 %); and (iii) thermoelectric energy generation from the Brazilian electricity matrix (BR grid) consumed in the process additive manufacturing (5.6%).

The same precursors also account for the BFBG contributions. In this technology, $CH_{4,f}$ emissions account for 54 % of CC impacts, while $CO_{2,f}$ is responsible for 33 %. Even though operating under less restrictive conditions concerning temperature, the BFBG-based process is also dependent on NG. Thus, as with EFG, NG extraction in São Paulo and Bolivia resulted in significant $CH_{4,f}$ (358 and 136 kg/RF) losses, in the same way as the respective refining processes (227 and 304 kg/RF). $CO_{2,f}$ emissions are concentrated once again, in the heat generation process for the syngas synthesis, due to the production of steam water (673 K) to be injected into the shift (10.4 t/RF) and heating of the air used in the dryer and roaster (6.75 and 1.65 t/RF). Syngas processing consumes 64.8 t/RF of bagasse, regardless of synthesis route. The production of this agricultural asset is associated with the emission of 6.67 t/RF of CO_2, due to changes in agricultural land use ($CO_{2,\ LT}$). In the case of the State of São Paulo, $CO_{2,\ LT}$ emissions originate from sugarcane plantation expansions over areas originally occupied by soybean and livestock (Moore et al., 2016).

Concerning PED, the sources of EFG impacts refer to consumption in the form of NRF (25 %), RB (64 %) and RW (10 %). The contributions to NRF originate from the thermal and electrical energy consumption imposed by the system. As expected, the most expressive participation is through the extraction of raw natural gas to supply the NG demanded in the process (7,107 m^3/RF). EFG technology also predisposes the consumption of electricity for N_2 and CO_2 compression, in order to enable transport and storage operations. This activity leads to NRF effects due to the participation of crude oil (2.4 %), coal (4.2 %) and NG (9.1 %) from the BR grid. The contributions to RW also originate from the same process, due to the participation of hydroelectricity (68 %) in that arrangement (EPE, 2017). The share referring to RB is fully translated into the primary energy contained in sugarcane, whose Gross Energy Value (GEV) ranges from 8,396 – 8,894 kJ/kg (u = 50 %) (Alena and Sahu, 2013). The PED profile for BFBG does not record contributions from the BR grid, because of the low significance of the power consumptions in this situation. The NRF represents 28 % of the impact as PED and is entirely associated with the extraction of raw natural gas that meets the NG demand of the system (10,732 m^3/RF). The remaining impacts occur as RB, again due to sugarcane GEV.

3.2 Environmental effect of bagasse and sugarcane cogasification in the BFBG system

The second step of the study investigated the environmental performance of the BFBG system, assuming that the gasifier was fed with variable amounts of bagasse and cane straw (u = 15 %wt) (the dotted line in Figure 1a). The system load remained constant (64.8 t/h of biomass, dry basis). The simulations projected inverse variation trends between ethanol and syngas yields and straw intake rates into the system, a condition that could be predicted beforehand by the coupling form of the distillation gasification unit and of the biomass characteristics involved in the process (Table 1). Table 3 describes these results, as well as the totalized and specific impact values (CC_s and PED_s) for the analyzed situations.

Table 3: Contributions of sugar cane bagasse and straw for the gasifier feed.

Straw (%wt)	Syngas Production (t_{sy})	Ethanol Production (L)	CC (kg CO_{2eq})	CC_s (kg CO_{2eq} /t_{sy})	PED (GJ)	PED_s (GJ/t_{sy})
0	155	42.8	62,903	406	593	3.83
20	157	30.2	56,162	358	543	3.46
40	154	20.2	49,858	323	501	3.24
50	153	15.9	48,502	317	487	3.18
60	152	12.1	44,177	291	465	3.06
80	149	5.44	40,010	269	437	2.94
100	147	0.015	35,083	239	409	2.78

The fact that straw is drier than the bagasse reduces the thermal needs of the drying and roasting units, and, because of this, the demand for NG in the burner is also lower. The dosage of the bagasse mixture at a [80:20] %wt ratio led to a consumption of 25.5 m^3 NG/ t_{sy} in the heater, whereas when the biomass was administered in the inverse proportion of [20:80] %wt, this need was of only 9.11 m^3 NG/t_{sy}. As a result, the $CH_{4,f}$ and $CO_{2,f}$ emissions occurring throughout the life cycle suffered significant decreases, accumulating lower CC_s values, with increasing straw content: CC_s = f(Straw added) (Figure 2a).

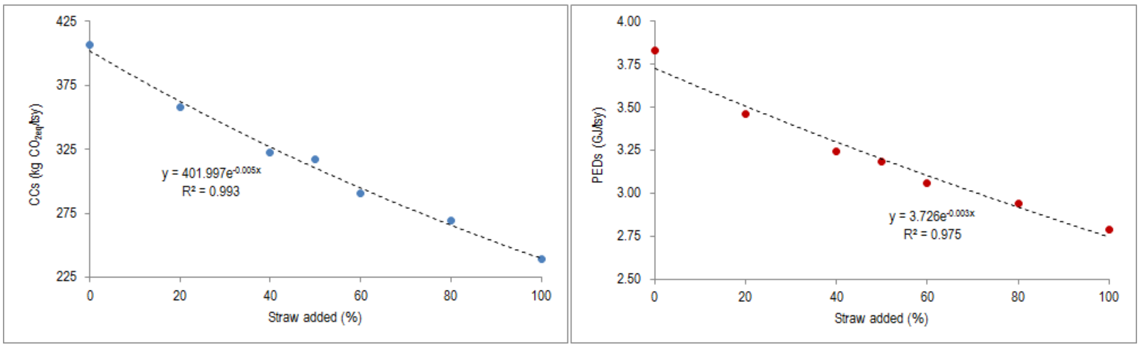

Figure 2: Effects of bagasse and straw ratio variations in terms of CCs (2a) and CCs (2b)

A similar behavior profile has been observed for PEDs = g (Straw added) (Figure 2b). In this case, however, the reductions of NRF were significant enough to generate decreasing PEDs values, even with the increase in RB contributions that the straw increments provided. The results suggest that the incorporation of straw into the process appears as an auspicious alternative in environmental terms.

Finally, it should be emphasized that both CCs and PEDs have a potential variation profile with respect to straw added.

4. Conclusions

This study aimed to investigate the environmental effects of technological and procedural variants, described in this case by the raw materials, in syngas synthesis from renewable inputs. The use of the Life Cycle Assessment technique with a cradle-to-gate approach was used to determine CC and PED impact categories. The analysis of the technological variants was performed by comparing the EFG and BFBG technologies. Under the analyzed conditions, the EFG system performance exceeded that of its counterpart in 38 % in relation to CC, and 27 % in terms of PED. The main reason for this discrepancy lies in the thermal BFBG requirements, which make use of significant amounts of natural gas to be met, resulting in atmospheric $CH_{4,f}$ and $CO_{2,f}$, emissions, in addition to the consumption of raw natural gas.

The verification of the environmental effect of the raw materials was due to the successive replacement of bagasse by straw in the BFBG system feed. Because it is drier than bagasse, the straw makes the system less restrictive in terms of thermal energy compared to when it operates only with bagasse. This circumstance provides decreases in CC and PED, impacts, which may reach up to 41 % and 27 %, respectively if the syngas synthesis is to be carried out only with straw instead of exclusively from bagasse.

These results suggest that the revaluation of straw from a sugarcane cultivation reject for the input of syngas processing is demonstrated as a promising alternative in terms of environmental performance and, therefore, accredited to be verified according to other approaches.

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