

Environmental assessment of Solid Oxide Fuel Cell technology integrated with a sugar-ethanol factories applying LCA.

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ABSTRACT

The integrated Solid Oxide Fuel Cell (SOFC) technology with sugar-ethanol factories is evaluated by a Life Cycle Assessment approach (LCA) to assess the environmental impact and by an Exergetic Life Cycle Assessment (ELCA) to account for the exergy efficiency of the system. The sugarcane is the primary feedstock and sugar, ethanol and electricity are the main products in the systems, which define the functional unit, being 9860 Kg/h of sugar, 2195 Kg/h of hydrated ethanol and 850 kWh of electricity.

The environmental impact (greenhouse gases and air pollution) and renewability parameter have been taken into account as an indicator for the comparative assessment of the sugar, ethanol and electricity technologies. The results of the LCA show that, the use of a SOFC technology involves a reduction of the greenhouse gas emissions and non-renewable source with respect to the conventional integrated sugar and ethanol plant. A detailed list of material and energy inputs is done using data from local factory and completed using simulation data by Aspen-Hysys.

Key Words: Life cycle Assessment, Exergy Efficiency, SOFC, Renewability parameter.

INTRODUCTION

Today, the effects of depletion of fossil fuel resources and global warming have pointed out the requirement of innovative energy generation systems that do not only increase efficiency and but also reduce harmful emissions and make use of renewable energy resources. Currently sugar cane is known likely the most productive biomass energy source by its rather efficient conversion of solar energy into high potential energy products (ethanol, bagasse and char). The bagasse released by sugar factories has long been a special feature on the electricity production through traditional cogeneration systems. Ethanol is the most widespread biofuel studied for a wide variety of energy systems, including recently also for fuel cells power plants. It is a point of discussion if ethanol, derived from sugar cane, maize (corn) and sugar beets, is a sustainable energy resource and if it offers environmental and long-term economic advantages over fossil fuels [1].

In Latin America, sugar cane is the main resource to obtain ethanol using the traditional two steps method: molasses fermentation with *sacharomises serevisiae* and distillation. However, ethanol is not the only product from sugar cane: there are different industrial valorization scenarios, such as sugar factories, alcohol distilleries, integrated sugar and alcohol plants, and electricity cogeneration plants using bagasse as fuel.

In previous papers published by Ensinas et al [2] thermal integration of the sugar and ethanol processes applying energy and exergy analysis was studied. Furthermore, four configurations of cogeneration systems (steam cycle, biomass gasification and combined cycle with biomass gasification) were evaluated by these authors. More recently Ensinas et al. [3] have also reported the irreversibilities of each component of the sugar factories, where the cogeneration system applying steam turbines is responsible for 63% of the total irreversibility generated, whereas the global exergetic efficiency is 35%. Contreras et al. [4] quantified the environmental impact of four alternatives of conventional sugar production in Cuba, using Life Cycle Assessment methodology (LCA). In this paper the sugar cane was considered as the main product, to which the total environmental load was attributed, while by-products ethanol, yeast and biogas were treated as avoided products. Different types of impacts were analyzed: global warming, acidification, ecotoxicity,

human toxicity and others. The integration of the sugar process with alcohol and biogas production proved to be the best alternative from an environmental perspective, exhibiting a better resource consumption pattern.

In addition Luo et al. [5] combined LCA and Life Cycle Costing (LCC) to quantify the environmental and economic impacts of ethanol from sugarcane in Brazil. The LCA and LCC included the gasoline production, agricultural production of sugarcane, ethanol, bagasse, sugar and electricity co-production, and finally the end use of ethanol blended with gasoline as automotive fuels. The results of LCC indicate that driving with ethanol fuels is more economical than gasoline.

Solid oxide fuel cells (SOFC) are considered to be an emerging technology characterized by a high efficiency, low CO₂ emissions, and high flexibility in terms of fuel type and installation requirements. Many works have been published in the field of thermodynamic models and optimization of the operational conditions of a SOFC power plant running on different primary fuels (ethanol, biomass and methane)[6,7].

The exergy tool has been used in the evaluation of SOFC running on biomass gasification gasses and ethanol [8,9]. Casas et al. [10] determined the effect of operational variables on the exergy efficiency and irreversibilities of an ethanol fueled solid oxide fuel cells system. The higher irreversibilities within the overall process were located at the fuel cell, post-combustor and the reformer. Also, the comparison of methane and ethanol as fuels for a SOFC power plant by means of exergy analysis was studied by Douvartzides et al. [11].

The integration of SOFC technology with turbine cycles has also been analyzed through exergy for a variety of renewable fuels previously converted in a gasification unit or in a reformer [12]. Some papers published recently focus on the environmental analysis of SOFC systems applying the Life Cycle Assessment (LCA) methodology. Strazza et al. [13] applied the LCA to compare the environmental impacts of a SOFC technology running on different fuels (methanol, natural gas, hydrogen from cracking, electrolysis and biomass gasification) with a conventionally diesel engine power system. The global warming, ozone layer depletion, acidification, eutrophication are some of the impact categories evaluated by these authors. On the other hand Meyer et al. [14]

used the ELCA methodology to assess an integrated SOFC system to allothermal biomass gasification. According to the explained above, the integration of traditional technology of sugar production, ethanol and bagasse cogeneration with a SOFC has not yet been studied considering the environmental impact. The aim of this paper is an environmental sustainability analysis through LCA and ELCA of a novel electricity generation system consisting in a solid oxide fuel cell unit integrated into a traditional sugar-ethanol production plants. The primary feedstock of the system is sugar cane. Several operational conditions in the SOFC system are evaluated to guarantee the defined functional units and to obtain the most feasible condition.

2. LCA METHODOLOGY

In the present paper two methods of assessing processes are integrated: LCA and ELCA. Life cycle assessment (LCA) is a method to define and reduce the environmental load from a product, process or activity by identifying and quantifying energy and materials usage and waste discharges, assessing the impacts of the wastes on the environment and evaluating opportunities for environmental improvements over the whole life cycle [15,16]. The exergy life cycle assessment (ELCA) is used to quantify the exergy input; it allows the quantification of the renewable and non-renewable materials needed in a specific production system. It also provides the basis for the assessment of the efficiency of the resources use.

2.1. Functional units

In the present paper two technological schemes are considered for sugar, ethanol and heat and power production from sugar cane. The first is the traditional integration of sugar and ethanol production processes including cogeneration with bagasse. The second scenario includes the Solid Oxide Fuel Cell (SOFC) technology using an intermediate stream (mix of ethanol and water) from ethanol process. The two schemes are presented in Figure 1. The sugar, ethanol and electricity are the outgoing products, a set of 9.86 ton/h sugar, 2.195 ton/h of hydrated ethanol (96% ethanol) and 847 kWh of electricity obtained from the sugarcane is considered as functional unit.

2.2. Description of the studied cases

2.2.1 Scheme 1. Traditional sugar-ethanol factory. Traditional sugar production, with ethanol produced from molasses via fermentation and distillation, and

steam and electricity production from bagasse combustion were considered in the scheme 1.

The sugar factory has a cane mill capacity of 105.00 ton/h, obtaining for this 9.86 ton/h of sugar, 4.12 ton/h of molasses and 31.50 ton/h of bagasse. The operation of the sugar mill is 100 d/year.

The non-sugar impurities of juice are separated in the flash tank and clarifier by the addition of several chemical additives as lime, sulfur, among others.

With respect to the ethanol process, chemical components used are nutrients (urea, sulfuric acid, etc) in the *saccharomyces cerevisiae* yeast growth. The fermented liquor has around 4-5 % w/w of ethanol concentration and is directed to the distillation process. The installed capacity of the distillery is 550 hL.day⁻¹ of hydrated ethanol (96 °GL), being mostly used by the liquor industry, in pharmaceutical applications and in the chemical industry.

Steam and electricity are produced by bagasse combustion (31.5 ton h⁻¹), steam cogeneration and supplemented with other fuels (0.105 ton h⁻¹ of diesel). The flue gases are considered as harmful emissions; their composition and quantities are obtained from a local factory and completed using simulation data by Aspen-Hysys. Bagasse with 50% of moisture content, 23.50% of carbon, 3.23 % of hydrogen, 22.00 % of oxygen and 1.25% of ash was assumed according to laboratory characterization. The surplus of electricity (315 kWh/hr) is distributed along of the National Network.

The ashes from bagasse combustion and the filter cake from the sugar process are used to substitute chemical fertilizers (avoided products) in the agriculture stage; such as urea, triple super phosphate and potassium chloride [4]. Wastewaters from the sugar and ethanol processes are treated by means of a biological process (oxidation lagoon), using the liquid product in ferti-irrigation, avoiding the use of fresh water and fertilizers. Due to its high protein content, yeast waste is considered as an avoided products as animal feed.

2.2.2 Scheme 2. SOFC technology integrated in a sugar-ethanol factory.

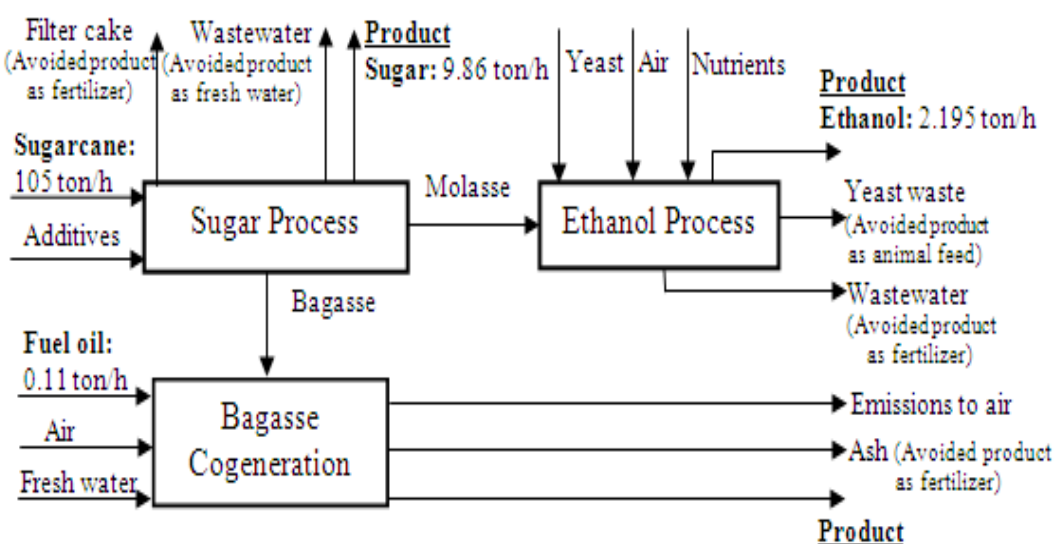
In Scheme 2, a SOFC system is integrated in the traditional sugar cane-ethanol production as follows. From the ethanol process, 0.310 ton h⁻¹ ethanol (56 % w/w) is transferred to the SOFC that produces 1.6 MJ/h heat (in exhaust gases), 486.18 kWh/hr electricity and 2.248 ton h⁻¹ of emissions to air.

The SOFC system consists of a vaporizer, a re-

former, fuel cell and post-combustor. In the vaporizer, the liquid mixture (water and ethanol) is vaporized and preheated before to the reformer inlet, where is converted into synthesis gases. The mixture leaving the reformer is fed and oxidized with air within a solid oxide fuel cell module; obtaining electricity, heat and exhaust gases by an electrochemical conversion. Finally, the fuel cell depleted gases reacts into a post-combustion unit to fulfill the energy requirements of the process.

Input and output data for this SOFC system have been calculated based on the works of Arteaga et al. and Casas et al. [17,10]. Critical is the ethanol steam reforming stage: changes of operating temperature and the water-ethanol fed molar ratio affects its efficiency and hence its environmental performance as well. Therefore, four operational water-ethanol fed molar ratios (R_{AE}) are investigated, resulting in alternative 2A, 2B, 2C and 2D. For each of these alternatives, operations at four different operational reactor temperature (T_{SR}) are considered, resulting into 16 variants for scheme 2; e.g. at $R_{AE}=5$, operations at 823, 873, 923 and 973 result in the four alternatives 2A1, 2A2, 2A3 and 2A4, respectively..

SCHEME 1



SCHEME 2

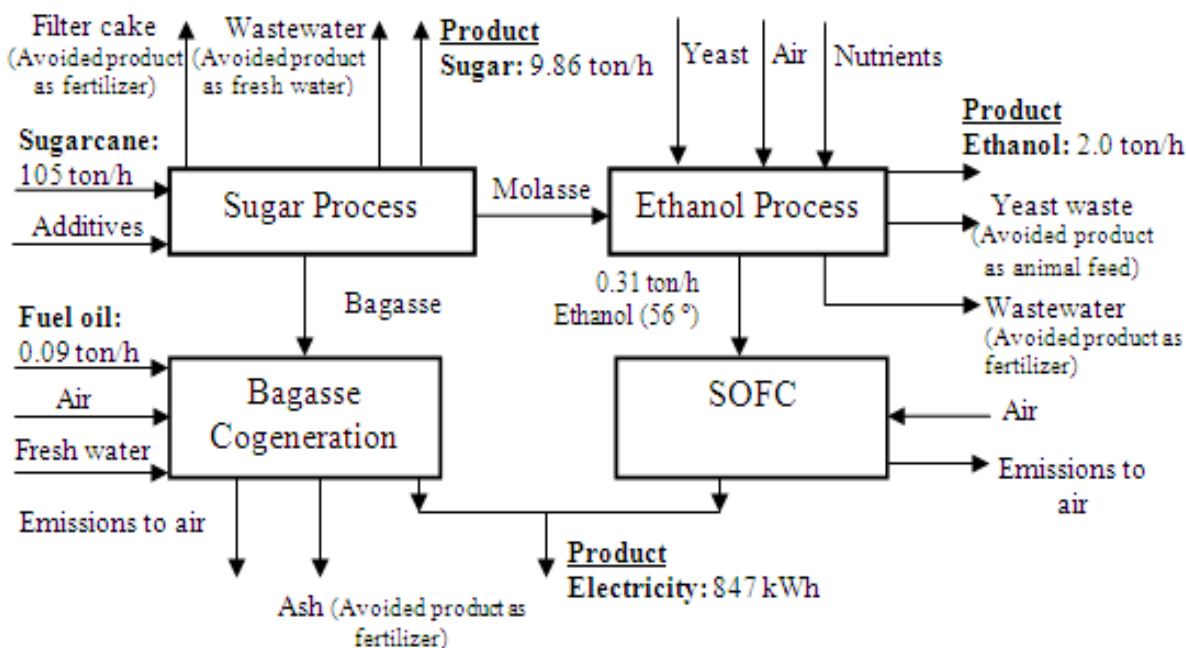


Figure 1. Technological schemes.

2.2 Environmental Impact assessment

2.2.1 Selected impact categories

Most environmental concern at the international level has focused over the last couple of decades on global warming. This makes also sense for cane processing: the main environmental impacts resulting from the lifecycle of sugar, ethanol and electricity corresponds to atmospheric emissions. Therefore, the lifecycle greenhouse gas and air pollution are considered as the main impacts in the present paper, being represented by CO₂ and NO_x equivalents respectively.

The greenhouse gases emissions results from all greenhouse gas flow rates are brought back to the same basis, namely CO₂ equivalent, by using their global warming potential (GWP). The GWP evaluated over 100 years is equal to 1 for carbon dioxide (CO₂) and 21 for CH₄ [18].

Direct emissions are calculated from the system mass balance according to:

$$m_{GHG}^{Total} = \sum (f_j^{GHG} \cdot GWP_j) \quad (1)$$

Where: f_{GHG}^{Total} is the total greenhouse gas emission of the system (kg_{eqCO₂} h⁻¹), f_j^{GHG} is direct emission of a greenhouse gas j in the considered system (kg h⁻¹); GWP_j is the global warming potential of greenhouse gas j (kg_{eqCO₂} kg⁻¹); n: pollutant emission number.

CO₂ emissions produced by bagasse combustion, ethanol steam reforming and the exhaust gases SOFC burned are balanced by atmospheric CO₂ absorbed during biomass re-growth. However, the bioenergy production to some extent still relies on the use of fossil energy and is not carbon neutral.

The Air Pollution (AP) is determined based on NO_x weighting coefficients [18]. In this case CO, NO_x and VOC_x are considered as pollutants. The weighting coefficients for CO, NO_x and VOC_x are 0.017, 1.00 and 0.64 respectively.

2.2.2 Resource utilization assessment.

Several researchers have suggested that the most appropriate means to correlate resource utilization is through exergy. It allows one to characterize the full set of natural resources used along the life cycle, e.g. in terms of renewability, and it is also able to analyses how efficient resources are converted into products. Exergy is a measure of the difference of a system's state in relation to the reference environment and hence represents its resource potential to be utilized. For the present analysis a temperature of T₀ = 298.15 K, pressure P = 1.013 bar and the

atmosphere composition of 75.67 % N₂, 20.35 % O₂, 0.03 % CO₂, 3.03 % H₂O and 0.92 % Ar are assumed as reference environment [19]. Freshwater and air exergy content is considered null at ambient temperature and pressure.

In the present paper the renewability parameter of the different alternatives are calculated. The renewability parameter (á) is defined as the relationship between the renewable exergy consumption (R_{Renewable}^{inlet}) and the total exergy consumption of process (R_{Total}^{inlet}), which is showed in the following equation:

$$\alpha = \frac{R_{Renewable}^{inlet}}{R_{Total}^{inlet}} \quad (2)$$

The total exergy consumption of an individual process can be calculated as a sum of all the exergetic streams used in each alternative, including both renewable and non-renewable resources.

The sugar cane is classified as a renewable resource, while the additives (lime, flocculants) used in the sugar juice clarification, chemicals (HCl and NaOH) to clean equipments, the nutrients (urea and H₂S) added in the fermentation stage, as well as fuel oil necessary to supply the heat and electricity demands are considered as non-renewable resources.

3. RESULTS AND DISCUSSION

3.1 Inventory

The results of the material and energy balances are the base of the assessment in each alternative.

The primary data inventory of the alternatives 1 (Alt 1) and four scenarios of the 16 variants derived from alternative 2 (Alt 2A1, 2B2, 2C3 and 2D4) is depicted in the Table 1, showing all resources contributing to the industrial stage such as:

- i) Renewable resources: sugarcane, water, air.
- ii) Imported (from outside of the system and usually non-renewable): fossil fuels, coolant, lubricant oil, yeast and chemical additives.

3.2 Global warming potential.

The comparison of the alternatives was carried out using three criteria: environmental impacts (GHG and AP), exergy efficiency and renewability parameter. The CO₂, green house gasses (GHG) and air pollution (AP) emissions are summarized in Table 2 for all the explored alternatives.

The total CO₂ amounts emitted to the environment exceeds 26.00 ton_{CO₂eq} h⁻¹, in all studied cases. The Alternative 2 (sugar-ethanol-SOFC) presented higher values (27.247 ton_{CO₂eq} h⁻¹) at all operational conditions. The biogenic CO₂ are higher in the second alternative (variants from 2A1 to 2D4) than in

Alternative 1 (1.494 ton_{CO₂eq} h⁻¹).

As can be seen, higher greenhouse gases (GHG) emissions (0.646 ton_{CO₂eq} h⁻¹) are observed for Alternative 1. This difference is mainly due to additional exhaust gases from non-renewable resource combustion (diesel) installed to fulfill a gap of 531.71 kWh of electricity (63 % of the functional unit). As the input of fossil fuel energy is lowered, the CO₂ emissions contributing to the GHG are reduced.

The integration of the SOFC power plant with a conventional sugar–ethanol process has a positive effect on GHG emissions. The GHG emissions reaches values of 0.309 and 0.289 ton_{CO₂eq} h⁻¹ for the variants 2A1 and 2D4 respectively, allowing reducing the CO₂ emissions in 0.360 ton_{CO₂eq} h⁻¹ in comparison to the maximum reported for the Alternative 1 (integrated sugar-ethanol factory).

Table 1. Primary data inventory for the production of sugar (9.86 ton/h), ethanol (2.194 ton/h) and electricity (847 kWh).

	Unit	Alt 1	Alt 2A1	Alt 2B1	Alt 2C1	Alt 2D1
Input						
Cane	Ton/h	105.00	109.82	109.82	109.82	109.82
Lime hydrated	Ton/h	0.068	0.071	0.071	0.071	0.071
NaOH 50% in H ₂ O	Ton/h	0.0015	0.0016	0.0016	0.0016	0.0016
HCl 30% in H ₂ O	Ton/h	0.116	0.122	0.122	0.122	0.122
Ammonium sulphate	Ton/h	0.00037	0.00038	0.00038	0.00038	0.00038
Sulfuric acid	Ton/h	0.077	0.082	0.082	0.082	0.082
River water	Ton/h	89.60	90.27	90.27	90.27	90.27
Air	Ton/h	140.36	141.97	141.97	141.97	141.97
Yeast	Ton/h	0.280	0.294	0.294	0.294	0.294
Urea	Ton/h	0.036	0.037	0.037	0.037	0.037
Diesel	Ton/h	0.223	0.1093	0.1092	0.1066	0.1076
Lubricant Oil	Ton/h	0.573	0.0330	0.0322	0.0197	0.0245
Coolant	Ton/h	0.071	0.0041	0.0040	0.0024	0.0031
Outputs						
Sugar	Ton/h	9.86	9.86	9.86	9.86	9.86
Electricity	kWh	847.00	847.00	847.00	847.00	847.00
Ethanol (96% H ₂ O)	Ton/h	2.194	2.194	2.194	2.194	2.194
Ash ^a	Ton/h	7.875	8.541	8.541	8.541	8.541
Filter cake ^a	Ton/h	2.194	2.295	2.295	2.295	2.295
Wastewater ^a	Ton/h	150.43	154.21	154.21	154.21	154.21
Yeast waste ^a	Ton/h	15.149	15.946	15.946	15.946	15.946
Emissions to air						
Particulate material (PM)	Ton/h	31.50	32.94	32.94	32.94	32.94
Nitrogen oxides	Ton/h	0.089	0.091	0.091	0.091	0.091
Total CO ₂	Ton/h	26.090	27.2474	27.2470	27.2417	27.262
CO	Ton/h	0.144	0.162	0.161	0.159	0.158

^a Avoided products

Table 2. Greenhouse gases (GHG) and air pollution (AP) emissions ($\text{ton}_{\text{CO}_2\text{eq}} \text{h}^{-1}$ and $\text{ton}_{\text{NO}_x\text{eq}} \text{h}^{-1}$ respectively).

Alternatives	Total _{CO2}	Net m _{GHG}	m _{CO}	m _{NOx}	PM	AP
Alternative 1	26.090	0.646	0.0024	0.054	31.50	0.0564
Alternative 2A1	27.247	0.309	0.0027	0.055	32.94	0.0577
2A2	27.246	0.305	0.0026	0.055	32.94	0.0576
2A3	27.247	0.301	0.0026	0.055	32.94	0.0576
2A4	27.232	0.291	0.0026	0.055	32.94	0.0576
Alternative 2B1	27.246	0.309	0.0027	0.055	32.94	0.0577
2B2	27.246	0.304	0.0027	0.055	32.94	0.0577
2B3	27.247	0.301	0.0026	0.055	32.94	0.0576
2B4	27.231	0.290	0.0026	0.055	32.94	0.0576
Alternative 2C1	27.241	0.302	0.0027	0.055	32.94	0.0577
2C2	27.243	0.301	0.0026	0.055	32.94	0.0576
2C3	27.240	0.299	0.0026	0.055	32.94	0.0576
2C4	27.231	0.290	0.0026	0.055	32.94	0.0576
Alternative 2D1	27.246	0.304	0.0026	0.055	32.94	0.0576
2D2	27.245	0.302	0.0026	0.055	32.94	0.0576
2D3	27.239	0.298	0.0026	0.055	32.94	0.0576
2D4	27.230	0.289	0.0026	0.055	32.94	0.0576

The previous mentioned is closely related to the conversion of an ethanol/water mixture into synthesis gas and power to fulfill the functional unit (847kWh). The syngas produced in the reforming reactor and the post-combustor off gases includes biogenic CO_2 to the total mass balance ($0.58 \text{ kg}_{\text{CO}_2\text{eq}} \text{h}^{-1} \text{ kW}^{-1}$ produced by SOFC) but not to the GHG category. Overall, GHG emissions are reduced by 52 (Alternative 2A1) to 55% (Alternative 2D4) when compared with Alternative 1.

All the studied alternatives show important contributions to air pollution; mainly due to the particulate matter and CO emissions produced in the bagasse conversion oven, caused by the turbulent movement of combustion gases with respect to the burning bagasse and resultant ash, as well as, the incomplete combustion of bagasse. No significant difference is noticed between the variants of Alternative 2, due to the variations of CO emissions associated to the SOFC are negligible with the increment of T_{SR} and R_{AE} . This performance is associated to the kinetics of the ethanol steam reforming and the fuel cell electrochemical model [17]. The emission of particulate material (in Table 2) is drastically increased between the two scenarios, taking values of (Alt 1) $20.216 \text{ ton}_{\text{NO}_x\text{eq}} \text{h}^{-1}$ and $21.143 \text{ ton}_{\text{NO}_x\text{eq}} \text{h}^{-1}$ (Alt 2A1) respectively. This increase is associated to the environmental burdens allocation corresponding to the production of 0.180 ton h^{-1} of extra ethanol by means of a Conventionally Supplementary Systems (CSS) and incomplete combustion of bagasse.

On the other hand, the effects of the reforming reactor operational parameters on the GHG emissions and AP were also analyzed. The GHG emissions are reduced when temperature increases from 823.73 K to 973.73 K and when water to ethanol molar ratios increases from 5.0 to 6.5, resulting into lower emissions at 973.73 K and R_{AE} of 6.5 (variant 2D4). Since the emission of the particulate matter is rather constant for all studied cases, the difference in the AP indicator is mainly affected by the variation of CO and NO_x emissions, which exhibit negligible changes for all investigated variants considering SOFC integration (2A1 to 2D4).

3.3 Renewability parameter.

Figure 2

reports the renewability parameter for each Alternative. The renewability degree of the alternatives is associated to the amounts of fossil fuels and chemicals, which in the present paper are considered as non-renewable resources.

The fossil fuel and chemicals used to produce the deficit of ethanol and electricity from CSS are added to the inlet stream for all alternatives so that for Alt.1 only fossil fuel used by the CSS is added, while chemicals necessary to produce 0.180 ton h⁻¹ of ethanol are included for all variants of Alternative 2. For this reason the chemicals consumptions are lower for Alt.1, while the diesel, lubricant oil and coolant are higher for Alt.2 according to the primary inventory data reported in the Table 1.

The reduction of non-renewable resources increases the renewability character of the process. Indeed, Alternatives 2 with integration of SOFC technology are more renewable than the traditional sugar-ethanol production, obtaining indexes near to 0.93 and 0.85 for Alt.2 and 1 respectively.

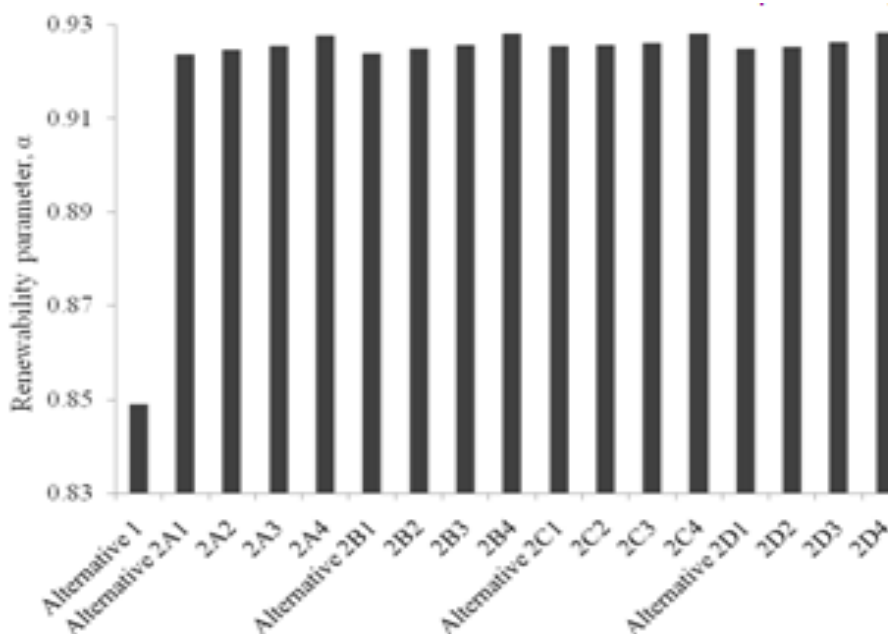


Figure 2

. Renewability parameter for each alternative.

On the other hand, the fuel cell power is directly proportional to the hydrogen obtained in the reformer (hydrogen yield); and this last is strongly improved when the reactor temperature and R_{AE} are increased [10,20]. According to the explanation above, the fossil fuel consumption is reduced at higher reformer temperatures and water to ethanol feed ratios, as well as the greenhouse gases emissions. For this reason, the renewability parameter is favored at higher temperature and R_{AE} . The renewability parameter reaches values ranging from 0.91 to 0.93 approximately in all alternatives with SOFC; the higher indexes are obtained at 973 K and R_{AE} of 6.5.

4. CONCLUSIONS.

This paper provides detailed results that enable an assessment of the environmental performance for the life cycle of sugar, ethanol and electricity from sugarcane both in traditional production pathways and with integration of SOFC technology. The analysis of the sugar and ethanol processes by the traditional method, including cogeneration with *bagasse* (Alternative 1) and the integration with a Solid Oxide Fuel Cell technology (Alternative 2) was performed based on different indicators: global warming potential, air pollution and renewability. It was demonstrated that the integration of SOFC technology with the traditional sugar-ethanol process and electricity using bagasse cogeneration are likely to be environmentally superior to Alternative 1, specifically with respect to greenhouse gas emissions and renewability.

Sugar, ethanol and electricity from sugarcane are renewable sources of energy only to a certain extent, since about 15.10 % and 7.6 % of the total inlets feedstock comes from fossil sources for Alternative 1 and 2 respectively.

This environmental assessment of SOFC technology might take advantage of an analysis of effects that it may bring forward in other fields, such as economic and social impact analysis.

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