Introduction of SOFC Technology into Cuban Energy Sector: Technical and Sustainability Analysis

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Abstract: The feasibility of integrating a solid oxide fuel cell (SOFC) technology into the Cuban energy sector is analyzed. In this context, two scenarios for power generation are assessed: the first (existing) combines a bagasse cogeneration unit and diesel combustion engines and for the second (future), diesel engines are replaced by a SOFC feed with ethanol and integrated into the sugar factory. The environmental impact (greenhouse gases), exergy efficiency, and a renewability parameter are considered as indicators for the assessment of the studied scenarios through a multifunctional unit (9.86t/h sugar, 2.195t/h of hydrated ethanol (96% w/w) and 847kWh of electricity) approach. The SOFC scenario shows significant advantages from an environmental point of view, obtaining a reduction of 55% greenhouse emissions and 60% fossil fuel consumption. At the same time, the overall process efficiency (38%) and renewability index (0.93) are higher than for the existing scenario. Furthermore, health impacts and their corresponding external cost related to airborne emissions (primary and secondary pollutant) are estimated applying the Uniform World Model (UWM). In this sense, the results show that the use of a SOFC technology involves a reduction of health impacts in 25.76 YOLL yr^{-1} (12%) and external costs of 52175 US$ yr^{-1} (12%). The potentiality of SOFC technology implementation into Cuban energy sector is assessed using a Strengths, Weaknesses, Opportunities and Threats (SWOT) approach. Nowadays, the main threat of implementation of this technology is associated to competitive energy market.

Keyword: SOFC technology, sugar-ethanol, exergy efficiency, renewability parameter, heath external cost, SWOT.

1. INTRODUCTION

The demand for energy is growing as well as the world population but the fossil fuel consumption is rapidly increasing, which makes that its natural reserves are drastically diminishing. Emissions from fossil fuel combustion are the main responsible of global warming and the degradation of air quality. In order to mitigate the emissions of greenhouse gases and fossil fuel consumption several researchers have focused their efforts on renewable energy sources and on developing new and more efficient technologies for energy production. According to this last point, fuel cells are considered as the most efficient energetic systems of the near future, since they can produce electricity without polluting the environment when run on pure hydrogen, and they possess the necessary specific power, power density and durability to replace conventional internal combustion engines from their current applications.

The studies on Solid Oxide Fuel Cell (SOFC) have been focused on thermodynamic models and optimization of the operational conditions of SOFC power plants running on different primary fuels (ethanol, biomass and methane) [1-3]. The exergy tool has been applied in the evaluation of SOFCs stacks using different biomass derived fuels as feedstock: syngas from ethanol [4], solid biomass gasification processes [5] and turbine cycles [6]. Furthermore Life Cycle Assessment [7] and Exergy Life Cycle assessment [8] methodologies have been applied to quantify the environmental impact of a nonintegrated SOFC technology.

In previous papers published by Ometto and Lopes [9] have evaluated the ethanol production from sugar cane applying exclusively Exergy Life Cycle Assessment (ELCA). In addition, Gopal and Kammen [10] determined the life cycle greenhouse gas emissions ($kg_{CO2\text{-}eq}$ MJ^{-1} of anhydrous ethanol) of the anhydrous ethanol produced from different combinations of molasses and cane juice feedstock. In the Cuban context, Contreras *et al*. [11] quantified the environmental impact of four alternatives of conventional sugar production in Cuba, using Life Cycle Assessment methodology (LCA). Moreover, Contreras *et al*. [12] the exergy life Cycle assessments (ELCA) have been applied in order to determine the

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renewability index of the sugar process. On the other hand, Perez *et al*. [13] has evaluated and compared the environmental impacts of the life cycle of different cogeneration technologies currently used in the Cuban sugar industry.

In Cuba, sugar cane is the main resource to obtain bioethanol through the traditional molasses fermentation with *Saccharomyces cerevisiae* and the distillation process. However, bioethanol is not the only product from sugar cane: there are different industrial valorization scenarios, including sugar factories, alcohol distilleries, integrated sugar and alcohol plants, and cogeneration plants using bagasse as fuel. The diversification of sugarcane use is a logical and economically advantageous strategy of development, which considers the high added value products and services that can be obtained from cane and its derivatives.

The integration of SOFC technology into a sugar industry will increase the net electricity production and the efficiency and sustainability of the existing factories. It can help in reducing the fossil fuel consumption as well as the pollutants released to the environment. The bagasse released by sugar factories has long been a special feature for the electricity production through traditional cogeneration systems. On the other hand, ethanol is the most widespread biofuel studied for a wide variety of energy systems, including recently also for fuel cell power plants. In our previous studies [14] we suggested the possibility for diversification of sugarcane industry by integration of the Solid Oxide fuel cell technology (using ethanol as feedstock) into its energy infrastructure. In this regard, we have recently reported on the effects of air emissions on the human health and its corresponding external cost [15], concluding that integration of SOFC technology into Cuban energy sector is likely to be environmentally superior to conventional systems. However the potentiality of implementation of SOFC technology into Cuban energy sector by means of strengths, weaknesses, opportunities and threats (SWOT) profile have not been thoroughly discussed.

According to the explained above, the purpose of this paper is to discuss the potential of sugar mill factory into Cuban energy sector, evaluating the feasibility of integration of this advanced technology (Solid Oxide fuel cell) into sugar-ethanol energy schemes. The exergy analysis, renewability index, global warming and acidification categories, as well as health external cost have been taken into accounted as sustainability indicators. The strengths, weaknesses, opportunities and threats (SWOT) profile of such implementation is also discussed.

2. SUGARCANE INDUSTRY AS ENERGY VECTOR

Cane and sugar made up an integral part of history, culture and tradition in Cuba. The database offered by FAO [16] shows how sugar has been the principal product in the Cuban economy through the years. Cane has been seeded historically with the basic objective to produce and commercialize sugar. The Cuban sugarcane production has fallen from $82*10^6$ ton in 1990 to $23.8*10^6$ ton in 2004 [17], mainly due to collapse of the Soviet Union and other Communist states in Eastern Europe, Cuba lost its traditional sugar markets. This phenomenon made that Government started a process of dismantling much of the country's sugar industry. Half of the land area previously under sugarcane cultivation was reassigned to food production and reforestation, and 46% of operating sugar mills were closed [18]. The individual and combined effects of certain management practices, i.e. planting date, row spacing, planting depth, fertilization rate, pest control and irrigation, have a great impact on the growth and yield of sugar cane. The deficit of fertilizers during the sugarcane growth is the main responsible for the decrease of agricultural yield in Cuba, and it is associated to commercial restrictions.

Currently, the total sugarcane milled is approaching $0.15*10^6$ ton. For this milling capacity $13.8*10^6$ ton of sugar and $2.1*10^6$ ton of molasses were produced during the crushing season 2008/2009 [19]. Bagasse is produced in large quantities by the sugarcane mills through the traditional sugarcane process scheme shown in Figure **1** and represent 30% of the milled sugarcane.

In general, the bagasse production was $4.5*10^4$ ton during the crushing season (2008/2009) [19], considering the yield of sugarcane to bagasse of $300kg_{bagasse}/ton_{sugarcane}$. The bagasse is traditionally incinerated to supply the heat and electricity demand of sugar-ethanol factories and the electricity surplus is delivered to the national grid. The existing steam supply and power generation at the sugar mills generate an average of 20-25kWh per ton of sugarcane in low efficiency Back Pressure Steam Turbines (BPST) [20]. In addition, the high energy requirements of the sugar process [21] result in low quantities of electricity exported to the national grid. At most sugar factories in Cuba, the final molasses are

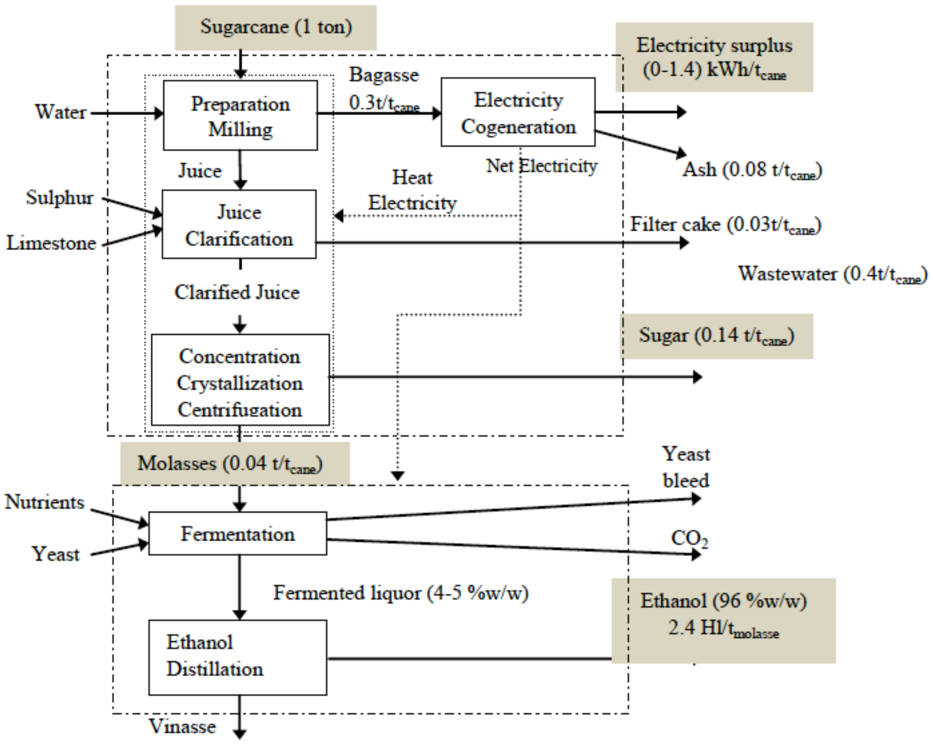

Figure 1: Traditional sugar-ethanol process scheme.

used as feedstock for production of fuel ethanol at a distillery annexed to the sugar factory, which are self sufficient in terms of production and consumption of energy. For all operations, the energy is supplied by the combustion of bagasse. In fact, 13 distilleries are operating with a total ethanol (96% w/w) production more than 5.30 million of hectoliters per year (2009) [19] with an installed capacity per industry between 200 and 1200hL/day [21]. Ethanol is mostly used by the liquor industry, in pharmaceutical applications and in the Cuban chemical industry. Nowadays bioethanol is gaining strength as biofuel in the transport sector [22] and power generation using fuel cells [3, 23] because of its low price and relatively large greenhouse gas emissions reduction potential. Most authors concur pointing out that the current complex situation demands that the sugar agro-industry undertakes important changes. In short, the sugar agro-industry should not focus solely on the production of sugar as its main objective. Instead it should endeavor to become a modern, high efficiency agro-industry with widespread by-product diversification. Besides, resource recovery through recycling of sugar processing by-products and wastes offers multiple advantages such as the generation of new products, energy self-efficiency and better pollution control, which will increase the overall economy of the process. Thus, such a strategy should take into account, besides the proportion of sugar, particularly the production of ethanol and electricity for sale outside of the plant. The sugar industry continues to be a strategic component of the development of renewable fuel sources.

Cuba provides an attractive scenario for introduction of Solid Oxide Fuel Cell using ethanol as feedstock due to:

1. The Cuban electricity sector is almost wholly dependent on fossil fuel, which increases the potential for attractive economics for decentralized electricity generation from bagasse cogeneration.

2. The diversification of the sugarcane agro-industry can be a path to improve the efficiency and economic profitability, as well as, to reduce the industrial waste production.

3. The close relationship between the sugar industry, the electricity utility industry, ethanol distillery and other key government institutions in Cuba could greatly facilitate the introduction of a new technology like fuel cell.

4. There is a high level of engineering and technical capacity in Cuba that could be trained to support such new technology.

Future options for reaching sustainable development goals include increasing the efficiency of the sugar sector and the diversification would be a path to improve the efficiency and profits, as well as, to reduce the industrial waste.

2.1. Biofuels and Energy from Sugarcane

Sugarcane mills represent a promising scenario to produce biofuels, specifically from bagasse, ethanol and biogas. They have notable environmental advantages due to the closed carbon cycle from the production of sugarcane by photosynthesis (during the biomass growth) to its combustion in mechanical engines [24]. Several routes can be undertaken to produce electricity from sugarcane; they are shown in Figure **2**. In practice the actual amount of energy obtained and the form of that energy vary from one conversion process to another.

Bagasse is a conventional fuel for electricity cogeneration plants in Cuba. It is converted directly (direct combustion) into steam and power using back pressure steam turbines (BPST) and advanced cogeneration systems such as condensing-extraction steam turbines [25, 26]. The efficiency of these processes is around 34% and 44% (LHV basis) for back pressure and advanced condensing-extraction steam turbines, respectively. Recently, bagasse gasification has been used as alternative for cogeneration in the Brazilian sugar industry [27], where the surplus of electricity generation in the sugarcane plant was increased by more than 70%. Bagasse can be also converted into liquid fuels, usually termed as bio-oil by pyrolysis [28] and ethanol through enzymatic hydrolysis [29], as well as combustible gases by gasification [27, 30]. Enzymatic hydrolysis is preferred to conventional acid hydrolysis processes for both environmental and economic reasons. However, pre-treatment is also one of the most energy intensive steps in the process and is therefore a substantial cost factor. The thermal efficiency can reach values of 56% (LHV), which is lower in comparison with the pyrolysis process (70%) according to Leibbrandt *et al*. [31]. On the other hand, Larson *et al*. [25] have studied the introduction of bagasse gasification/ gas turbine combined cycle integrated cogeneration systems in the Cuban sugarcane industry. The efficiency of this system is around 57% (LHV base). Nevertheless, bioethanol is the most widespread sugarcane-derived fuel, which is usually used as gasoline additive to increase the octane number and improve vehicle emissions [22, 32]. On the other hand, ethanol has many advantages as a source of hydrogen, since it is easy to store, handle and transport in a safe way due to its lower toxicity and volatility. In addition, this alcohol can be produced from a wide variety of biomass sources, including sugarcane molasses, lignocelluloses and waste materials from agro-industries, etc. [33, 34]. Furthermore, by considering its high heating value (HHV=29.7MJ/kg) and its high hydrogen atom content, ethanol has been the subject of several works aiming at both the production of hydrogen through reforming processes [3, 35, 36]. In this sense, Arteaga *et al*. [3] have reported that ethanol steam reforming efficiency can be more than 60% (base LHV). The energetic auto-sustainability of SOFC power plants using hydrogen from ethanol steam reforming has been explained by Arteaga *et al*. [3]. The

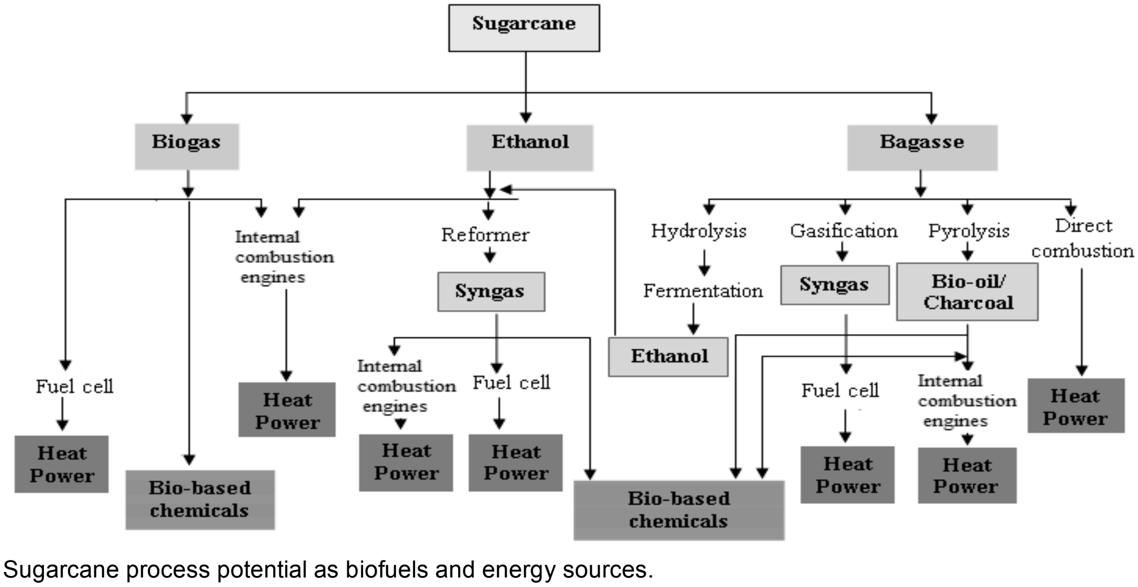

Figure 2: Sugarcane process potential as biofuels and energy sources.

overall energy efficiency of ethanol to electricity conversion (including ethanol steam process efficiency) is more than 40% (base LHV). Similar results of energy efficiency (45-52%) have been shown by Hernandez and Kafarov [37]. It is remarkable that the process efficiency is higher than the ideal efficiency of traditional power cycles (Rankine cycle 26%, combined cycle of gas-steam 48.7%) [38]. The reforming of ethanol, the pyrolysis and gasification of bagasse can give more opportunities for diversification of sugarcane industry, not only bringing renewable energy sources (bagasse, ethanol, biogas, etc) but, also bio-based chemicals for biorefinery products. Based on the existing industrial infrastructure for ethanol production from sugarcane in Cuba, the hydrogen production from ethanol could be an attractive strategy of development.

2.2. Fuel Cells

Fuel cells are considered as a major energy conversion technology of the future, due to certain inherent advantages of electrochemical conversion processes as compared to thermal combustion processes. Theoretical electrical efficiency of fuel cell takes value from 40-65% (LHV base) using pure hydrogen as feedstock, being higher than heat engines (25-40%). On the other hand, the low harmful emissions constitute an important advantage of fuel cell systems. The reason of low emissions is the lower operating temperature of a FC compared with a conventional burner, preventing the formation of NO, from oxygen/nitrogen reactions which typically starts 1000°C [39]. Some of the pollutants that are significantly lower for fuel cells are nitrogen oxides and unburned hydrocarbons (ground-level ozone precursor), and carbon monoxide (a poisonous gas) and particulate material. Currently, the main disadvantages of fuel cells technology are its high cost. However, increased development of fuel cells may decrease these capital costs. For instance, the capital costs of SOFC are expected to fall substantially from 1500 to 400 US$/kW [40, 41].

SOFC technology is the most demanding from a materials stand point and is developed for its potential market competitiveness arising from the following items [42]:

- The elevated operating temperature means that carbon monoxide and methane, always produced during the reforming of hydrocarbon fuels, is a fuel to the electrodes used within the stack, rather than a poison. This considerably simplifies the fuel processing regime and reduces cost. The high grade waste heat produced by the SOFC is of value in combined heat and power (CHP) applications and can be used to drive the endothermic fuel processing reactions *via* an integrated heat exchanger. Its efficiency can be further increased when coupled with a gas turbine (GT) cycle up to 70% [3, 43].
- Pure hydrogen fuel is not required, although hydrogen can, of course, still be used as the fuel.
- SOFCs do not present any moving parts.
- They have a potential long life expectancy of more that 40000-80000 hours (5-10 year of operation).
- The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing SOFC technology [44].

SOFCs are much in the news since they appear to be one of the most efficient and effective solutions to environmental problems that we face today. It is now well established that global warming is taking place due to effluent gas emission. They could compete with combined cycle gas turbines for decentralized applications. Moreover, its integration with the sugar-cane agro-industry sector (sugar-ethanol factories) could be a sustainable scenario for the Cuban sugar process diversification. The technical, economic and environmental analysis could be used in order to evaluate the potentialities of fuel cell and its introduction and integration in the Cuban energy sector.

3. DESCRIPTION OF STUDIED CASES

The industrial scheme under study is an integrated sugar factory and an ethanol distillery, both using the same steam, electricity and water facilities, and including bagasse incineration. The sugar factory has a cane mill capacity of 105.0t/h, obtaining 9.86t/h of sugar and 31.50t/h of bagasse. The bagasse is used as fuel at the cogeneration system in order to supply the steam and electricity process demand. The surplus of electricity (315kWh per hour) is distributed along of the National Network. However, the amount of bagasse is not enough to supply de overall electricity (847kWh) take to national network. In this case, the energy deficit (532kWh per hour) is supplied using two processes (See Figure **3**): a conventional diesel combustion engine (existing scenario) and Solid Oxide Fuel Cell technology using ethanol as feedstock from the distillery (future scenario).

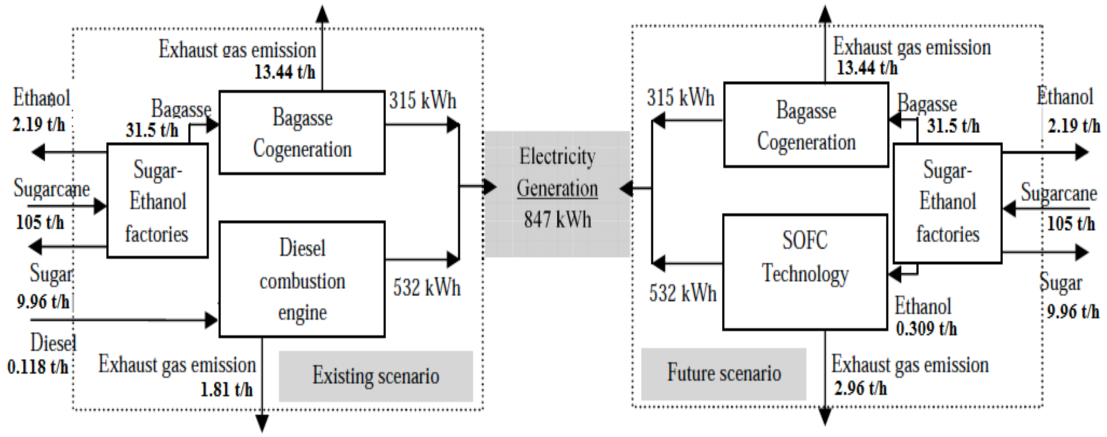

Figure 3: General description of scenarios. (Source: Casas *et al*. [15]).

Table 1: Products from each Scenario and CSS

	Products of the Sugar Plant			**Products from CSS**	
				CSS1	**CSS2**
Scenarios	Electricity, kWh	Ethanol, t/h	Sugar, t/h	Electricity, kWh	Ethanol, t/h
Existing scenario	315.00	2.194	9.860	532.00	0.00
Future scenario	847.00	2.015	9.860	0.00	0.180

The sugar, ethanol and electricity are the outgoing products, a set of 9.86t/h sugar, 2.195t/h of hydrated ethanol (96% w/w) and 847kWh of electricity obtained from the sugarcane is considered as functional unit. These data are based on a typical sugar cane factory with a daily intake of 105 tonnes of cane. The amounts of ethanol and electricity produced are different for the two technological alternatives; therefore the two schemes are extended with Conventionally Supplementary Systems (CSS) (electricity from conventional engine technology using diesel: CSS1 for existing scenario, and ethanol from cane molasses fermentation: CSS2 for future scenario). The products from two scenarios and CSS are shown in Table **1**.

The detailed description for sugar-ethanol process can be to find in Casas *et al*. [45]. According to a detailed description previously reported Arteaga *et al.* [3] and Casas *et al*. [4], the SOFC system consists of a vaporizer, a reformer, fuel cell and post-combustor. In the vaporizer, the liquid mixture (water and ethanol) is vaporized and preheated before the reformer inlet, where it is converted into synthesis gases. The mixture leaving the reformer is fed and oxidized with air inside a solid oxide fuel cell module obtaining electricity, heat and exhaust gases by an electrochemical conversion. Finally, the fuel cell depleted gases react into a post-combustion unit to fulfill the energy requirements of the process.

The main assumptions taken into account for comparison of both scenarios are listed below:

- The lower heating value of bagasse was calculated using Hugot's correlation [46]. 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.

- Primary pollutant compositions and quantities stack characteristics (high and diameter) and emission temperatures are obtained from the local factory database and completed using simulation data by Aspen-Hysys for SOFC technology [3].

- Ethanol steam reforming temperature of 973 K, a water to ethanol molar ratio of 6.5 mol/mol and a fuel utilization coefficient of 80% for SOFC power plant.

- The yeast waste is used as animal feed due to its high protein content.

- The wastewater coming from ethanol and sugar process are treated by means of a biological process (oxidation lagoon), using the liquid product in ferti-irrigation.

- The ashes from bagasse combustion and the filter cake from the sugar process are used to substitute chemical fertilizers in the agriculture stage.
- The exhaust gases from bagasse and fossil fuel combustion are the main sources of atmospheric pollution for the traditional and future scenario; their composition and quantities are obtained from a sugar-ethanol local factory and completed using energy and material balances.

3. SUSTAINABILITY ANALYSIS

3.1. Environmental Impact

The greenhouse gas emissions are considered as the most relevant environmental impacts resulting from the life cycle of sugar, ethanol and electricity. For direct emissions, all greenhouse gas flow rates are brought back to the same basis, namely CO_2 equivalent, by using their global warming potential (GWP). The GWP evaluated over 100 years is equal to 1 for carbon dioxide (CO_2) and 21 for CH_4 [47]. The GWP of direct emissions can be calculated according to the following equation:

$$m_{GHG}^{Total} = \sum_{j=1}^{n}\left(f_j^{GHG}.GWP_j\right) \tag{1}$$

where: m_{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.

CO_2 emissions produced by bagasse combustion, ethanol steam reforming and the exhaust gases SOFC burned are balanced by atmospheric CO_2 absorbed during biomass re-growth. However, the bioenergy production to some extent relies on the use of fossil energy and is not carbon neutral.

3.2. Resource Utilization Efficiency

Several researchers have suggested that the most appropriate means to correlate resource utilization is through exergy [48]. It allows, on one hand, to characterize the full set of natural resources used along the life cycle, e.g. in terms of renewability, and on the other hand to analyze the efficiency of resources conversion. Exergy is a measure of the difference of a system's state in relation to the reference environment and hence represents its potential to be utilized. For the present analysis a temperature of T_o = 298.15 K, pressure P_o = 1.013 bar and the atmosphere composition of 75.67% N_2, 20.35%O_2, 0.03%CO_2, 3.03% H_2O and 0.92% Ar are assumed as reference environment [49]. Freshwater and air exergy content is considered null at ambient temperature and pressure. The exergy of the material streams is expressed as the sum of the physical and chemical components; the kinetic and potential exergies were neglected. Life cycle exergy efficiency, irreversibility and renewability parameter of the different alternatives are calculated. The renewability parameter (α) is defined as the relationship between the renewable exergy consumption $\left(R_{\mathrm{Re}newable}^{inlet}\right)$ and the total exergy consumption of process $\left(R_{Total}^{inlet}\right)$, which is shown in the following equation [50]:

$$\alpha = \frac{R_{Renewable}^{inlet}}{R_{Total}^{inlet}} \tag{2}$$

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

The sugar cane is classified as a renewable resource; nevertheless, additives (lime, flocculants) used in the juice clarification, chemicals (HCl and NaOH) to clean, nutrients (urea and H_2S) for yeast in fermentation, as well as the fuel oil necessary to supply the heat and electricity are considered as non-renewable resources.

Life cycle exergy efficiency of the whole system (Eq.3) is defined as the ratio between the exergy of the products (sugar, ethanol and electricity) and the primary fuels *(standard exergy of all stream feed to system)* [4].

$$\eta_{exergy} = \frac{\sum_{p=1}^{3}\left(f_p.e_p^0\right)}{\sum\left(f_j^{inlet}.e_p^0\right)} : p_1 = sugar; p_2 = ethanol; p_3 = electricity \tag{3}$$

3.3. Heath External Cost

In order to estimate de health impacts and damage external cost the impact pathway approach methodology was used [51], which consists of four steps: quantification of emission sources, pollutants dispersion, physical impacts and monetary valuation.

- *Quantification of the emissions to air*: technical specifications (stack height, stack diameter, exhaust gas temperature, type of fuel etc), location (rural/urban) and emission data (pollutants emission rate, depletion velocity).

- *Pollutants dispersion*: calculation of increased pollutant concentrations in all potentially affected regions using atmospheric dispersion models for local and regional domains. PM_{10}, SO_2 and NO_x are primary pollutants; their impacts take place in the local domain, while sulfates and nitrates aerosols are produced from chemical transformation of primary pollutants (SO_2 and NO_x) and higher environmental effects are addressed in a regional domain. For the local area (<50 km from the source) a Gaussian plume model (Industrial Source Complex) is recommended to estimate the pollutant concentrations at the local domain, which was developed for EPA [52]. This model involves variables like chimney height, gas velocity and temperature, physical and chemical properties of the gases, meteorological conditions like wind direction and velocity and also topographic conditions (atmospheric stability).
- *Quantification of physical impacts (human health) on the specific receptor*. Calculation of the cumulated exposure from the increased pollutants concentration, followed by calculation of impacts (damage in physical units) from this exposure; using an Exposure-Response Function (ERF).

In the present study, the Uniform World Model (UWM) considering the IAEA simplifications is implemented due to lack of detailed atmospheric and local population distribution in the studied geographic range. The Uniform World Model (UWM) is derived by simplifying the more detailed approach of IPM function (Eq.4) shown below [53, 54]:

$$I = \int_{area} \rho(r)\, F_{er}\left(r, C(Q_m)\right) dA \qquad (4)$$

Where: I is the health impact (cases or Year of Life Loss (YOLL)), ρ is the receptor density (person/m^2), F_{er} is the slope of the exposure response function (ERF) (cases/(person.year.μg/m^3)), C is the incremental change in ambient air concentration at the earth's surface due to emission Q_m (μg/m^3), A is the impact area (m^2) and r is the source-receptor position vector (m).

- *Cost Estimation:* The physical impacts are expressed in monetary terms, e.g. damage cost by asthma is obtained by multiplication of asthma physical impact and its unit cost.

The damage costs are determined by the impacts calculated from equation 5 (e.g., asthma cases) times the unit cost (e.g. US$ per asthma attack). Unit costs for health impacts include cost of illness, and wage and productivity losses.

Damage costs are estimated according to Externel [51] and expressed by Eq. 5:

$$D_i = I_i C_i \qquad (5)$$

where D_i is the damage costs associated to each health impact (i) expressed in US$/yr, I_i is the health impact (cases or YOLL), and C_i is the unit cost (US$/cases or YOLL). The unit damage costs used within the ExterneE project for valuing health damages are presented in Table **2**. The unit costs are expressed in US dollars for the base year 2000. The following relationship is recommended to transfer these values (EU) to another country [55]:

$$\text{Unit Cost Cuba} = \text{Unit Cost EU} * \left(\frac{\text{GNP}_{\text{Cuba}}}{\text{GNP}_{\text{EU}}}\right)^{\gamma} \qquad (6)$$

where GNP gross national product normalized per capita, γ is the income elasticity coefficient; typical values ranging from 0.3 to 1 [56]. In this case it was taken as 1, assuming that a Cuban person is willing to spend the same percentage of the income as someone living in Europe in order to achieve the same health

Table 2: Unit Cost for Health Impact Assessment

Health Impacts	Cuba Unit Cost (US$$_{2000}$) Per Case YOLL	Sources
Chronic mortality	14421.39	[54]
Acute mortality	25207.60	[54]
Chronic bronchitis	2538.69	[54]
Acute asthma crisis	30.4	[58]
Hospital Admission for respiratory causes	325.42	[51]
Emergency room visits	79.48	[58]
Restricted activity days	17.87	[58]

benefit. The GNP per capita for Cuba is for the year 2009 was 5565.39 US$ [57]. The value for the EU (36615.86 US$) was extracted from the same source. The values of Year of Life Loss (YOLL) were taken from Spadaro [54] and are the base for costs evaluation and converted from dollars of the year 2000 to dollars of the year 2009 using an annual inflation rate of 3%.

4. RESULTS AND DISCUSSION

4.1. Environmental Impact

The effect of environmental impact associated to greenhouse gases (GHG) is depicted in Figure **4**. The higher greenhouse gases (GHG) emissions (646 $t_{CO2eq}h^{-1}$) are obtained for traditional sugar-ethanol process. This difference is mainly due to additional exhaust gases from non-renewable resource combustion (diesel) installed to fulfill a gap of 531.71kWh of electricity, which represent 63% of overall electricity consumption. Integration of the SOFC power plant with a conventional sugar-ethanol process has a positive effect on GHG emissions, allowing a reduction of the CO_2 emissions by 360 $t_{CO2eq}h^{-1}$ in comparison to the reported for sugar-ethanol factory. The main reason is that the syngas produced in the reforming reactor and the post-combustor off gases include biogenic CO_2 to the total mass balance (0.58kg_{CO2eq} h^{-1} kW^{-1} produced by SOFC) but not to the GHG category. Overall, GHG emissions are reduced by 55% when compared with traditional sugar-ethanol process. The lower greenhouse emissions are associated to the primary fuel (non-renewable fuel), if it is obtained from renewable resources (bioethanol and bagasse), establishing a carbon closed loop, from the photosynthesis to the final conversion step.

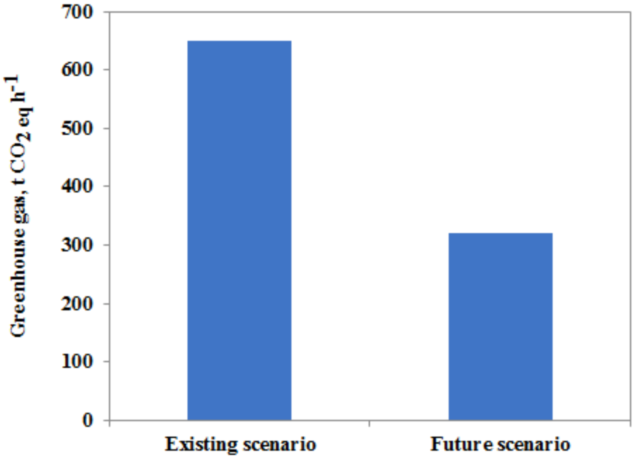

Figure 4: Greenhouse gas emissions for both studied scenarios.

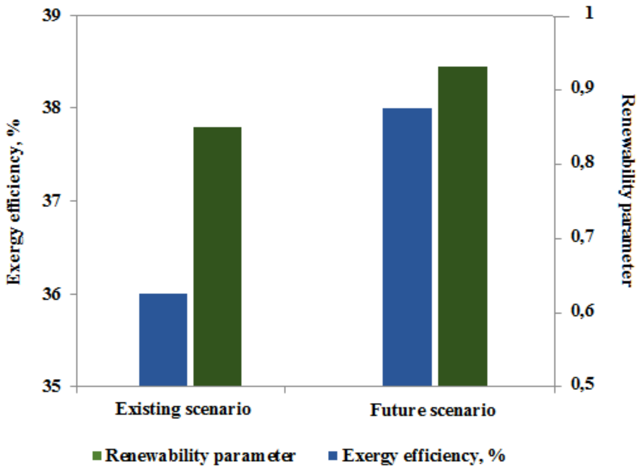

Figure 5: Exergy efficiency and renewability parameter for studied scenarios.

4.2. Resource Utilization Efficiency

Figure **5** shows the comparison of the exergy efficiency and renewability parameter for each scenario, traditional sugar-ethanol process (existing scenario) and integration of SOFC technology (future scenario). The renewability and exergy efficiency are also affected by fuel quantities, specifically from non-renewable resources. Sugar, ethanol and electricity from sugarcane are renewable sources of energy only to a certain extent, since about 15.1% and 7.6% of the total inlet feedstock come from fossil sources in both scenarios. The use of the SOFC technology has a positive effect on the exergy efficiency with respect to conventional sugar-ethanol process. The efficiency varied between 38.0% and 36.18% for integration of SOFC technology and traditional sugar-ethanol process. According to the definition written previously (Eq. 3), the resources and their quality have a strong influence (inversely proportional) on the exergy efficiency; for this reason, the exergy efficiency of existing scenario presents lower values, which means that the resource consumption is higher in comparison with future scenario.

The renewability parameter is associated with the amounts of fossil fuels and chemicals, which are considered as non-renewable resources. The reduction of non-renewable resources increases the renewability character of the process. Indeed, the integration of SOFC technology is more renewable than the traditional sugar-ethanol production, obtaining indexes near to 0.93 for future scenario as well as 0.85 for the traditional process. This performance is related with the high fossil fuel consumption to produce the deficit of electricity (532kWh) using diesel combustion engines for traditional sugar-ethanol process.

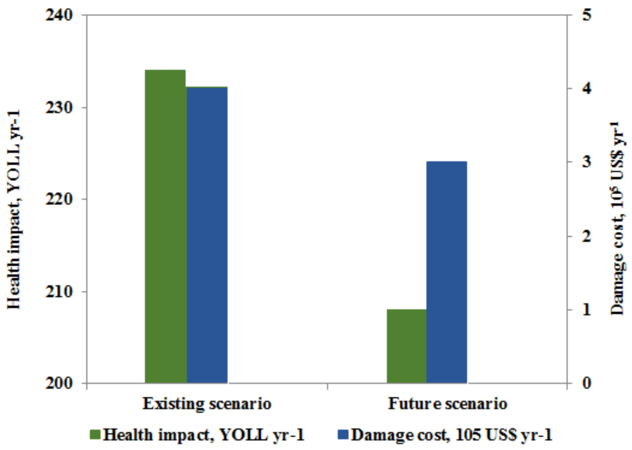

Figure 6: Health impact and damage cost for each studied scenario.

4.3. Health External Cost

According to the definition written previously (Eq. (4)), the amounts of air pollutants have a strong influence (directly proportional) on the health impact and their corresponding damage cost; for this reason the total health impact of the existing scenario presents higher (232 YOLL yr^{-1}) values than future scenario (208 YOLL yr^{-1}). Diesel engine could be replaced by SOFC technology Figure **6**, avoiding the health impacts and health external costs around 12%. The amounts of air pollutants have a strong influence (directly proportional) on these results, so that the atmospheric emissions are lower for the future scenario (integration of SOFC technology). Moreover, the fuel quality and type is another factor that affects directly the health external cost. In this study, the ethanol used as feedstock in the SOFC is free of sulfur, while the diesel has more than 3.5% of sulfur. The bagasse cogeneration system is the main way to produce electricity from biomass in Cuba, allowing the reduction of the fossil fuel consumption. A sugarcane bagasse ton (on a 50% wet basis) is equal to 1.6 barrels of fuel oil on an energy basis. However the emission derived of it has a notable influence on human heath, mainly by the quantities of PM emitted to air [11, 45]. In this sense, the bagasse cogeneration has higher contributions on the health costs (close by 88% of the total external cost), mainly due to low efficiency of cogeneration system (low efficiency boilers and low pressures and temperature of steam turbines) which favors the increment of air emissions, specifically PM_{10}.

4.4. SWOT Profile

Strengths Weaknesses Opportunities Threats (SWOT) profile of SOFC provides clear and an unbiased view of the key technology strengths and weaknesses and the potential opportunities and threats (See Table **3**). The profile helps to formulate business strategies and to better understand partners, customers and competitors needs.

Higher thermodynamic efficiencies, lower environmental pollution, and cogeneration applications are the most relevant *strenghts* of SOFC technology. The cogeneration application is still in the future, but such an elegant system is interesting. Whichever path, it may be possible for heat engines to capture 'waste'

Table 3: SWOT Analysis of SOFC Technology

Strenghts	Weaknesses
Technology design: High electrical efficiency Uninterruptible power supplies Higher volumetric power density Low pollution levels Absence of the movable mechanical parts Complete Fuel flexibility Application diversity: Cogeneration system with gas turbine (SOFT-GT) Mobile and stationary application	Technology design: Hydrocarbon fuels need pre-reforming such: Natural gas Diesel Propane Alcohols etc. Commercial application restricted: Operating temperatures High amount of exhaust gasses
Opportunities	**Threats**
Business Expansion Increase Renewable Energy technology Replace the fossil fuel power source Diversification of sugar factory	Competitive energy market Current technology (advanced cogeneration system, steam turbines, gas turbine combine cycle) Lack of consumers knowledge

Table 4: Exergy Efficiency (η_{EXE}) of Integration of SOFC into Traditional and Novel Energy Systems

System	Fuel	η_{EXE} (%)	Ref.	System	Fuel	η_{EXE} (%)	Ref.
Gasification-ST-SOFC	Wood chips	43	[41]	Gasification-SOFC	Charcoal	45.72	[60]
Gasification-SOFC-Stirling	Wood chips	40	[61]	SOFC-ORC-Chiller	Natural gas	35-36	[62]
Reforming-SOFC	Ethanol	33.9	[4]	SOFC-GT	Natural gas	46.7	[63]
SOFC-CHP	Natural gas	54.4	[64]	Gasification- SOFC	Bagasse	35.2	[30]

heat from SOFCs. Combined heat-power cycles (integration with turbine gas) have been highlighted by Calise *et al*. [6] and [59], which obtained efficiencies of more than 70% considering heat recovery. SOFC based decentralized power generation systems have received much attention for their efficiency, fuel flexibility and integration potential to traditional and novel Combined Heat and Power cycles (CHP) (See Table **4**).

As reported in Table **4**, average benefits to all of the above-mentioned systems, in terms of exergy efficiency, are an increments of 10-25%. This effect can vary depending on the integration strategy and utility management along the process units.

Taking into consideration the objectives of the Cuban National Energy Sources Development Program and the priorities set by Cuba for research and development in the near term, the major energy policies chosen for evaluation were: (i) reducing the dependence on energy imports, (ii) increasing the share of renewable energy sources and (iii) improving energy efficiency of sugar factories. However for SOFCs, these strengths and opportunities come at operating temperatures and can result into degradation and failure of the delicate anode-electrolyte-cathode structure, a critical roadblock in bringing this technology to the point of commercial viability. This is the most important *weakness* found currently.

The SOFC technologies are in its development stage, but their commercial productions are yet limited. In this sense, many efforts have been done for development of suitable materials and the fabrication of ceramic structures, which are the main technical limitation toward SOFCs technology [44]. The *Threats* are associated mainly to the competitive energy market. The gas turbine/steam turbine combined cycle is the main competitor to large SOFC/turbine hybrid systems from a cost-of-electricity point of view. Specific investment and maintenance costs are low, resulting in a low cost of electricity (approximately 2.5 US cents per kWh). This can be regarded as a reference commodity price for electricity from the grid. Gas engines like diesels and gas turbines have a lower electrical efficiency together with higher emissions and higher maintenance cost, but the installed cost is attractive. The capital costs of SOFC are expected to fall substantially from 1500 to 400 US$/kW [61], but the range of projected unit cost reductions is wide and depends heavily on government policies and the place of deployment. The competitive energy market is the main *Threats* of SOFC technology (Table **1**). As was previously explained the existing technologies such steam and gas turbine can compete with fuel cell technology from installed cost point of view. With regard to this query, a preliminary comparative analysis between SOFC technology and existing bagasse cogeneration technology (condensing-extraction

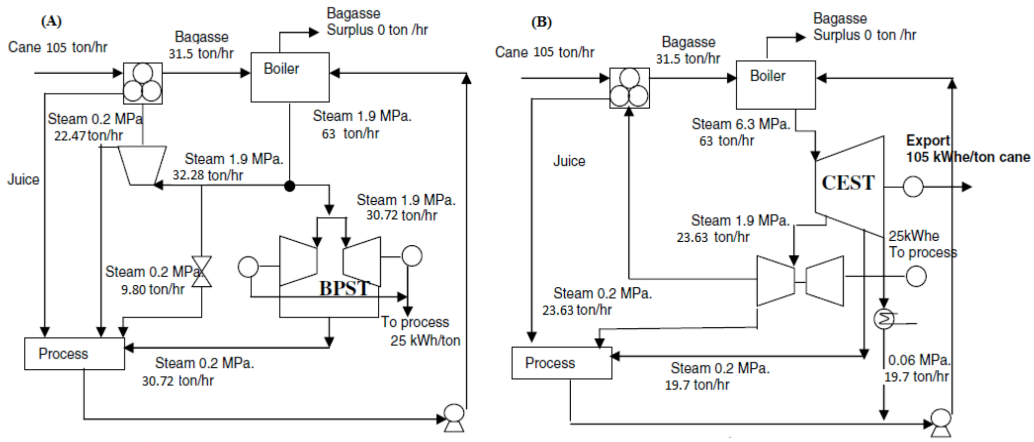

Figure 7: Bagasse cogeneration systems. A back pressure steam turbine (BPST). B condensing- extraction steam turbine (CEST) with two extractions.

steam turbine) is discussed. The traditional back pressure steal turbine (BPST) and advanced condensating-extraction steam turbine (CEST) bagasse cogeneration systems are shown in Figure **7**.

The existing steam supply and power generation systems at the sugar mills in Cuba generate an average of 20-25kWh per ton of sugarcane in low efficiency back pressure steam turbines (BPST). At the same time it contributes to high air emissions. The BPST case is a typical small boiler which burns all bagasse that is produced per ton of produced sugar. It operates at low pressure (1.9 MPa) and temperature (593K). The cogeneration system in sugar mills needs to be improved in order to reduce the current electricity shortage.

In order to analyze the effect of technology on efficiency of sugar factory a comparison between SOFC and traditionally schemes is performed. Condensation-extraction steam turbine (CEST) and biomass integrated gasifier/gas turbine combine cycle (BG/GTCC) are used to improve energetically the bagasse cogeneration efficiency [25, 26]. The BG/GTCC does not yet have a sufficient maturity for its large-scale implementation in the sugar industry around the world. There is also the additional expenditure in ensuring the power-heat system capable of handling this higher pressure, plus a higher investment cost. The estimated cost for a BG/GTCC (60 MW cogeneration system) is 1400US$/kWe [17].

However, the CEST technology is from a technical point of view and in scale of installed capacities nearest to the current operational parameters currently used in the sugar industry. In this sense, this technology is selected to be compared with SOFC technology in the future. The analysis relies on overall exergy efficiency, investment costs and environmental benefits (reduction of CO_2 emissions). Exergy efficiency of the overall sugar-ethanol-electricity process is calculated using the Eq. 3. The sugar factory has a cane mill capacity of 105.00t/h, obtaining 9.86t/h of sugar, 4.12t/h of molasses and 31.50t/h of bagasse (50% wet). The operation of the sugar mill is 100d/year. The preliminary results are depicted in Table **5**.

With the successful implementation of cogeneration systems (CEST) and SOFC technology into sugar mills factory outlined in this dissertation, it is evident that both technologies are feasible solutions to improve the overall energy usage. Both scenarios can also reduce dependency of industries on the electricity grids for power requirements to be optimized. This would save the plant from unexpected disturbances of the power system. Furthermore, the non-required electricity to be transferred over a long distances, the transmission and distribution losses would be negligible. In addition, it may enable them to diversify their energy base as well as the rehabilitation, modernization and centralization of cane-milling activities. On the other hand, the fossil fuel consumption and its CO_2 emissions are reduced for two technologies. However in the current economic situation, the implementation of advanced cogeneration system (CEST) in a sugar mill factory is a more attractive scenario than SOFC technology from exergy efficiency and the net CO_2 emissions point of view. The net electricity cogeneration (130kWh/ton$_{\text{sugarcane}}$), the electricity surplus (105kWh/ton$_{\text{sugarcane}}$), and global exergy efficiency (42%) are higher for CEST. The additional electricity surplus supplied to the grid should avoid electricity generation from fossil fuels, reducing the consumption and CO_2 emissions from its combustion. This is equivalent to a reduction of 0.16% and 0.02% net tons$_{CO2}$ annually for CEST and BPST+SOFC.

Table 5: Future Sugar Mill Process Configuration

Parameters	CEST	BPST + SOFC
Operational conditions	6.3 MPa and 793 K	0.2 MPa and 873 K
Fuel	Bagasse	Bagasse/ethanol
Electricity cogeneration, kWh/ton$_{\text{sugarcane}}$	130	33
Electricity surplus, kWh/ton$_{\text{sugarcane}}$	105	10
Overall efficiency, %	42	38
Investment cost, US$/kW	1109	1500-400
Fossil fuel consumption reduction[a], %	0.16	0.02
Net CO_2 emission reduction, %	0.16	0.02

[a] It is referred to total fossil fuel ($4.5*10^6$ tons annual) used to produce electricity in Cuba [19].

From the economic point of view, the CEST and SOFC technology show comparative investment costs. For a CEST 41 MW cogeneration system, investment cost are 1109 US$/kW [26], and for SOFC technology it can take values from 1500-400 US$/kW. According to the U.S. Department of Energy Office of Fossil Energy, SOFC systems cost about $400 per kW in 2010 [40, 41]. Analyzing each technology independently, the SOFC has higher fuel conversion into electricity (38% LHV basis) than CEST (20%) [25]. Furthermore, the main emissions obtained from ethanol electrochemical conversion according to results of Casas *et al*. [4] are CO_2 (5.12%), CO (0.14%), H_2O (24%), N_2 (62%), and O_2 (9%), which are free of particulate material, NO_x and sulfur dioxide. The most significant pollutant emitted by bagasse-fired boilers is particulate matter [11, 13]. SO_2 and NO_x are also emitted to air, which are lower than conventional fossil fuels according to Janghathaikul and Gheewala [65], due to the characteristically low levels of sulfur (0.63% dry base) and nitrogen (0.3% dry base) associated with bagasse. Considering the emission factors for bagasse-fired boilers reported by EPA [66], air emission mass fractions are: 33% of PM_{10}, 37% CO_2, 29% NO_x, and a little amount of polycyclic organic matter (0.024%). On the other hand, the results corroborate that the bagasse cogeneration is responsible of 88% health damage costs, which are associated mainly to higher PM_{10} emitted to air, while the contribution of SOFC on health external cost are null. Beside, another limitation of CEST with respect of SOFC is focused on the fuels availability; bagasse is only available in the sugar mills on-season and can be extended just few months in off-season, while the ethanol can be used all year.

5. CONCLUSION

The Solid Oxide Fuel Cell technology and its integration into the Cuban sugar sector have been studied, giving novel and important information about sustainability of this process. In this context, the integration of SOFC technology with the traditional sugar-ethanol process and electricity, using bagasse cogeneration, is environmentally feasible, specifically with respect to greenhouse gas emissions, renewability and exergy efficiency. The lower greenhouse emissions are associated to the primary fuel, if it is obtained from renewable resources (bioethanol and bagasse), establishing a carbon closed loop, from the photosynthesis to the final conversion step. The renewability and exergy efficiency are also affected by fuel quantities, specifically from non-renewable resources. Sugar, ethanol and electricity from sugarcane are renewable sources of energy only to a certain extent, since about 15.1% and 7.6% of the total inlet feedstock come from fossil sources in both scenarios. The substitution of diesel internal combustion engines by SOFC technology in a sugar-ethanol industry has a reduction on health impact and total damage cost of 25.76 YOLL yr^{-1} and 296042.46 US$ yr^{-1} respectively. The implementation of SOFC technology into sugar-ethanol factories has a net cost-benefit of $2.6*10^5$ US$/year. Nowadays, the SOFC technology implementation in Cuba mills factory might be affected by competing cogeneration technology, energy policy and priorities adopted by the Cuban government.

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