Integrating Life Cycle Assessment and Input-Output Analysis for the assessment of ethanol greenhouse gases emission in Brazil

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Abstract

The increasing ethanol production in Brazil is deeply related to the global demand for alternative energy sources which can both decrease the reliance of economic sectors on non-renewable energy and drive global energy production towards a more sustainable situation. Simultaneously, it is important to improve techniques that allow the assessment of environmental impacts from different scenarios of biofuel production, aiming to improve its sustainability. The Life Cycle Assessment (LCA) is recognized as a powerful methodology that provides detailed information about the environmental impacts related to agricultural production, industrial stage and consumption phase of sugarcane-based products and co-products. However, LCA has some limitations regarding the definition of system boundaries and also requires huge effort during the data collection for Life Cycle Inventory. In this sense, a different technique such as the LCA integration with Input-Output Analysis (IOA) emerges as an alternative approach which allows expanding the boundaries of LCA studies to the country's economy without losing important information provided in the life cycle inventory. This approach is based on the country's input-output matrix, which allows calculating the direct and indirect impacts related to all production sectors of a country. In this paper, such integrated approach will be used to simulate the greenhouse gases emission related to different technological scenarios of bioethanol production in the Virtual Sugarcane Biorefinery (VSB), under development by the Brazilian Bioethanol Science and Technology Laboratory (CTBE). Data for the assessment were obtained from literature and computing simulation. Preliminary results show that integrated first and second generation ethanol production (1G2G) has the lowest global warming potential (measured in $CO_{2\text{-eq}}$) when compared with first generation ethanol production technologies in Brazil.

Keywords: *life cycle assessment, input-output analysis, ethanol production, greenhouse gases emission*

1. Introduction

The Technological Assessment Program of the Brazilian Bioethanol Science and Technology Laboratory (CTBE) is developing a comprehensive tool called Virtual Sugarcane Biorefinery (VSB) to evaluate, from a sustainability standpoint, different biorefinery configurations (Bonomi et al. 2012; Cavalett et al., 2012). Currently, Life Cycle Assessment is used in environmental evaluations whereas I-O analysis provides information about the economic and social impacts of different sugarcane biorefinery alternatives. Aiming at the continuous improvement of the VSB framework, this paper will show the preliminary results of LCA and Input-Output analysis integration for the assessment of ethanol production technologies in Brazil.

Apparently, I-O analysis and LCA are unrelated methods. However, international scientific literature reveals that they feature complementary aspects for at least two decades. One of the first LCA studies including the I-O approach in its scope, Moriguchi et al. (1993), had the goal of calculating the life cycle CO_2 emissions of an automobile through a combination of a process-based life cycle inventory with input-output matrices of Japan. Over time, studies have been performed using at least four basic approaches: Tiered hybrid LCA, Input-Output-based hybrid LCA, Economic Input-Output Life Cycle Assessment, and Integrated Hybrid LCA (Rojas, 2009).

Although LCA and I-O methods were first integrated during the mid 1990's, the potential of I-O approach of estimating the materials and energy resources required for and the environmental emissions resulting from activities in a country's economy have been explored since the 1970's by Wassily Leontief based on his earlier input-output work from the 1930's (Hendrickson et al., 2006). Also during the mid 1990's, researchers at the Green Design Institute of Carnegie Mellon University operationalized Leontief's method, once sufficient computing power was widely available to perform the large-scale matrix manipulations required in real-time. This approach is called Economic Input-Output Life Cycle Assessment (EIO-LCA), which provides guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain (GDI, 2012).

In order to perform a preliminary case study to evaluate greenhouse gases emissions of different sugarcane ethanol production alternatives in Brazil, this paper discuss the main findings of using integrated LCA and IO for the assessment of greenhouse gases emission using the Brazilian input-output table of 2009.

2. Methods

2.1 The EIO-LCA approach

Among the various IO-LCA integration approaches described in the literature, this paper will focus on the Economic Input-Output Life Cycle Assessment (EIO-LCA). The theoretical framework was developed by Wassily Leontief in the 1970s based on his earlier input-output work from the 1930s for which he received the Nobel Prize in Economy. Researchers at the Green Design Institute of Carnegie Mellon University operationalized Leontief's method in the mid-1990s, once sufficient computing power was widely available to perform the large-scale matrix manipulations required in real-time.

Basically, from the Input-Output accounts a matrix or table *A* is created. The elements in matrix *A* indicate the amount of output from one industry required to produce one dollar of output from another industry. The Leontief inverse $(I - A)^{-1}$ allows calculating the vector including all suppliers output (X) based on an incremental change in final demand (Y), according to the equation below (Hendrickson et al., 2006):

$$X = (I-A)^{-1}Y \qquad (1)$$

To determine the total (direct plus indirect) impact throughout the economy, the direct impact value is used with the EIO model. A vector of the total external impacts (*E*) can be obtained according to the expression below, where R is a diagonal matrix used to denote the environmental impact in sectors, and *X* is the vector of relative change in total output based on an incremental change in final demand *(Y)*:

$$E = r_1X_1+r_2X_2+\ldots+r_nX_n = R.X = R[I-A]^{-1}Y \qquad (2)$$

According to Hendrickson et al. (2006), a variety of impacts can be included in the matrix R - resource inputs such as energy, electricity, or water; or environmental burdens such as criteria air pollutants, global warming gases, or hazardous waste. In this paper, R matrix is related to the greenhouse gases emitted by sectors of Brazilian economy.

The Environmental Input-Output Life Cycle, which is basically divided in the following steps: i) obtaining the matrix *A* of technical coefficients of Brazilian sectors, ii) simulating a shock in final demand (*Y*) for each scenario, iii) obtaining the impact on all suppliers output (*X*) e iv) obtaining the environmental impact (*E*) from all suppliers output based on matrix R.

Three main scenarios of ethanol production technologies will be evaluated: (i) 1G-2009, which represents first generation ethanol production with average technological conditions of Brazilian autonomous distilleries in 2009; (ii) 1G-optimized corresponds to a situation by which all Brazilian autonomous distilleries have implemented the best current technologies for first generation ethanol production that allows selling the surplus electricity by using straw (transported from the field to the industry), reducing steam demand and using a more efficient cogeneration system to produce steam and electricity; (iii) 1G2G represents the integrated first and second generation ethanol production with pentoses biodigestion (with future hydrolysis technology) selling electricity surplus.

Table 1. Description of scenarios evaluated for autonomous distilleries in the Virtual Sugarcane Biorefinery.

Scenario	**Description**
1G-2009	First generation ethanol production, average technology of 2009.
	Ethanol (64.7 kg/ton of sugarcane). No electricity surplus. No sugar production.
1G-optimized	Optimized first generation ethanol production, with electricity production.
	Ethanol (64.8 kg/TC). Electricity surplus (180 kWh/TC). No sugar production.
1G2G	Integrated first and second ethanol production, with electricity production.
	Ethanol (92.3 kg/TC). Electricity surplus (80 kWh/TC). No sugar production.

These different technological scenarios of bioethanol production will be inserted into the Brazilian *A* matrix of 110 products and 56 sectors estimated by Guilhoto and Sesso Filho (2005) and Guilhoto and Sesso Filho (2010) according to official data published by the Brazilian Institute of Geography and Statistics (IBGE). Moreover, three sugarcane production scenarios will be considered and also inserted into the A matrix, since each distillery will use different sugarcane type as input: (i) sugarcane cultivated using average agricultural technology of Brazil in 2009 (called "Sugarcane 2009") will be an input to 1G-2009 scenario; (ii) sugarcane cultivated in optimized agricultural conditions without straw burning and with straw removal and delivery to the biorefinery ("Sugarcane-S 1G"), which will be an input to the 1G-optimized scenario; and (iii) sugarcane produced in optimized technological conditions ("Sugarcane-S 1G2G") with trash removal and reduced use of fertilizer as more vinasse is produced per ton of sugarcane processed in an 1G2G autonomous distillery. Data for the assessment were obtained from literature and computing simulation carried out in the Brazilian Science and Technology Bioethanol Laboratory (CTBE).

3. Results

3.1 Matrix of technical coefficients

Technical coefficients are necessary to describe the set of different sugarcane and ethanol production technologies. In this paper, different technologies are described both in columns (sectors) and rows (products). Based on Guilhoto e Sesso Filho (2010), sugarcane and ethanol production scenarios were inserted in the Brazilian input-output table of 2009. Such new table has 65 sectors (10 new sectors were added to the original 55-sector table) and 120 products (10 new products were added to the initial 110-product table), as summarized in table 2. Rows related to products ethanol 1G-2009, ethanol 1G-optimized, Ethanol 1G2G, Electricity 1G-optimized and Electricity 1G2G are full of zeros. It means that these products are not consumed in intermediate consumption (as inputs to produce other inputs) but are fully allocated to final demand by consumers. Technical coefficients for new technologies were obtained by computer simulation in CTBE (Bonomi et al. 2012). Coefficients for the other sectors were based on official data of Brazilian National Accounts System according to the 2009 estimates from Guilhoto and Sesso Filho (2010).

Table 2. Summarized table of technical coefficients for sugarcane and ethanol production technologies in 2009.

	Sugarcane industry – average	Autonomous distillery 1G 2009	Autonomous distillery 1G optimized	Autonomous distillery 1G2G	Sugarcane sector - average	Sugarcane sector – 1G 2009	Sugarcane sector – 1G-optimized	Sugarcane sector – 1G2G	Electricity production (rest of economy)	Electricity distribution	Rest of economy (55 sectors)
Sugarcane, 2009	0,0000	0,4569	0,0000	0,0000	0,0000	0,0424	0,0000	0,0000	0,0000	0,0000	0,0000
Sugarcane-S 1G	0,0000	0,0000	0,3686	0,0000	0,0000	0,0000	0,0425	0,0000	0,0000	0,0000	0,0000
Sugarcane-S 1G2G	0,0000	0,0000	0,0000	0,3102	0,0000	0,0000	0,0000	0,0428	0,0000	0,0000	0,0000
Ethanol 1G-2009	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Ethanol 1G-optimized	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Ethanol 1G2G	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Rest of electricity (generated)	0,0036	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,3481	0,0466
Electricity 1G-optimized	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Electricity 1G2G	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Distributed electricity	0,0017	0,0000	0,0000	0,0000	0,0054	0,0000	0,0000	0,0000	0,0000	0,0000	0,3196
Rest of the economy (110 prod.)	0,6418	0,1052	0,0820	0,0777	0,3431	0,3251	0,3327	0,3258	0,4001	0,4016	0,3061

* This table is a simplification of the original matrix of technical coefficients, which has 120 rows and 65 columns (7800 cells).

3.2 Economic impact of ethanol production

Using the input-output model of Brazilian economy in 2009, this paper simulates the economic impact of a shock in ethanol production final demand considering three different technologies: autonomous distillery 1G 2009, autonomous distillery 1G optimized and autonomous distillery 1G2G. In order to compare the product "ethanol", three shocks in final demand for ethanol were simulated by separate. These shocks intend to simulate the isolated effect of additional R$ 1,000,000 of ethanol to the entire Brazilian economy, considering different ethanol production technologies.

Before simulating the impact of ethanol technologies on Brazilian economy, it is important to highlight that producing R$ 1 million of ethanol in autonomous distillery 1G 2009 represents a shock of R$ 1 million for ethanol final demand. However, for autonomous 1G-optimized and 1G2G distilleries, the shock in final demand is greater than R$ 1 million since there is electricity as a co-product of ethanol production. Then, for producing R$ 1 million of ethanol in 1G optimized autonomous distillery, there is an actual shock of R$ 1,316,000 due to a simultaneous electricity output of R$ 316,000 in this technological configuration. Complimentary, for producing R$ 1 million of ethanol in 1G2G autonomous distillery the overall shock in the economy is R$ 1,097,000 due to an electricity output of R$ 97,000. All calculations were made by considering ethanol and electricity prices at R$ 1 per liter and R$ 0.141 per kWh, respectively.

Simulations of three different shocks were carried out using the input-output model. Table 3 shows the economic impact related to three different technologies of ethanol production. Sugarcane production is deeply tied to these three scenarios, since it is the main input for ethanol production. In the first scenario (1G-2009), inorganic chemical products represent the third most important output mostly due to the need of fertilizer application during the agricultural phase. For the other two scenarios (1G optimized and 1G2G), electricity generation is the third most important product since it is a co-product of ethanol production.

In general, scenario 1G2G is related to the lowest overall impact to the economy (roughly R$1,900,000), which indicates a more efficient technology, since it requires less resources from the economy to produce the same R$ 1 million of ethanol when compared with the other two scenarios. Subtracting values of ethanol production and electricity co-generation (rough R$ 100,000) from the list of overall impacts, it is possible to infer that R$ 1 million of 1G2G ethanol required R$ 800,000 as direct and indirect resources from the entire economy.

The highest overall impact to the economy is related to ethanol 1G optimized (R$ 2,420,000). However, after subtracting values of ethanol production (R$ 1,000,000) and electricity co-generation (rough R$ 300,000) from the list of overall impacts, direct and indirect resources required from the entire economy corresponds to nearly R$ 1,120,000. This number is very close to the 1G-2009: considering the overall impact (R$ 2,050,000) and the fact that there is no electricity output, direct and indirect resources required from the entire economy to produce R$ 1,000,000 of ethanol corresponds to roughly R$ 1,050,000.

3.3 Environmental impact of ethanol production

Based on the economic impact of ethanol production, this paper will also show a preliminary assessment of greenhouse gases (GHGs) emission from three different ethanol production technologies. In order to do so, this paper will calculate the GHGs from products according to the EIO-LCA (Economic Input-Output Life Cycle Assessment) approach. Then, a vector of GHGs emission is required. Basically, this vector provides the amount of direct $CO_{2\text{-eq}}$ emissions (due to CO_2, CH_4 and N_2O) in order to produce R$ 1 of a given product as stated in the Brazilian input-output table. In this paper, a vector with 120 values was required, since Brazilian economy is described as a set of 120 products. Values of 110 products were obtained from Cunha (2012) estimative based on official data from Ministry of Science and Technology (MCT). The remaining 10 products are related to sugarcane, ethanol and electricity production technologies; these values were obtained by computing simulations carried out in CTBE. Therefore, it is possible to convert economic impact into its environmental impact measured in greenhouse gases emission ($CO_{2\text{-eq}}$), as shown in Table 4.

Table 3. Economic impact in Brazilian economy due to ethanol production considering three different technological scenarios.

Scenario 1		**Scenario 2**		**Scenario 3**	
Autonomous distillerie (1G 2009)	**Impact (R$)**	**Autonomous distillerie (1G optimized)**	**Impact (R$)**	**Autonomous distillerie (1G2G)**	**Impact (R$)**
Ethanol (1G 2009)	1,000,000	Ethanol (T-1G optmized)	1,000,000	Ethanol (T-1G2G)	1,000,000
Sugarcane (1G-2009)	477,114	Sugarcane (T-1G optimized)	506,648	Sugarcane (T-1G2G)	355,749
Inorganic chemicals	85,019	Electricity generation (1G optimized)	316,068	Electricity generation (T-1G2G)	97,646
Trade	58,408	Inorganic chemicals	84,425	Inorganic chemicals	55,914
Diesel	50,023	Diesel	62,358	Diesel	45,151
Petroleum and natural gas	39,330	Trade	62,054	Trade	44,990
Other refined petroleum products and coke	35,225	Petroleum and gas	37,172	Petroleum and natural gás	26,241
Cargo transportation services	30,846	Cargo transportation services	31,856	Cargo transportation services	22,780
Electricity, gas, water, sewage and urban cleaning	19,368	Other non-metallic mineral products	21,664	Other chemicals	19,738
Financial services and insurance	18,947	Electricity, gas, water, sewage and urban cleaning	20,548	Electricity, gas, water, sewage, urban cleaning	15,151
Agricultural pesticides	18,722	Financial services and insurance	20,517	Other non-metallic mineral products	15,039
Services to companies	18,143	Agricultural pesticides	19,907	Financial services and insurance	14,778
Other non-metallic mineral products	17,385	Services to companies	19,047	Agricultural pesticides	14,099
Electricity generation	15,306	Other refined petroleum products and coke	17,664	Services to companies	13,858
Pharmaceuticals	13,834	Pharmaceuticals	17,320	Pharmaceuticals	12,869
Gasoline	13,756	Other chemicals	16,751	Other refined petroleum products and coke	11,291
Sugar	12,265	Electricity generation	15,083	Electricity generation	10,673
Non-metallic minerals	9,894	Gasoline	12,960	Gasoline	9,143
Information services	9,801	Sugar	12,086	Sugar	8,552
Repair and maintenance services	9,720	Repair and maintenance services	11,678	Repair and maintenance services	8,413
Real state services	8,855	Information services	10,459	Information services	7,695
Other chemicals	8,163	Non-metalic minerals	10,397	Non-metalic minerals	7,196
Organic chemicals	7,257	Real state services	8,906	Organic chemicals	6,664
Electric power transmission	6,977	Organic chemicals	8,475	Real state services	6,378
Sugarcane	6,632	Rubber products	8,029	Rubber products	5,846
Rubber products	6,186	Electric power transmission	7,175	Electric power transmission	5,010
Ethanol	5,710	Sugarcane	6,538	Sugarcane	4,627
Metal products	5,665	Metal products	5,923	Metal products	4,486

Sum of other products (92 products remaining)	41,519	Sum of other products (92 products remaining)	51,766	Sum of other products (92 products remaining)	38,570
Overall	2,050,094	Overall	2,423,486	Overall	1,888,558

Table 4. Environmental impact of GHG´s emission for ethanol production considering three different technological scenarios.

Scenario 1 **Autonomous distillerie (1G 2009)**	**Emission** **(g CO_{2-eq}/L)**	**Scenario 2** **Autonomous distillerie (1G optimized)**	**Emission** **(g CO_{2-eq}/L)**	**Scenario 3** **Autonomous distillerie (1G2G)**	**Emission** **(g CO_{2-eq}/L)**
Sugarcane (1G-2009)	414.29	Diesel	117.20	Diesel	101.62
Diesel	123.71	Sugarcane (1G-optimized)	82.53	Sugarcane (1G2G)	76.27
Ethanol (1G 2009)	45.11	Etanol (1G-optimized)	47.13	Ethanol (1G2G)	32.29
Gasoline	35.70	Gasoline	25.56	Gasoline	21.59
Inorganic chemicals	12.99	Inorganic chemicals	9.80	Inorganic chemicals	7.77
Other refined petroleum products and coke	10.11	Petroleum and natural gas	6.29	Petroleum and natural gas	5.32
Petroleum and natural gas	8.76	Cement	6.14	Cement	5.30
Fuel oil	7.00	Fuel oil	5.64	Fuel oil	4.76
Cement	6.97	Other non-metallic mineral products	5.46	Other non-metallic mineral products	4.54
Other non-metallic mineral products	5.76	Other refined petroleum products and coke	3.85	Electricity generation	3.08
Electricity generation	4.86	Electricity generation	3.64	Sugarcane	2.99
Sugarcane	4.72	Electricity generation (1G-optimized)	3.58	Other refined petroleum products and coke	2.95
Organic chemicals	2.32	Sugarcane	3.53	Organic chemicals	1.94
Electric power transmission	2.22	Organic chemicals	2.06	Electricity, gas, water, sewage and urban cleaning	1.51
Electricity, gas, water, sewage and urban cleaning	2.12	Electric power transmission	1.73	Electric power transmission	1.45
Coal	0.97	Electricity, gas, water, sewage and urban cleaning	1.71	Resins and elastomers	0.83
Cargo transportation services	0.92	Resins and elastomers	0.78	Coal	0.66
Resins and elastomers	0.72	Coal	0.77	Cargo transportation services	0.62
Cattle and other livestock	0.61	Cargo transportation services	0.72	Cattle and other livestock	0.45
Agricultural pesticides	0.43	Cattle and other livestock	0.50	Other chemicals	0.42
Pig iron and ferro alloys	0.33	Agricultural pesticides	0.35	Agricultural pesticides	0.30
Ethanol	0.31	Other chemicals	0.30	Electricity generation (1G2G)	0.28
Rubber products	0.29	Rubber products	0.29	Rubber products	0.25
Pharmaceuticals	0.28	Pig iron and ferro alloys	0.27	Pharmaceuticals	0.24
Trade	0.25	Pharmaceuticals	0.27	Pig iron and ferro alloys	0.23
Non-ferrous metallurgy	0.21	Ethanol	0.24	Ethanol	0.20

Other chemicals	0.19	Trade	0.20	Trade	0.18
Passenger transportation services	0.16	Non-ferrous metallurgy	0.17	Non-ferrous metallurgy	0.15
Sum of other products (92 products remaining)	1.15	Sum of other products (92 products remaining)	1.11	Sum of other products (92 products remaining)	0.98
Overall	693.45	Overall	331.81	Overall	279.15

Table 4 shows that ethanol produced in 1G2G autonomous distillery is related to the lowest GHGs emissions when compared with 1G-2009 and 1G-optimized technologies. The direct and indirect impacts of 1G2G ethanol production were summed up and the result was 279 g $CO_{2\text{-eq}}$ per liter. This impact is less than half of 1G-2009 (693 g $CO_{2\text{-eq}}$/L) and is lower than 1G-optimized emissions (332 g $CO_{2\text{-eq}}$/L). In regard to 1G-optimized and 1G2G, emissions were allocated between ethanol and electricity according to the economic criteria. In case of scenario 1G-2009, the GHGs emissions were fully allocated to ethanol.

The main contributor to greenhouse gases emission in 1G-2009 ethanol production was the agricultural stage: 1G-2009 sugarcane production had higher impacts (414 g$CO_{2\text{-eq}}$/L) than other technologies (83 and 76 g$CO_{2\text{-eq}}$/L for 1G optimized and 1G2G, respectively) mostly because of emissions from straw burning required before manual harvesting. On the other hand, scenarios 1G-optimized and 1G2G are configured with mechanical harvesting only, which excludes the necessity of straw burning in sugarcane fields. Most of the 1G-optimized and 1G2G sugarcane emissions are related to straw, filter cake and vinasse decomposition in the soil.

Emissions resulting from diesel consumption were the main source of GHGs emissions for 1G-optimized and 1G2G technologies. Besides the direct use of diesel in agricultural machinery, ethanol supply chain indirectly requires inputs which in turn require diesel. Table 4 shows that the largest emission from diesel are related to 1G-2009 technology (124 g $CO_{2\text{-eq}}$/L) followed by 1G-optimized (117 g $CO_{2\text{-eq}}$/L) and 1G2G (102 g $CO_{2\text{-eq}}$/L). Similarly, another important emission in all scenarios is related to gasoline. Ethanol supply chain also requires inputs which in turn require gasoline. Observing table 3, indirect purchases of gasoline for ethanol production ranges from 16^{th} to 18^{th} position in the list of products in the entire supply-chain. However, gasoline has a high emission factor, which is nearly 2,300 g $CO_{2\text{-eq}}$ for each R$ 1 of gasoline due to emissions related to petroleum refining processes and pipe emissions (to get a comparison, inorganic chemicals are related to 133 g $CO_{2\text{-eq}}$/R$). Consequently, gasoline has a huge contribution to the global GHGs emission and is related to the fourth position in the ranking of GHG contributions. Considering that ethanol doesn't directly require gasoline to be produced, this impact could be reduced if other upstream sectors of Brazilian economy changed their technological structure aiming at producing with less fossil fuel inputs.

Another important emission in all scenarios is related to industrial emissions in distilleries. Although carbon dioxide from fermentation processes are considered as a biogenic source of CO_2 (which means no global warming potential), there are emissions of other GHGs due to bagasse and straw burning in boilers, such as N_2O and CH_4. These emissions are higher in 1G-optimized, since it corresponds to highest electricity surplus (180 kWh/ton of processed sugarcane) among all scenarios. Consequently, there are more GHGs emissions from bagasse and straw combustion in 1G-optimized. In case of 1G2G technology, there is lower GHG emission due to lower electricity surplus (80 kWh/TC) since part of bagasse and straw is diverted to second generation ethanol production. In regard to 1G-2009, although there is no electricity surplus, there is bagasse burning in boilers to feed internal industrial processes. However, due to the lower ethanol yield (64.7 kg of ethanol/TC), GHGs emission from industrial stage is higher than 1G2G (which produces 92.3 kg of ethanol/TC). Moreover, for 1G-optimized and 1G2G, industrial emissions are allocated between ethanol and electricity according to the economic criteria. In case of scenario 1G-2009, the impact of GHGs emissions from industrial stage is fully allocated to ethanol, which means more emissions per liter.

The emissions resulting from inorganic chemical products are mostly related to GHGs industrial emissions from fertilizer production which is also reliant upon fossil fuel inputs. As shown in Table 4, scenario 1G2G has the lowest emission resulting from fertilizer use due to two main reasons: firstly, 1G2G has the highest ethanol yield among all scenarios, fact that contributes to decrease the value of emissions per liter; second, 1G2G industrial stage produces more vinasse (which is a residual substance left after sugarcane alcohol distillation) when compared with the other scenarios. Considering that more vinasse is recycled to sugarcane croplands in 1G2G when compared with 1G-2009 and 1G-optimized, less fertilizer is used to produce sugarcane. Therefore, 1G2G emissions from inorganic chemicals are lower (7.77 g $CO_{2\text{-eq}}$/L) than observed in 1G-optmized and 1G-2009 (9.80 and 13 g $CO_{2\text{-eq}}$/L, respectively).

4. Conclusions

Results in this paper demonstrate the great potential of integrating Life Cycle Assessment and Input Output Analysis for carrying out socioeconomic and environmental assessments of ethanol production technologies. This study is important because it expands the system boundary of traditional life cycle assessment to the entire economy and considers "tropical" data coming from Brazilian input-output table. The comparison of GHG emissions among scenarios has shown that advanced ethanol production technologies (1G-optimized and 1G2G) are better than the average technology of autonomous distilleries in 2009. As highlighted in the results, 1G2G ethanol has a potential of reducing more than half the GHG emissions observed in 1G-2009 ethanol. Moreover, results of scenario 2 indicates that optimized first generation technology is an intermediate step to achieve better environmental indicators, especially when it comes to reduce GHG emission in the agricultural phase due to the absence of straw burning.

Further studies shall include socioeconomic data in order to detail the social implications of different ethanol production technologies in Brazilian economy such as number of jobs created and the effects of income on the economy. Moreover, a sensitivity analysis shall be done since values of GHGs emission for different products is deeply reliant on sugarcane and ethanol prices . In addition, further studies will include other environmental vectors such as eutrophication potential, human toxicity, abiotic depletion potential and other environmental indicators.

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