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Economic and GHG emissions analyses for sugarcane ethanol in Brazil: Looking forward

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ABSTRACT

There have been many efforts to improve sugarcane cultivation and conversion technologies in the ethanol industry. In this study, an economic assessment and greenhouse gas (GHG) emissions analysis are performed on ethanol produced conventionally from sugarcane sugar and on an emerging process where the sugarcane bagasse is additionally used to produce ethanol. The combined conventional plus lignocellulosic ethanol pathway is found to be less economically favorable than the conventional ethanol pathway unless a series of technical challenges associated with cost reductions in lignocellulosic ethanol production are overcome, reaching a production cost at 0.31 $/L. This is expected to be achieved in a prospective 2020 scenario. GHG emissions savings against gasoline for both the conventional ethanol and the conventional plus lignocellulosic ethanol pathways are confirmed and found to increase with technological developments projected to occur over time. However, the absolute numbers are highly sensitive to the way of claiming credits from surplus electricity co-generated in the mill. These are 86%, 110% and 150% for the conventional ethanol in the 2020 scenario when the surplus electricity is assumed to replace the average electricity, the 'combined-sources' based electricity and the marginal electricity, respectively. For the conventional plus lignocellulosic ethanol pathway, they are 80%, 85% and 95% respectively in the 2020 scenario. Finally, a series of sensitivity analyses found the comparison in the GHG emissions between the two production pathways is not sensitive to changes in the sugarcane yield or the emissions factor for the enzymes used in the lignocellulosic ethanol process. However, the plant size is an influential factor on both the ethanol production cost (a lowest MESP of 0.26 $/L at the scale of 4 MM tonne cane/yr) and the GHG emission factors, partially because of the important role that transport of feedstock biomass (sugarcane and trash) plays in both elements.

Contents

Abbreviations: 1G, 1st generation; 2G, 2nd generation; AD, anaerobic digestion; BAU, business-as-usual; CHP, combined heat and power; COD, chemical oxygen demand; DAP, Diammonium phosphate; EF, emission factor; FAO, Food and Agriculture Organization of the United Nations; FAPRI, Food and Agricultural Policy Research Institute; FFV, flexible-fuel vehicle; FPU, filter paper unit; GHG, greenhouse gas; GREET, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model; H_2SO_4, sulphuric acid; H_3PO_4, phosphoric acid; IPCC, intergovernmental panel on climate change; ISBL, inside battery limits (of the plant); K_2O, potassium oxide; KCL, potassium chloride; LCA, life cycle assessment; LHV, lower heating value; MESP, minimum ethanol selling price; NREL, National Renewable Energy Laboratory; OPT, optimistic; P_2O_5, phosphorus pentoxide; R&D, research and development; UNICA, Brazilian Sugarcane Industry Association; WWT, wastewater treatment

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1. Introduction

Due to growing concerns over energy and climate security, ethanol produced from renewable sources is seen as an important alternative to fossil fuels [1]. As one of the worlds' largest ethanol producers, Brazil has used sugarcane as feedstock to produce over 27 billion litres of ethanol in 2011 [2], most of which was destined for use as a fuel. Brazil ethanol production has been commercialized for over 30 years and is entirely based on the fermentation of simple sugars extracted from harvested sugarcane stem either in autonomous distilleries or in annexed plants co-located with sugar mills that co-produce ethanol and crystalline sugar [3]. This type of conventional ethanol produced from sugarcane sugar juice is often referred to as 1st generation (1G) ethanol, and has the lowest production cost worldwide compared to other sugar or starch-derived ethanol [4]. Currently the biofuel industry in Brazil is expected to expand to meet the increasing domestic and global market demand either by increasing the capacity of the 1G ethanol industry or by introducing lignocellulosic ethanol (referred to here as 2nd generation (2G) ethanol) which is produced from lignocellulosic biomass such as wood, straw or sugarcane bagasse and/or trash [5].

Efforts by academic researchers and industry are also focused on improving sugarcane yields, seeking out new feedstocks and enhancing technologies in the ethanol production process etc [6]. Sugarcane bagasse refers to a lignocellulosic residue from sugarcane crushing, which used to be regarded as a waste product, but is now used to generate process heat and electricity [6]. Bagasse is also becoming an attractive biomass feedstock to produce 2G ethanol which is expected to deliver improved environmental benefits compared to 1G ethanol such as reduced GHG emissions and better energy ratio. However, the cost and GHG emissions of 2G ethanol still remains higher than those of 1G ethanol, though substantial efforts to achieve technological breakthroughs have been made [4,7,8].

With regards to technological improvements, focus areas for the future are: (1) achieving higher sugarcane yields due to better genetics and cultivation practices, lower fertilizer application rates and increased levels of mechanized harvesting to avoid field burning [9]; (2) aiming for higher 2G ethanol yields by optimizing pretreatment and enzyme stages of the process [10,11] (3) improving the energy balance in ethanol production by optimizing process design and increasing solid to liquid ratios in reactions [12]; and (4) enhancing boiler efficiency in the bagasse combined heat and power (CHP) sector which could benefit both 1G and 2G ethanol [13,14].

Several studies have been done on sugarcane ethanol regarding its techno-economic and environmental performance: Macedo et al. conducted a scenario study of life cycle GHG emissions analysis on 1G sugarcane ethanol including improvements in the agricultural sector [9]. Dias et al. performed techno-economic analysis on sugarcane ethanol with particular focus on the effects of optimizing simulation processes and improving boiler efficiency [7,13,15]. Albarelli et al. compared the economics of 2G with 1G ethanol by modeling a specific supercritical water pretreatment technology on sugarcane bagasse [16]. A recent techno-economic study on sugarcane ethanol by Macrelli et al. considered technology improvement in the ethanol production sector and scenarios of using trash as feedstock, but without taking into account the option of using pentose (C5 sugar) as a source for ethanol production [4].

However, none of these studies incorporate improvements in both the agricultural and ethanol production sectors of sugarcane ethanol production. Nor do they consider linking the economic and environmental scenarios in assessing potential technological improvements to the process. These issues are the main aims for this study, which will: (1) analyze the full supply chain for conventional 1G sugarcane ethanol production and (2) investigate the current economic feasibility via minimum ethanol selling price (with 2010 as reference year and USD as reference currency, without taking into consideration fluctuations in exchange rate) and GHG emissions performance of emerging 1G+2G sugarcane ethanol pathways and then project the prospects for these into the near- (2015 scenario) and mid-term (2020 scenario).

In addition to the above aims, there is also considerable public interest [17] in the economic and environmental effects of increasing the size of sugarcane plant capacity (from current dominant 2 million tonne [18] to a larger capacity of 4 million tonne or more, and/or cluster integrated plants representative of more advanced players and will likely to be the way forward [19]), including resulting logistic issues/opportunities. The impacts of such an increase in scale of sugarcane processing is included in a sensitivity analysis in this study, which also covers the effect of assumptions made on some influential factors such as the emission factor (EF) of enzyme used in 2G ethanol production, the sugarcane yield in the agricultural sector and the treatment of co-produced electricity in the calculation of GHG emissions.

2. Methodology

2.1. Sugarcane ethanol supply chain

Fig. 1 shows the supply chain of sugarcane ethanol which includes sugarcane cultivation, sugarcane harvesting and trash collection, biomass transportation, ethanol production, ethanol distribution and its end use. These sub-processes are described in the subsequent sections with more details given in Appendix A–C.

2.1.1. Sugarcane biomass

In central-south Brazil, the average sugarcane yield is reported by Brazilian Sugarcane Industry Association (UNICA) to have increased from 48 t cane/ha in 1980 to 70 t cane/ha in 2010 [2]. Considering this trend as a linear increase, the sugarcane yields for 2015 and 2020 were estimated to be 79 t cane/ha and 84 t cane/ha respectively with an average increase rate of 1.3% per year. This increase rate is between a modest prediction of 1% by Food and Agricultural Policy Research Institute (FAPRI) and a linear trend prediction of 1.6%, both of which based on recent yield data (2000–2008) [20]. However, the predicted sugarcane yield in 2020 by literature varies in a large range from 80 to 95 t/ha [9,20]. These variations may affect findings from the economic and environmental analysis; therefore are looked into in the sensitivity analysis in this study. The average composition of sugarcane, sugarcane bagasse and trash are summarized in Table A.1 in Appendix A.1 and these data were used to develop the process simulation model as described in Section 2.1.3.

2.1.2. Sugarcane cultivation and harvest

Sugarcane is usually grown on a 6-year crop cycle with five cuts and 4 ratoons (without replanting) [9]. The main change in agricultural practice in the next 10 years is cane planting and harvesting (Table A.2 in Appendix A), which will involve more mechanical harvesting of unburned cane rather than manual harvesting of burned cane [9]. In addition, the fraction of trash recovered from the field is expected to increase from 0% in 2010 to 40% by 2020 [9]. As a result, greater amounts of trash will be available to be either burnt as fuel or converted to ethanol. Stillage and filter cake, which are residues from the sugarcane ethanol distillery, are applied to the field.

For the logistics, the collection and transport distance (d) of sugarcane from field to ethanol plant was determined using the following equation [21]:

$$d = 2 \times \sigma \times \frac{2}{3}\sqrt{\frac{n \times C_p}{100 \times \alpha \pi Y}} \quad (1)$$

where C_p (tonne of sugarcane crushed per year) is the distillery capacity to process cane, α represents the proportion of distillery catchment area covered by sugarcane (25% used in this study [17]), Y (tonne/ha) is the sugarcane yield, and σ is a 'Tortuosity' factor—the actual distance travelled to the straight line distance (taken as 1.5 in this study). For geometrical simplicity the process plant it often assumed to be at the centre of a circle. To improve this assumption the model adopted here assumes that geography will constrain the harvest area to some fraction $1/n$ of a circular geometry and assumes the plant locates at the apex of a 'pie slice' shape harvest area (take 'n' as 1.5 for near circular geometry—complete circular geometry filled with crop would give an 'n' value of 1 with complex or hilly terrain would be in excess of 3). The same equation was used to estimate the transport distance of collecting sugarcane trash [22]. However, the bulk density of trash is much lower than that of sugarcane resulting in higher transport cost and GHG emissions for collecting every tonne of trash than sugarcane. The cost and GHG emissions of biomass transport were then calculated according to this transport distance in Sections 2.2 and 2.3, respectively.

2.1.3. Sugarcane processing and ethanol production simulation

Parameters for the 1G and 2G ethanol production simulation were obtained from the literature and by consulting industry experts [7,9,16,23]. The process simulation models were developed in process engineering software AspenPlus™ which has been widely used for ethanol production simulation in other studies [4,15,24]. The baseline scenario assumes a typical plant processes 500 t cane/day (2 MM tonne cane/yr) and has an operation time of 167 days [7]. It is assumed that in both 1G and 2G ethanol pathways, sugar juice is solely used to produce ethanol with no crystal sugars. The effects of plant size on economic performance and GHG emissions analysis are discussed in the sensitivity analysis.

1G anhydrous ethanol was assumed to be produced from an autonomous distillery consisting of the main sub-processes as shown in Fig. 2: sugarcane milling and extraction, sugar juice treatment and evaporation, fermentation, distillation and CHP. In three scenarios with different timelines (2010, 2015, and 2020), several improvements to the technology such as boiler efficiencies, boiler pressure and recovery rate of trash were incorporated (shown in Table 1). Detailed process description and parameters can be found in Appendix A. 2.

Fig. 3 shows the process design for 1G+2G ethanol production. The sugar juice evaporation section is removed because the additional sugars from 2G enzymatic hydrolysis increase the sugar concentration in the fermentation feed stream. In this process, part of bagasse goes through a pretreatment step and enzymatic hydrolysis before the resulting sugar syrup is combined with the sugar juice in the fermentation step. More details about the process design and parameters can be found in Appendix A.3 and assumptions made on technological improvements are listed in Table 1.

In 2020 scenarios, a drying process was applied to dry the CHP feed stream (bagasse/trash) to increase the solid content to 75% to

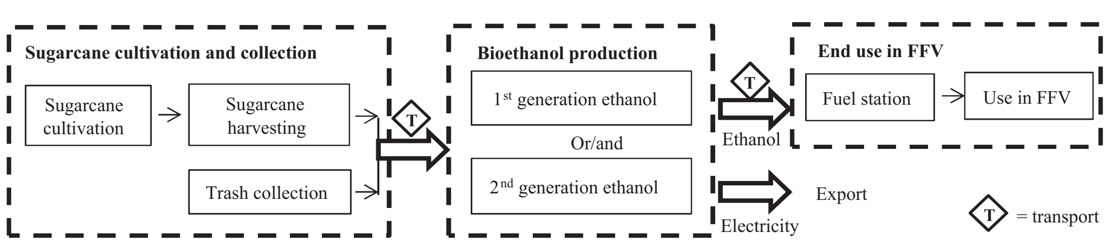

Fig. 1. Structure of the supply chain of sugarcane ethanol (dashed line shows sub-processes, FFV= Flexible-fuel vehicle).

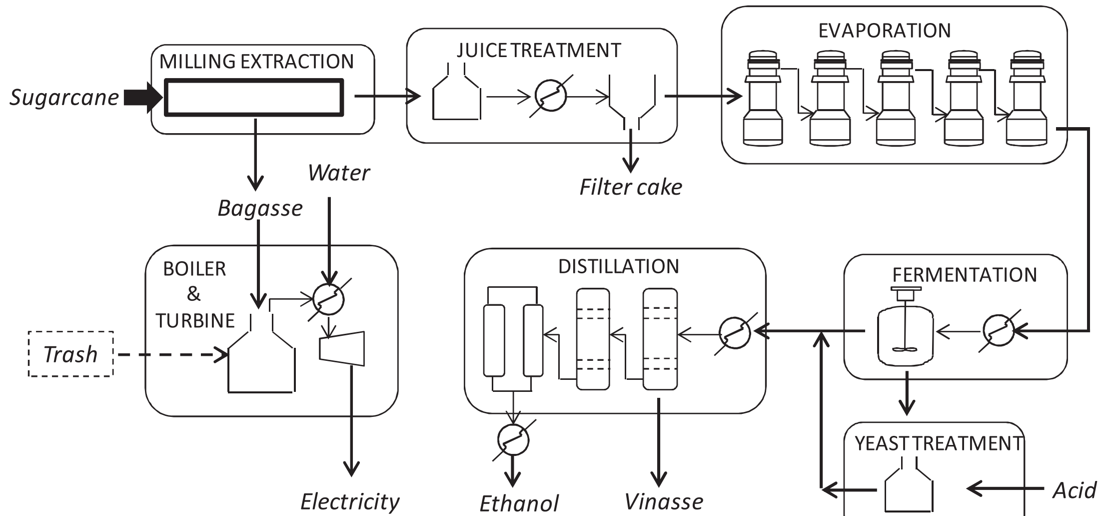

Fig. 2. The scheme of 1G sugarcane ethanol production (the dashed array means differences in process design of scenarios).

Table 1
Process design and parameters in scenarios for 1G ethanol and 1G+2G ethanol production [a].

Scenario	2010	2015	2020	Reference
1G ethanol				
Boiler pressure (bar)/Temperature (°C)	22/300	65/485	90/520	[13,16]
Boiler efficiency (% lower heating value (LHV))	75	80	86	[13,16]
Trash recovery (% dry wt)	0	20	40	[9]
Scenario	2010	2015	2020	
2G ethanol				
Solid loading in pretreatment (wt%)	20	25	30	[7]
Solid loading in enzymatic hydrolysis (wt%)	10	15	20	[7]
Enzyme loading (FPU/g cellulose)	15	10	5	[23]
Cellulose to glucose (wt%)	60	70	85	[43]
Hemicelluloses to xylose (wt%)	50	60	70	[43]
Hydrolysis time (h)	72	72	48	[23]
Ways of dealing with C5 sugars	AD	Ferment	Ferment	
C5 sugars to ethanol in fermentation (wt%)	–	40	80	[24]
Application of dryer in CHP	No	No	Yes	
COD removal efficiency in AD (wt%)	70	80	91	[7]
Ways of dealing with trash	–	CHP	CHP+Ethanol	

[a] Data are from literature listed and also based on our estimation.

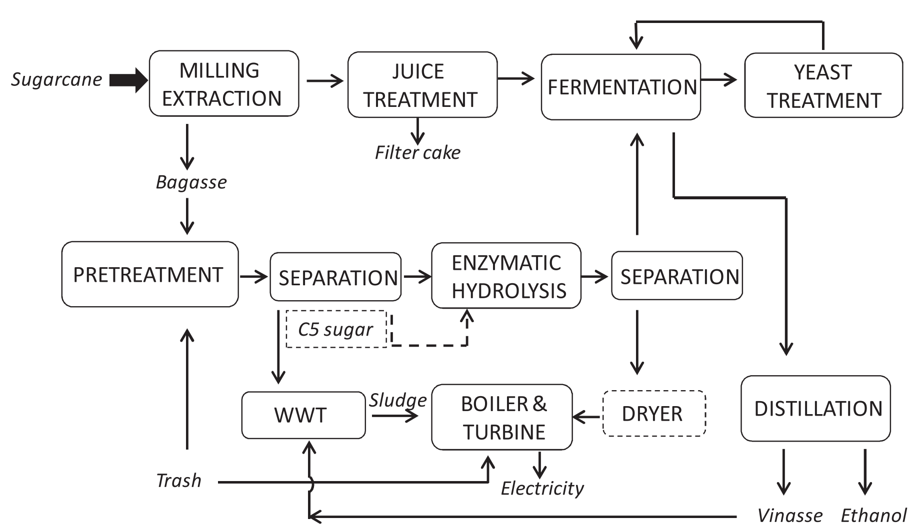

Fig. 3. The scheme of 1G+2G sugarcane ethanol production (dashed array and unit mean differences in process design of scenarios).

enable more complete combustion. In addition to the technology improvements in the 1G+2G pathway, different ways of dealing with C5 sugars in the future were modeled and different options for dealing with trash were also applied in the scenarios study (Table 1). Due to the possibility of fermenting C5 sugars by genetically modified microorganisms, C5 sugars were sent to the fermentation section in 2015 and 2020 scenarios [24].

Using trash as solid fuel in CHP presents a challenge since trash contains high level of alkali silicates [22]. Prabhakar et al. [22] demonstrated in their study that the proportion of trash in the CHP feed stream needs to be under 27% (wt) to ensure the total alkali concentration below the threshold level (0.17 kg/GJ) above which the combustor fouling risk increases significantly. In our process designs for 1G ethanol (2015 and 2020 scenarios) and 1G+2G ethanol 2015 scenarios, the percentage of trash in CHP feed stream is below 27%. Whilst in 1G+2G ethanol 2020 scenario where 40% of recovered trash is available, part of trash needs to be diverted to produce ethanol in order to ensure the 27% threshold level.

2.1.4. Distribution and end use of ethanol

Sugarcane ethanol was assumed to be distributed domestically within Brazil over distances of 340 km by truck and 1000 km by pipeline with a fraction of ethanol distributed by pipeline increased from 0% in 2010 to 20% in 2020 [18].With regards to end use, it was assumed that all carbon in the fuel is emitted from the vehicle exhausts as CO_2 without considering other emissions (e.g. N_2O and CH_4) or effects of vehicle efficiency and fuel economy etc.

2.2. Economic assessment

Total capital investment, variable and fixed operating costs are determined using 2010 as a reference year according to the methods described in Appendix B. In this study, USD (US dollars) is used as reference currency without considering the fluctuation in exchange rate in order to simplify the analysis and to keep the study comparable with most literature. A discounted cash flow method with a discounted rate of 10% was adopted from a corn stover-to-ethanol study by the US National Renewable Energy Laboratory (NREL) to calculate the minimum ethanol selling price (MESP) for 1G and 1G+2G ethanol pathways. This method has been widely used to estimate the economic potential for biofuel from various lignocellulosic biomass feedstocks [25–27]. Methods description, assumptions and parameters are presented in Appendix B.

2.3. GHG emissions calculation

A life cycle analysis (LCA) approach is applied to count GHG emissions for 1G and 1G+2G sugarcane ethanol pathways through their 'well-to-wheel' life cycles in the various scenarios. The functional unit is defined as 'MJ of fuel (i.e. ethanol or gasoline)'. With regards to the bioethanol production system, unit processes shown in Fig. 1 include: (1) sugarcane cultivation, (2) sugarcane/trash collection and transportation, (3) bioethanol production, and (4) bioethanol distribution and end use.

In addition to literature reviews, computer models and expert consultancy were used to develop LCA inventories in this study. Sugarcane cultivation inventory data are presented in Table 2. The mass balances including chemical utilization and GHG emissions in ethanol production process were obtained from the process simulation models described in Section 2.1.3.

The fertilizer use in the sugarcane cultivation sector and their inventory are from the Food and Agriculture Organization of the United Nations (FAO) [28] and Ecoinvent database v2.2 [29] (Table C.1 in Appendix C). The production inventory of diesel, fertilizers, other chemicals and infrastructure were also taken from Ecoinvent database v2.2 [29] while GHG emissions for the production of machinery in the agricultural sector was assumed to be 1.25 kg CO_2 eq./kg [9]. EFs for use of diesel and lime were adopted from IPCC [30]. EFs for use of N fertilizer, trash burnt and trash left in the field as well as those from stillage and filter cake were obtained from Macedo et al. [9]. The EF of enzyme was 5.1 kg CO_2 eq./kg enzyme as an average of the range given in Maclean and Spatari's study [31] and an assumption of 75% and 50% on this factor is made for 2015 and 2020 scenarios, respectively. A sensitivity analysis on this assumption was performed.

2.4. Sensitivity analysis

A sensitivity analysis is performed in this study on (1) the electricity (average mix, combined-sources and marginal) substituted by the surplus electricity co-product, (2), sugarcane yield, (3) the EF for enzyme used in 2G ethanol production, and (4) the capacity of ethanol plant.

Concerning the GHG emissions of the sugarcane ethanol life cycle, an influential factor is the assumption made on the GHG credit arising from surplus electricity export. The surplus electricity can be assumed to replace the average electricity mix or substitute the marginal electricity used in Brazil. The average electricity mix (year 2009) in Brazil is composed of 83.8% hydropower, 8.1% of fossil fuel (oil, natural gas and coal), 5% of biomass and 2.8% of nuclear [32]. Based on the inventory for fuel sources from the GREET model [33]

Table 2
A summary of GHG emissions factors [9,29].

	Production GHG EF of input materials used in agricultural process, kg CO_2 eq./kg material	Consumption and in-field GHG EF in agricultural process, kg CO_2 eq./kg material		GHG EF in ethanol production process, kg CO_2 eq./kg or kW h
Diesel[a]	0.427	2.98 [30]	DAP	2.76
Nitrogen fertilizer	3.89	7.76 (as N_2O and CO_2)	H_2SO_4	0.12
P_2O_5 fertilizer	1.75	–	H_3PO_4	1.38
K_2O fertilizer	0.50	–	Enzyme	5.1 [31]
Lime ($CaCO_3$)	0.013	0.477 (as CO_2)	Electricity	−0.081[c] [46]
Herbicide	10	–	Ash to landfill	5.6E−3
Insecticide	16.3	–		
Burnt trash	–	0.083 (as N_2O and CH_4)		
Unburnt trash	–	0.028(as N_2O)		
Stillage[b]	–	0.002(as N_2O)		
Filter cake	–	0.071(as N_2O)		

[a] CO_2 eq./L diesel.
[b] kg CO_2 eq./m^3 stillage.
[c] Credits by replacing the national grid (average mix), −0.268 kg CO_2 eq./kW h (combined-sources) and −0.622 kg CO_2 eq./kW h (natural gas).

this has a relatively low EF of 81 kg CO_2 eq./MW h. By contrast, marginal electricity is likely to be based on natural gas and fuel or diesel oil which represent the main additional sources of power from non-hydroelectric generation [34]. The natural gas derived electricity has a much higher EF of 622 kg CO_2 eq./MW h [33]. Alternatively in Walter et al.'s study [35], a 'combined-sources' GHG emissions factor of 267.7 kg CO_2 eq./MW h was used, which represents a combination of existing power plants and new projects (effectively a 50:50 average: marginal electricity mix) [36]. In the baseline scenario, surplus electricity was assumed to substitute this combined-sources electricity whilst substitution for the average mix electricity and marginal natural-gas based electricity were considered in the alternative scenarios.

Sugarcane yield (tonne/ha) used in all scenarios (baseline scenario) is projected based on historical data with an assumption that it increases linearly in the future. This sort of simplified assumption was also used in other studies to project sugarcane yield [20]. However, it is difficult to predict sugarcane yield, which is affected not only by climate conditions, disease, and field management etc. but also by policy oriented investment in technology research and development (R&D). To assess the impacts of the assumptions made on sugarcane yield projection on GHG emission results, a 'business-as-usual' ('BAU') case considers no improvements in sugarcane yields from 2010 whilst an optimistic ('OPT') scenario assumes a 15% increase in the yields projected in the baseline scenario. The sugarcane yield projected in 'OPT' for the 2020 scenario is 96 t cane/ha which is close to the highest projected in the literature for the Brazil south-central region average (95 t cane/ha) [9] and this has been achieved in some productive area in Brazil and Australia [37].

Regarding the assumed reduction in enzyme production emissions factor in future scenarios, the baseline case considers a reduction of 25% and 50% in carbon intensity of enzyme in 2015 scenario and 2020 scenario, respectively. Whilst 'BAU' case considers no reduction in both scenarios and an 'OPT' case assumes a 50% reduction in 2015 scenario and 75% in 2020 scenario.

With regard to the capacity of the ethanol distillery, two size-related components affecting ethanol production cost are capital cost and logistics cost, particularly the cost for biomass collection and transportation. With increasing size of ethanol plant, the capital cost per unit of ethanol will decrease to a small extent whilst the logistic cost increases due to increased distance required for collecting biomass. In this study, the effects of plant size on economic and environmental analyses were examined by taking the 1G ethanol pathway (2020) as an example.

3. Results and discussion

3.1. Mass and energy balance

A plant size of 500 t cane processed/day (2 MM tonne cane/yr) is modeled for the baseline scenarios. Mass and energy balance results for 1G and 1G+2G sugarcane ethanol pathways are presented in Table 3.

Table 3
Mass and energy balance results for 1G and 1G+2G sugarcane ethanol pathways.

Scenario	2010	2015	2020
1G ethanol			
Ethanol yield (L/t cane)	81.2	81.2	81.2
Surplus electricity (kW h/t cane)	60	139	191
Steam consumption (kg/t cane)	334	347	443
Water consumption (kg/t cane)	568	692	792
Scenario	2010	2015	2020
1G+2G ethanol			
Ethanol yield (L/t cane)	93.9	113	130
Fraction of bagasse for 2G ethanol (%)	70	100	87
Fraction of trash for CHP, % of recovered trash	–	100	40
Surplus electricity (kW h/t cane)	0	30.9	48
Steam consumption (kg/t cane)	410	435	572
Water consumption (kg/t cane)	494	438	527

For 1G ethanol, surplus electricity increases significantly over time due to the improved boiler efficiency and the higher temperatures and pressures assumed (see Table 1). For 1G+2G ethanol pathways, ethanol yields increase along the timeline because of enhanced sugar yields in enzymatic hydrolysis and increased ethanol yields in fermentation (see Table 1). It is noticed that not all bagasse is used to produce ethanol in scenario 2010 because 30% of bagasse is required to join with solid residue from distillation bottom, cell mass and biogas from wastewater treatment unit to meet the internal energy needs for the whole plant. In 2015 scenario, all bagasse is used to produce ethanol whilst energy requirement is met by burning trash (20% recover rate). In 2020 scenario, only 40% of recovered trash (16% of available trash in sugarcane field) and also 13% of bagasse are sent to CHP to control the combustor fouling risk.

3.2. Economic analysis

Fig. 4 shows MESP for 1G and 1G+2G sugarcane ethanol pathways with assumptions made regarding technology improvements and with alternative options of using trash. The cost for both 1G ethanol (2020 scenario) and 1G+2G ethanol (2020 scenario where 40% of trash is sent to CHP and the rest to produce ethanol) drop and converge with a difference less than 1 cent/L.

Contribution analysis results for 1G+2G ethanol in scenarios 2010, 2015 and 2020 (based on assumptions shown in Table 1) are also presented in Fig. 4. Feedstock cost is the biggest contributor to the gross production cost (up to 45%), followed by capital cost (up to 29%), income tax (up to 9%) and fixed operation costs (up to 9%). Enzyme cost is included in the 'other raw material' module and its contribution decreases gradually over time because of assumed reductions in enzyme costs and increased efficiency of use, from 13.3 cent/L (50 cent/gallon) in 2G ethanol scenario 2010 [7,23] to 2.6 cent/L (10 cent/gallon) 2G ethanol in scenario 2020 as an optimistic assumption of a twofold reduction. Benefits of exporting the surplus electricity are presented as 'below-the-line' scores which increase over time and partially offset the ethanol production costs.

Our findings on MESPs for sugarcane ethanol are consistent with other studies, which report MESPs for 1G sugarcane ethanol of 0.31 $/L [13] and for 1G+2G ethanol in the range of 0.33 $/L and 0.58 $/L, depending on assumptions in their studies [3,4,13]. Dias et al. found in their study that the increase of solid loading in enzymatic hydrolysis and the utilization of C5 sugars for ethanol production were the two main factors reducing 1G+2G ethanol costs from 0.39 $/L to 0.33 $/L, however, this was without considering changes in boiler efficiency [7]. Macelli et al. also found the reduced enzyme dosage an important contributor to the decreased ethanol cost in future scenarios [4]. In another recent study, Macelli et al. pointed out that a combined 1G + 2G ethanol plant could potentially outperform a 1G plant through technology improvements [38]. The progress ratios in terms of ethanol costs reduction for 1G ethanol and 1G+2G ethanol are 79% and 70%, respectively, similar to 71% found over a period of 1985 to 2005 in Goldemberg et al.'s study [39].

3.3. GHG emissions and their sensitivities

3.3.1. Total GHG emissions (excluding electricity credits)

Fig. 5 illustrates the total GHG emissions of 1G and 1G+2G sugarcane ethanol life cycles and their contribution analysis

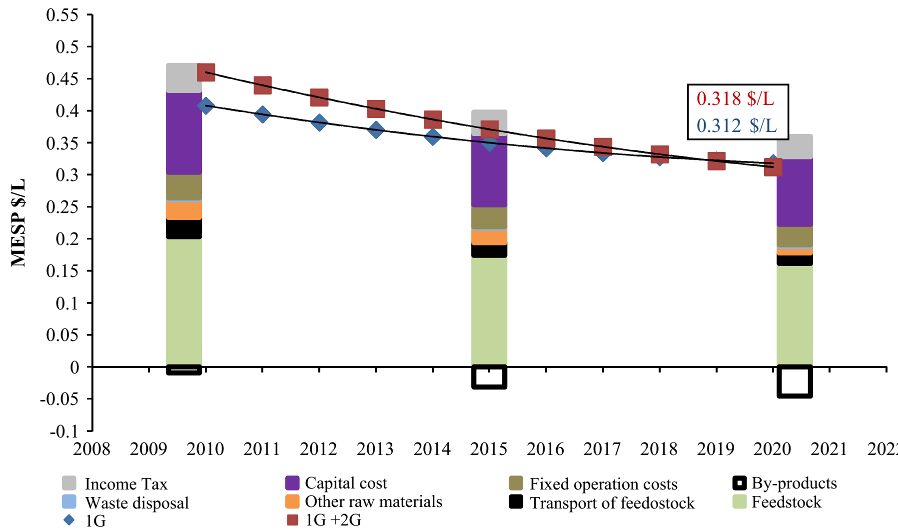

Fig. 4. MESPs of 1G and 1G+2G sugarcane ethanol pathways are shown in lines and contribution analysis for 1G+2G ethanol for the 2010, 2015 and 2020 a scenarios are shown in columns.

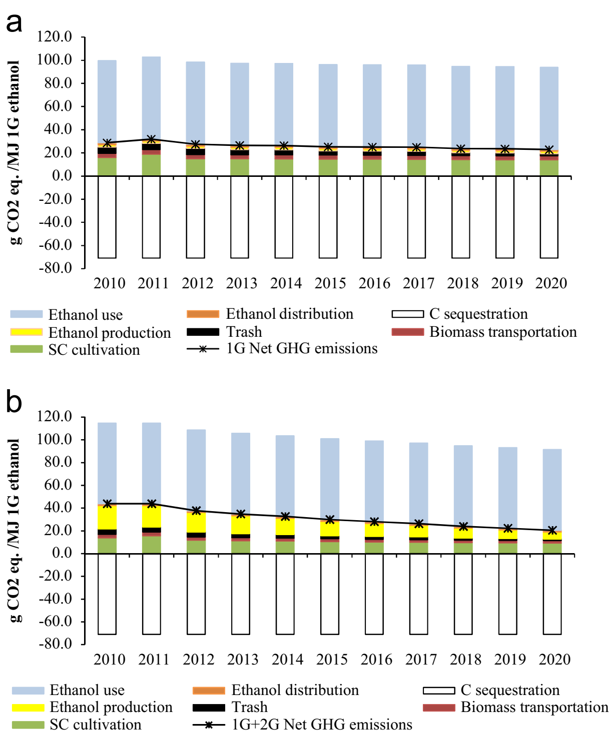

Fig. 5. GHG emissions of 1G (a) and 1G+2G (b) sugarcane ethanol life cycle without claiming credits from surplus electricity (Unit: 'MJ of ethanol').

results. The total emissions include GHG emissions from all sub-processes of ethanol life cycle but exclude credits from by-products electricity and those from ethanol replacing gasoline. The 'above-the-line' emissions are environmental burdens whilst the 'below-the-line' ones are biogenic carbon sequestered in biomass feedstock and credits from surplus electricity replacing the average mix national grid and associated displacement of fossil-carbon emissions.

As shown in both Fig. 5(a) and (b), the biggest 'above-the-line' GHG emissions in the pathways are due to ethanol combustion in vehicles. These are assumed to be offset by carbon originally sequestered in the biomass feedstock ('C sequestration') but in practice this depends on the land use counterfactual and the net impact on above and below ground carbon stocks in the sugarcane plantation over time. The sugarcane cultivation process ('SC cultivation') is another significant GHG emissions contributor in both 1G and 1G+2G pathways due to the production and use of diesel and fertilizer in field operations. In the 1G+2G pathway, the contribution by the 'ethanol production' module is gradually decreased from 17% (2010 scenario) to 4% (2020 scenario) of environmental burdens because of a reduction in enzyme usage. In addition to this, emissions due to trash are observed to decrease over time because more trash is being recovered and used in CHP, rather than burnt in the field. Moreover, the rest of trash left in the field increases soil carbon stock via decomposition, though emissions are also generated. A proportion no lower than 50% of trash is also suggested to be left in the field to act as weed control, though no effect of trash on sugarcane yield has been fully studied yet [40].

Overall, total GHG emissions for the 1G pathway stay relatively stable from 29 to 23 g CO_2 eq./MJ, whilst those for the 1G+2G pathway are gradually reduced from 44 to 20 g CO_2 eq./MJ. The increase shown in the 2011 scenario for both pathways is due to an exceptional low sugarcane yield in that year which increases the GHG emissions from sugarcane cultivation and transportation processes.

Macedo et al. estimated the total GHG emissions factor for 1G ethanol (excluding electricity credits) to be 18 g CO_2 eq./MJ in a 2020 scenario [9] while that for 1G+2G ethanol to be 11 g CO_2 eq./MJ in a 2020 scenario [18]. The reasons for these lower EFs than those from our study are (1) a higher sugarcane yield is estimated in Macedo et al.'s study (95 t cane/ha in 2020 scenario), therefore emissions from the agricultural sector normalized based on each tonne sugarcane are lower than those in our study and (2) enzyme was assumed to be produced on-site using sugarcane sugar as source in Macedo et al.'s study and therefore its emissions factor is significantly smaller than that in our study, which was obtained from the vendor. The impacts of these two factors (i.e. sugarcane yield and enzyme EFs) on GHG emissions results are further discussed in the sensitivity analysis (Section 3.4).

3.3.2. Net GHG emissions—How to claim surplus electricity credits

Concerning claiming credits from surplus electricity, there have been debates on whether the surplus electricity should substitute (or complement) the Brazilian average mix national grid or

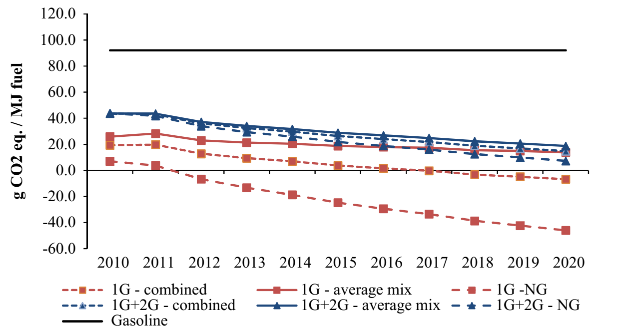

Fig. 6. Sensitivity analysis on the inventory of electricity substituted (Unit: 'MJ of fuel').

marginal electricity. In this study, three options from the literature were studied shown in Fig. 6). It can be seen that in the baseline scenario where combination-source based electricity (with a carbon intensity of 267.7 CO_2 eq./kW h) is assumed to be replaced, GHG emissions for 1G ethanol are 19.4 and −6.8 g CO_2 eq./MJ in 2010 and 2020 scenarios, respectively. The net GHG emissions, where the surplus electricity replaces the average electricity, decrease from 26 g CO_2 eq./MJ in scenario 2010 to 14 g CO_2 eq./MJ in 2020 for 1G ethanol. When the marginal electricity was assumed to be substituted, GHG emissions for 1G ethanol are found to be 7 g CO_2 eq./MJ in 2010 scenario and −46 g CO_2 eq./MJ in 2020 scenario, respectively.

GHG emissions savings of 1G ethanol against gasoline (at a carbon intensity assumed to be 92 g CO_2 eq./MJ [33]) are therefore enhanced from 86% in 2020 scenario where the average electricity is substituted, to 110% and 150% when the combined-source based electricity and marginal electricity are considered, respectively.

Similarly for 1G+2G ethanol, gradual reductions in net GHG emissions in all three scenarios are found but they are slightly less affected by assumptions on substitution electricity compared to 1G ethanol, with a change in GHG emission savings relative to gasoline from 80% (average electricity) to 84% (combined-source based) to 92% (marginal electricity), based on scenario 2020.

The conclusions from our study that 1G and 1G+2G ethanol deliver large GHG emissions savings relative to gasoline are consistent with other studies [3,9,35,41,42], although in other studies a wide range of life cycle GHG emissions results are presented due to different assumptions (mostly around the GHG emissions credits for substituted electricity). Macedo et al. estimated net GHG emissions of −22 g CO_2 eq./MJ where an electricity EF of world average power generation (579 g CO_2 eq./kW h) was applied [9]. Their net emissions number is higher than −46 g CO_2 eq./MJ in our case where the marginal electricity is replaced. This is because in Macedo et al. [9] (1) the amount of surplus electricity was underestimated (135 kW h/tc compared with 191 kW h/tc in this study) without considering the advanced boiler technology, and (2) the carbon intensity of substitution electricity is lower than that for the marginal electricity in our study. Later Seabra et al. extended Macedo et al.'s study and reported a life cycle GHG emissions factor of 5 g CO_2 eq./MJ for 1G+2G ethanol in a 2020 scenario which is close to the value of 7.3 g CO_2 eq./MJ found in this study's 1G+2G−NG scenario [41]. Walter et al. [35] reported GHG emissions of 9 g CO_2 eq./MJ for 1G+2G ethanol in a 2020 scenario by applying an avoided GHG emissions factor for electricity of 267.7 g CO_2 eq./kW h. This is lower than the value of 15 g CO_2 eq./MJ on a combined-sourced base in our study primarily due to the higher enzyme EF used [35,36]. The authors also mentioned substituting surplus electricity by electricity generated from a coal power plant (with a GHG emissions factor of 800 CO_2 eq./kW h) which would enhance the GHG emissions advantages of ethanol against gasoline significantly [35].

The above comparison from the available literature shows differences in reporting life cycle GHG emissions for either 1G or 1G+2G sugarcane ethanol due to varied assumptions on the technology improvements and emissions factors of substituted electricity (i.e. average, combined-sources, and marginal). These findings suggest that it is necessary and important to conduct and report sensitivity analysis on this matter in order to maintain completeness and transparency in the life cycle GHG emissions analysis for ethanol. Furthermore, the sugarcane harvesting period (March–December) overlaps with the dry season in Brazil (May–November). Our findings suggest bagasse-powered electricity rather than natural gas-powered electricity may be better to use to meet any potential hydroelectricity shortage during this period.

3.4. Sensitivity analysis

In the sensitivity analyses performed below, net GHG emissions were calculated based on claiming electricity credits from substituting combined-sources based electricity.

3.4.1. Sensitivity analysis on sugarcane yield

Fig. 7 shows the impacts caused by assumptions about sugarcane yields on GHG emissions results for 1G and 1G+2G ethanol pathways. In the baseline scenario, sugarcane yield was estimated based on historical data with a linear trend whilst no improvement was assumed in the 'BAU' scenario and an additional 15% increase compared to the baseline scenario was assumed in the 'OPT' scenario. These changes resulted in the net GHG emissions for both 1G and 1G+2G pathways varying in a range of ±10% around the baseline scenario. These variations are partially because (1) changes in the agricultural sector where the GHG emissions burdens allocated on each tonne of sugarcane depend

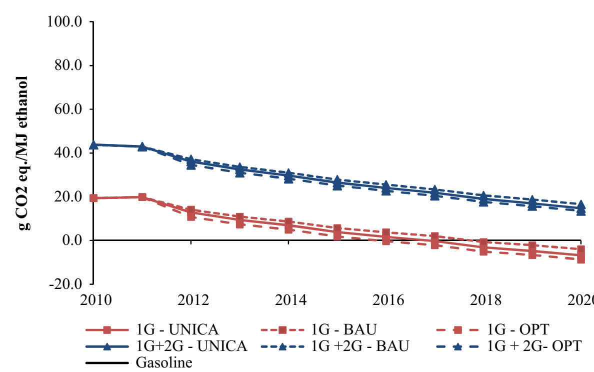

Fig. 7. Effects of assumptions about sugarcane yields on GHG emissions results for 1G and 1G+2G ethanol pathway.

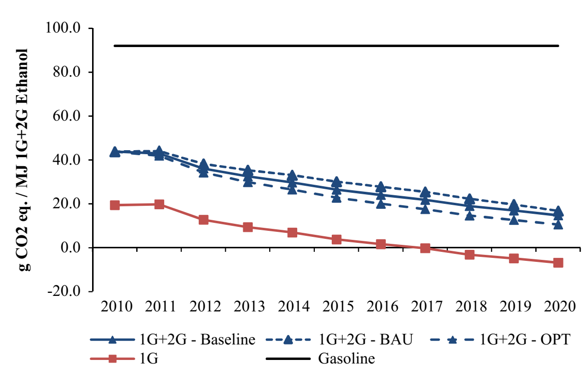

Fig. 8. Effects of assumptions about enzyme emission factors on GHG emissions results for 1G+2G ethanol pathway.

on the sugarcane yield and (2) changes in the sugarcane transport sector where the size of catchment area is influenced by the sugarcane yield. Nevertheless, conclusions that (1) 1G pathway has lower net GHG emissions than 1G+2G ethanol pathway and (2) both 1G and 1G+2G pathways deliver GHG emissions savings against gasoline remain unchanged, when combined-source electricity is assumed to be substituted.

3.4.2. Sensitivity analysis on enzyme emission factor

Fig. 8 shows the effects of assumptions made on the enzyme emissions factors on GHG emissions results for 1G+2G ethanol pathway. The baseline case assumes a 25% and 50% reduction in enzyme carbon intensity in 2015 and 2020 scenarios, respectively. Whilst the 'BAU' case considers no reduction and the 'OPT' case assumes the reductions are 50% and 75% for 2015 and 2020 scenarios. It is found that under the assumption that combined-source based electricity is substituted, the net GHG emissions of 1G+2G ethanol pathway are varied in a range of −5% to 10% between the different cases. However, the conclusion that it is more favorable to use bagasse as solid fuel rather than ethanol feedstock remains unchanged until the 2020 scenario where the GHG emissions for 1G+2G ethanol pathway becomes very close to that for 1G ethanol pathway.

3.4.3. Sensitivity analysis on plant size

The size of ethanol plant is an area of interest in biofuel supply chain studies. In general, the ethanol production cost decreases whilst logistic costs increase with a larger plant size. In this study, a sensitivity analysis shown in Fig. 9 included the effects of the plant size on MESP and GHG emissions of the 1G ethanol pathway (2020 scenario).

As expected, the ethanol production cost (excl. feedstock transport cost) decreases whilst the feedstock transport cost increases with increasing plant size mainly due to the increased cost for collecting trash (Fig. 9). It is indicated in the scenario studied here (1G ethanol 2020 with 40% of trash recovered) that the feedstock transport cost is a game-changing factor because its growth overwhelms the reduction in ethanol production cost; therefore, a turning point in MESP is observed (incl. feedstock transport cost) when the plant size is around 4 MM tonne cane/yr. By contrast in Fig. 9(b), the overall GHG emissions increase with increasing plant size because of emissions from additional transportation, despite GHG emissions for the ethanol production process decreasing.

Overall, these results suggest that the size of ethanol plant is an influential factor for both MESP and GHG emissions of sugarcane ethanol a plant size of 4 MM tonne cane/yr was observed from the scenario studied (1G ethanol with 40% trash recovered as solid fuel) to result in minimized MESP. However, for other scenarios where the collection of trash is not substantial, the transport cost is not a game changing factor for ethanol production cost (data is not shown here). In addition, the average transport distance in our logistic model is a simple representation based on several optimum assumptions. The need for a larger distillery to be supplied with biomass from outside its immediate area, with potential logistics switch from road to rail, could lead to a different transport factors and therefore in the associated cost and GHG emissions.

4. Conclusion

Economic assessment (with 2010 as reference year and USD as reference currency) and 'Well-to-Wheel' life cycle GHG emissions analysis of two sugarcane pathways incorporating technology improvements have been studied over a timeline from 2010 to 2020. These two pathways are (1) an ethanol pathway, where ethanol is produced directly from sugarcane juice and bagasse is used to generate electricity (1G); and (2) a combined ethanol pathway, where bagasse is also used to produce lignocellulosic ethanol in addition to sugar juice (1G+2G).

It is found that currently, the 1G+2G ethanol pathway remains less economically favorable than the 1G ethanol pathway, but could become competitive in the prospective 2020 scenario, where a series of technology challenges are projected to be addressed. GHG emission savings from replacing gasoline with ethanol are increased from 80% in the 2010 scenario to 110% in the 2020 scenario for the 1G ethanol pathway and from 55% to 85% for the 1G+2G ethanol pathway by considering surplus electricity from the ethanol plant substituting a 'combined-sources' based electricity (50:50 average: marginal electricity mix). When the natural gas derived marginal electricity is assumed to be substituted, these numbers are substantially enhanced for both pathways, for example, to 150% for 1G ethanol and to 95% for 1G+2G ethanol respectively in 2020 scenarios.

Overall, combining results from economic and GHG emissions analyses, it is suggested that it is more favorable to use sugarcane bagasse for generating electricity rather than ethanol before the commercialization of lignocellulosic ethanol from sugarcane bagasse. In addition, a series of sensitivity analyses show the comparison in

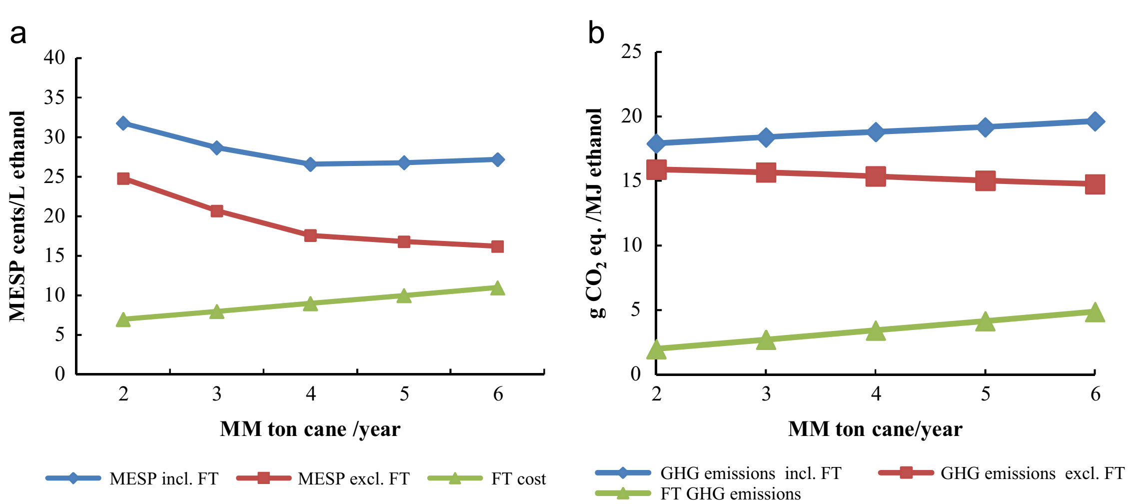

Fig. 9. Effects of plant size on (a) MESP (FT cost refers to the right *y* axis) and (b) GHG emissions for 1G ethanol pathway (2020) (FT=feedstock transportation).

GHG emissions between 1G and 1G+2G scenarios are not sensitive to sugarcane yield and the enzyme emissions factor. And the plant size is an influential factor for both ethanol production cost and GHG emissions partially because of the important role that transport of feedstock biomass (sugarcane and trash) plays.

Acknowledgements

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Appendix A

Appendix A.1: Inputs data for conducting models in agricultural sector are presented here

Table A.1 is a summary of the average composition of sugarcane, bagasse and trash whilst Table A.2 presents the inputs in sugarcane cultivation process.

Table A.1
A summary of the average composition of sugarcane, sugarcane bagasse and trash (all composition data are presented on wet basis unless stated).

Parameters	Value	Reference
Sugarcane		
Moisture content	71.3%	[16]
Reducing sugar as glucose content	0.62%	[16]
Sucrose content	13.3%	[16]
Fibre content	12%	[16]
Dirt as SiO_2 content	0.6%	[16]
Minerals as (potassium oxide (K_2O))	0.2%	[16]
Impurities as (potassium chloride (KCL))	1.8%	[16]
Trash yield	140 kg/t (dry basis)	[9]
Bagasse and trash		
Bagasse moisture content	50%	[7]
Trash moisture content	15%	[9]
Bagasse/trash cellulose content	43.4% (dry basis)	[7]
Bagasse/trash hemicelluloses content	25.63% (dry basis)	[7]
Bagasse/trash lignin content	23.24% (dry basis)	[7]
Bagasse/trash extractives content	4.82% (dry basis)	[7]
Bagasse/trash ash content	2.94% (dry basis)	[7]
Bagasse LHV	7,565 kJ/kg	[15]
Trash LHV	12,960 kJ/kg	[15]

Appendix A.2: First generation (1G) ethanol production

After being washed to remove soil, the harvested cane enters the shredding and extraction system which cuts the cane using electricity-driven rotating knives and then extracts the juice by compression, with a sugar recovery efficiency of 96 wt% [16]. The sugarcane bagasse is then warm-washed by recycled water and sent to the CHP system, while the sugar juice goes to a treatment section, where it is heated with phosphoric acid at a concentration of 0.03 wt% phosphate and then with lime (0.88 kg/t cane) [16]. The non-sugar impurities are precipitated and separated as filter cake by centrifuging. Part of the cleaned sugar juice is concentrated via 5-effect evaporators and then combined with the rest to reach an overall 20% (wt) sugar content in the fermentation feed stream. Fermentation with yeast is carried out at 30 °C with an efficiency of 90%. The yeast is recycled after a sulphuric acid treatment.

The resulting beer from fermentation is sent to a distillation column followed by a rectification column and molecular sieve treatment to obtain ethanol with a purity of 99.6% (wt) and vinasse as the distillation bottoms. The steam extracted from turbines (at 13 atm, 250 °C; 9.5 atm, 178 °C and 2.5 atm 128 °C), and electricity generated in the CHP plant, supply the whole plant, whilst surplus electricity is exported.

Appendix A.3: Combined first and second generation (1G+2G) ethanol production

After extracting the juice, bagasse is sent to a pretreatment step where steam explosion is carried out at 205 °C for 10 min. During this process, 3.2% of cellulose is converted to glucose while 80% of xylan become xylose [43]. After a filter separation, the solid fraction is sent to enzymatic hydrolysis where polymeric carbohydrates are converted to monomer sugars which are then fermented to ethanol in the fermentation area.

In this 1G+2G process design, a waste water treatment (WWT) section including anaerobic digestion (AD) and aerobic digestion is applied to clean used water and digest extra vinasse, whose amount exceeds the field application level stated in Table A.2. In AD (at 35 °C), organic matter, including C5 sugars from pretreatment, are converted to sludge and biogas with a composition of 51% CH_4/49% CO_2 (dry molar basis) and a yield of 228 g biogas/kg chemical oxygen demand (COD) removed [24]. The treated water is further cleaned in by aerobic digestion, where 96% of the remaining soluble organic matter is removed. Together with

Table A.2
A summary of inputs in sugarcane cultivation process.

Scenario	2010	2015	2020	Reference
Sugarcane yield (t/ha yr)[a]	70.5	80.0	84.0	[47]
Fertilizer utilization (kg/ha yr)[b]				[18]
Nitrogen	56.3	52.7	49.0	
Phosphorus pentoxide (P_2O_5)	24.6	24.6	24.6	
K_2O	35.4	33.8	32.2	
Herbicide (kg/ha yr)	2.2	2.2	2.2	[9]
Insecticide (kg/ha yr)	0.16	0.16	0.16	[9]
Lime (kg/ha yr)	380	390	400	[9]
Stillage application (m^3/ha)	76.8	80	84	[9]
Mechanical harvesting rate (%)	50	80	100	[9]
Machinery utilization (kg/ha)	205	274	343	[9]
Diesel consumption (L/ha)	230	280	314	[9]
Unburned cane harvesting rate (%)	30	50	80	[9]
Trash recovery (%)	0	20	40	[9]

[a] Sugarcane yield represents the average in south-central Brazil.
[b] Total average, including fertilizer use in plant and ratoon cane, in areas with and without stillage.

biogas, the lignin obtained from the hydrolysate and sludge from WWT are sent to the CHP plant to generate steam and electricity.

Appendix B

Appendix B.1: Cost estimation

Once mass and energy balances for the ethanol production processes have been produced, the economics can be determined.

Table B.1
A summary of variable operating costs.

Materials/chemicals/energy	Cost/price	Reference
Sugarcane	19.50 $/t	[4]
Sugarcane trash	17.05 $/t	[7]
Sulphuric acid (concentrated)	100 $/t	[4]
Diammonium phosphate (DAP)	500 $/t	[24]
Phosphoric acid (as 50 wt%)	500 $/t	[4]
Lime	220 $/t	[24]
Well water	0.33 $/t	[4]
Boiler chemicals	2800 $/t	[24]
Cooling tower chemicals	2000 $/t	[24]
Ash disposal	38 $/t	[48]
Grid electricity	84.88 $/MW h	[4]
Stillage	1.6 $/t	[4]

Table B.2
Parameters in discounted cash flow method [24].

Parameters	Value
Plant life	30 years
Discount rate	10%
Financing	40% equity
Loan terms	10-year loan at 8% APR
General plant depreciation	200% declining balance
General plant recovery period	7 years
Steam plant depreciation	150% declining balance
Steam plant recovery period	20 years
Corporation tax rates	34% [7]
Construction period	3 years
0–12 months	8% of project cost
12–24 months	60% of project cost
24–36 months	32% of project cost
Working capital	5% of fixed capital investment
Start-up time	3 months
Revenues during start-up	50%
Variable costs incurred during start-up	75%
Fixed costs incurred during start-up	100%

The total capital investment is calculated according to:

$$\text{Total capital investment} = \text{Equipment costs} + \text{Direct costs} + \text{Indirect costs} \quad (B.1)$$

Equipment costs for sugarcane wash, milling and extraction and sugar juice evaporation were estimated to be 31 MM USD in total, scaled up based on Ensinas et al.'s study [44]. The equipment costs for the rest of processes were firstly estimated based on NREL's vendor quotations [24] by scaling up or down according to the exponential scaling expression. The purchased equipment cost was then indexed to the reference year of 2010 [45]. Direct costs, including warehouse, site development and additional piping comprise 25% in total of the inside-battery-limits (ISBL) equipment costs for the main processes excluding offsite processes (i.e. WWT and utilities). Indirect costs, including pro-rateable costs, construction, project contingency and other costs, in total account for 25% of equipment costs for offsite processes.

The variable operating costs including raw materials, waste handling charges and by-product credits are shown in Table B.1. Enzyme costs were reduced due to the lower enzyme loading in future scenarios. The current enzyme cost in 2010 scenario was estimated to be 13.3 cent/L (50 cent/gallon) 2G ethanol [23] and consequently to be 5.3 cent/L (20 cent/gallon) 2G ethanol in 2015 [7] and 2.6 cent/L (10 cent/gallon) as an optimistic assumption in 2020 scenarios.

Sugarcane costs and trash costs found in the literature are in a wide range of 16.58–23.05 $/tonne and 15–22.1 $/tone, respectively [3,4,7,15]. The median in the range for each was used. Collection and transportation cost of sugarcane from field to the plant was calculated by multiplying transport distance obtained from Eq. (1) by the operation cost of a 38 t truck (1.87 $/km [17]).

Fixed operating costs include labor and various overhead items which are incurred whether or not the plant is producing at full capacity. Labor cost was estimated as 0.48 million USD per year [16]. Annual maintenance materials were estimated as 3% of the ISBL capital cost. Local property tax and property insurance were assumed to be 0.7% of the fixed capital investment [24].

Appendix B.2: Discounted cash flow method

A discounted cash flow method was used to estimate MESP once the total capital investment and operating costs have been determined. The MESP refers to the bioethanol price at which the net present value of the project is zero at a set discount rate of 10%. The other parameters used in calculating MESP are listed in Table B.2. This model is based on '*n*th-plant' assumption which assumes several plants using the same technology are currently operating—this eliminates additional costs associated with pioneer plants.

Appendix C

The composition of fertilizer used in Brazil is shown in Table C.1.

Table C.1
The composition of fertilizer used in Brazil [28].

Nutrient	Product	%	Nutrient	Product	%	Nutrient	Product	%
N	Ammonium sulphate	16	P_2O_5	Diammonium phosphate	45	K_2O	Potassium chloride	98
	Urea	48		Single superphosphate	29		Potassium sulphate	1
	Ammonium nitrate	16		Triple superphosphate	16		Potassium nitrate	1
	Diammonium phosphate	14		Thermophosphate	1			
	Potassium nitrate	1		Reactive phosphate rock	4			
	NPK	5		NPK	5			

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