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Techno-economic and Environmental Assessment of Second Generation Ethanol: Short and Long Term Prospects

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In this work, the integration of first and second generation (1G2G) ethanol production processes was assessed, considering short and long term prospects for the process steps that comprise second generation (2G) process. Comparison to a first generation (1G) ethanol plant using all lignocellulosic material as fuel to maximize electricity production was carried out. Another scenario evaluated was the integrated 1G2G process using energy cane, a high fiber variety of sugarcane, as feedstock.
Results showed that 1G plant presents a better economic performance in the short term; however, in the long term, the 1G2G process can significantly decrease ethanol production costs as well as environmental impacts, such as climate change and agricultural land occupation. The breakdown of ethanol production costs indicated that capital cost, biomass and enzyme (used only in 2G process) are responsible for up to 90 % of total costs. In addition, the introduction of energy cane allowed reducing the biomass cost and its contribution on ethanol production cost due to the higher agricultural productivities forecasted to this feedstock. Environmental assessment showed that 2G process can significantly decrease impacts, while energy cane still presents high impacts when short term 2G technology is considered, due to the relatively low ethanol yield per tonne of feedstock.

1. Introduction

The use of lignocellulosic materials, such as agricultural residues and energy crops, for the production of second generation (2G) ethanol has been increasingly investigated worldwide. In Brazil, ethanol is conventionally produced through sugarcane juice fermentation, which is known as first generation (1G) process. The integration of 2G ethanol production in the Brazilian sugarcane industry can take advantage of the sugarcane lignocellulosic materials: bagasse, produced after sugars extraction, and straw, which includes tops and dry leaves.
Moreover, the integration between 1G and 2G processes, compared to a 2G stand-alone process, has several economic benefits: reduced capital cost due to the possibility of sharing infrastructure (fermentation, distillation, cogeneration and storage); use of unreacted solids from hydrolysis as fuel in the cogeneration, which allows displacing sugarcane bagasse and straw to be used as feedstock for 2G ethanol production; lower transportation costs for feedstock since it is already available at plant site (Dias et al., 2014).
In order to assess the sustainability impacts of different technological developments and alternative routes within the biorefinery context, the Virtual Sugarcane Biorefinery (VSB) was developed by CTBE (Brazilian Bioethanol Science and Technology Laboratory) of CNPEM (National Center for Research in Energy and Materials). The VSB integrates computer simulation platforms with economic, social and environmental evaluation tools, taking into account the entire sugarcane production chain: agricultural production, feedstock transport, industrial biorefinery conversion, products transport, commercialization and final use and/or disposal of the products.
Using the VSB, Cavalett et al. (2011) evaluated different 1G sugarcane biorefineries, including introduction of optimization features to increase electricity generation as well as production of sugar aiming product

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diversification, showing that these alternatives improve the sustainability of sugarcane biorefineries. In addition, Pereira et al. (2014) assessed the production of butanol using ethanol, from an integrated 1G and 2G ethanol production process, as feedstock. The authors observed that there is a great potential to increase plant profitability but with high financial risks due to the uncertainties in the market prices, especially for butanol that could be used either as fuel or as chemical.
In the present work, the integration of 1G and 2G ethanol production processes was assessed, considering short and long term prospects supported by companies related to the cellulosic ethanol production chain in Brazil and abroad. Comparison with a 1G ethanol plant using all lignocellulosic material as fuel to maximize electricity production was carried out. Moreover, introduction of energy cane, a high fiber and high productivity variety of sugarcane, as feedstock for integrated 1G2G was evaluated.

2. Methods

2.1 Agricultural and process simulation

Within the VSB framework, agricultural simulation is carried out using the CanaSoft model, an in-house tool that integrates and quantifies inputs and outputs in the biomass production stages as well as estimates biomass production cost. This model, initially developed for sugarcane, has been adapted to different biomasses (e.g. corn, sweet sorghum and energy cane).
For industrial process, Aspen Plus® simulation environment is used to obtain mass and energy balances for each biorefinery scenario.
Production process for 1G ethanol is composed of sugarcane cleaning, sugars extraction, juice treatment and concentration, fermentation, distillation and dehydration as well as a cogeneration unit to supply steam and electricity to the process through the use of sugarcane bagasse and straw as fuels in the boilers. Further description of 1G process can be found in Dias et al. (2014). The recovery of straw (50 % of that produced in the field) and optimization features, such as reduced steam consumption, efficient high-pressure boilers and molecular sieves for dehydration process, allow achieving large electricity surplus. Since sugarcane degradation constrains its storage, the 1G process runs only during the harvesting period (season), which is around 200 days per year.
In this work, the design of 2G process includes a steam explosion pretreatment followed by a separate hydrolysis and fermentation process. In the integrated 1G2G process, glucose (C6) liquor is fermented along with 1G juice (rich in sucrose) using a conventional yeast (*S. cerevisiae*), while pentoses (C5) liquor is fermented separately using a genetically modified microorganism. Residual solids are burnt in the cogeneration sector, making available a larger amount of lignocellulosic material (sugarcane bagasse and straw) for production of 2G ethanol. A fraction of the lignocellulosic material is stored to run the 2G plant in the off-season period, thus the 2G process is operated all year-round (330 days). Block flow diagram for an integrated 1G2G process is presented in Figure 1. Process parameters for 2G process, considering short and long term prospects are summarized in Table 1.

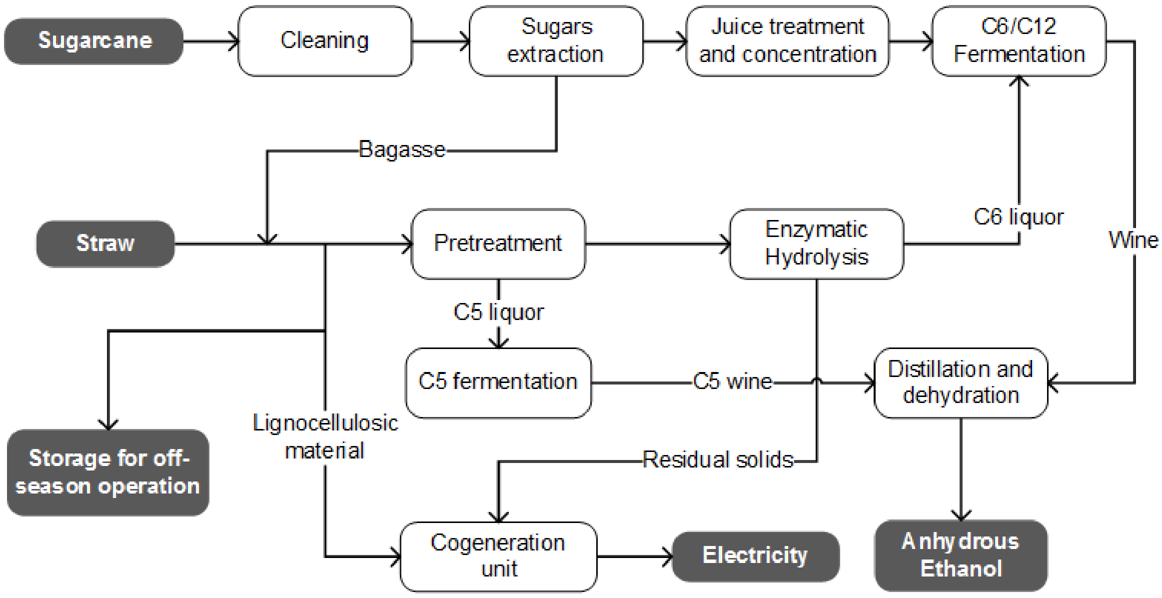

Figure 1: Block flow diagram for integrated 1G2G ethanol production in a sugarcane-based biorefinery

Table 1: Summary of technical parameters for second generation process considering short and long term prospects

Parameter	Short term	Long term
Pretreatment		
Temperature (°C)	190	210
Residence time (min)	15	5
Cellulose solubilization (%)	5.0	5.5
Xylan conversion to monomers and oligomers (%)	60	80
Enzymatic hydrolysis		
Temperature (°C)	50	65
Residence time (h)	48	36
Solids content (%)	15	25
Cellulose conversion to glucose (%)	60	80
Xylan conversion to xylose (%)	60	80
C6/C12 fermentation - conversion to ethanol (%)	88	90
C5 fermentation		
Temperature (°C)	33	33
Residence time (h)	48	24
Xylose oligomers conversion to xylose (%)	80	90
C6 conversion to ethanol (%)	90	90
C5 conversion to ethanol (%)	80	85

The use of integral energy cane (including stalks and straw) as an alternative feedstock in the 1G2G process is also simulated, considering higher fiber (21.3 %) and lower reducing sugar contents (11 %), compared to conventional sugarcane that contains 13 % and 15.3 %, respectively. Due to the higher fiber content and the use of a 2 mill-tandem (instead of 5), sugars extraction efficiency for energy cane was assumed to be lower (80 %) than that usually achieved for sugarcane (96 %). Additionally, it was assumed that energy cane can be harvested throughout the year, since it is less susceptible to dry stress for sugar accumulation. It is worthwhile to mention that there are still several uncertainties related to energy cane, such as its agricultural management, productivities, composition and processing efficiencies, since this variety is starting to be introduced in the sugar-energy sector.
In order to evaluate the integration of 2G ethanol production process as well as the use of energy cane as alternative feedstock, four biorefinery scenarios are defined as shown in Table 2.

Table 2: Main characteristics of the biorefinery scenarios

Characteristic	1G	1G2G-ST	1G2G-LT	1G2G-EC
Sugarcane processing (10^6 t/y)	4.0	4.0	4.0	-
Sugarcane straw recovery (10^6 t/y, dry basis)*	0.18	0.18	0.18	-
Energy cane processing (10^6 t/y)	-	-	-	4.3
Industrial operation (d/y)	200	330	330	330
2G technology	-	short term	long term	short term

* Amount of sugarcane straw recovered through baling system.

2.2 Techno-economic assessment

The assessment based on a cash flow analysis relies on data associated with the investment required to build a biorefinery as well as on its main cash inflows (revenues) and outflows (expenses). These are based on process simulation results for the biorefinery alternatives and average market prices from historical data observed over the last decade for ethanol and electricity in Brazil. Table 3 presents important parameters assumed in the cash flow analysis.
Concerning the biomass costs, this work considers a vertically integrated model. In the VSB, this definition means that the biomass production cost, which is an output of CanaSoft model, is considered as an input to the industrial cash flow analysis. It is worth to mention that, in this case, the agricultural system is fully integrated to the industrial scenarios, i.e., biomass production costs are directly affected by the industrial scenarios. Assumed agricultural productivities for sugarcane and energy cane are 80 and 200 t/ha, respectively. Half of the sugarcane straw that remains in the field after harvest of stalks is collected through baling system. Estimated costs (US$/t) are around 22, 28 and 13 for sugarcane stalks, straw (dry basis) and energy cane, respectively.

Another important input data to the techno-economic analysis are related to the investment associated with the industrial plants, which is calculated using the VSB databank for equipment costs and calculated capacities based on process simulation results.

Table 3: Main parameters considered in the techno-economic analysis

Parameter	Value	Reference
Expected plant life time	25 years	Assumption
Discount rate	12 % per year	Assumption
Reference date	July 2015	Assumption
Exchange rate	3.22 BRL/US$	Market data
Depreciation	10 years, linear	Assumption
Anhydrous ethanol price	US$ 0.46/L	CEPEA (2014)
Electricity price	US$ 48.71/ MWh	MME (2014), EPE (2015)
Enzyme cost (short term)	US$ 0.13/L 2G ethanol	Enzyme suppliers
Enzyme cost (long term)	US$ 0.06/L 2G ethanol	Enzyme suppliers

2.3 Environmental assessment

Environmental impacts for ethanol production in the biorefinery scenarios are evaluated using Life Cycle Assessment (LCA), which is a methodology for determination of environmental impacts of a product during its entire life cycle (Cavalett et al., 2011). In this work, a cradle-to-gate analysis is considered, which includes from production of raw materials, transport of inputs and outputs to industrial processing. Software package SimaPro® (PRé Consultants B.V.) and the ReCiPe Hierarchist Midpoint v1.05 method are employed in this work. Inventories for each scenario are based in both agricultural and process simulations and comprise raw materials, products, emissions, among other flows. Datasets for raw materials are taken from *ecoinvent* 2.2 database, modified to represent Brazilian reality by Chagas et al. (2012). Allocation of the environmental impacts between ethanol and electricity considers economic criteria, i. e., is based on the participation of each product on revenues. One kg of anhydrous ethanol (99.6 wt%) is defined as reference flow for comparison.

3. Results and discussion

Biorefinery outputs for each scenario are presented in Table 4. It can be noticed that 2G process increases ethanol production from 26 to 46 %, but reducing electricity by about 60 %. The energy cane processing decreases 1G ethanol production, however it allows a larger 2G ethanol production, when compared to the 1G2G-ST scenario.

Capital expenditures are summarized in Table 5. In the 1G2G scenarios, 1G process includes sugarcane reception and handling, sugars extraction and juice treatment and concentration. 1G2G interface denotes the shared industrial infrastructure (e.g. distillation and cogeneration) as well as engineering, insurance, administration, and infrastructure costs. The capital expenses related to the 2G areas are associated with pretreatment, enzymatic hydrolysis, C5 fermentation and solid-liquid separation operations.

In order to provide a comparison among scenarios, the main parameters used in Engineering Economy such as net present value (NPV), internal rate of return (IRR), and the production costs were assessed as depicted in Figures 2 and 3.

As observed in Figure 2, the 1G2G-ST scenario is related to both lower IRR and NPV when compared to the 1G scenario. Moreover, ethanol production costs (Figure 3) for 1G2G-ST scenario are the highest among all scenarios mainly due to its higher capital and enzyme costs which are affected both by the pre-treatment and enzymatic hydrolysis technologies that are still under development.

Table 4: Ethanol and electricity production in the biorefinery scenarios

Parameter	1G	1G2G-ST	1G2G-LT	1G2G-EC
1G ethanol production (L/t of cane*)	85.4	85.4	85.4	50.5
2G ethanol production (L/t of cane*)	-	22.1	39.4	32.9
Overall ethanol production (L/t of cane*)	85.4	107.5	124.8	83.4
Surplus electricity (kWh/t of cane*)	185.8	77.4	61.6	71.9

* Either conventional cane or energy cane.

Table 5: Capital expenditures (US$ million) for each biorefinery scenario

Section	1G	1G2G-ST	1G2G-LT	1G2G-EC
1G process + 1G2G interface	318.9	276.8	273.0	179.5
2G process	-	108.0	85.1	124.5
Overall process	318.9	384.8	358.1	304.0

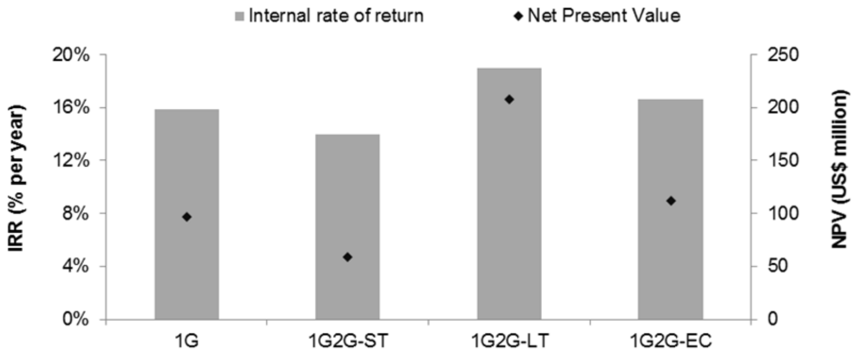

Figure 2: Results of cash flow analysis considering different biorefinery scenarios

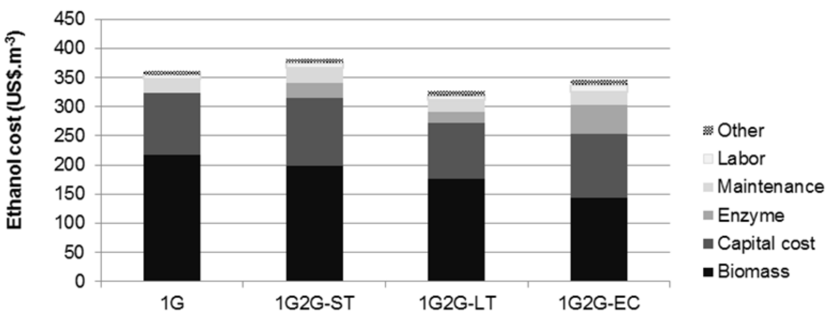

Figure 3: Breakdown of ethanol production costs for 1G and 1G2G scenarios

When considering technological improvements that will take place in 2G process – such as higher hydrolysis yields and enzyme cost reduction – the 1G2G-LT ethanol production costs (Figure 3) may decrease, mainly due to the impacts of higher ethanol production both on biomass and capital costs. Besides, 1G2G-LT presents much better economic results, considering its NPV and IRR (US$ 208 million and 19 % per year), that are the highest values among all scenarios.

The energy cane processing (1G2G-EC scenario) also presents economic viability (IRR near 17% per year) and significant cost reduction especially due to biomass cost reduction which is the lowest among the scenarios (about US$ 0.143 per liter). This result is achieved through the significant increase in biomass productivities obtained in the energy cane production, when compared to conventional sugarcane. In all the scenarios, capital cost, biomass, enzymes (used in 2G process) are the main components in the ethanol production cost, being responsible for up 90 % of total costs.

Environmental impacts are depicted in Figure 4. As observed, both alternatives (2G process and energy cane) reduce the impacts on agricultural land occupation, since it is closely related to the amount of ethanol produced per area. Inclusion of 2G process increases ethanol production (per tonne of feedstock) when compared to 1G process, since more ethanol is produced per tonne of feedstock. On the other hand, energy cane has a high agricultural productivity (200 t/ha) and, even with lower ethanol yields (per tonne of feedstock), it can significantly increase ethanol production per area.

Considering only the scenarios based on conventional sugarcane (1G, 1G2G-ST and 1G2G-LT), as ethanol production per tonne of feedstock increases, the impacts are diluted since the sugarcane production is the major component in the environmental impacts for all the evaluated categories. However, the use of inputs (e.g. ammonia and enzymes) in 2G process intensify fossil depletion and freshwater eutrophication, reducing the difference between 1G and 1G2G scenarios.

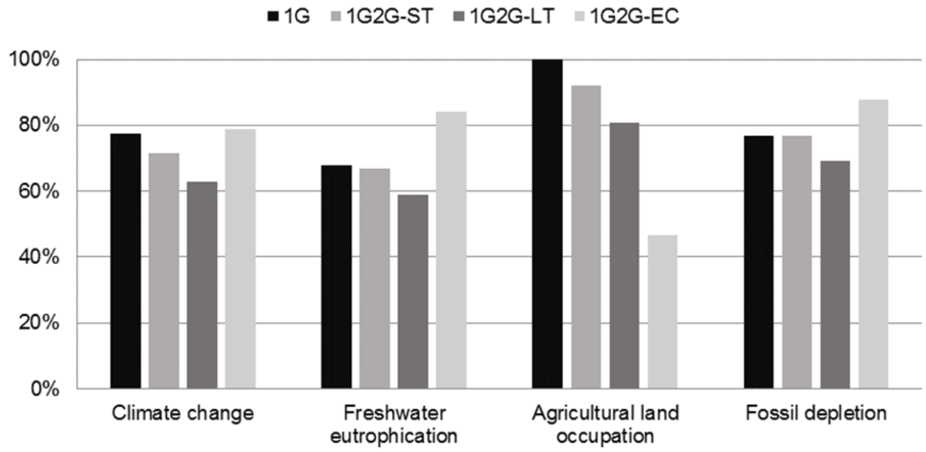

Figure 4: Environmental impacts per unit of mass of anhydrous ethanol produced in each scenario

In spite of the higher agricultural productivity, the introduction of energy cane with short term 2G technology did not improve environmental results, with exception of agricultural land occupation, since most impacts are related to the agricultural operations that are proportional to the amount of feedstock (e.g harvesting and transportation) and a relatively low ethanol yield per mass of feedstock is achieved.

4. Conclusions

This work indicated that both energy cane and second generation ethanol will represent economically viable alternatives for sugarcane biorefineries. Even considering that energy cane production may face technical difficulties in the near future (related to both agricultural and processing operations), 1G2G ethanol production with conventional sugarcane may also configure a clear alternative to decrease ethanol production costs and to increase the economic viability of sugarcane biorefineries. In terms of environmental impacts, 1G2G ethanol production with conventional sugarcane showed lower impacts for all categories, with exception of agricultural land occupation, when energy cane scenario has the lowest impact.

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References

Cavalett O., Cunha M.P., Junqueira T.L., Dias M.O.S., Jesus C.D.F., Mantelatto P.E., Cardoso T.F., Franco H.C.J., Maciel Filho R., Bonomi A., 2011, Environmental and economic assessment of bioethanol, sugar and bioelectricity. Chemical Engineering Transactions, 25, 1007-1012, DOI: 10.3303/CET1125168.

CEPEA (Center for Advanced Studies on Applied Economics), 2015, The CEPEA registers, <www.cepea.esalq.usp.br> accessed 03.12.2015.

Chagas, M.F., Cavalett, O., Silva, C.R.U., Seabra, J.E.A., Bonomi, A., 2012, Adaptação de Inventários de Ciclo de Vida da cadeia produtiva do etanol de cana-de-açúcar no Brasil. In: III Congresso Brasileiro em Gestão do Ciclo de Vida de Produtos e Serviços, Maringá, Brazil, 2012.

Dias M.O.S., Cavalett O., Maciel Filho R., Bonomi A., 2014, Integrated First and Second Generation Ethanol Production from Sugarcane. Chemical Engineering Transactions, 37, 445-450, DOI: 10.3303/CET1437075.

EPE (Brazilian Energy Research Company), 2015, Prices in electricity auctions. <www.epe.gov.br/leiloes/Paginas/default.aspx> accessed 03.12.2015.

MME (Ministry of Mines and Energy), 2014, Energy auctions, <www.mme.gov.br/programas/leiloes_de_energia/> accessed 20.07.2014.

Pereira L.G., Dias M.O.S., Junqueira T.L., Chagas M.F., Cavalett O., Maciel Filho R., Bonomi A., 2014, Production of Butanol and Other High Valued Chemicals Using Ethanol as Feedstock Integrated to a First and Second Generation Sugarcane Distillery. Chemical Engineering Transactions, 37, 805-810, DOI: 10.3303/CET1437135.