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Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash

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ABSTRACT

Ethanol production from lignocellulosic materials is often conceived considering independent, stand-alone production plants; in the Brazilian scenario, where part of the potential feedstock (sugarcane bagasse) for second generation ethanol production is already available at conventional first generation production plants, an integrated first and second generation production process seems to be the most obvious option. In this study stand-alone second generation ethanol production from surplus sugarcane bagasse and trash is compared with conventional first generation ethanol production from sugarcane and with integrated first and second generation; simulations were developed to represent the different technological scenarios, which provided data for economic and environmental analysis. Results show that the integrated first and second generation ethanol production process from sugarcane leads to better economic results when compared with the stand-alone plant, especially when advanced hydrolysis technologies and pentoses fermentation are included.

1. Introduction

Increasing concerns about climate change and energy security have motivated the search for alternative forms of energy (Karuppiah et al., 2008). Since the transportation sector is responsible for a significant fraction of the greenhouse gases emissions, substitution of oil derived fuels by biofuels, like ethanol, could significantly decrease environmental impacts, besides providing gains on the socio-economic levels as well.

Brazil and the US are the world's largest bioethanol producers, using sugarcane and corn as feedstock, respectively. In the Brazilian sugarcane industry, large amounts of lignocellulosic materials (sugarcane bagasse and trash) are produced during sugar and ethanol production. Sugarcane bagasse is currently used as fuel, supplying the energy required for the plant, while sugarcane trash, previously burnt to improve the harvest procedure, is today mostly left in the field for agricultural purposes (Alonso Pippo et al., 2011). Therefore, banning of burning practices significantly improved the amount of sugarcane trash available for use in the industry (Seabra et al., 2010).

Second generation bioethanol, produced from lignocellulosic materials, has been envisioned as the biofuel with the largest potential to replace fossil derived fuels with lower impacts than the conventional, first generation bioethanol (Martín and Grossmann, in press; Ojeda et al., 2011; Seabra et al., 2010). Besides being cheap and abundant, production of lignocellulosic materials has limited competition with food production, thus they do not compromise food security (Alvira et al., 2010; Čuček et al., 2011). In the sugarcane industry another advantage for the use of lignocellulosic material as feedstock for bioethanol production is clear: since they are already available at plant site (for bagasse), or close to it (trash), second generation bioethanol production may share part of the infrastructure where first generation ethanol production takes place (for instance concentration, fermentation, distillation, storage and cogeneration facilities). In addition, potential fermentation inhibitors generated in the lignocellulosic material pretreatment may have a decreased effect on fermentation yields, since the hydrolyzed liquor may be fermented mixed with sugarcane juice, diluting these inhibitors. Nevertheless, the recalcitrance of lignocellulosic materials hinders the transformation of cellulose into fermentable sugars; the second generation ethanol production processes therefore require more sophisticated equipment and investment than conventional first generation ethanol production (Nigam and Singh, 2011).

Since second generation ethanol production is not yet a commercial reality, different process configurations have been investi-

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gated in order to develop efficient conversion processes. Several authors have analyzed biorefineries configurations through modeling and simulation (Alvarado-Morales et al., 2009; Čuček et al., 2011; Dias et al., 2009; Huang et al., 2009; Kazi et al., 2010; Seabra et al., 2010; Tao and Aden, 2009). Čuček et al. (2011) studied the integration of the first and second generation ethanol production from the entire corn plant (corn grain and stover). Seabra and Macedo (2011) indicate that the conclusions of such strategies are dependent on the assumptions and geographical region of application, thus the analyses made should be carried out considering local and specific technical parameters in order to correspond to reality.

Production of second generation ethanol from sugarcane bagasse and trash was evaluated for stand-alone and integrated (with first generation ethanol production from sugarcane juice) plants. An optimized first generation plant, with decreased steam consumption and recovery of 50% of the trash produced in the field, among other improvements over conventional bioethanol production, was used as basis for the analysis. Different hydrolysis technologies, including improvements on hydrolysis yields, pentoses biodigestion and fermentation to ethanol, were evaluated. The increase on ethanol production due to the use of sugarcane lignocellulosic fractions as feedstock for second generation was evaluated for the selected technologies. Sensitivity analyses were carried out to assess the impact of changes of important parameters (prices, investment and inputs) on the economic and environmental indicators.

2. Methods

2.1. First generation ethanol production

For first generation bioethanol production process, data were collected from the literature (Ensinas et al., 2007; Macedo et al., 2008), obtained at an industrial plant or from interviews with specialists. Anhydrous bioethanol production from sugarcane in an autonomous distillery is comprised by the major steps illustrated in Fig. 1. Details about the process may be found in a previous study (Dias et al., 2011a).

Because sugarcane bagasse is used as a fuel in the conventional bioethanol production from sugarcane, the autonomous distillery must reduce its process steam consumption in order to produce larger amounts of lignocellulosic material surplus, which will be used as feedstock for second generation ethanol production.

An optimized autonomous first generation distillery is assumed in this study, on which efficient 90 bar boilers are employed, and ethanol dehydration is done employing molecular sieves (which present lower steam consumption in comparison with other commercial dehydration methods) (Simo et al., 2008). All the drivers are electrified, which represents the current trend for new plants in Brazil (Seabra et al., 2010). In addition, a 20% reduction on process (2.5 bar) steam consumption was assumed: it may be achieved by means of process integration (Dias et al., 2011b).

The main parameters of the optimized first generation plant are displayed in Table 1.

2.2. Second generation ethanol production

Second generation ethanol production consists of pretreatment and hydrolysis of the lignocellulosic material. The available lignocellulosic material is sent to the pretreatment operation, comprised by steam explosion followed, or not, by an alkaline delignification step (depending on the scenario configuration). In the steam explosion, most (70%) of the hemicellulose is hydrolyzed into pentoses, with small cellulose losses and no lignin solubilization (Ojeda et al., 2011). The pretreated solids are separated from the obtained pentoses liquor using a filter; pentoses are either fermented into ethanol or biodigested (producing biogas for the cogeneration system), depending on the scenario configuration.

In some configurations pretreatment is followed by an alkaline delignification step, where most of the lignin is removed from the pretreated material decreasing its inhibitory effects on enzymes in the enzymatic hydrolysis step (Rocha et al., 2012).

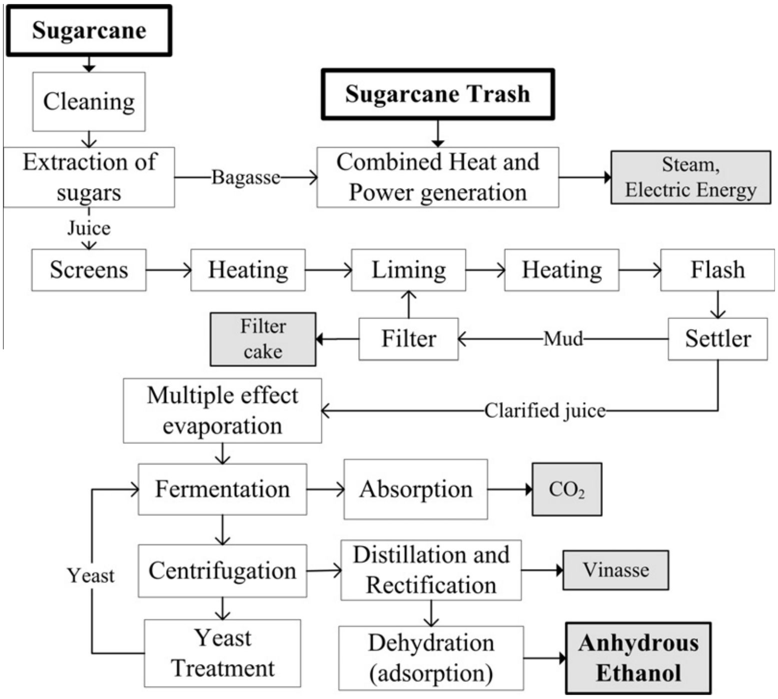

Fig. 1. Block flow diagram of the optimized autonomous distillery producing anhydrous bioethanol from sugarcane.

Table 1
Parameters adopted in the simulation of the optimized autonomous distillery.

Parameter	Value
Sugarcane processed (wet basis)	500 TC/h[a]
Days of operation	167 days/year
Sugarcane trash produced (dry basis)	140 kg/TC
Sugarcane total reducing sugars content (wet basis)	15.3%
Sugarcane fibers content (wet basis)	13%
Sugarcane bagasse/trash cellulose content (dry basis)	43.38%
Sugarcane bagasse/trash hemicellulose content (dry basis)	25.63%
Sugarcane bagasse/trash lignin content (dry basis)	23.24%
Sugarcane bagasse moisture	50%
Sugarcane trash moisture	15%
Efficiency of juice extraction in the mills	96%
Fermentation efficiency	90%
Ethanol content of the wine fed in the distillation columns	8.5°GL
Hydrated ethanol (HE) purity	93 wt.%
Anhydrous ethanol (AE) purity	99.6 wt.%
Fraction of bagasse for start-ups of the plant	5%
Fraction of trash recovered from the field	50%
90 bar boiler efficiency – LHV basis	87%
90 bar steam temperature	520 °C
Turbines isentropic efficiency – 1st stage	72%
Turbines isentropic efficiency – 2nd stage	81%
Generator efficiency	98%
Steam pressure – process	2.5 bar
Steam pressure – molecular sieves	6 bar
Process electric energy consumption	30 kWh/TC
Molecular sieves steam consumption	0.6 kg steam/LAE[b]

[a] TC: metric tons of sugarcane.
[b] LAE: liter of anhydrous ethanol.

The solid fraction obtained after filtration of the material is sent to enzymatic hydrolysis. The hydrolyzed liquor produced in the enzymatic hydrolysis, rich in glucose, is separated from the unreacted solids (residual cellulignin), which are used as fuels in the cogeneration system. In the integrated process, the hydrolyzed liquor is mixed with sugarcane juice; thus, concentration, fermentation, distillation and dehydration operations are shared between both processes. The same conversion of first generation fermentation reactions (conversion of glucose to ethanol) was assumed for the second generation process, both in the integrated and stand-alone configurations.

Three technological scenarios were created in order to evaluate second generation ethanol production from sugarcane bagasse and trash, considering different yields, solids loading on hydrolysis and destination of pentoses (biodigestion to biogas used in the cogeneration system or fermentation to ethanol). Two levels for hydrolysis were considered: current technology (low yield, low solids loading) and a second level, potentially available in 2015 (higher yields and solids loading, lower investment and lower enzyme cost). In both scenarios steam explosion is the pretreatment method, but in the 2015 technology scenario it is followed by an alkaline delignification step, which leads to higher yields on the subsequent enzymatic hydrolysis step due to removal of lignin (Yin et al., 2011). Pentoses produced during pretreatment are either biodigested, producing biogas for use as a fuel, increasing the amount of surplus lignocellulosic material, or fermented to ethanol. Fermentation of pentoses to ethanol is assumed to be available only at the most futuristic scenarios (possible scenario in 2015–2020) because conventional microorganisms employed in industrial fermentation processes are not able to ferment pentoses. Gírio et al. (2010) provided an extensive review on the processes through which hemicellulose may be converted to ethanol. Fermentation yields of 95% have been reported, but several problems (microorganism tolerance to ethanol and other inhibitors and low productivity among them) remain to be solved in order for those high yields to be achieved at industrial operations. In this work a conversion of 80% of pentoses to ethanol was adopted in the scenarios where pentoses fermentation is assumed.

A block-flow diagram of the integrated first and second generation ethanol production from sugarcane is displayed in Fig. 2.

Characteristics of the different technologies including yields and operating conditions are reported in Table 2, and are based on literature data (Leibbrandt et al., 2011; Ojeda et al., 2011) and on information provided by specialists.

In addition to the technical parameters displayed in Table 2, the 2015 technology for second generation ethanol production would present lower investment, mainly due to the decrease on hydrolysis reactors size, as well as lower enzymes costs, when compared with current technology. These data are shown in Section 2.5.

2.3. Scenarios definition

In order to compare integrated and stand-alone second generation ethanol production, different scenarios were simulated and evaluated. Their characteristics are shown in Table 3. In all scenarios a 20% reduction on process (2.5 bar) steam consumption was assumed, including those with second generation ethanol production.

Scenario 1 represents the optimized autonomous distillery with maximization of surplus electricity (all the bagasse and trash are used as fuels for electricity production). In scenario 1a bagasse and trash are burnt only to supply the energy demand of the plant; thus, there is a surplus of lignocellulosic material which is sold to be processed in the stand-alone second generation plant (scenario 5). Nevertheless, surplus electricity is sold in all scenarios because efficient, high pressure boilers are employed and the amount of electricity produced due to steam expansion on back pressure steam turbines is larger than the electricity demand of the processes. In scenario 2, integrated first and second generation (with current hydrolysis technology) and pentoses biodigestion takes place. Scenarios 3 and 4 represent integrated first and second generation (with 2015 expected hydrolysis technology) and pentoses biodigestion and fermentation, respectively. Scenario 5 represents the stand-alone second generation plant with 2015 expected technology and pentoses fermentation; this plant presents, besides the pretreatment and hydrolysis units, independent fermentation, distillation and cogeneration sections, since it is not integrated to a first generation facility.

2.4. Process simulation procedure

Simulations of the different scenarios were carried out using software Aspen Plus. Since components of the lignocellulosic material were not available in the Aspen Plus databank, their properties were obtained from the databank for biofuels components developed by the NREL (Wooley and Putsche, 1996); however, lignin structure was modified to represent sugarcane lignin, with molecular formula $C_9O_{2.9}H_{8.6}(OCH_3)$ and its enthalpy of formation was determined based on enthalpy of combustion (27,000 kJ/kg) given by Stanmore (2010), resulting in 25,689 kJ/kg. Fiber components (cellulose, hemicellulose and lignin) were inserted as solids; streams containing those components are defined as MIXCISLD streams in the simulation, which represent streams with conventional solids with no particle distribution.

As an example, the simulation flowsheet developed to represent scenario 3 is illustrated in Fig. 3; in this configuration the pentoses released during pretreatment are sent to the cogeneration system, where biodigestion takes place.

All the unit operations necessary to represent the process were inserted into the correspondent hierarchy block (MILLS for sugarcane cleaning and extraction of sugars; TREATFER for juice treatment and fermentation; DISTILL for distillation; DEHYD for

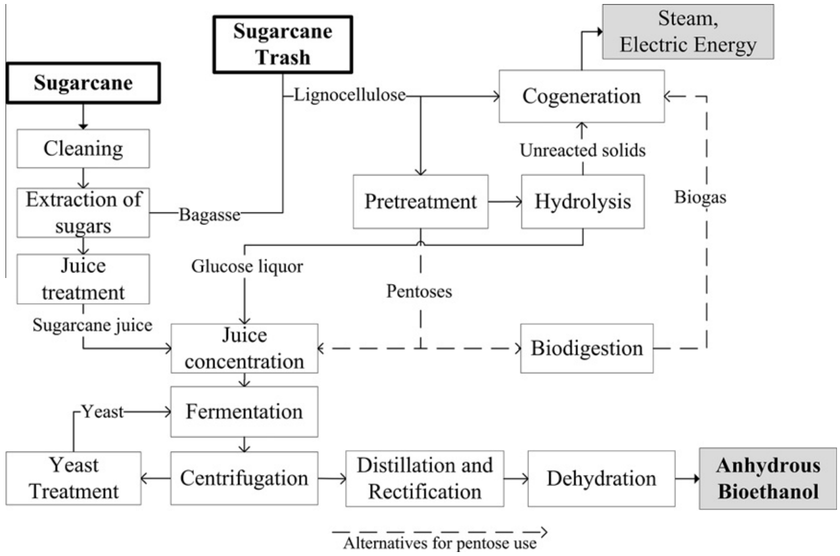

Fig. 2. Simplified block flow diagram of the integrated first and second generation bioethanol production from sugarcane.

Table 2
Parameters adopted in the simulation of the second generation ethanol production process.

Parameter	Value
Pretreatment – hemicellulose conversion	70%
Pretreatment – cellulose conversion	2%
Pretreatment – temperature	190 °C
Pretreatment – reaction time	15 min
Alkaline delignification – lignin solubilization (2015 technology)	90%
Alkaline delignification – temperature (2015 technology)	100 °C
Alkaline delignification – reaction time (2015 technology)	1 h
Alkaline delignification – solids loading (2015 technology)	10%
Alkaline delignification – NaOH content (2015 technology)	1% (m/V)
Hydrolysis – cellulose conversion (current/2015 technology)	60/70%
Hydrolysis – hemicellulose conversion (current/2015 technology)	60/70%
Hydrolysis – solids loading (current/2015 technology)	10/15%
Hydrolysis – reaction time (current/2015 technology)	72/48 h
Pentose biodigestion – chemical oxygen demand (COD) removal	70%
Pentose fermentation to ethanol conversion	80%
Filters – efficiency of solids recovery	99.5%
Filters – soluble solids losses	10%
Electricity consumption	24 kWh/ton LM[a]

[a] LM: lignocellulosic material for second generation (wet basis).

Table 3
Characteristics of the evaluated scenarios.

Parameter	Scenario					
	1	1a	2	3	4	5
1st generation ethanol production	X	X	X	X	X	
2nd generation ethanol production			X	X	X	X
Sell of surplus electricity	X	X	X	X	X	X
Sell of surplus bagasse		X				
Current technology for 2nd generation			X			
2015 technology for 2nd generation				X	X	X
Pentoses biodigestion			X	X		
Pentoses fermentation					X	X

dehydration, COGEN for cogeneration and 2G for second generation – pretreatment and hydrolysis, as shown in Fig. 3). The main parameters used to simulate the first generation ethanol production were displayed in Table 1. More details about the simulation are provided in the Appendix.

Due to the various recycle streams present in the simulation, convergence of the process is not easily achieved. This is a consequence of the fact that the exact amount of surplus lignocellulosic material (stream LM in Fig. 3) directed for 2G process depends on the amount of residues (LIGNIN, CELLULOS and PENTOSE) produced in second generation operations (represented by the block 2G) and on the entire steam consumption of the process, which in turn depends on the amount of hydrolyzed liquor (HYDROL) sent to fermentation with the sugarcane juice.

2.5. Economic analysis

Investment data for the first generation autonomous distillery were calculated based on data provided by Dedini (one of the major equipment manufacturer for the ethanol industry in Brazil): a conventional autonomous distillery, crushing two million tons of sugarcane per year, operating with 22 bar boilers and with azeotropic distillation as the ethanol dehydration method costs around US$ 180 million (exchange rate of R$ 1.76 = US$ 1.00 – 2010 average). Most of the investment lies on the extraction sector (US$ 27 million), juice treatment, fermentation and distillation (US$ 31 million) and cogeneration (US$ 54 million). Since an optimized distillery was considered as a basis in this study, an increase of 40% on the investment of the distillation and cogeneration sectors was assumed due to the use of molecular sieves as dehydration method and of 90 bar boilers for steam generation. An additional increase of 10% on the investment of the distillation sector was assumed to account for the heat exchanger network, which accounts for the theoretical decrease of 20% on process steam consumption. Changes in equipment capacity were correlated to costs considering a coefficient of 0.6 (Tao and Aden, 2009).

Investment for the second generation ethanol production plant was based on data provided in the literature (CGEE, 2009), for two technological levels: an integrated second generation ethanol production plant processing 268 thousand tons of sugarcane bagasse per year in 2015 costs around US$ 75 million, while a plant processing 426 thousand tons of sugarcane bagasse per year in 2025 costs about US$ 80 million (values for 2010). In these figures a reduction on the investment over time is assumed mainly due to the decrease on hydrolysis reactors size. More details about the assumptions in the investment for second generation plants are provided in a previous work (Dias et al., 2011c). The first value was used to calculate the investment required on the current hydrolysis technology scenario (scenario 2), while the second represents the 2015 expected hydrolysis technology (scenarios 3–5), considering the amount of lignocellulosic material processed on each scenario.

Economic analysis was carried out assuming the parameters displayed in Table 4.

The internal rate of return (IRR) was evaluated using the parameters displayed on Table 4; the products production costs were calculated as the prices which correspond to an IRR equal to zero, considering the same reduction on ethanol and electricity prices on each scenario. No differentiation between first and second generation ethanol was made when determining production costs.

2.6. Life cycle analysis

Environmental assessment was made by using the Life Cycle Assessment (LCA). LCA is a method for determining the environmental impact of a product (good or service) during its entire life cycle or, as in the case of this study, from production of raw materials, transport of inputs and outputs and ethanol industrial processing. The method consists of four main steps: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 1998, 2006a,b).

In goal and scope definition the intended application of the study, system boundaries, functional unit and the level of detail to be considered are defined. In this study system boundaries are defined as cradle-to-gate and include all raw materials and emissions of sugarcane cultivation, transport and industrial processing, but the use and discard of the products are not included. Functional unit considered is one kg of anhydrous ethanol.

Life cycle inventory (LCI) is the methodological step where an overview is given of the environmental interventions (energy use, resource extraction or emission to an environmental compartment) caused by or required for the processes within the boundaries of the studied system. In this study, the inventories of the sugarcane industrial biorefinery scenarios are based on the results from computer simulations of the process, described in Sections 2.1–2.4. For agricultural stage, inventory is based on typical values for sugarcane production in Center-South region of Brazil. It is important to point out that differences in the agricultural production system were considered because different amounts of vinasse are returned to the agricultural field for fertirrigation in each scenario and, consequently, different inputs for vinasse spreading and different amounts of fertilizers are used in the agricultural stage.

Impact assessment examines the environmental pressures of the emissions and resource use quantified in the inventory analysis. The software package SimaPro® (PRé Consultants B.V.) and the CML 2 Baseline 2000 v2.05 method have been used as tools for the environmental impact assessment (Guineé et al., 2002). The environmental impacts are categorized into 10 environmental categories: Abiotic Depletion (ADP) measured in kg of $Sb_{eq.}$; Acidification (AP) measured in kg of $SO_{2eq.}$; Eutrophication (EP) measured in kg of $PO_4^{-3}{}_{eq.}$; Global Warming (GWP) measured in kg of $CO_{2eq.}$; Ozone Layer Depletion (ODP) measured in kg of CFC-$11_{eq.}$; Human Toxicity (HTP) measured in kg of 1,4 $DB_{eq.}$ (dichlorobenzene); Fresh Water Aquatic Ecotoxicity (FWAET) measured in kg of 1,4 DB_{eq}; Marine Aquatic Ecotoxicity (MAET) measured in kg of 1,4 $DB_{eq.}$; Terrestrial Ecotoxicity (TET) measured in kg of 1,4 $DB_{eq.}$; and Photochemical Oxidation (POP) measured in kg of C_2H_{4eq}. Identification of significant issues, conclusions and recommendations are made in the interpretation step. The approach applied is compliant with the ISO 14040-14044 standards and follows the current state of the art of LCA methodology documents (ISO, 2006a,b).

According to LCA methodology, allocation is required for multi-output processes. In this study economic allocation based on the market value of the process output (the same used for the production costs) was applied, as specified in the ISO 14040-14044 documents (ISO, 2006a,b).

3. Results and discussion

3.1. Techno-economic analysis

The main results for the process simulation and economic analysis (anhydrous ethanol and surplus electricity production, lignocellulosic material (LM) hydrolyzed, second generation ethanol production, investment, internal rate of return (IRR) and production costs) for each scenario are displayed in Table 5.

Besides ethanol and electricity, surplus lignocellulosic material is sold as well in scenario 1a (for the stand-alone plant of scenario 5). The lignocellulosic material price in scenario 1a was calculated to provide an IRR for scenario 1a equal to that of scenario 1; thus, an opportunity price for the lignocellulosic material, that is, the price it should have in order to grant the same profitability obtained selling electricity on scenario 1, was calculated (approximately US$ 60/ton dry lignocellulosic material, using the average

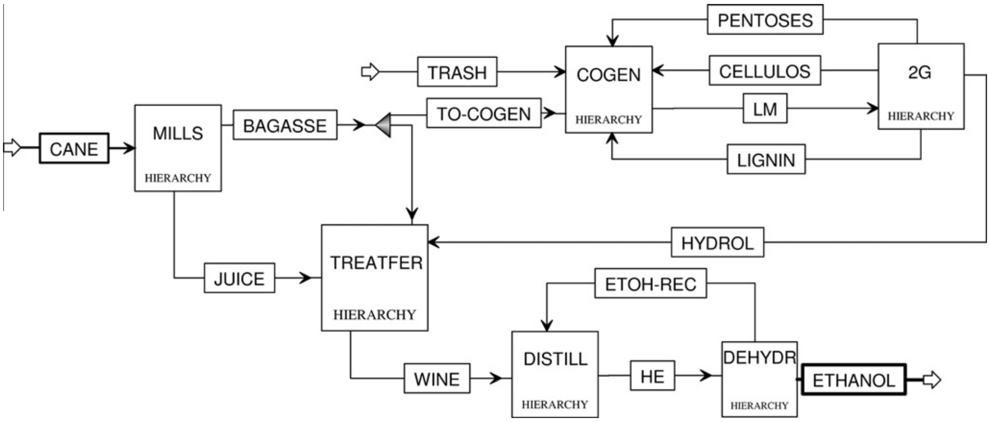

Fig. 3. Simulation flow sheet developed in Aspen Plus for scenario 3: integrated first and second generation ethanol production from sugarcane, using advanced hydrolysis technologies and pentoses biodigestion (TREATFER: juice treatment and fermentation; DISTILL: distillation; DEHYD: dehydration; HE: hydrated ethanol; COGEN: cogeneration).

Table 4
Prices, taxes and project parameters used in the economic analysis.

Parameters	Value
Project lifetime	25 years
Salvage value of equipment	0
Construction and start-up	2 years
Depreciation (linear)	10 years
Tax rate (income and social contributions)	34.0%
Sugarcane price (US$/TC)[a]	23.25
Sugarcane trash price (US$/ton)[b]	17.05
Electricity price (US$/MWh)[c]	84.88
Anhydrous ethanol price (US$/L)[d]	0.60
Enzyme price – current technology (US$/L cellulosic ethanol)[e]	0.11
Enzyme price – 2015 technology (US$/L cellulosic ethanol)[b]	0.05

[a] Six years moving average of sugarcane prices (per ton of sugarcane – TC) (December 2010 values) in São Paulo state (SP), from January 2001 to December 2010 (UDOP, 2011); US$1.00 = R$ 1.76 (2010 average exchange rate).

[b] Values provided by specialists of the sugarcane industry.

[c] Average prices obtained at renewable energy auctions in Brazil (2010 values).

[d] Six years moving average of anhydrous ethanol prices paid to the producer (December 2010 values) in SP, from January 2001 to December 2010 (CEPEA, 2011).

[e] Enzyme price for the current technology is based on an estimate provided by Novozymes.

prices for all the products and feedstock during the 2001–2010 period). This was the price of the feedstock for scenario 5.

Scenario 2, which represents the integrated first and second generation ethanol production with the current hydrolysis technology, has the largest investment among the studied scenarios; its IRR is only greater than that of the stand-alone second generation plant (scenario 5), but it presents the higher ethanol production costs. The use of advanced hydrolysis technologies in the integrated process improves ethanol production (scenarios 3 and 4), but only when pentoses fermentation takes place (scenario 4) the IRR is larger than that of the optimized first generation autonomous distillery (scenario 1). The stand-alone second generation plant (scenario 5) has the lowest IRR mainly due to large investment, which is close to that of scenario 1a, and low ethanol production.

Second generation ethanol production increases from scenario 2 (158 L/ton dry lignocellulosic material – LM) to 3 (181 L/ton) due to the use of more advanced hydrolysis technologies (higher yields and solids loading), but significant improvements are only achieved when pentoses are fermented to ethanol (scenarios 3 and 4), when ethanol production reaches 335 L/ton dry LM. The difference in specific second generation ethanol production in scenarios 2 and 3 (158 and 181 L/ton LM – around 15%) is smaller than the difference in second generation ethanol production in these scenarios (19 and 24 L/TC – around 25%) because in scenario 3 higher solids loading are employed in hydrolysis reactors, leading to a decrease on energy consumption (from 682 to 642 kg of steam per ton of sugarcane in the entire process) and allowing for a larger amount of lignocellulosic material to be hydrolyzed; thus, even though higher hydrolysis yields produce less residues (unreacted cellulose and lignin) that are used as fuels in the boiler, reduced steam consumption leads to higher ethanol production in scenario 3.

It can be verified that the amount of ethanol and electricity produced adding the production of scenarios 1a (first generation plant that produces the feedstock for the stand alone plant) and 5 (stand-alone plant) is about the same as that produced on scenario 4 (integrated process with advanced hydrolysis and pentoses fermentation), but the investment required is about 30% larger; the internal rate of return of the stand-alone second generation plant is significantly reduced, when compared with the integrated production. In addition, ethanol production cost in scenario 4 is the lowest among the evaluated scenarios. It is clear that mass and energy integration between first and second generation ethanol production and reduced steam consumption will play a significant role in the feasibility of second generation ethanol production from sugarcane. Thus, the integration of first and second generation ethanol production presents several advantages over the stand-alone, second generation ethanol production plant, but more detailed analyses considering important variables not evaluated in this work, such as water use, and a detailed energy integration study like that presented by Čuček et al. (2011), must be carried out.

3.2. Life cycle analysis

Fig. 4 compares the environmental impact indicators obtained for the evaluated scenarios. These scores give the comparison of environmental impact emanating from the life cycle of ethanol production including agricultural production process, transport of sugarcane, raw-materials, consumables and industrial residues back to the field and industrial conversion in the biorefinery.

Considering only the first generation processes, it can be observed that the scenario maximizing electricity output (scenario 1) outperforms scenario with lignocellulosic material output (scenario 1a). The inputs for these two processes are similar; however, differences observed on their environmental impacts are mainly due to higher allocation factor to the ethanol production in scenario 1a derived from lower electricity production, not compensated by the lignocellulosic material output.

Results show that integrating first and second generation processes using current technology for second generation ethanol production and pentoses biodigestion (scenario 2) presents the best environmental indicators for most categories among all the evaluated alternatives. In addition, integrated first and second generation ethanol production shares some equipment (concentration, fermentation, distillation and cogeneration), thus requiring less steel and yielding more electricity output per unit of ethanol produced than stand-alone second generation ethanol production. However, sensitivity analyses presented in Section 3.3 indicated that steel used in the industrial equipment has little influence on the ethanol environmental impacts. Higher environmental impacts presented in the future second generation ethanol scenarios (3–5) are mainly related to high sodium hydroxide consumption for alkaline delignification prior to hydrolysis. These results show that technological improvements are necessary in this process for improving environmental sustainability of the future second generation ethanol production; if sodium hydroxide recycling or other methods of delignification using environmentally friendly solvents are employed, the advanced second generation ethanol production considered in this study will present lower environmental impacts. It is also important to highlight that the databank used in this assessment was updated with Brazilian sodium hydroxide production data, which presents environmental impacts remarkably lower than European and American production processes. Scenario 5 presented the highest environmental impacts because it produces only second generation ethanol and, contrary to scenarios 2–4, it does not have the first generation ethanol production to “dilute” the environmental impacts of second generation process. However, comparing the environmental impacts of integrated first and second generation ethanol production in scenario 4 with the equivalent stand alone plant in scenario 1a plus 5 (weighted average), results show that ethanol production in the integrated scenario 4 present lower environmental impacts. For example, GWP is reduced 16%; EP is reduced 26% and MAET is reduced 42% for ethanol production in scenario 4 compared with the weighted average ethanol production in scenario 1a plus 5.

In some environmental impact categories such as acidification potential and global warming potential, first generation ethanol production exporting lignocellulosic material (scenario 1a) and integrated first and second generation ethanol production with

Table 5
Main results of the simulation (ethanol and electricity production, steam and lignocellulosic material (LM) consumption) and economic analysis (internal rate of return (IRR), ethanol and electricity production costs).

Parameter	Scenario					
	1	1a	2	3	4	5[a]
Anhydrous ethanol production (L/TC[b])	82	82	102	107	116	35
Surplus electricity (kWh/TC)	173	34	86	77	81	42
Process steam consumption (kg steam/TC)	902[c]	373	682	642	649	270
Lignocellulosic material hydrolyzed (kg/TC, dry basis)	–	–	123	133	102	104
Second generation ethanol production (L/ton dry LM)	–	–	158	181	335	338
Second generation ethanol production (L/TC)	–	–	19	24	34	35
Investment (million US$)	263	218	367	346	316	200
IRR (% per year)	14.9	14.9	11.6	13.4	16.8	10.0
Ethanol production costs (US$/L)	0.37	0.39	0.39	0.36	0.33	0.35
Electricity production costs (US$/MWh)	52.63	55.69	55.53	51.83	46.48	49.25

[a] No sugarcane is processed in scenario 5 (results are provided on a sugarcane basis for comparison purposes only).
[b] TC: tons of sugarcane.
[c] All the lignocellulosic material is burnt to produce steam; steam required in the production process is equal to 373 kg of steam/TC; the rest is processed in condensing turbines.

future technology and pentoses fermentation to ethanol (scenario 4) present equivalent impacts. This means that the integrated first and second ethanol plant is able to produce ethanol with environmental impact categories equivalent to a modern first generation scenario, in spite of producing a larger amount of ethanol per unit of biomass (around 30% more). This fact highlights the benefits of integrating second generation ethanol production to the first generation units in Brazil, as well in countries with similar conditions.

Melamu and von Blottnitz (2011) showed that diverting bagasse (which is replaced by coal as source of energy for the process) for second generation ethanol production without efficiency improvements from its current use in an ethanol biorefinery in South Africa would backfire for its environmental impacts. However, results from the present study show that current technologies for second generation ethanol production in Brazil (scenario 2) present better environmental impacts in relation to the first generation ethanol production process (scenarios 1 and 1a). This is achieved mainly because partial trash recovery from the sugarcane field, significant improvements in the industrial process energy efficiency and the use of residues (pentoses and lignin) as fuels provide surplus energy and lignocellulosic material for second generation ethanol production, without requiring extra sources of energy from fossil fuels. This reinforces that energy efficiency improvements in the industrial process, considering energy integration among first and second generation ethanol production, as well as efficient technologies for trash recovery are crucial points for the success of the integration of second generation ethanol production process into the first generation sugarcane biorefineries in Brazil.

3.3. Sensitivity analyses

In order to evaluate the impact of changes of prices and investment on the internal rate of return (IRR), taking into consideration eventual uncertainties on the investment and market fluctuations, sensitivity analyses were carried out. For ethanol, electricity and sugarcane prices and investment, changes on the IRR due to variation of ±25% over the average value of these variables (displayed in Tables 4 and 5) were assumed. For enzyme and sugarcane trash costs, changes of ±50% on prices were evaluated. Results are shown in Fig. 5.

It can be verified that among the studied variables, the one which presents the most significant impact on the IRR is ethanol price: variation of ±25% causes the largest changes on the IRR in all the scenarios evaluated. Changes of ±25% on the investment and sugarcane prices also affect the IRR significantly, but with less intensity than ethanol prices. Changes in electricity prices have small impacts on the IRR, and changes of ±50% on enzyme and sugarcane trash prices have very little effect on the IRR in all the scenarios.

Sugarcane trash is not yet transported in large scale to the industrial plant in Brazil because of its low density and consequent high transportation costs. Nevertheless, the impact of changes of ±50% in sugarcane trash price on the IRR of whole enterprise over all the project lifetime is very low, even when an increase of 50% on sugarcane trash price is considered (in this situation, sugarcane trash (with 15% moisture) costs more than sugarcane – US$ 25.58/ton trash against US$ 17.05/TC). For enzyme price, a similar

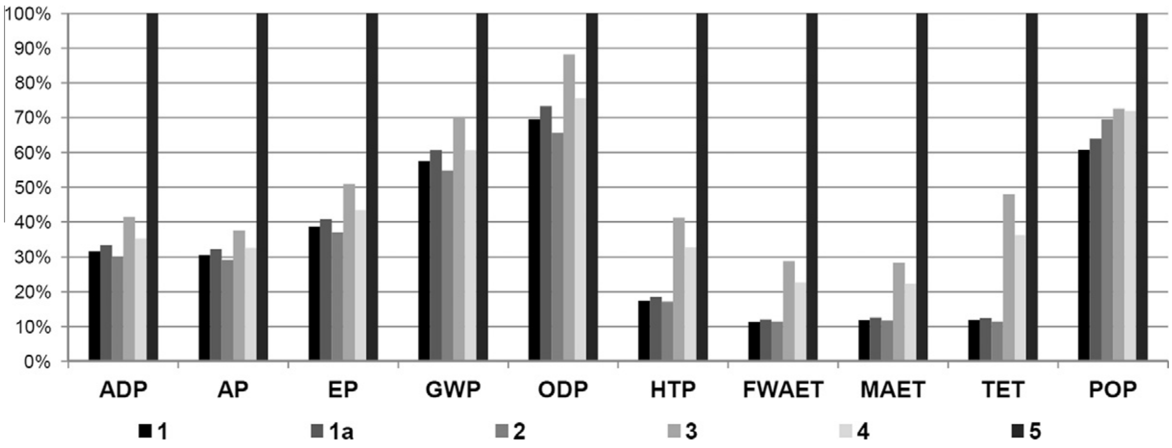

Fig. 4. Comparative environmental impact indicators of the different scenarios.

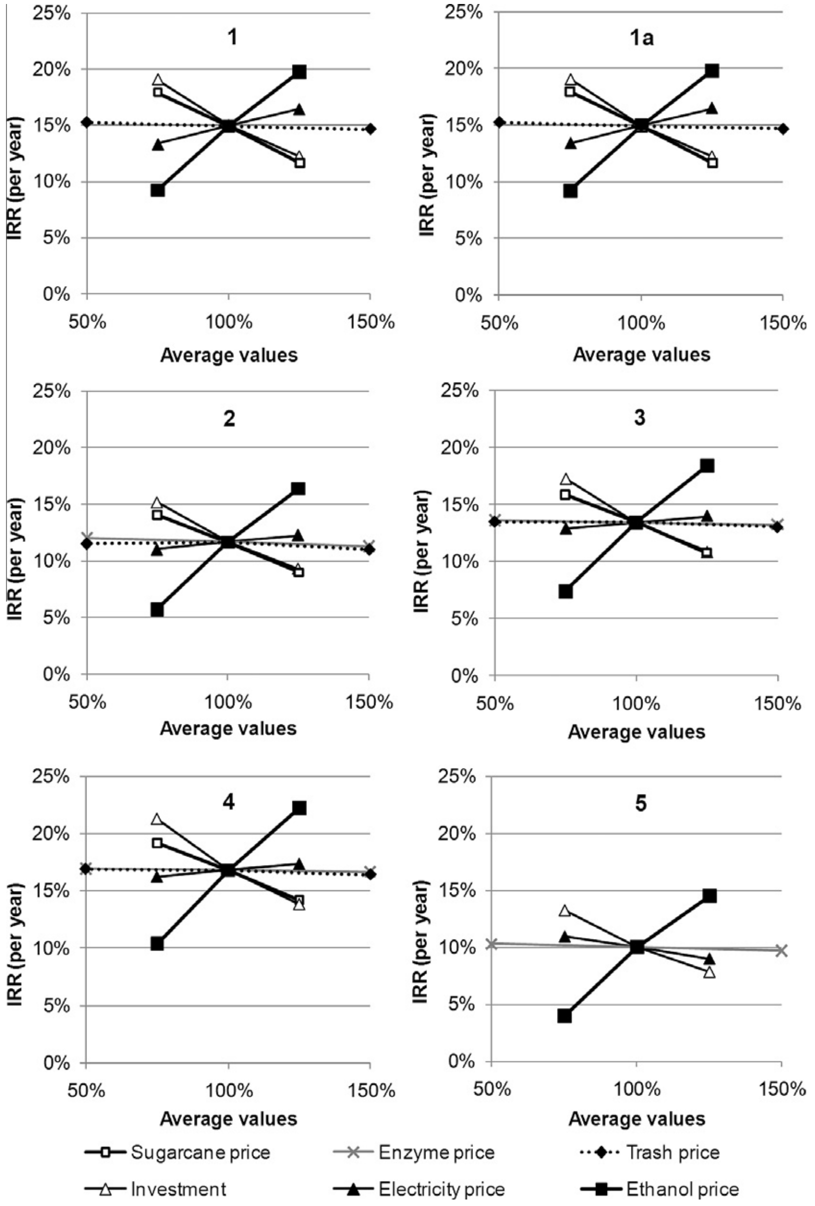

Fig. 5. Sensitivity analyses for the impact of investment and ethanol, electricity, sugarcane, sugarcane trash and enzymes prices on the internal rate of return (IRR) for the studied scenarios.

situation is observed: very small effects on the IRR for changes of ±50% on enzyme prices, considering an average value of US$ 0.11/L cellulosic ethanol. Since the fraction of costs in the industrial process concerning enzymes is proportional to the amount of cellulosic ethanol produced, which correspond to a small fraction of the overall ethanol produced, the impact of enzymes on all the costs is not so significant in the entire project lifetime.

An important observation is that in scenario 5, an increase in electricity prices does not lead to an increase on the IRR, differently from the other scenarios, since feedstock price in scenario 5 (lignocellulosic material) is calculated as the opportunity price of the lignocellulosic material in scenario 1a. Thus, higher electricity prices lead to higher feedstock prices on scenario 5, and as a consequence the IRR is decreased.

IRR on scenario 4, which represents the integrated first and second generation with advanced hydrolysis technologies and pentoses fermentation, reaches the highest values considering the changes on the selected variables. For this scenario, the worst situation (lower ethanol prices) causes an IRR of 10%, which is the highest value obtained for the worst result in the IRR among all the scenarios in the sensitivity analysis. The stand-alone second generation plant presents the lowest IRR values for all the variables.

A sensitivity analysis was performed to assess the impact of selected environmental impact categories as well. In this analysis scenario 4 was selected because it presented the best results in the economic evaluation. Three important environmental impact categories were selected: Global Warming Potential (GWP), Eutrophication Potential (EP) and Human Toxicity Potential (HTP) (Fig. 6). Quantity variation in five important process inputs were evaluated: sodium hydroxide, zeolite and equipment weight (steel) for the ethanol industrial process; and nitrogen fertilizer and diesel used in the agricultural operations for sugarcane growing and harvesting. As expected by the results already discussed in this study, sodium hydroxide is the most impacting parameter in GWP

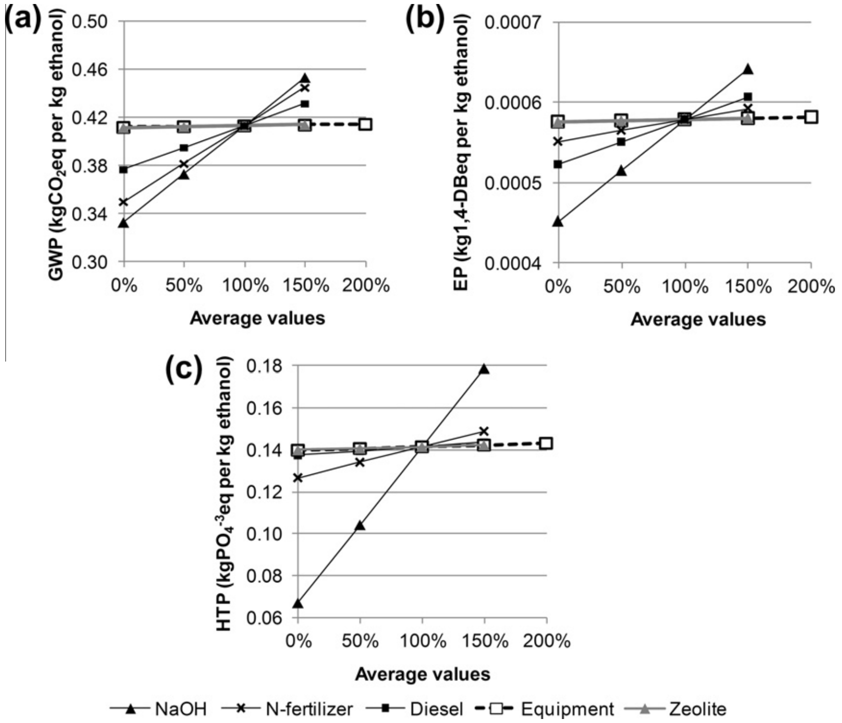

Fig. 6. Sensitivity analyses for Global Warming Potential (GWP) (a) Eutrophication Potential (EP) (b) and Human Toxicity Potential (HTP) (c) for scenario 4 (integrated first and second generation ethanol production from sugarcane, using advanced hydrolysis technologies and pentoses fermentation).

(Fig. 6a), EP (Fig. 6b) and HTP (Fig. 6c). Nitrogen fertilizers and diesel used in the agricultural operations also play an important role in the three environmental impacts evaluated while zeolite and equipment used in the industrial process have minor influence in the ethanol production environmental impacts.

Based on the sensitivity analysis, scenarios 3–5 were evaluated considering that all the sodium hydroxide is recovered in the industrial production process. Results indicate that ethanol production in scenario 4 presents lower environmental impacts than scenarios 1, 1a, 2 and 3. Ethanol production in scenario 5 would present the lowest environmental impacts if all the sodium hydroxide would be recovered; this is mainly due the low economic value of the lignocellulosic material reflecting on its allocation factor (because economic allocation is used in this paper). The economic value of the lignocellulosic material was evaluated in this study as the opportunity price of electricity generation. Using economic allocation criteria, most of the ethanol production environmental impacts in scenario 1a are attributed to ethanol (81%) and smaller part to the lignocellulosic material (14%) and electricity (5%) output. Because of that, second generation ethanol production in scenario 5 is carried out using this "clean" lignocellulosic material from scenario 1a. However, scenario 4 still presents a better environmental profile in comparison to ethanol production in the equivalent stand alone plant in scenario 1a plus 5 (weighted average) even if would be possible to recover all the sodium hydroxide in the second generation ethanol production process.

4. Conclusions

Evaluation of scenarios considering different levels of integration between first and second generation ethanol production plants from sugarcane showed that the integrated first and second generation process using advanced hydrolysis technologies and pentoses fermentation presents several advantages over the stand-alone second generation ethanol production plants, besides the largest ethanol production and the best economic results. If the solvent used in the alkaline delignification is recovered, this configuration also presents the best environmental indicators among the alternatives.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biortech.2011.09.120.

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