CHEMICAL ENGINEERING RESEARCH AND DESIGN 91 (2013) 1411–1417

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Cogeneration in integrated first and second generation ethanol from sugarcane

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ABSTRACT

Sugarcane bagasse and trash are used as fuels in cogeneration systems for bioethanol production, supplying steam and electricity, but may also be used as feedstock for second generation ethanol. The amount of surplus lignocellulosic material used as feedstock depends on the energy consumption of the production process; residues of the pretreatment and hydrolysis operations (residual cellulose, lignin and eventually biogas from pentoses biodigestion) may be used as fuels and increase the amount of lignocellulosic material available as feedstock in hydrolysis. The configuration of the cogeneration system (boiler pressure, lignocellulosic material consumption and steam production, turbines efficiencies, among others) has a significant impact on consumption of fuel and electricity output; in the integrated first and second generation, it also affects overall ethanol production. Simulations of the integrated first and second generation ethanol production processes were carried out using Aspen Plus, comparing different configurations of the cogeneration systems and pentoses use (biodigestion and fermentation). Economic analysis shows that electricity sale can benefit second generation ethanol, even in relatively small amounts. Environmental analysis shows that the integrated first and second generation process has higher environmental impacts in most of the categories evaluated than first generation.

Keywords: Cogeneration; Ethanol; Simulation; Sugarcane; Biorefinery; Economic analysis; Life cycle analysis

1. Introduction

Climate change and concern about the future of oil prices and reserves have motivated the search for renewable fuels, such as bioethanol (Luo et al., 2009), which is foreseen as the biofuel with the largest potential to replace fossil fuels. Second generation ethanol (derived from lignocellulosic materials) presents advantages over conventional first generation, such as no competition with food production and abundance and low price of feedstock (Čuček et al., 2011). Thus, increasing ethanol production using lignocellulosic feedstock is of fundamental importance to establish a sustainable energy future (Nigam and Singh, 2011).

First generation ethanol from sugarcane has been produced on large scale for more than thirty years in Brazil (Soccol et al., 2010), following the national program Pró-álcool created by the government as a response to the oil crisis (Kostin et al., 2012). The integration of second generation ethanol production process from lignocellulose, such as sugarcane bagasse, with first generation ethanol production from sugarcane may improve its feasibility. In comparison with a stand-alone second generation unit, the integrated process will require a lower investment, since some operations (e.g. concentration, fermentation, distillation, storage and cogeneration) may be shared between both plants (Dias et al., 2009). In addition, fermentation inhibitors generated during pretreatment will

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Received 1 October 2012; Received in revised form 9 May 2013; Accepted 13 May 2013
0263-8762/$ – see front matter
http://dx.doi.org/10.1016/j.cherd.2013.05.009

have minor effects on yields since the hydrolyzed liquor will be fermented mixed with sugarcane juice (Dias et al., 2012a).

Since sugarcane bagasse and trash are used as fuels in conventional bioethanol production for generation of steam and electricity in cogeneration systems (Ensinas et al., 2007), the amount of surplus lignocellulosic material used as feedstock for bioethanol production depends on the energy consumption of the production process (Dias et al., 2009). Residues of the pretreatment and hydrolysis operations (residual cellulose, lignin and eventually biogas from pentoses biodigestion, as a first approach to pentoses utilization) may be used as fuels and increase the amount of lignocellulosic material available for hydrolysis. The configuration of the cogeneration system (boiler pressure, lignocellulosic material consumption and steam production, turbines efficiencies, among others) has a significant impact on consumption of fuel and electricity output; in the integrated first and second generation, it also has an important impact on overall ethanol production.

Several authors have evaluated the feasibility of different technological alternatives for bioethanol production through process simulation and mathematical modelling (Čuček et al., 2011; Dias et al., 2009; Franceschin et al., 2008; Furlan et al., 2012; Ojeda et al., 2011; Palacios-Bereche et al., 2011; Pellegrini and Oliveira, 2011; Seabra et al., 2010). The configuration of the cogeneration system, however, has not been given much consideration in the integrated first and second generation ethanol production process. In a previous work (Dias et al., 2012b), it was shown that the use of efficient, low pressure boilers allows small increases in ethanol production in the integrated first and second generation ethanol production process, but the gains on electricity production for high pressure boilers are more significant. However, economic and environmental indicators of the different cogeneration systems remained to be evaluated.

To evaluate the impact of different cogeneration systems in the integrated first and second generation ethanol production process from sugarcane, simulations were carried out using Aspen Plus, in order to assess the most suitable configuration for integration of the second generation ethanol production process from sugarcane in an autonomous distillery. Economic and environmental analyses were carried out as well, to provide strong bases for the comparison of different configurations.

2. Process description

An integrated first and second generation ethanol production process from sugarcane was evaluated in this study; 500 tonnes of sugarcane are processed per hour. The main steps of the process are illustrated in Fig. 1. Lignocellulose was pretreated using steam explosion, followed by alkaline delignification and enzymatic hydrolysis. Further details about the ethanol production processes may be found in a previous work (Dias et al., 2012a).

In the integrated process, surplus bagasse and trash were used as feedstock for second generation, as shown in Fig. 1. The pentoses released in the lignocellulosic material pretreatment may be used in different ways, since there is not yet a commercial technology for pentoses conversion to ethanol (Franceschin et al., 2011). In this work, pentoses biodigestion and fermentation to ethanol were evaluated.

Table 1 – Parameters adopted in the simulation of the integrated first and second generation ethanol production from sugarcane.

Parameter	Value
Sugarcane processed	500 TC/h[a]
Days of operation	167 days/year
Sugarcane total reducing sugars content	15.3%
Sugarcane fibres content	13%
Sugarcane trash produced in the field (dry basis)	140 kg/TC
Fraction of sugarcane trash transported to the industry	50%
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%
Anhydrous ethanol (AE) purity	99.6 wt%
Fraction of bagasse for start-ups of the plant	5%
Steam pressure – process/molecular sieves	2.5/6 bar
Steam demand – molecular sieves	0.6 kg/L AE
Pretreatment – cellulose/hemicellulose conversion	70%/2%
Pretreatment – reaction time/temperature	15 min/190 °C
Alkaline delignification – lignin solubilization/temperature	90%/100 °C
Alkaline delignification – reaction time/solids loading	1 h/10%
Alkaline delignification – NaOH content	1% (m/V)
Hydrolysis – cellulose/hemicellulose conversion	70%/70%
Hydrolysis – solids loading/reaction time	15%/48 h
Pentoses biodigestion – COD removal	70%
Pentoses fermentation to ethanol – conversion	80%
Filters – efficiency of solids recovery	99.5%
Filters – soluble solids losses	10%
Electricity consumption (second generation)	24 kW h/t LM[b]

[a] TC, tonnes of sugarcane.
[b] LM, lignocellulosic material.

The main parameters of the main operations are shown in Table 1.

Different configurations of the cogeneration systems were evaluated; parameters for boilers were obtained in the industry, and represent those commercially available today. In most of the industrial plants, however, low efficiency cogeneration systems are employed, since their lifetime expands over 25 years and only after the late 1990s the mills decided to invest more on electricity generation (Seabra and Macedo, 2011). The main parameters of the cogeneration systems were provided by Dedini (personal communication), and are shown in Table 2.

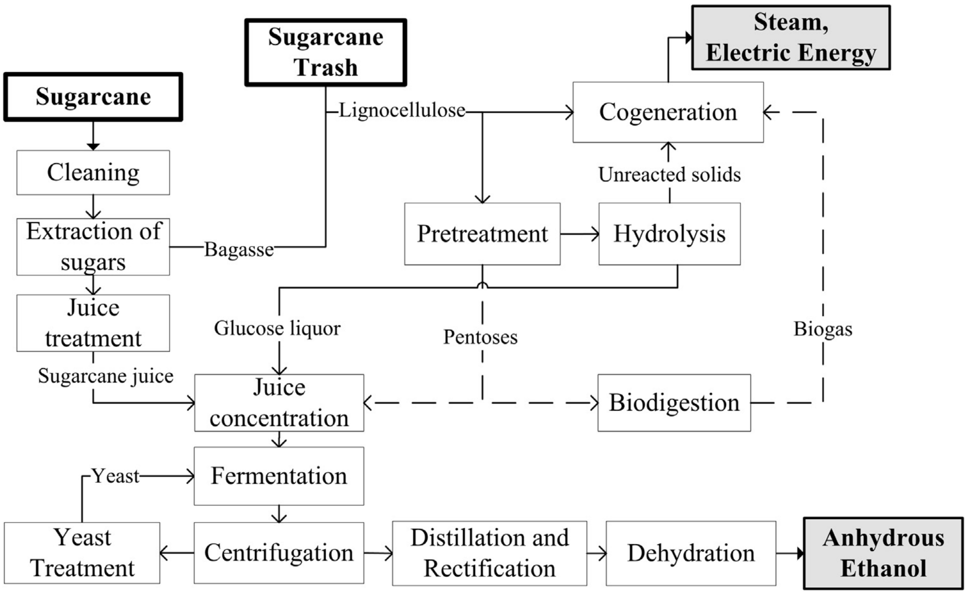

Fig. 1 – Block flow diagram of the integrated first and second generation ethanol production process from sugarcane (dashed lines represent alternatives for pentoses use).

Table 2 – Parameters of the cogeneration systems.

Parameter	Boiler pressure			
	22	42	65	82
Steam pressure (bar)	22	42	65	82
Steam temperature (°C)	300	400	485	520
Steam production (kg steam/kg bagasse)	2.50	2.36	2.23	2.18
Boiler efficiency – LHV basis (%)	85.8	87.0	87.2	87.3
Gases outlet temperature (°C)	180	160	160	160
Electricity demand – direct drives (kW h/TC)	16	16	–	–
Electricity demand – electric drives (kW h/TC)	30	30	30	30
Direct steam drive efficiency (%)	55	55	–	–
Steam turbines efficiency (Mello, 2007) (%)	78	78	85	85
Generator efficiency (%)	98	98	98	98

3. Methodology

3.1. Simulation

Simulations were carried out using Aspen Plus. Combinations of the integrated first and second generation ethanol production process and different cogeneration systems were evaluated through technical, economic and environmental analyses, in addition to an optimized first generation plant with maximized electricity generation (82 bar boilers, condensing steam turbines). The ethanol production process in the optimized first generation autonomous distillery is comprised by the following main steps: sugarcane cleaning, extraction of sugars, juice treatment, concentration and fermentation, distillation and dehydration (using molecular sieves). A reduction on the calculated process steam consumption of 20% was assumed; this figure would be achieved by thermal integration (Dias et al., 2012a). Further details about the simulation and methodology for the economic and environmental analyses may be found in a previous work (Dias et al., 2012a). Pentoses biodigestion, producing biogas as fuel in cogeneration, and fermentation to ethanol were evaluated.

Due to the various interactions among each simulation block, convergence of the simulation was not easily achieved; iterative calculations were carried out until the energy (steam) produced in the cogeneration system was equal to the energy demand of the process (both first and second generation), which in turn provided fuels (unreacted solids) to be used in cogeneration as well as received feedstock (surplus bagasse and trash) for the production process. The interactions between each step of the process are illustrated in Fig. 2.

In addition to the first generation plant, simulations were developed to represent the integrated first and second generation process with cogeneration systems for the production of 22, 42, 65 and 82 bar steam. For 22 and 42 bar boilers, both direct drives and electric engines for mills and other equipment were analyzed; for 65 and 82 bar boilers, only electric engines were evaluated. Pentoses biodigestion, producing biogas to be used as fuel in the cogeneration system, and fermentation to ethanol were assessed.

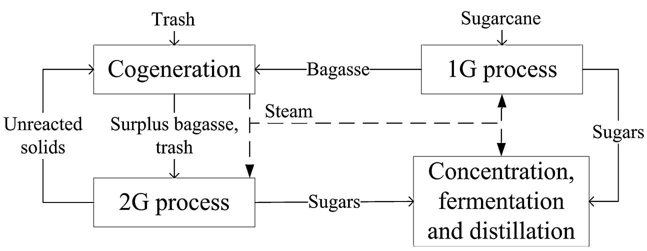

Fig. 2 – Simplified scheme of the simulation developed to represent the integrated first and second generation ethanol production from sugarcane.

Table 3 – Data used in the economic analysis (values for 2010).

Parameter	Value[a]
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 (R$/TC)[b]	40.91
Sugarcane trash price (R$/t)	30.00
Electricity price (R$/MWh)	149.33
Anhydrous ethanol price (R$/L)[c]	1.05
Enzyme price (R$/L cellulosic ethanol)	0.08

[a] US$ 1.00 = R$ 1.76 (2010 average).
[b] 6 Years moving average of sugarcane prices, from January 2001 to December 2010 (UDOP, 2011).
[c] 6 Years moving average of anhydrous ethanol price paid to the producer, from January 2001 to December 2010 (CEPEA, 2011).

Besides bagasse, other fuels are used in the cogeneration system in the integrated first and second generation ethanol production process (trash, residual cellulose and lignin, biogas from pentoses biodigestion); the same boiler efficiencies shown in Table 2 were assumed for these fuels.

3.2. *Economic analysis*

Economic analysis was carried out using a spreadsheet on which data representing the Brazilian scenario were inserted. The main parameters adopted in the economic analysis are shown in Table 3.

Investment was estimated based on data provided by Dedini, one of the major manufacturers of equipment for the sugarcane industry in Brazil: a standard autonomous distillery processing two million tonnes of sugarcane per year, using azeotropic distillation and cogeneration for the production of 22 bar steam requires an investment of R$ 300 million (2009 value), distributed into each sector of the plant according with the fractions displayed in Table 4; 2009 values were updated for 2010 according with inflation for the period (5.9%).

According to Dedini, an increase of 40% in the investment of the section including distillation must be considered when dehydration is done employing adsorption on molecular sieves. In addition, increases of 40% and 30% in the investment of the cogeneration system must be assumed when boilers for the production of 82 and 65 bar steam, respectively, are used. An increase of 20% in the cogeneration sector was assumed for 42 bar boilers. No changes on investment were assumed when electric drives were employed, and a 10% increase on the distillation sector was assumed to account for the heat exchanger network responsible for the reduction of 20% in process steam consumption. Additionally to the values previously shown, an investment of R$ 20 million for transmission lines was included – this value represents an estimate for the investment in transmission lines of 40 km, which is the average distance between mills and distribution stations in the Center-South region in Brazil.

Table 4 – Investment data for the traditional first generation autonomous distillery.

Investment by sector	Share (%)
Sugarcane reception and juice extraction	15
Juice treatment, fermentation and distillation	17
Cogeneration system	30
Buildings, laboratories, water treatment	5
Control and automation, insulation	7
Packaging and transportation	3
Set up	20
Engineering, services	3

For the second generation plant, investment data was based on CGEE (2009), which provided an estimate for the investment in a second generation ethanol production plant annexed to a first generation autonomous distillery, considering two technological levels. Details about the investment in the second generation plant are provided in a previous work (Dias et al., 2011). In this study, the most advanced technology was assumed, for which an investment of R$ 133 million is required to process 462 thousand tonnes of lignocellulosic material (2009 value). Changes in processing capacity were correlated to costs considering a coefficient of 0.6 (Tao and Aden, 2009).

Economic analysis was based on estimation of the internal rate of return (IRR) and production costs. Ethanol and electricity production costs were evaluated as the prices which lead to an IRR equal to zero, decreasing the actual prices shown in Table 3 simultaneously at the same rate (Dias et al., 2011).

3.3. *Life cycle analysis*

Life cycle analysis (LCA) was carried out to compare the environmental impacts of ethanol production in the configurations evaluated in this study; the methodology used (described in detail in a previous work – Dias et al., 2012a), is in accordance with the ISO 14040-14044 standards and follows the current state of the art of LCA methodology (ISO, 2006a,b). The software SimaPro7.3® (PRé Consultants B.V.) and the CML 2 (baseline 2000 v2.05) life cycle impact assessment method have been used (Guinée et al., 2002). The environmental impacts are categorized into ten 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 potential (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}. Since allocation is required for multi-output processes, economic allocation based on the market value of the process output was applied, as described in the ISO 14040-14044 documents (ISO, 2006a,b).

4. Results and discussion

Results for the first generation plant with maximization of electricity production (82 bar boilers, condensing steam turbines – all the lignocelullosic material available is burnt) are shown in Table 5.

This was the configuration used as basis for the comparison of the integrated first and second generation ethanol production processes.

4.1. *Use of electric engines or direct drives*

Firstly, the use of direct drive steam turbines and electric engines was compared for the integrated process with

Table 5 – Results for the autonomous distillery (first generation ethanol only) with maximization of surplus electricity.

Parameter	Value
Anhydrous ethanol production	82.3 L/TC
Surplus electricity	199 kW h/TC
Investment	R$ 462 million
IRR	15.9%
Ethanol production cost	R$ 0.63/L

(modern) 22 and 42 bar boilers and pentoses biodigestion. This comparison was made because the use of direct drives represents an important fraction of the energy consumption of the process and is present in most of the sugarcane mills (Ensinas et al., 2009). Results are shown in Table 6.

Electric engines are more efficient than direct drives; thus, even though the electric engine increases electricity demand, steam is used more efficiently and more surplus electricity is produced when compared with the systems employing direct drives for mills and other equipment. This leads to small gains on the IRR for the systems employing electric drives.

22 bar boilers consume less bagasse to produce steam, as shown in Table 2; thus, small increases on the amount of lignocellulosic material available for hydrolysis are obtained, when compared with 42 bar boilers. The investment for the cogeneration system with 22 bar boilers is lower than that of the system with 42 bar. Nevertheless, the increase on ethanol production and lower investment do not compensate for the losses in electricity production, and the IRR of the processes employing 22 bar boilers is lower than the IRR of the ones with 42 bar boilers.

The IRR of the configurations presented in Table 6 is lower than the IRR of the optimized first generation autonomous distillery, even though ethanol production in the integrated process is up to 33% higher than that of the first generation plant.

Since ethanol production costs were calculated as the prices that provide an IRR equal to zero, as described in Section 3.2, ethanol production costs also decrease for electric drives and for 42 bar boilers, in comparison with direct drives and 22 bar boilers, respectively. Because of their advantages, only electric engines for mills and other equipment were considered in the remaining configurations.

4.2. *High pressure boilers*

65 bar boilers represent the current trend in Brazilian sugarcane mills (Seabra et al., 2010), but higher pressure boilers (82–100 bar steam) are available in the industry. 65 and 82 bar boilers were evaluated in the integrated process with pentoses biodigestion as well. Results are shown in Table 7.

Table 7 – Results for the integrated first and second generation ethanol production with pentoses biodigestion and 65 and 82 bar boilers.

Parameter	Boiler pressure	
	65 bar	82 bar
Anhydrous ethanol production (L/TC)	106.7	105.8
Surplus electricity (kW h/TC)	79.0	89.5
Steam consumption (kg/TC)	658	651
Hydrolyzed LM (dry kg/TC)	134	129
Second generation ethanol production (L/t dry LM)	181	181
Investment (R$ million)	600	606
IRR (% per year)	13.7	13.7
Ethanol production cost (R$/L)	0.64	0.63

Comparing the results shown in Table 7 with those for the optimized autonomous distillery shown in Table 5, ethanol production in the integrated process is lower for higher pressure boilers, but surplus electricity is much larger – at the expense of a higher investment. Electricity surplus in the integrated process is significantly smaller than that of the optimized first generation plant, a result also obtained by Furlan et al. (2012). IRR of the processes with high pressure boilers is higher than those with low pressure boilers, but still lower than that of the first generation ethanol production plant (shown in Table 5).

4.3. *Pentoses fermentation*

In all the results previously presented, the pentose liquor obtained after lignocellulosic material pretreatment was biodigested, producing biogas that was burnt in the cogeneration system. In order to verify the impact of increased ethanol production, pentoses fermentation into ethanol was evaluated as well. In this case, no pentoses biodigestion takes place, and a conversion of pentoses to ethanol of 80% was assumed. This is not yet feasible in industrial scale, but is expected to be so in the years to come.

Results for the integrated first and second generation ethanol production with pentoses fermentation are shown in Table 8.

Thus, the use of low pressure (22 bar) boilers in the integrated first and second generation ethanol production process with pentoses fermentation allows an increase in ethanol production of almost 50%, when compared with the first generation process; an increase of 41% is obtained for high pressure (82 bar) boilers. When pentoses fermentation takes

Table 6 – Results for the integrated first and second generation ethanol production with pentoses biodigestion and 22 and 42 bar boilers, with direct drive and electric engines.

Parameter	Configuration			
	22 direct	22 electric	42 direct	42 electric
Anhydrous ethanol (L/TC)	109.2	109.0	108.6	108.1
Surplus electricity (kW h/TC)	20.3	25.2	45.3	50.8
Steam consumption (kg/TC)	707	708	672	680
Hydrolyzed LM (dry kg/TC)	148	147	144	142
Second generation ethanol (L/t dry LM)	181	181	181	181
Investment (R$ million)	582	581	598	597
IRR (% per year)	12.8	12.9	13.1	13.2
Ethanol production cost (R$/L)	0.67	0.66	0.66	0.65

Table 8 – Results for the integrated first and second generation ethanol production with 22, 42, 65 and 82 bar boilers and pentoses fermentation.

Parameter	Boiler pressure			
	22	42	65	82
Anhydrous ethanol (L/TC)	121.7	119.5	117.9	115.7
Surplus electricity (kW h/TC)	26.5	52.3	80.0	91.7
Steam consumption (kg/TC)	703	678	654	654
Hydrolyzed LM (dry kg/TC)	117	111	106	100
Second generation ethanol (L/t dry LM)	336	334	334	335
Investment (R$ million)	533	549	553	559
IRR (% per year)	16.8	16.7	17.1	16.9
Ethanol production cost (R$/L)	0.58	0.58	0.57	0.57

place, ethanol production increases significantly and the IRR of the configurations with pentoses fermentation are much higher than those with pentoses biodigestion – in this case, all the configurations present an IRR higher than that of the optimized first generation ethanol production as well.

The highest IRR is obtained for the process with boilers for the production of 65 bar steam – this configuration presents an electricity output of 80 kW h/TC and an increase on ethanol production of 43% (compared with the first generation plant). Even though the process with 82 bar boilers presents a higher electricity output (91 kW h/TC), higher investment and lower ethanol production lead to a lower IRR. The processes with low pressure boilers have a lower investment and higher ethanol production, but the low electricity output (26 and 52 kW h/TC for 22 and 42 bar boilers) balances those advantages and leads to lower IRR values. Nevertheless, the IRR obtained for all the configurations with pentoses fermentation are similar.

An additional configuration was evaluated, to assess the impact of electricity sale in the integrated process with pentoses fermentation – since the electricity output is much lower than that of the other configurations, a simulation of the process with 22 bar boiler was carried out considering that no surplus electricity is produced (1G2G 22WE). Therefore, the investment is reduced (R$ 514 million), since no transmission lines are required. In this case, ethanol production reaches 122.2 L/TC; more lignocellulosic material is hydrolyzed (119 kg/TC), but the IRR is reduced (16.6% per year), when compared with the same configuration selling surplus electricity. Thus, sale of surplus electricity in relatively low amounts leads to a small increase in the IRR, even though investment is increased – the revenues of electricity sale do not balance the decrease on investment, when no surplus electricity for sale is produced. Therefore, integrated first and second generation ethanol and electricity production promotes economic gains and contributes to the country's energy security, by diversification of the energy matrix (Grisi et al., 2012). Nevertheless, if there is no market for electricity sale, small gains may be obtained in ethanol production when employing efficient, low pressure boilers.

Fig. 3 shows the comparative environmental impact scores for ethanol production in different assessed scenarios with pentose fermentation to ethanol. These scores give the relative environmental impacts resulting from the life cycle of ethanol production (Ojeda et al., 2011), including agricultural production process, sugarcane transport and industrial conversion. Results show that integrating first and second generation ethanol production (1G2G with boiler pressures of 22, 42, 65 and 82 bar, besides the configuration with no electricity sale – 1G2G 22WE) presents higher environmental impacts than the optimized first generation process (1G) in most categories. As pointed out by Dias et al. (2012a), high environmental impacts are observed in the integrated first and second generation ethanol scenarios due to high sodium hydroxide consumption in alkaline delignification of the lignocellulosic material, indicating this process deserves further improvement. However, integrated first and second generation ethanol presented lower impacts than first generation for acidification and eutrophication. These impact categories are mainly related to fertilizer use in the agricultural stage. Since more ethanol is produced per unit of area on integrated scenarios, this process present better results for AP and EP categories.

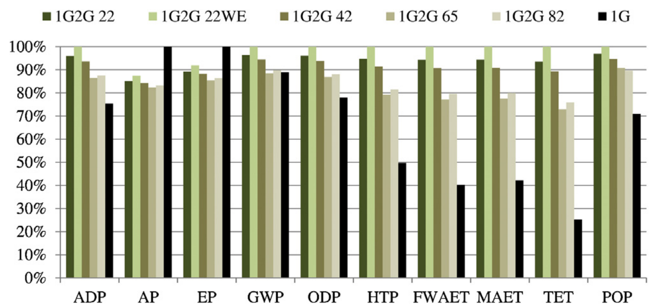

Fig. 3 – Comparative environmental impact scores for ethanol production different biorefinery scenarios (ADP: abiotic depletion; AP: acidification; EP: eutrophication; GWP: global warming; ODP: ozone layer depletion; HTP: human toxicity; FWAET: fresh water aquatic ecotoxicity; MAET: marine aquatic ecotoxicity; TET: terrestrial ecotoxicity; POP: photochemical oxidation).

Integrated first and second generation ethanol using 65 bar boilers (1G2G 65) present global warming potential equivalent to the first generation process. Results also show that integrated first and second generation ethanol production with 22 bar boilers generating electricity output (1G2G 22) presents better results than the same configuration without electricity output (1G2G 22). Lower environmental impacts are obtained for the integrated first and second generation ethanol production process with 65 bar boilers (except in the POP category). These results are in accordance with the economic evaluation, since this configuration also presented the highest IRR.

5. Conclusions

Different configurations of the integrated first and second generation ethanol production process were compared through process simulation, economic and environmental analyses. Different cogeneration systems were evaluated, as well as different destinations for the pentoses obtained after pretreatment of the lignocellulosic material (biodigestion or fermentation to ethanol). Economic analyses based on estimates provided by the industry and by specialists showed that coupling electricity production with second generation in the integrated process improves its profitability, even when electricity is produced in relatively low amounts, as is the case with 22 bar boilers. Pentoses fermentation allow an increase on ethanol production over first generation between 40 and 50%, when compared with the gains of around 30% obtained when pentoses are biodigested. High pressure boilers consume more bagasse than low pressure boilers, thus ethanol output for high pressure boilers is smaller. Nevertheless, revenues obtained with sale of electricity in the processes employing cogeneration systems with high pressure boilers outweigh the losses in ethanol production and the increased investment of these systems. Among the integrated first and second generation process configurations, the one with 65 bar boilers presents the lowest environmental impacts in most categories.

Acknowledgments

The authors would like to thank Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for financial support (contract grant number 2011/19396-6 under the BIOEN Thematic project “An Integrated Process for Total Bioethanol Production and Zero CO_2 Emission”, grant number 08/57873-8).

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