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Utilization of pentoses from sugarcane biomass: Techno-economics of biogas vs. butanol production

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HIGHLIGHTS

- Greenfield projects of a second-generation sugarcane biorefinery were evaluated.
- Pentoses from sugarcane biomass were used either for biogas or *n*-butanol production.
- Production of *n*-butanol and acetone led to increased and diversified revenues.
- Energy efficiency of the butanol plant affected power and ethanol production.
- Energy reduction in the butanol plant enhanced the profitability of the biorefinery.

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ABSTRACT

This paper presents the techno-economics of greenfield projects of an integrated first and second-generation sugarcane biorefinery in which pentose sugars obtained from sugarcane biomass are used either for biogas (consumed internally in the power boiler) or *n*-butanol production via the ABE batch fermentation process. The complete sugarcane biorefinery was simulated using Aspen Plus®. Although the pentoses stream available in the sugarcane biorefinery gives room for a relatively small biobutanol plant (7.1–12 thousand tonnes per year), the introduction of butanol and acetone to the product portfolio of the biorefinery increased and diversified its revenues. Whereas the IRR of the investment on a biorefinery with biogas production is 11.3%, IRR varied between 13.1% and 15.2% in the butanol production option, depending on technology (regular or engineered microorganism with improved butanol yield and pentoses conversion) and target market (chemicals or automotive fuels). Additional discussions include the effects of energy-efficient technologies for butanol processing on the profitability of the biorefinery.

1. Introduction

In Brazil, the great majority of the current annual bioethanol production of about 25 billion liters is based on the fermentation of sugars (glucose + fructose) obtained from the sugarcane juice in mills called first-generation (1G) biorefineries. Basically, there are two biorefinery models, namely annexed plants and autonomous distilleries. In the former, sugars from the sugarcane juice are converted to ethanol and food-grade sugar, and the sugarcane bagasse is burnt to generate steam and power. This model accounts for approximately 70% of the Brazilian sugarcane biorefineries (Cavalett et al., 2012). In the latter, on the other hand, sugar is not produced. In both cases, if efficient high-pressure boilers (65–90 bar) are employed in the cogeneration system, surplus electricity can be sold to the power grid. Still valid for both models, the concept of second-generation (2G) biorefineries is defined by the utilization of fermentable sugars extracted from the lignocellulosic portion of the sugarcane plant, such as the bagasse, in order to produce ethanol.

The integration of second-generation units with conventional first-generation biorefineries, in contrast to stand-alone second-generation units, has the potential to offer significant economic advantages since important operations (concentration, fermentation, distillation and cogeneration) and feedstock (sugarcane bagasse is already available at plant site) may be shared between both plants (Dias et al., 2012). Furthermore, extending to the technical side, the effects on fermentation yields of inhibitors gener-

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ated during biomass pretreatment can be minimized, if not eliminated, by mixing the hydrolyzed liquor with sugarcane juice. However, an important fraction (~25%) of the sugars available in the bagasse, the pentose sugars, cannot be fermented by the yeast *Saccharomyces cerevisiae* employed in sugarcane biorefineries. Although engineered microorganisms able to ferment pentoses to ethanol have been developed, to date none of them could outperform the high fermentation yield and productivity achieved with *S. cerevisiae* (Chandel et al., 2011). In face of this limitation, the biodigestion of the pentose sugars for the production of biogas is an interesting solution to increase ethanol production (Rabelo et al., 2011). The logic is straightforward. Since bagasse is used to produce steam and power, the amount of bagasse available as feedstock for ethanol production depends on the thermal energy consumption of the biorefinery. By supplementing the cogeneration system with biogas, this additional source of energy increases the availability of bagasse for ethanol production.

Alternatively, pentose sugars could be used for the production of added-value chemicals or advanced biofuels, resulting in increased revenues. Particularly, *n*-butanol, hereafter simply butanol, has attracted the attention of investors due to its potential use as a drop-in biofuel and demand by the chemical market. The opportunities around butanol, as phrased by Mascal (2012), are extraordinarily diverse, and have a real potential to permanently impact the renewable energy and materials landscape. Moreover, in the biorefinery context, butanol production from pentose sugar rich hemicellulose streams resulting from agricultural and wood processing plants is an attractive option given the broad substrate ranges of solventogenic clostridia, including pentose sugars (Green, 2011). For example, from the fractionation of corn stover, the Chinese company Jilin Songyuan Laihe Chemicals is producing cellulose as raw material for paper, polyether polyol and phenolic resins from lignin, and butanol from the hemicellulose fraction (http://www.laihe.net/en.aspx).

Nevertheless, a technical aspect related to fermentation processes in general, and markedly present in the butanol processing, may have an important effect on the availability of biomass for ethanol production. The fermentation to produce butanol is characteristically much diluted and, consequently, steam-consuming operations such as sterilization of the sugar solution and downstream product recovery (distillation) are energy-intensive (Vane, 2008; Mariano and Maciel Filho, 2012). In this manner, by opting to use the pentoses stream for butanol production, the 2G ethanol production is expected to decrease due to (i) increased thermal energy consumption in the biorefinery, and (ii) absence of the additional biogas energy stream. In face of these technical aspects, critical questions must be addressed in order to evaluate the economics of the two competing options for pentoses utilization considered in this study. Would the selling of additional products, butanol and the by-product acetone, bring economic advantages despite the reduction in second-generation ethanol production? What is the effect of the butanol plant on the excess power generated by the biorefinery? And perhaps most importantly, given that a great deal of effort has been put into developing energy-efficient technologies for butanol processing, how much would a reduction in steam consumption in the butanol plant affect the profitability of the biorefinery? To answer these questions, this paper presents a technical and economic assessment of greenfield projects of an integrated first and second-generation sugarcane biorefinery (annexed plant model) in which pentose sugars obtained from sugarcane biomass are used either for biogas or butanol production. The biorefinery concepts were assessed with regard to important technical performance parameters, such as biomass utilization breakdown (cogeneration and ethanol production), products output, steam and power consumption, and wastewater footprint. Revenue diversification, steam consumption in the butanol plant, and technology advances in butanol processing guided the discussions of the economic analysis.

2. Methods

2.1. Process description

In the base case scenario, the second-generation ethanol production is integrated to an annexed plant with a processing capacity of 503 tonnes of sugarcane stalks (TC) per hour in 167 days per year (~2 million tonnes of sugarcane/year). After cleaning and crushing the stalks, 122 kg of bagasse in dry basis are produced per TC (lower heating value – LHV of bagasse with 50 wt.% moisture content is 7.5 MJ/kg). Additionally, 50% of the sugarcane straw (tops and leaves) produced in the field is transported to the biorefinery, i.e. 68 dry kg/TC (LHV of straw with 15 wt.% moisture content is 15.1 MJ/kg). Five percent of the bagasse is stockpiled for boiler start-ups. In this manner, 92 dry tonnes of biomass per hour (63% bagasse; 37% straw) are available for the biorefinery. In dry basis, the contents of cellulose, hemicellulose, and lignin in the biomass are 47, 28, 25 wt.%, respectively (Dias et al., 2011a, 2012).

The juice extracted from the sugarcane stalks (133 kg sucrose/TC + 6 kg reducing sugars/TC) is split into two equal streams used for the production of sugar and anhydrous ethanol (99.5 wt.%). Molasses (16 kg sucrose/TC + 3 kg reducing sugars/TC), the concentrated residual solution obtained after sugar crystallization, is also used for ethanol production. Steam (12, 6, 2.5 bar) and power are obtained from the combustion of sugarcane bagasse and sugarcane straw in the cogeneration system. In accordance with the current trend for new plants in Brazil, the cogeneration system of the biorefinery has a 90-bar boiler (86% thermal efficiency in LHV basis) integrated with back pressure turbines. This boiler is more efficient than the traditional 22-bar boilers (75% thermal efficiency) and allows for an excess of power, which is sold to the grid. The amount of bagasse and straw sent for cogeneration is determined by the steam consumption of the biorefinery. Thus, lower steam demand in the production processes leads to higher amounts of bagasse and straw available for second-generation ethanol production. Surplus bagasse and straw are converted into fermentable sugars through pretreatment (steam explosion, 12-bar steam, 190 °C, 15 min) and enzymatic hydrolysis. By steam exploding the biomass, part of the hemicellulose is converted into pentoses and, simultaneously, cellulose becomes available to enzymatic hydrolysis (Martín et al., 2002). In this operation, hemicellulose and cellulose hydrolysis yields are, respectively, 70% and 2%. In the enzymatic hydrolysis step, it was assumed a hydrolysis yield of 60% and solids loading of 10 wt.% according to the current technology for lignocellulosic ethanol production (Dias et al., 2011b). The hexose fraction obtained in the hydrolysis is mixed with sugarcane juice and, after concentration in multiple effect evaporators, fermented to ethanol. The pentose fraction is anaerobically digested to produce biogas, which is burnt in the cogeneration system. Unreacted solids obtained after filtration of the hydrolysis products are also used as fuel in the boiler, along with straw and bagasse. For the different fuels, boiler efficiency was assumed to be 86%. In the competing scenario, the same design is considered, however, the pentose fraction is sent to a butanol plant integrated to the biorefinery. This plant produces butanol along with the by-products acetone and hydrous ethanol (85 wt.%). A block flow diagram with the major processing steps and products of the biorefinery, along with the alternative uses for pentoses, is shown in Fig. 1.

Process parameters for the ethanol, sugar and cogeneration plants are representative of Brazilian industrial large scale plants (over 1 million L of ethanol per day) and were obtained from the literature (Ensinas et al., 2007; Macedo et al., 2008) and interviews