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Environmental and Economic Assessment of Bioethanol, Sugar and Bioelectricity Production from Sugarcane

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The study of optimization scenarios taking into consideration not only technical and energy parameters but also economic and environmental aspects is fundamental for sustainability of biorefinery systems. This study focuses on the environmental and economic impacts of autonomous and annexed sugarcane processing plants in Brazil using an innovative framework, where computer simulation is linked to the environmental and economic assessment. Results showed that considering only the industrial processing stage for ethanol production, autonomous plant present better environmental performance. However it was not possible to establish significant differences between annexed and autonomous plants when the complete life cycle of the ethanol production from sugarcane is considered. Optimized biorefineries showed lower environmental impacts and better economic results in comparison to the base scenarios for both annexed and autonomous plants. Economic results also indicated that, in the base scenario, annexed plant presents slightly higher internal rate of return and slightly lower ethanol production costs. Optimized biorefinery scenarios showed that autonomous plant present higher internal rate of return while annexed and autonomous plants showed equivalent ethanol production costs.

1. Introduction

Environmental and economic aspects are fundamental for the sustainability assessment of the current and novel designs of bioethanol industries, especially in Brazil, where the sugarcane processing plant can be considered as a biorefinery, converting the feedstock (sugarcane) into a variety of products such as sugar, bioethanol, electricity and others by-products. Optimization studies taking into consideration not only energy savings but also economic and environmental aspects are fundamental for the future sugarcane biorefineries in Brazil and to support the strategic decision making process (De Benedetto and Klemeš, 2009; Krotshek and Nardoslawsky, 1996; Vlysidis et al., 2010).
Most of the bioethanol produced in Brazil is obtained as a co-product in annexed distilleries, on which fractions of the sugarcane (usually around 50 %) are diverted to

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sugar and ethanol production. However, most of the new biorefineries are autonomous distilleries where all the sugarcane is used for ethanol production. In both cases sugarcane bagasse is used to attend the process steam and electricity demand and the surplus electricity can be sold to the grid. Optimized annexed and autonomous scenarios are also considered in this study for comparative evaluation of optimization biorefinery technologies. There are also significant differences in the agricultural process of these biorefinery alternatives because different amounts of residues are returned to the field and, consequently, different rates of fertilizer application, agricultural operations and soil emissions are expected.

Literature presents several Life Cycle Assessments (LCA) focusing on environmental impacts of ethanol production from sugarcane with different degrees of data quality, transparency and methodological consistency. These studies usually show a reduction of fossil fuel use and GHG emissions of this biofuel in relation to fossil fuels (Macedo et al., 2008; Luo et al., 2009). However, other environmental impacts including eutrofication, acidification and ecotoxicity as well as integrated economic-environmental assessments of different plant configurations received much less attention (De Benedetto and Klemeš, 2009; Luo et al., 2009).

This paper focuses on the environmental and economic impacts of different alternatives of sugarcane biorefinery in Brazil using an innovative framework, where computer simulation is linked to the environmental and economic assessment. This approach allows identifying and comparing technical, environmental and economic aspects for optimization of different scenarios of sugarcane biorefinery in Brazil.

2. Material and Methods

2.1 Process alternatives

In order to determine the economic and environmental impacts of different production process alternatives, process flowsheets giving material and energy balances are required. Computer simulations for the alternative processes have been developed using Aspen Plus® and provided necessary data about technical aspects, input and output streams and equipments that were used for the economic analysis and for life cycle inventory. Figure 1 shows the flowsheet with main flows and outputs of the annexed plant. Optimized annexed and autonomous scenarios are also considered in this study for comparative evaluation of optimization technologies, including reduction of the steam demand in the process by electrification of sugarcane milling process; thermal integration; and use of alternative dehydration methods (Dias et al., 2010). In addition, high pressure boilers (90 bar) were included aiming at maximization of electricity output. Approximately 193 kWh/t of processed sugarcane are sold to the grid in the optimized scenarios.

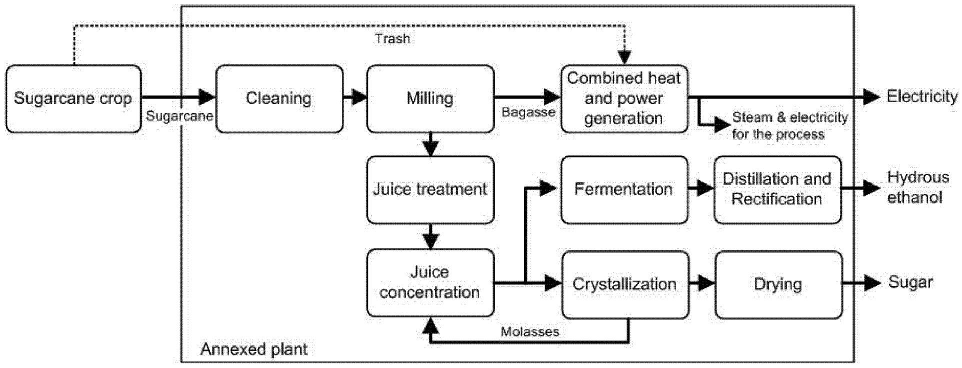

Figure 1: Processes flowsheet of the annexed ethanol, sugar and bioelectricity plant.

2.2 Economic and Environmental assessment

The economic evaluation was made by means of traditional economic indicators including production cost and internal rate of return (IRR). 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 software package SimaPro® (PRé Consultants B.V.) and the CML 2 Baseline 2000 v2.05 method have been used for the environmental impact assessment. The environmental impact categories evaluated were Abiotic Depletion (ADP), Acidification (AP), Eutrophication (EP), Global Warming (GWP), Ozone Layer Depletion (ODP), Human Toxicity (HTP), Fresh Water Aquatic Ecotoxicity (FWAET), Marine Aquatic Ecotoxicity (MAET), Terrestrial Ecotoxicity (TET) and Photochemical Oxidation (POP). The approach used is compliant with the ISO 14040-14044 standards and follows the current state of the art of LCA methodology documents (ISO 14040, 2006; ISO 14044, 2006).

System boundaries, functional unit and allocation

System boundaries are defined as cradle-to-gate and include all raw materials and emissions of sugarcane cultivation, transport and industrial processing. Functional unit is one kg of hydrous ethanol (96 %vv). 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 was applied, as specified in the ISO 14040-14044 documents (ISO 14040, 2006; ISO 14044, 2006).

3. Results and discussion

3.1 Environmental assessment

Figure 2 compares the absolute scores after characterization for ethanol production scenarios in annexed and autonomous plants, considering base and optimized scenarios. These scores give the magnitude of environmental impact emanating from the life cycle of ethanol production including agricultural production process, transport and industrial conversion in the biorefinery.

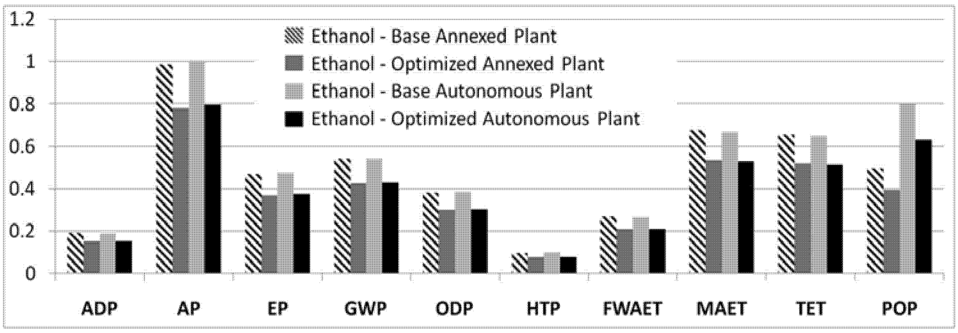

Figure 2: Absolute impact Scores after characterization for the different alternatives of ethanol production.

For the evaluated scenarios a decrease is observed in all environmental impacts in the optimized scenarios. Annexed plant presented slightly lower environmental impacts in the impact categories ADP, FWAET, MAET and TET in the base scenario. In the optimized scenarios annexed plant present lower environmental impacts only in MAET and TET impact categories. However it was not possible to notice significant differences on environmental impacts of the annexed and autonomous plants.
Agricultural production and sugarcane transport processes have sharp influence in the results obtained (except for the POP category) as exemplified in Figure 3, which shows the environmental impacts contribution breakdown for the base annexed plant. These results indicate that environmental impacts are strongly affected by the sugarcane production stage. Environmental impacts only for the industrial biorefinery stage are showed in Figure 4, for better visualizing differences in the biorefinery alternatives for ethanol production.

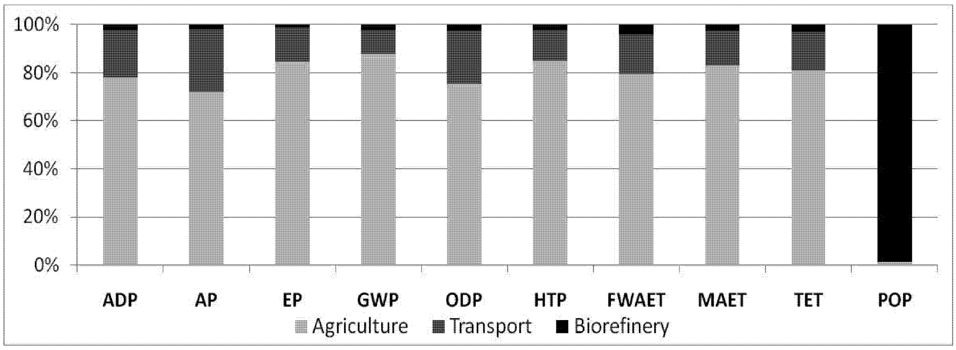

Figure 3: Comparative process contribution for ethanol production in the Annexed base plant.

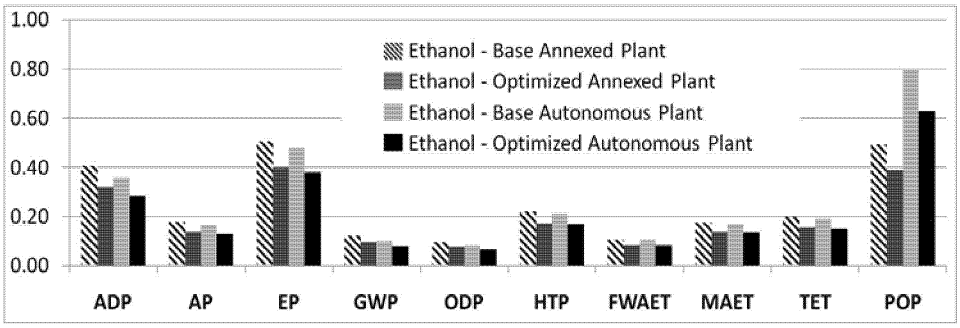

Figure 4: Absolute impact Scores after characterization for the different ethanol biorefinery scenarios considering only the industrial processing stage.

Considering the industrial process separately, comparison between the annexed and autonomous plants in terms of environmental impacts indicates that the autonomous plant shows a better performance in all the categories except in POP. The high POP value in autonomous plant is related to more ethanol production and consequently more ethanol losses in the distillation process. These results considering the industrial stage separately are different from those considering the life cycle of ethanol production including agricultural and sugarcane transport phases (Figure 2). This is primarily due to the fact that autonomous plant generates more vinasse that is returned to the agricultural field for fertirrigation and, consequently, more inputs for vinasse spreading and less fertilizer are used in the agricultural stage. Since agricultural stage is responsible for the greatest fraction of the environmental impacts (Figure 3), autonomous distilleries have slightly higher environmental impacts in some environmental impact categories when considering complete life cycle of ethanol production process, even though it presents lower impacts in the industrial processing stage.

3.2 Economic assessment

Internal rates of return (IRR) were calculated assuming the average price of the last 10 years for ethanol and sugar in Brazil. Production costs were determined decreasing product prices proportionally until zero IRR. Results for the base scenarios show that annexed plant present slightly higher IRR (13.5 %) in comparison to autonomous one (13.4 %). Likewise, ethanol production costs are slightly lower in annexed plant (0.34 US$/l) in comparison to autonomous ones (0.35 US$/L). For the optimized scenarios autonomous plant present higher IRR (18.4 %) in comparison to annexed one (16.6 %). However, ethanol production costs are equivalent in both alternatives (0.34 US$/L). In the same way as showed by the environmental assessment indicators, it was not possible to notice significant differences in the economic indicators for annexed and autonomous alternatives using average price of the last 10 years for ethanol and sugar. However, the historical variation of the price of these products suggests that there were periods where economic indicators were very different for autonomous and annexed plants.

4. Conclusions

The used approach allowed identifying and comparing technical, environmental and economic aspects for optimization of different options for a sugarcane biorefinery. Life Cycle Assessment results showed that optimized technologies present lower environmental impacts in comparison to base scenarios. Autonomous plant presents better environmental performance considering the industrial stage separately. However it is not possible to establish significant differences between annexed and autonomous plants when all life cycle stages of ethanol production are considered. Economic results showed that, in the base scenario, annexed plant presents slightly higher IRR and slightly lower ethanol production costs. Optimized scenarios showed that autonomous plant presents higher IRR while annexed and autonomous plants showed equivalent ethanol production costs. Since environmental and economic results for autonomous and annexed biorefineries are similar, it indicates that annexed plant, by producing diversified products, presents more potential for sustainability in relation to autonomous plant.

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