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Multiobjective optimization of a sugarcane biorefinery involving process and environmental aspects

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ABSTRACT

Process modeling and simulation are essential to predict process energetic demands, and determine possible throughputs and process emissions in biorefineries. In this paper non-linear multiobjective optimization studies with conflicting process and environmental objectives are performed in a sugarcane biorefinery. The process produces bioethanol (first and second generation), bioelectricity and concentrates vinasse in multiple-effect evaporators. Objective functions, concerning process and environmental issues, are defined and studied in five optimization problems. Decision variables are fraction of bagasse diverted to E2G production (*Var1*), and the fraction of vinasse that is concentrated up to 7.0°Bx in multiple-effect evaporator (*Var2*). The results show that *Var1* cannot assume values greater than circa 0.5, due to thermal demands of the integrated process, while *Var2* cannot be lower than 0.15, due to process demands for vegetal steam. Flows of concentrated vinasse are generally higher when maximization of bioethanol throughputs is imposed. When electric power generation and bioethanol throughput maximization are the objectives, the former varies 45.6%, while the latter varies 16.6%, among non-dominated solutions. The adopted approach can be used as a decision-making tool that may help to choose suitable operating conditions, in order to obtain a trade-off between greater profits and a more sustainable process.

1. Introduction

The increasing energy demands, the awareness that fossil reserves are finite, the instabilities in their prices and the concern with the environment make renewable energy technologies of paramount importance. Renewable energy can be classified into two categories [1]: electricity and transportation fuels. Concerning liquid fuels, bioethanol is an interesting alternative, with a perspective of world ethanol market to be developed [2–4]. Particularly in Brazil, the second world ethanol producer, sugarcane industry was catalyzed in the 1970s due to the oil crise [5], evolving from a typical single product industry (sugar) to a biorefinery (sugar, ethanol and electricity) [2]. Due to increased interest in ethanol, many sugarcane industrial plants are the so-called autonomous distilleries, in which all sugarcane juice is used to produce ethanol, with no production of sugar.

Renewable energy accounted for 46.4% of Brazilian Energy Matrix in 2013, 19.1% of the total energy (41.1% of the renewable energy) relative to sugarcane products (both bioelectricity and bioethanol) [6]. Power generation using sugarcane bagasse as boiler fuel in cogeneration systems represents 79.9% of biomass-based generation in Brazil [7]. Excess electricity, to be sold to the grid, is an important product of the sugarcane industry. On the other hand, bioethanol nowadays represents 27% of composition of gasoline [8], and 88.2% of the vehicles (both cars and light commercials) manufactured in the country in 2014 were flex–fuel [9], i.e. they are flexible regarding to fuel composition, ranging from 0% gasoline-100% ethanol (hydrous) to 100% gasoline.

The first generation Brazilian ethanol (E1G) is obtained by fermentation of sugars (mainly sucrose) present in the juice of sugarcane, the feedstock with the lowest production cost and the highest yield in liters of ethanol per hectare, when compared to

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corn and sugarbeet [10]. There are constant discussions about whether biofuels production would compromise the production of food [11], and a way to increase bioethanol production without increasing land use would be the its biological production from waste of agrobusiness, such as sugarcane bagasse and straw, wheat straw or corn stover [3,12]. This requires a technology based on the hydrolysis of the cellulose and the hemicellulose of these materials into fermentable sugars. The bioethanol produced from the fermentation of these sugars is the second generation ethanol (E2G). Besides bioethanol, a portfolio of chemicals and fuels, in the broad sense of biorefinery, can be produced from biomass, through a set of physical, chemical and biological processes [13,14].

In Brazil, the rational feedstock for E2G production in sugarcane industry is bagasse, since it is already present on site, available as output of sugarcane mills. Also, the integration of E2G production process with conventional E1G production is a natural alternative, with expected lower investment (when compared to stand-alone processes), due to shared facilities, and minimized fermentation inhibition effects [15]. However, in an E1G and E2G integrated process, bagasse has two possible uses: boiler fuel and E2G production. Although lignin, unhydrolyzed cellulose and sugarcane trash can be thought as complementary boiler fuels, the increased steam demand by the integrated process certainly poses a challenge to process feasibility. Furthermore, the production of E2G definitely affects power generation, which could represent a decrease in industry profit.

Other important aspect to take into account in the integrated E1G and E2G process is the environmental one. Main effluents of this industry are CO_2 and vinasse (also known as stillage), a pollutant produced in large amounts (around 10 times the amount of bioethanol) and with high concentration of organic matter (major compounds are glycerol, ethanol, lactic and acetic acid), although it is mainly composed by water (ca. 97% [16]). Vinasse has also low pH, and presents corrosive characteristic [17]. Spreading of dilute or concentrated vinasse on agricultural fields is a possibility for fertilization purposes, for its content of cations such as potassium, calcium and magnesium [18]. Fertigation with vinasse is a common practice in Brazil, and it has presented positive results in agricultural productivity, besides lowering costs with chemical fertilizers [16,19]. But not all vinasse can be used in an economic and environmental conscious base, due to logistics (transportation) costs and soil contamination. Direct application of vinasse in the soil can cause adverse environmental impacts, such as the enrichment of soil in salt, leaching of metals present in the soil to groundwater, and changes in soil quality [16–19]. A process alternative to alleviate this problem is vinasse concentration, since fertigation not always can dispose of total volume of vinasse produced, and transportation costs to further land areas are diminished [16]. Concentrated vinasse has improved fertilizer quality, besides the benefit of decreasing water use in the plant. However, this alternative increases steam consumption by the process (if evaporators are used), which is already increased by increased ethanol production (E1G + E2G). Also, with E2G production, vinasse production is increased (when compared to a sole E1G process), although CO_2 production is decreased (combustion of all organic bagasse components produces more carbon dioxide than sugars fermentation). This poses a conflict between process and environmental objectives. In order to increase the throughput of bioethanol and decrease carbon dioxide emissions, more bagasse should be diverted to the second generation ethanol production steps of the process, and, consequently, more vinasse is produced and less bagasse is available to produce steam to the process and bioelectricity to the grid.

In order to evaluate conflict between process and environmental interests, process systems engineering tools are helpful. Process modeling and simulation are essential to predict process energetic demands, and determine possible throughputs and process emissions in biorefineries, producing biofuels, electricity and/or chemicals. In this sense, some interesting papers can be found in the literature. Sugarcane mills producing sugar, ethanol (50% of sugarcane used for producing sugar, and 50% for E1G) and electricity were evaluated through exergy analysis using different cogeneration system configurations, and with modifications in the process (heat integration) [2]. In order to do so, a global steady state model in EES (Engineering Equation Solver) software was developed, which indicated that electricity surplus can be increased in 150% with advanced cogeneration systems. Dias et al. [15] made process improvements in a standalone first-generation sugarcane industrial plant in order to increase the surplus of lignocellulosic material, and then evaluated the integrated E1G and E2G production process in Aspen Plus. Results show that ethanol production can be significantly increased with high-pressure boilers. Rivera et al. [20] used central composite design to make a techno-economic evaluation of an autonomous E1G distillery, represented by a set of computer-aided tools that simulate the sugarcane agricultural production system, its transportation, and the industrial processing. Concerning production of bioethanol in a biorefinery concept, different scenarios for the oil palm industry in Colombia were evaluated [21], with production of biodiesel, bioethanol and poly-3-hydroxybutyrate (PHB). Aspen Plus (linked to MatLab, for kinetics calculations), Aspen Economic Analyzer and WAR (Waste Algorithm Reduction) GUI software were used to make simulations, economic analysis and calculations of Potential Environmental Impact (PEI) of the different scenarios. Both economic and environmental metrics could be improved by integration to obtain multiple products (instead of stand-alone processes). Also Kim et al. [22] evaluated the productivity and economics of a biorefinery based on starch and a mixture of various lignocelluloses (corn stem, rice straw and barely straw) for producing bioethanol and 7-ACA (7aminocephalosporanic acid) using SuperPro Designer software.

Furthermore, optimization studies, both single and multi-objective ones, can indicate best operating policies in biorefineries, taking into account different objectives. Many papers [23–27] in the literature deal with optimization (both single or multiobjective) studies in the scope of biorefineries producing biofuels (bioethanol included), but are concerned with large-scale supply chain problems. With scope other than supply chain, the best choice for surplus bagasse utilization in sugarcane mills in Thailand was studied, considering surplus bagasse could be burned to produce electricity to be sold to the grid, and/or it could be used to produce bioethanol. However, second generation ethanol was considered to be produced offsite (model takes into account transportation, location and size of the second generation ethanol plants), and it should be then mixed to gasoline to compose a 10% blend to be used as fuel. LINGO software was used to perform an optimization study in which an economic and an environmental (mainly impacts of emissions of green house gases) objective were combined, with different weights, in a single objective function [28]. Furlan et al. [29] also evaluated utilization of sugarcane bagasse in sugarcane mills. However, in their study, the production of E2G was integrated to the first generation one, and no sugar was produced (autonomous distilleries). Ethanol, electric energy and bagasse were considered as industry products, and four case studies were considered, three of which were optimized with Particle Swarm Optimization (PSO) algorithm in EMSO (Environment for Modeling, Simulation and Optimization) software [30]. Single optimization problems were evaluated in order to determine the amount of bagasse to energetic fulfill the plant, and to maximize an economic function.

Some contributions are found in literature dealing with