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Multi-objective optimization of a sugarcane biorefinery for integrated ethanol and methanol production

Juliana Q. Albarelli [a, *], Sandro Onorati [b], Priscilla Caliandro [c], Emanuela Peduzzi [c], M Angela A. Meireles [a], François Marechal [c], Adriano V. Ensinas [c, d]

[a] School of Food Engineering, University of Campinas (UNICAMP), Cidade Universitária Zeferino Vaz, Rua Monteiro Lobato, 80 - CEP, 13083-862, Campinas, Brazil
[b] Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129, Torino, Italy
[c] Ecole Polytechnique Federal de Lausanne, STI-IGM-IPESE, Station 9, 1015, Lausanne, Switzerland
[d] Center of Engineering, Modeling and Social Sciences (CECS), Federal University of ABC (UFABC), Avenida dos Estados, 5001- CEP, 09210-580, Santo André, Brazil

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A B S T R A C T

The present study evaluates a sugarcane biorefinery producing ethanol through juice fermentation and methanol via gasification of sugarcane lignocellulosic residues and liquid fuel synthesis. Two technologies of gasification named entrained flow and circulating fluidized bed are compared. Flowsheet modeling and thermo-economic analysis methods are applied, followed by a multi-objective optimization based on a genetic algorithm. The optimum Ethanol–Methanol biorefinery design options are compared with other previously studied sugarcane biorefineries. The results show that the biorefinery's energy efficiency increases significantly with the integration of a methanol production plant in a conventional ethanol distillery. The configuration using an entrained flow gasifier presents lower conversion efficiency than the one using a circulating fluidized bed gasifier. However, for the entrained flow gasifier configuration, the size of the methanol production process could be bigger since more heat is available for the ethanol process favouring the integration with the ethanol plant. Higher energy efficiency due to increase of methanol production leads to a higher total investment for both gasification technologies. The cost analysis shows that the calculated methanol production cost is 30% higher than its current market price. Environmental incentives for biofuels could change this scenario but are not in the scope of this study.

1. Introduction

Sugarcane industry is one of the largest biofuels producers in the world. The biggest part of the production consists in the traditional ethanol process from sugarcane juice fermentation. Lignocellulosic residues are available in large quantity in the sugarcane cultivation, harvesting and processing. They consist mainly in green and dry leaves that are normally burned or left on the field and the fiber part of the sugarcane stalk, obtained after juice extraction, named bagasse. Bagasse is commonly used as fuel for producing heat and power in cogeneration systems. Both the industrial and the academic sectors have been carrying out several initiatives to increase biofuel production in the sugarcane biorefinery, through modernization and product diversification [1]. Efforts in the agricultural sector are improving and tailoring sugarcane productivity [2]. In the industrial facilities, the use of modern and efficient equipment is improving the current process, enabling less energy and water consumption. Important energy savings can be obtained by modern fermentation [3] and distillation systems [4] with positive impact in energy recovery in the plant. A large amount of bagasse can be available as raw material for novel processes by the improvements on the process energy integration, with investment in heat recovery technology and without affecting the electricity production significantly [5].

The use of sugarcane bagasse and leaves as raw material for second generation (2G) biofuel production in the sugarcane sector is usually investigated based on two main conversion technologies:

* Corresponding author. Tel.: +55 19 3521 0100.
E-mail address: jualbarelli@gmail.com (J.Q. Albarelli).

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Abbreviations

1G	first generation
2G	second generation
CD	conventional distillery, without second generation ethanol production
c_{fix}	carbon fixation
CFB	circulating fluidized bed gasifier
CL	cleaning
DS	distillation
$\dot{E}$	net electricity balance [kW]
EF	entrained flow gasifier
EtOH	ethanol
GS	gasifier
i	annual interest rate [-]
k	payback time [years]
HHV	Higher heating value [MJ/kg]
$\dot{m}$	mass flow [kg/s]
MeOH	methanol
$MeOH_{eq}$	methanol equivalent power
MSY	methanol synthesis
MUSD	million US dollars
n	Project lifetime [years]
NSP	net system power [kW]
p	pressure
QC	quench
s	stoichiometric ratio at the methanol synthesis reaction
SNG	synthetic natural gas
T	temperature
η_{en}	energy efficiency [-]

- The bio-chemical route, based on enzymatic hydrolysis of the lignocellulosic material through a variety of enzymes that act breaking the lignocellulosic material into sugars. Most of the studies that analyze this possibility integrated to the sugarcane biorefinery consider the fermentation of these sugars to produce ethanol [6].
- The thermo-chemical route, based on the gasification technologies at high temperature for synthesis gas (syngas) production. This syngas can then be converted into different types of liquid or gaseous fuels. Examples of these "synthetic fuels" are Fischer–Tropsch fuels [7], ethanol [8], synthetic natural gas [9] and methanol [10].

Different studies analyze the integration of second generation processes using sugarcane bagasse as raw material to first generation process in a biorefinery concept [11]. The integration of different separation and conversion processes, in analogy to oil-based refinery, shows several advantages over the decentralized biofuel production, lowering production costs and enabling process integration alternatives. In addition, product diversification in a biorefinery concept has demonstrated an important role in enhancing the economic feasibility of second generation biofuels [12]. New biorefinery schemes for the sugarcane sector have been recently presented in the literature integrating first and second biofuel production and other derived chemicals, as butanodiol [13] and poly-3-hydroxybutyrate (PHB) [14], and also considering the integration of third generation biofuels [15]. As a result of these new sugarcane biorefinery concept developments, the authors concluded that the production of chemicals, as well as, closing the CO_2 cycle by algae growth and sequential biodiesel production (third generation biofuel) added to the respective sugarcane biorefinery sustainability, both economically and environmentally.

Because biorefining strives to recover the maximum value from each fraction at minimum energy cost, and this aim can be achieved using different production processes, several biorefinery options have been addressed [16]. Biomass gasification has been broadly investigated as a precursor step for biofuel synthesis enabling economically the production of liquid transportation fuels [12]. The production of biomass derived fuels in complex biorefinery concepts integrating multiple biofuel production (first, second and third generation) considering biomass gasification is the topic of different projects, as the BioRefill project [17]. Even tough, only a few of the studies evaluate the use of residues in a new biofuel production process integrated with the sugarcane biorefinery, consider gasification-derived fuels. Fisher-Tropsh fuel production from bagasse gasification was evaluated integrated to the conventional ethanol production process [18], demonstrating higher energetic efficiency than the use of bagasse in a 2G ethanol production process by enzymatic hydrolysis route. Biomass gasification technology integrated with methanol synthesis from syngas could be a promising alternative for valorization of the lignocellulosic part of sugarcane, replacing fossil derived methanol used as a feedstock in the chemical industry and as an additive for transport fuels. According to literature [19], the methanol production from sugarcane bagasse presents high fossil fuel energy ratio (i.e. ratio of fuel energy content by energy fossil consumed during the methanol production process). The production of methanol from bagasse associated to a sugarcane mill producing sugar and/or ethanol 1G presents high energy demand when thermal integration is not consider, therefore the inclusion of sugarcane straw as a supplement at the cogeneration system, and also the use of advanced systems such as cogeneration BIG–GT (biomass integrated combined cycle gasification-gas turbine) would improve the energy and exergy efficiency of the plant [10]. The life cycle analysis of methanol production from bagasse shows that the gasification and methanol synthesis have significant pollutants emissions, which results in larger contributions to some environmental impacts [19], but the agricultural stage (cultivation and transportation) of the biomass is the phase with the major environmental impact significance in the production of biofuels [10].

In this context, the main task of this paper is to evaluate economically a thermal-integrated sugarcane biorefinery producing ethanol from sugarcane juice, and methanol from bagasse gasification in the same industrial site and compare this alternative with other possible sugarcane biorfenery schemes. The biorefinery is analyzed using flowsheet modeling software and process integration is performed through Pinch analysis using MILP (mixed integer linear programming) [20]. A thermo-economic model is developed in order to analyze the energy efficiency, as well as, the economic impact of the integrated process in the traditional ethanol production process. Multi-objective optimization using a genetic algorithm [21] is performed, allowing the analysis of several process configurations for the conflictive objectives: energy efficiency and investment cost. The optimized methanol–ethanol biorefinery is then compared to other optimized sugarcane biorefineries developed by the authors, aiming at evaluating different routes of biofuel production integrated to the conventional ethanol production in order to propose feasible paths to establish a biorefinery of the sugarcane industry.

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