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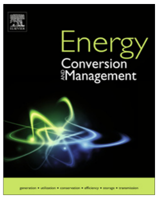

Bioethanol and power from integrated second generation biomass: A Monte Carlo simulation

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ABSTRACT

The main objective of this work is to assess the impacts of integrating new biomass conversion technologies into an existing sugarcane industrial processing plant in terms of its multi-objective optimal operating conditions. A typical sugarcane mill is identified and a second generation ethanol production pathway is incorporated to give the operator the possibility of controlling the ratio between the rates of burning bagasse and straw (sugarcane tops and leaves) to their second generation processing to achieve optimal ethanol and electricity outputs. A set of equations describing the associated conversion unit operations and chemical reactions is simulated by the Monte Carlo method and the corresponding operating envelope is constructed and statistically analyzed. These equations permit to calculate ethanol production and electricity generation in terms of a virtually infinite number of scenarios characterized by two controlled variables (burning bagasse and straw mass flow rates) and several uncontrolled variables (biomass composition, cellulose, hemicelluloses and lignin yields, fermentation efficiencies, etc.). Results reveal that the input variables have specific statistical characteristics when the corresponding operating states lay near the maximum energy limit (Pareto frontier). For example, since the objectives being optimized are intrinsically antagonistic, i.e. the increase of one dictates the decrease of the other, it is better to convert bagasse to ethanol via second generation pathway because of the high energy requirements of its dewatering prior to combustion and low heat content of cellulose and hemicelluloses compared with lignin. Another interesting result concerns biomass composition: for both bagasse and straw, higher lignin contents favor simultaneously optimality and robustness.

1. Introduction

The development of alternatives to fossil energy resources is a global priority and biomass is certainly a feedstock of great potential. However, the development of sustainable processes for large scale biomass production and conversion into energy carriers is an open challenge requiring multidisciplinary research approaches ranging from plant breeding, crop production, harvesting, and industrial processing, to economic and environmental sciences. In general, industrial production and conversion of biomass is viable within a specific range of processing scales characterized by the plantation area. Lower limits are generally determined by initial and fixed costs (equipment, staff, rent, land and buildings, taxes, etc.), while upper limits are determined by agricultural and logistics costs. Biofuels and electricity are actually low added value products and, consequently, economicity is achieved through intensive use of land (minimum crop rotation and increased use of fertilizers) and high use of capital to improve economies of scale. Many large scale agro-industrial projects fit into this model, such as sugar beet, corn, wheat and sugarcane processing industries.

Biomass has become an important alternative feedstock for the production of energy carriers and carbon based chemicals. Recent reports reveal that global biomass technical potentials could supply as much as four times the current global needs. Although the assumptions behind these calculations lead to overestimated numbers, because they ignore all competing land uses and socioeconomic constraints [1–3], these results give a real perspective of the important role that biomass can play in substituting displacing fossil resources.

The biorefinery concept emerged as new agro-industrial paradigm in which biomass is carefully deconstructed to produce low-value/large-volume liquid transportation fuel such as biodiesel or bioethanol and, additionally, to produce low-volume/high-value products such as pharmaceuticals and nutritional compounds. It is just realistic to suppose that many of these new biorefineries will evolve from the existing biomass processing industries [3]. This actually constitutes the central objective of this work: to

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Nomenclature

η_{geth}	glucose to ethanol conversion efficiency	$\dot{m}_{xeth}$	mass flow rate of ethanol from xylose
η_{gluc}	cellulose to glucose conversion efficiency	$\dot{m}_{xylo}$	mass flow rate of xylose
η_{therm}	efficiency of Rankine cycle	M_{cel}	molecular mass of cellulose
η_{xeth}	xylose to ethanol conversion efficiency	M_{eth}	molecular mass of ethanol
η_{xylo}	hemicelluloses to xylose conversion efficiency	M_{glu}	molecular mass of glucose
$\dot{m}$	mass flow rate	M_{hem}	molecular mass of hemicelluloses
$\dot{m}_{bg}$	bagasse mass flow rate	M_{xylo}	molecular mass of xylose
$\dot{m}_{cel}$	mass flow rate of cellulose	$\dot{W}$	power
$\dot{m}_{geth}$	mass flow rate of ethanol from glucose	$\dot{W}_{bg}$	power from burned bagasse
$\dot{m}_{gluc}$	mass flow rate of glucose	$\dot{W}_{lig}$	power from burned lignin
$\dot{m}_{hem}$	mass flow rate of hemicelluloses	$\dot{W}_{st}$	power from burned straw
$\dot{m}_{st}$	straw mass flow rate	$\dot{W}_{tot}$	total power

assess the impacts of integrating new biomass conversion technologies into an existing sugarcane industrial processing plant in terms of its multi-objective optimal operating conditions. Although the work is based on the Brazilian sugarcane sector, the same approach is applicable to other agricultural crops.

2. The reference sugarcane processing plant WITH integrated production of second generation ethanol

The average size of a sugarcane cultivation area, which results from the equilibrium between revenue and variable costs, is approximately 30 kha. In fact, 70% of the plantations in the state of São Paulo vary between 20 and 40 kha as it can be seen in Fig.1. The average productivity is around 75 tons of sugarcane per hectare (tsc/ha) [2]. Thus, adopting a harvesting period of 210 days, the resulting round-the-clock biomass processing rate will be about 500 tsc/h, which may be converted into approximately 65 t/h of refined sugar [4] or 43 m^3/h of hydrous ethanol [5,6]. Electricity generation is based on steam cycles operating at pressures typically of 2.2 MPa, which is enough to generate potential average surpluses of 100 kW h/tsc [7,8]. Recently, higher boiler pressures ranging from 5 to 15 MPa are being adopted in order to increase electricity surpluses from the same feedstock. Despite significant variations due to differences in fiber content, boiler pressure, etc., these numbers are representative of the processing scales that should be practiced in order to achieve economicity.

At the industrial site, sugarcane conversion starts by mechanically preparing it to enhance subsequent extraction of sucrose by roll mills or through a diffuser. After extraction and dewatering, at the reference processing rate of 500 tsc/h, approximately 150 t/h of bagasse having 50% moisture is sent to the boiler to generate electricity and heating. Approximately 150 t/h of straw is produced for this same sugarcane rate and 50% of this is usually left in the fields to protect the soil.

Hydrothermal pretreatment of bagasse is generally carried out around 0.4–2.5 MPa @ 160–240 °C [9]. At these subcritical conditions water is still liquid and has a range of very interesting physicochemical properties when compared with those at ambient conditions. For example, at 220 °C water viscosity drops approximately to 12% while its density is still at 85% of the corresponding initial values at 20 °C. This means that its penetration through biomass interstices is significantly improved without penalizing its ability to greatly expand during decompression ($\sim 10^3$ times). Also, the dielectric constant decreases from 80.22 @ 20 °C to 31.50 @ 220 °C, which gives rise to increased solubility of hydrophobic organic compounds, such as free fatty acids [10,11]. An important negative side effect is that solubility of salts is decreased at subcritical conditions, what might cause the formation of precipitates that easily attach to the surfaces of pipes, heat exchangers and reactors, thereby causing fouling or even blockage [12,13]. Despite this, hydrothermal pretreatment is one of the most promising techniques for large scale applications due to its simplicity and robustness.

Integrating a second generation ethanol production process to an already operating sugarcane mill can be accomplished through different strategies. However, because our first concern in this work is to investigate how optimal operating conditions are chan-

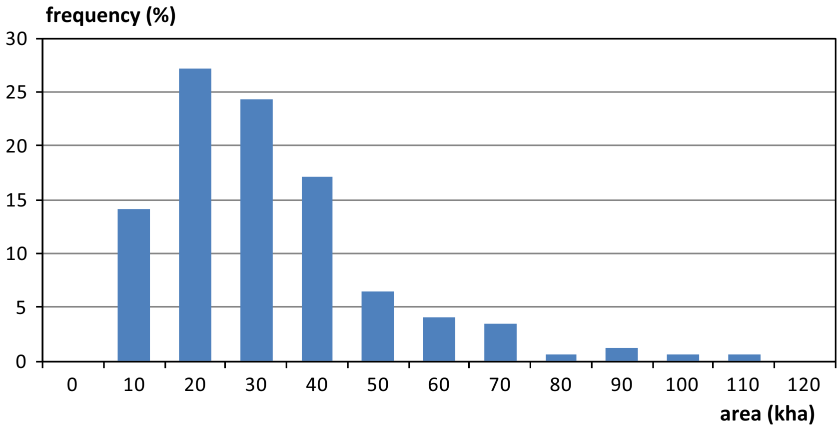

Fig. 1. Sugarcane cultivation areas in the state of São Paulo – Brazil. *Source:* adapted of UNICA, www.unica.com.b.

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