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Optimizing ethanol and bioelectricity production in sugarcane biorefineries in Brazil

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ABSTRACT

In sugarcane biorefineries, the lignocellulosic portion of the sugarcane biomass (i.e. bagasse and cane trash) can be used as fuel for electricity production and/or feedstock for second generation (2G) ethanol. This study presents a techno-economic analysis of upgraded sugarcane biorefineries in Brazil, aiming at utilizing surplus bagasse and cane trash for electricity and/or ethanol production. The study investigates the trade-off on sugarcane biomass use for energy production: bioelectricity versus 2G ethanol production. The BeWhere mixed integer and spatially explicit model is used for evaluating the choice of technological options. Different scenarios are developed to find the optimal utilization of sugarcane biomass. The study finds that energy prices, type of electricity substituted, biofuel support and carbon tax, investment costs, and conversion efficiencies are the major factors influencing the technological choice. At the existing market and technological conditions applied in the upgraded biorefineries, 300 PJ y^{-1} 2G ethanol could be optimally produced and exported to the EU, which corresponds to 2.5% of total transport fuel demand in the EU. This study provides a methodological framework on how to optimize the alternative use of agricultural residues and industrial co-products for energy production in agro-industries considering biomass supply chains, the pattern of domestic energy demand, and biofuel trade.

1. Introduction

Sugarcane is one of the key renewable sources in Brazil. In 2013, it comprised 19% of the country's energy matrix [1]. Sugarcane juice, bagasse (stalk fibers: fibrous residue left over after squeezing sugarcane for its juice), and sugarcane leaves/tops (straw, also known as trash) each represents one-third of sugarcane energy content [2,3]. 40% of the fuel used in Otto-cycle engines (light duty vehicles) comes from first generation sugarcane juice ethanol in Brazil [3,4]. However, the lignocellulosic portion of the sugarcane biomass, which includes bagasse and trash, is still underutilized [5–11]. Surplus bagasse obtained in sugarcane mills and trash left or burnt in the field during harvesting can also be collected and used for energy production. Bagasse and trash can be alternatively used as fuel for power (electricity) generation or feedstock for second generation biofuel.

There is room for upgrading the existing sugarcane mills as there is plenty of surplus sugarcane biomass (i.e. cane trash and bagasse) readily available. Cane trash and bagasse also have similar fuel characteristics, making them suitable for energy production [12]. There are several biomass conversion technologies, for that purpose, for example, cogeneration systems, thermochemical, and biochemical processes [13–17]. In this context, it is important to analyze alternatives and determine the best suitable option for optimally producing energy services and diversifying the industry. Both techno-economic and environmental performance need to be considered. A concept of 'biorefinery', which is analogous to the 'oil-refinery', is currently being developed for the conversion of lignocellulosic biomass, and simultaneous production of commercial liquid biofuels, heat and power, and a wide range of bio-products [18,19]. The utilization of lignocellulosic biomass feedstock (e.g. crop harvest residues: straw/trash and industrial co-products: bagasse) for biofuel production would be preferable

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considering the potential impacts of sugar/starch and oil seeds based biofuel production on food security and land use changes [16,20]. Biomass based advanced cogeneration technologies for electricity generation are quite mature and commercially available [21,22] while second generation biofuel from lignocellulosic biomass has not yet become an industrial reality due to high investment and production costs [16,23]. Meanwhile, the soaring biofuels demand, especially due to renewable mandates and targets in many countries, is promoting global market formation and trade of biofuels [24]. Therefore, domestic demand, international biofuels market/trade, and the completion with electricity generation from the use of lignocellulosic biomass should be taken into account while selecting the suitable biofuel/bioenergy pathways. This study considers the sugarcane mills operating in one of the sugarcane producing states in Brazil, and their upgrading into biorefineries for producing bioelectricity and/or second generation (2G) ethanol using sugarcane biomass. Sugarcane bagasse and leaves/trash can be used in the production of bio-products [25] but the utilization of sugarcane biomass for non-energy production is beyond the scope of this paper. The study investigates the best technological options - second generation (2G) ethanol (2G option) or bioelectricity (electricity option) - for converting sugarcane biomass to useful energy products.

A number of studies have performed the techno-economic analysis of biofuel production at the plant level [6,7,9,11,26–28]. Seabra et al. (2010) have evaluated the techno-economic performance of thermochemical and biochemical conversion of sugarcane residues, considering sugarcane mill clustering [26]. Walter and Ensinas (2010) have described the technological pathways of biofuel production from sugarcane biomass and analyzed the impact of process integration with a conventional sugarcane distillery [7]. Systems performance is simulated for the technical, economic and environmental merit of power generation and ethanol production from sugarcane residual biomass, considering conversion plants adjacent to a sugarcane mill [6]. Dias et al. (2011) have performed simulation studies to determine the suitable option when selecting second generation or bioelectricity from the sugarcane biomass feedstock [9]. Macrelli et al. (2012) have described the competitiveness of second generation ethanol from sugarcane bagasse and leaves [10]. Lago et al. (2012) have demonstrated the positive conditions for the development of second generation ethanol derived from sugarcane biomass (bagasse and cane trash) in Brazil considering different industrial scenarios [29]. Dias et al. (2012) have examined how process optimization increases the production of second generation ethanol in sugarcane distilleries [11]. Recently, Furlan et al. (2013) and Dias et al. (2013) have investigated the economic advantages of a flexible (able to switch between 2G ethanol and bioelectricity production) sugarcane biorefinery [30,31]. Some authors claim that lignocellulosic ethanol may require policy support for implementation [32]. In addition, Dias et al. (2012) have simulated stand-alone and integrated second generation ethanol production from sugarcane biomass considering different technological scenarios [28]. Tittmann et al. (2010) have presented a spatially explicit techno-economic optimization model of bioenergy and biofuels production system in California, considering location/size of bioenergy plants, conversion technologies, and feedstock profile and its supply chain configuration [33]. The model aims at maximizing the profit of a biofuel industry at given feedstock price, transportation cost, conversion cost, and price for fuels, electricity, and co-products. However, no analysis has been carried out at the regional level yet, considering the entire biofuels production chain in general and the sugarcane biofuel (1G ethanol and 2G ethanol) production chain in particular. In addition, previous studies have not addressed the climate impacts or GHG offsets of the biofuel production systems. In addition to exploring optimal technological options, this study also presents the dynamics of the total costs and lifecycle emissions by internalizing the costs of emissions in the optimization model.

This study performs a techno-economic analysis for the bulk of sugarcane production area and industries located in the Brazilian state of Sao Paulo (SP). Biofuel production and international trade have been gradually growing over the last decade [34]. Therefore, it is important to understand how policies and economic/market factors/forces (e.g. price, carbon tax, biofuel support, etc.) affect the international trade of liquid biofuels. The trade of 2G ethanol to the European Union (EU) is taken into account here. The study considers that ethanol produced from sugarcane juice (1G ethanol) through fermentation is domestically consumed while the second generation (2G) ethanol, if produced, can be exported to the EU. Bioelectricity produced is fed into the grid and utilized in Brazil. 1G ethanol is already mature and commercially competitive. However, 2G ethanol is still not produced in commercial scale. Therefore, we scrutinize the technological choices and the role of market and policy instruments for energy (2G ethanol and/or bioelectricity) production from sugarcane biomass, also looking into international trade of 2G ethanol.

The study examines the alternative uses of sugarcane biomass (i.e. bagasse and cane trash) for 2G ethanol and/or bioelectricity production in the state of Sao Paulo in Brazil. The study performs the techno-economic optimization analysis of sugarcane mills, assuming technological improvements of existing mills. There is still a limited amount of research in modeling of biomass supply chains when it comes to investigating the impact of technological change, policy drivers/incentives, and market volatilities [35]. The study considers how the energy prices, conversion costs, and policy instruments such as biofuel support and carbon tax affect the choice of technology (2G ethanol option or electricity option), including the export of bioethanol to the EU. This paper aims to complement existing research studies, which are mainly focused on optimization of the economic and environmental benefits of biorefineries at the plant level in Brazil and other countries, by examining the costs and emissions of the entire supply chains, as well as the interactions with external parameters (e.g. energy prices, biofuel support, carbon tax, and international biofuel trade) in providing sustainable energy services for the welfare of the region.

The BeWhere model is used to determine the choice of technological improvements. The model is spatially explicit and has previously been applied for assessing the optimization of bioenergy production, mainly aiming at identifying the optimal location and size of biomass conversion units in Europe, see Refs. [36–39]. Sugarcane biomass is a geographically dependent renewable resource. It is important to develop an optimization model for determining suitable size/location of biofuel plants and conversion technologies, considering biomass supply, transport costs, and energy demand/prices. As the location and size of sugarcane mills is fixed in this study, we only simulate the technological options using the sugarcane biomass (bagasse and trash). This spatially explicit study is the first study of its kind in the Brazilian context in which sugarcane biomass - agricultural residue (tops/leaves or trash) and agro-industrial co-product (bagasse) - is used for energy production in sugarcane biorefineries. The study also provides important information on lifecycle emissions and costs/prices of advanced biorefineries using lignocellulosic sugarcane biomass in Brazil. It shall contribute for further development of the BeWhere model when the country seeks alternative pathways for producing modern bioenergy services, considering all features of the spatial modeling approach. Many developing countries have a huge potential to harness bioenergy/biofuel derived from crop residues (e.g. sugarcane trash, rice husk, straw, etc.) [40–42]. This model