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Research paper

Carbon mass balance in sugarcane biorefineries in Brazil for evaluating carbon capture and utilization opportunities

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ABSTRACT

Sugarcane biorefineries, despite their contribution to sustainable transportation fuels and mitigation of carbon emissions in the mobility sector, produce a large amount of carbon dioxide in their conversion processes. According to the Paris climate agreement, a carbon neutral energy system has to be launched in the years to come, and in this scenario, greenhouse gases emission free industrial processes and alternative carbon sources will be needed. Therefore, this paper presents the evaluation of carbon mass balance of a typical Brazilian ethanol mill to better understand its potential for energy and carbon yield improvement. Due to the fact that Brazilian sugarcane mills are evolving from first generation to integrated first and second generation plant, four different scenarios were analysed. For a first generation plant without (S-I) and with conversion of straw to electricity (S-II) and for the integrated plant (S-III), results of carbon mass balance showed that the harvested sugarcane carbon was mainly converted into CO_2 and in a smaller proportion into ethanol. In the modelled cases S-I to S-III the conversion of sugarcane carbon into CO_2 and ethanol ranged from 41% to 53% and 17%–22%, respectively. Because this carbon amount in the CO_2 flows provides an interesting platform to both increase the bioenergy produced and the harvested carbon-to-fuels ratio, a fourth scenario (S-IV) that studies the integration of power-to-gas (PtG) technologies into the mill was also considered. PtG can increase the sugarcane fuels energy content from 9.3 kW/ha to 33.6 kW/ha using 1361.3 MW_e of electricity, increasing the amount of sugarcane carbon transformed into sugarcane based fuels to 54% and converting CO_2 into a high value added product.

1. Introduction

Sugarcane production is one of the most important economic activities for domestic and export markets in Brazil [1]. Brazilian sugarcane biorefineries are considered one of the most developed and integrated biofuel and bioenergy agribusiness in the world, accounting for approximately 20% and 25% of the global ethanol and sugar production, respectively [2]. In the crop season 2013/2014 approximately 654 million tons of sugarcane was produced in the country [3] corresponding to a GDP (gross domestic product) of U$ 43 billion [4]. The turnover of the industry was U$ 107 billion and the sector generated 1 million direct jobs and 3.6 million indirect jobs [4].

Approximately 88% of the sugarcane plantations are located in the centre-south region of Brazil and São Paulo state alone accounts for more than half of the national sugarcane production [3]. The sugarcane plantations are employed in sugar and ethanol production in an approximate 50%/50% proportion of sugar to ethanol [5]. There are three different types of sugarcane plants in use: Sugar and ethanol producing facilities (integrated mills with an annex distillery that produce sugar and ethanol in an integrated plant), sugar producing facilities and autonomous distilleries (ethanol producing facilities). The production share of sugar and ethanol is based on market prices and government policies.

Several studies have been conducted looking into the increase in sugarcane ethanol production using optimization, or evaluating sustainability and greenhouse gases (GHG) emissions: Dias et al. performed techno-economic analysis of sugarcane ethanol production with particular focus on optimizing simulation processes

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Abbreviations

PtG	Power-to-gas
GDP	Gross domestic product
GHG	Green House Gases
1G	First generation ethanol plant
2G	Second generation ethanol plant
1G2G	Integrated first and second generation ethanol plant
CHP	Combined heat and power system
CCU	Carbon capture and utilization
SNG	Synthetic natural gas
PtF	Power-to-fuels
RE	Renewable energy
VLE	Vapour-liquid-equilibrium
SRK	Soave-Redlich-Kwong equation
FGT	Flue gas treatment
TC	tons of cane
LHV	Low heating value

and improving boiler efficiency [6–8]. Albarelli et al. compared the economics of second generation (2G) and first generation (1G) ethanol production by modelling a novel supercritical water pretreatment technology as sugarcane bagasse pre-treatment process [9]. Macrelli et al. considered technology improvement in the ethanol sector and scenarios of using trash as feedstock [10]. Beeharry studied the carbon balance of sugarcane bioenergy systems aiming at identification of their GHG mitigation potential [11]. Pippo and Luengo carried out an assessment on sugarcane feedstock availability and its energy use considering both environmental and techno-economic aspects [12]. Lago et al. demonstrated the positive conditions of the sugarcane industry for the development of second generation ethanol, performing a carbon balance to assess the added value to the carbon present in different sugarcane biorefinery products [13]. However, none of these studies focused on understanding the carbon balance of different sugarcane bioenergy systems, and the potential of the utilization of formed CO_2 as an alternative carbon source that can improve the energy and carbon yield per hectare of harvested sugarcane. The urgent need for a carbon neutral energy system stated by the Paris climate agreement may convert carbon into a scarce resource in the future. Therefore, it is important to evaluate not only energy efficiency but also carbon efficiency of industrial processes, aiming at reducing the processes' carbon footprint and finding alternative carbon sources. The assessed scenarios evaluate some options for maximising the carbon efficiency and use in connection to sugarcane industry. In order to do so, the integration of PtG technology to the sugarcane factory was considered.

Carbon balance is a suitable tool that provides information about biorefinery products using a common functional unit [13]. Within the carbon balance results, it is possible to observe the potential of adding value to the carbon present in sugarcane byproducts, such as CO_2. Considering the progress towards a carbon constrained world and that one of future sugarcane biorefineries' aims will be to maximize the utilization of the carbon available in the feedstock [13], the analysis of potential value-added products is of great importance and should be looked at carefully.

Therefore the objective of this paper was to study the carbon mass balances of current 1G and future integrated first and second generation (1G2G) bioethanol production processes. This includes four sub-objectives: (1) to develop relevant scenarios for current and future ethanol mills in Brazil, (2) to develop simulation models to estimate systematically the full mass and energy balance of the processes, (3) to evaluate carbon mass balances based on the mass balances results, and (4) to propose a carbon capture and utilization technology capable of increasing the energy and carbon efficiency per unit of sugarcane harvested land.

The objectives of this paper led us to answer the following research questions: (1) in recent and future Brazilian sugarcane mill configurations, what is the potential for maximising carbon efficiency? (2) Is PtG capable of doing so? And, finally, (3) can sugarcane industries play an important role in a carbon neutral energy system?

2. Context of sugar and ethanol biorefineries in Brazil and future perspectives

During the 70's, when the oil crisis affected the prices of fuels in the whole world, the Brazilian government established the Pro-Alcohol program that encouraged sugarcane industry to start to produce alcohol fuel for the automotive industry alongside sugar. Since then, the sugar and ethanol productivity in Brazil has increased significantly from 8.25 million tons and 3 million m^3 in 1980 to 37.7 million tons and 27.5 million m^3 in 2014 [3], respectively. Meanwhile, however, the country faced various political, economic, environmental and social changes that resulted in innovations on both sugarcane agricultural and industrial areas, leading to important cost reductions and increases in crop productivities.

One of the biggest transformations that highly contributed to the sustainability improvement of the sugarcane agroindustry was the use of bagasse (and most recently the use of straw as well) as an industrial feedstock for bioelectricity and heat generation. In the course of Pro-Alcohol program, the bagasse, a lignocellulosic residue from sugarcane juice extraction process, started to be used in combined heat and power systems (CHP) coupled to sugarcane facilities. This has transformed a substantial number of mills in Brazil into energy self-sufficient plants by the time. In such CHP system, bagasse is burned to provide heat and electricity for the sugar and ethanol production process [5]. At that time, the conversion of bagasse to energy had low efficiency mainly due to the regulatory framework of the electricity sector, which did not allow the sale of surplus electricity. The difficulty to store and/or sell the bagasse on the other hand forced the mills to maximize the burning of bagasse [14].

In the early 2000s, an interest in increasing electricity production from sugarcane residues arose motivated by the changes in the Brazilian electricity sector regulation and the electricity shortage crisis in 2001. A small number of mills adopted a more efficient cogeneration system that supplied an energy surplus to be sold to the grid, providing a new source of income to the mills [15]. Nowadays, a considerable number (47%) of sugarcane factories in operation in the country have efficient boiler systems and are selling electricity to the grid [16]. Furthermore, all sugarcane refineries in Brazil are energetically self-sufficient.

In 2002, public policies have been implemented in certain regions of Brazil to restrict cane straw (tips, dry leaves and green leaves) burning in sugarcane fields targeting at diminishing black carbon and other GHG emissions from the harvesting operation. In São Paulo state, which accounts for 56% of the national sugarcane supply [3], a new state law (11.241/2002) prescribed a schedule for the elimination of burning in the field and the implementation of mechanical harvesting [17,18]. Furthermore, all new sugarcane-ethanol operations currently being established in Brazil, including new areas in the Centre-West region, are required by law to implement harvesting operations without burning [19]. These are ongoing programs that will significantly increase the sugarcane