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Environmental impacts of technology learning curve for cellulosic ethanol in Brazil

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ABSTRACT

This study presents a Life Cycle Assessment of second-generation ethanol production in Brazil considering current and future technologies to represent its technology evolution, compared to the first-generation process. With the start of the learning curve of the cellulosic ethanol production, improvements are expected on both biomass industrial conversion and agricultural production phases. Increased sugarcane yields and gradual introduction of more productive varieties, such as energy cane, are expected, affecting both first- and second-generation ethanol production processes. In environmental impact categories very relevant in the biofuel production debate, such as climate change, fossil depletion and agricultural land occupation, scenarios with second-generation process present lower impacts than first-generation process for the same time horizon. There is a trend of reduction of environmental impacts over time, reflecting the environmental advantages due to advances on the learning curve of second-generation ethanol technology and on biomass production system. The contribution of second-generation ethanol production will be extremely relevant to help Brazil to meet its targets in the international environmental agreements.

1. Introduction

Increased production and use of ethanol with emphasis on advanced biofuels participation (such as cellulosic ethanol, also known as second-generation or 2G) is a commitment recognized by many countries in the world, including the Brazilian Government in its Intended Nationally Determined Contribution (INDC) to COP 21 (UNFCCC, 2015). Therefore, potential environmental benefits of different alternatives for 2G ethanol production should be properly quantified for supporting public policy formulation that will affect the future of climate and other environmental aspects of our planet.

Since 2G technologies are in its initial stage of development, there is still a large potential for improvements in the entire production chain with time, as the learning curve of the process initializes.

Numerous studies identified the current and future technical, economic and environmental performance of sugarcane ethanol first-generation processing (Silva et al., 2014; Cavalett et al., 2012; Wang et al., 2012; De Vries et al., 2010; Macedo et al., 2008), including representation of the learning curve for first-generation ethanol (Van den Wall Bake et al., 2009; Goldemberg et al., 2004). The conversion of lignocellulosic feedstock with second-generation processes have been assessed by different authors (Dias et al., 2012, 2013; Macrelli et al., 2012, 2014; Humbird et al., 2011; Hamelinck et al., 2005). Overall these authors indicated that improvements on the industrial efficiency and/or change of conversion technology, as well as the advancement of technology design are key factors affecting industrial processing costs.

However, studies looking at the future prospects for 2G technologies are limited. An important paper from Hamelinck et al. (2005) projected future yields and techno-economic performance of 2G technologies. Jonker et al. (2015) provided an outlook for first and second-generation ethanol production costs in Brazil up to 2030 for different biomass crops and industrial technologies. Besides a comprehensive modeling approach for biomass production systems, future 2G technologies were based on Hamelinck et al. (2005). A recent study from Wang et al. (2014) provided economic and GHG emissions analyses for sugarcane ethanol in Brazil considering evolution of 2G technology. In their study, however, data on 2G learning curve, were based on literature review.

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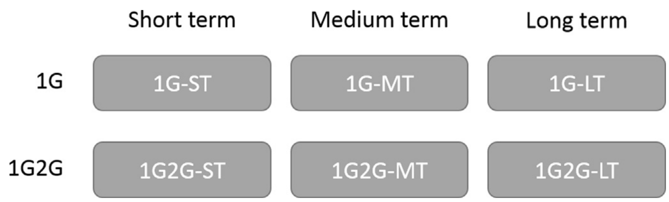

Fig. 1. Set of scenarios representing technological evolution over time (1G: first-generation; 1G2G: integrated first- and second-generation).

On the other hand, Milanez et al. (2015) evaluated technical and economic aspects of 2G technologies considering short, medium and long term projections for ethanol production in Brazil. This study established the expected improvements not only for the sugarcane production systems including new fiber-rich sugarcane varieties, but also for first- and second-generation industrial technologies. These current and future scenarios were designed based on a series of interviews and workshops carried out with main companies worldwide related to cellulosic ethanol production chain. We believe these scenarios approach a consensus of the main stakeholders and can be considered the best available information regarding future ethanol scenarios. Junqueira et al. (2016) detailed technical and economic aspects of future 2G technologies based on data from Milanez et al. (2015).

Considering economics of 2G learning curve, the study from Milanez et al. (2015) indicated that 2G ethanol production will be competitive with 1G ethanol from the medium term on (after 2024). The main factors contributing for the 2G ethanol production cost were identified as investment in the plant, biomass and enzymes, in this order. According to the assumptions of the study, 2G ethanol cost would be competitive with an oil price of 44 US$ per barrel, in the long term.

It is still open the question about the potential environmental benefits of these future 2G scenarios. The objective of this paper is to examine the environmental impacts of second-generation ethanol production in Brazil using the life cycle assessment methodology. Environmental impacts of current and future technologies for 2G ethanol were quantified to represent the technology learning curve. Other impacts rather than climate change and energy use are also considered to improve the understanding of the present and future environmental sustainability of cellulosic ethanol.

2. Material and methods

2.1. Scenarios description

Current and future scenarios for 1G and 2G technologies were designed based on interviews with the main worldwide stakeholders related to the cellulosic ethanol production chain, such as representatives from sugarcane sector, chemical industry, governmental agencies and research institutions. These scenarios were previously used to assess 2G ethanol technical aspects and production costs in Brazil including public polices issues and recommendations (Milanez et al., 2015; Junqueira et al., 2016).

In the present study, the assessed scenarios were divided into three time horizons: short, medium and long term. Short term is considered to represent the period of 2016–2020, medium term of 2021–2025, and long term of 2026–2030. They represent the projected first- and second-generation technology evolution and demonstrate potential environmental benefits of current and future technologies for 2G ethanol production in comparison to 1G technology. As a matter of consistency, expected improvements were also considered for the 1G process. Fig. 1 summarizes the set of scenarios evaluated in this study representing technological evolution of ethanol production over time.

In addition to industrial efficiency improvement, change of conversion technology and improvement of technology set-up, advances on biomass production were also considered, such as higher sugarcane yields and straw recovery rates, more efficient agricultural operations and gradual introduction of cane varieties with higher fiber content, improved yields and longer production cycle, i.e. energy-cane, as complementary feedstock to sugarcane. These assumptions and characteristics are summarized in Table 1.

Industrial process for 1G and integrated 1G2G process is shown in Fig. 2. As indicated in this figure, fermentation of pentoses liquor (rich in C5 sugars) was considered to occur separately from the hydrolysate (rich in C6 sugars), which is fermented mixed to sugarcane juice from 1G process.

Both industrial plants (1G and 1G2G) refer to modern plants with high-pressure boilers and low energy consumption, which, in addition to straw recovery, allow achieving high levels of electricity production. In addition, introduction of vinasse biodigestion was assumed for medium and long terms, considering that biogas can replace up to 70% of diesel used in the agricultural operations and transport. When exceeding the fleet demand, biogas is used as fuel in internal combustion engines for additional electricity production. More detailed information about 2G technical improvements from Milanez et al. (2015) are presented in Table 2.

Main inputs and outputs of the industrial process are presented in Table 3. The expected technical improvements on both agricultural production and industrial conversion phases resulted in larger industrial plants in medium and long terms due to increased biomass processing and higher industrial yields over time. The largest ethanol output is achieved in the 1G2G-LT scenario, with an annual production of approximately 1 billion liters; however, its electricity output is less than one third of the equivalent 1G scenario.

2.2. Life cycle assessment

This study uses the Life Cycle Assessment methodology (LCA) for the quantitative assessment of environmental impacts. This method is described in ISO 14000 series of standards (ISO, 2006a, 2006b) and other important international documents (BSI PAS 2050, 2011; European Commission, 2010). The objective is to perform an attributional life cycle assessment to compare environmental impacts of present and future scenarios for 2G integrated to first-generation ethanol production in Brazil representing its technology learning curve. The scope is defined as cradle-to-factory gate considering agricultural production systems, transportation of biomass to the biorefinery and conversion of feedstock into ethanol and electricity. The ecoinvent database v2.2 (http://www.ecoinvent.ch/) was used to obtain the environmental profile of inputs used in the evaluated product system (e.g. chemicals, diesel production, fertilizers, pesticides, and beyond other background processes). Reference flow considered for results comparison is 1 MJ of ethanol produced in the different scenarios.

Environmental impacts were quantified using mid-point indicators for ReCiPe method (Goedkoop et al., 2008). The most relevant environmental impact categories for agriculture-based processes were selected for this study as indicated by Cox et al. (2014), namely fossil depletion, water depletion, climate change, freshwater and marine eutrophication, human toxicity, and agricultural land occupation. Furthermore, particulate matter formation was added to this list due to its relevance to the set of scenarios considered in this LCA.

2.2.1. Economic allocation

More than one product is obtained in all the evaluated ethanol production scenarios. Therefore, it is necessary to split part of the environmental impacts to each one of the products. This division

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