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Economic-energy-environment analysis of prospective sugarcane bioethanol production in Brazil

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HIGHLIGHTS

- A Hybrid IO-MOLP model is formulated for energy-economic-environmental analysis.
- Scenarios for sugarcane cultivation and 1st- and 2nd-generation bioethanol production.
- Higher energy use and GHG emissions due to chemicals in 2G processes.
- Lower overall employment level in the 1G + 2G scenarios compared to the 1G scenario.
- Policies and technological choices should consider direct and indirect effects of 2G.

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ABSTRACT

Bioethanol from sugarcane can be produced using first-generation (1G) or second-generation (2G) technologies. 2G technologies can increase the capacity of production per sugarcane mass input and are expected to have a key role in future reductions of environmental impacts of sugarcane bioethanol. A hybrid Input-Output (IO) framework is developed for Brazil coupling the System of National Accounts and the National Energy Balance, which is extended to assess Greenhouse Gas (GHG) emissions. Life-cycle based estimates for two sugarcane cultivation systems, two 1G and eight 2G bioethanol production scenarios, are coupled in the IO framework. A multi-objective linear programming (MOLP) model is formulated based on this framework for energy-economic-environmental analysis of the Brazilian economic system and domestic bioethanol supply in prospective scenarios. Twenty-four solutions are computed: four "extreme" solutions resulting from the individual optimization of each objective function (GDP, employment level, total energy consumption and total GHG emissions - 1G scenario), ten compromise solutions minimizing the distance of the feasible region to the ideal solution (1G, 1G-optimized and prospective 1G + 2G scenarios), and ten solutions maximizing the total bioethanol production (1G, 1G-optimized and prospective 1G + 2G scenarios). Higher diesel oil and lubricants consumption in the mechanical harvesting process has counterbalanced the positive effects of more efficient trucks leading to higher energy consumption and GHG emissions. Lower overall employment level in the 1G + 2G scenarios is achieved such that policies linked to reabsorption of sugarcane cutters in alternative activities are positive. Indirect effects from maximizing the bioethanol production increase the total energy consumption and the GHG emissions thus requiring efficiency measures and fossil energy substitution by cleaner sources. The integrated- or country-based analysis of the whole economic system has complemented the process design and process-based analysis, contributing to identify direct and indirect effects that can offset the benefits. Direct and indirect effects on the whole economic system have to be considered in policies and technological choices for prospective bioethanol production, since positive direct effects of 1G + 2G plants can be counterbalanced by indirect impacts on other sectors, mainly from chemicals in the process.

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Acronyms

1G	first generation bioethanol
1G + 2G	combined and integrated 1G and 2G technologies
2G	second generation bioethanol
CH_4	methane
CO_2	carbon dioxide
EH	enzymatic hidrolysis
EIO-LCA	economic input-output life cycle analysis
GDP	Gross Domestic Product
GHG	Greenhouse Gases
IO	Input-Output
IOA	Input Output Analysis
IO-MOLP	input-output multi-objective linear programming
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LP	Linear Programming
MOLP	Multi-objective Linear Programming
NO_2	nitrous oxide
NPISH	non-profit institution serving households
PROALCOOL	Brazilian Alcohol Program
R$	Brazilian Real
WIS	water insoluble solids

Notation

ba	anhydrous bioethanol
bh	hydrous bioethanol
ci	change in inventories
debt	public debt
ec	total energy consumption
emp	employment level
exp	exports
gdp	gross domestic product
gdpcurr	gross domestic product at current prices
gfcf	gross fixed capital formation
ggb	public administration global balance
ghg	total greenhouse gas emissions
gva	gross value added
imp	imports
pc	public consumption
rc	resident consumption
sc	sugarcane
ts	taxes less subsides on products
ydcurr	resident's disposable income at current prices

1. Introduction

The 1970s worldwide oil crisis impelled Brazil to increase the production of the first-generation (1G) bioethanol based entirely on the fermentation of sugar juice from sugarcane and/or molasses as an alternative fuel in the transportation sector. After some decades, policies in the scope of the Brazilian Alcohol Program (PROALCOOL) have been responsible to consolidate the agriculture and industrial supply by increasing investments on sugarcane cultivation and construction of new bioethanol plants in Brazil. In addition, the PROALCOOL has been responsible for the creation of an important domestic market for this fuel by incentivizing the substitution of petrol with bioethanol as much as the bioethanol price was made competitive due to taxes on petrol and subsides on bioethanol production. Nowadays, Brazil is the second major bioethanol producer with 28% of the total worldwide, while the United States, which is the major producer, is responsible for 58.5% of the total [1]. In the 2014/2015 harvest, 634.8 Mt of sugarcane have been produced in Brazil, resulting in 11.7 GL of anhydrous and 16.9 GL of hydrous bioethanol (a total of 28.7 GL) [2]. In 2014 bioethanol was responsible for 32.3% of the total energy consumed in light vehicles in Brazil [3].

In Brazil, bioethanol is produced in mixed sugar-bioethanol plants (the most common type of bioethanol plants, producing both bioethanol and crystallized sugar) and in autonomous distilleries (producing only bioethanol). A lignocellulosic residue (called bagasse) is also produced in the sugarcane processing. The bagasse is burnt in boilers to generate heat and electricity that are used in the bioethanol plant. Electricity surplus can be exported to the national electricity system. More efficient and expensive boilers for the combustion of bagasse have improved the capacity of the plants in generating electricity surpluses, therefore allowing to increase the return from each plant [4,5].

Prospective technologies for lignocellulosic bioethanol production, also referred to as the second-generation (2G) bioethanol, increase the role of bagasse in the process [6,7]. The use of bagasse in 2G technologies as a raw material for bioethanol production can increase the total capacity of production per unit of sugarcane. The 2G technologies are expected to have a key role in future reductions of environmental impacts of sugarcane bioethanol by using sugarcane leaves and tops in bioethanol production. Instead of being burnt in the field as in the near past (nowadays most of the sugarcane is mechanically harvested in Brazil) or discarded as residues of the mechanical harvesting (being waived or burnt), leaves and tops can be used as energy sources to replace bagasse burnt in the boilers or even used to produce 2G bioethanol. However, the 2G technologies have not been commercially competitive in Brazil due to high production costs (compared to the 1G technology) and some bottlenecks regarding the conversion of lignocellulose into fermentable sugars and the downstream processing pose a challenge for this option in the near future [8–11]. Combined and integrated 1G and 2G technologies (1G + 2G) for bioethanol production can also be implemented. Macrelli et al. [12] performed a techno-economic evaluation of the integration of 1G + 2G bioethanol production from sugarcane for fourteen scenarios, considering several operating conditions and process layouts. According to the simulations, the production of 2G bioethanol from sugarcane bagasse and leaves in Brazil is already competitive (without subsidies) with 1G starch-based bioethanol production in Europe. Moreover 2G bioethanol could be produced at a lower cost if subsidies were used to compensate for the opportunity cost from the sale of excess electricity and the cost of enzymes continues to fall. In addition, other factors as energy prices, plant efficiency and costs, type of electricity substituted, and policy instruments can influence the sugarcane biomass use for 2G or electricity production [13].

The International Organization for Standardization (ISO) 14040 standard defines Life Cycle Assessment (LCA) as "a compilation and evaluation of the inputs, outputs and potential environmental impacts from a productive system throughout its life cycle" [14]. The LCA methodology assesses the environmental impacts associated with the life cycle of the product under study [15,16]. LCA has an important role on public and private environmental management, comparing alternative products or helping in the development of new products with lower environmental impacts [17]. Some studies [18–21] have used LCA to investigate the energy and Greenhouse Gases (GHG) balances of sugarcane-based bioethanol and, in a smaller number of cases, a wide-range of impacts [22]. However, setting tight boundaries in the supply chain of the analyzed system as required by the LCA approach can