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Integrated economic and life cycle assessment of thermochemical production of bioethanol to reduce production cost by exploiting excess of greenhouse gas savings

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HIGHLIGHTS

- Assessment of economics and sustainability of thermochemical ethanol production.
- Exploitation of excess CO_2 saving by either importing fossil energy or CO_2 trading.
- Significant increase in alcohol production by replacing biomass with natural gas.
- CO_2 emission trading is not cost-competitive versus import of fossil energy.
- Lowest ethanol production cost for partial oxidation as reforming technology.

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ABSTRACT

In this work, two options are investigated to enhance the economics of the catalytic production of bioethanol from biomass gasification by exploiting the excess of CO_2 emission saving: (i) to import fossil energy, in the form of natural gas and electricity or (ii) to trade CO_2 emissions. To this end, an integrated life cycle and economic assessment is carried out for four process configurations, each using a different light hydrocarbon reforming technology: partial oxidation, steam methane reforming, tar reforming and autothermal reforming. The results show that for all process configurations the production of bioethanol and other alcohols significantly increases when natural gas displaces biomass, maintaining the total energy content of the feedstock. The economic advantage of the partial substitution of biomass by natural gas depends on their prices and this is explored by carrying out a sensitivity analysis, taking historical prices into account. It is also concluded that the trade of CO_2 emissions is not cost-competitive compared to the import of natural gas if the CO_2 emission price remains within historical European prices. The CO_2 emission price would have to double or even quadruple the highest CO_2 historical price for CO_2 emission trading to be a cost-competitive option.

1. Introduction

Bioethanol is the transportation fuel with largest worldwide production: $87.2 \cdot 10^3$ millions of litres in 2013 [1]. Most bioethanol is produced in first generation processes, mainly from starch crops, such as corn in USA, or sugar crops, such as sugar cane in Brazil. The environmental benefits of first generation (1G) ethanol have been evaluated by numerous studies by means of Life Cycle Assessment (LCA) [2]. There is a wide range of results due to different assumptions and calculation methodologies in the LCA. In particular, the most important factors for the wide range of results are input parameter values, such as crop yields and fertilizer requirements, system boundaries, allocation procedure and fossil reference systems [3]. In this sense, in Europe some authors demand more detailed rules for the application of the European Renewable Energy Directive (ERED) [4] guidelines, like decisions about nature of waste material or definition of boundaries between the processes [5]. Regarding corn-based ethanol, most studies have concluded that when used as a transportation fuel to displace petroleum-based gasoline, a reduction of greenhouse gas (GHG) emissions is achieved [3]. Some studies question the GHG benefits of corn-based ethanol arguing that non-carbon emissions from soil due to the use of fertilizers [6] or effect of crop residue removal

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Nomenclature

1G or 2G	first or second generation
ATR	autothermal reforming/reformer
EFG	entrained flow gasification
GHG	greenhouse gas
iCFBG	steam–air indirect circulating fluidized bed gasification/gasifier
LCA	Life Cycle Assessment
MESP	minimum ethanol selling price
POX	partial oxidation
SMR	steam methane reforming/reformer
TR	tar reforming/reformer
WTT	Well-To-Tank

are not properly accounted for and these nullify the benefits of GHG savings. On the other hand, all LCA studies on bioethanol from sugar cane have concluded that much higher GHG savings than corn-based ethanol are achieved, thereby constituting the highest GHG savings of first generation biofuels [2]. However, these studies do not take into account the depletion of carbon pools when sugar cane plantation replaces tropical forest (deforestation). This land use change may counterbalance the GHG savings of bioethanol from sugar cane [2,7].

Second generation (2G) ethanol is produced from lignocellulosic biomass, such as residues from agriculture, forestry and industry and/or dedicated lignocellulosic energy crops, by either thermochemical or biochemical processing, as well as by a combination of both. In the thermochemical route, biomass is first converted by gasification, typically above 800 °C, into synthesis gas, which is thereafter conditioned and catalytically converted into ethanol. The catalytic conversion of syngas to ethanol can be accomplished in one step (direct routes) or several steps through intermediates (indirect routes) [8–11]. In the biochemical route, sugars contained in lignocellulosic biomass are extracted and then fermented into ethanol in an aqueous medium. In the approach combining the thermochemical and biochemical routes, the synthesis gas from biomass gasification is fermented to produce ethanol [12]. There are some commercial plants producing 2G ethanol either by means of biochemical processing, thermochemical processing via indirect routes or fermentation of syngas [13–16]. To the best of our knowledge, there are no commercial plants converting syngas to ethanol by direct catalytic route.

The vast majority of LCA studies on 2G ethanol are focused on the biochemical route and most of them conclude that greater GHG savings than 1G ethanol can be achieved [2,3,17,18]. Exceptions may occur when the energy used to feed the biomass conversion process comes from carbon-intensive fossil sources, such as coal [19]. Good reviews on LCA of 2G biochemical ethanol are provided by [17,18]. Recent environmental assessments of the biochemical route analyse factors such as biomass pretreatment [20–22], plantation management and location [22]. Integrated economic and life cycle assessments of biochemical production of ethanol have been published by Petrou et al. [23] who used an aggregate index which consider both economic and environmental performance to select between different ethanol production systems, and Juneja et al. [24] who studied ethanol production from two types of straw.

LCA studies on 2G ethanol by thermochemical processing are scarce [25–30] and they are all based on the thermochemical process proposed by NREL [31]. The most important features of NREL's process is the use of an indirect fluidized bed gasifier for biomass gasification, an alkali-doped MoS_2 mixed alcohols catalyst for ethanol synthesis, and a tar reformer to reform hydrocarbons produced in the gasifier and synthesis reactor. Mu et al. [25] compared the biochemical and thermochemical production of ethanol by means of LCA for various technological scenarios (current, short term and long term) and different feedstock. They concluded that the biochemical conversion has slightly lower overall GHG emissions and fossil fuel consumption. This is mainly due to the larger export of electricity in the biochemical process, which provides remarkable credits. The reason is that fuel mix for electricity in USA is largely dominated by coal, a carbon-intensive fuel. However, if the higher alcohols co-produced in the thermochemical conversion are sold as chemicals instead of fuel, the environmental performance is better than biochemical conversion due to the credits associated with chemicals being displaced. They also concluded that if natural gas were imported to produce heat and steam instead of using synthesis gas from biomass, ethanol production would increase at the expense of larger GHG emissions and fossil fuel consumption. Kou et al. [26] concluded that for thermochemical ethanol production, a multifeedstock approach, considering agricultural residues, wood and municipal solid waste, reduces the risk of bankruptcy and results in lower GHG emissions per litre of ethanol compared to a single feedstock approach, if feedstock supply disruption is taken into account. Daystar et al. [30] calculated GHG emissions of ethanol from waste biomass (pine residues) and concluded that the greatest impact of emissions were due to the thermochemical conversion process. This study compared a base case scenario without allocation to pine residues of the GHG emissions of pine forest establishment, maintenance and harvest with a scenario that allocated these emissions to the primary wood product and residues by mass fraction. They concluded that GHG emissions of bioethanol were not sensitive to the method of allocation. Daystar et al. [27] also studied the impact of feedstock composition on ethanol yield and GHG emissions for thermochemical ethanol production and their results indicate that the moisture and ash contents of biomass greatly influence both outcomes. Finally, Muth et al. [29] analysed the influences of biorefinery size, biomass supply system designs and feedstock specifications on process economics and environmental sustainability of thermochemical production of bioethanol from woody feedstock. They concluded that the additional cost of advanced logistic supply systems is off-set by the economy of scale of larger biorefineries and the ability to reduce the moisture and ash of the feedstock, which benefits the storage and conversion process.

A common feature of these LCA studies on thermochemical ethanol production is that the process is designed to be energy self-sustained, that is, without the import of heat or electricity. This decision implies that GHG emissions incurred in the production of ethanol are minimized, but this may not be optimal from an economic point of view. The import of fossil fuel and/or electricity may improve the economics of the process at the expense of lower environmental performance. Only Mu et al. [25] studied the effect of importing natural gas on ethanol productivity and GHG emissions, but not on the economics of the plant.

This paper is the third part of a study which aims to evaluate different types of biomass gasification technologies (entrained-flow gasification, EFG, and indirect circulating fluidized bed gasification, iCFBG) and mixed alcohol catalysts ($Rh–Mn/SiO_2$ and $KCoMoS_2$) for the thermochemical production of ethanol. The first part of the study dealt with processes based on EFG [32], while the second part assessed several configurations based on iCFBG and