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Balance and saving of GHG emissions in thermochemical biorefineries

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HIGHLIGHTS

- A simplified methodology for the balance and saving of GHG emissions is provided.
- The GHG balance has a physical meaning and does not depend on the fossil reference.
- The GHG saving depends on regulation of energy carriers.
- The impact of Bio-CCS incorporation and multiproduction is analyzed.
- The co-production of chemicals needs to be included in future regulation.

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ABSTRACT

In this study, a simplified methodology for the calculation of the balance of greenhouse gas (GHG) emissions and corresponding saving compared with the fossil reference is presented. The proposed methodology allows the estimation of the anthropogenic GHG emissions of thermochemical biorefineries (net emitted to the atmosphere). In the calculation of the GHG balance, all relevant factors have been identified and analyzed including multiproduction, emissions from biogenic carbon capture and storage (Bio-CCS), co-feeding of fossil fuels (secondary feedstock) and possible carbon storage in biomass-derived products (chemicals). Therefore, it is possible to calculate the balance of GHG emissions of a hypothetical thermochemical biorefinery considering different alternatives of land-use, biomass feedstock, co-feeding of fossil fuels, Bio-CCS incorporation and final use of the products. The comparison of the estimated GHG balance with the corresponding fossil reference for each product is of special relevance in the methodology since it is the parameter used in European regulation for the fulfillment of sustainability criteria in biomass-derived fuels and liquids. The proposed methodology is tested using a previously assessed set of different process concepts of thermochemical biorefineries (techno-economic analysis). The resulting GHG balance and saving are analyzed to identify uncertainties and provide recommendations for future regulation. In all process concepts, the GHG savings are above the minimum requirement of GHG emissions for 2018. In the case of incorporating Bio-CCS, cradle-to-grave negative GHG emissions are obtained. However, in order to assess the role of chemical co-production from biomass, they need to be included in future regulation.

1. Introduction

A thermochemical biorefinery is a facility which processes biomass by means of pyrolysis and/or gasification to produce one or several products (commonly energy carriers: transportation fuel or fuel for heat or electricity generation; but also chemicals) and services (heat, electricity). The thermochemical conversion of biomass leads to syngas (gasification) or bio-oil (pyrolysis), which are processed in a similar fashion to conventional refineries or petrochemical plants. For instance, the technologies and know-how from the petrochemical industry apply to the design of thermochemical biorefineries [1]. However, nowadays, thermochemical biorefineries are not yet commercial. Important efforts are being made for their commercialization by Enerkem Company in Canada (gasification of municipal solid waste and production of ethanol) [2]. There are also several public demonstration plants producing dimethyl ether (DME) in Sweden (BioDME project) and Germany (bioliq® project), and substitute natural gas (SNG) in Sweden (GoBiGas project)

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Nomenclature

A	factor scaling to the area concerned
CC	carbon content (g of CO_2 eq./MJ of chemical)
CS_A	carbon stock per unit area associated with the actual land use
CS_R	carbon stock per unit area associated with the reference land use
C_{VEG}	above and below ground vegetation carbon stock
E	GHG balance (g CO_2 eq./MJ of all products)
e_B	bonus of 29 g CO_2 eq./MJ energy carrier if biomass is obtained from restored degraded land
e_{ccs}	emissions saving from Bio-CCS (g CO_2 eq./MJ of all products)
E_{CS}	equivalent carbon storage in chemicals (%)
e_{ec}	emissions from the extraction or cultivation of raw materials (g CO_2 eq./MJ of all products)
E_F	anthropogenic emissions of the fossil reference: transportation fuel, heat or electricity generation (g CO_2 eq./MJ of fossil reference)
E_i	GHG balance of product i (g CO_2 eq./MJ of i)
e_l	annualized emissions from carbon stock changes caused by land-use change (g CO_2 eq./MJ all products)
e_p	emissions in the biorefinery (g CO_2 eq./MJ of all products)
e_{td}	emissions from transport and distribution (g CO_2 eq./MJ of all products)
$e_{u,i}$	emissions in the final use of i (g CO_2 eq./MJ of i)
F_I	input factor (soil organic carbon)
F_{LU}	land use factor
F_{MG}	management factor
GS_i	grade of substitution for product i (MJ of fossil reference/MJ of i)
P	productivity of the crop (MJ/ha)
$saving_i$	individual saving of product i
SOC	soil organic carbon
SOC_{ST}	standard soil organic carbon in the 0–30 cm topsoil layer
x_i	fraction of product i in total plant production (lower heating value basis)

[3–5]. All these examples are of thermochemical biorefineries producing a single product.

The success of thermochemical biorefineries depends on the combination of three pillars of sustainability: economic (the biorefinery must be profitable), environmental (there must be a significant saving of greenhouse gas, GHG) and societal/regulation (there should be public promotion through supranational regulation). The fulfillment of these three pillars leads to a sustainable process able to reduce fossil fuel dependence.

Regarding the economic pillar, energy carriers produced in thermochemical biorefineries cannot compete with fossil fuels unless public financial support is offered (e.g. subsidies). Conventional refineries require less processing and have larger energy efficiencies (from feedstock to final products) [1,6–9]. However, biomass is the only source for renewable carbon. In order to enhance plant economics, a different approach was proposed in the design of thermochemical biorefineries with multiproduction (co-producing energy carriers and chemicals) [10]. Like in refineries, there is potentially large energy and material integration in these plants, so product diversification would neither adversely affect energy efficiency, nor process economics. These biorefineries could achieve high profitability if low-value high-volume products (energy carriers and/or commodities for the petrochemical sector) are co-produced along with high-value low-volume products (high-value chemicals) [1,10].

Focusing on the environmental pillar, thermochemical biorefineries usually have a higher saving of GHG emissions (cradle-to-grave) compared to biochemical biorefineries (Fig. 1). Fig. 1 shows the GHG saving (cradle-to-grave) of thermochemical and biochemical biorefineries from the literature. The saving for ethanol is the average from references [24,25] (thermochemical biorefinery) and [26–30] (biochemical biorefinery). The values for DME, Fisher–Tropsch diesel (FT) and SNG are taken from references [9,30–32]. The value for H_2 are taken from [9] (thermochemical biorefinery) and [33–36] (biochemical biorefinery). However, the values presented in Fig. 1 are based on data resulting from the different conditions of, e.g. biomass cultivation and land-use change, and methodology from the references does not follow any regulations on biofuels. The incorporation of biogenic carbon capture and storage (Bio-CCS), i.e. a biogenic CO_2-rich stream is captured, pressurized and transported to an onshore or offshore geological storage facility (sequestration), can lead to significant removal of CO_2 from the atmosphere [11,12] and the impact of the sale of captured CO_2 has been analyzed in several techno-economic assessments [13–23]. Nonetheless, a cradle-to-grave GHG balance of the process is necessary before considering storage (sequestrated) CO_2 as a negative emission of the process [1]. Biogenic carbon capture and replacement (Bio-CCR), i.e. a biogenic CO_2-rich stream is captured and used for the production of other products e.g. urea, requires further analysis with regard to the products made from the reutilized CO_2 [37–41].

Concerning the regulation pillar, governments have regulated the bioenergy sector in order to secure investment and promote the best available technologies for greatest GHG saving and the reduction of fossil fuels dependence. To date, regulation has been limited to financial support for energy carriers, and in the European Union (EU) to the implementation of minimum GHG saving. Neither Bio-CCS nor rewarding for the achievement of substantial GHG saving (above the regulated target) have been

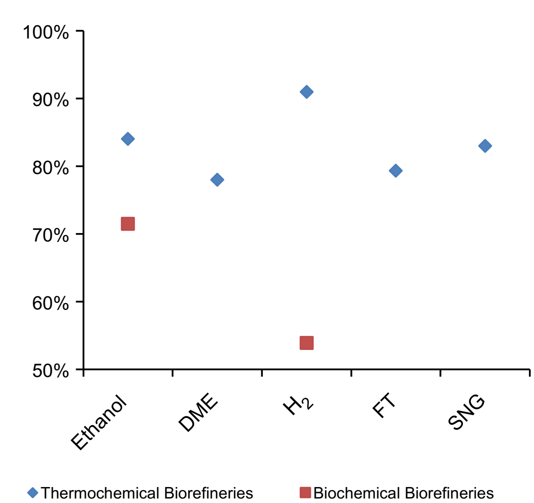

Fig. 1. GHG saving (cradle-to-grave) of thermochemical and biochemical biorefineries from the literature [9,24–36].