Bioresource Technology 111 (2012) 191–200

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

An economic, sustainability, and energetic model of biodiesel production from microalgae

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ARTICLE INFO

Article history:
Received 25 October 2011
Received in revised form 3 February 2012
Accepted 4 February 2012
Available online 14 February 2012

Keywords:
Algal biodiesel
GHG emission rate
Global sensitivity analysis
Net energy ratio
Production cost
Water footprint

ABSTRACT

A new process evaluation methodology of microalgae biodiesel has been developed. Based on four evaluation criteria, i.e. the net energy ratio (NER), biodiesel production costs, greenhouse gases (GHG) emission rate and water footprint, the model compares various technologies for each step of the process, from cultivation to oil upgrading. An innovative pathway (hybrid raceway/PBR cultivation system, belt filter press for dewatering, wet lipid extraction, oil hydrotreating and anaerobic digestion of residues) shows good results in comparison to a reference pathway (doubled NER, lower GHG emission rate and water footprint). The production costs are still unfavourable (between 1.94 and 3.35 €/L of biodiesel). The most influential parameters have been targeted through a global sensitivity analysis and classified: (i) lipid productivity, (ii) the cultivation step, and (iii) the downstream processes. The use of low-carbon energy sources is required to achieve significant reductions of the biodiesel GHG emission rate compared to petroleum diesel.

1. Introduction

Microalgae have been considered recently as a feedstock with great potential for biofuel production since they present many advantages (e.g. high productivity, lipid accumulation, and ability to grow on waste). However, major drawbacks limit the industrial development of microalgae biodiesel. One of these technical challenges is related to the dilution of microalgae biomass, typically around 0.5–1 kg/m^3 in open ponds and 5–10 kg/m^3 in photobioreactors (PBRs). Extremely high volumes of water need to be processed during cultivation, harvesting and especially drying. This leads to a high electricity and heat consumption.

After the first studies from Weissman and Goebel (1987) or Benemann and Oswald (1996), numerous techno-economic analyses and life cycle analyses (LCA) have been published especially over the last two or three years with the principal objective to evaluate the real potential of microalgae biodiesel production at full-scale. Techno-economic analyses generally focus on production costs only. They usually point out the high production cost of both microalgae biodiesel (from transesterification of oil) and green diesel (from hydrotreating of oil) from 1.06 €/L in the best cases (in open ponds for Lundquist et al., 2010) up to 7.44 €/L (Rosenberg et al., 2011). Despite some discrepancies in the results, Sun et al. (2011) showed that this variability can be greatly reduced if a normalised set of input assumptions is used in the models.

LCA studies investigate energy balances and GHG emissions. The energy balance of microalgae diesel production seems to be very fragile (net energy ratio, NER, ratio between the energy produced and the primary energy consumed in the process, of 1.08 for Batan et al., 2010). The NER depends on the type of cultivation process used (NER <1 for horizontal tubular PBRs and >1 for raceway ponds and flat-plate PBRs, data from Jorquera et al., 2010) or on the combination of both cultivation and conversion processes used (Clarens et al., 2011). These analyses point out the necessity to recover the energy content of the microalgae residue after lipid extraction (Lardon et al., 2009) which can help in reducing the biodiesel production cost as well as the carbon emission (by 33% and 75%, respectively for Harun et al., 2011). Another important criterion for evaluating a process is its water consumption which is rarely considered but can significantly impact the environmental sustainability of the process. Subhadra and Edwards (2011) calculated algal biodiesel water footprints of 23 and 62 L/MJ (920 and 2480 L of water/L of biodiesel at 40 MJ/L of LHV, low heating

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doi:10.1016/j.biortech.2012.02.020

value) for different scenarios (i.e. two or three co-products and biomass concentrations of 0.5 or 1.0 g/L). These results highlight the need to use non-potable water.

The three criteria altogether (energetic, economic, and environmental) have their importance in the evaluation of a process, especially for the biofuel industry. This present work aims at developing an improved model for microalgae diesel production that simultaneously evaluates these three criteria. Since both the transesterification and hydrotreating pathways have been considered, the term biodiesel has been used thereafter for both biodiesel and green diesel non-discriminately.

A major disadvantage of usual techno-economic analysis is that it generally considers one technology for each step of the process which does not allow the comparison of the multiple available technologies and their optimised process pathways. For these reasons, this study proposes a model with various technologies for each step of the process. Also, to account for the uncertainties on the microalgae biodiesel production industry, the model parameters are varying within a range.

Only local sensitivity analyses (SA) have been published so far. For example, Davis et al. (2011) defined three scenarios and concluded that the lipid content is the most influential parameter for both open ponds and PBRs. However, to provide relevant results, local SA involves defining a base case where a model simulation is run with all parameters set to a fixed value. Each parameter is perturbed in turn, keeping all other parameters at their fixed value. The main disadvantage of local SA for microalgae biofuel production is the lack of public data regarding full-scale optimised model parameters (e.g. lipid and biomass productivity, operating conditions) needed to define the base case. A global SA differs in that all the model parameters vary simultaneously with no need for a base case. To overcome the drawback of local SA, a global SA has been performed in this study to determine the most influential model parameters.

The proposed model is also used to define an innovative pathway for microalgae biodiesel production, and show which targets should be considered with priority for future research and development efforts.

2. Methods

2.1. System description

The system considered by the model includes all the process steps from microalgae cultivation to biodiesel (Fig. 1). The production of algal biodiesel is assumed to be located in a sunny area in France (South-East), with sources of CO_2 from flue gases and wastewater at disposal. These assumptions may be considered as optimistic but have been chosen to simplify the model. The production infrastructures are included in the economic estimations but are not considered in the energy balance and in the GHG emission rate calculations. The total volume of microalgae cultivation is set at 1000,000 m^3 which is equivalent to a cultivation surface of 333.3 ha of 30 cm-depth raceways. This volume has been considered as a reasonable prospection of what would be an industrial facility of microalgae cultivation dedicated to biofuel production. Mass balance calculations for nutrients are based on the microalgae formula from Grobbelaar (2004): $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$. On this particular point, various elemental analyses have been conducted by different research teams with similar results (Supplemental Table 1). The water refill is assumed to be done using wastewater in order to limit the impact of water on the three criteria (economic, energetic and environmental) and to benefit from the wastewater treatment potential of microalgae (Park et al., 2011). The exceeding nutrient demand is delivered by additional nutrients (ammonium diphosphate for phosphorus and anhydrous ammonia for nitrogen). Water is recycled from the harvesting, dewatering and drying steps to the cultivation step (Fig. 1). The recycled fraction is estimated by the model (see Section 2.5 for details).

2.2. Model description

The model is based on the mass and energy balances equations coming from process evaluation of each technology. Model parameters listed in Table 1 have been optimally reduced in order to minimise possible degrees of freedom and to avoid any dependence between model parameters (required for the global sensitivity analysis). A single parameter for the lipid content, defined as convertible lipids (CLs), has been selected (Table 1). CLs account for lipids that are effectively extracted from the harvested biomass and converted into biofuel. This principally concerns triacylglycerides (TAGs) since phospholipids are to be removed (by a degumming process not considered in the present model) in order to avoid phosphorus in the biofuel (Lu et al., 2009).

2.2.1. Monte Carlo sampling method

Since technologies considered in this study are not yet mature, a Monte-Carlo sampling method has been adopted in order to account for the variability and the uncertainty of the parameter value. According to this method, each parameter is defined by its minimum and maximum values between which they vary in a random manner. The average values of the model parameters (for mass and energy balances and for economic evaluation) have been determined based on a detailed and critical literature review. The data used originates from peer-reviewed literature as well as technical reports. Then, the minima and maxima have been defined using methods depending on the data availability: (i) from the literature, if consistent minima and maxima are available (ii) from the value found in the literature plus or minus 50% (iii) from the results of the ProSimPlus® simulations for lipid extraction since its energy demand is driven by the varying solvent to biomass ratio.

2.2.2. Capital cost estimation

Assuming an overnight construction, the capital costs of each process have been evaluated based on the literature survey for well-documented processes (raceways, PBRs, harvesting, drying, anaerobic digestion and gasification) and on estimations based on the method described by Chauvel et al. (2001) for lipid extraction technologies and conversion processes. All prices have been updated to 2011 Euros. Conversions of dollar into euro have been made based on an exchange rate of 1.42 €/$ (data from April 2011). The capital cost estimations using the method from Chauvel et al. (2001) have been assumed to be in the range [−50%; +50%] (values in Supplemental Table 8).

2.2.3. Technologies considered by the model

This section describes all the technologies that have been considered for the model. The calculations made to estimate the energy demands and the capital costs as well as the references used in these calculations have not been included but are available in the Supplemental Data together with comparison of results to other techno-economic analyses and LCA. Concerning the process choices, the aim here is not to be exhaustive but rather to select reference processes (such as *n*-hexane lipid extraction or alkaline transesterification) together with innovative ones, representative of promising process approach: for example hybrid PBR/raceway cultivation systems, low-cost dewatering technologies (e.g. belt filter press or solar drying) and wet extraction processes (like di-methyl ether, DME, lipid extraction, from Kanda and Li, 2011).