Algal Research 16 (2016) 292–307

Contents lists available at ScienceDirect

Algal Research

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

Multi-scenario energy-economic evaluation for a biorefinery based on microalgae biomass with application of anaerobic digestion

Cristián P. Bravo-Fritz [a,*], César A. Sáez-Navarrete [a], Leandro A. Herrera-Zeppelin [b], Felipe Varas-Concha [a]

[a] Chemical and Bioprocess Engineering Department, Engineering Faculty, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Macul, 7820436 Santiago, Chile
[b] Chemical Engineering and Biotechnology Department, Universidad de Chile, Beauchef 851, 8370456 Santiago, Chile

ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form 5 March 2016
Accepted 12 March 2016
Available online xxxx

Keywords:
Techno-economic
Energy
Sensitivity analysis
Critical variables
Biodiesel
Biogas

SUMMARY

Microalgae are a source of biomass that has aroused the interest of the bioenergy industry due to its sustainability potential and maximum use of different abundant natural resources. This research proposes an energy-economic evaluation model for 11 scenarios for a biorefinery based on microalgae biomass, including a final stage of anaerobic digestion. Furthermore, it allows for comparisons between different scales of production, farming technologies and microalgae species, in line with latest industry information. Results are displayed by means of economic (NPV) and energy (EROI) indicators. Almost all the scenarios evaluated returned negative economic profitability, except for the extraction and commercialization of concentrated proteins (the PE scenario with protein sales of US$3/kg). In order to guide future research and investment in microalgae projects, a sensitivity analysis was conducted into the critical variables of the overall process. An optimistic context, led by the increase of the percentage of biomass lipids, allows a minimum biodiesel selling price to be reached which is close to the international value of fossil diesel (US$1/L) for scenarios in which this biofuel is commercialized.

1. Introduction

Global energy consumption has continued to rise in recent years, primarily driven by the economic development and opening up of emerging nations (Brazil, Russia, India and China). Projections from the Energy Information Administration (EIA) postulate that the current energy consumption of non-OECD (Organization for Economic Co-operation and Development) nations will almost double by 2040, resulting in a global consumption increase from 529 QBTU (QBTU = Quadrillion British Thermal Unit, 10^{15} BTU) (in 2012) to 820 QBTU (projection to 2040) [1]. Accordingly, one of the main challenges of the 21st century will be finding sustainable energy sources capable of sustaining the projected energy scenario, as well as the lifestyle of contemporary society.

Over the last decade, the energy sector has been maintained through the exploitation of fossil-based resources rich in carbon, whether derived from petroleum, natural gas or coal. The percentage of the global energy matrix represented by the sum of the aforementioned sources comes to 86%, which in addition has undergone no variation over the last ten years [1].

A direct consequence of dependence on fossil fuels is the emission of combustion gases into the atmosphere, primarily in the form of CO_2. These emissions exceed the natural rate with which the planet's ecosystems capture and fix this compound, resulting in a large accumulation of CO_2 in the atmosphere [2,3]. This accumulation has strengthened the natural greenhouse effect of the Earth, raising the average temperature of the planet in the process [4,5].

Regardless of the results or consequences arising from the emission of greenhouse gases (GHG), there are two concepts which provide a certain amount of security in regard to an uncertain future: prevention and resource diversification.

For the energy sector, renewable energy surpassed 7.5% of global energy consumption in 2002, and 9% in 2012. This increase is largely the result of the greater participation of Non-Conventional Renewable Energy (NCRE), which has tripled in generation capacity, essentially via the development of wind, solar and biomass energy [1].

Motivation behind this research lies specifically in the field of bioenergy. Traditional forms of bioenergy relate to electricity generated from the direct combustion of biomass or biogas, stemming from their anaerobic degradation, as well as the use of liquid biofuels which entirely or partially displace those derived from petroleum [6,7]. Among the liquid fuels, ethanol is usually produced via the fermentation of raw material rich in glycosides (or carbohydrates), such as corn and sugar cane [8,9]. Alternatively, biodiesel is obtained through the esterification and transesterification of used oils and oleaginous products obtained from the farming of soybean, rapeseed, palm oil and other different seeds [8,10]. However, there is a less conventional alternative to consider and evaluate within the bioenergy industry: biomass obtained from microalgae.

While research in the field of microalgae has increased over the last decade, it dates back to the mid-19th century, when isolated microalgae

---

* Corresponding author.
E-mail address: ctbravo@uc.cl (C.P. Bravo-Fritz).

http://dx.doi.org/10.1016/j.algal.2016.03.028
2211-9264/© 2016 Elsevier B.V. All rights reserved.

were cultured in laboratory conditions [11]. Subsequently, towards the end of the 1970s the US Department of Energy created a division called the Aquatic Species Programme (ASP), which remained active until 1996. The aim of this programme was to study the economic feasibility, the scaling to pilot and industrial scales and the application of different technologies for the farming and processing of microalgae for bioenergy purposes [12]. Currently, industrial-scale farming is restricted to the production of feed for the aquaculture industry, or as a source of high-value metabolites (proteins, special oils or antioxidant pigments) which are of interest to the pharmaceutical industry [13].

The production of bioenergy from microalgae reached only pilot level, due to its high operational and related capital costs. Diverse research groups have conducted evaluations into the cost of producing biofuel from microalgae, determining that the minimum selling price of biodiesel should be around US$4/L, in order to ensure the sustainable economic development of the industry (see Fig. 1) [14–19]. This far exceeds the US$0.94/L of diesel, as per its global average price at the beginning of 2015 [20].

Economic evaluation results of microalgae biodiesel demonstrated that its production on an industrial scale will only become economically viable through the generation of products with a higher commercial value than that of traditional fuels. This provides greater relevance to the biorefinery concept. Biorefineries are chemical plants or factories which integrate the concept of “zero waste”, in which all biomass fractions (proteins, glycosides and lipids) are utilized to generate different types of products and energy [10,21,22].

Generally, microalgae biomass can have different bioenergy uses [23]. Consequently, it is necessary to evaluate and understand the multiple configurations of the processes which make up a biorefinery. This will facilitate the development of a sustainable industrial-scale design.

In conceptual models in which a biorefinery is described, anaerobic digestion (AD) usually emerges as a stage of final biomass recovery, supplementary to the main process, and which enables its transformation into energy [24]. For example, if the objective is to produce biodiesel, the AD should be undertaken at the end of the process, by degrading the glycerol and residual glycosides and proteins as well as all cell debris. In other cases, when the main objective is to produce electricity, only a single operating unit of energy recovery is usually evaluated, either through the generation of biogas with AD or via direct combustion [25].

Over the last decade, the AD of numerous species of microalgae have undergone experimentation in order to determine: a) the empirical biogas production yields based on a fraction or the total amount of processed biomass; b) special and restricted cases associated with the use of microalgae; and c) the operational parameters (hydraulic retention time [HRT], temperature, and mixing speed, among others) that optimize the AD [24,26]. There is currently only limited evidence relating to microalgae AD plants on a pilot scale [27].

Biogas production yield from microalgae biomass can be determined experimentally or through theoretical procedures. These allow estimates to be devised for the amount and composition of the biogas, based on a particular residue with a known elemental chemical formula (CHONS). A stoichiometry formula was proposed by Buswell and Mueller in 1952 [28], as follows:

$$\begin{aligned} & C_cH_hO_oN_nS_s \\ & + \left(\frac{4c-h-2o+3n+2s}{4}\right)H_2O \rightarrow \left(\frac{4c+h-2o-3n-2s}{8}\right)CH_4 \\ & + \left(\frac{4c-\mathrm{h}+2\mathrm{o}+3\mathrm{n}+2s}{8}\right)CO_2 + nNH_3 + sH_2S. \end{aligned}$$

It should be noted that this theoretical formula usually overestimates the production of biogas by approximately 40% [27]. Nevertheless, the formula remains useful to identify what changes occur inside the digesters, as well as helping to generate a first dimensioning of the overall process.

AD begins with the hydrolysis of complex polymers or macromolecules (glycosides, proteins and lipids [for elemental chemical formulas see Table 1]) and proceeds towards simpler, lower molecular weight compounds. Consequently, in order to determine the elemental chemical formula of the biomass for biogas production, the particular characterization of the residue (in terms of its percentages of the three aforementioned macromolecules) can be used with the CHONS formula [27]. Typically, microalgae biomass is usually characterized in the same way. This approach would allow for other theoretical yields of biogas generation to be devised, as well as their comparisons with the reported experimental productivities. Table 2 was devised in this way. It shows the elemental chemical formula of different microalgae and provides evidence that the Buswell and Mueller (1952) [28] formula overestimates real biogas production.

Prior to addressing the design and economic evaluation of microalgae AD, consideration should be made and care taken regarding three possible inhibitory variables in the process, specific to the characteristics of the

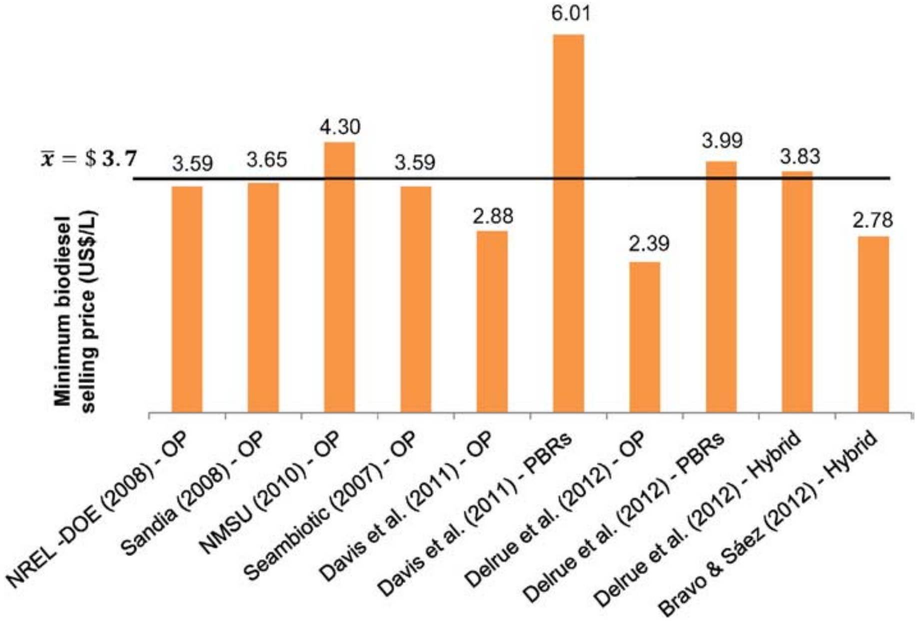

Fig. 1. Estimates of the minimum selling price per litter of microalgae biodiesel (OP = open ponds; PBRs = photobioreactors; Hybrid = OP + PBRs).