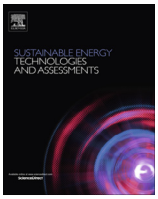
Sustainable Energy Technologies and Assessments 7 (2014) 247–256

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

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



Original Research Article

The role of allocation and coproducts in environmental evaluation of microalgal biofuels: How important?

George G. Zaimes, Vikas Khanna *

Department of Civil and Environmental Engineering, University of Pittsburgh, United States

ARTICLE INFO

Article history:
Received 11 September 2013
Revised 4 January 2014
Accepted 23 January 2014

Keywords:
Life cycle assessment
Allocation
Coproducts
Microalgae
Sustainability

ABSTRACT

This work evaluates the life cycle environmental impacts of producing microalgal biodiesel via *baseline* and *improved* technological routes under several coproduct options and allocation schemes, and compares the results to traditional petroleum diesel. Multiple environmental impact categories, as well as sustainability metrics are utilized to assess the environmental sustainability and viability of emerging microalgal biofuels. Analysis reveals that for *baseline scenarios* the fossil energy return on investment ($EROI_{fossil}$) ranges from 0.16 to 0.45, energy return on investment (EROI) from 0.15 to 0.40, and life cycle greenhouse gas (GHG) emissions (gCO_2 eq./MJ-fuel) from 142 to 352—depending on the choice of allocation methodology and coproduct option. For *improved scenarios* $EROI_{fossil}$ range from 0.50 to 1.87, EROI from 0.39 to 1.18, and life cycle GHG emissions from 35 to 141. Further analysis reveals that microalgal fuels provide benefits in only two out of the ten examined environmental impact categories–relative to petroleum diesel. The results are compelling as they suggest that the choice of production pathway and allocation scheme has a significant impact on algae's energy and environmental performance, and in select cases can alter the net energy balance and GHG reduction potential of microalgal fuel production from negative to positive.

Introduction

Mounting issues of global climate change, fossil resource depletion, energy security concerns, and regulatory renewable fuel mandates are driving the domestic production of low carbon biofuels in the United States (US) [1,2]. Currently, corn-derived ethanol and soybean-derived biodiesel (BD) constitute the majority of total US domestic biofuel production. However, there is concern that the production of first generation biofuels may divert farmland and/or displace food crops that would otherwise be used for human or animal consumption, which could inadvertently lead to food shortages and inflation of global food prices [3,4]. Thermodynamic analysis has shown that corn ethanol and some first generation biofuels have a marginally positive energy balance, and thus provide only a limited potential for reducing dependence on fossil and energy resources [3]. Furthermore, research has reported that carbon emissions resulting from direct and indirect land conversion may negate the greenhouse gas reduction potential of first generation biofuels, potentially resulting in overall higher life cycle greenhouse (GHG) emissions relative to baseline petroleum fuels [5–8]. Accordingly, researchers are investigating the production of biofuels from non-food biofeedstocks that can be sustainability grown or harvested on non-arable land [9]. Recently, liquid transportation fuels derived from microalgae have generated intense international interest from leaders in academia, government, and industry [10,11]. Microalgae's unique features such as high photosynthetic yield [12], high lipid content, potential to utilize carbon dioxide (CO_2) from industrial flue gas [13,14] and nutrients from wastewater resources for growth [15–19], and ability to be cultivated on marginal lands make it an appealing feedstock for biofuel production.

In recent years, life-cycle assessment (LCA) has emerged as the preferential method for modeling the life cycle environmental performance of biomass-to-biofuels systems [20]. Numerous

---

Abbreviations: AZ, Arizona; BD, biodiesel; CO_2, carbon dioxide; CHP, combined heat and power; CED, cumulative energy demand; GHG, greenhouse gas; EROI, energy return on investment; EPA, environmental protection agency; FER, fossil energy ratio; $EROI_{fossil}$, fossil energy return on investment; LCA, life cycle assessment; MEA, monoethanolamine; N, nitrogen; ORP, open raceway pond; P, phosphorus; PBR, photobioreactor; PVC, polyvinyl chloride; RDB, residual de-oiled biomass; ROI, return on investment; SBE, system boundary expansion; TRACI, tool for the reduction and assessment of chemical impacts; US, United States; USLCI, United States life cycle inventory; w/w, weight per weight.

* Corresponding author. Address: 742 Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261, United States. Tel.: +1 412 6249603.

E-mail addresses: ggz2@pitt.edu (G.G. Zaimes), khannav@pitt.edu (V. Khanna).

http://dx.doi.org/10.1016/j.seta.2014.01.011
2213-1388/

microalgae LCA have been conducted [21–23], yet the results have remained inconclusive–due to the high variability in reported environmental and energy performance indicators [24]. Subsequently, this has led some researchers to question whether the high variability in algae's environmental performance is due to the large variety of process technologies used to produce algal fuels or is representative of the modeling assumptions/parameters considered in the analysis. Several previous studies have compared the performance of microalgal fuels under multiple technological routes [25–27], and recent efforts to harmonize and systematically compare past studies have sought to address this issue [24,28]. Fig. 1 presents the energy return on investment (discussed in detail under sustainability indicators) and life cycle GHG emissions for producing algal biofuels reported by prior studies.

Prior research has suggested that allocation and coproduct methods can significantly impact biofuel LCA outcomes [29–31]. However, to-date there has been little emphasis on evaluating the role of coproduct options and allocation methodology in assessing the environmental sustainability of microalgal fuels. Understanding and quantifying the impact of different allocation methodologies is of critical importance if LCA is to be used as a tool to support political decision-making.

To address this shortcoming, this work evaluates the life cycle environmental impacts of producing microalgae derived BD via multiple technological routes under several coproduct options and allocation schemes, and compares the results to traditional petroleum diesel. Microalgal biofuel production is evaluated over a large technological space, to provide an indication of the life cycle energy and environmental performance of both current and future algal processing technologies. Multiple environmental impact categories, as well as sustainability metrics are utilized to assess the environmental sustainability and viability of emerging microalgae biofuels. A particularly novel contribution of this work is quantifying the influence of different combinations of allocation and coproduct options on microalgae biofuel production, to determine if variations in these parameters significantly impact the energy balance and GHG reduction potential of microalgal fuels.

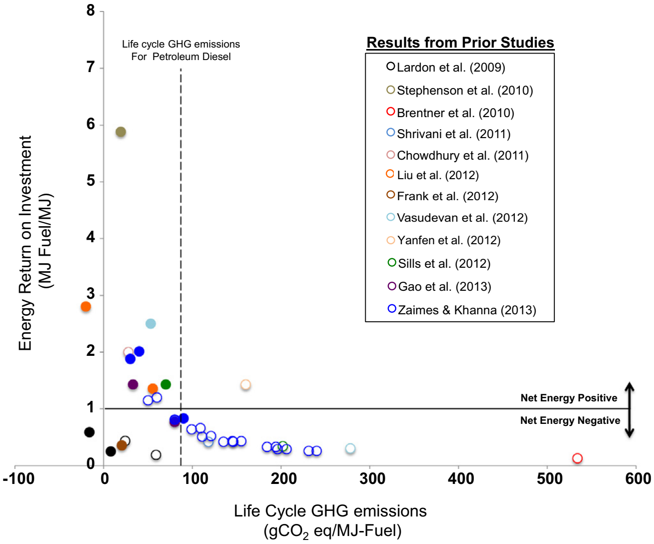


Fig. 1. Energy return on investment (EROI) and greenhouse gas emissions for prior microalgae biofuel LCAs. Data points on the graph that are filled (i.e. ●) utilize wet extraction; while data points that are *not* filled (i.e. ○) indicate dry extraction. Data for Liu et al. (2012) was obtained from Ref. [24]. Data for Zaimes & Khanna (2013) was obtained from ref [26]. Data for all other studies was obtained from Gao et al. (2013), see ref [59]. Biofuel studies in the order as they appear in the legend: Ref. [41], Ref. [32], Ref. [27], Ref. [60], Ref. [61], Ref. [62], Ref. [25], Ref. [63], Ref. [28], Ref. [59], Ref. [26].

The analysis performed in this work provides a framework for quantifying the role of coproduct options and allocation schemes on the energetic and environmental performance of microalgal biofuels, which can shed light on the high variability in reported environmental sustainability indicators for microalgal fuels. Furthermore, this analysis provides insights into the energy and environmental tradeoffs between different fuel production pathways. Understanding the impacts of microalgal fuel production across multiple environmental sustainability criteria is crucial for determining the potential widespread environmental ramifications that may result as a consequence of full-scale commercialization of these fuels.

Materials and methods

Model overview

Biomass-to-biofuel production is modeled via a theoretical 1000-ha integrated microalgal open raceway pond (ORP) biorefinery located in Phoenix, Arizona (AZ). It was assumed that 500 ha are used for open raceway ponds and 500 ha are utilized for infrastructure requirements. Prior research has shown that ORPs have significantly lower capital and operating costs as well as environmental impacts as compared to photobioreactors (PBRs) [32–34]. For these reasons polyvinyl chloride (PVC) lined algal raceway ponds were evaluated in this study. It is assumed that the integrated biorefinery would be co-located with a natural gas fired power plant, which would provide CO_2 as a source of carbon for algal growth [35,36]. The fractional composition of the biomass was assumed to be 25% lipids, 28% carbohydrates, and 47% proteins [37]. Average microalgal growth rates were constructed based on 30-year solar insolation data obtained from the national solar radiation database [38]; as well as solar efficiency terms obtained from peer reviewed literature [12]. The integrated biorefinery operates for an 8-month cycle; with an average growth rate of 23.5 (g/m^2-day). Cultivation and harvesting parameters were based off of peer reviewed and technical literature and were chosen to reflect standard industrial practice. Algal fuel upgrading and drying processes were modeled based on unit processes and assumptions for soybean-derived fuels. Life cycle data for material and energy inputs as well as transportation processes were obtained from the Ecoinvent [39] and United States life cycle inventory (USLCI) databases [40]. Detailed information regarding data collection, modeling parameters, and life cycle inventory is provided in the supporting information.

Technological routes and process options for microalgal biofuel production

Microalgal biofuel production consists of a combination of cultivation, primary and secondary harvesting, drying, lipid extraction and coproduct upgrading processes. An overview of the modeled biomass-to-fuel process chain is shown in Fig. 2. Two sets of technological routes—*baseline* and *improved* scenarios were evaluated for producing algal fuels. *Baseline scenarios* use current commercially available and mature technologies to produce algal fuels while *improved scenarios* utilize future technologies and process options that have undergone pilot scale testing but have yet to be demonstrated at a commercial scale.

In the baseline scenarios industrial flue gas from a co-located power plant is separated into pure CO_2 via monoethanolamine (MEA) scrubbing. This pure CO_2 is compressed and injected into the open raceway ponds via low-pressure blowers [36], to provide a carbon source for algal growth. Baseline technological scenarios consider dry extraction of the biomass; this requires the biomass