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Process energy comparison for the production and harvesting of algal biomass as a biofuel feedstock

Matthew K. Weschler [a], William J. Barr [b], Willie F. Harper [c], Amy E. Landis [b,*]

[a] Department of Civil and Environmental Engineering, University of Pittsburgh, 3700 O'Hara Street, Pittsburgh, PA 15261, United States
[b] School of Sustainable Engineering and the Built Environment, Global Institute of Sustainability, Arizona State University, ISTB4 781 E Terrace Road, Tempe, AZ 85287, United States
[c] Department of Systems and Engineering Management, Air Force Institute of Technology, 2950 Hobson Way, WPAFB, OH 45433, United States

HIGHLIGHTS

- Energy demand of 122 microalgae biomass production scenarios were compared.
- Choice of harvesting technology affected energy demand of other phases.
- Raceway ponds, settling, and chamber filter press consumed the least energy.
- Total energy demand for biomass production depends on final concentration.

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ABSTRACT

Harvesting and drying are often described as the most energy intensive stages of microalgal biofuel production. This study analyzes two cultivation and eleven harvest technologies for the production of microalgae biomass with and without the use of drying. These technologies were combined to form 122 different production scenarios. The results of this study present a calculation methodology and optimization of total energy demand for the production of algal biomass for biofuel production.

The energetic interaction between unit processes and total process energy demand are compared for each scenario. Energy requirements are shown to be highly dependent on final mass concentration, with thermal drying being the largest energy consumer. Scenarios that omit thermal drying in favor of lipid extraction from wet biomass show the most promise for energy efficient biofuel production. Scenarios which used open ponds for cultivation, followed by settling and membrane filtration were the most energy efficient.

1. Introduction

The United States is largely dependent on non-renewable liquid fuels to meet increasing energy demand. In recent years concerns over energy security, fossil fuel depletion and greenhouse gas emissions have lead researchers to investigate the commercialization of renewable fuel sources. To encourage the production of renewable fuels in the United States, policy makers developed the Energy Independence and Security Act (EISA) of 2007 and Renewable Fuel Standard (RFS) to increase vehicle fuel economy, energy savings, and energy security (EISA, 2007). Algal biofuels can contribute to the advanced biofuels volumetric goals set forth by EISA through biomass based biodiesel and ethanol production. Despite the potential of algae biofuels as a renewable energy source, a number of factors pose challenges to their commercialization. Three major factors include (1) high water demand during algae cultivation, (2) high energy requirements and mineral phosphorus depletion associated with fertilizer consumption, and (3) low energy return on investment (EROI) due to the high-energy requirements associated with the harvesting and drying of the biomass feedstock (Hunter-Cevera et al., 2012). This study will focus on the process energy consumption associated with microalgae biomass feedstock production.

Energy return on investments (EROI) between 0.13 and 3.33 have been estimated in the literature for the production of algal biofuel using open pond cultivation systems (Brentner et al., 2011; Clarens et al., 2010; Hunter-Cevera et al., 2012; Sander and Murthy, 2010; Stephenson et al., 2010). This wide range of values is due to differences in the choice of final products and production scenarios included in each study. Important factors that affect the EROI include: (1) sources of carbon dioxide (industrially produced, flue gas), (2) sources of nutrients (industrially produced, wastewater), (3) product and coproduct allocation (electricity, nutrient

* Corresponding author. Address: School of Sustainable Engineering and the Built Environment, Global Institute of Sustainability, Arizona State University, 375 ISTB4 781 E Terrace Road, Tempe, AZ 85287, United States. Tel.: +1 (480) 965 2975.
E-mail address: Amy.Landis@asu.edu (A.E. Landis).

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recovery, bioethanol, biogas), (4) extraction and processing (hexane/esterification, supercritical methanol, lysing method), and (5) biomass production process (open pond, photobioreactor, harvesting method).

Research has shown that the energy consumption for algal biomass production, which includes cultivation, harvesting and drying phases, is a limiting factor for algal biofuel commercialization, and thus warrants detailed analysis (Lardon et al., 2009; Lohrey and Kochergin, 2012; Stephenson et al., 2010; Xu et al., 2011). Cultivation options include photobioreactors (PBR) and raceway ponds (RP). Multiple studies have been conducted to determine the feasibility of commercialization of each mode of cultivation. The two most common PBR designs for algae cultivation are flat plate and tubular PBRs. Tubular PBRs however, are too energy intensive to compete with RPs and flat-plate PBRs (Jorquera et al., 2010). Drying has been shown to be the most energy intensive regardless of the technology selected (Lardon et al., 2009; Lohrey and Kochergin, 2012; Xu et al., 2011). Solar drying has been considered (Show et al., 2013), but the data is limited and how this process will affect lipid recovery and fuel conversion is unknown and is therefore excluded from this study. The high cost of drying has led researchers to consider other fuel conversion methods such as wet lipid extraction and supercritical extraction, (Brentner et al., 2011; Yoo et al., 2012).

Harvesting has also been shown to be an energy intensive step of algae biofuel production (Soratana et al., 2012). While the current number of cultivation and drying methods are limited, there are far more options for harvesting. Show et al. (2013) discuss recent advances in harvesting and drying technologies for biofuel production for a large number of processes. They consider sedimentation, air flotation, and electroflotation/coagulation technologies. The air flotation and electro techniques are more energy intensive than the sedimentation methods but the coagulation methods could negatively affect the biomass quality. Centrifugation and filtration can be used to further concentrate the microalgae. Both methods effectively dewater algae to greater than 10% biomass (w/w) and in some cases greater than 20% (w/w). Filtration methods require significant maintenance, such as filter cleaning and replacement. Centrifugation methods are very efficient but energy intensive. Despite the large number of currently available harvesting methods, most studies have only evaluated five or less harvesting scenarios.

A number of studies assess the algal biomass production process in conjunction with biofuel production. Lohrey and Kochergin (2012) considered five different harvesting technologies using two different production scenarios prior to drying. Lardon et al. (2009) considered two harvesting technologies and one production scenario. The authors explicitly avoided centrifugation, because of its high energy demand. Instead of exploring different harvesting technologies, they compared dry lipid extraction based on the same established process for soybeans and wet lipid extraction to avoid the exorbitant energy consumption associated with thermal drying. Xu et al. (2011) considered three harvesting technologies and one scenario before thermal drying for their dry route analysis and the same harvesting scenario without drying for their wet lipid extraction analysis. Stephenson et al. (2010) selected two harvesting methods and one production scenario with no drying.

The goal of this study is to perform a comprehensive process energy analysis of harvesting technologies for potential use in industrial-scale algal biofuel production. In this study we explore the use of multiple technologies and scenarios to reach desired concentrations. We consider cultivation, harvesting, and drying to demonstrate the interdependency of these three phases based on their energy requirements, solids concentrating potential, and biomass recovery efficiencies.

2. Methodology

A process model was constructed to compare 122 different algal biomass production scenarios using different combinations of technologies. The Supplemental information explains how these technologies were combined to form the production scenarios. The functional unit was defined as 1000 kg algae biomass. Process energy (kWh) inputs were calculated for each unit process. Each of the 122 scenarios was divided into three groups based on the final concentration of the algae. Parameters for these groups are summarized in Table 1, and the biomass production methods are listed in Table 2.

2.1. Scope of the analysis

Only process energy consumption for biomass production was considered in calculations. Process energy for biomass production includes energy used directly by cultivation, harvest, and drying technology and excludes energy required for raw material extraction, electricity generation and distribution, transportation, infrastructure, maintenance, and final waste disposal, as would be included in a traditional cradle-to-grave life cycle analysis (LCA). Energy required for the production of inputs into the microalgae biomass production process, including fertilizers, carbon dioxide, flocculants, and polymer filters were excluded from the calculation of energy demand. The scope of analysis was limited in this regard to focus solely on the unit processes used for biomass production and avoid the uncertainty associated with upstream and downstream process options. If the energy required for nutrient production was included, for example, the energy demand for cultivation might be overestimated, since up to 73% of the energy required for the production of nutrients can be recovered if anaerobic digestion of the residual algal biomass is chosen as a downstream process option (Brentner et al., 2011). Future LCAs can then use the results presented in Section 3 of this study to model energy requirements for algae biomass production, while determining for themselves the utility of energy recovery using anaerobic digestion in downstream processing.

2.2. Biomass production process

The production of algal biomass can be described as a series of unit processes which amplify algal solids concentration and are summarized as follows: (1) cultivation, in which the algal biomass is grown to a dilute concentration ~0.1–0.26% (w/w) (2) primary harvest (thickening), in which the concentration is increased to ~1.5–10.0% (w/w), (3) secondary harvest (dewatering), in which the solid content is increased to ~12.0–27.0% (w/w), (4) thermal drying, in which unbound water is removed from the biomass (Greenwell et al., 2010; Mohn, 1980; Pulz, 2001; Shelef et al., 1984; Uduman et al., 2010). The algae production process is summarized in Fig. 1.

Table 1
Summary of the three groups of scenarios.

	Concentration w/w (%)	Final unit process	# of Scenarios
Low biomass concentration, wet harvest	3–10	Primary harvest	14
High biomass concentration, wet harvest	12–27	Secondary harvest	54
Dry harvest	90	Thermal drying	54