BIOMASS AND BIOENERGY 72 (2015) 45–54

Available online at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

Techno-economic analysis of transportation fuels from defatted microalgae via hydrothermal liquefaction and hydroprocessing

Longwen Ou [a], Rajeeva Thilakaratne [a], Robert C. Brown [a,b], Mark M. Wright [a,*]

[a] Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, United States
[b] Bioeconomy Institute, Iowa State University, Ames, IA 50011, United States

ARTICLE INFO

Article history:
Received 1 August 2014
Received in revised form
14 November 2014
Accepted 20 November 2014
Available online

Keywords:
Defatted microalgae
Hydrothermal liquefaction
Biofuel
Process modeling
Minimum fuel selling price
Uncertainty analysis

ABSTRACT

This study describes a techno-economic analysis to evaluate the economic feasibility of transportation fuel production by hydrothermal liquefaction (HTL) of defatted microalgae followed by hydroprocessing of the resulting bio-crude. A 2000 dry tonne per day biorefinery produces 112 dam^3 of gasoline-range fuels and 121 dam^3 of diesel-range fuels per year. We estimate the total project investment is 504 M$ and the annual operating cost is 158 M$. The minimum fuel-selling price (MFSP) is 679 $ m^{-3} assuming a 10% internal rate of return assuming 30-year plant life. Sensitivity analysis shows that MFSP is most sensitive to product fuel yield indicating the relative importance of HTL conversion performance. Feedstock cost also strongly influences MFSP, which varied between 584 $ m^{-3} and 869 $ m^{-3} for feedstock cost of 33 and 132 $ dry $tonne^{-1}$, respectively. A Monte-Carlo analysis suggests an 80% probability of MFSP being between 607 and 833 $ m^{-3}.

1. Introduction

Environmental concerns and land availability constraints for energy use have prompted the search for clean sources of high-yielding biomass. Microalgae are a potential biomass resource for the production of renewable biofuels with low emissions and reduced land requirements [1–4]. Microalgae present several advantages for biomass production compared to lignocellulosic feedstock. These advantages include low maintenance cultivation, rapid growth, limited need of fresh water, and low nutrient utilization [3]. Microalgae are primarily composed of lipids, carbohydrates, and protein [5]. Their varied composition makes them suitable for multiple applications. They can be employed for ethanol production via fermentation [6] and hydrocarbon fuel synthesis via thermochemical pathways such as fast pyrolysis and gasification [7–9].

Defatted microalgae are a by-product of biodiesel production via lipid extraction from microalgae [10–12]. The defatted microalgae, which can account for as high as 85% of the whole microalgae in weight percent on a dry basis [5], has similar carbon and hydrogen content as lipids [13] and could be used for biofuel production [5]. Previous studies identified several

* *Corresponding author*. Tel.: +1 515 294 0913.
E-mail address: markmw@iastate.edu (M.M. Wright).
http://dx.doi.org/10.1016/j.biombioe.2014.11.018

applications for defatted microalgae, including animal feeding supplements [14], biogas generation feedstock via anaerobic digestion (AD) [15,16] and chemical production substrate via fermentation [17]. Defatted microalgae could also be converted into drop-in liquid fuels that are compatible with existing vehicles and transportation fuel infrastructure.

Several thermochemical routes such as pyrolysis, gasification and hydrothermal liquefaction (HTL) [18–20], can convert biomass into biofuels. However, pyrolysis and gasification have a disadvantage with respect to high moisture feedstocks such as defatted microalgae due to the significant energy losses associated with drying the material [21,22]. HTL, on the other hand, is considered a promising pathway for processing feedstock with high moisture content [21]. HTL involves processing biomass in pressurized water at temperatures between 250 and 550 °C, and pressures of 5–25 MPa. HTL produces a crude oil, an aqueous fraction and a gaseous fraction [21,23]. HTL crude oil, often called bio-crude, has a relative high heating value (>30 MJ kg^{-1}) [23–25] compared to pyrolysis oils (around 20 MJ kg^{-1}) [26–28]. HTL has been utilized to process lignocellulosic biomass in the presence of catalyst to produce high-energy content bio-crude [29,30]. However, the intrinsic characteristics of HTL suggest that it is more economically advantageous for processing feedstock with high water content such as algae, sludge, etc. by eliminating the need to dry feedstock.

The advantages of HTL include: a) avoidance of the costly feedstock drying; b) high yield of bio-crude [31,32]; c) and the possibility of recycling the high nutrient containing aqueous fraction [33]. However, a significant drawback of HTL is the severe operating condition required (high pressure and high temperature), which incurs high investment and operating cost [1]. There is limited public literature on the costs of biofuel production from the HTL of algae feedstock [1,5]. Therefore, this study seeks to evaluate the economic feasibility of converting defatted microalgae into biofuels via HTL with the understanding that it is in an early development phase.

To our knowledge, only a limited number of studies investigate the feasibility of producing liquid biofuels from defatted microalgae [5,32]. Slow pyrolysis and HTL were examined as potential ways of converting defatted microalgae into high-energy content oils [32], which could be subsequently upgraded to liquid fuels via hydrotreating and hydrocracking. Previous research has shown that HTL has a more attractive energy balance than slow pyrolysis [32].

In this study, we conduct a techno-economic analysis (TEA) to evaluate the potential of producing liquid fuels from defatted microalgae by HTL followed by upgrading of bio-crude. A commercial-scale 2000 dry tonne per day HTL and hydroprocessing facility is modeled to estimate its total project investment and annual operating costs. The process model assumes that the facility is the *n*th plant of its kind meaning that major technical challenges have been overcome and requisite equipment is commercially available. The commercialization potential is determined by the competitiveness of the minimum fuel-selling price (MFSP) relative to market alternatives. The MFSP is estimated based on a 10% internal rate of return (IRR) and 30-year facility lifetime.

2. Materials and methods

The TEA employs chemical process modeling and economic cost estimates to determine the process profitability. This study employs ChemCAD 6.5 software by Chemstations™ for process modeling. Purchase costs of common equipment such as compressors, pumps, and heat exchangers are estimated using ChemCAD. Purchase costs of custom engineered equipment such as the HTL reactor and hydrogen plant are projected based on a power law with the commonly employed scaling factor of 0.6 for chemical processing equipment [34–37]. The return on investment is evaluated with a 30-year discounted cash flow rate-of-return (DCFROR) spreadsheet. Some major assumptions made in this analysis are listed below:

- Plant capacity is 2000 dry tonne per day of defatted microalgae.
- The wet feedstock contains 80% moisture.
- Liquid effluent and solids from the HTL reactor are directed to a wastewater treatment plant and solid waste disposal plant, respectively.
- Process off-gases are combusted for heat recovery.
- The cost analysis represents an *n*th plant design, which assumes that major technical obstacles have been overcome and requisite equipment is commercially available.

2.1. *Process modeling*

The chemical process model comprises 5 areas: hydrothermal liquefaction, hydroprocessing, hydrogen generation, product refining, and a combined heat and power (CHP) plant as illustrated in Fig. 1. Fig. 2 shows a simplified flow diagram of the HTL, hydroprocessing and product refining processes. The following sections describe assumptions relevant to each of these areas. Waste handling and disposal facilities are not modeled in this analysis. Instead, we assume that HTL wastewater could be treated by a third-party facility at a fixed price per unit volume (0.89 \$ m^{-3}) [38], and solid waste can be disposed at a fixed price per unit mass (36.98 \$ $tonne^{-1}$) [39]. These costs assume that the waste treatment facilities are capable of handling all potential contaminants without additional capital investment or major infrastructure modifications.

2.1.1. *Biomass feedstock*

Both raw and defatted microalgae can be used as feedstock of HTL process considering their high moisture content. However, estimated production cost of raw microalgae cultivation can be as high as 3000 \$ $tonne^{-1}$, impairing the potential of raw microalgae as HTL feedstock [12]. Prices of defatted microalgae, on the other hand, are expected to be in line with wet distiller's grain with solubles (WDGS) considering the fact that they share similar protein and moisture content and can both be used as animal feed supplement. The lower price of defatted microalgae grants it advantage as a potential HTL feedstock.

Vardon et al. [32] reported the elemental composition of raw *Scenedesmus* and defatted *Scenedesmus*, as listed in Table 1.