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Techno-economic assessment of open microalgae production systems

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ABSTRACT

Microalgae represents a promising feedstock due to inherent advantages such as high solar energy efficiencies, large lipid fractions, and utilization of various waste streams including industrial flue gas. This study directly evaluates and compares the economic viability of biomass production from two different open cultivation platforms, 1) algal turf scrubbers and 2) open raceway ponds. Modular sub-process models were developed and leveraged for the economic comparison of the systems on the metric of harvested biomass. The system boundary was expanded to include downstream processing for the production of renewable diesel through thermochemical conversion for a comparison of the production platforms on a cost per gallon of fuel. Economic results of the two production pathways show a biomass production cost for the algal turf scrubber of \$510 tonne^{-1} and \$8.34 per gallon for fuel. Open raceway pond results give a biomass cost of \$673 tonne^{-1} and a fuel cost of \$6.27 per gallon. Sensitivity analysis show productivity and culture stability to be critical factors in the economic viability. Multiple scenarios are presented with baseline results directly compared to literature and highlight the need for robust growth modelling.

1. Introduction

Large uncertainties associated with future oil supplies and costs have increased interest in alternative fuel sources. A variety of feedstocks are being investigated for the production of biofuel, with microalgae representing a promising alternative to first and second generation terrestrial crops primarily due to superior productivity and use of non-arable land [26,36,52]. As a biofuel feedstock, microalgae is characterized by high solar energy yield, high lipid content, year-round cultivation, can be integrated with various waste streams, and the ability to use low quality water [33,35,42,49]. Defining the economic viability of the microalgae to biofuel processes has proven challenging based on the current immaturity of the technology.

A number of techno-economic assessments (TEA) have been completed to analyze the economic feasibility of biofuels derived from a microalgae feedstock [1,2,5–8,11,12,14,22,25,30,33,38–40,43,47,48,53]. The results range from a low of \$2.20 per gallon reported by [30] to \$31.36 per gallon reported by [40] for commercial scale facilities. Inconsistencies in process boundaries, core modeling assumptions, and variation in processing pathways resulted in two separate harmonization efforts completed by Sun et al. [47] and [2]. A large contributing factor to the variability of results is due to uncertainty in the cost for the production of biomass in the growth system. A small number of studies have focused on understanding the cost to produce and harvest algal biomass. Norsker et al. [31] report a cost of \$4520 tonne^{-1} but also report that with optimizations the cost could drop to \$740 tonne^{-1} (assumed photosynthetic efficiency 5%). Davis et al. [14] and Jones et al. [22] have evaluated downstream processing through algal fractionation and hydrothermal liquefaction, respectively, with an arbitrary biomass production cost of \$474 tonne^{-1}. The majority of current TEAs have failed to explore the impacts of different cultivation systems on biomass production costs [2,3,5,11,14,15,22,25].

The majority of TEAs have assumed the use of an open pond or closed photobioreactor production systems [12,25,41]. An alternative open growth system for producing algae is the algal turf scrubber (ATS). An ATS is an open flow attached growth system. The system employs a substrate that supports attached algal growth. The entire system is constructed on a sloped surface that allows contaminated water to flow over algae which in turn take up inorganic compounds. A critical components of ATS systems is the integration with contaminated water systems such as estuaries or agricultural run-off. The integration of the ATS systems with contaminated waterways reduces the raw nutrient inputs required to maintain high growth rate production while providing an environmental service. ATS systems are based on a native culture which dynamically adapts to changing conditions decreasing culture crash events seen in homogeneous cultures [24]. ATS systems are relatively simple in design and yield a biomass that can be easily harvested utilizing farm equipment [34]. ATS systems have currently

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been used commercially for contaminated water treatment with the produced biomass representing a co-product to water reclamation [21]. The stability of the systems and promising productivities make the ATS a system of interest as a biomass production platform for biofuels. The cultivation and harvesting of native cultures while improving culture robustness does yield low lipid algae typically with a high ash content [9,18,23,44]. The low lipid algae and high ash content represent hurdles that need to be overcome in the commercialization of ATS systems for the production of a bioenergy feedstock. ATS systems are of interest in terms of a growth platform for the production of a biofuel feedstock based on the advantages described with the need to better understand the economic viability compared to traditional open raceway systems as a function of inherent operational tradeoffs.

Based on the current state of the field there exists a need to quantify the costs associated with microalgae feedstock production in large-scale open systems. A systems engineering process model was developed and integrated with economic modeling to evaluate the cost of producing biomass in an ATS and open raceway pond (ORP) growth systems. Results from this study focus on a direct comparison of the cost for the production and harvest of biomass through the two growth platforms. Modularity in model construction facilitated the integration of downstream processing through hydrothermal liquefaction (HTL) for an economic evaluation of the production of fuel. Multiple case scenarios are evaluated that are intended to represent a conservative near term system and an optimistic scenario envisioned to represent performance that includes advancements from research and development. Discussion focuses on sensitivities of the individual processes, optimization of each system for a final fuel cost of $3 per gallon of gasoline equivalent (GGE), and a direct comparison of results to literature.

2. Methods

An engineering systems model was generated for both the ATS and ORP growth and harvest systems. Biomass production for each system was 500 ktonne ash free dry weight per year [12,14,22]. Modeling and results for each of the production systems was divided into two efforts corresponding to the evaluation of the costs associated with biomass production and extension of the work for the evaluation of fuel production corresponding to system boundaries defined as 1) growth system and 2) biofuel system, respectively, Fig. 1. The first boundary, growth system, was limited to the production and harvesting of biomass to 20% solids. The second boundary, biofuel system, expands work to include the production of renewable diesel through HTL. Energy and mass flows from the engineering process model were combined with economic modeling to evaluate the viability of production through the alternative pathways and directly compare the two growth architectures. Results are presented on a cost per metric ton of 20% solids ash free dry weight biomass for the first system boundary and cost per gallon of renewable diesel for the second system boundary with all results presented in 2014 dollars. Detailed assumptions are presented in the next sections.

2.1. ATS growth system

Systems modeling was used to develop and assess microalgae growth utilizing an ATS system. Foundational inputs for the ATS growth system are listed in Table 1. The growth rate was set at 20 g m^{-2} d^{-1} with an assumed lipid content of 10% based on data provided by Sandia National Laboratories (SNL) and literature [27–29]. This growth rate is based on experimental data collected through SNL and industry represents a conservative annual average productivity. The low lipid is characteristic of polyculture systems [9,18,23,44]. The ATS module length was set at 152 m (500 ft.) with each ATS unit set to 405 ha (1000 acres). The module is a slightly sloped growth platform were contaminated water is passed from the top of the system to the bottom. A schematic drawing and images of ATS systems are presented in the supplementary material. ATS systems are designed to integrate with contaminated water systems and do not require additional nutrients to be added to the system with the assumed growth rate observed at pilot scale. The designed system is assumed to limit the delivery of water to a single pass with water delivered through a head rail system. The required hydraulic loading rate is 124 lpm per linear meter. Pumping efficiency was assumed to be 67% with 4 m of pumping head. The power required was calculated using Eq. (1) where g is gravity, R_H is the hydraulic loading rate, n is the number of ATS modules, W_m is the width of each module and η is the pumping efficiency:

$$P_{ph} = \frac{g^* R_H * n^* W_m}{\eta} \quad (1)$$

The resulting power that is required is 0.80 MW m^{-1}. Accounting for 14 h of total pumping per day results in a power consumption of 4100 MWh m^{-1} $year^{-1}$. The ATS system is designed with a 0.5% slope and utilizes a liner and 3D attachment screen to provide a textured substrate for improved productivity. Capital costs associated with earthworks, roads, piping and land are $371 k, $297 k, $863 k and $3 M per 405 ha respectively [25]. Earthworks is a critical component to the system as a slight slope is required for proper water flow. Liner and attachment screen costs represent significant capital investment at $22 million per 405 ha. The liners are more robust than a standard pond liner as they must withstand harvesting operations. There are no costs associated with nutrient loading due to the assumption that the ATS utilizes waste and contaminated water systems to provide required nitrogen, phosphorous, and carbon. The system is designed and assumed to operate on native algae to the system resulting in a polyculture. Detailed capital assumptions are included in the Supplementary material.

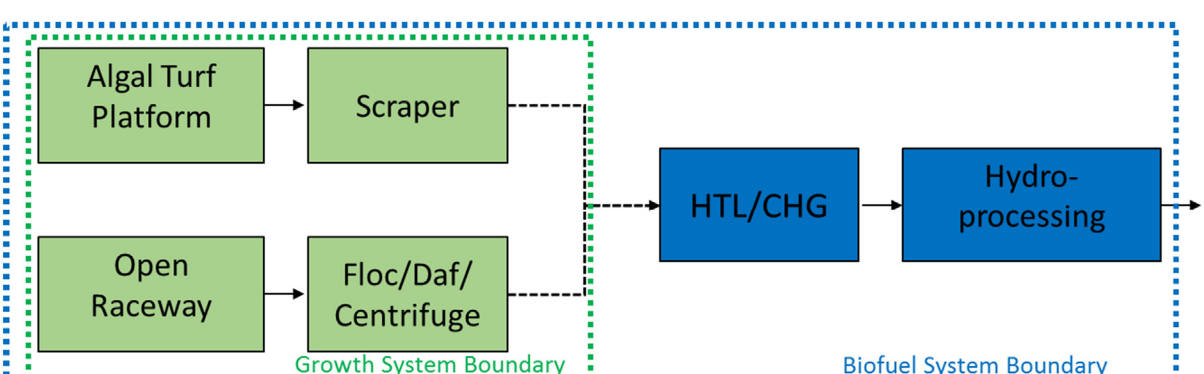

Fig. 1. System boundaries allowing for comparisons of ATS and ORP growth systems on the metrics of biomass cost per tonne and fuel cost per gallon.