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A critical analysis of paddlewheel-driven raceway ponds for algal biofuel production at commercial scales☆

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ABSTRACT

Microalgae have been promoted as the next frontier of green biotechnology and gained widespread attention as desirable feedstocks for biofuels. Using conservative assumptions for microalgal growth rates (15 g m^{-2} d^{-1}) and total lipid content (25%), the entire "pond-to-pump" lifecycle of algal biofuels for 1000 bbl d^{-1} of crude algae oil production is modeled with approximately 4875 ha of raceway ponds for solar collection and cultivation and 1463 MLD (385 MGD) of water handling capacity in the current analysis. Technoeconomic analysis based on an array of 6000 modular 0.8 ha (2 acre) paddlewheel-driven ponds in New Mexico identified several cost barriers and resources challenges (i.e., nutrient and water resources). For 10- and 20-year capital return scenarios, the cost of algal oil production – \$4.10 L^{-1} (\$15.52 gal^{-1}) and \$3.21 L^{-1} (\$12.14 gal^{-1}), respectively – requires substantial capital and facility maintenance investments with principal cost sensitivities attributed to extraction efficiency and lipid content. Baseline conditions result in an energy return on investment (EROI) of 2.73. Uncertainty in energy requirements for paddlewheels as well as water supply and circulation significantly affect the EROI and operating costs. Alternative strategies to address the major cost barriers are needed for algal biofuels to realize their full potential.

1. Introduction

The social, environmental, and economic pressures of human activity require ever increasing energy resources. The rise of developing nations coupled with a predicted expansion of the world population to at least 9 billion by 2050 [1] correlates to a global increase in energy use from 533 quadrillion (10^{15}) kJ in 2008 to 812 quadrillion kJ by 2035 [2]. Photosynthetic biomass grown as a bioenergy crop has the potential to contribute a significant amount of renewable fuel while simultaneously absorbing point sources of carbon dioxide (CO_2). The United States has a goal of 17% reduction in CO_2 emissions by 2020. Current projections show energy-related CO_2 emissions in 2020 to be only 9% below their 2005 level [2]. Therefore, an intensified expansion of carbon neutral renewables will be necessary to meet the milestone within the coming decade.

Microalgae are perhaps the most prolific source of photosynthetic biomass on the planet. The controlled cultivation of microalgae on large-scale farms offers an avenue to enhance domestic energy production while minimizing land resources requirements. In 2010, liquid biofuels represented only 1% of the total U.S. fuel portfolio and are

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Abbreviations: AD, Anaerobic Digestion; ANL, Argonne National Laboratory; APD, Algae Process Description Tool; ASP, Aquatic Species Program; BD, Biodiesel; BGY, Billion Gallons per Year; BLY, Billion Liters per Year; CO_2, Carbon Dioxide; COP, Cost of Production; DAF, Dissolved Air Flotation; DARPA, Defense Advanced Research Projects Agency; DAP, Diammonium Phosphate; DOE, U.S. Department of Energy; DW, Dry Weight; EE, Extraction Efficiency; EERE, Energy Efficiency & Renewable Energy; EIA, Energy Information Administration; EISA, Energy Independence and Security Act of 2007; EPA, Environmental Protection Agency; EROI, Energy Return on Investment; FWC, Flue-gas and Wastewater Co-utilization; g L^{-1}, Grams per Liter; GHG, Green House Gas; ha, Hectare; HDPE, High-Density Polyethylene; HRP, High Rate Ponds; kW, Kilowatts; kWh, Kilowatt Hours; LANL, Los Alamos National Laboratory; LCA, Life-Cycle Analysis; LEA, Lipid Extracted Algae; LLE, Liquid–Liquid Extraction; MGY, Million Gallons per Year; MGD, Million Gallons per Day; MLD, Million Liters per Day; NMSU, New Mexico State University; NREL, National Renewable Energy Laboratory; NWIS, National Water Information System; PA, Polyacrylamide; PBR, Photobioreactor; PE, Photosynthetic Efficiency; RA, Resource Assessment; RD, Renewable Diesel; RFS, Renewable Fuel Standard; TEA, Techno-Economic Analysis; USGS, U. S. Geological Survey; WWT, Wastewater Treatment; WWTP, Wastewater Treatment Plant.

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expected to reach 4% by 2035 with nearly all of their consumption attributed to the transportation sector [2]. Algal biofuels may ease this inevitable energy transition by fulfilling a significant role in our portfolio of alternatives to fossil fuels.

Microalgae have been promoted as one of the more promising third-generation biofuels for their ability to accumulate substantial amounts of lipids, divide rapidly, grow in low quality water, absorb CO_2, and grow on non-arable land [3]. There is a wealth of literature that documents the commercial scale growth of various microalgal species for natural products as well as the progression of both basic and applied biological research, improvements to photobioreactor (PBR) and pond design, and lifecycle analyses of algal biofuels [4–6]. The mass cultivation of microalgae was pioneered in the early 1950s with *Chlorella* [7] and quickly transitioned into a modular production process using Oswald's raceway design termed “high rate ponds” (HRPs) for large-scale recirculating algae cultivation [8]. Although there is some debate surrounding the “carbon neutrality” of biofuels in general, microalgae offer significant advantages over other alternatives. Yet, the lack of uniformity in these technologies and microbial crops still makes assessment of the costs and energy requirements complex. Some of the major factors affecting algal biomass productivity include inherent photosynthetic constraints as well as the bioprocessing challenges related to large-scale cultivation of microbes in water.

When cultivating algae in an artificial environment (e.g., outdoor pond), it is essential that growth factors are plentiful in order to maximize growth rates [9]. While CO_2 can be acquired from the atmosphere, it is commonly fed into algae media to improve production [10–12]. In addition to CO_2, nitrogen and phosphorus are the major nutrients required for algae growth. It has become an accepted measure that marine plankton have relatively constrained elemental ratios of 106:16:1 (C:N:P) [13–15]. Although some algae species, primarily cyanobacteria, can fix nitrogen from the air [16,17], most microalgae require a soluble form, such as urea or ammonia [18].

In raceway ponds, paddlewheels are used to maintain constant mixing of the algae. A single paddlewheel has been shown to provide sufficient mixing for algae biomass cultivation for arrays of connected ponds covering areas as large as 5 ha [19,20]. While this shows promise for paddlewheels in HRPs, larger ponds require scale-up of the number of paddlewheels to maintain sufficient mixing. With a turbulent mixing velocity, the culture can maintain a uniform density. The addition of eddies generated from the paddlewheel helps to reduce the residence time of the algae in the dark regime. At a low velocity, laminar flow will decrease the productivity of the pond; yet, as the velocity increases, the power required to generate the new velocity increases cubically. This presents problems for the mixing velocity at rates greater than 30 cm s^{-1}, specifically manifested in increased energy costs [21].

Algae based biofuels received recent support as qualified feedstock, making algae-derived biofuels eligible for $1.01 tax credit per gal (Section 40 of United States Code). Despite the general public awareness of the various biological sources of liquid fuels and their potentially significant contribution to greenhouse gas (GHG) reduction [22], there remains little consensus on the lifecycle analyses (LCA) and TEA of these biofuels [23,24]. Some of the most recent information on algal biofuel technoeconomics shows that algae may have a favorable energy return on investment (EROI) compared to fossil fuels, first-, and even second generation biofuels [25]. However, the existence of multiple biofuel production pathways, different productivity assumptions and limited commercial-scale production makes it difficult to establish theoretical mass and energy balance equations [26].

In the present study, the production costs and EROI of a hypothetical algae farm and biocrude oil refinery of commercially relevant production capacity (1000 bbl d^{-1}) were evaluated for a variety of operating scenarios. The overall feasibility of this facility and its scalability to meet 5 and 10 billion gallon per year (BGY) production goals, equivalent to 18.9 and 37.8 billion liters per year (BLY), were explored for the geography and climate of New Mexico based on technical and economic analyses. In particular, this algae oil process model focuses on upstream cultivation using conventional technologies (i.e., raceway ponds) and locally sourced water and energy inputs. The impact of well-established harvesting, dewatering, and separating of methodologies on the sustainability of downstream processing was also assessed. The results of this technoeconomic study identify the major energy demands, water requirements, and capital investments associated with traditional algal biofuel production. The ultimate conclusions regarding cost of production (COP) and sustainability are held in comparison with empirical data from the New Mexico State University (NMSU) microalgae cultivation testbed.

2. Methods

2.1. Production assumptions and scalability

The model in the present study was developed in order to estimate the scale of a facility to produce 1000 barrels of crude algae oil per day (bbl d^{-1}). Nutrient demand was determined from the Redfield ratio elemental composition of $C_{106}H_{181}O_{45}N_{16}P$, resulting in nutrient requirements of 525.1 mg C g^{-1}-algae DW, 91.9 mg N g^{-1}-algae DW, and 12.7 mg P g^{-1}-algae DW. All references made to algal biomass in this model pertain to the biomass dry weight (DW). As a simplifying assumption, a year averaged microalgal growth rate of 15 g m^{-2} d^{-1} was chosen. Estimates for growth culture density (0.5 g L^{-1}), harvesting rate (10%), extraction efficiency (80%), and lipid content (25%) were used as the baseline condition of the model. Due to the uncertainty of lipid fractions and the effects of specific growth conditions, all lipids were assumed to be useable as a precursor to renewable diesel (RD) conversion. Based on the assumptions, a growth surface area of 4875 ha will produce 730,000 ± 2000 kg d^{-1} algal biomass, yielding 1000 bbl d^{-1} algae oil. So as not to exceed the paddlewheel capabilities individual ponds were sized at 0.81 ha each, requiring 6000 ponds for production. The growth surface area has a depth of 30 cm resulting in a total volume of 14.627 billion liters. By maintaining the culture density at 0.5 g L^{-1} the ponds can contain 7.3 M kg-algae, of which only 10% of the total raceway volume will be harvested daily. This allows the ponds to maintain production and operate in a continuous steady state by balancing the harvesting rate with the photosynthetic growth rate. Wages were estimated to contribute 12% of the total operating costs. This estimate was chosen based on similar analyses of the industry [6]. Maintenance costs were estimated as 3% of the process equipment and raceway pond costs [27]. All equipment was assumed to operate for 24 h d^{-1} 365 d yr^{-1}. As a simplifying assumption, an average cost of electricity of $0.11 kWh^{-1} was used to account for seasonal variations.

One of the main goals of the current study was to evaluate the potential scalability of algae facilities. The U.S. Energy Independence Security Act of 2007 (EISA) has mandated 36 billion gallons (136B L) of renewable fuel by 2022 that will in turn be ramped up to 60 billion gallons (227B L) of biofuel by 2030 with provisions to emphasize the development of advanced, non-corn ethanol biofuels [28]. To evaluate the scale up feasibility of algae production, we assumed that algae oil will contribute a moderate portion of these mandates by producing 5 BGY (18.9 BLY) of algae oil by 2022 with an increase to 10 BGY (37.8 BLY) by 2030. The current model was designed with New Mexico as a possible site for algal production due to its climate (low seasonal variation and high solar irradiance) and geography (flat topography). The current study evaluated the capital and operating requirements associated with algae-oil production of 1000 bbl d^{-1}. Results from a single model production plant were used to assess the scalability and key limitations of algal biofuels from both economic and sustainability perspectives [25]. The process flow of baseline estimates for the current model is shown in Fig. 2.1a.

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