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Algal biofuel production for fuels and feed in a 100-ha facility: A comprehensive techno-economic analysis and life cycle assessment

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ABSTRACT

This techno-economic analysis/life-cycle assessment is based on actual production by the Cornell Marine Algal Biofuels Consortium with biomass productivity > 23 g/m^2-day. Ten distinct cases are presented for two locations, Texas and Hawaii, based on a 100-ha production facility with end-to-end processing that yields fungible co-products including biocrude, animal feed, and ethanol. Several processing technologies were evaluated: centrifugation and solvent extraction (POS Biosciences), thermochemical conversion (Valicor), hydrothermal liquefaction (PNNL), catalytic hydrothermal gasification (Genifuel), combined heat and power, wet extraction (OpenAlgae), and fermentation. The facility design was optimized by co-location with waste CO_2, a terraced design for gravity flow, using renewable energy, and low cost materials. The case studies are used to determine the impact of design choices on the energy return on investment, minimum fuel and feed sale prices, discounted payback period, as well as water depletion potential, human health, ecosystem quality, non-renewable resources, and climate change environmental indicators. The most promising cases would be economically competitive at market prices around \$2/L for crude oil, while also providing major environmental benefits and freshwater savings. As global demands for fuels and protein continue rising, these results are important steps towards economical and environmentally sustainable production at an industrial scale.

1. Introduction

Algae are among the most promising feedstock candidates to produce second-generation biofuels that satisfy the national mandate in the Renewable Fuels Standards that was enacted into United States' law in the Energy Independence and Security Act of 2007 [1]. Marine algae are especially promising because they do not require arable land or freshwater – thereby avoiding competition with conventional crops for these resources – and they often contain large quantities of oil, protein, carbohydrates, omega-3 fatty acids, and pigments such as astaxanthin. However, the flurry of investment into algal biofuels in the late 2000s in both public and private sectors [2–4] has not yielded economical large-scale algal biofuel production due to the following barriers: unreliable cultivation methods, large nutrient requirements (for carbon, nitrogen, and phosphorus), low energy return on investment (EROI), high capital costs, and competition from existing commodity products with tight margins (primarily crude oil, soy meal, and corn meal) [5–9].

We address all of these barriers in this study in the following ways: Biomass productivity was measured during extended demonstration-scale experiments with consistently high yields from two selected strains (as described in a companion manuscript [10]). The facility modeled in this study is co-located with a carbon dioxide waste stream and utilizes nutrient recycling in most scenarios. Using gravity-fed volume transfers, airlift pond circulation, naturally settling algal species, and efficient conversion/extraction processes, the EROI values obtained in this model are among the highest ever reported. Low capital costs were targeted by designing large cultivation systems to achieve economies of scale, specifying cost-effective pond liners, using multi-purpose

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pipelines to reduce pipe costs, and eliminating most pumps. Current market prices were used for valuing the biofuel and animal feed, however, the animal feed was shown to have several added benefits over conventional feeds during feed trials with poultry, swine, and fish, such as the high content of protein and omega-3 fatty acids — thereby potentially warranting greater financial value [11,12].

Of the many recent techno-economic analyses (TEA) and life-cycle assessments (LCA) describing the production of biofuel from algae, most evaluate a few selected production pathways based on assumed or modeled biomass and lipid yields for a specific geographical location and the TEA/LCA is conducted after the system (theoretical or experimental) has been designed [4,6,13–23]. By contrast, in this study, we used actual large-scale production results to evaluate a wide range of processing technology combinations for two geographic locations (Texas and Hawaii) and then employed TEA/LCA as a design tool, using the results of one processing scenario to inform design choices for subsequent iterations. This combination is critical to avoid recommending environmentally friendly designs that are not profitable, and vice versa.

There have been a wide range of functional units used for algal biofuel TEA/LCA studies [14,24–26] and we chose 1 ha of facility area to enable comparisons with conventional crops and avoid allocation of environmental impacts among co-products [27]. The TEA/LCA analysis yields results for 20 cases in the following metrics: EROI (unitless), minimum feed and fuel sale prices (in \$/MT and \$/L, respectively), discounted payback period (in years) and the LCA impacts of water depletion potential (m^3/ha over a 30 year span), human health, ecosystem quality, non-renewable resources, and climate change (all of which are reported in units of LCA points of environmental damage per hectare). Thus, by combining the large-scale experimental biomass productivity data with novel technology designs and thorough TEA/LCA analysis, this study offers a realistic and comprehensive evaluation of the emerging algal biofuels and animal feed industries.

2. Material and methods

2.1. The model

This study evaluates a nominal 100-ha facility model that justifiably expands on the Kona Demonstration Facility (KDF), which is now Cellana LLC – as described by Huntley [10] – and does not exceed reasonable capital finance (on the order of tens-of-millions of dollars). The KDF was used from April 2010 to August 2011 for sustained production in a 0.5-ha hybrid cultivation system of photobioreactors (PBRs) and open ponds that yielded >23 g/m^2-day of biomass productivity [10]. Cultivation of two algal species (a diatom, *Staurosira* sp., and a chlorophyte, *Desmodesmus* sp.) is modeled based on actual KDF results and both species are cultivated in seawater. In the model, carbon is obtained from a local waste stream while other nutrients (nitrogen, phosphorus, and silicon, when applicable) are provided from commercial fertilizers. Co-location with a wastewater treatment plant was considered [28,29], however the nutrient demand for high-rate biomass production exceeds the low nutrient content in most wastewater primary effluents; in our analysis, the cost of pipes and pumping outweighed the nutrient savings. The facility is designed in terraces, enabling low-energy water recycling, and the cultivation system is modeled as a hybrid system of PBRs and ponds [10]. Based on the authors' experience with large-scale algae production in this integrated system, the facility is assumed to operate 347 days per year, which corresponds to a 95% capacity factor.

Several processing technology configurations were evaluated in this study. The harvesting and dewatering methods considered include 1) natural settling [10] followed by centrifugation [30–32] and a ring dryer [33] (yielding 90% solids), and 2) natural settling and a belt filter press [22,32,35] (yielding 20% solids). The extraction/conversion processes in this study include combinations of hexane extraction [14,36], Valicor's thermochemical conversion technology [37], hydrothermal liquefaction (HTL) [7,38], OpenAlgae's lipid extraction process [39], ethanol fermentation [40], catalytic hydrothermal gasification (CHG) [38], and combined heat and power (CHP) [40]. The output products include biocrude, protein-rich and omega-3-fatty-acid rich animal feed, and ethanol. Livestock feed and aquafeed trials were conducted in parallel [11,12] and demonstrate the ability to use algae as protein-rich animal feed and justify the co-product value assigned to the residual biomass after biocrude separation.

2.2. Facility design

The cultivation process is described by Huntley et al. [10] and the modeled facility (Appendix A of the supplemental information (SI)) in this study contains 480 PBR's with 50 m^3 of culture volume each, 16 1-day ponds, and 64 2-day ponds, both of which contain 1500 m^3 of growth volume per pond. The total facility culture volume is 114,000 m^3. Each PBR has 250 m^2 of lit area and each pond has 10,000 m^2 (1 ha) of lit area, yielding a total lit growth area for the facility of 92 ha. As shown in Appendix A of the SI, the 111 ha facility is a rectangular land plot with 11 terraces built into a natural 1% slope that enable gravity-fed volume transfers. Contrary to previous land assessments [41], this design is suitable for natural grades steeper than 1%; steeper slopes require more site preparation, but allow faster volume transfers and/or smaller pipe sizes. The upper terrace contains a parking lot, office and lab facilities, a seawater reservoir, nutrient stock tanks, and PBRs. New seawater is acquired from an offshore water intake located 5 km from the Texas site and a saline aquifer well (17 m depth) in the Hawaii location. Each of the main terraces contains one 1-day pond and four 2-day ponds on either side of the access road.

Each day, 50% of all PBRs are harvested and combined to inoculate the 1-day ponds. The 1-day ponds are drained entirely each day and used to inoculate the 2-day ponds, half of which are harvested daily. As described in Appendix B of the SI, the daily volume transfers are initiated by harvesting the lowest main terrace — the algal sludge is sent to downstream processing and the supernatant is discharged. Once the lowest ponds are emptied, the second-lowest terrace is harvested — the algal sludge is sent to downstream processing and the supernatant is sent to the lowest terrace for reuse. This process is repeated as the harvesting process moves uphill. New seawater is supplied from the reservoir as needed. All cases require roughly 27,000 m^3 of new seawater each day, which represents roughly 75% daily seawater recycling. Salinity increases as the seawater is reused (due to evaporation at 2.8% per day [42]) and the discharged seawater from the lowest terrace contains 39 g of salt/L, which is non-inhibitory for algal growth (authors' experience with these species).

2.3. Case descriptions

Ten distinct cases were constructed and evaluated in two geographical locations, yielding a total of twenty case studies. The ten cases are summarized in Table 1, illustrated in Fig. 1, and Appendix C of the SI contains a description of the detailed operations for each process. There are two company-specific processes included in this study: 1) the Valicor thermochemical conversion process that converts wet biomass into biocrude, a carbohydrate-rich aqueous phase, and dry residual biomass [37], and 2) the OpenAlgae extraction process that utilizes a semi-permeable membrane to recover lipids from an algal slurry [29,39]. The biomass productivity and composition for both species is based directly on experimental measurements from large-scale cultivation as described by Huntley et al. [10]. The remainder of the data is modeled. Some processes were used during large scale production or experimentally tested for proof of principle, but lack published experimental data: natural settling, centrifugation, ring drying, belt filter press, POS hexane extraction, and the Valicor thermochemical