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Assessment of algal farm designs using a dynamic modular approach

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ABSTRACT

The notion of renewable energy provides an important mechanism for diversifying an energy portfolio, which ultimately would have numerous benefits including increased energy resilience, reduced reliance on foreign energy supplies, reduced GHG emissions, development of a green energy sector that contributes to economic growth, and providing a sustainable energy supply. The conversion of autotrophic algae to liquid transportation fuels is the basis of several decades of research to competitively bring energy-scale production into reality; however, many challenges still remain for making algal biofuels economically viable. Addressing current challenges associated with algal production systems, in part, requires the ability to assess spatial and temporal variability, rapidly evaluate alternative algal production system designs, and perform large-scale assessments considering multiple scenarios for thousands of potential sites. We introduce the development and application of the Algae Logistics Model (ALM) which is tailored to help address these challenges. The flexible nature of the ALM architecture allows the model to: 1) interface with external biomass production and resource assessment models, as well as other relevant datasets including those with spatiotemporal granularity; 2) interchange design processes to enable operational and economic assessments of multiple design configurations, including the integration of current and new innovative technologies; and 3) conduct trade-off analysis to help understand the site-specific techno-economic trade-offs and inform technology decisions. This study uses the ALM to investigate a baseline open-pond production system determined by model harmonization efforts conducted by the U.S. Department of Energy. Six sites in the U.S. southern-tier were sub-selected and assessed using daily site-specific algae biomass productivity data to determine the economic viability of large-scale open-pond systems. Results show that costs can vary significantly depending on location and biomass productivity and that integration of novel dewatering equipment, order of operations, and equipment scaling can also have significant impacts on economics.

1. Introduction

Biofuels provide a critical component in a renewable energy portfolio, primarily because of the growing demand for sustainable, renewable, and reduced-emission liquid transportation fuels. Autotrophic microalgae provide a promising alternative to conventional fossil fuels in part due to their versatility in growth media and growing conditions, the variety of strains available to satisfy locally-available resources and environmental conditions [1], their high-density growth per unit area [2], high lipid content [3], and their ability to provide a variety of different fuel end-products including drop-in fuels [4]. In addition, a number of key policy issues are addressed including reductions in GHG emissions [5], wastewater remediation [6–8], potential non-compete with food resources [9], increased national energy independence and security, and strengthening rural economics and the green energy market. Microalgae processing and conversion can also produce valuable co-products, including ethanol, methane, fertilizer, livestock feed, and co-firing [10], though it should be noted that these characteristics are highly dependent upon the strain of microalgae, how it was grown, and the processes used for harvest and dewatering. Third generation feedstocks or “energy crops,” which include microalgae, have been shown to provide reduced emissions relative to diesel-derived petroleum sources while remaining non-toxic and biodegradable [11–13].

These benefits, however, come with challenges of sustainable resource use, in terms of water, land, CO_2, nutrients, and required infrastructure [14–17]. Significant technological and engineering challenges need to be addressed in order to achieve required energy-scale production as well as making this energy resource economically feasible and cost competitive with petroleum-based fuels [2,18]. Nonetheless, under the U.S. Energy Independence and Security Act (EISA) of 2007,

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the Renewable Fuels Standard (RFS) mandates the production and use of 36 billion gallons per year (BGY) of renewable fuels by 2022, of which 5 BGY are to be derived from advanced fuels and biodiesel [19].

One of the challenges of assessing algal production systems is the temporal and spatial variability of biomass productivity and the impact that this variability has on the economics of converting microalgae to biofuels. Evaluating long periods of record (~30-years) allows for the consideration of extreme meteorological events and patterns which directly influence the economics of biomass production. There have been numerous studies investigating the feasibility of commercial microalgae production facilities, but a majority of these studies are limited to a specific location or use broad biomass productivity assumptions to perform regional assessments. To our knowledge, existing techno-economic assessment (TEA) models lack the ability to efficiently and inherently assess algal production systems around local variability. This paper describes the Algae Logistics Model (ALM), an integrated, techno-economic, spatiotemporally-aware system dynamics and data management system that is comprised of a design configuration of operation modules that evaluate the capacity, throughput, mass balance, energy requirements, performance, and economics via capital expenditures (CapEx) and operational expenditures (OpEx) at fine spatial and temporal scales. The ALM stems from another modeling effort, the Biomass Logistics Model (BLM) which focuses on terrestrial feedstock supply systems [20]. The ALM is built using a modular framework, thus providing the required analysis flexibility to address current challenges by evaluating a suite of design, equipment, and operation scenarios. The flexible nature of the ALM architecture allows the model to: 1) interface with external biomass production and resource assessment models, as well as other relevant datasets including those with spatiotemporal granularity; 2) interchange design processes to enable operational and economic assessments of multiple design configurations, including the integration of current and new innovative technologies; and 3) conduct trade-off analysis to help understand the site-specific techno-economic and inform technology decisions. Furthermore, with the ability to interface with advanced biophysical-based production and resource assessment models such as those found in the Biomass Assessment Tool (BAT), thousands of sites can be evaluated with relatively little effort [13,15,16].

Several prior feasibility studies have been performed using microalgae for bioenergy production [3,21,22]. These studies assessed microalgae cultivation for biofuel and biogas production using available engineering and biological technologies. The economic viability of the systems varied based on biomass productivity and the algal production system design assumptions. Assessments were limited to a single site and therefore did not consider the spatial constraints of the proposed design. Recent modeling efforts demonstrate various pathways for cultivating and converting microalgae to bioenergy [13,22–26]. These assessments address many of the existing challenges associated with making microalgae a viable resource for bioenergy production.

Richardson et al. [24] performed an assessment using a Monte Carlo simulation that relied upon several key input variables, including evaporation rate, water cost, water depth, days of operation, cost of algal growth medium, carbon dioxide, algae production rate, and algal oil content. The assessment included two hypothetical scenarios of commercial-scale microalgae farms. The first scenario used data collected from literature, while the second scenario used data collected from a 0.2-ha experimental algal farm in the Southwestern United States. Both scenarios assumed 405 ha of open pond with microalgae biomass productivity ranging from 20–30 g/m^2-day to 18–25 g/m^2-day and a lipid content ranging from 20–40% to 40–60%, respectively. “Scenario 1” assessed a production window of 10 months/year with an average production of nearly 21,400 L_{oil}/ha-year, while “Scenario 2” assumed a continuous growth environment producing over 42,600 L_{oil}/ha-year. The study concluded that costs are highly variable due to inherent risks in producing biofuel from microalgae.

Zamalloa et al. [25] performed a techno-economic assessment using microalgae to produce methane to generate electricity through anaerobic digestion. Many capital and operating expense assumptions were derived from the Benneman and Oswald [27] report. Three studies using constant daily productivity were conducted to assess the viability of algal biomass as a resource for biogas production. Sensitivity analysis was performed considering several factors. While the study did not investigate microalgae for biofuel, it is important to recognize other pathways for producing energy from microalgae, especially using methods that could be integrated into algal farms to produce power and help reduce overall costs of producing algal biofuels.

In 2011, Davis et al. [23] performed a techno-economic study on autotrophic microalgae for open-pond and photobioreactor systems. The study used a process simulation model to perform mass and energy balances to evaluate the two algal production systems. A top-down approach was taken by first setting a biofuel production goal and then, based on biomass productivity and farm operating assumptions, determining the infrastructure required to produce the biofuel target. For the open-pond scenario, a steady-state simulation was performed assuming a daily algae biomass productivity of 25 g/m^2-day with a lipid content of 25% and an operation window of 330 days per year. The process simulation model was used to simulate a microalgae facility producing 10 MM gal/year of biofuel requiring a facility footprint of over 2900 ha, with an open-pond area representing approximately 1950 ha of the facility total. The study determined that triacylglycerol (TAG) could be sold for $8.52/gal and that the price could be further reduced by using co-products onsite or selling them in the open-market.

Sun et al. [26] performed a comparative analysis of existing studies that explored the cost of producing TAG. The comparative analysis included U.S. DOE national laboratories, industry, and academia. These studies included a diverse range of assumptions and end products. As a result of this diversity, the cost associated with obtaining TAG varied significantly. Sun et al. used a normalized set of input assumptions for the previous studies and was able to reduce economic variability with cost ranging from $10.87/gal to $13.32/gal.

Recently, the U.S. DOE's Bioenergy Technologies Office began an initiative to harmonize existing modeling efforts across its national laboratories [28]. Existing techno-economic, resource assessment, and life-cycle analysis models were coordinated to establish a conservative baseline algal production system design. The harmonized effort enabled quantification of cost, greenhouse gas emissions, and resource requirements using consistent infrastructure and operating assumptions from cultivation through biodiesel production. In-depth discussion of the original techno-economic, resource assessment and life-cycle models can be found in Davis et al. [23], Wigmosta et al. [13], and Frank et al. [29], respectively. The harmonized effort assessed several scenarios for the 5 BGY goal including a steady state and seasonal productivity scenario. Potential suitable algal farms within a region around the U.S. Gulf Coast were clustered and the average productivity was assessed. The cost of biodiesel between clusters varied as much as $3.50/gal, demonstrating the direct impact spatial variability can have in algal production systems. Another assessment investigated the impacts of using steady-state productivity versus dynamic variability driven by seasonal climatic conditions. Assessments using the seasonal scale increased the cost of biodiesel by nearly $1.00/gal, therefore demonstrating the impact of temporal variability within algal production systems.

While these studies contribute to overcoming existing barriers in microalgae fuel production, they do not address the temporal and spatial dynamics at the fidelity needed to assess large numbers of individual algal production system sites, such as the ~90,000 potential unit farm pond sites identified by Wigmosta et al. [13]. Understanding the impacts of temporal and spatial variability on production cost is important to the viability of algal biofuel production. Furthermore, the ability to assess and integrate new processes and technologies for assessment into an algal production system design can be challenging. The ALM presented in this paper provides a mechanism to address temporal and spatial