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An integrated assessment of location-dependent scaling for microalgae biofuel production facilities

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ABSTRACT

Successful development of a large-scale microalgae-based biofuels industry requires comprehensive analysis and understanding of the feedstock supply chain—from facility siting and design through processing and upgrading of the feedstock to a fuel product. The evolution from pilot-scale production facilities to energy-scale operations presents many multi-disciplinary challenges, including a sustainable supply of water and nutrients, operational and infrastructure logistics, and economic competitiveness with petroleum-based fuels. These challenges are partially addressed by applying the Integrated Assessment Framework (IAF) – an integrated multi-scale modeling, analysis, and data management suite – to address key issues in developing and operating an open-pond microalgae production facility. This is done by analyzing how variability and uncertainty over space and through time affect feedstock production rates, and determining the site-specific "optimum" facility scale to minimize capital and operational expenses. This approach explicitly and systematically assesses the interdependence of biofuel production potential, associated resource requirements, and production system design trade-offs. To provide a baseline analysis, the IAF was applied to a set of sites in the southeastern U.S. with the potential to cumulatively produce 5 billion gallons per year. The results indicate costs can be reduced by scaling downstream processing capabilities to fit site-specific growing conditions, available and economically viable resources, and specific microalgal strains.

1. Introduction

The global demand for energy is projected to increase 26% by the year 2035 because of emerging economies and population growth centers [1]. The demand for liquid transportation fuels is expected to increase the most among energy sectors, placing more pressure on conventional and unconventional petroleum-based fuels. This demand makes it more likely that balance-of-trade issues in the global market will lead to price instabilities, supply interruptions, and more challenges to national security (both direct and indirect) [2]. Chu and Majumdar [3] call for a new industrial revolution where sources of energy are affordable, accessible, and sustainable. They point to alternative energy innovations that can displace conventional sources and make the energy system more robust through greater diversity of energy sources.

One alternative liquid transportation fuel is sourced from photoautotrophic microalgae, where high fuel yields per unit area of land can be achieved using existing/waste sources of CO_2 and a range of water types and sources. Microalgae can be used in many different fuel conversion pathways, such that they can be tailored to produce a variety of drop-in fuels. A large body of research surrounds microalgae production—from microbiology and bioinformatics to system operations and life-cycle analysis to social impacts and policy. All of this research seeks to understand the potential viability and sustainability of a microalgae-based biofuels industry in terms of resource-use, feedstock demand, net energy production, system benefits, and economics.

Developing a large energy-scale microalgae-based biofuels industry requires a comprehensive analysis and understanding of the feedstock supply chain, including 1) facility siting and design; 2) resource requirements, availability, and recycling; 3) strain selection and methods of

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growth; 4) harvesting and dewatering; 5) transport logistics; and 6) upgrading the feedstock to different fuel pathways. Such analyses, many of which are addressed in this paper, are required to evaluate 1) the specific site conditions such as suitable land availability and cost; 2) local meteorology and climate considering multi-scale temporal trends and variability that affect feedstock growth; 3) available resources such as water, CO_2, power, transportation infrastructure, and the costs and logistics associated with each required resource; 4) the best performing microalgae strains for the climate, water chemistry, and ultimate fuel conversion pathway; and 5) the site design and function, including the methods of cultivation, harvesting, dewatering, extraction, nutrient and water recycling, blowdown requirements, net energetics, and economics of the operation.

Evaluation of these factors in microalgal biofuel enterprise design requires explicit consideration of spatial and temporal variability in feedstock production as a function of the local weather variability on hourly, daily, seasonal, annual, and even decadal time scales. The evolution from pilot- to energy-scale operations presents many multi-disciplinary challenges beyond microbiology and chemical engineering, including identifying and establishing sustainable resource supplies, operational and infrastructure logistics, and process engineering, all of which drive toward economic competitiveness with petroleum-based fuels [4–10].

This study describes and demonstrates a new modeling capability – the Integrated Assessment Framework (IAF) – that directly integrates spatiotemporal-based resource analysis with techno-economic analysis (TEA) capabilities in a high-performance environment. This integration provides the ability to 1) assess variability and uncertainty in unit area biomass production over time and space; and 2) evaluate the effects of site-specific facility scaling on capital and operational expenses. This study also demonstrates the mutual benefit and modeling advancements that come from integrating a suite of resource assessment models with a techno-economic model.

1.1. Resource assessment

A major research area defined by the US DOE and the National Resource Council regards further understanding of resources around microalgae biofuel production potential and requirements to support sustainable production [5,11]. This notion is not new, however, as resource assessments were conducted under the US DOE Aquatic Species Program (1978–1996) in order to understand the potential future and viability of microalgal-based biofuel production in the United States [5,12–15]. Maxwell and Folger [12] stressed the intrinsic interconnection between available natural resources, environmental conditions, and the future success and sustainability of aquatic biomass production systems. Resource assessment includes the resource potential (e.g., biomass/lipid production rates and quantity of production per unit time and area), the resource demand (e.g., suitable land area; water type, quality, source, supply, and transport; availability and transport of nutrients and CO2; soils and geology; and existing competition for resources), and the risks that impact the resource supply or demand (e.g., droughts, floods, earthquakes, infrastructure availability, supply disruptions, temporal availability). Many prior studies established and demonstrated resource assessment from which this research is directly or indirectly built upon [8–10,12–21]. Resource assessment used in concert with TEA helps to identify the most probable and sustainable locations for microalgae production facility development using the best available knowledge of resources, as described above, and the economics driving required resource supplies, production, and product delivery.

1.2. Techno-economic analysis

TEA is a valuable approach for identifying and understanding key cost and subsequent technology constraints that potentially affect the commercialization and success of a microalgae biofuel industry. TEA is effective for modeling the process design, performance, and resulting costs, as individual components of a facility or enterprise, thus enabling a measure of performance relative to cost among various technologies and design scenarios. However, as noted by Pienkos et al., [22] TEA is a conceptual process to understand how system designs impact performance and costs. An increasing number of TEA studies have addressed the feasibility of commercial microalgae production with different cultivation and process designs, harvesting, dewatering, conversion pathways, and assumptions [6–8,16,23–30].

For the TEA studies that compared the economics of an open pond to a photobioreactor system, the open pond systems were significantly less expensive and growth rate and lipid content were the major drivers for improved economics. However, as noted by a joint model and parameter harmonization study by Argonne National Laboratory (ANL), the National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL) [8], increased productivity yields and lipid content alone would not lower costs to the point of being cost-competitive with petroleum fuels and meeting established greenhouse gas targets. This suggests the need to inspect engineering and operational details [25], including site and process engineering (e.g., pond liners, soil compaction and plugging, system energy and resource efficiencies) and evaluate the use of different algal strains at different locations and for different seasons of the year [16,21].

The variability of algal biomass production over space is well represented in Wigmosta et al. [18], Quinn et al. [19], and ANL/NREL/PNNL [8] and represents dominant production factors of light and temperature; however, these studies place less emphasis on production variability over time. A majority of the referenced TEA studies are set up and demonstrated at a single location, limited geographic domain, or use broad generalizations to represent large geographic areas. Additionally, many of these studies use a time-invariant steady-state production condition or mean annual production value and neglect production variability driven by environmental forcings over time. However, the literature emphasizes the importance of spatially and temporally explicit calculations of biomass production and its intrinsic linkage to production cost [6–8,16,19,29].

1.3. Scaling

The notion of scaling plays a central role in production theory and is critical in most industries where an understanding of how the economies or diseconomies of scale and diminishing returns affect the cost of the product being produced. The ideal efficiency determines, among the many variables in an operation, when the minimal cost of unit inputs provides the maximum amount of unit financial return. Additional factors beyond input costs and output gains, including environmental, social, and policy needs, must also be evaluated.

Within the energy sector, effective scaling approaches have been applied in the petroleum and power generation industries [31,32], and a large body of work has ensued for the terrestrial biofuels industry [33–36]. Experience within these other industries suggests that with each feedstock/strain, harvesting, processing, and conversion pathway, a unique combination of process specific unit scaling, which culminates to the overall facility, identifies an ideal site-specific biomass production capacity which drives toward efficiencies and optimal gains. In addition, the influence of time (i.e., duration and magnitude of feedstock supply rates) and space (i.e., geographic distribution and quantity of production and processing facilities) has been demonstrated to be variable and suggests there may also be an impact on scaling [6–10,16,19,21,29].

The ideal scaling of an open pond microalgae production facility depends on the type or strain of microalgae grown; the media type; pond depth; nutrient application; mixing; the process used for harvesting, dewatering, and recycling of water and nutrients; and the fuel