ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Financial tradeoffs of energy and food uses of algal biomass under stochastic conditions

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HIGHLIGHTS

- Stochastic financial analysis of algal food and energy pathways.
- Fishmeal substitute outperforms all other product options, even under uncertainty.
- Fuel and crop substitutes require reductions in CAPEX and OPEX to be viable.
- Multimodal strategies increase product revenue, but high CAPEX lowers returns.
- The impacts of several technology, economic and policy scenarios are explored.

ARTICLE INFO

Keywords:
Algae
New food technology
Biofuels
Techno-economic analysis
Financial forecasting
Food-energy nexus

ABSTRACT

The industrial cultivation of microalgae can produce oil and protein rich biomass at areal yields higher than those of conventional agriculture. Given that algae has been demonstrated as both a potential biofuel and a food product, it is important to consider the environmental and economic tradeoffs associated with these uses. Here we evaluate the financial value of capital options for three processing strategies that produce food and fuel from algae. We show, in stochastic price regimes for production inputs and outputs, that the greatest returns are achieved when algal biomass is valorized as a high value fishmeal replacement. A co-production technology strategy that valorizes extracted oils as fuel and residual biomass as fishmeal replacement can enable the economic production of a renewable biofuel. Consistent with other studies, fuel-only production remains uneconomical, but becomes preferred if a low value commodity crop substitute is considered as the rendered food product. Potential improvements in capital and operational costs to enable economic production of fuel and low-value food are explored. Multimodal biorefineries ensure continued production during periods that are economically unfavorable with a single-mode approach, but have lower returns due to larger upfront capital investment. An analysis of a biorefinery with fuel, food, and coproduction modes demonstrated that mode selection was mostly influenced by output product prices when food and energy prices were competitive. Nitrogen fertilizer prices had a moderate influence on mode selection, while other inputs (phosphorus, electricity, natural gas) had negligible influence. The application of a carbon tax places a penalty on food production, but improves returns when renewable electricity is utilized in production. This analysis demonstrates an approach for evaluating financial tradeoffs at the food-energy nexus under uncertain market conditions.

1. Introduction

Energy, food, and water security are critical to meet sustainable development goals [1]. These three sectors are largely interlinked through agriculture where rising demand for bioenergy and food crops places pressure on land availability and water resources. Achieving goals in one sector of the energy-food-water nexus is likely to put pressure on the other two. For example, increasing demand for liquid fuels derived from terrestrial biomass can increase demand and prices for all crops, leading to impacts on agricultural land, food security, and water use [2–4]. Further, the transition from fossil to renewable energy resources has the potential to impact food production and water use in

Abbreviations: CAPEX, capital expenses; CHG, catalytic hydrothermal gasification; CHP, combined heat and power; DAP, diammonium phosphate; DBF, direct biomass to food; HTL, hydrothermal liquefaction; LEA, lipid-extracted algae; LCA, life cycle assessment; NREL, National Renewable Energy Laboratory; TEA, technoeconomic assessment; WE, wet extraction

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http://dx.doi.org/10.1016/j.apenergy.2017.08.060
Received 11 November 2016; Received in revised form 6 May 2017; Accepted 11 August 2017

numerous ways. Notably by lowering the cost and emissions associated with energy-intensive novel food technologies that may avoid some of the land and water use impacts of conventional agriculture.

Industrially cultivated algal biomass is an example of such a technology. Historically, much of the attention given to algae stemmed from its potential as a biofuel and that it did not compete with conventional food crops for agricultural land [5]. Furthermore, some species of algae can be cultivated using seawater and brackish water from saline aquifers as opposed to freshwater-demanding conventional crops. Algae can also grow on various waste streams such as CO_2 emissions and wastewater, potentially providing valuable mitigation services. However, algal cultivation requires significant capital expenditures and energy inputs, which have challenged the production economics and life cycle performance of algal fuels especially during times of low energy prices [6].

Alternatively, algal biomass could be used as a food source [7,8], either whole, or as defatted co-product from biofuel production. Nutritional compositions of algal biomass vary by species, but algae generally exhibit higher protein levels than most commodity crops [9]. Feed trials have shown that algae can be substituted for corn, soy and oil seeds in the diets of various livestock [10–14]. Algal biomass can also be rich in amino acids such as methionine [9] and lipids such as omega-3 fatty acids [15], both essential elements of aquaculture diets [16]. As such algae has been demonstrated as a substitute for commodity crops and fishmeal in the diets of salmon, carp and shrimp [17,18].

Given the variety of algal strains, cultivation conditions and post-cultivation processing pathways, algal biomass has the potential to deliver a wide variety of nutritional and energy products, each with tradeoffs in capital costs, operational expenses, opportunity, risk, and environmental impact. Certain food product markets have the potential to be more lucrative than liquid fuels. In particular, fishmeal prices have surpassed \$2,000 USD t^{-1} in recent years following a sharp decline in production from a peak in 30.2 Mt in 1994 to levels ranging from 10 Mt y^{-1} to 20 Mt y^{-1} throughout the 2010's [19]. Such market conditions may be favorable to algae, given previously evaluated analysis of cultivation economics [20–22]. Furthermore, recent declines in energy prices have stalled investment into algal-sourced energy and prompted several commercial ventures to pivot toward producing higher value food products, nutraceuticals, cosmetics, and other specialty products. In addition, the use of algae as a food product in lieu of conventional crops may reduce water use, land-use change (LUC), and LUC emissions [23].

Previous techno-economic assessments of algae production have focused primarily on fuel rendering pathways [6]. Several have explored the use of co-products to enable economic production of biofuels using scenario analysis [20,24] or probabilistic methods [22,25]. However, large changes in commodity prices over recent years have demonstrated the need for a more comprehensive evaluation of the financial and operational performance of novel bioenergy and bioproduct technologies. To capture the uncertainty associated with markets, stochastic methods are being used in technological assessments of bioenergy pathways [26–28]. Specific policy scenarios have also been evaluated using stochastic methods [29]. Such analysis is beneficial in mitigating risk and guiding investment by identifying potential challenges and opportunities.

Here we apply stochastic price forecasts to several mutually exclusive design options of an integrated algal farm and biorefinery to determine the financial tradeoff between food and fuel uses of algal biomass. These price forecasts include major production inputs (energy, fertilizer) and outputs (food, diesel fuel). Further, our analysis employs a hedonic pricing method [30,31] to estimate price pathways for a high-value fishmeal substitute and a conventional crop product substitute. We also explore operational strategies that maximize gross profit through technology switching [32]. Finally, we estimate the financial performances of these pathways under alternative financial and policy scenarios to elucidate potential strategies for success.

2. Materials & methods

2.1. Modeling framework and general approach

A computational framework that synthesizes unit process models, techno-economic assessments, stochastic price forecasts based on historical market behaviors, and life cycle emissions factors was used to model potential configurations for an integrated algal farm and biorefinery. Capital costs and process requirements for algal cultivation and processing pathways were used to develop a technology-flexible financial and operational model in a Python 3.5 environment. Our analysis evaluates facility performance over a 30-year discounted time frame with quarterly time steps. We explore the impact on profitability and operational behavior by using stochastic simulations of 1,000 price pathways in inputs (ammonia, diammonium phosphate [DAP], electricity and heat) and product substitutes for targeted markets (fishmeal, food crops, and diesel fuel). This is used as a basis for a scenario analysis focused on the different target products, capital costs, and a carbon tax. Experiments with the baseline case, using 10,000 simulated price pathways, did not yield significantly different results. Selection of technologies, markets, prices, and parameters required some subjective decisions by the authors. We use scenario analysis to demonstrate the impacts of some of these decisions and find that our methodology is sufficient to demonstrate financial tradeoffs between food and energy uses of algal biomass.

For the illustrative purposes of this study we evaluate the production of food and/or fuel under two algal target food product cases (Fig. 1): (1) fishmeal substitute of high value; and, (2) a lower value general commodity crop product representing broader markets (nutritional specifications defined in Table 1). Within each of these cases, we compare the financial performance of seven different mutually exclusive capital investment scenarios: one for each processing technology in exclusive use; and, for all four potential combinations of each technology.

2.2. Target product and production pathways considered

The fishmeal and commodity crop target products are respectfully representative of a high price regime influenced by supply constraints and a low price regime where technology progress is depressing

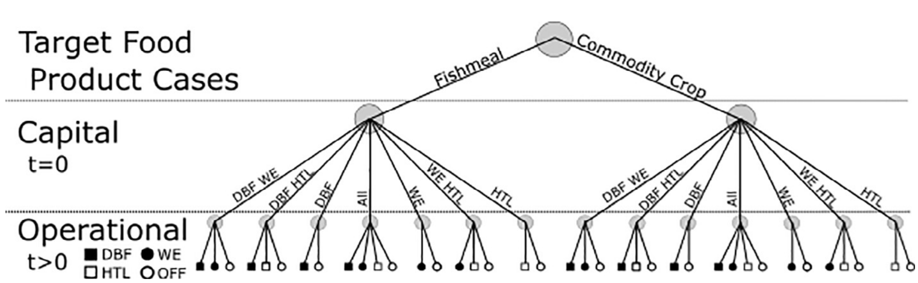

Fig. 1. Decision tree showing evaluated options in this study. Performance of different capital options, each with a different combination of operational modes (Direct Biomass to Food – DBF; Wet Extraction – WE; Hydrothermal Liquefaction – HTL; and an offline mode – OFF) is evaluated under two distinct target food product cases. When possible modes are selected to maximize profits in a given period (t).