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Cost structures and life cycle impacts of algal biomass and biofuel production

By

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A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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Abstract

Development and extraction of energy sources, energy production and energy use have huge economic, environmental and geopolitical impacts. Increasing energy demands in tandem with reductions in fossil fuel production has led to significant investments in research into alternative forms of energy. One that is promising but yet not commercially established is the production of biofuel from algae. This research quantitatively assessed the potential of algae biofuel production by examining its cost and environmental impacts.

First, two models developed by the RAND corporation were employed to assess Cost Growth defined as the ratio of actual costs to estimated costs, and Plant Performance defined as the ratio of actual production levels to design performance, of three algal biofuel production technologies. The three algal biofuel production technologies examined to open raceway ponds (ORPs), photobioreactors (PBRs), and a system that couples PBRs to ORPs (PBR-ORPs). Though these analyses lack precision due to uncertainty, the results highlight the risks associated with implementing algal biofuel systems, as all scenarios examined were predicted to have Cost Growth, ranging from 1.2 to 1.8, and Plant Performance was projected as less than 50% of design performance for all cases.

Second, the Framework the Evaluation of Biomass Energy Feedstocks (FEBEF) was used to assess the cost and environmental impacts of biodiesel produced from three algal production technologies. When these results were compared with ethanol from corn and biodiesel from soybeans, biodiesel from algae

produced from the different technologies were estimated to be more expensive, suffered from low energy gains, and did not result in lower greenhouse gas emissions.

To identify likely routes to making algal biofuels more competitive, a third study was undertaken. In this case, FEBEF was employed to examine pinch-points (defined as the most costly, energy consuming, greenhouse gas producing processes), in three algal production and fuel conversion scenarios, and then to estimate the improvement to cost and environmental impacts of proposed solutions to the pinch-points. These results illuminated significant opportunities to improve the economics and environmental impacts from producing algal biofuels produced in ORP, PBR, and PBR-ORPs. No single solution examined appeared to be sufficient to reduce the cost of fuel energy from algae to a competitive level with current petroleum diesel prices (4.20 \$/gal, ca. \$28/GJ). However, if multiple pinch-points are overcome, e.g., simultaneous increases in (1) radiation use efficiency and (2) oil content or simultaneous decreases in (3) irrigation, (4) harvesting, (5) labor and (6) PBR costs are achieved then low Fuel Energy Costs (the ratio of total production and conversion costs to total energy available in the fuel) and low Total Energy Costs (the ratio of total production and conversion costs to total energy available in the fuel and co-products) are possible; with estimates ranging from 48 to 11 \$/GJ.

Chapter 1. Introduction

With an ever increasing demand for crude oil and diminishing levels of growth in oil supply, the world oil markets are expected to continue to tighten, leading to higher oil prices (EIA, 2011). While efforts to offset the rising oil prices in the United States include opening up Arctic National Wildlife Refuge (ARWR) for drilling crude oil and continued deep water drilling for crude oil in the Gulf of Mexico, these options are complicated by environmental concerns (Joyce, 2010). These drilling options also require years of planning, investment and development to lead to meaningful supply increases and consequential price decline. The combined need for cheap fuel energy sources along with concern over the environmental impacts, like global climate change, related to continued use of crude oil for transportation fuel, has led to the promotion of transportation fuels from biomass. These fuels, known as biofuels include, ethanol and biodiesel produced from crops like corn and soybeans. Yet, first generation biofuels production capacity cannot meet the energy needs of the United States and have been criticized for having low energy gains and for increasing food costs (Hill et al. 2006). Second generation biofuels produced from cellulosic crops suffer from higher conversion costs, claims of low energy gains, and claims that biomass production on arable land for fuels leads to increased food prices (Sanhueza, 2008). In contrast, algal biofuel production is thought to have huge potential for pushing the United States toward energy independence because of the potential for high productivity of energy dense fuels on non-arable land with non-potable water sources (Wijffels and Barbosa, 2010).

The potential and difficulties of biofuel production from algae were studied intensely once before in the United States, from 1976-1996, under the US Department of Energy's Aquatics Species Program. That research program concluded that the potential for algae was great, but that the cost of large-scale production was prohibitive given the low cost of crude oil (Sheehan et al. 1998). Fifteen years later, with ever increasing oil prices, with the need to combat global climate change, and with advances in biotechnology, supporters claim that the cost of algal biofuels may not be prohibitive at the commercial scale (Chisti, 2007; Rodolfi, 2008). This dissertation serves to evaluate the potential cost and environmental impacts of commercial algal biofuel production, and therefore attempts to quantify the ability of algal production technologies to catch up with its potential.

Objectives

The first objective (detailed in Chapter 2) of this dissertation was to evaluate and compare the Cost Growth and Plant Performance of three proposed algal production pathways. The second objective (detailed in Chapter 3) was to complete and compare techno-economic assessments (TEAs) and life-cycle assessments (LCAs) of the same three algal production pathways along with biodiesel conversion. To provide context, the techno-economic and lifecycle analyses results for the three algal production and fuel conversion scenarios were compared to other terrestrial cropping systems modeled (corn, switchgrass, and Miscanthus) and conversion to ethanol and published literature estimates for soybeans conversion to biodiesel.

Completion of TEAs and LCAs led to the identification of economic and environmental pinch points in the production of algal biomass. Each scenario was broken down by into components (i.e. unit operations) that were related to cost, energy, and greenhouse gas (GHG) emissions. By accounting for total cost, energy, and GHG-emissions on a unit-operations basis, the most costly, most energy-consuming, and most GHG-producing unit operations were identified – these were then considered “pinch points.” It was critical to understand the nature of the barriers associated with those pinch points. To gain such an understanding, pinch-points were dissected to reveal the chemical, physical, or biological processes that underlie the barrier. Based on such an analysis, novel technical solutions for overcoming the pinch points were identified (detailed in Chapter 4) and estimates of the potential improvements in cost, energy return, and greenhouse gas emission yielded by such changes were made.

Dissertation organization

This dissertation is organized into five chapters. The first chapter contains an introduction, consisting of an explanation of the dissertation organization and objectives, and a literature review that serves to support the motivation behind this research, outlines gaps in the literature, and explains how this research addresses the gaps. The second chapter contains the manuscript “*Predicting the cost growth and performance of first-generation algal production systems.*” The third chapter contains the manuscript “*EIO-LCA Based Comparison of Algal Production Technologies,*” along with a detailed appendix explaining the structure of the model employed and providing key equations and assumptions embedded in them model.

The fourth chapter contains the manuscript “*Pathways forward for biodiesel production from algae.*” The fifth chapter contains conclusions derived from the three manuscripts, offers specific recommendations for future work, and discusses the outlook for algal biofuels in light of this work.

Literature Review

The Energy Information Administration has estimated that in the near term, liquid fuels will remain the largest source of energy worldwide, contributing more than 30% of the global marketed energy for the next 20 years (EIA, 2009). To help combat global climate change by reducing greenhouse gas emissions while meeting world-wide energy demands, petroleum based liquid transportation fuels will need to be replaced with renewable, carbon-neutral or carbon-negative fuels. Biodiesel from soybeans and ethanol, known as first generation biofuels, from corn grain, for example, reduce greenhouse gas emissions relative to the fossil fuels they replace by 41% and 12%, respectively (Hill et al., 2006). However, only 12% of the gasoline demand and 6% of the diesel demand would be met by converting all of the U.S. corn and soybean production to biofuels (Hill et al., 2006). The EIA (2007) estimated that 10% of the gasoline consumption could be replaced by biofuels only if the following conditions were met: (1) existing energy crops realized increased yields; (2) corn and soybeans were replaced or supplemented with cellulosic biomass or higher yielding oilseeds for second generation biofuels; and (3) cropland dedicated to bioenergy crop production were increased.

There are reservations about increasing the area of terrestrial crops intended for biofuel production because of unintended, harmful consequences on food security and environmental quality. Pimental et al., (2009) argued that any diversion of cropland to energy feedstocks ignores the need to reduce fossil fuel and land use and exacerbates malnourishment worldwide. Searchinger et al., (2008) argued using US cropland for biofuels would increase greenhouse gas emissions due to indirect land use changes. Sanhueza (2009) argued that energy crop production for biofuels increase greenhouse gas emissions and is partly responsible for food price increases. Sanhueza (2009) projected that increased bioenergy crop production could lead to other negative effects like loss of biodiversity and increased soil erosion and water pollution. Donner and Kucharik (2009) showed that increased corn-based ethanol production will likely prolong the bottom-water hypoxia in the Gulf of Mexico, and Costello et al. (2009) noted that moving from corn to cellulosic crops will decrease nitrate in the Mississippi, but not sufficiently meet EPA management targets for hypoxia in the Gulf. In light of these concerns for first and second generation biofuel feedstocks, algae are viewed as a promising feedstock alternative that enjoys potentially higher productivity per unit land area (Griffiths et al., 2009), allows for greater control of nutrient use, and presents little competition with food crops (Lardon et al., 2009).

Algae

Since the late 1970's, researchers have regarded algae as an ideal feedstock for biofuel production because it would not compete with food production and because it has the ability to use concentrated carbon dioxide from industrial sources

i.e., smokestacks (Lardon et al., 2009). Algae is also viewed as attractive because some algal species can achieve oil concentrations as high as 80% on a dry weight basis (Spolaore et al., 2006) thus delivering fixed carbon in a form more readily processed than lignocellulosic biomass. Algae can, under the appropriate conditions, produce more energy-dense biomass at faster growth rates than terrestrial plants, and algae can be harvested daily (Chisti, 2007; Gouveia and Oliveira, 2009). Algae have higher photosynthetic efficiencies than terrestrial crops which can translate into higher carbon dioxide capture and biomass accumulation. While terrestrial crops such as sugar cane only achieve photosynthetic efficiencies approaching 3.5% (Robertson, 1996), Zittelli et al., (2006) documented 9.4% photosynthetic efficiency for *Tetraselmis suecica* in photobioreactors and Melis (2005) reported increasing the photosynthetic efficiency of *Chlamydomonas reinhardtii* via mutagenesis five-fold, to over 15%. However, the actual photosynthetic efficiency and resulting carbon capture and accumulation observed in production of particular algal species can vary greatly depending on the type of culture system (Erikson, 2007; Borowitzka, 1999).

Cultivation

Numerous algal culture systems have been built or proposed as shown in Table 1. Other cultivation systems, e.g., for heterotrophic algae or hydrogen producing algae, are beyond the scope of this research. A discussion about the operation, expenses and challenges of the different algal culture systems helps to explain the motivation behind this research.

Table 1. Algal Culture Systems and Types

Systems	Types
Ponds	1) Large open 2) Circular with mixing 3) Open raceway
Closed Photobioreactors (PBR)	1) Tubular 2) Flat panel 3) Column
Emerging Technologies	1) Open thin-layer panels 2) Polymer bags 3) Immobilized beds

One of the simplest and lowest capital algal culturing systems is the large open pond. In Australia, large unstirred open ponds have been used to cultivate *Dunaliella salina* to commercially produce β -carotene (Shen, 2009) which is a nutraceutical that can sell for $\$54 \text{ g}^{-1}$ at retail. Large open ponds with depths of less than 50 cm have relatively low capital and maintenance costs but have problems with low productivity and contamination (Borowitzka, 1999; Shen, 2009). Circular ponds have been used in Japan and Taiwan to cultivate *Chlorella* sp. for β -carotene production (Borowitzka, 1999; Shen, 2009) and total biomass production varied 10-fold from 5.8 to 60 Mg/ha/yr (Moheimani and Borowitzka, 2006). Circular ponds with mixing arms have maximum diameters of 45 m and depths between 30 and 70 cm (Shen, 2009). Mixing is improved in circular ponds compared to large open ponds, but the challenges of contamination and low productivity remain, and in addition, these systems have scale-up problems (Borowitzka, 1999; Shen, 2009). Open raceway ponds have been used around the world to cultivate *Spirulina* sp. (Mexico

and Spain), *Spirulina platensis* (Spain and Israel), *Anabaena* sp (Spain), *Dunaliella salina* (Australia and Spain), *Phaeodactylum tricornutum* (Hawaii), and *Pleurochrysis carterae* (Australia) (Moheimani and Borowitzka, 2006) for products like β -carotene and other food supplements (Shen, 2009). Reported algal biomass productivity in open raceway ponds range twenty-fold, from 7 Mg /ha/yr to 135 Mg/ha/yr (dry weight basis, Moheimani and Borowitzka, 2006). Open raceway ponds with depths of 15-30 cm typically use paddlewheels agitation, thereby increasing mass transfer of CO₂ and light exposure of algae. However, all open air systems face challenges of maintaining sterility, low productivity and high harvesting costs due to low cell densities (Shen, 2009).

Shen (2009) reported cost estimates for the production of *Dunaliella salina* in open raceway ponds as \$26,000 dry Mg⁻¹ of algal biomass when optimized for intended for β -carotene harvesting, decreasing to \$3,500 dry Mg⁻¹ algal biomass for lipid harvesting, the difference in costs due to the low biomass yield realized when optimizing operating conditions to produce β -carotene. Chisti (2007) estimated \$3,800 dry Mg⁻¹ algal biomass production cost intended for biodiesel in an open raceway pond at annual production of 100 dry Mg year⁻¹ and due to economies of scale a reduced cost of \$600 dry Mg⁻¹ algal biomass at annual production of 10,000 dry Mg year⁻¹, implying an economy of scale sizing exponent, $n=0.4$, a number reflecting the relationship between cost reduction and corresponding facility size increases. Low sizing exponents are associated with large tanks, equipment with low surface area to volume ratios, and not with equipment that have high surface areas

like heat exchangers. Thus the assumption of such a low sizing exponent seems extremely optimistic. Chisti (2007) also noted cellular densities are approximately 30 times less in open raceways than in PBRs, which result in significantly higher harvesting costs in the open systems.

Beyond lower harvesting costs, PBRs offer additional benefits over open ponds including reduced contamination risks, large surface area to volume ratios, and greater control over temperature, pH, light exposure, and nutrients (Shen, 2009; Chisti, 2007; Borowitzka, 1999). Photobioreactors, constructed from either glass or plastic, are limited in diameter by light penetration through the dense algal culture (Shen, 2009; Chisti, 2007; Eriksen, 2008). Tubular PBRs may be configured in a number of ways and have reportedly achieved dry biomass productivities ranging from 70-150 dry Mg/ha/yr and photosynthetic efficiencies ranging from 1.3% to 8.1% (Shen, 2009; Erikson, 2008). Flat panel reactors are usually inclined or vertically aligned rectangular containers and have reportedly achieved biomass productivities ranging from 70-100 dry Mg/ha/yr (Shen, 2009; Erikson, 2008). Column reactors (bubble or CSTR) offer the best control over growth conditions, have high gas transfer rates, and mix most efficiently (Erikson, 2008). Column PBR cultures of *Tetraselmis* achieved a dry mass dry 138 Mg/ha/yr with photosynthetic efficiency of 9.6% (Shen, 2009). Although the productivity of PBRs is 2-3 times greater per unit surface area than for open ponds, the construction costs alone are 3.5 to 10 times higher per unit surface area (Shen, 2009), suggesting production prices even higher than those reported for open systems. Shen (2009) reported the cost of producing *S.*

almeriensis for biofuels in a 30 m³ tubular PBR system was \$34 per kg dry biomass. Grima et al., (2003) reported the production of *P. tricornutum* in tubular PBRs lead to a cost of \$32 per kg dry biomass. These numbers can be compared to those reported by Chisti (2007), who estimated \$2.95 per kg dry algal biomass production cost intended for biodiesel in PBRs at annual production of 100 dry Mg year⁻¹ and due to economies of scale a reduced cost of \$0.47 per kg dry algal biomass at annual production of 10,000 dry Mg year⁻¹ (again, n=0.4). They can also be compared to DOE target prices for terrestrial biomass cost of \$35 dry Mg⁻¹ or \$0.035 dry kg⁻¹. However, it is hoped that novel PBR designs and materials are likely to lead to radically lower production costs (Erikson, 2008).

A novel PBR-open pond coupled industrial sized production system was built in Hawaii that takes advantage of the sterility and high productivity offered by PBRs and the low capital costs of open ponds. Huntely and Redalje (2007) reported success with operating the two stage system that used photobioreactors to propagate *Haematococcus pluvialis* continuously and then harvest on a three day batch cycle from an open pond system with nutrient conditions set to stress the algae into producing oil or astaxanthin. Huntely and Redalje (2007) estimated the cost of producing algae oil with no improvements in the technology to be \$74 per bbl, and further determined that technological improvements could reduce the costs to \$51 per bbl. However, they relied on Benemann and Oswald (1996) techno-economic analysis (adjusted for inflation) for production costs. Their optimistic estimates were not based on this novel system's actual costs, though they reported

Spending 20 million (USD) over a four years on the construction and operation of the 2 ha facility, or approximately 35 times as much as their estimate for a large commercial system.

Other novel cultivation systems include polymer bags (Svoboda, 2007; Borowitzka, 1999). Bags used for in the aquaculture industry must be operated indoors and tend to be light limited and labor intensive with production costs ranging for \$25,000 dry Mg⁻¹ to \$600,000 dry Mg⁻¹ (Borowitzka, 1999). The Solix Company in Colorado is using a unique polymer bag system to cultivate algae for biofuels claimed an annual algal oil production capability near 14,000 L ha⁻¹ (Mascarelli, 2009).

The costs of algal production from emerging technologies like immobilized beds are difficult to estimate. Algae productivity could be higher and harvesting easier from immobilized beds but the challenges of high material costs; difficult scale-up and identifying the right algae for immobilized growth pose series barriers to the advancement of this cultivation system (Shen, 2009).

Mascarelli (2009) noted that despite \$1 billion injected into the algae to energy research, there are still barriers like those listed above to overcome before algal biofuels can compete economically with petroleum. Chisti (2007) previously argued that only the cost of producing (including harvesting) algae biomass is relevant factor in comparing production schemes like open raceways and PBRs, since the recovery of oil from algae and conversion to biodiesel is not impacted by

the production system. The National Algal Biofuels Technology Roadmap (2009) reported triglyceride production costs from ten different algal production scenarios ranging from \$2 per gallon ($\7.6 L^{-1}) to over \$40 per gallon ($\150 L^{-1}). Chisti (2007); Grima (2003) reported costs of biodiesel produced from algae cultivated in PBRs to be $\$2.8 \text{ L}^{-1}$ and $\$352 \text{ L}^{-1}$, respectively. This huge range of estimated production costs highlights the potential and challenges of algal biofuel production systems.

Al Darzins, of the algal biofuels program at NREL, recently stated that “ In the end, it’s all going to come down to economics and what it’s going to cost to produce this algal oil on a large, commercial scale on a dollar-per gallon basis,” (Mascarelli, 2009). Others, like Hill et al., (2006) implore that viable alternatives to petroleum, while being economically competitive, should yield positive energy returns, have quantifiable environmental gains, and be cultivated in ways that avoid affecting food supplies and prices. In the United States, the federal government established Renewable Fuel Standards with the Energy Independence and Security Act of 2007 established specific greenhouse gas emission thresholds for different types of renewable fuels, requiring a percentage improvement compared to a baseline of the gasoline and diesel. The EISA required a 20% reduction in Lifecycle GHG emissions for any renewable fuel produced at new facilities, a 50% reduction in order to be classified as a biomass-based diesel or advanced biofuel. As mandated by EISA the GHG emission assessments must evaluate the full life cycle emission impacts of fuel production including both direct and indirect emissions, including significant emissions from land use changes. Life cycle assessment is analytical tool that can

be utilized to identify and evaluate net energetics and environmental impacts of specific or competing processes (Liu and Ma, 2009). The current state of life cycle assessments for algal production systems is limited. A review of the current literature highlights algal biofuels estimated ability to meet the Renewable Fuel Standard rules and gaps in the research.

Life Cycle Assessments

Aresta et al., (2005) developed a software program, COMPUBIO, intended to compute the net energy of different algal production operations based on LCA approach and reported positive preliminary results for macro-algae production with a net energy gain of 11,000 MJ per dry ton of algae. Kadam (2002) sought to quantify the environmental benefits of virtual microalgae cultivation with flue gas input and subsequent co-firing with coal-fired electricity plant and determined that in four categories analyzed lower greenhouse potential and air acidification potential were lower with algal co-firing but depletion of natural resources and eutrophication potential were greater. Conversely, Lardon et al., (2009) completed a life cycle assessment of a virtual scenario of biodiesel production from microalgae and made comparisons of a low-nitrogen culture condition to oilseed crops. Though algae biodiesel production via open raceway ponds appeared as the worst option compared to the other crops in certain areas like global warming and ozone depletion, it had low eutrophication and land use impacts. Liu and Ma (2009) completed an LCA of microalgae-based fuel methanol and determined a positive energy gain of 1.24 and claimed the environmental impact load (computed from politically determined environmental targets and weightings based on the

Environmental Design of Industrial Products (EDIP) method which included the categories: global warming, acidification, nutrient enrichment, photochemical ozone formation, solid waste, and slag and ashes) of gasoline was 4.4 greater than microalgae-based fuel methanol. The great variability in current estimates for algal biomass and oil yields, production costs, and life cycle impacts for algal production scenarios is likely the result of a lack of a systematic approach to assessing each technology.

Feasibility Analysis

Given the unrealized production potential of algae with current technologies some researchers have sought to highlight and examine the technological challenges (Walker, 2009) and advancements that could serve to reduce costs and increase yields (Greenwell et al. 2009, Raetz, 2009). Wijffels et al. (2010) discussed the potential cost reduction of algal biomass production given advancements for ORP systems, tubular PBRs, and flat panel reactors. The sensitivity analysis performed by Wijffels et al. (2010) examined the cost reduction potential of free nutrients, lower energy needs, higher photosynthetic efficiencies, and changes in location on those systems and determined that even with those improvements producing algae only for biodiesel is not feasible. Raetz et al. (2009) kept the technical analysis to biosynthetic control, genetic engineering, strain selection, and improved PBR design and concluded these improvements would reduce the cost of biodiesel from algae but lack quantitative data to support that conclusion. Greenwell et al. (2009) examined harvesting and processing of biomass

and fuel conversion methods other than transesterification of algal oils to biodiesel including pyrolysis, cracking, catalysis and deoxygenation of fatty acids to make green diesel and also modeling approaches to optimize operation of systems, yields, financial modeling and risk analysis yet did not report any financial gains from improvements discussed.

Motivations

It is difficult to determine the actual impact of improvements in algal production systems on production costs and life cycle impacts. Furthermore, economists have assumed that in a free and open market the “best” technology will rightly out-compete the others; however, the market can behave absurdly and embrace on a technology inferior to other options (Pool, 1995). Though, individuals in the market had made rational and logical decisions according to “the best available information,” a weaker technology may get “locked in,” preventing other, superior technologies from entering the market (Pool, 1995). Thus, to avoid a case of Technological Lock-in with commercial algae production schemes, it becomes crucial to provide information for researchers, policy makers and investors of the cost structures and life cycle impacts, limitations and barriers of algal production technologies, and also the impacts of proposed technological advancements thought to remedy pinch points. Insight into algal production systems’ cost structures, including cost growth, life cycle impacts, and the impacts of proposed advancements can help to focus and avoid mistakes in allocating resources, proposing subsidies and decisions about commercialization and for making comparisons between competing alternative fuel systems.

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Chapter 2. Predicting cost growth and performance of first-generation algal production systems

Abstract

Algae are promoted as a promising feedstock for renewable chemical and fuel production, and multiple algae production scenarios have been proposed. While algae possess many favorable traits, there are still significant challenges to their commercial cultivation and harvesting. Estimates of the cost of algal production vary widely due to differences in assumptions regarding factors like technology costs, productivity, productivity improvements, and carbon dioxide credits. These differences in assumptions make meaningful comparisons between proposed algal production systems difficult. Furthermore, existing economic analyses have ignored the potential capital cost growth and under performance of early generation algal production plants, which together impact the preliminary unit cost of algal biofuels, which could affect investment decisions. The early performance of algal production facilities could have implications regarding the long-term promise of algal production systems. Therefore the goal of this work was to systematically compare the capital Cost Growth (ratio of actual to estimated cost), Plant Performance (ratio of actual performance to design), and Unit Cost Growth Factor (the ratio of Cost Growth to Plant Performance), of potential algal production pathways. Three production technologies were investigated, including 1) open raceway ponds (ORP), 2) tubular photobioreactors (PBR), and 3) systems coupling photobioreactors to open raceway ponds. All production technologies were analyzed under two scenarios, a “favorable case” and a “worst case.” The greatest Cost Growth (1.5 – 1.8) was estimated for PBR systems, while the lowest Cost Growth (1.2 – 1.4) was estimated for the ORP

systems and coupled systems. The lowest Plant Performance of nameplate capacity was estimated to be 13% for each system's worst case scenarios, while the highest Plant Performance of nameplate capacity was estimated to be 40% in the favorable case for ORP scenarios. These results imply that Unit Cost Growth for algal biofuels could range from 3 to 14 times current predictions, and illustrates there are large hurdles facing a biofuels technologies that have yet to be implemented at scale.

Keywords: algae, biofuels, renewable energy/chemicals

Introduction

In the near term, liquid fuels are expected to remain the largest source of energy consumed by humans worldwide, accounting for more than 30% of the energy marketed globally over the next 20 years (EIA, 2009). One approach to combat climate change is to replace petroleum based liquid transportation fuels with renewable, carbon-neutral or carbon-negative liquid fuels. Biodiesel from soybeans and ethanol from corn grain are first generation biofuels with reduced greenhouse gas emissions relative to fossil fuels (Huo et al., 2009, Wang et al., 2007), but both of these are limited in the amount of petroleum they can displace. For example, only 12% of the U.S. gasoline demand and 6% of the U.S. diesel demand are estimated to be achievable by converting all of the current U.S. corn and soybean production to biofuels (Hill et al. 2006).

Various strategies, such as increasing yields of existing energy crops, supplementing or replacing them with cellulosic biomass or higher oil yielding seeds, tapping unused agricultural residue streams, and increasing the area of energy crop production, could enable more biofuel production. However, increasing production of

first and second generation energy crops has raised concerns about unintended, negative consequences on food security (Pimental et al., 2009; Sanhueza, 2009), and on water, air and soil quality (Sanhueza, 2009; Donner and Kucharik, 2009; and Costello et al., 2009). In light of these concerns with first and second generation biofuel feedstocks, algae are viewed as a potential feedstock alternative with higher productivity per unit land area (Griffiths et al., 2009), greater control of nutrient use and hence reduced nutrient export, the ability to receive and metabolize concentrated CO₂ flows from industrial sources, and that avoid competition with food crops (Lardon et al., 2009). Algae are also attractive because certain species have oil concentrations as high as 80% on a dry weight basis (Spolaore et al., 2006), thus delivering fixed carbon in a form more readily processed into liquid transportation fuels than lignocellulosic biomass. Algae can, under the right conditions, produce more energy-dense biomass at faster growth rates than terrestrial plants, and algae can be harvested daily (Chisti, 2007; Gouveia and Oliveira, 2009). Algae's high productivity is the result of their higher photosynthetic efficiencies (PE) than terrestrial crops: While terrestrial crops such as sugarcane only achieve a PE approaching 3.5% (Robertson, 1996), Zittelli et al. (2006) documented 9.4% PE for *Tetraselmis suecica* in photobioreactors, and Melis (2005) reported increasing the PE of *Chlamydomonas reinhardtii* five-fold (via mutagenesis), to over 15%. However, the actual PE observed in production of particular algal species can vary greatly depending on the type of algal culture systems (Erikson, 2007; Borowitzka, 1999).

Numerous types of algal culture systems have been built or proposed, and a few are listed in Table 1, along with representative yields and production costs

reported in the literature. Open pond systems are shallow, outdoor cultivation devices that achieve relatively low algal cell densities and that suffer from poor process control, but are the least capital intensive. In contrast to open pond systems, closed systems (often referred to as photobioreactors) are transparent tubes or tanks (typically constructed from glass or plastic) allowing photosynthetically active radiation to penetrate into the algae culture within. Photobioreactors allow far greater process control but have high capital costs. Emerging cultivation technologies (e.g., Table 1 and described below), may offer alternatives to ponds and photobioreactors, perhaps yielding lower capital costs and higher cellular densities, resulting in lower overall biomass production costs than the other systems.

Table 1. Algal Culture Systems, Types, Yields, and Cost of Production Estimates

Systems	Types	Yield (dry Mg/ha/yr)	Cost \$/kg dry biomass
Ponds	1) Open raceway 2) Circular with mixing 3) Large open	7 – 135 ¹	\$0.60-\$3.80 ²
Closed Photobioreactors (PBR)	1) Tubular 2) Flat panel 3) Column	70-150	\$0.47 ² - \$34 ⁴
Emerging Technologies	1) Open thin-layer panel 2) Polymer bags 3) Immobilized beds	Not reported.	\$25-\$600 ⁵

1. Moheimani and Borowitzka, 2006
2. Chisti, Y.(2007)
3. Shen, 2009 and Erikson, 2008
4. Grima et al (2003)
5. Borowitzka M.A. (1999).

Open raceway ponds (ORPs) with depths of 15-30 cm typically use paddlewheels agitation, thereby increasing mass transfer of CO₂ and O₂, and making light exposure more uniform. However, open air systems face challenges of maintaining the algal monoculture, and of low productivity and high harvesting costs due to relatively low cell densities (Shen, 2009). For example, Chisti (2007) noted cellular densities are approximately 30 times less in ORPs than in PBRs, resulting in significantly higher harvesting costs in the open systems.

Beyond decreased harvesting costs, PBRs offer additional benefits over open ponds including reduced risk of contamination of algal strains, larger surface area to volume ratios, and greater control over temperature, pH, light exposure, and nutrients (Shen, 2009, Chisti, 2007, and Borowitzka, 1999). Tubular PBRs can be built in multiple configurations and have reportedly achieved PEs ranging from 1.3% to 8.1% (Shen, 2009; Erikson, 2008). Although the productivity of PBRs can be two to three times greater per unit surface area than that of open ponds, the construction costs are 3.5 to 10 times higher per unit surface area (Shen, 2009). The high densities of algae in PBRs may reduce separation costs, but require small diameter tubes so that light may reach cells deep in the tube. This drives high material costs for these systems. (Shen, 2009, Chisti, 2007 and Erikson, 2008). However, novel PBR designs and materials may lead to lower production costs (Erikson, 2008).

A coupled PBR-ORP production system was built at industrial scale (i.e., 2 ha) in Hawaii to leverage the sterility and high productivity offered by PBRs and the low capital costs of open ponds. Huntely and Redalje (2007) reported success with

operating this two stage system that used photobioreactors to propagate *Haematococcus pluvialis* continuously, and then harvest on a three day batch cycle from an open pond system with nutrient conditions set to stress the algae into producing oil or astaxanthin. The group now operates the company HP Biopeteroleum using the proprietary two-stage process called Alduo.

There are emerging algal culture processes that may become important in the future of algal production, such as polymer bags (Svoboda, 2007 and Borowitzka, 1999). The Solix Company in Colorado is using a polymer bag system to cultivate algae for biofuels and has reported an oil mass areal productivity (MAP) of 14,000 L/ha/yr (Mascarelli, 2009). The costs of algal production from emerging technologies like polymer bags and immobilized beds are difficult to estimate. Immobilized beds may provide higher algae productivity and easier harvesting, but the challenges of high material costs, difficult scale-up, and proper strain identification for immobilized growth pose serious barriers to the advancement of this cultivation system.

Mascarelli (2009) noted that despite the approximately one billion dollars invested in the algal biofuels area from 2006 – 2009, barriers to commercial production remain with the major one being cost. As noted earlier, estimates for cost of algal production vary widely (Table 1) reflecting the variability in the cost estimates driven by assumptions of the estimators and compounded by the immaturity of the production technologies. Algae production has yet to develop and implement technologies that afford ease of production and profitability. Traditionally, economists have assumed that in a free and open market, the “best” technology will out-compete the others; however, the market can behave irrationally and settle on a

technology inferior to other choices (Pool, 1995). Even when individuals in the market make rational and logical decisions according to “the best available information,” a weaker technology may “lock in,” preventing other, superior technologies from entering the market (Pool, 1995). To avoid technological lock-in with commercial algae production schemes, it is crucial that researchers, policy-makers, and investors have an understanding of the cost structures of commercially unproven algal production technologies.

Yet it is difficult to predict the potential economics of these non-commercial systems. The authors know of no public reports that exist detailing the economics of full-scale algal production for fuel. The current products made by full-scale algal production facilities have unit values several orders of magnitude greater than those of fuel (Frucht and Kanon, 2005). It is possible to make cost estimates based on a thorough examination of unit operations. However, cost estimates can be misleading, as they are often biased low.

While capital underestimation is the norm for all plants, estimates of commercially established plants are relatively close to the actual costs and become more accurate as the project nears completion. However, commercially unproven technologies – like those employed in algal production – may cause design, construction, and start-up challenges leading to higher than expected final plant costs (Morrow et al., 1981). The RAND Corporation carried out the Pioneer Plant Study (PPS) (Morrow et al., 1981) to understand the degree to which final plant costs exceed the design estimated cost. The PPS generated a model which predicts the first-plant (i.e., *pioneer plant*) Cost Growth in chemical process plants, where

Cost Growth is defined as the ratio of actual plant cost to the design estimate. The RAND Cost Growth Model (RCGM) (Merrow et al., 1981) revealed that estimates for chemical process plants using commercially unproven technologies are not only biased low, but are highly uncertain. When used with caution, the RCGM can help to control biases and reduce the uncertainty of cost estimates for new technologies, and can allow comparison of technologies at different developmental stages (Merrow et al., 1981). Applying the Cost Growth analysis to algal production systems should result in a better understanding of the Cost Growth for these projects, and should enable improved comparison between systems.

Plant Performance – defined as the fraction of design capacity achieved by a plant (Merrow et al., 1981) - is an important point for comparing algal production technologies. Because chemical process plants are capital intensive, production costs increase rapidly with any decline in Plant Performance (Merrow et al., 1981). Achieving design capacity as quickly as possible after start-up is important to preserve the economics of the plant: poor performance is damaging because of the time value of money (Merrow et al., 1981). The RAND Corporation study that developed the RCGM also developed the Rand Plant Performance Model (RPPM) from the same data set. RAND showed that the amount of new technology employed by a plant could be used to predict the time a plant took to achieve its design performance. RAND found that plants with several new steps and a high percentage of total estimated plant cost in commercially unproven technologies, like algae production scenarios, are inherently economically risky. Employing the RPPM to predict Plant Performance of different algae production designs can shed light on

the financial risk of algae pioneer plants, and can identify technologically weak spots and opportunities for process improvements. The RPPM can be used to estimate production costs, overall plant economics, and unit costs. Algae plants constructed subsequent to pioneer algae plants may make gains in Plant Performance and reduce Cost Growth, as there is greater knowledge of and experience with the technology and system operations. These types of gains can be described by experience or learning curves. The experience curve concept links developments in production costs with cumulative production, representing accumulated experience of production; production costs tend to decline with a fixed percentage over each doubling in cumulative production (Hettinga et al. 2009). For example, corn production costs in the US have declined by 62% over 30 years and total ethanol production costs have declined by 60% since 1980 (Hettinga et al. 2009). Future production costs of ethanol may decline by 28-44%, due solely to technological learning (Hettinga et al. 2009). Experience curves could be a valuable tool to describe potential future cost reductions for algae production scenarios and thus discern a technology's prospect. Yet, the possibility of experience curve gains for algal production plants does not replace the need for accurate cost estimates and Plant Performance projections. An accurate picture of pioneer plant economics and performance can serve to direct policy and investments by industry and government in innovations that improve the profitability and performance of algal production plants.

The fundamental goal of this work was to evaluate and compare the Cost Growth and Plant Performance of several proposed algal production pathways. To

do so, three proposed algal production pathways were modeled with a similar level of granularity (i.e. unit operations and corresponding capital costs were assessed at the equivalent degrees), allowing the Cost Growth and Plant Performance of each to be evaluated within the RAND framework.

Materials and Methods

This study applied the RCGM and RPPM to three proposed algae production scenarios, as follow: 1) open raceway ponds, 2) tubular photobioreactors and 3) systems coupling photobioreactor to open raceway ponds.

RCGM and RPPM Description

We used the RCGM to estimate the Cost Growth ratio of pioneer plants representing three different algal-production facilities. The RCGM form is specified in Equation 1, where b_i represents the parameter estimates detailed in Table 2, and a represents the intercept. The model was developed from a dataset, collected from various chemical industry companies by the RAND Corporation that revealed an R-squared value of 0.83 with a $\pm 8.3\%$ standard error of estimate. The Cost Growth ratio output from the RCGM functions as a divisor (i.e., smaller number indicates greater Cost Growth). We inverted the ratio to represent the Cost Growth as a multiplicative factor (with greater factors implying greater growth).

Equation 1:

$$\begin{aligned} \text{Cost Growth Ratio} = & a + b_1 \{\text{PCTNEW}\} + b_2 \{\text{IMPURITIES}\} + \\ & b_3 \{\text{COMPLEXITY}\} + \\ & + b_4 \{\text{INCLUSIVENESS}\} + b_5 \{\text{PROJECT DEFINITION}\} \end{aligned}$$

Table 2. RAND Cost Growth Model Parameters and Descriptions

Variable Name	Definition	Range of Values	Parameter Estimate (b _i)
Intercept		NA	1.12196
PCTNEW	Percent of estimate incorporating technology unproven in commercial use	0 to 100	-0.00297
IMPURITIES	Assessment by industry process engineers of difficulties with process impurities encountered during development.	0-5	-0.02125
COMPLEXITY	Block count of all process steps in plant	1+	-0.01137
INCLUSIVENESS	Derived from checklist measuring completeness of estimate (percent of items included)	0-100	0.00111
PROJECT DEFINITION	Levels of site specific information and engineering included in estimate	2-8	-0.04011* - 0.06361**

NA-not applicable

*Precommercial/commercial

**R&D

The variable name PROJECT DEFINITION requires further explanation than that given in Table 2. PROJECT DEFINITION was defined by RAND as an average value computed from numerically assigned values representing the Categorical Site Specific Information and the Level of Engineering. The Categorical Site Specific Information was rated in four categories: on-site and off-site unit configurations, soils and hydrology data, health and safety requirements, and environmental requirements. The rating followed the scale where 1 was assigned for definitive or

completed work in a category, 2 was assigned for preliminary or limited work completed in a category, 3 was assigned for an assumed or implicit analysis in a category, and 4 was assigned when a category was not used in the cost estimate at all. The Level of Engineering completed for an estimate could range from 1) design specification: engineering completed, 2) study design: moderate or extensive basis, 3) study design: limited basis, 4) screening study: least definition (Morrow et al. 1981).

We used RPPM to estimate pioneer Plant Performance for three algae production scenarios. The RPPM form is specified in Equation 2 where b_i represents the parameter estimates detailed in Table 3 and a represents the intercept. The model was developed from the same dataset gathered by the RAND Corporation for the Cost Growth model, and revealed an R-squared value of 0.90 with a $\pm 9.3\%$ standard error of estimate.

Equation 2:

$$\text{Plant Performance} = a + b_1 \{\text{NEWSTEPS}\} + b_2 \{\text{BALEQS}\} + b_3 \{\text{SOLIDS}\} + b_4 \{\text{WASTE}\}$$

Table 3. RAND Plant Performance Model and Descriptions

Variable Name	Definition	Range of Values	Parameter Estimate
Intercept		NA	85.77
NEWSTEPS	Number of process units that incorporate technology unproven in commercial use	0 to total of # process steps	-9.69
BALANCE EQUATIONS(BALEQS)	Percent of heat and mass balance equations based on actual data from prior plants	0 to 100	0.33
WASTE	Assessment by industry process engineers of difficulties with waste handling encountered during development (greater value implies greater difficulty)	0 to 5	-4.12
SOLIDS	Designates that a plant processes primarily solid (feedstocks or products)	1 if solids plant, otherwise 0	-17.91

Scenarios

Peer-reviewed Techno-Economic Analyses (TEA) of commercial algal production technologies were referenced for collecting several of the RCGM and RPPM model inputs. The maturity of each algal production technology described in the TEAs was assessed under two cases of assumptions: a favorable case (FC) and a worst case (WC); we assumed the original publication values could be considered an optimistic case. The sets of assumptions for each case were based on engineering judgment supported by algae production and research literature and is further described below.

Assumptions varied for the RCGM and RPPM inputs for each scenario at the two cases of FC and WC. The degree of commercialization for technologies employed in each scenario was assigned a status of *complete*, *some*, or *no*. Those technologies assumed to have no degree of commercialization were classified as *unproven technologies* in the favorable case. Those technologies assumed to have *no* and *some* degree of commercialization were classified as *unproven technologies* in the worst-case.

The algal production scenarios examined were ORP, Coupled PBR and ORP and PBR, the TEA used for each scenario are detailed below. As shown in figure 1 the proposed algal production pathways were modeled with a similar level of granularity for unit operations.

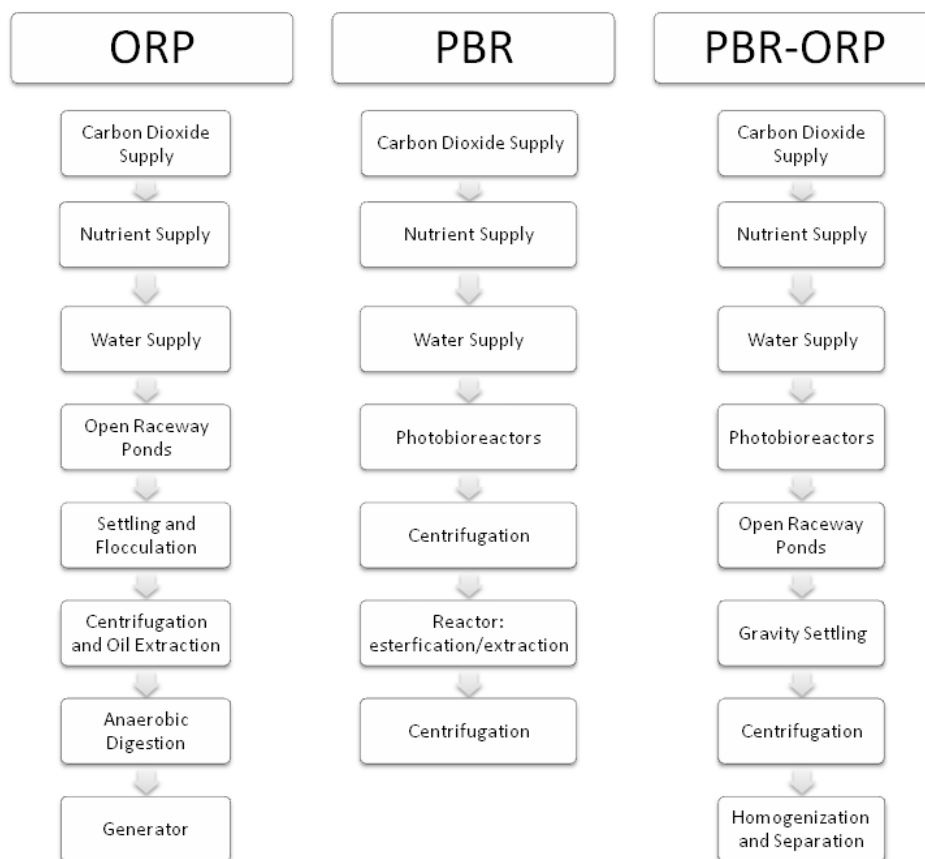


Figure 1. Schematic diagram depicting granularity of unit operations for algal production scenarios examined. (ORP-Open Raceway Ponds, PBR-Photobioreactors, and PBR-ORP- Photobioreactors coupled with Open Raceway Ponds)

Technology Assessments of Scenarios for Model Parameters

Open Raceway Ponds

The Benemann and Oswald (1996) PETC Final Report was the source for the techno-economic assessment for algal production in ORPs. The original study analyzed four scenarios based upon two MAPs (30 and 60 g/m²/day) and two carbon sources (pure carbon dioxide or flue gas from a power plant). Capital costs were estimated for each of the proposed four designs in 1994 dollars per hectare. Tables 4a and 4b list the values calculated or assumed for each of the models' input parameters.

Table 4a. Open Raceway Pond Parameter Value Assignments for RAND Cost Growth Model (FC-Favorable Case and WC-Worst Case). Bold text indicates a calculated value)

RCGM Parameter	30 g/m ² /day				60 g/m ² /day			
	Pure CO ₂		Flue Gas		Pure CO ₂		Flue Gas	
	FC	WC	FC	WC	FC	WC	FC	WC
PCTNEW	22	43	22	36	32	54	33	44
IMPURITIES ^a	2.5	4	3	5	2.5	4	3	5
COMPLEXITY ^a	7	6	7	6	7	6	7	6
INCLUSIVENESS ^b	66	66	66	66	66	66	66	66
PROJECT DEFINITION ^b	5	7	5	7	5	7	5	7

^aAssumptions about plant IMPURITIES and COMPLEXITY differed between the pure carbon dioxide and flue gas plants as the IMPURITIES are likely to be greater with flue gas than with pure carbon dioxide and COMPLEXITY of the production system is the block count of the connected unit operations and therefore increases with pure carbon dioxide design because of the addition of the generator.

^bINCLUSIVENESS and PROJECT DEFINITION remained the same for all cases for the Cost Growth.

The PCTNEW input parameter was calculated by: 1) updating the cost values to 2010 dollars to account for inflation, 2) assigning capital cost items a degree of

commercialization, 3) summing unproven technologies' costs and 4) dividing the sum of the total unproven technology cost by total capital costs. In Figure 2 is a list of the unit operations and their commercialization classification (some or no) for all scenarios.

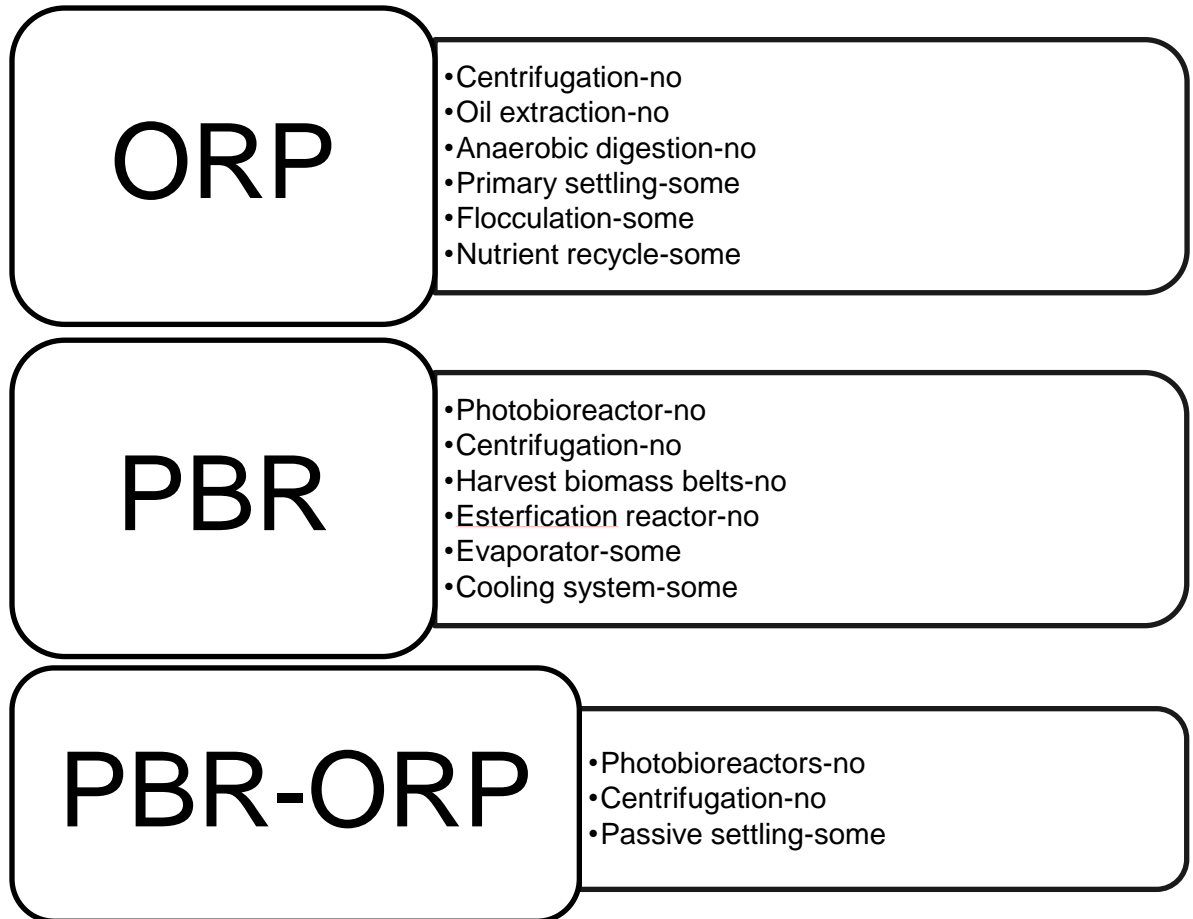


Figure 2. A description of commercialization classification for each scenario's unit operations: "no"-unit operation included in PCTNEW and NEWSTEPS for Favorable Case and Worst Case, "some"-unit operation only included in PCTNEW and NEWSTEPS for Worst Case.

Table 4b. Open Raceway Pond Parameter Value Assignments for RCGM. (FC-Favorable, WC-Worst Case)

Parameter	30 g/m ² /day				60 g/m ² /day			
	Pure CO ₂		Flue Gas		Pure CO ₂		Flue Gas	
	FC	WC	FC	WC	FC	WC	FC	WC
NEWSTEPS	2	4	2	4	2	4	2	4
BALANCE EQUATIONS	0%	0%	0%	0%	0%	0%	0%	0%
WASTE	2.5	4	2.5	4	2.5	4	2.5	4
SOLIDS	1	1	1	1	1	1	1	1

Photobioreactors

The Grima et al. (2003) economic study for the commercial production of microalgae in photobioreactors was utilized as the first costing for algal production in PBRs. The basis of the study was a facility that would produce 430 kg/yr of 96% pure Eicosapentaenoic acid (EPA), corresponding to 26.2 ton/yr of biomass-free esterified crude extract; the projected MAP was approximately 10.7 g/m²/day based on a volumetric productivity of 1.25 kg/m³/day in continuous culture (Grima et al. 2003). Only the unit operations and the associated costs needed for the cultivation of the algae and up to the extraction of the oil from the algae were included in our analysis.

The EPA production / oil extraction and esterification process has been demonstrated at a pilot scale using *Phaeodactylum tricornutum* (Grima et al., 2003).

As with all bioreactors, the scale up of PBRs to commercial scale is not trivial, and is made particularly challenging by issues of illumination, gas transfer, and temperature control (Olaizola, 2003). For example, increasing PBR reactor diameters causes illumination problems, and increasing tube length can result in pH changes and gas transfer problems (Grima et al. 1999). Thus, we labeled scaled PBRs as new equipment which is in line with the RAND models' classification of technological change. Initial investment cost in most types of plants and equipment exhibits economies of scale. For most equipment, an increase in capacity and output does not require a proportionate increase in material because of geometric relationships relating the material required for the building of equipment to the equipment's capacity (Haldi and Whitcomb, 1967). However, no reliable systematic scale-up relationship exists for photobioreactors (Grima et al., 1999) and thus an empirical scale coefficient for PBRs is unknown. Scale up is therefore envisioned as occurring by multiplication of identical tubular modules (Grima et al. 1999). Multiple units are used when equipment scale economies have been exhausted-expansion by multiple units will not give further plant economies of scale (Haldi and Whitcomb, 1967). Tables 5a and 5b list the values assumed each of the models' parameters.

Table 5a. Photobioreactors Parameter Value Assignments for RCGM (bold values represent calculated values).

Parameter	FC	WC
PCTNEW	55	57
IMPURITIES ^a	3	5
COMPLEXITY ^b	7	7
INCLUSIVENESS	66	66
PROJECT DEFINITION	5	7

^aThe IMPURITIES risks arise from the recycle stream solute(s) buildup and oxygen accumulation.

^bBlock count of the connected unit operations and is the same for both FC and WC

Table 5B. Photobioreactors Parameter Value Assignments for RPPM (FC-Favorable and WC-Worst-case).

Parameter	FC	WC
NEWSTEPS	3	4
BALANCE EQUATIONS	0%	0%
WASTE	2	4
SOLIDS	1	1

System of Photobioreactors coupled to Open Raceway Ponds

Unlike the previous two scenarios which were each based on a single published report, the coupled system was based on three publications (Huntley and

Redalje 2007, Olaizola 2000, and Olaizola 2003), supplemented with our own engineering estimates. Huntley and Redalje (2007) reported general specifications of the Aquasearch (now HP petroleum)-coupled production systems for photosynthetic microbes and referred to Olaizola (2000, 2003) for a more detailed description of the system. The MAP for the coupled system is 10.2 g/m²/day for the PBR and 15.1 g/m²/day for the ORPs. Huntely and Redalje (2007) estimated the cost of producing a barrel of algae oil with no improvements with the Aquasearch-coupled technology to be \$74 per bbl and further determined that technological improvements could reduce the costs to \$51 per bbl. However, they relied on Benemann and Oswald (1996) techno-economic analysis (adjusted for inflation) for capital costs for the open raceway ponds and on Hallenbeck and Benemann (2002) for photobioreactor cost estimates. Huntely and Redalje's estimates appear optimistic and were not based on this novel system's actual costs, though they reported spending 20 million (USD) over a four years on the construction and operation of the 2 ha facility, or approximately 35 times as much as their estimate for a large commercial system. Given such a large discrepancy, we decided to estimate the capital costs based on the details of the production system from the three publications previously mentioned.

The facility description states that production chain is the Aquasearch Growth Modules (AGM) which consists of a series of PBRs that have scaled-up from 20-L carboy cultures to 1000-L, to 5000-L and then finally to 25,000-L capacity PBRs that operate continuously and feed ORPs. The ORPs are 417 m² each, have an average

depth of 12 cm, and are plastic lined, use paddlewheels for circulation, and do not have temperature control. The ORPs are operated on a batch process; the PBRs are operated at steady state by harvesting a fraction of the culture daily, approximately equivalent to mass of cells grown daily. These cells are then transferred to the ORP. The retention time prior to harvest in the ORPs is three days. Harvesting involves gravity settling to concentrate the cells into a slurry, further concentration by centrifugation of the slurry, and separating the oil from the algal biomass with a homogenizer. Tables 6a and 6b list the values assumed each of the models' parameters.

Table 6a. Coupled Photobioreactors with Open Raceway Ponds Parameter Value Assignments for RCGM. (FC-Favorable Case, WC-Worst Case)

Parameter	FC	WC
PCTNEW	22	36
IMPURITIES	2	3
COMPLEXITY ^a	7	7
INCLUSIVENESS ^b	33	33
PROJECT DEFINITION	5	7

^aBlock count of the connected unit operations and is the same for both cases.

^b Same for both cases; only the plant inventory was complete.

Table 6b. Coupled Photobioreactors with Open Raceway Ponds Parameter Value Assignments for RPPM (FC-Favorable Case and WC-Worst Case).

Parameter	FC	WC
NEWSTEPS	3	5
BALANCE EQUATIONS	0%	0%
WASTE	2	4
SOLIDS	1	1

Method Challenges

A fundamental challenge in this work is that the best available estimates of plant function and cost are from TEAs with plants ranging from 1 to 400 ha. This implies that direct comparison of capital costs could be unjust due to economies of scale. The dataset, upon which both the RCGM and RPPM were developed, contained information from 44 commercial-scale chemical process plants (Merrow, 1981). Although the production capacity of these plants ranged 21-fold (from 100 to 2100 million lbs/yr) and although over 400 variables describing the process plants and projects were collected, scale did not emerge as a parameter that could significantly describe Cost Growth or Plant Performance. The RAND study did note that the use of ratios (estimated cost/actual cost) avoids distortions due to scale that would occur on absolute dollar differences. Thus, we focused on estimating Cost Growth (which is expressed on a total plant cost basis) and Plant Performance to avoid scale distortions. In addition, we combine these two values to compute Cost

Growth on a unit plant output basis. Two significant factors in the cost of any full-scale algal production system would be location and algal species. For this work, whatever location and species was assumed in the original TEA from the literature was carried forward and no effort was made to examine changes in location or species. Given the metrics examined in this work, Cost Growth and Plant Performance, ignoring the differences in location and species does not affect the comparability of the systems because these two variables were not considered in the two RAND models.

Unit Cost Growth Factor Analysis

The Unit Cost Growth Factor was calculated by dividing the Cost Growth Inverse by the Plant Performance estimate for each scenario. The Unit Cost Growth provides insight into the relative impact of the combination Cost Growth and Plant Performance for each algal production scenario.

Confidence Intervals

The Confidence Intervals (CI) for the Cost Growth and Plant Performance were based on the method described the RAND User's Manual, if the user's data were within one standard deviation of the RAND model data, a CI of one standard deviation, 68%, was used. When the user's data were within two standard deviations of the RAND model data, the CI was adjusted appropriately. For the Unit Cost Growth Factor, a ratio of Cost Growth to Plant Performance, a range was calculated

by coupling the low and upper end of the ratio of Cost Growth to upper and low end based on their respective confidence intervals.

Uncertainty Analysis: Monte Carlo Simulations

We used Monte Carlo simulations to integrate and fully account for both uncertainty in model inputs (data from the TEAs) under each scenario and statistical uncertainty in the parameter estimates in the predictive models, RCGM and RPPM. Monte Carlo simulation is an algorithmic approach that can be employed to estimate set of a set of model outputs with corresponding probabilities (Bennett and Anex, 2009). Monte Carlo simulations are useful because they can integrate the uncertainty arising from randomly sampled input values and/or equation parameters. For each simulation, numerous iterations are used to assemble a distribution of model outputs. One can then compute the mean (e.g. most likely) result as well as the confidence intervals of the distribution. One should note that the output of such a simulation is dependent on the simulation inputs (Dorner et al., 2001; Bennett and Anex, 2009). Input distributions may be defined by the user to be rectangular, triangular, skewed, discrete values or any other distribution that represents the probabilistic uncertainty in the input variables (Dorner et al, 2001). So too, uncertainty in model parameters is easily incorporated if mean estimates and standard errors are available, as was the case with the RCGM and RPPM models. The distributions of these parameters should conform to the assumptions under which the model parameters were fit to the data.

Four separate Monte Carlo simulations were completed, two to understand the parametric uncertainty and two to understand the algal production scenarios' input uncertainty for Cost Growth and . Each Monte Carlo simulation used 10,000 iterations to generate the results distribution. To understand parametric uncertainty, the RCGM variables listed in Table 2 were randomly generated based on the parameter estimate and the standard deviation while the data inputs for each scenario were the inputs for the FC scenarios. For each Monte Carlo simulation completed to understand parametric uncertainty with the RPPM, variables listed in Table 3 were randomly generated based on the parameter estimate and the standard deviation while the data inputs for each scenario were the inputs for the FC scenarios.

To assess the input uncertainty, for each Monte Carlo iteration input values for each variable were generated according to a user defined probability function that described the estimated distribution of each input variable for both the RCGM and RPPM. User defined discrete probability distributions were assumed for all inputs except for PCTNEW for which a BETA distribution was employed. The discrete probability distributions were defined to sample with replacement from the range of values for the inputs from both models as shown in Tables 2 and 3. The probabilities assigned to the range of values for the inputs assumed are shown in Table 7. The probabilities assigned to the different inputs were chosen based our current understanding of the technologies and designs proposed for the different scenarios.

Table 7. User defined discrete probabilities for Cost Growth and Plant Performance model inputs for the Monte Carlo analyses of the different algae production scenarios which samples from the range given the probabilities listed in the parentheses*.

Input	Range	ORP-30P	ORP-30F	ORP-60P	ORP-60F	PBR	PBR-ORP
IMPURITIES	0-5	(0,.05,.2,.5,.2,.05)	(0,.05,.2,.3,.4,.2)	(0,.05,.2,.5,.2,.05)	(0,.05,.2,.3,.4,.2)	(0,.05,.2,.3,.4,.2)	(0,.1,.4,.3,.2,.2)
COMPLEXITY	9:15	(.05,.1,.12,.25,.15,.1 2,.05)	(.05,.1,.12,.25,.15, .12,.05)	(.05,.1,.12,.25,.15,.12, .05)	(.05,.1,.12,.25,.15,.12, .05)	(.05,.1,.12,.25,.15, .12,.05)	(.05,.1,.12,.25,.15, .12,.05)
INCLUSIVENESS	33,66,100	(.2,.79,.01)	(.2,.79,.01)	(.2,.79,.01)	(.2,.79,.01)	(.2,.79,.01)	(.2,.79,.01)
PROJECT DEFINITION	2:8	(.05,.05,.1,.2,.2,.1,.1)	(.05,.05,.1,.2,.2,.1, .1)	(.05,.05,.1,.2,.2,.1,.1)	(.05,.05,.1,.2,.2,.1,.1)	(.05,.05,.1,.2,.2,.1, .1)	(.05,.05,.1,.2,.2,.1, .1)
NEWSTEPS	0:4	(0,.05,.25,.25,.2)	(0,.05,.2,.25,.25)	(0,.05,.25,.25,.2)	(0,.05,.2,.25,.25)	(0,.05,.05,.6,.3)	(0,.05,.2,.5,.25)
BALANCE EQUATIONS	0-100	0	0	0	0	0	0
WASTE	0:5	(0,.05,.2,.5,.2,.05),	(0,.05,.2,.2,.5,.1)	(0,.05,.2,.5,.2,.05)	(0,.05,.2,.2,.5,.1)	(0,.05,.1,.2,.4,.3)	(0,.05,.2,.5,.2,.05)
SOLIDS	0 or 1	1	1	1	1	1	1

*For example, the probabilities for the range given for IMPURITIES for ORP can be interpreted as 0% chance of input value 0, 5% chance of input value 1, 20% chance of input value 2, 50% chance of input value 3, 20% chance of input value 4, and 5% chance of input value 5.

Results and Discussion

Pioneer Plant Cost Growth Estimates

The Cost Growth Factors (the inverse of the RCGM output) estimated for the scenarios are shown in Figures 3a and 3b. The bars indicate the 68% confidence interval around the predicted Cost Growth factor. The PBR scenario had the highest Cost Growth factor (inverse) than all other scenarios at each case, estimated Cost Growth to be less than 1.8 times the original estimate. The ORP-PBR-FC and the ORP with the lower production goal of 30 g/m²/day with pure carbon dioxide supplied to the algae had the lowest Cost Growth factor, but the differences between the two scenarios are likely negligible. All of the ORP scenarios have similar Cost Growth factors between 1.2 and 1.5 times the original estimate. The Cost Growth estimate for the coupled system does not differ appreciably from any of the ORP systems. The high capital costs associated with PBRs and their commercial immaturity are the likely reason for the striking difference in the Cost Growth estimates between the PBR and the ORP and coupled system. The difference may be explained by much smaller contribution the PBR unit operations play in the coupled system; PBRs only account for approximately 8% of the total capital costs for the coupled system, while the PBR unit operations account for nearly 30% of the PBR system.

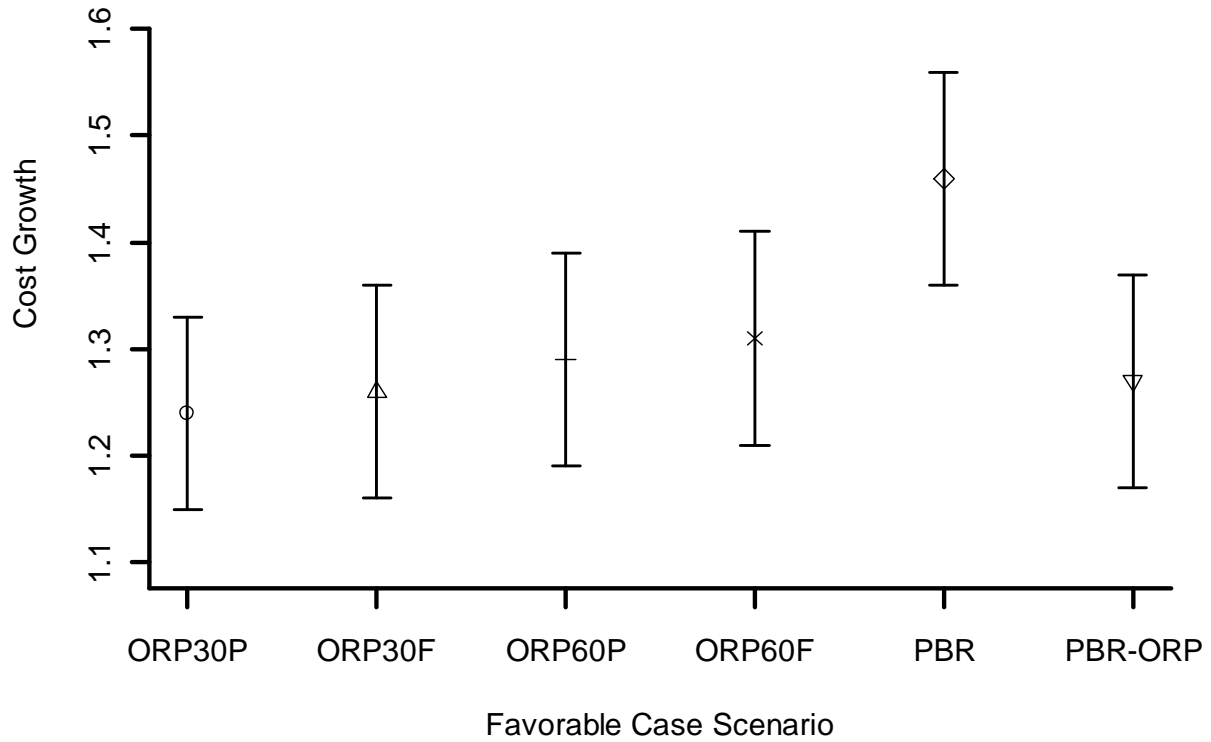


Figure 3a. RAND Cost Growth Ratio Inverse Algal Production Scenarios (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, P-Pure carbon dioxide, F-flue gas, 30-30 $\text{g}/\text{m}^2/\text{day}$, 60-60 $\text{g}/\text{m}^2/\text{day}$)

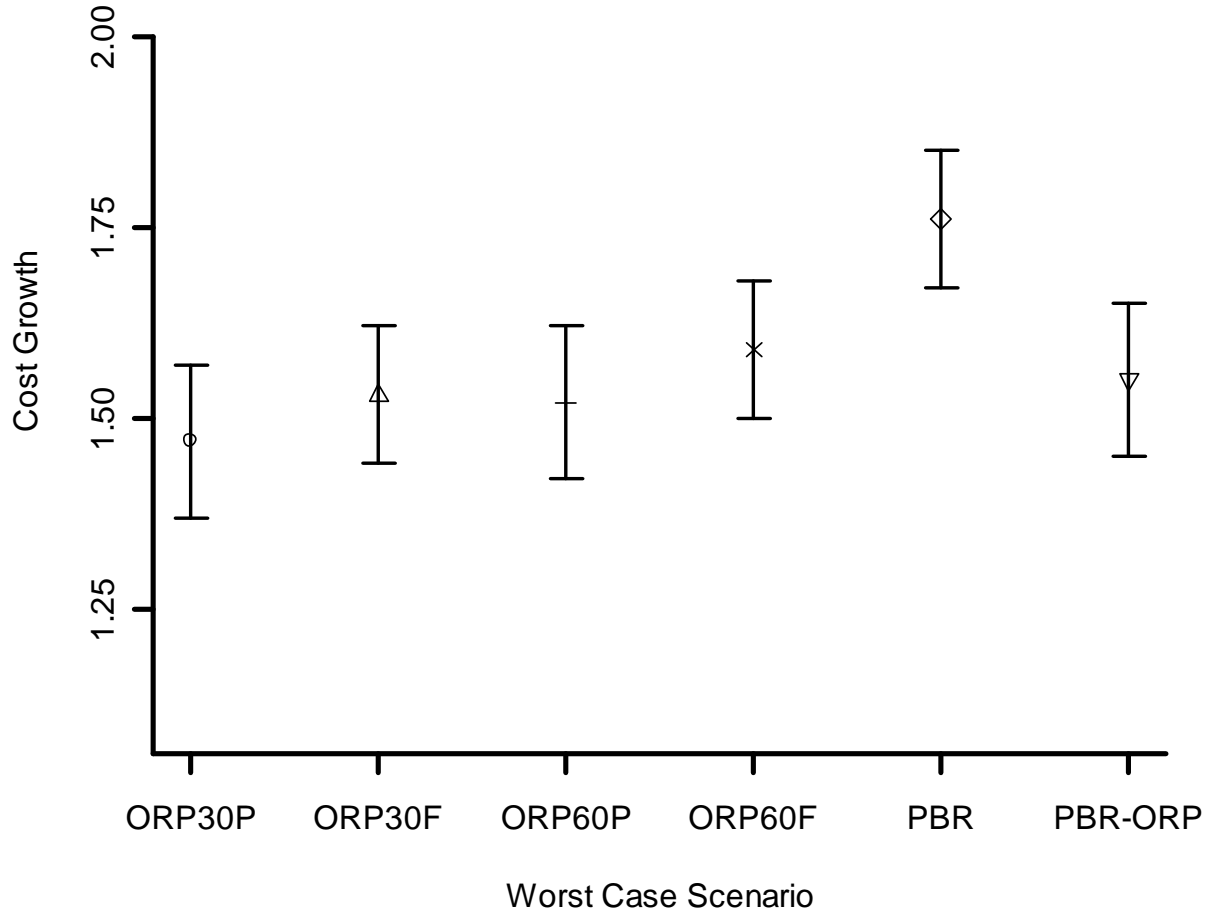


Figure 3b. RAND Cost Growth Ratio Inverse Algal Production Scenarios (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, P-Pure carbon dioxide, F-flue gas, 30-30 g/m²/day, 60-60 g/m²/day)

Pioneer Plant Performance Estimates

The estimates of Pioneer Plant Performance for all scenarios at each case are shown in Figures 4a and 4b. There are fewer bars than in Figure 4 because the predicted Plant Performance of the ORP was the same for all production cases and carbon sources so only one set of bars is shown for the ORPs. The bars indicate the 68% confidence interval around the predicted for Plant Performance. The FC set of scenarios for the ORP systems were predicted to have the greatest performance. The PBR and coupled technology had the same estimated performance in FC cases, and in WC cases. The Plant Performance minimum and maximum estimates all overlap when comparing algal production systems and scenarios. Even if 100% of the data were available for BALANCE EQUATIONS for each of the plants, the Plant Performance estimates would not change appreciably. This is because the parameter for BALANCE EQUATIONS is small compared to the other parameters; the model is not as sensitive to BALANCE EQUATIONS as to NEW STEPS. The confidence intervals shown in Figure 4 are larger than those of the Cost Growth because the input data were greater than one standard deviation away from the RAND Plant Performance data set means. Figure 4 shows that the relatively untested nature of all algal scenarios and especially of the PBR suggests that pioneer Plant Performance will likely be significantly lower than the design capacity.

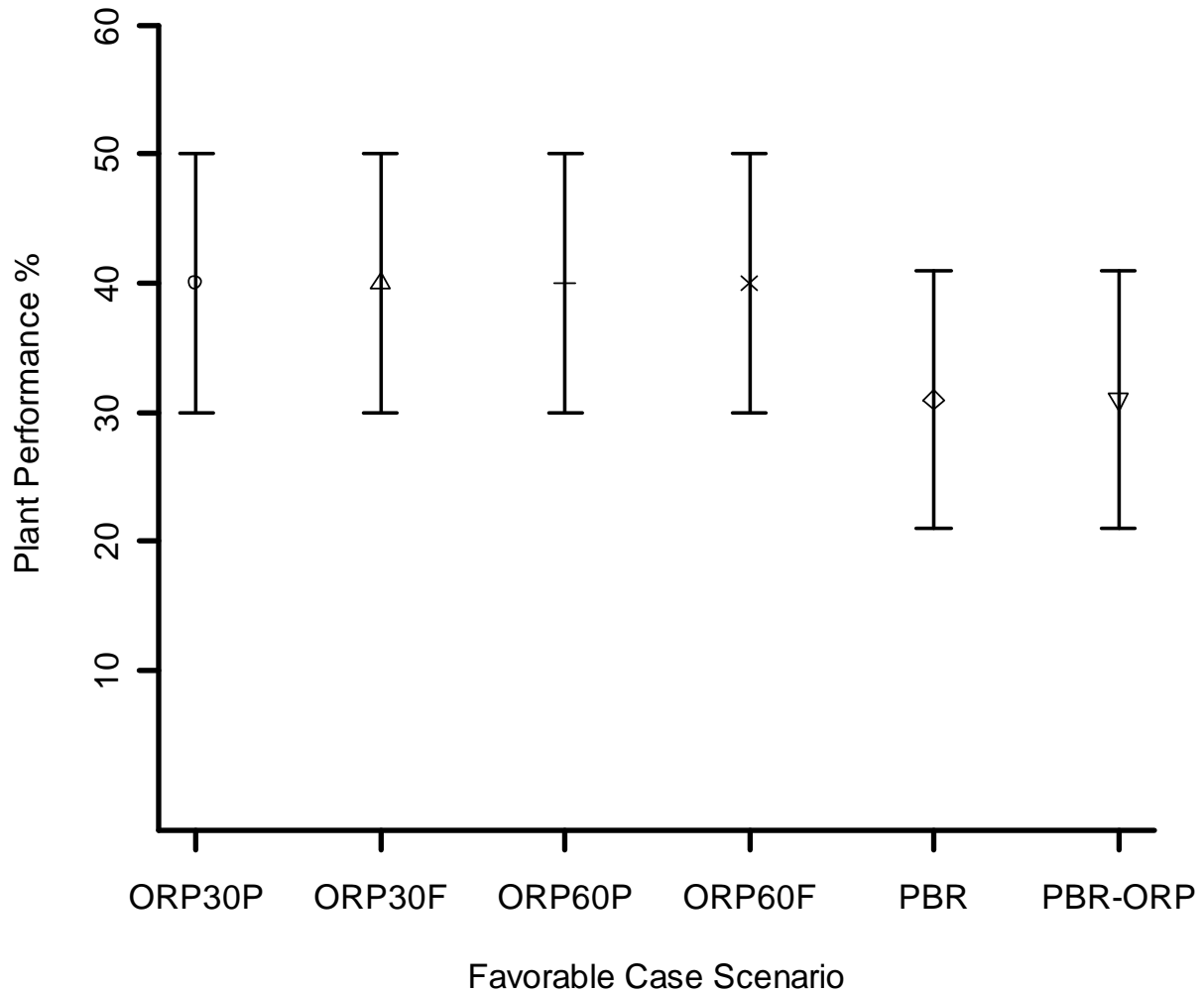


Figure 4a. RAND Pioneer Plant Performance Model of Three Algal Production Scenarios (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, F-flue gas, 30-30 g/m²/day, 60-60 g/m²/day)

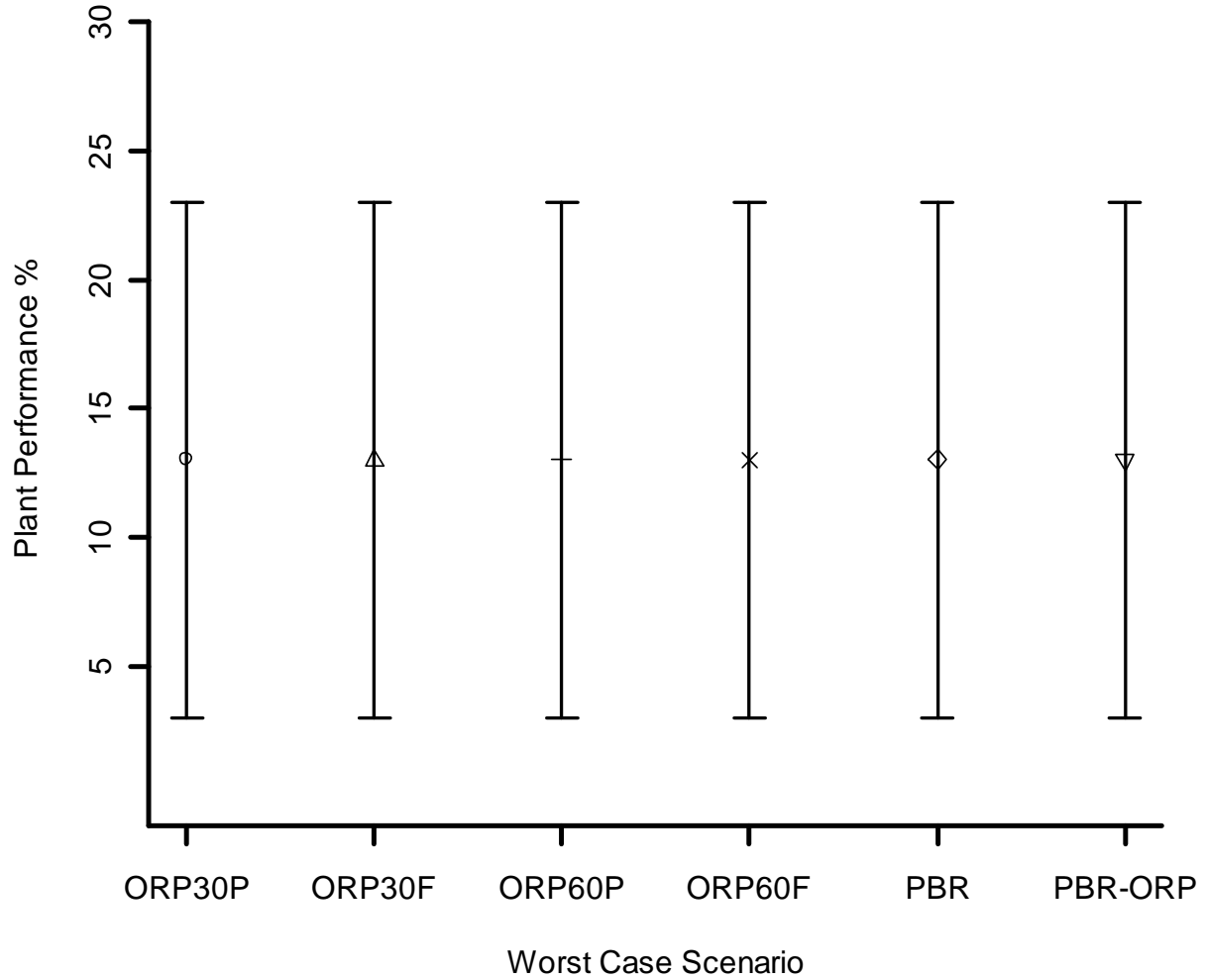


Figure 4b. RAND Pioneer Plant Performance Model of Three Algal Production Scenarios (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, F-flue gas, 30-30 g/m²/day, 60-60 g/m²/day)

Unit Cost Growth Factor Analysis

Figure 5 depicts the estimated range for Unit Cost Growth Factor for all scenarios at each case. The bars indicate the range of unit Cost Growth based on the lower and upper ends of the ratio of Cost Growth to Plant Performance which takes into account their respective confidence intervals as shown in equations 3a and 3b. The worst case scenarios have such a large range due to the large CI for Plant Performance estimates. The ORP FC scenarios had the lowest unit Cost Growth which can be attributed to the lower capital costs and also the slightly greater maturity of the system design. The PBR system had the greatest unit Cost Growth, with a considerable range of possibilities. The estimates for Unit Cost Growth Factor overlap just slightly between production systems for the FC and WC scenarios.

Equation 3a:
$$UCG (high) = \frac{Cost\ Growth + CI}{Plant\ Performance - CI}$$

Equation 3b:
$$UCG (low) = \frac{Cost\ Growth - CI}{Plant\ Performance + CI}$$

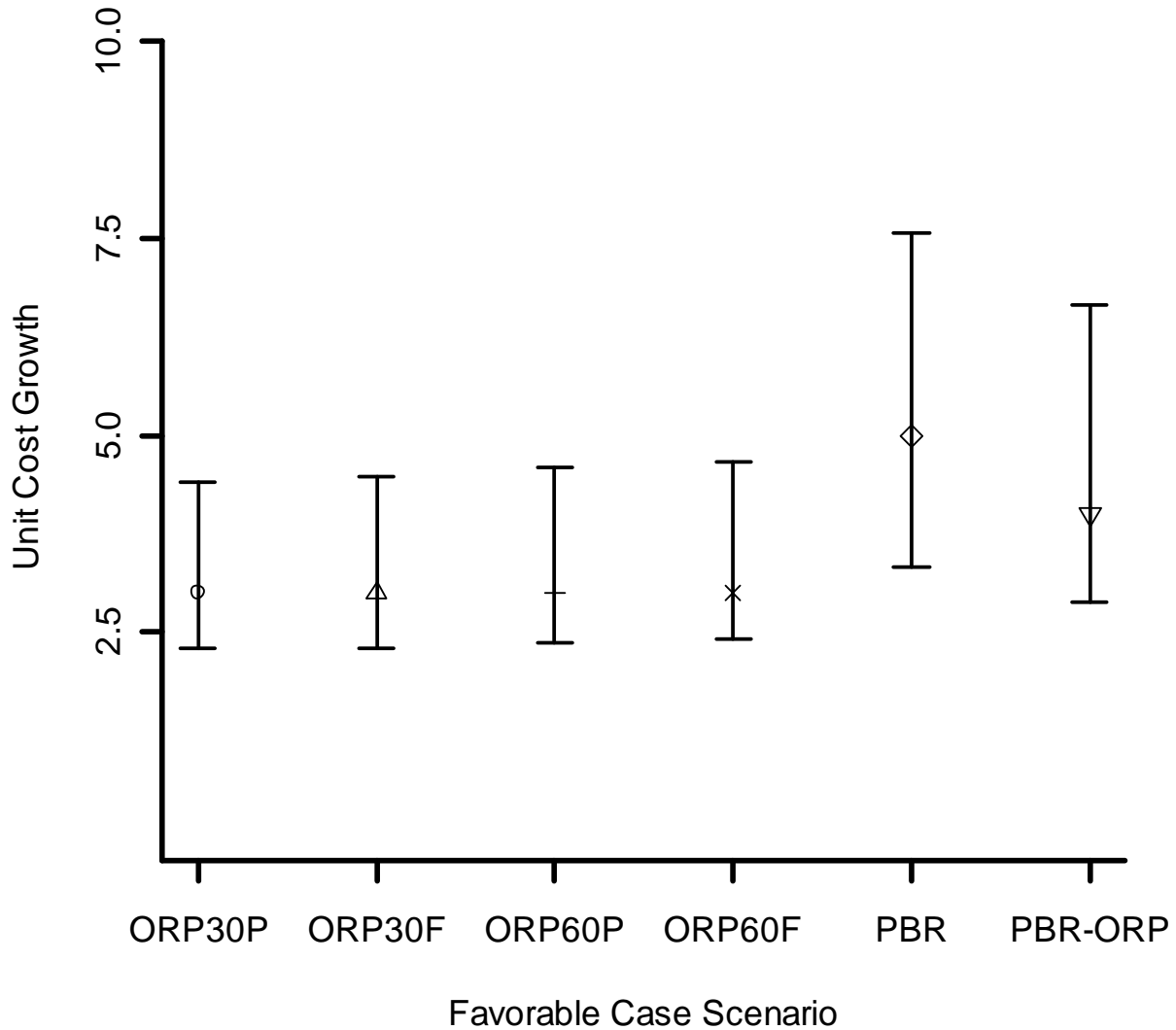


Figure 5a. Range of Unit Cost Growth Factors for three algal production favorable case scenarios (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, fed by either P-Pure carbon dioxide or F-flue gas). Bars extend over range (low to high) of Unit Cost Growth Factors computed, based upon the confidence intervals of Cost Growth and Plant Performance.

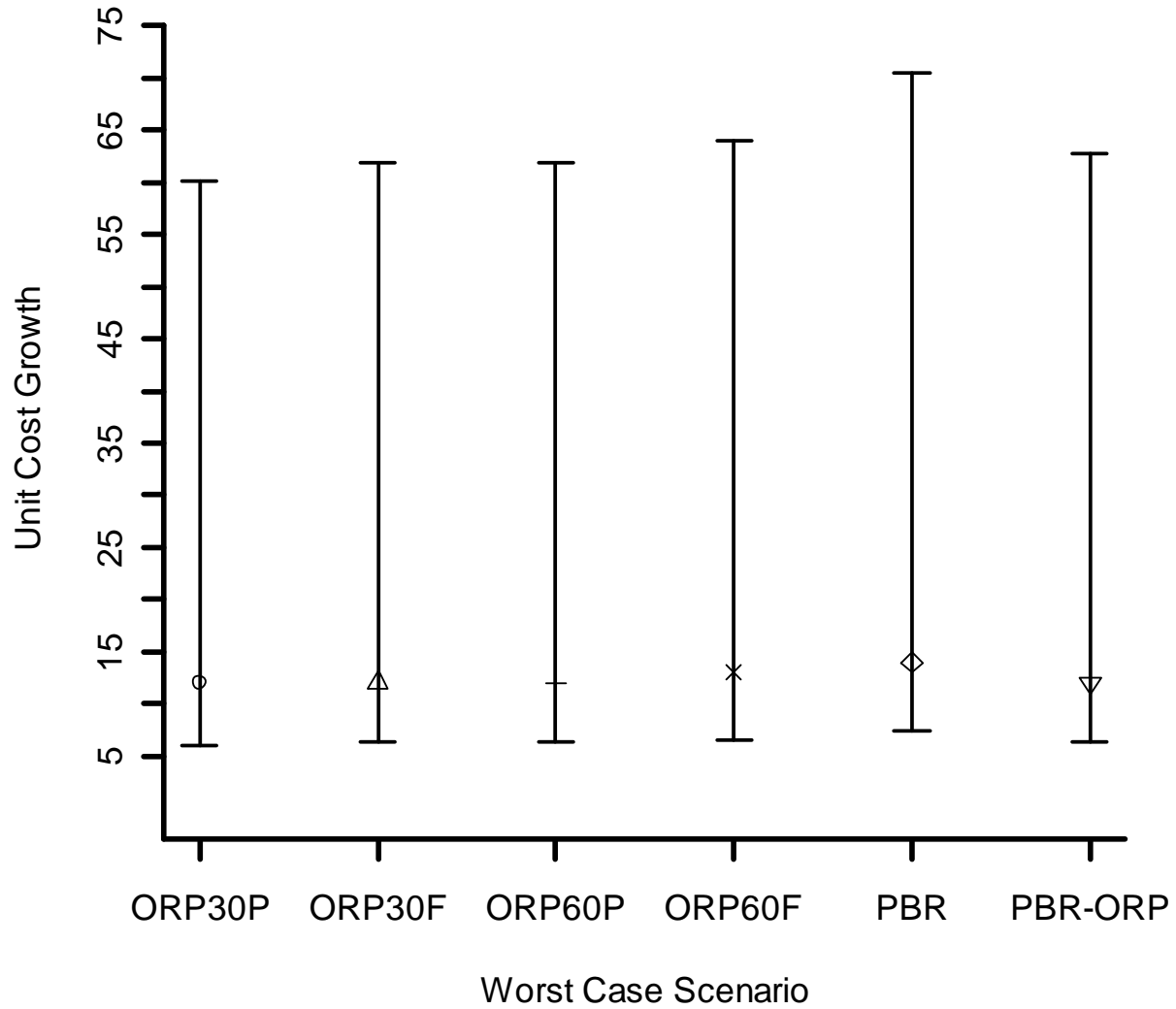


Figure 5b. Range of Unit Cost Growth Factors for three algal production worst case scenarios (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, fed by either P-Pure carbon dioxide or F-flue gas). Bars extend over range (low to high) of Unit Cost Growth Factors computed, based upon the confidence intervals of Cost Growth and Plant Performance.

Parametric Uncertainty: Monte Carlo Simulation

The estimated mean and 68% confidence intervals for the pioneer plant Cost Growth for each scenario from the Monte Carlo simulations are shown in Figure 6a. As expected the means do not vary from the previous FC results presented in Figure 3, nor do the means vary much between scenarios.

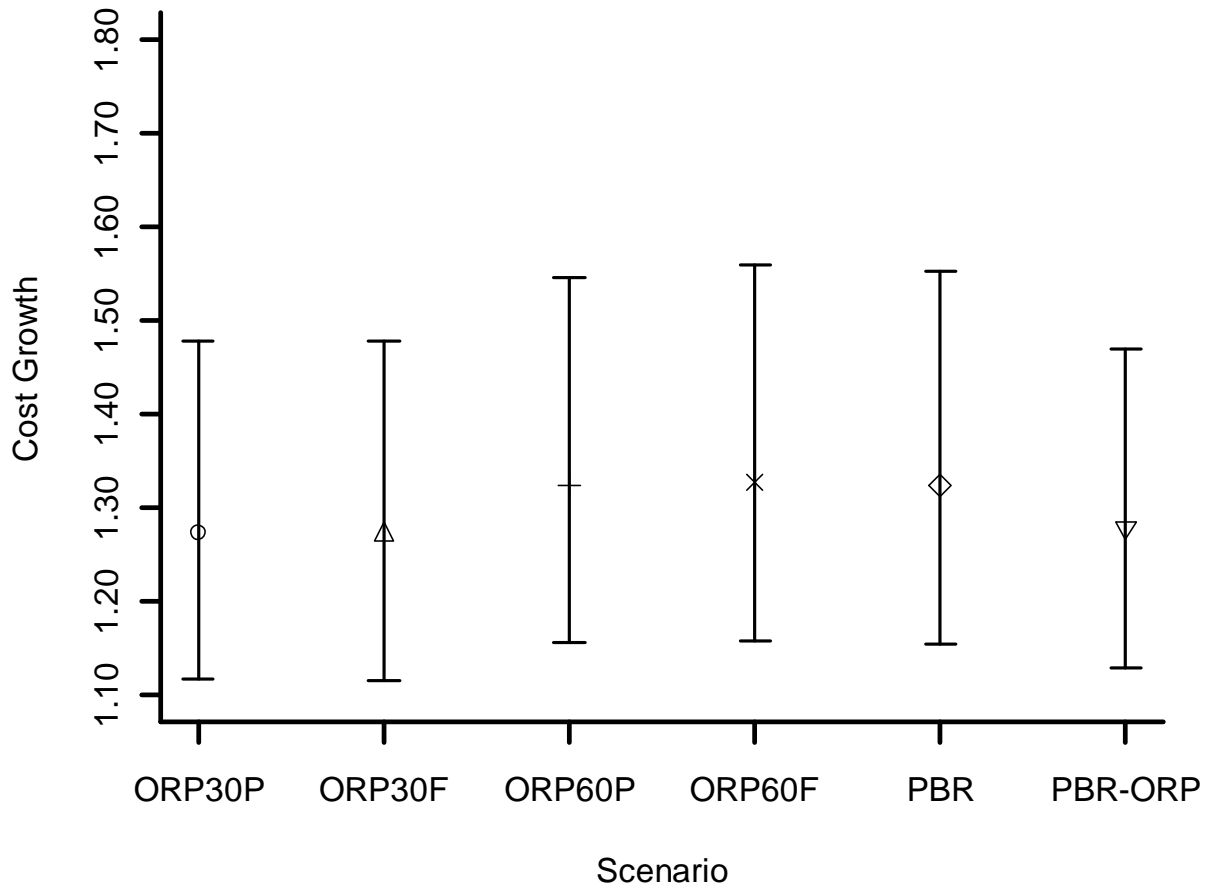


Figure 6a. Monte Carlo results displaying parametric uncertainty associated with RAND Cost Growth Model for algal production scenarios. (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, fed by either P-Pure carbon dioxide or F-flue gas).

The estimated mean and 68% confidence intervals for the pioneer Plant Performance for each scenario from the Monte Carlo simulations are shown in Figure 6b. As expected, the means do not vary from the previous FC results presented in Figure 4, while there is still the same 10% difference between ORP and the other two production scenarios.

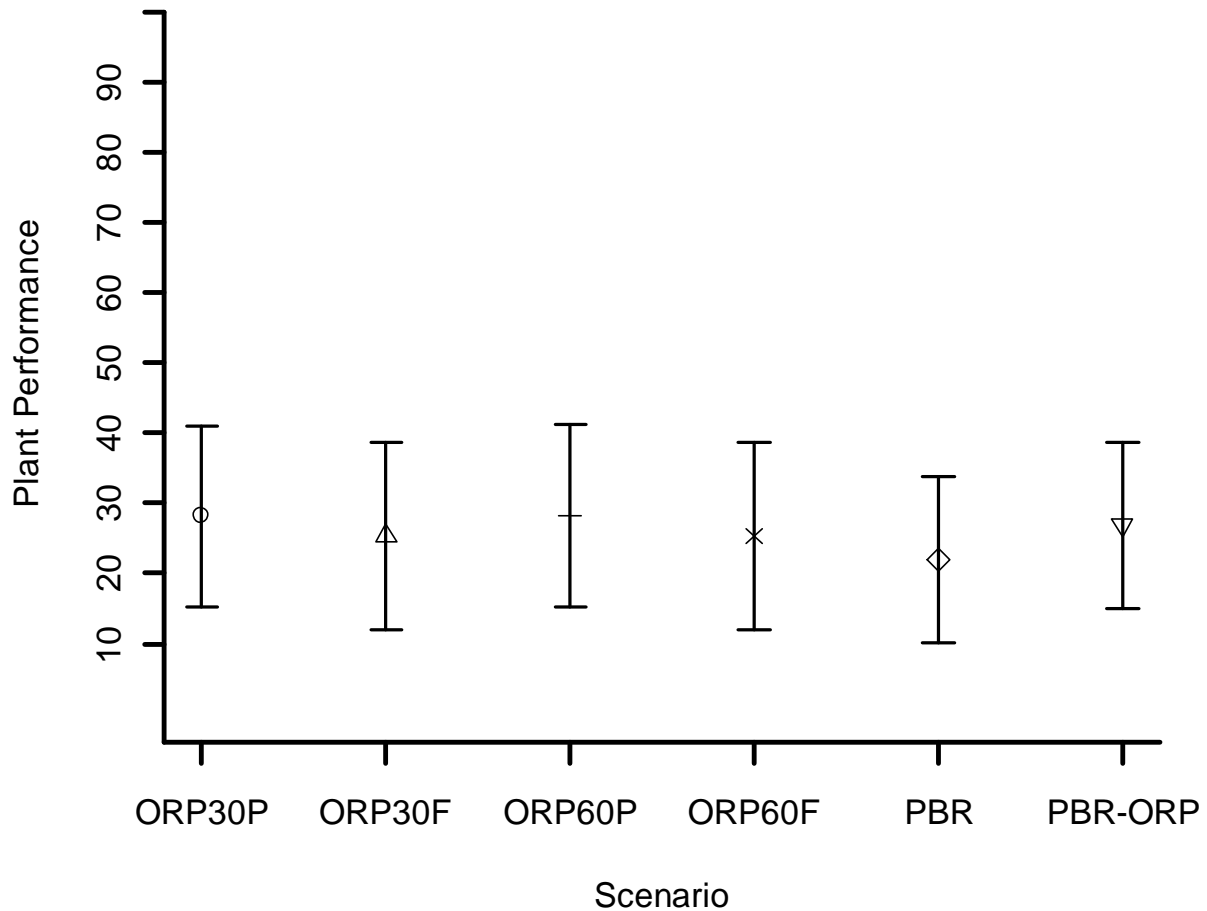


Figure 6b. Monte Carlo results displaying parametric uncertainty associated with RAND Plant Performance Model for algal production scenarios. (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, fed by either P-Pure carbon dioxide or F-flue gas).

Algal Production Scenario Uncertainty: Monte Carlo Simulation

The estimated mean and 68% confidence intervals for the pioneer plant Cost Growth for each scenario from the Monte Carlo simulations are shown in Figure 7a. The means are slightly greater than the previous FC results presented in Figure 3 but still vary a little between scenarios. The differences between Figure 7a and 6a are due to the RCGM accounting for the potential differences in PCTNEW and other model inputs as defined by the probabilities listed in Table 8. There is the potential for small Cost Growth or dangerously high Cost Growth for all scenarios.

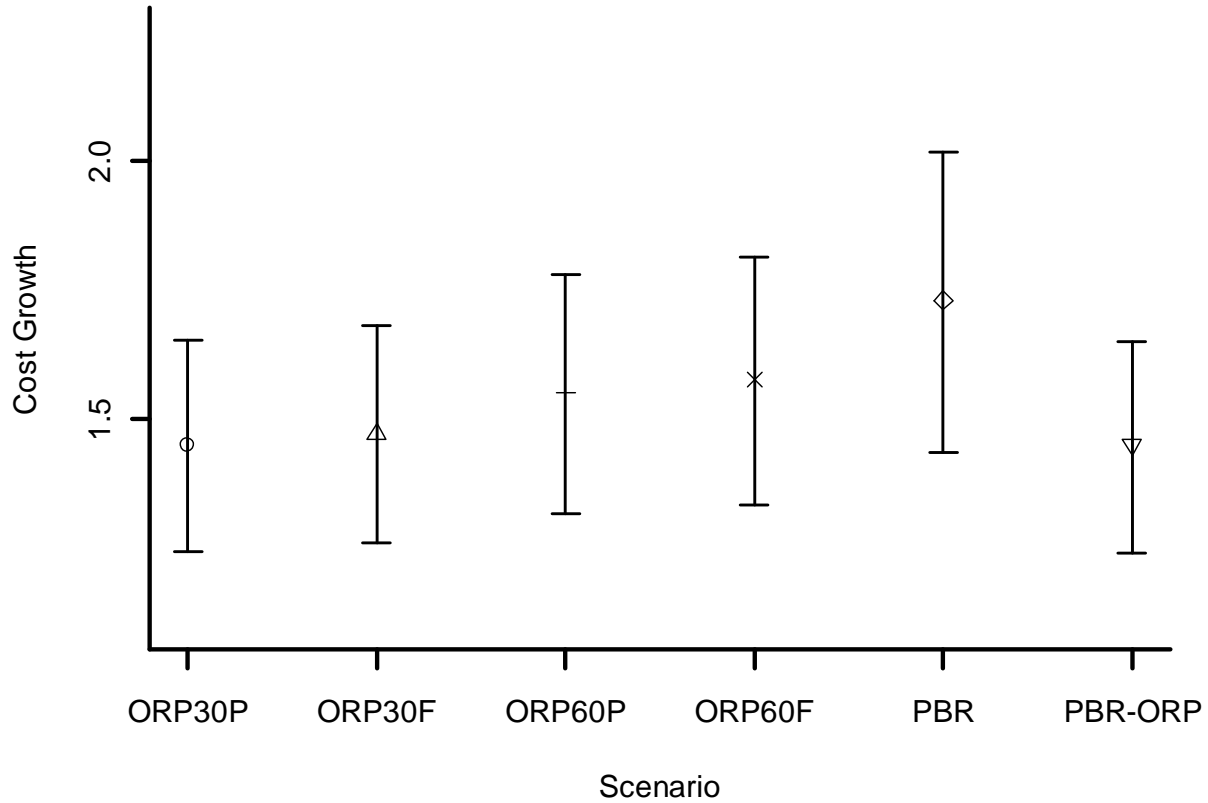


Figure 7a. Monte Carlo results displaying input uncertainty associated with RAND Cost Growth Model for algal production scenarios. (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, fed by either P-Pure carbon dioxide or F-flue gas).

The estimated mean and 68% confidence intervals for the pioneer Plant Performance for each scenario from the Monte Carlo simulations are shown in Figure 7b. The means are slightly less than the previous FC results presented in Figure 4 and vary a little between scenarios. This is likely due to RPPM being composed of inputs as listed in Table 2 that are poorly informed like BALANCE EQUATIONS. The model also does not include a way to provide discriminating information between the algal production scenarios. While the number of NEWSTEPS could be equal the technical

challenges incurred with each of the NEWSTEPS in the different production scenarios could be vastly different. While the Plant Performances seem similar it appears there is little potential for each scenario to reach full production capacity.

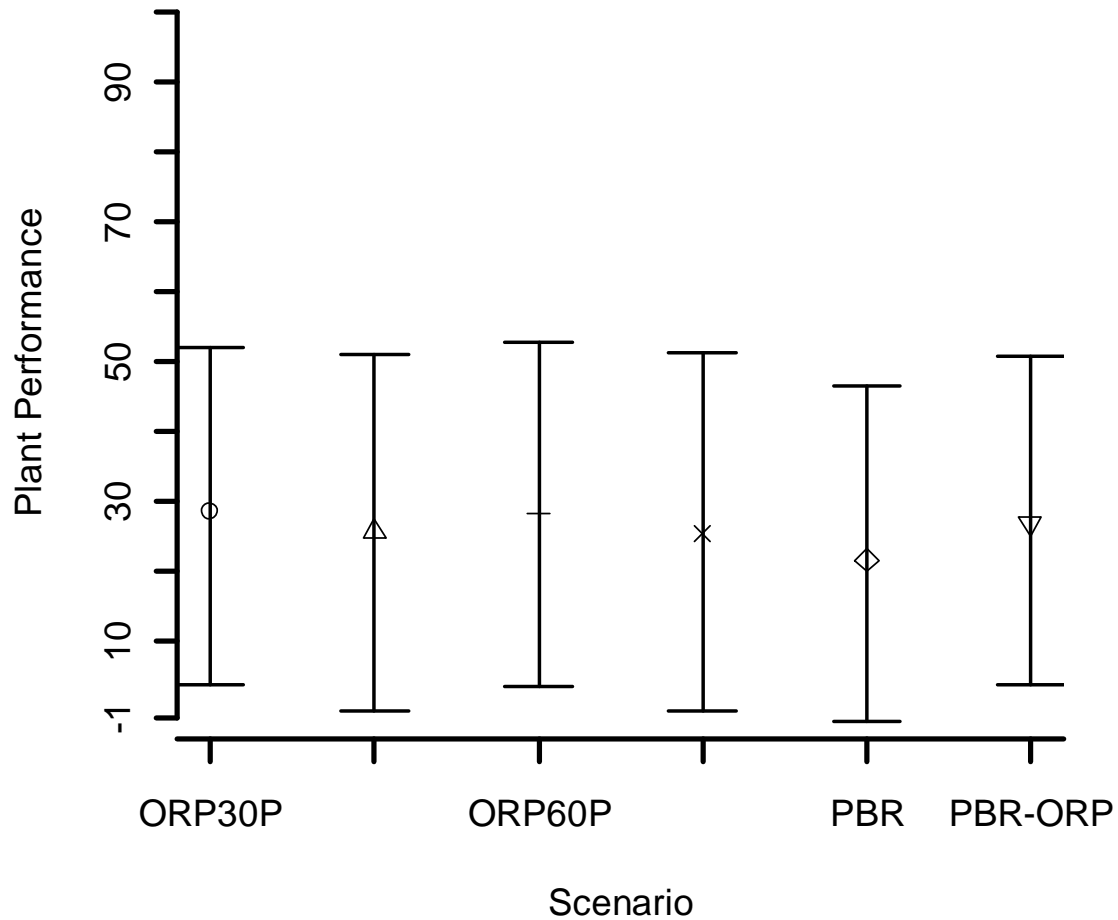


Figure 7b. Monte Carlo results displaying input uncertainty associated with RAND Plant Performance Model for algal production scenarios. (ORP-Open Raceway Pond, PBR-Photobioreactor, and ORP-PBR-Coupled Photobioreactors and Open Raceway Ponds, fed by either P-Pure carbon dioxide or F-flue gas).

Conclusions

For all of the scenarios considered, the greatest Cost Growth was predicted for the pioneer algae plant using the PBR technology production scheme outlined in Grima et al. (2003). The lowest Cost Growth was estimated for the ORP-PBR and ORP FC scenarios, this is perhaps not surprising because the ORP systems that exist at full-scale (not for biofuels production) have fewer, cheaper technologies being implemented. The lowest pioneer Plant Performance was predicted to be the PBR and PBR-ORP systems at the WC case. Contrastingly, the highest Plant Performance was estimated to be for the ORP scenarios at the FC case. Finally, the greatest Unit Cost Growth Factor was predicted to be for PBR system where the lowest Unit Cost Growth Factor predictions were for the ORP-PBR and ORP scenarios at the FC cases. While we decided in the beginning to leave scale out of the discussion to avoid disproportionate comparisons, it is important to note that there is nearly a 25 fold difference in total cost per hectare between the ORP and PBR/PBR-ORP systems modeled, even with similar Cost Growth factors and Plant Performance estimates the actual total price differences between the technologies will likely affect the adoption of technologies. While these results have large uncertainties, they highlight the high risks associated with implementing new technologies, as all production systems had some degree of Cost Growth and estimates of Plant Performance achieving less than 50% of the projected output.

These results suggest that the economic viability of pioneer algal production for biofuels is highly uncertain and risky. Given predictions for Unit Cost Growth Factor is predicted to be somewhere between three and 14 times greater than predicted, low cost

transportation fuels from algae are not producible given current and even proposed (PBR and ORP-PBR) technologies. Furthermore, if the algae are only 30% oil, that means the Unit Cost Growth Factor for algal oil would be somewhere between 10-46 times the proposed price. However, technological and economic data from the pilot plant algae production facilities of companies like Sapphire Energy or Solix that mentioned frequently in the media tout impressive technological developments and operations that could improve the economic outlook of low cost algal biofuels. But these extraordinary claims should be backed by extraordinary evidence (Sagan, 1979), ideally in the form of third-party validated cost estimates, or economically viable operation at fuel selling prices of \$87/bbl (selling price of crude as of 02-17-2011).

Demonstrating new technologies at larger than pilot scale that could improve industrial algal Plant Performance. This could improve the economic outlook for proposed algal biofuel production scenarios. Merrow et al. (1981) noted the decision to proceed with plants that incorporate a large percentage of new technology in a new process (like algal biofuels) should be based on the technology's long term prospects rather than the returns of first plants. The long term prospects for algal production could be predicted by projecting potential experience curve gains. The results of this analysis suggest that near and perhaps mid-term cheap algal biofuels seem unlikely.

Economically, it may be more sensible and profitable to move the focus from biofuels to the production of higher value chemicals produced by algae like Solix, an algal production company that has signed a collaborative agreement to make specialty chemicals with BASF, a global chemical manufacturer (Sims, 2010). Specialty chemicals like Astaxanthin, a high value compound that is less prevalent than oil in

algae, extracted from algae has value of around 7 M\$/Mg (Frucht and Kanon, 2005) which is approximately 11,000 times more valuable than a metric ton of crude oil at 83 \$/barrel, could serve to improve the economic viability of algal pioneer plants. While the cost of oil from algae could be offset by high value compounds, it seems unlikely that a company would focus on increasing the yield of low value compounds like oil over high value ones. However, the market for high value compounds is not as large as the market for transportation fuel so perhaps companies can learn from algae production aimed at high value products and then improve technology and methods that lead to competitive fuel production.

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Chapter 3. EIO-LCA based comparison of algal production technologies

Abstract

Algae are promoted as a feedstock for biofuel production offering cheap energy and climate change benefits. Yet estimates of the cost and environmental gains of algal production and conversion to biofuels vary widely due to differences in assumptions regarding factors like technology costs, productivity, and co-product credits. The Framework for the Evaluation of Biomass Energy Feedstocks (FEBEF), a spreadsheet-based model developed to normalize feedstock comparisons, was modified to include computations for feedstock to fuel conversion. The FEBEF was then employed to compare estimated economic, energetic, and environmental metrics of algae produced in Open Raceway Ponds (ORP), Photobioreactors (PBR), and a system that couples PBR with ORPs (PBR-ORPs). Assuming climactic conditions in New Mexico, Arizona, and Hawaii the biomass productivity, for ORPs, PBRs, and PBR-ORPs attained model yields of 66, 97, and 90 Mg/ha respectively, which is six times greater than the 2010 average US corn yield (10 Mg/ha). Estimates of fuel (biodiesel) energy cost (FEC) ranged from 53-107 \$/GJ. Including a co-product credit yielded the Total Energy Cost (TEC), which were in the range of 30-62 \$/GJ. The lowest FEC of biodiesel from ORPs is 53 \$/GJ corresponding to a TEC of 30 \$/GJ -a value equivalent with petroleum at 175 \$/bbl. Biodiesel from PBRs had the highest FEC (107 \$/GJ) along with a TEC of 62 \$/GJ. The biodiesel from algae produced in PBR and PBR-ORP released more GHG emissions, 105 and 107 kg CO_{2 eq}/GJ, respectively, than gasoline (67 kg CO_{2 eq}/GJ). In

contrast, ORP-sourced biodiesel had a Carbon Intensity of 56 kg CO_{2 eq}/GJ, a value lower than gasoline but not ethanol from corn (42 kg CO_{2 eq}/GJ). The Energy Return on Investment (EROI) including the Co-Product Credit for the different systems modeled ranged from 0.69 to 0.90; the lowest EROI was estimated for PBRs while the highest for ORPs. Without meaningful biological and physical engineering advances, cheap fuel energy from algae that offers climate change benefits seems unlikely in the near future.

Introduction

Algae have been promoted as an energy feedstock that can provide the world with about 1.3 trillion gallons of fuel per year, by only cultivating on tens of millions acres of marginal land (van Beilen, 2010). This and other claims surrounding the potential yields of cheap algal feedstocks for biofuels such as meeting global climate change goals and simultaneously meeting the world demand for liquid fuels are hopeful. Algal biofuels have been regularly suggested as alternatives to starch-based biofuels, because they have high yield potentials, avoid food-for-fuel competition, and claim lower green-house gas (GHG) emissions. Yet significant biological and engineering barriers remain to be overcome before these algal biofuels can compete economically with petroleum, and environmentally with starch and lignocellulosic based biofuels (van Beilen, 2010 and Clarens et al., 2010).

Most algae research focused on overcoming those barriers deal with phototrophic algae based production. The most inexpensive phototrophic algal production system uses Open Raceway Ponds (ORPs) as the growth system for algae. Open Raceway Ponds operate with depths of 15-30 cm and use paddlewheels for agitation, yet all open air systems are hampered by low productivity, difficulty in

maintaining sterility, and high harvesting costs due to low cell densities (Shen, 2009). Recently, closed photobioreactors (PBRs) have gained traction over ORPs due to their higher biomass productivity, lower harvesting costs, reduced contamination risks, larger surface area to volume ratios, and greater control over temperature, pH, light exposure, and nutrients (Shen, 2009; Chisti, 2007; Borowitzka, 1999). However, closed PBRs which are made of glass or plastic are expensive, with the large amounts of embedded energy in their production potentially offsetting their increased ability to harvest energy. A PBR-ORP coupled production system appears to leverage the sterility and high productivity offered by PBRs and the low capital costs of ORPs. Huntley and Redjale (2007) estimated the cost of producing algae oil in coupled PBR-ORP systems as 74 \$/bbl, and suggested that technological improvements could reduce the costs to \$51 per bbl. The group now operates as the company HP Biopetroleum. Recently, the Royal Shell company announced it will exit the joint venture between HP Biopetroleum and Shell, citing that “this decision will allow Shell to focus on other options that have shown a better fit with Shell’s biofuels portfolio and strategy” (Lane, 2011). This move suggests that the technical uncertainties and hurdles associated with the coupled system are not being solved fast enough to meet the investment standards and goals of Shell. Technical uncertainties remain problematic for emerging technologies such as flat panel PBRs, immobilized beds, and polymer bags, so while these technologies are thought to offer lower production costs and higher productivities than existing cultivation methods, their potential is extremely difficult to estimate.

Existing studies concerning ORP, PBR and coupled production systems have reported disparate estimates (Benemann and Oswald,1996; Chisti, 2007; Grima et al.,2003; Huntley &Redjale,2007), making it difficult to discern the economic feasibility and environmental impacts of algal biofuels. To address economic feasibility, systematic, internally-consistent, and conservative techno-economic analyses (TEA) of potential algae production and conversion schemes are needed. Similarly, to address greenhouse gas emission benefits, systematic, internally-consistent, and conservative life cycle analyses (LCA) of potential algae production and conversion schemes are needed. Reports of direct TEA and LCA comparisons between algae to biofuel production systems are limited.

The TEAs of algae production systems use unique assumptions and reporting methods. Shen (2009) reported cost estimates for the production of *Dunaliella salina* in open raceway ponds for lipid harvesting as \$3,500 Mg⁻¹ algal biomass. Chisti (2007) estimated algal biomass production cost as \$3,800 Mg⁻¹ in ORP systems intended for biodiesel production at production rates of 100 Mg yr⁻¹, and due to economies of scale a reduced cost of \$600 Mg⁻¹ algal biomass at annual production of 10,000 Mg yr⁻¹. While algal biomass production costs were calculated for three different algal production systems: open ponds, horizontal tubular photobioreactors and flat panel photobioreactors by Norsker et al. (2010) and found to be 6,580, 5,510, 7,920 \$/Mg, which can be attributed to differences in assumptions concerning scale and major equipment costs. Shen (2009) reported the cost of producing *S. almeriensis* for biofuels in a 30 m³ tubular PBR system was 34 \$/kg biomass. Grima et al., (2003) reported the production of *P. tricornutum* in tubular PBRs lead to a cost of \$32 per kg

biomass. These numbers can be compared to those reported for PBRs by Chisti (2007), who estimated \$2.95 per kg algal biomass production cost intended for biodiesel in PBRs at annual production of 100 Mg year⁻¹ and due to economies of scale a reduced cost of \$0.47 per kg algal biomass at annual production of 10,000 Mg year⁻¹. Gallagher (2010) reported a range of 2.33-3.33 \$/gal for biodiesel converted from algae grown in ORPs, while, Kovacevic and Wesseler (2010) estimated ORP-sourced diesel prices of approximately \$8.75 gal⁻¹ (\$70 GJ⁻¹). Given the differences in selecting a processing end point (biomass, oil, biodiesel) accurate comparisons across TEA studies are difficult.

The process based LCAs of algal production scenarios make different assumptions about system boundaries and units thus making comparisons difficult. These process LCA studies, while addressing environmental impacts and/or energy return on investment (EROI) (Murphy and Hall, 2010), frequently do not include a comprehensive economic analysis. For example, Lardon et al., (2009) completed a life-cycle assessment of biodiesel production from microalgae and made comparisons of a low-nitrogen algae culture to oilseed crops. Though algae biodiesel production via open raceway ponds appeared as the worst option compared to the other crops in certain impact areas like global warming and ozone depletion, it had low eutrophication potential and land use impacts but cited nothing in regards to economic potentials. In another example, Clarens et al. (2010) found similar results; algae outperform conventional feedstocks like corn in the impact areas of total land use and eutrophication potential but algae have higher impacts in energy use, GHG emissions, and water use but again cited nothing in regards to economic potentials. Another

example, Sander and Murphy's (2010) Well-to-Pump Process LCA thoroughly examined the energy and carbon dioxide emissions associated with the production of algae, both in total and as individual unit operations. Based on their study's system boundary, Sander and Murphy (2010) determined that with even given a low algae oil content, 5%, algal biofuel has a net energy gain, but has greater CO₂ emissions per unit energy than gasoline and did not provide any insight into the economic potential of the systems modeled. Another example where economic analysis is ignored was completed by, Stephenson et al. (2010) who found that the biodiesel from algae in ORPs had a 78% lower GWP and 85% lower energy input than fossil-derived diesel but the GWP of biodiesel from algae in PBRs was much greater, around 273% and 362% than fossil-derived diesel. A final example of a study examining algal production systems that ignored economics; Batan et al. (2010) found that polyethylene bag-based PBRs produced algal biodiesel with lower GHG emissions and energy inputs than soybean derived biodiesel, and lower GHG emissions than petroleum diesel. Batan et al. (2010) assumed that the algal species cultivated, *Nannochloropsis salina*, would achieve a 50% oil content in addition to assuming that the system would be located an area that would require little thermoregulation of the growth chambers. These assumptions (a low energy input for cooling or heating, low evaporation rates, and high energy output) help explain the Batan et al. (2010) contradictory findings when compared to other algae LCAs. Lastly, Campbell et al. (2011) completed a unique LCA and economic analysis of biodiesel production from algae in ORPs and compared the results to canola and diesel. While they found the GHG emissions to be lower for algae the production costs were lower for algae only under high productivities. The great variability in current estimates

for algal biomass and oil yields, production costs, and life cycle impacts for algal production scenarios is likely the result of a lack of a systematic approach to assessing each algal production technology.

Comparing the potential of different algal biofuels production systems to meet energy and climate change needs requires an understanding of the performance differences between them on several levels, including cost per unit energy, energy return on investment, and greenhouse gas production per unit energy delivered (Raman et al., 2010). However, the reports cited above fail to allow for such comparisons as they are based on process LCAs. Process LCAs are often complex, difficult to update and manipulate, difficult to compare across studies as assumptions and inputs vary, and can suffer from truncation errors. In contrast, Economic Input-Output LCA (EIO-LCA) offers a straightforward and comprehensive alternative. The EIO-LCA combines economic data with non-economic data such as greenhouse gas emissions. The EIO-LCA method includes all transactions and emissions from all sectors and therefore avoids the problem of boundary definition observed in process LCAs (Carnegie Mellon University Green Design Institute. 2008). Even “self-sector” transactions are included which eliminates the problem of circularity effects in process-based models. (Carnegie Mellon University Green Design Institute. 2008). However, using EIO-LCA for feedstock production assessments has challenges related to linking physical units and processes to expenditures in addition to the challenges incurred with the aggregated and dated data sources and assessing uncertainties related to EIO inputs (Raman et al. 2010, Hendrickson, 2006).

The Framework for the Evaluation of Biomass Energy Feedstocks (FEBEF) is a spreadsheet-based model that was originally developed to address problems associated with Process LCAs and EIO-LCAs that allowed for comparison of feedstocks on various economic, energetic, and environmental metrics, on an as-harvested basis (Raman et al., 2010). That is, the original FEBEF model did not include the economic, energy, and lifecycle costs of feedstock conversion to fuel, thus limiting the utility of the insight that could be provided by the model. To overcome this limitation, we modified FEBEF to include computations through fuel conversion. The model was enhanced so that it still provided comparison between feedstocks on the same group of economic, energetic, and environmental metrics.

FEBEF utilizes a collection of meteorological, plant physiological, agronomic, and economic inputs. Employing FEBEF allows for not only commensurate economic, energetic and environmental metrics of different algal production scenarios but also identification of pinch points, the most costly, energy consuming and greenhouse gas producing steps, in production systems. Comparison of key metrics and identification of pinch points could help inform researchers and investors with future algae to fuel production developments. FEBEF partitions feedstock dependent information in such a way that allows for side by side comparisons of input categories such as costs and physiological factors which impact the computational minor and major outputs. The goal of the work was to systemically compare the potential of three algal production systems using the modified version of FEBEF by assessing key economic, energetic, and environmental metrics.

Materials and Methods

The three different potential algal production systems modeled and their assumed locations are Open Raceway Ponds (ORP), in Tucumcari, NM, Photobioreactor (PBR) in Phoenix, AZ, and a coupled PBR-ORP system in Honolulu, HI. The locations were chosen because of the solar energy (all three offer more than 200 days of production) and non-arable land availability. Specifically, ORP were placed in NM because of past efforts by the DOE to operate ORPs there along with algae start-ups like Solazyme. Similarly, PBRs were placed in AZ to avoid the high evaporation observed with ORPs. Finally, HI was chosen for the coupled system because of the ability to compare these results with those already published for the coupled algal production facility in HI. Each operation was assumed to have 100 ha production area, with algae achieving algal oil content (AOC) of 30% for all scenarios and oil transesterification efficiency (TE) of 98%.

We used FEBEF to (i) document and transform knowledge and assumptions as detailed in the appendix about algae production systems' biology and costs into clearly defined line-items that are common across biomass feedstocks and production and conversion systems, (ii) perform distinct internal computations that serve to connect meteorological, plant physiological, agronomic, and economic inputs to key outputs which are described explicitly in the appendix (iii) estimate multiple performance metrics for each of the systems, including: MHY (Maximum Harvestable Yield, Mg/ha/yr), MEYG, (Maximum Energy Yield Gross, GJ/ha/yr), MEYN (Maximum Energy Yield Net, GJ/ha/yr), $EROI_{raw}$ (Energy Return on Investment, dimensionless), BPC (Biomass Production Cost, USD/Mg), EPC-as harvested basis, (Energy Production Cost,

USD/GJ), GHG-Areal-Production(kg CO_{2 eq}/ha/yr), and GHG Intensity-Production (kg CO_{2 eq}/GJ).

We modified FEBEF to extend the system boundary of the LCA to including processing biomass into fuel. To do so, the Primary Results worksheet (PR tab) was amended to include economic and environmental impacts for the conversion of biomass feedstocks to liquid transportation fuels, in the case of algae the fuel modeled was biodiesel. A series of assumptions, theoretical calculations, and custom model EIO-LCA multipliers were used to estimate additional key model outputs as shown in Table 1. The exact steps to compute the newly added model performance metrics is described below.

Table 1. Conversion computations and key model outputs added to FEBEF.

Output	Units	Abbreviation
Transportation Fuel Energy Out	GJ _{out} /Mg Biomass	TFEO
Maximum Fuel Energy Yield –Net Converted	GJ/ha/yr	MFEY _{NC}
Maximum Fuel Energy Yield –Net Converted with Co-Product Credit	GJ/ha/yr	MFEY _{NCCP}
Energy Return on Investment without Co-Product Credit	dimensionless	EROI
Energy Return on Investment with Co-Product Credit	dimensionless	EROI _{CPC}
Fuel Energy Cost	USD/GJ	FPC
GHG Total –Areal Basis	kg CO _{2 eq} /ha/yr	GHG _{TAB}
Carbon Intensity of Fuel Energy Source	kg CO _{2 eq} /GJ	CIFES

Transportation Fuel Energy Out

The TFEO was based on AOC, Transesterification Efficiency (mass biodiesel/mass raw oil) and the energy content of biodiesel (ECB) from microalgae, 41 MJ/kg (ref), as shown in equation 1:

$$TFEO \left(\frac{GJ_{out}}{dry\ Mg\ biomass} \right) = AOC \left(\frac{kg\ oil}{kg\ biomass} \right) * Transesterification\ Efficiency * ECB \left(\frac{GJ}{Mg} \right)$$

(eq. 1)

Total Fuel Energy Yield

The TFEY was based on TFEO and the Maximum Harvestable Yield (MHY) as shown in equation 2:

$$TFEY \left(\frac{\frac{GJ_{out}}{ha}}{yr} \right) = TFEO \left(\frac{GJ_{out}}{dry\ Mg\ biomass} \right) * MHY \left(\frac{dry\ Mg\ biomass}{ha} \right) \text{ (eq. 2)}$$

Co-Product Credit

The Co-Product Credit was assumed to be the energy content in the de-oiled algal biomass sold as feed as shown in equation 3:

$$CPC \left(\frac{GJ_{out}}{L\ biodiesel} \right) = \frac{Deoiled\ Algae\ Biomass \left(\frac{GJ}{Mg\ Biomass} \right)}{Biodiesel\ Yield \left(\frac{L}{Mg\ Biomass} \right)} \text{ (eq. 3)}$$

Indirect GHG Emissions

The Indirect GHG Emissions associated with the conversion of the algal biomass to biodiesel was estimated using a custom GHG EIO-LCA Multiplier, a literature based estimate for the cost of conversion (CC), and the TFEY as shown in equation 4. The

custom GHG multiplier for algae biodiesel conversion was built using an economic impact study of biodiesel (Urbanchuck , 2007) and the EIO-LCA custom model tool (Carnegie Mellon University Green Design Institute, 2010). Specifically, the purchases (\$/yr) made by the biodiesel industry from 11 sectors of the economy were used as inputs in the EIO-LCA custom model tool to compute the associated GHG output for each sector given those expenditures.

$$I_{GHG} \left(\frac{Mg CO_2e}{ha yr} \right) = GHG_{EIO} \left(\frac{Mg CO_2e}{\$} \right) * CC \left(\frac{\$}{GJ_{out}} \right) * TFEY \left(\frac{GJ_{out}}{ha yr} \right)$$

(eq.4)

Carbon Intensity of Fuel Energy Source

The sum of the conversion and production GHG direct and indirect emissions term gave the total GHG on an areal basis. The Carbon Intensity of Fuel Energy Source (CIFES) was calculated by using the GHG total (areal basis) and TEFY as shown in equation 5:

$$CIFES \left(\frac{kg CO_2e}{GJ_{out}} \right) = \frac{GHGT \left(\frac{MT CO_2}{ha yr} \right)}{TEFY \left(\frac{GJ_{out}}{ha yr} \right)} * 1000(kg/Mg) \text{ (eq. 5)}$$

Indirect Energy for Conversion

The Indirect Energy for Conversion (ID_{Energy}) of the algal biomass to biodiesel was estimated using a custom Conversion Energy EIO-LCA Multiplier, a literature based estimate for the cost of conversion, and the TFEY as shown in equation 6. The custom Conversion Energy multiplier was built using an economic impact study of biodiesel (Urbanchuck (2007)) and the EIO-LCA custom model tool (Carnegie Mellon

University Green Design Institute. 2010). Specifically, the purchases (\$/yr) made by the biodiesel industry from 11 sectors of the economy were used as inputs in the EIO-LCA custom model tool to compute the associated energy expended by each sector given those expenditures.

$$ID_{Energy} \left(\frac{GJ}{yr} \right) = Conversion\ Energy_{EIO} \left(\frac{GJ}{\$} \right) * Cost\ of\ Conversion \left(\frac{\$}{GJ_{out}} \right) * TFEY \left(\frac{GJ_{out}}{ha\ yr} \right)$$

(eq. 6)

Maximum Fuel Energy Yield-Net Converted

The Maximum Fuel Energy Yield-Net Converted (MFEY_{NC}) for producing and converting algal biomass to biodiesel was estimated using TFEY, Total Energy Use (direct and indirect) for Production (TEUP), and Total Energy Use for Conversion (TEUC) as shown in equation 7, where all terms are in units of GJ ha⁻¹ yr⁻¹.

$$MFEY_{NC} = TFEY - TEUP - TEUC \text{ (eq. 7)}$$

Maximum Fuel Energy Yield-Net Converted with Co-Product Credit

The TFEY, Total Energy Use (direct and indirect) for Production (TEUP), and Total Energy Use for Conversion with Co-Product Credit (TEUC_{CPC}) were used to compute the Maximum Fuel Energy Yield-Net Converted with Co-Product Credit (MFEY_{NC-CPC}) for producing and converting algal biomass as shown in equation 8, where all terms are in units of GJ ha⁻¹ yr⁻¹.

$$MFEY_{NC-CPC} = TFEY - TEUP - TEUC_{CPC} \text{ (eq. 8)}$$

Energy Return on Investment (EROI)

The TFEY and Total Energy Use for Production and Conversion (TEUPC) were used to compute the Energy Return on Investment (EROI) as shown in equation 9, where all terms are in units of $\text{GJ ha}^{-1} \text{ yr}^{-1}$.

$$EROI = \frac{TFEY}{TEUPC} \text{ (eq. 9)}$$

Energy Return on Investment (EROI) with Co-Product Credit

The TFEY, CPC and Total Energy Use for Production and Conversion (TEUPC) were used to compute the Energy Return on Investment (EROI) as shown in equation 10, where all terms are in units of $\text{GJ ha}^{-1} \text{ yr}^{-1}$.

$$EROI_{CPC} = \frac{TFEY + CPC}{TEUPC} \text{ (eq.10)}$$

Cost for Conversion of Fuel Energy Produced

The TFEY and cost of conversion were used to compute Cost for Conversion of Fuel Energy Produced (CCFEP) as shown in equation 11:

$$CCFEP \left(\frac{\$}{\text{ha}} \right) = TFEY \left(\frac{\text{GJ}}{\text{ha}} \right) * \text{Cost of Conversion} \left(\frac{\$}{\text{GJ}} \right) \text{ (eq.11)}$$

Total Cost for Fuel Energy Produced

The Total Cost for Production and the CCFEP were used to compute Total Cost for Fuel Energy Produced as shown below in equation 12 where all terms are in units of $\$ \text{ ha}^{-1} \text{ yr}^{-1}$.

$$TCFEP = TCP + CCFEP \text{ (eq.12)}$$

Fuel Energy Cost

The CCFEP and the TFEY were used to compute Cost for Fuel Energy Produced (CFEP) as shown in equation 13:

$$FEC \left(\frac{\$}{GJ} \right) = CCFEP \left(\frac{\$}{ha} / yr \right) / TFEY \left(\frac{GJ}{ha} / yr \right) \text{ (eq. 13)}$$

Total Energy Cost (production, conversion (fuel and co-product credit)

The Cost for All Energy Produced (CAEP) including fuel and co-product credits from production to conversion was estimated as shown in equation 14:

$$TEC \left(\frac{\$}{GJ_{out}} \right) = TCFEP \left(\frac{\$}{ha} / yr \right) / \left(TFEY \left(\frac{GJ_{out}}{ha} / yr \right) + CPC \left(\frac{GJ_{out}}{ha} / yr \right) \right) \text{ (eq.14)}$$

EIO-LCA Uncertainties

The properties that make EIO-LCA a simpler, transparent, and comprehensive alternative to Process LCA also limit in its use and accuracy. Because the data are aggregated the method becomes inadequate for comparison of products from the same industry classification and more importantly limits the detail achieved in analysis (Lave et al., 1995). EIO-LCA also has challenges in linking dollar values to physical units (Raman et al., 2010). Additionally, with EIO-LCA proportionality is assumed for both input and emission intensities and does not reflect improvements for both intensities that can be realized with economies of scale (Hendrickson, 2006). Perhaps more important in this model is the pairing of current and future economic activity to environmental impacts of the past. While the economy is dynamic there is considerable consistency over time; changes in the coefficients for the economic flows between sectors is relatively stable over time while the environmental outputs are subject to

greater change to due standards and technological advancements (Lave et al. 1995, Hendrickson, 2006). Yet, the strengths related to the versatility and transparency of the EIO-LCA method offset the uncertainties in outputs which can be examined using Monte Carlo analysis and the limitations due to aggregation which can be dealt with by building custom models.

Results and Discussion

Biomass production from algae in ORP, PBRs and PBR-ORP systems were compared on the basis of MHY (Maximum Harvestable Yield, Mg/ha/yr), BPC (Biomass Production Cost, USD/Mg), EPC-as harvested basis, (Energy Production Cost, USD/GJ), GEY (Gross Energy Yield, GJ/ha/yr), NEY (Net Energy Yield, GJ/ha/yr), EROI-Production (Energy Return on Investment, dimensionless), GHG-Areal-Production (kg CO₂ eq/ha/yr), and GHG Intensity-Production (kg CO₂ eq/GJ). The greatest biomass production was found to be with PBR's in Arizona as shown in figure 1, nearly 50% greater than the ORP but only 7% greater than the PBR-ORP. All of the yields for algae from the different systems are more than triple the MHY of terrestrial crops modeled in FEBEF such as corn and Miscanthus which were 20 and 18 Mg/ha/yr (Raman et al., 2010) which supports the claims about the higher productivity of algae over terrestrial crops.

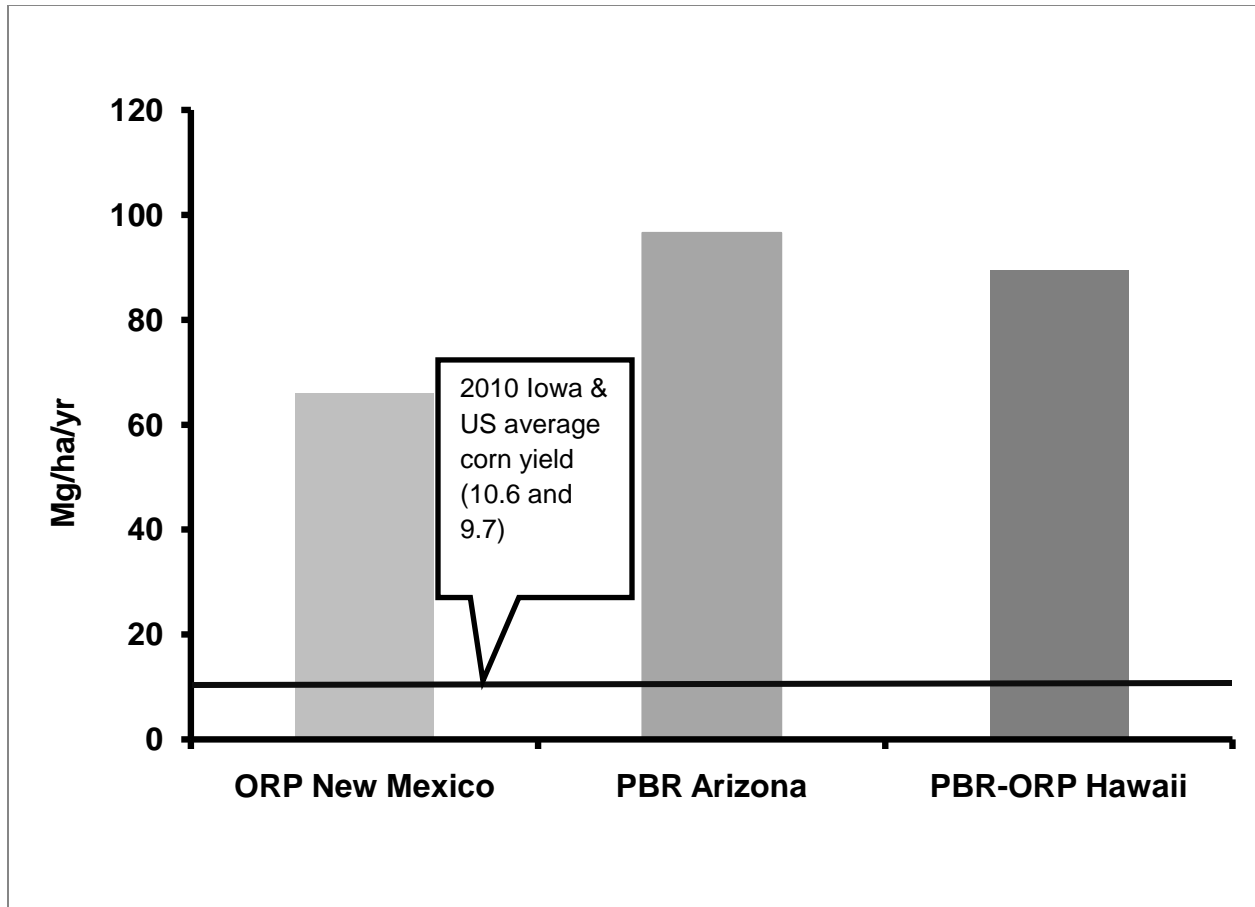


Figure 1: Maximum Harvestable Yield of Algal Biomass for Algae Production Scenarios.

Iowa 2010 state average corn grain harvests^a and estimated US 2010 average total corn harvest^b lines are provided for reference.

^a <http://www.extension.iastate.edu/CropNews/2010/1008elmore.htm>)

^b http://www.agweb.com/article/usdas_crop_estimates_dominant_2010_news/)

However, the BPC (Biomass Production Cost, USD/Mg) values indicate that unit costs for algae are more than triple the costs of terrestrial crops. The profile for the BPC, which includes the cost for drying the biomass, indicates that the cost of algal biomass from PBRs is more than double that of the PBR-ORP and the ORP as shown in figure 2. Amortized capital costs and labor costs account for these large differences in

BPC: Amortized capital costs are nearly 5 times greater for PBRs than for ORPs and PBR-ORPs, while labor costs are more than 6 and 3 times greater for PBRs than ORPs and PBR-ORPs, respectively. The BPC values found with FEBEF are lower for ORPs than the 600-3800 \$/Mg reported by Shen (2009), Chisti (2007), and Nosker (2010). The BPC values estimated with FEBEF fall within the large range discussed above (470-34,000 \$/Mg) for PBRs. Contrary to Huntley and Redjale (2007), FEBEF predicts that there is no economical benefit gained by utilizing the PBR-ORP system; the biomass production cost is nearly the same for the ORP and PBR-ORP system. This discrepancy is most likely due to Huntley and Redjale (2007) assumption about the capital costs of PBRs being 100 \$/m² which FEBEF does not make. Additionally, the facility that Huntley and Redjale (2007) discussed uses a unique deep sea cooling system that was built in Hawaii and it is unlikely that the system can be replicated elsewhere without significantly (approximately 20% of total capital costs) adding to capital costs and thus BPC.

Unsurprisingly, the BPC profile is echoed in the as-harvested EPC (Energy Production Cost, USD/GJ), as illustrated in figure 3. The EPC is greatest for energy production on an as harvested basis from algae in PBRs, more than double the predicted EPCs for ORP and PBR-ORP systems. It is important to note that the energy on an as harvested basis means the biomass has not been converted to a common, useful fuel. Such conversion will increase costs while reducing net energy gains.

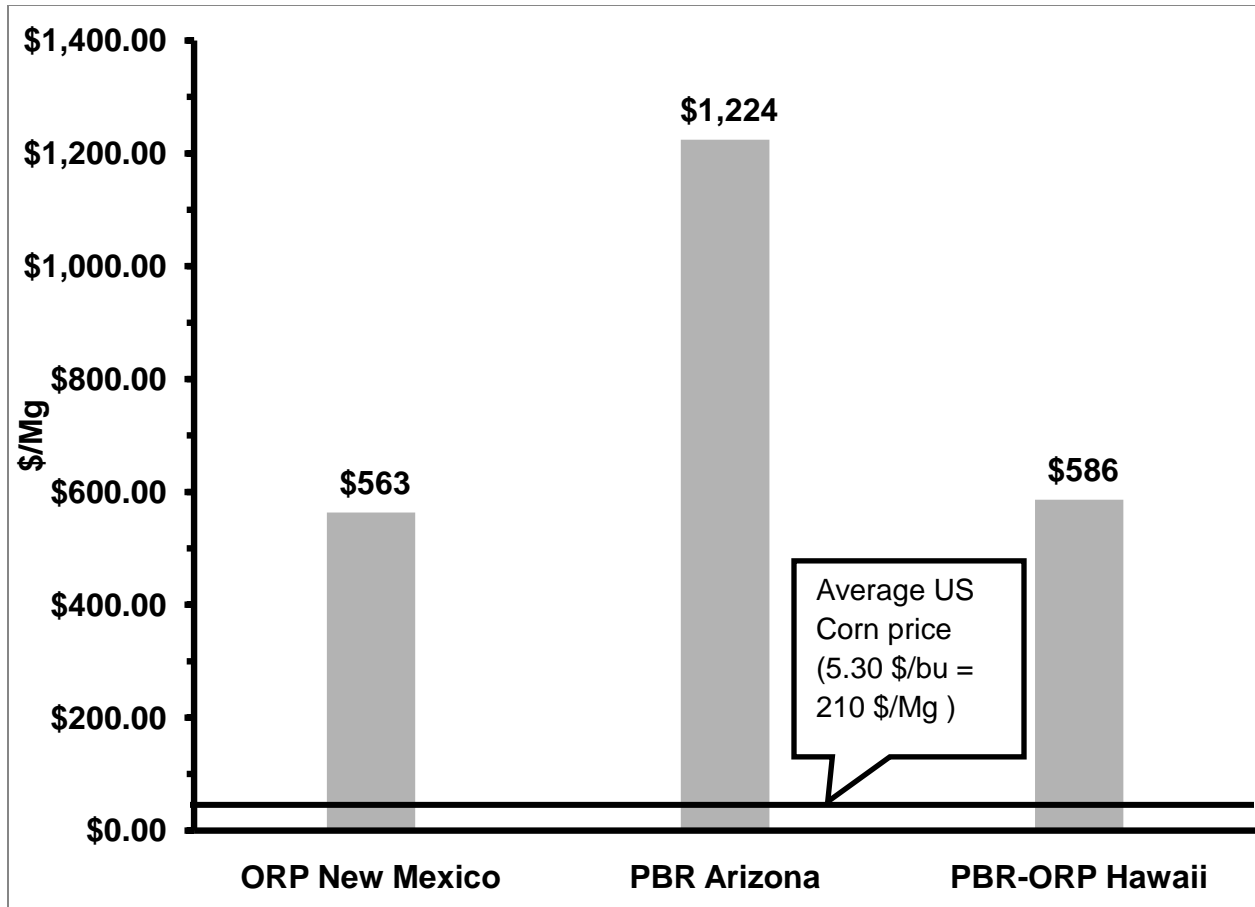


Figure 2: Estimates for Algal Biomass Cost for Algae Production Scenarios with US 2010 average corn grain price line is provided for reference (<https://www.msu.edu/~hilker/outlook.htm>).

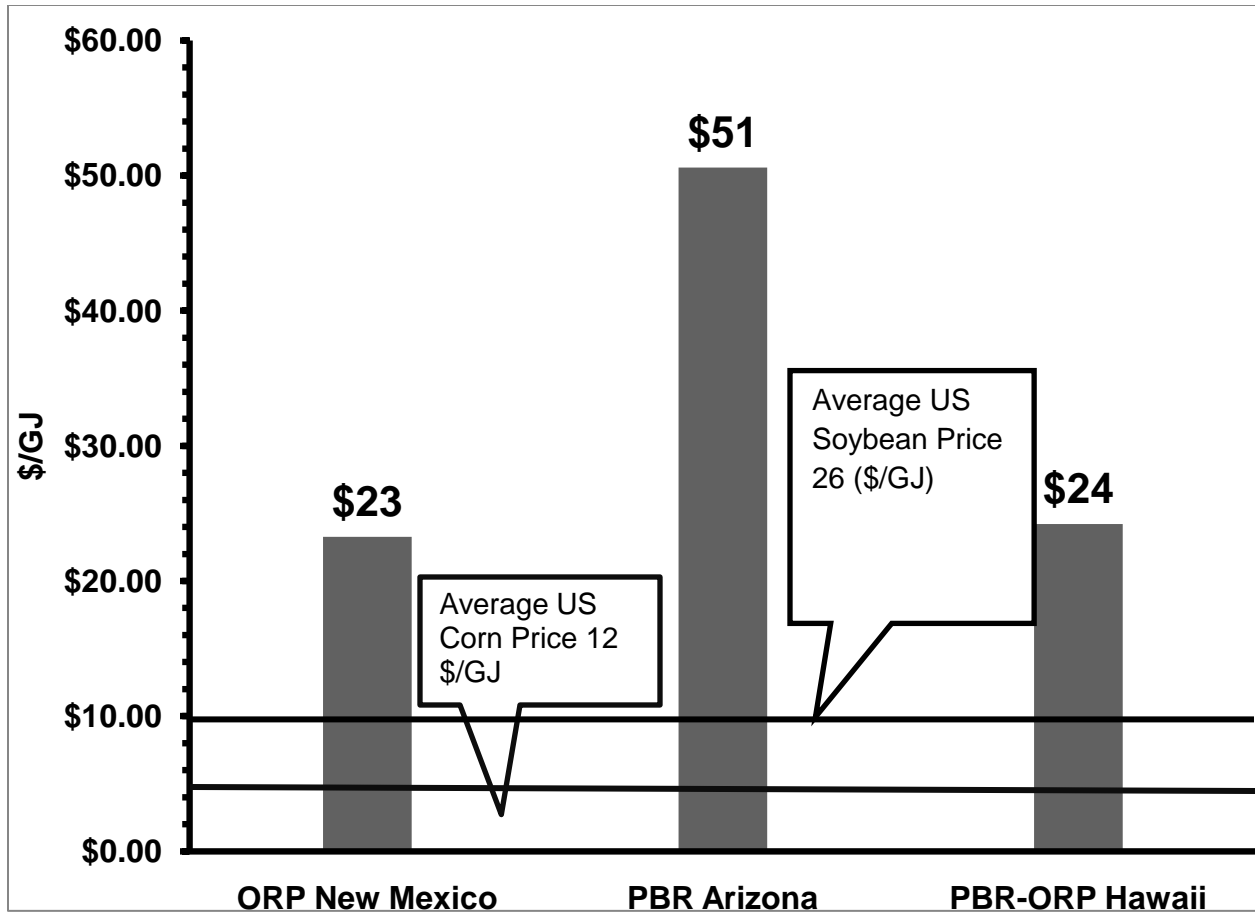


Figure 3: Energy Production Cost of Harvested Algal Biomass for Algal Production Scenarios. US 2010 average corn grain and soybean price lines, converted into cost per unit energy, are provided for reference: (<http://cornandsoybeandigest.com/issues/2010-crop-production-declines>).

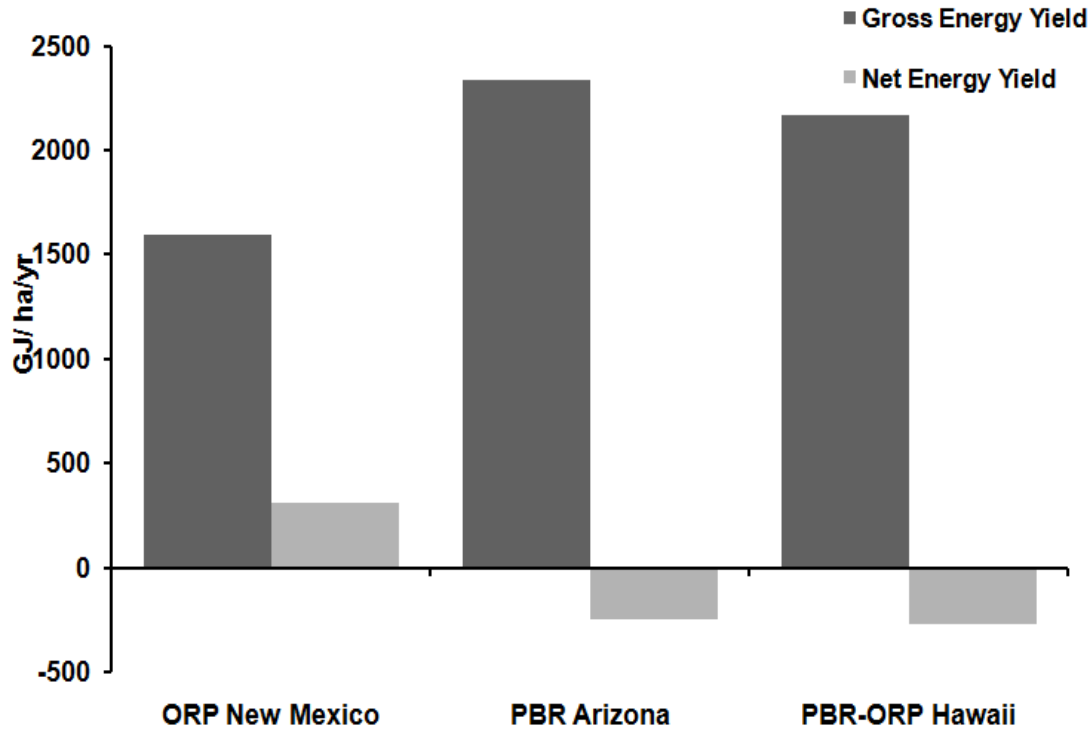


Figure 4: Gross and Net Energy Yield for Harvested Algae Biomass

The energy produced on an as harvested basis is only positive for algal produced in the ORP system, as shown in figure 4. While the Gross Energy Yield (GEY) is greatest for the PBR system, the Net Energy Yield (NEY) is negative, even prior to conversion of the algal oil into biodiesel which adds an insignificant amount of energy use. The differences in energy yields can be explained by the differences in embedded energy of labor and amortized capital for the algae production systems. The PBR systems have the highest estimated capital and labor costs.

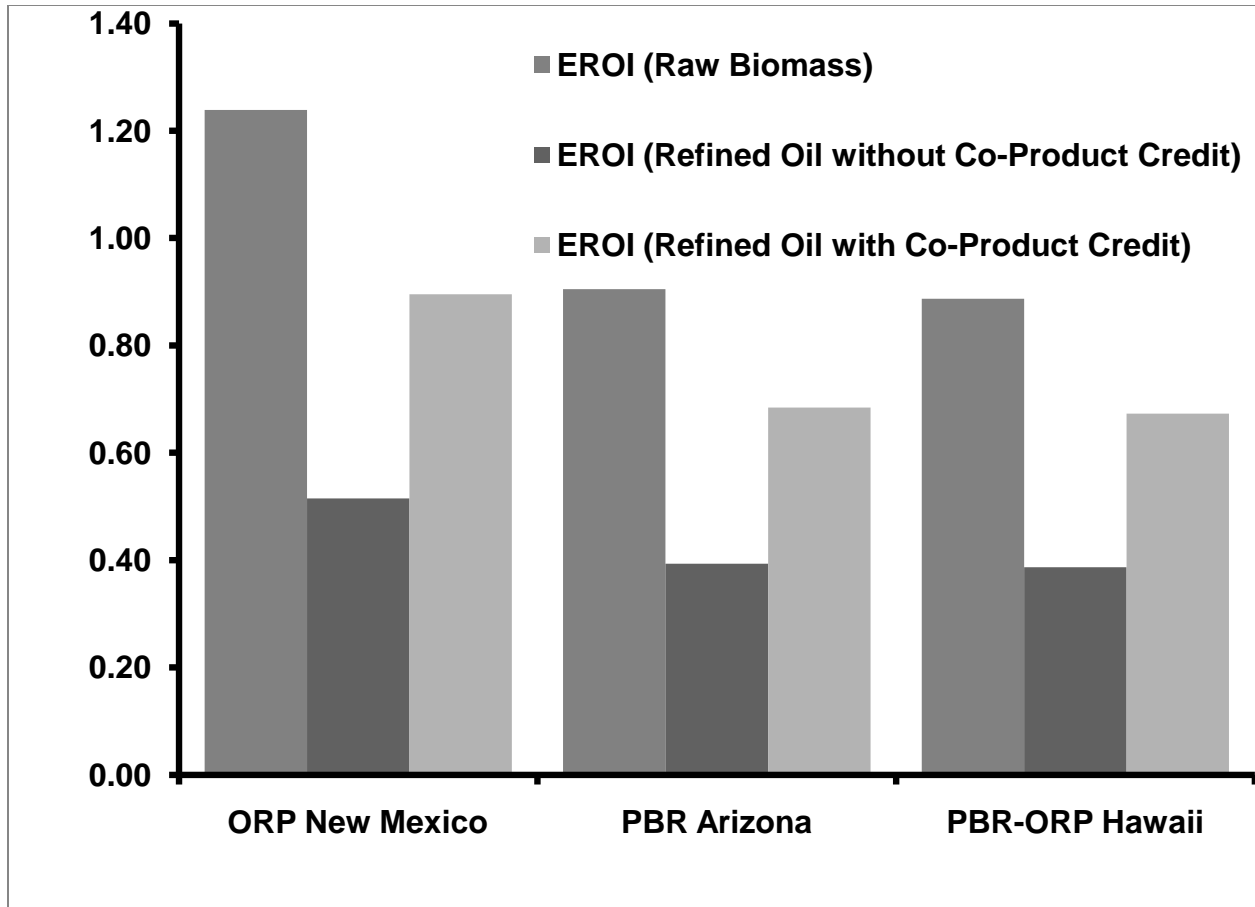


Figure 5: EROI for Production of Raw Biomass, Refined oil without Co-Product Credit, and Refined oil with Co-Product Credit.

Correspondingly, the EROI (for production only), the ratio of GEY to energy input, was lowest for the PBRs and the coupled PBR-ORP system, and greatest for the ORP as shown in figure 5. Following conversion of algal oil to biodiesel, the EROI, the ratio of MFEY_{NC} to energy input (production and conversion), has a similar profile to the EROI for production as shown in Figure 5. The EROI even when including the energy gained with the co-product credit is lower for the PBRs and the coupled PBR-ORP system, and greatest for the ORP. Yet the EROI of these systems is quite low, near or below one. The EROIs without the Co-Product Credit and with Co-Product Credit for corn and

Miscanthus biologically converted to ethanol as reported by Raman et al. (2010) are greater than all algae biofuels conversion systems, 2.9 and 3.9, and 4.0 and 4.6, respectively. Farrell et al. (2007) and Hammerschlag (2006) both reported on studies of ethanol from corn to have an EROI ranging between 1.2 and 1.6. Pradhan et al. (2008) reported a range of EROIs from past studies for biodiesel from soybeans to be 0.79 to 3.21. It appears the claims and even the modeled potential about high yields for algae biomass does not translate into promising EROIs given estimates about current technologies.

The model accounts for the direct energy needed to reduce the moisture content of algae to a specified level for fuel conversion. We made a fairly optimistic assumption that only 20% of the direct energy required for complete water removal is needed for which the accounting is detailed in the appendix. It is important to note that the EROI is sensitive to the direct energy requirements for drying algae. If oil moisture removal unit operations can greatly reduce energy inputs or be skipped entirely, the EROI of these systems improve greatly, the EROI (Production only) for the ORP system was predicted to be 2.6 with an EROI for biodiesel with the co-product credit was predicted to be 1.6.

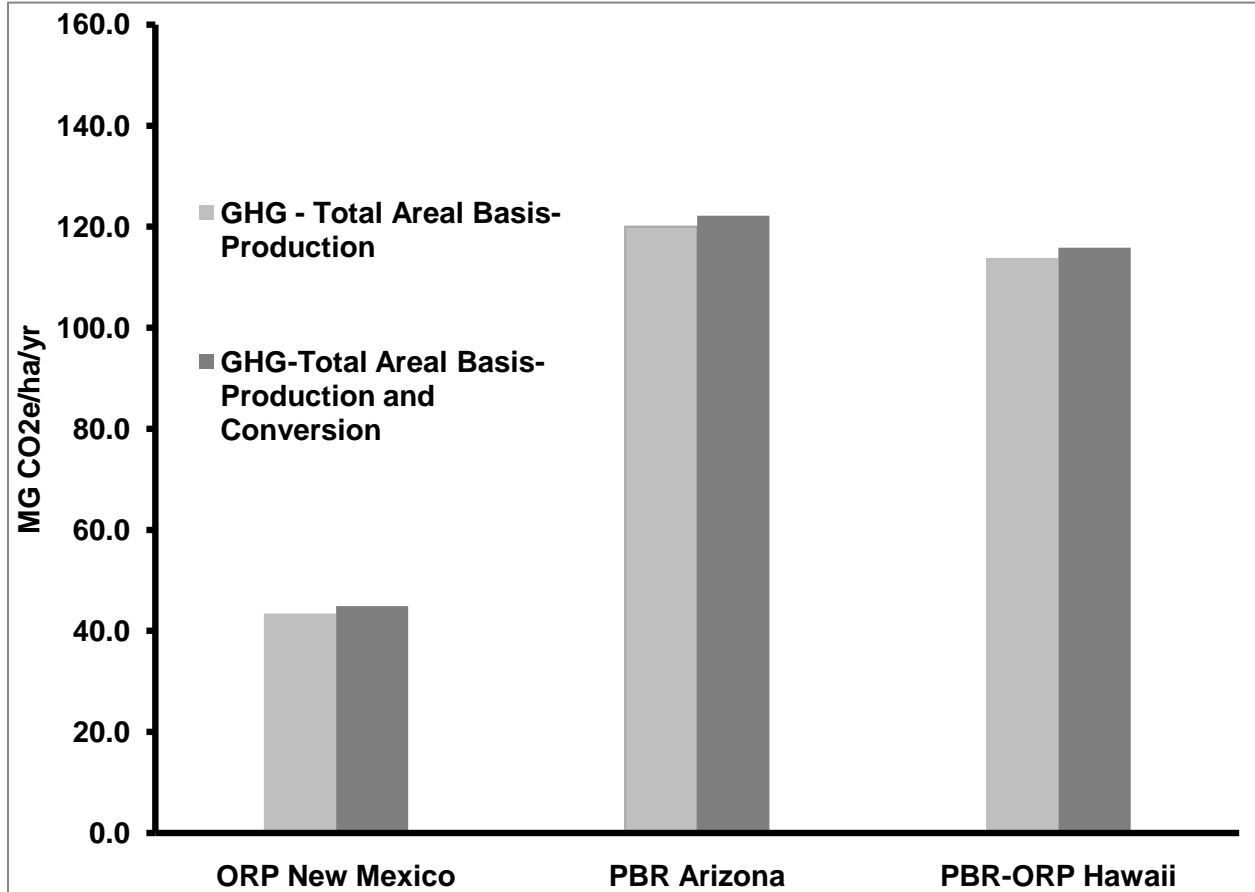


Figure 6: GHG emissions for Algal Biomass and Biodiesel for Algae Production Scenarios.

The net emissions estimated for the production and conversion of algae to biodiesel is only slightly greater than the emissions estimated for the production of algae as shown in figure 6. The total GHG emissions were greatest for algae produced in PBRs, nearly triple the emissions of the ORP and PBR-ORP system.

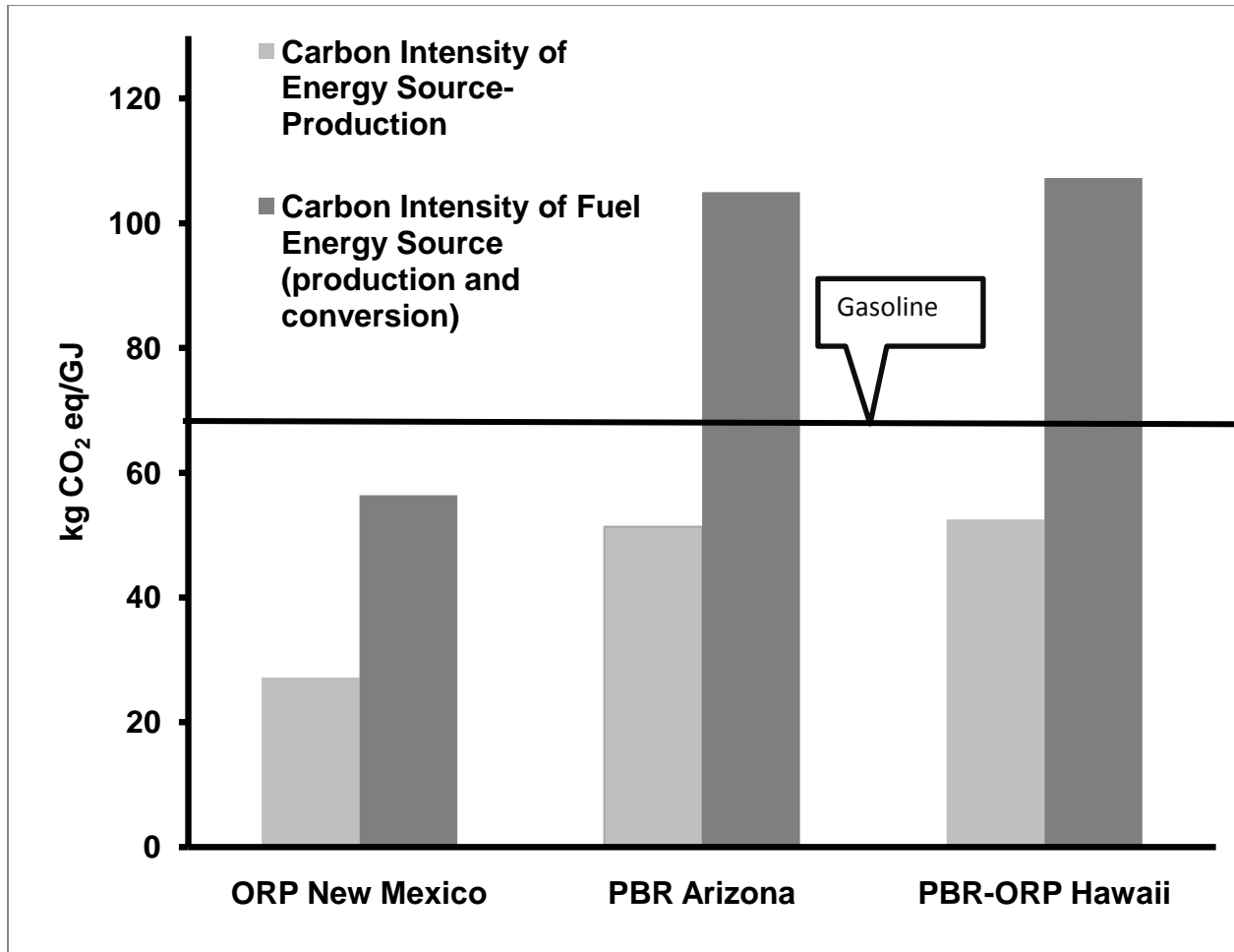


Figure 7: Carbon Intensity of Algal Biomass and Biodiesel for Algae Production Scenarios

Contrastingly, the estimates of Carbon Intensity of the Energy Source (CIES), associated only with algae production and Carbon Intensity of Fuel Energy Source (CIFES) are appreciably different as shown in figure 7 due to the energy loss associated with separating the biomass and the oil. These results suggest that biodiesel from algae produced in PBR and PBR-ORP release more GHG emissions than gasoline which releases around 67 kg CO₂ eq/GJ and ethanol from corn which releases around 42 kg CO₂ eq/GJ (Raman et al., 2010). It is noteworthy that the biodiesel produced from algae

in ORPs has a lower CIFES than gasoline but not ethanol from corn, which is in conflict with claims that algae have lower GHG emissions than first generation biofuels. It appears the estimates for CIFES using FEBEF are comparable to those found in process LCA analyses: the estimate for algae produced in ORPs by Clarens et al. (2010) for CIES was 57 kg CO_{2 eq}/GJ and Stephenson et al. (2010) found the CIES for algae produced in tubular PBRs to be around 300 kg CO_{2 eq}/GJ and in ORPs around 50 kg CO_{2 eq}/GJ which suggests our estimates are conservative.

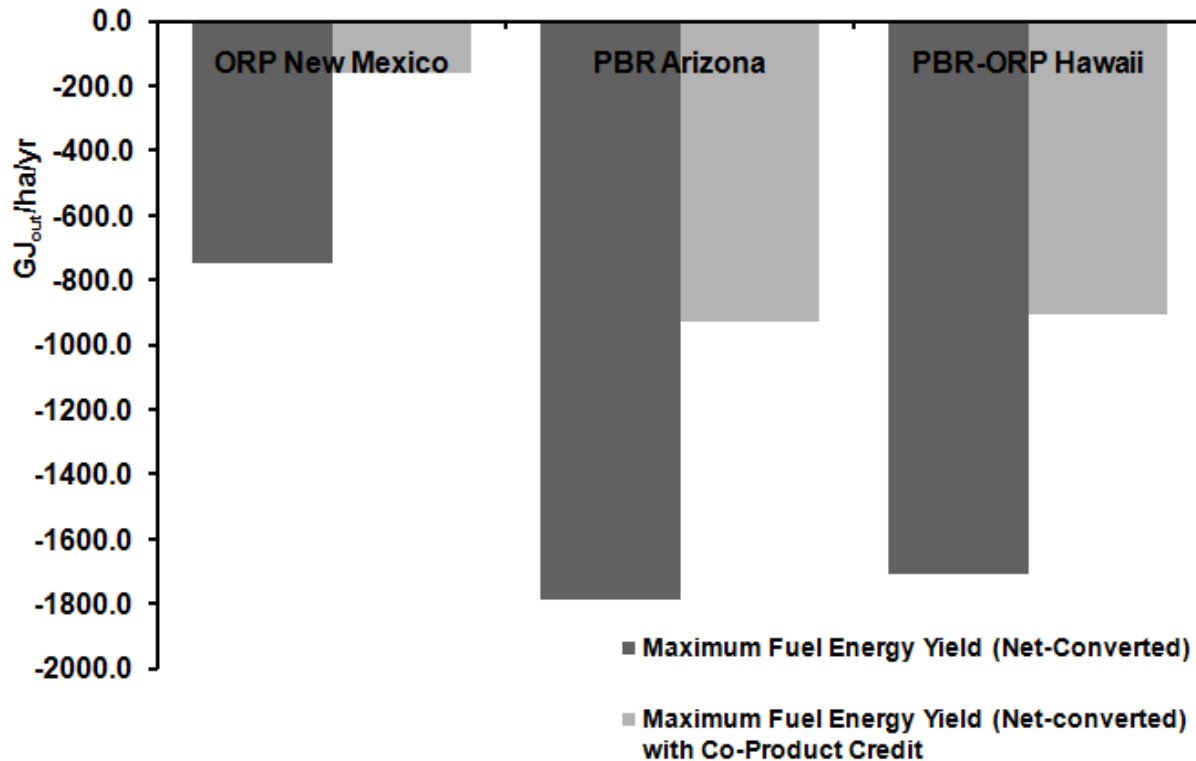


Figure 8: Maximum Fuel Energy Yield from Algal Biomass converted to Biodiesel for Algae Production Scenarios.

The Maximum Fuel Energy Yield (MFEY) is not estimated to be positive for any of the scenarios converting algae to biodiesel, as shown in figure 8. The Co-Product Credit changes the MFEY by approximately 80% and 50%, for ORP and PBR and PBR-ORP systems, respectively. Similarly, the Co-Product Credit decreased the Total Energy Cost (TEC) compared to the Fuel Energy Cost (FEC). The FEC ranges from 53 to 107 \$/GJ. When factoring the gains obtained by the co-product credit the metric, Total Energy Cost (TEC), lowers the range to approximately 30-62 \$/GJ. The lowest FEC estimated for biodiesel produced from algae was via the ORP system at 53 \$/GJ (6.88 \$/gge), this FEC is competitive with 310 \$/bbl crude oil (53 \$/GJ). With the co-product credit, the TEC decreased to 30 \$/GJ which is competitive with 175 \$/bbl crude oil. Kovacevic and Wesseler (2010) estimated a higher TEC for biodiesel from algae grown in ORPs to range 61-70 \$/GJ while Gallagher (2010) estimated a range of 17- 24 \$/GJ but did not include the capital costs as a recurring cost. The next lowest FEC was for biodiesel produced in the coupled system, not appreciably different from the ORP, 31 \$/GJ (7.13 \$/gge) which is competitive with 185 \$/bbl crude oil. For further reference the estimated FEC of ethanol from corn grain is 23 \$/GJ (2.97 \$/gge) and the TEC of corn grain ethanol is 17 \$/GJ (2.20 \$/gge) while ethanol from cellulosic feedstocks has an FEC range 27-28 \$/GJ (3.50 to 3.70 \$/gge) and a TEC of 23-25 \$/GJ (Raman et al., 2010). Even with the co-product credit, biodiesel produced from algae grown in PBRs, the TEC is quite high, 62 \$/GJ. However, the TEC includes the co-product credit which ignores that the difference in quality of the co-product credit energy to the liquid fuel product; for example crude oil, higher quality energy is more valueable than natural gas, a lower quality energy source (Mulder and Hagens, 2008). It appears that biodiesel from

algae cannot compete with petroleum or biofuels from corn or cellulosic feedstocks even while ignoring the lower quality and value of the energy associated with the co-product credit.

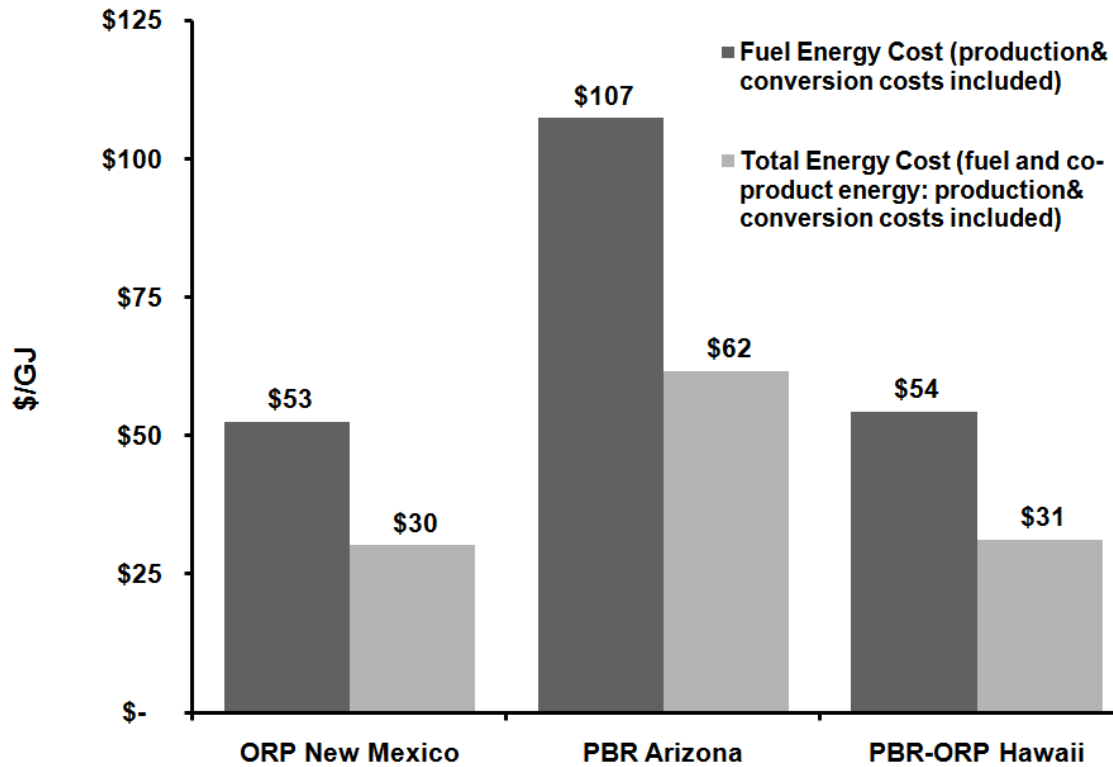


Figure 9: Fuel Energy Cost for Algae Biodiesel for three scenarios: ORP (Open Raceway Ponds), PBR (Photobioreactors), and PBR-ORP (Hawaii).

Conclusions

These results indicate that biodiesel from algae produced in modeled ORP, PBR, and PBR-ORP are more expensive and are not necessarily more environmentally friendly than other biofuel feedstocks. The lowest FEC for biodiesel from ORPs is 53 \$/GJ with the lowest TEC of 30 \$/GJ, but these values were not much different than those for the coupled system, 54 and 31 \$/GJ, for FEC and TEC, respectively. The biodiesel from algae produced in PBR and PBR-ORP release more GHG emissions,

105 and 107 kg CO_{2 eq}/GJ, respectively, than gasoline and ethanol from corn. Yet, the biodiesel produced from algae in ORPs has a Carbon Intensity, 56 kg CO_{2 eq}/GJ, which is lower than gasoline but not lower than ethanol from corn. Furthermore, given the estimates of EROIs for both algal and biodiesel, such low energy gains made are not beneficial to the US given an increasing energy demand. Mulder and Hagens (2008) argue that given the likelihood of energy scarcity in the future, net energy gains are more important than cost analyses for countries with an economy based on high energy inputs. These results suggest that cheap algal biofuels offering climate change benefits are not attainable with the given estimates of the modeled production technologies and offer little gains in terms of energy security or environmental gains.

Perhaps emerging culture technologies such as flat panel PBRs, immobilized beds, and polymer bags combined with will advances in algal genetic engineering, will together succeed in lowering production costs. Such successes and advances can improve the economics and environmental impacts of algal biofuels to fulfill the claims surrounding algae's potential. However, such significant advances will take time. Until then; biofuels from algae seem unattractive from a cost, environmental or EROI standpoint.

Terms

AOC-Algae Oil Content (kg oil/kg biomass)

ECB-Energy Content of Biodiesel from microalgae (MJ/kg)

MHY-Maximum Harvestable Yield (Mg/ha/yr)

GEY-Gross Energy Yield (GJ/ha/yr)

NEY-Net Energy Yield (GJ/ha/yr)

EROI-Production-Energy Return on Investment (Production only) (dimensionless)

BPC -Biomass Production Cost (USD/Mg)

EPC- Energy Production Cost (as harvested basis) (USD/GJ)

GHG-Areal-Production (kg CO_{2 eq}/ha/yr)

GHG Intensity-Production (kg CO_{2 eq}/GJ)

TFEO (Transportation Fuel Energy Out, $\text{GJ}_{\text{out}}/\text{Mg Biomass}$)
 TFEY -Total Fuel Energy Yield ($\text{GJ}_{\text{out}}/\text{ha}/\text{yr}$)
 MFEY_{NC}-Maximum Fuel Energy Yield –Net Converted ($\text{GJ}/\text{ha}/\text{yr}$)
 MFEY_{NCCP} -Maximum Fuel Energy Yield –Net Converted with Co-Product Credit ($\text{GJ}/\text{ha}/\text{yr}$)
 EROI Energy Return on Investment (dimensionless)
 EROI_{CP} -Energy Return on Investment with Co-Product Credit (dimensionless)
 FPC- Fuel Production Cost (USD/GJ)
 GHG_{TAB} GHG Total –Areal Basis ($\text{kg CO}_2 \text{ eq}/\text{ha}/\text{yr}$)
 CIFES-Carbon Intensity of Fuel Energy Source ($\text{kg CO}_2 \text{ eq}/\text{GJ}$)
 CPC- Co-Product Credit ($\text{GJout}/\text{L biodiesel}$)
 I_{GHG}-Indirect Green-house Gas ($\text{Mg CO}_2 \text{ eq}/\text{ha}/\text{yr}$)
 I_{Energy}-Indirect Energy ($\text{GJ}/\text{ha}/\text{yr}$)
 TEUP-Total Energy Use for Production ($\text{GJ}/\text{ha}/\text{yr}$)
 TEUC-Total Energy Use for Conversion ($\text{GJ}/\text{ha}/\text{yr}$)
 TEUCCPC-Total Energy Use for Conversion with Co-Product Credit ($\text{GJ}/\text{ha}/\text{yr}$)
 TEUPC-Total Energy Use for Production and Conversion ($\text{GJ}/\text{ha}/\text{yr}$)
 CCFEP-Cost for Conversion of Energy Produced ($\$/\text{ha}/\text{yr}$)
 TCFEP-Total Cost for Fuel Energy Produced ($\$/\text{ha}/\text{yr}$)
 FEC-Fuel Energy Cost ($\$/\text{GJ}$)
 TEC- Total Energy Cost (production, conversion(fuel & Co-Product Credit)) ($\$/\text{GJ}$)

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Appendix: FEBEF Methodology

Five worksheets comprise FEBEF, as follow: (a) Background Assumptions and Calculations, containing conversion factors, constants, elemental compositions for the different feedstocks, and climatic data inputs for the model. (b) Cost vs. Yield, containing literature-based (3-5) factors to enable production costs to scale on predicted yields assuming that each line-item in the cost model is either linearly-dependent on yield, or completely independent of yield. (c) Algae Cost Model, modeling algal production costs in open raceway ponds, based primarily on reference 4, scaled to 100 ha. This worksheet also includes free water surface evaporation estimates to enable water consumption calculations. (d) Primary Assumptions, containing location and crop-physiological factors, crop-cost components, EIO-LCA Greenhouse Gas (GHG) and Energy computations. (e) Primary Results, containing intermediate and final computations for model outputs. The fourth and fifth worksheets constitute the core of the model. In both worksheets, feedstocks are organized in columns so that cross comparisons between feedstock can be made readily.

The approach of FEBEF is as follows: Compute an energy-limited carbon-capture by using growing-season solar energy inputs coupled with knowledge of the maximum photosynthetic rates of each feedstock. Similarly, compute a water-limited carbon-capture by using growing-season rainfall coupled with knowledge of the maximum water use efficiency (WUE) of each feedstock. De-rate both these carbon-capture estimates to account for multiple losses such as respiration and non-harvestable fraction, to estimate a light-limited and water-limited yield. Pick the lower of the two to estimate the yield. Break the cost of production into fewer than a dozen line-

items that are common across feedstocks, and use literature estimates to populate those cost estimates. Scale some of the line-items by yield (details below). Use an economic-input-output-life-cycle-analysis approach to compute the embedded energy and greenhouse-gas emissions from each cost line-item; sum both of these to find total embedded energy and GHG for each feedstock. With maximum yield, cost, energy input, and GHG emissions for each feedstock, key model outputs can be computed. These are presented in bar graphs labeled as follow: MEYG (Maximum Energy Yield Gross, GJ/ha/yr), MHY (Maximum Harvestable Yield, Mg/ha/yr), BRY & MHY (Best Reported Yield and Maximum Harvestable Yield, Mg/ha/yr), MEY G&N (Maximum Energy Yield, Gross and Net, GJ/ha/yr), EROI (Energy Return on Investment, dimensionless), BPC (Biomass Production Cost, USD/ton – in US customary units for easy comparison to existing feedstock prices), EPC, (Energy Production Cost, USD/GJ), GHG-Areal ($\text{kg CO}_2 \text{ eq/ha/yr}$), and GHG Intensity ($\text{kg CO}_2 \text{ eq/GJ}$).

Background Assumptions and Calculations Worksheet

The Background Assumptions and Calculations worksheet (BACC tab) contains the following: (a) Text-color conventions used in the workbook. (b) Common conversion factors in named cells (e.g., cell B12 is named *kg per Mg* and has a value of 1000). These conversions can be referred to by name elsewhere to reduce the incidence of hard-coding errors in the spreadsheet. (c) Economic assumptions including interest rates and fuel prices. (d) Molecular weights and densities of relevant materials. (e) Energy contents and utility costs including diesel-energy to cost ratio. (f) Theoretical limits on plant physiological parameters to allow an upper bound on the performance of the biomass. (g) Computations to convert literature data into ratios of root-exudate

carbon to root stored carbon for switchgrass and Miscanthus. (h) A listing of best reported yields for each biomass type. Ideally these would be from identical environments in plots greater than 10 ha as the modeled case (central Iowa in this work), but this was only possible for corn; values for switchgrass, Miscanthus, and algae were from more distant sites. (i) Raw data and linear regression of land rental costs vs. productivity data. (3) (j) Economic-Input-Output-Life-Cycle-Assessment energy multiplier factors for perennial grass seeding. (k) Fertilizer costs and pre-computations. (l) Fertilizer application rate crosscheck. (m) Solar and precipitation values. This includes raw meteorological data as well as data modified by the planting and harvesting dates listed in the Primary Assumptions worksheet.

Cost vs. Yield Worksheet

The Cost vs. Yield worksheet (CvsY tab) scales line item production costs based upon predicted yields by assuming that some line items are yield-independent (i.e., scale factor $n = 0$), while others are linearly scaled with yield ($n = 1$). This binary segregation of costs is an oversimplification, but one which yields overall cost vs. scale responses consistent with those reported for corn (data not shown). The yield-appropriate costs computed in the Cost vs. Yield worksheet are used by the Primary Assumptions worksheet in the core cost model.

Algae Cost Model Worksheet

The Algae Cost Model worksheet (ACM tab) contains the amortized capital, labor, irrigation, and direct energy cost calculations and free water evaporation calculation for three different algal production technologies in four different locations. The three different types of algal plants and the locations are Open Raceway Ponds

(ORP) in Ames, IA, ORP, in Tucumcari, NM, Photobioreactor (PBR) in Phoenix, NM, and a coupled PBR-ORP system in Honolulu, HI. Each operation was assumed to have 100 ha production area. The amortized capital cost, labor, and direct energy estimates for the production scenarios were based on literature reports, updated for inflation, and supplemented with engineering estimates when data was lacking. The irrigation costs were calculated from local pan evaporation data, growing season rainfall, and water rates.

Open Raceway Ponds (ORP)-Ames, IA

The ORP amortized capital costs were based on the 400 ha, 30 g/m²/day production scenario using pure carbon dioxide outlined by (6). Capital costs for conversion equipment of algae oil to biodiesel, listed in the original publication, are excluded as a different source/method is used for fuel conversion capital cost estimates.

Line item capital costs were adjusted for inflation from 1994 dollars to 2008 dollars as shown in equation 1.

Inflation adjusted cost for year y =

$$\text{Known cost in year } x * \left(\frac{\text{Inflation index factor for year } y}{\text{Inflation index factor for year } x} \right) \quad (\text{eq. 1})$$

The total cost per line item for the 400 ha system was calculated. Using scale factors, assigned using engineering judgment to each line item, a total cost per line item for a 100 ha system is calculated as shown in equation 2.

Predicted Cost of spec'd eqp =

$$\text{Known Cost of baseline eqp} * \left(\frac{\text{Size of spec'd eqp}}{\text{Size of baseline eqp}} \right)^{\text{sizing exponent}} \quad (\text{eq. 2})$$

The sum of the line items gives a total capital investment. The yearly capital charges are calculated using the PMT function in Excel; the annual rate of return

assumed in 10%, over a 20 year period, and total capital investment was the principal. The yearly capital charges (\$/yr) is divided by 100 ha and converted to the reported estimate of amortized capital in \$/acre/year.

The labor costs were based on (6) and were adjusted for inflation and seasonal labor needs. The baseline labor rate in \$/ha/yr was adjusted for inflation as shown in equation 1. The labor was prorated for the variation in the seasonal labor needs, as shown in equation 3:

$$\text{Labor rate} = \text{Inflation Corrected Labor Rate} * (\text{Fraction of Year Growing Algae} + \text{Fraction of Year Idle} * \text{Personnel Requirements in Off Season}) \quad (\text{eq. 3})$$

This prorated value was then scaled by system size, and adjusted for inflation.

The direct energy estimate was based on (6). The power requirements (kWh/ha/yr) for mixing, centrifugation, water pumping, and other (nutrient pumping and building needs) were summed to find the total power requirement. The total power requirement (kWh/ha/yr) was then multiplied by the local electricity rate (\$/kWh) (7) to give a direct energy cost in (\$/ha/yr), which was converted to \$/acre/yr as reported in the Primary Assumptions tab.

The irrigation costs for all of the algal production scenarios in the four different locations were estimated using the same method. We assumed that the evaporation of the free standing water at the different production plants was similar to lakes (8), and that all of the evaporation occurred during the growing season. Local pan evaporation data (in/yr) (9) was manipulated by pan to lake evaporation factor, as shown in equation 4.

$$\text{Lake evaporation} \left(\frac{\text{in}}{\text{yr}} \right) = \text{Pan evaporation} \left(\frac{\text{in}}{\text{yr}} \right) * \text{Ratio of Lake to Pan Evaporation}$$

(eq. 4)

Then, daily evaporation rate was calculated as shown in equation 5.

$$\text{Daily Evaporation} \left(\frac{\text{cm}}{\text{day}} \right) = \text{Lake evaporation} * \frac{\text{cmperinch}}{\text{Season length (days)}} \quad (\text{eq. 5})$$

The daily evaporation rate was converted to cubic meters per day. The mass of water evaporated is calculated as shown in equation 6.

$$\text{Mass water evaporated} \left(\frac{\text{kg}}{\text{day}} \right) = \text{Daily evaporation} \left(\frac{\text{m}^3}{\text{day}} \right) * \text{Density of water} \left(\frac{\text{kg}}{\text{m}^3} \right) \quad (\text{eq. 6})$$

As a cross-check, an effective “water use efficiency” was calculated for the algal scenarios as shown in equation 7:

$$\text{Water Use Efficiency} = \frac{\left(\frac{\text{Maximum Harvestable Yield} \left(\frac{\text{Mg}}{\text{ha}} \right) * 1000 \text{kg} * 100 \text{ha}}{\text{Season Length} - \text{days}} \right)}{\text{Mass water evaporated kg/day}}$$

(eq. 7)

Water use was corrected for local, annual precipitation as shown in equation 8.

$$\begin{aligned} \llbracket \text{Water Use} \rrbracket_{\text{(precipitation corrected)}} (\text{m/season}) \\ = [((\text{Evap. Rate}(\text{cm/day}) * \text{Grow. Seas. Leng. (day)}) - (\text{Precip. (cm/year)} \\ * \text{Frac. Water Avail. During Grow. Seas.})) / \text{cmperinch}] \end{aligned}$$

(eq. 8)

The volume of water evaporated over the whole free water area corrected for precipitation was calculated as shown in equation 9.

$$\begin{aligned} \text{Water Use}_{\text{precip.corr.}} \left(\frac{\text{ft}^3}{\text{year}} \right) \\ = \text{Water Use}_{\text{precip.corr.}} \left(\frac{\text{m}}{\text{season}} \right) * 100 \text{ ha} * \text{m}^2 \text{perha} * \text{ftperm}^3 \end{aligned}$$

(eq. 9)

For the PBR in Phoenix, AZ, the calculation was adjusted to correct for the area of water baths, which was a fraction of the 100 ha.

Annual irrigation costs were calculated by multiplying the local industry water rates (\$/cubic feet) (10-12) by the Seasonal Water Use (cubic feet/season). The irrigation costs on an area basis are calculated as shown in equation 10.

$$\text{Irrigation costs } (\$/\text{ha}/\text{year}) = \frac{\text{Yearly Irrigation Cost } \left(\frac{\$}{\text{year}}\right)}{100 \text{ ha}} \quad (\text{eq. 10})$$

The irrigation costs (\$/ha/year) are converted to a (\$/acre/year) basis.

Algae Harvesting

The harvesting of algae from the production reactors (ponds or PBRs) included the capital costs for a primary settling followed by centrifugation. We assumed the centrifugation produced 15% solids from the ORP systems and 20% solids from the PBR systems. For the ORPs we calculated the additional direct energy it would require to reach 20% solids, as shown in equation 11 below.

$$\text{Direct Energy}_{\text{algae slurry}} = \text{MHY} * \text{Hvap} * \text{MR}\% * (\text{MC}\% / (1 - \text{MC}\%)) \quad (\text{eq. 11})$$

Where, MHY is Maximum Harvestable Yield, Hvap is the heat of vaporization for water, MR% is the moisture % needed to remove to reach 10% solids, and MC% is the moisture content of the slurry exiting the centrifuge.

Open Raceway Ponds (ORP) – Tucumcari, NM

The approach for computing amortized capital costs and labor costs was identical to that used for Ames, IA. The direct energy and irrigation costs used the same method but with electricity and water rates specific to Tucumcari, NM.

Photobioreactor (PBR) – Phoenix, NM

The PBR amortized capital costs were based on (13) report on commercial production of microalgae in photobioreactors. The basis of that study was a facility with a projected biomass productivity of 1.25 kg/m³/day (approximately 10.7 g/m²/day) in continuous culture (13). We included only the unit operations and the associated costs needed for the cultivation of the algae and up through harvesting the algae.

The original line item capital costs included in the amortized capital estimate in 2001 dollars were adjusted for inflation as shown in equation 1 to 2008 dollars. The cost estimate was then scaled from the area of foot print (approximately 1 ha) of the PBR calculated from measurements given in (13) to a 100 ha area using equation 2.

The centrifugation costs provided by (13) were replaced with a yield scaled centrifugation cost from (4) as shown in equation 12. This allowed for consistency with the same unit operation across technologies.

$$\begin{aligned} \text{Centrifugation costs}_{tech} (\$) \\ = \left(\frac{\text{Maximum Harvestable Yield}_{tech}}{\text{Maximum Harvestable Yield}_{OPR}} \right) * \text{Centrifugation Costs}_{OPR} \end{aligned} \quad (\text{eq. 12})$$

The total capital cost was the summation of the scaled costs. The yearly capital charge was computed using an annual rate of return at 10% over a 20 year period. The yearly capital charge (\$/yr) was divided by 100 ha and converted to the reported estimate of amortized capital in \$/acre/year.

The labor costs were based on (13), adjusted for inflation and scale. These labor costs were prorated based on the growing season length (fewer workers off season).

The direct energy estimate was also based on the (13), using local electrical rates (7) in Phoenix, AZ and converted to \$/acre/yr for the direct energy costs.

Coupled PBR-ORP system – Honolulu, HI

The Coupled PBR-ORP amortized capital costs based primarily on (14) which reported the general specifications of the Aquasearch (now HP petroleum) coupled production systems for photosynthetic microbes. Biomass production was estimated at 10.2 g/m²/day for the PBR and 15.1 g/m²/day for the ORPs. The authors of (14) relied on the (6) techno-economic analysis (adjusted for inflation) for capital costs for the open raceway ponds, and on Hallenbeck and Benemann (2002) for photobioreactor cost estimates. We included only the unit operations and the associated costs needed for the cultivation of the algae and up through harvesting the algae.

Capital costs were adjusted for inflation and scaled. Centrifugation costs were calculated as outlined above using equation 11. The yearly capital charge was computed using an annual rate of return at 10% over a 20 year period. The yearly capital charge (\$/yr) was divided by 100 ha and converted to the reported estimate of amortized capital in \$/acre/year.

The labor costs were calculated based on the both the previous PBR and ORP labor estimates. The percentage area the PBR and ORP unit operations comprised of the total operational area was calculated. The labor costs for the coupled system were estimated by distributing the percentage area with the labor costs, as shown in equation 13.

$$Labor\ cost_{PBR-ORP} = PBR\ area\ \% * Labor\ Cost_{PBR} + ORP\ area\ \% * Labor\ Cost_{ORP} \quad (eq. 13)$$

These labor costs were prorated based on the growing season length (fewer workers off season).

The direct energy costs were calculated with on the both the previous PBR and ORP power estimates. The power needs for the coupled system were estimated by distributing the percentage area with the direct energy estimates, as shown in equation 14.

$$Power\ Requirement_{PBR-ORP} \left(\frac{kWh}{ha\ yr} \right) = PBR\ area\ \% * Power\ Requirement_{PBR} + ORP\ area\ \% * Power\ Requirement_{ORP} \quad (eq. 14)$$

This estimated power requirement was then multiplied by the electricity rates in HI (7) to calculate the direct energy cost in \$/ha/yr and then converted to \$/acre/year.

Primary Assumptions Worksheet

The Primary Assumptions worksheet (PA tab) compiled literature-based measurements and assumptions about climate, plant growth, production costs, energy requirements, greenhouse gas emissions, water use, and eutrophication potential. In some cases data came directly from literature sources, while in others it was based on computations in the supporting worksheets that have been previously described. In all cases the data for each feedstock was organized in a single column. Details of the contents of the Primary Assumptions worksheet follow:

Location-Specific Climatic Assumptions

Annual average solar irradiation (W/m^2) (15), fraction of solar radiation in as photosynthetically available radiation (PAR) (16), annual total rainfall (18), planting date,

and harvesting date (19-21) are the four fundamental assumptions entered into the climate section of the model. These fundamental assumptions are used to compute growing season length, fraction of solar available during growing season, and fraction water available during growing season. To find the latter two items, intermediate calculations are conducted in the Background Assumptions and Calculations worksheet.

Crop Physiological Assumptions

Crop performance data and cost estimates are based on literature values without extrapolations based on future technological advances.

Literature Reported Radiation Use Efficiency values

Radiation use efficiency is a measure of biomass accumulation given photosynthetically available radiation (PAR). Instantaneous Radiation use efficiencies (g of biomass/MJ of PAR) from were estimated for C4 plants from (22) and for algae from (23) by converting gas evolved (CO₂ or O₂) and photon flux density converted to a radiation use efficiency.

RUE actual to RUE Theoretical Maximum (RUE_R)

The maximum theoretical radiation use efficiency is assumed to be 30% on PAR basis (16). The ratio of the crops' actual RUE to the RUE theoretical maximum is calculated by FEBEF, as shown below in Equation 15, where RSR is the Root: Shoot Ratio at harvest:

$$RUE_R = \left(\frac{RUE_{actual} \left(\frac{g \text{ biomass}}{MJ} \right) * Biomass \text{ Energy Content} \left(\frac{MJ}{g} \right)}{RUE_{Max} \left(\frac{g \text{ biomass}}{MJ} \right)} \right) * (1 + RSR) \quad (\text{eq. 15})$$

Literature Reported WUE Values

The instantaneous water use efficiency values for the terrestrial crops, defined as the ratio of biomass accumulated to crop water transpired, was experimentally

determined in (24), and these values were used in the model. The term WUE is normally not used when referring to aquatic plants. However, if one pictures the entire culture system as a giant “leaf,” an effective WUE can be computed. The WUE of the algal crop was computed as the growing season evaporation from pond divided by the algal biomass produced. The transpiration calculations were previously described in equation 7.

Ratio of WUE actual to WUE Theoretical Maximum (WUER)

The theoretical maximum WUE was estimated based on an assumed leaf temperature, ambient relative humidity, maximum net photosynthetic rate, and water vapor flux for a typical Iowa crop. The calculations were shown in the Background Assumptions Worksheet. The value estimated and used in the model was 0.02 kg biomass/kg water.

Respiration Loss of Fixed C (RLC) - Growing Seasonal Average (GSA)

Stored chemical energy is lost via respiration which supports physiological needs including transportation and translocation of nutrients, protein and lipid synthesis, and cellulose synthesis. While the respiration losses are dependent on the needs the plant, we estimated growing seasonal average (25).

Root: Shoot Ratio @ harvest (RSR)

This experimentally determined value is the ratio of dry belowground structural root biomass to dry aboveground biomass. Literature reported values for the different terrestrial crops (26-28) were used.

C to soil organisms / C in root (GSA) CSORR

For terrestrial crops, a fraction of the carbon captured is transferred to the soil in the form of root turnover, root cap mucigel and organic exudates (29). Literature reported values for net rhizodeposited carbon for the different terrestrial crops (29-31) were converted to a root basis ratio. Those conversion calculations were done in the Background Assumptions worksheet.

Fraction of Stover Collected

In light of equipment collection limitations and sustainable collection guidelines, the fraction of corn stover collected was assumed to be 60%. (32)

Harvestable Fraction of Above Ground Biomass (hf_{AGB})

The factor accounted for mechanical limitations of the production harvest systems. Literature reported values for the different terrestrial crops and algae (33-35, 14) were used.

Harvestable Fraction of Total Biomass (hf_{TB})

This factor accounted for the belowground biomass and was calculated in FEBEF by Equation 16, as shown below:

$$hf_{TB} = \frac{\text{Harvest Index}}{1+RSR} \quad (\text{eq. 16})$$

Harvestable Fraction of Total Fixed Carbohydrate (hf_{TFC})

This term represented the harvestable portion of carbon captured by the plant over the season. FEBEF calculated this factor by Equation 17:

$$hf_{TFC} = \frac{hf_{AGB}}{(1+RSR+RSR*(CSORR))*(1-RLC)} \quad (\text{eq. 17})$$

Biomass Energy Content (BEC)

The higher heating values of the crops were experimentally determined and reported in (36-40) and were utilized in the model in units of MJ/kg.

Biomass Moisture Content @ Harvest

A literature based estimate for the amount of moisture remaining in the biomass following harvesting.

Additional Moisture Removal Needed

An estimate of the amount of moisture needed to be removed from the biomass to allow for storage and/or fuel processing.

Direct Energy for Moisture Removal

This calculation is described earlier in equation 11 to estimate the additional direct energy it would require to reach 10% solids, as shown in equation 11 below for the algae systems.

Technological Improvement Energy Reduction for Dewatering

This value is an estimate that attempts to credit algal production technologies with harvesting developments that result in lower direct energy costs to meet desired moisture content levels.

Direct Energy Cost for Moisture Removal

This calculation estimates the direct energy cost needed to meet desired moisture content using natural gas to remove the moisture while also crediting for technological improvements to harvesting as shown in Equation 18:

DEC =

$$\frac{\left(\text{Direct Energy}_{\text{algae slurry}} * 1000 \frac{\text{kWh}}{\text{MJ}} * \frac{\text{GJ}}{1000\text{MJ}} * \text{Natural Gas Cost} \frac{\$}{\text{kWh}}\right) * (1 - \text{Technological Improvement for Dewatering})}{\left(2.471 \frac{\text{acres}}{\text{ha}}\right)}$$

(eq. 18)

Crop-Cost Components

Land rental cost was assumed to be proportional to biomass harvest. A linear regression model was developed from the reported cash rental rates and typical corn yields for high, medium and low quality cropland (3). Arguments have been made that feedstocks other than corn, including algae, for biofuels could be grown on marginal land and avoid competing for high value land, and therefore lower production costs. However, cash rental rates typically reflect average yields and we assume that this trend would apply to all bioenergy crops. The application of this model not only indirectly reflects nutrient removal from soil given yields for the terrestrial crops but also that higher output generates a surplus that is likely to be appropriated by the land owner in the charge of rent.

Amortized capital, labor, direct energy, biological capital, and lime and biocide costs for the terrestrial production scenarios were estimated by taking baseline values and either as is, or scaled to yield. Amortized capital costs were assumed independent of yield. While this is not true in the extremes – greater yields could conceivably require larger machinery – we argue it is a good first approximation. In contrast, labor costs, direct energy costs and biological capital are assumed proportional to yield. Lime & biocides (pesticides, herbicides) are assumed to be independent of yield. Original production cost values were gleaned from (4-5). Chemical costs, while proportional to yield, were computed based on the N, P, and K content of the harvested biomass (33, 41-46) and upon an assumption of the fraction of chemicals in the harvested biomass compared to the fraction applied. Irrigation costs for algal scenarios came from the algae cost model page.

Single Pass Corn Grain and Stover Harvesting Assessment:

Based on (47) which assumes that 2/3 (10% more than the for double pass) of the corn stover can be harvested in a single pass along with corn grain, with a reduced combine harvesting efficiency of 55% from 70% the following estimates were made concerning the crop cost component classes. Assuming a field harvest grind that achieves a bulk density of 74 dry kg/m³ for the stover, the amortized capital costs are about 10% higher (the combine costs increase by 30% but combine costs make up less than 40% of the amortized capital costs), given the 15% decrease in harvest efficiency the direct labor requirements increase by 15%, and the direct energy is also increases by 30%. These increase only result in a 3% increase overall from the system of two passes now modeled, so not that different. All crop cost components inputs used in the modeled are reported in 2009 US \$/acre/year.

Economic Assumptions

Utility, fuel, and chemical prices are highly volatile and therefore introduce tremendous variability into the results of the analysis. These values are easily changed in the spreadsheet, but for the purposes of the analysis presented herein, the average value for 2007, 2008, and 2009 were used.

EIO-LCA Greenhouse Gas Computations

The greenhouse gas (GHG) emissions data were divided into two categories: direct emissions and indirect emissions. We used EIO-LCA model factors to estimate the supply chain, indirect greenhouse gas emissions (as CO₂, CH₄, and N₂O) from the EIO-LCA model developed by Carnegie Mellon University (48). The GHG emission

rates (units of CO₂ equivalents) were expressed on an areal (Mg CO₂/ha/yr) and net fuel (Mg CO₂/GJ_{net} and ton CO₂/gallon-of-gasoline-equivalent) basis.

When considering direct emissions, the literature is split between the flux chamber and the soil organic carbon (SOC) methods, with flux chamber methods generally yielding higher CO₂ emission estimates. An emission of 20.9 Mg/ha/yr was reported in (49) on the no-till operation system, an emission of 21.6 Mg/ha/yr for Moldboard Plow (MP) systems, and an emission of 22.7 Mg/ha/yr on short-term chisel (CP) systems. An emission of 16.1 Mg/ha/yr on various types of corn and soybean rotations was reported in (50). In contrast, using a SOC method, (51) report an emission of -0.6 Mg/ha/yr to 0.5 Mg/ha/yr, depends on the farming operation management. This suggests that the long term emission is negligible which is consistent with the guidelines by Intergovernmental Panel on Climate Change (IPCC). In (52), the authors adopted a standard inventory time period of 20 year for the majority of bioenergy crops which means the field reaches a new equilibrium and carbon dioxide is no longer sequestered in soil organic matter. In this analysis, we adopted the SOC (Soil Organic Carbon) approach so that direct CO₂ emissions were assumed to be negligible.

Methane constitutes less than 10% of the N₂O emission when converting to CO₂ emission equivalent measurement. Therefore, in this analysis, we assumed it is negligible as well.

Since N₂O emission is most important component, we focused on N₂O emission in our analysis. In (52), the authors used synthetic fertilizer application rate to estimate N₂O emissions. They reported that 1.325% of N in synthetic fertilizer is emitted as N in N₂O, implying 0.042 g N₂O emitted per g N fertilizer applied. Using a multiplier of 296 kg

$\text{CO}_2\text{eq}/\text{kg N}_2\text{O}$, we estimated the direct GHG emissions from each crop as $0.124 \text{ Mg CO}_2\text{eq}/\text{kg N}$ applied. When this was done for algae, the numbers were quite high, and were hard to compare with any existing literature because of a paucity of studies on direct greenhouse gas emission from algal systems. The researchers in (2) only included the greenhouse gas emissions associated with the inputs for the production of algae, including N_2O emissions. However, when direct N_2O emissions from multiple green algae species grown in urea have been reported (52), emission rates of up to $6.1 \cdot 10^{-8} \text{ mol N}_2\text{O}/\text{mg}_{\text{dw}}$ were found, corresponding to roughly $60 \text{ Mg CO}_2\text{eq}/\text{MT}_{\text{dry}}$, which was the same order of magnitude estimated by our $0.124 \text{ Mg CO}_2\text{eq}/\text{kg N}$ applied method.

Indirect Emissions

We found the EIO-LCA indirect greenhouse gas emissions multipliers for seven categories of economic activity in the production of biomass feedstocks. For the eighth category – biological capital – we computed an indirect GHG emission factor internally based on the direct emission values for each crop. The indirect greenhouse gas emissions were then calculated by multiplying the economic activity cost with the greenhouse gas emission multiplier. The economic activity and the EIO-LCA model categories are presented in Table 1 for all five production scenarios.

Table 1. Pairings of Categories for Production Activity and EIO-LCA factors.

Economic Activity	EIO-LCA Category
Land Rental	Real Estate
Amortized capital	Amortized capital
Direct labor	Ag & Forestry Support Activities (direct)
Direct energy costs	Power generation and supply**
Biological Capital	Biological Capital*
Chemical	Fertilizer manufacturing
Lime & Biocides (pesticides, herbicides)	Pesticide and other agricultural chemical manufacturing
Irrigation	Water, sewage and other systems

*Computed in FEBEF based on direct emissions

**Power generation and supply used for algae, while terrestrial crops used diesel fuel factor computed internally

EIO-LCA Energy Computations

We used EIO-LCA model factors to estimate the direct and embedded energy use from the EIO-LCA model (47). We found the EIO-LCA energy use multipliers for eight categories of economic activity in the production of biomass feedstocks. The energy use multiplier for Direct Energy was computed internally in the FEBEF model. The Energy Use for the different categories of production was then calculated by multiplying the economic activity cost with the energy use multiplier. The Total Energy Use (TE) for each crop was computed by summing all of the production categorical

energy uses. The economic activity and the EIO-LCA model categories are the same as those used for GHG emissions and are shown in Table 1.

Primary Results Worksheet

The Primary Results worksheet (PR tab) Two performance metrics form the foundation of the model computations: Water use efficiency (WUE), the ratio of carbon captured to water transpired by a plant, and radiation use efficiency (RUE), the ratio of carbon captured to incident solar energy received by a plant. Multiplying WUE with growing-season rainfall and multiplying RUE with growing-season solar energy enables a first-order approximation of the maximum possible biomass accumulation on a water- or light-limited basis. These two maximum biomass accumulations are converted into maximum harvestable yields by accounting for losses due to respiration, losses due to root exudates, and the fraction of biomass left in the field after harvest. The lower of the two maximum harvestable yields is selected as the predicted yield. The exact calculations are described in detail below.

Maximum Annual Biomass at Theoretical Maximum RUE

The Maximum Annual Biomass yield potential based on RUE_{max} and PAR available was calculated in Equation 19, as shown below:

$$MABTM_{RUE}(Mg/ha/yr) = \frac{\text{Annual PAR} \left(\frac{W}{m^2}\right) * RUE_{max} \left(\frac{g_{biomass}}{MJ}\right)}{BEC \left(\frac{MJ}{g_{biomass}}\right)} \quad (\text{eq. 19})$$

Maximum Seasonal Biomass at Theoretical Maximum RUE

The Maximum Seasonal Biomass yield potential based on RUE_{max} and seasonally available PAR was calculated in Equation 20.

$$MSBTM_{RUE}(Mg/ha/yr) = MABTM_{RUE}(Mg/ha/yr) * \text{Seasonal Fraction Solar Available} \quad (\text{eq. 20})$$

Maximum Seasonal Biomass at Actual RUE

The Maximum Seasonal Biomass yield potential based on RUE_{actual} and seasonally available PAR was calculated in Equation 21, as shown below:

$$MSBA_{RUE}(Mg/ha/yr) = MSBTM_{RUE}(Mg/ha/yr) * RUE_{R} \quad (\text{eq. 21})$$

Maximum Harvestable Yield-Light Limited

The Maximum Seasonal Biomass yield potential based on RUE_{actual} , Seasonally available PAR and de-rated for carbon and harvest losses was calculated in Equation 22, as shown below:

$$MHY_{RUE}(Mg/ha/yr) = MSBA_{RUE}(Mg/ha/yr) * hf_{TFC} \quad (\text{eq. 22})$$

Maximum Annual Biomass at Theoretical Maximum WUE

The Maximum Annual Biomass yield potential based on WUE_{max} and Annual Rainfall available was calculated in Equation 23, as shown below:

$$MABTM_{WUE}(Mg/ha/yr) = \frac{\text{Annual Total Rainfall}(cm) * WUE_{max} \left(\frac{g \text{ biomass}}{kg H_2O} \right) * (\text{Molecular Weight C} / \text{Molecular Weight } CO_2)}{\text{Crop Carbon Content} \left(\frac{g}{kg} \right)} \quad (\text{eq. 23})$$

Maximum Seasonal Biomass at Theoretical Maximum WUE

The Maximum Seasonal Biomass yield potential based on WUE_{max} and seasonally available PAR was calculated in Equation 24, as shown below:

$$MSBTM_{WUE}(Mg/ha/yr) = MABTM_{WUE}(Mg/ha/yr) * \text{Seasonal Fraction Water Available} \quad (\text{eq. 24})$$

Maximum Seasonal Biomass at Actual WUE

The Maximum Seasonal Biomass yield potential based on WUE_{actual} and seasonally available rainfall was calculated in Equation 25, as shown below:

$$MSBA_{WUE}(Mg/ha/yr) = MSBTM_{WUE}(Mg/ha/yr) * WUE_{R} \quad (\text{eq. 25})$$

Maximum Harvestable Yield-Water Limited

The Maximum Seasonal Biomass yield potential based on WUE_{actual} , Seasonally available rainfall and de-rated for carbon and harvest losses was calculated in Equation 26, as shown below:

$$MHY_{WUE}(Mg/ha/yr) = MSBA_{WUE}(Mg/ha/yr) * hf_{TFC} \quad (\text{eq. 26})$$

Ratio of Max light to Max water yields (RMHY)

The ratio of maximum harvestable yields from the water and light limited scenarios was calculated in Equation 27, as shown below:

$$RMHY = \frac{MHY_{RUE}(Mg/ha/yr)}{MHY_{WUE}(Mg/ha/yr)} \quad (\text{eq. 27})$$

Maximum Harvestable Yield

As mentioned above, the model feeds forward a predicted yield from either the MHY_{WUE} or MHY_{RUE} , whichever is lower.

Anticipated yield in 2015 assuming historical yield improvements:

Assumption is made that yield improvements are smooth and constant from year to year. Yearly yield improvement data is based on literature. In FEBEF model, we add one row with the yearly percentage improvement from the previous year so that we can calculate yield of any future year of interest.

Gross Maximum Energy Yield

The gross Maximum Energy Yield calculated by Equation 28, as shown below:

$$MEY_g(GJ/ha/yr) = MHY(Mg/ha/yr) * BEC(MJ/kg) \quad (\text{eq. 28})$$

Net Maximum Energy Yield

The net Maximum Energy Yield as calculated by Equation 29 shown below:

$$MEY_n(GJ/ha/yr) = MEY_g(GJ/ha/yr) - TE(GJ/ha/yr) \quad (\text{eq. 29})$$

MEY_n was also reported in units of gallons gasoline equivalents (gge)/acre/year.

Water intensity factor (transpired for biomass vs. fuel)

The ratio of water use on the basis of that transpired by the crop to fuel potential (MEY_n in terms of gasoline equivalent units) was reported in units of gal H₂O/ gge was calculated as shown below in equation 30:

$$WIF_{TB} = \frac{MHY (Mg/ha/yr)}{WUE_{actual} \left(\frac{g_{biomass}}{kgH_2O} \right)} * \frac{1}{MEY_n (GJ/ha/yr)} \quad (\text{eq. 30})$$

Net eutrophication potential (N and P discharges) for all crops:

The net eutrophication analysis is based on DAYCENT simulation of corn at eight sites in the Midwest. We have taken raw data from (54) for yield, fertilization, and eutrophication. They express eutrophication on the basis of g PO₄- eq/kg grain basis. We have then computed eutrophication potential on an areal basis. We have also computed N applied per unit grain produced, total N and P applied per unit area, and N+P per unit grain. Each of these has been correlated on total eutrophication per unit grain produced and per unit area. The highest correlation is between N/grain and eutrophication per unit grain (linear r = 0.97, r² = 0.95). Fitting this to a logarithmic curve gives r² = 0.976, so this expression was used. The equation 2.6602ln(x) + 11.836 is then used with FEBEF model data on N/grain to compute the eutrophication potential per unit grain for the grain scenario.

Energy Return on Investment (EROI)

The EROI was calculated based on gross maximum energy yield and total energy use. Equation 31 shown below was used for the calculation:

$$EROI = \frac{MEY_g (GJ/ha/yr)}{TE (GJ/ha/yr)} \quad (\text{eq. 31})$$

Total Production Cost (TPC)

The total cost of production was calculated and reported in terms of \$/ha and \$/ac. The calculation used is shown in Equation 32 below:

$$\begin{aligned}
 TPC \left(\frac{\$}{\frac{ha}{yr}} \right) \\
 = \sum \left(\begin{array}{l} \text{Land Rental, Amortized Capital Costs, Direct Labor, Direct Energy,} \\ \text{Biological Capital(excluding Algae), Nutrients,} \\ \text{Biocides, and Irrigation (Algae only)} \end{array} \right)
 \end{aligned}
 \tag{eq. 32}$$

Biomass Production Cost (BPC)

The biomass production cost was calculated and reported in terms as shown in Equation 33 below:

$$BPC \left(\frac{\$}{Mg} \right) = \frac{TPC (\$/ha/yr)}{MHY(Mg/ha/yr)} \tag{eq. 33}$$

BPC was also reported in \$/ton.

Energy Cost (EC)

The energy cost, which accounts for production up to the harvesting of the biomass, was calculated as shown in Equation 34 below:

$$EC \left(\frac{\$}{GJ} \right) = \frac{TPC(\$/ha/yr)}{MEY_G(GJ/ha/yr)} \tag{eq. 34}$$

EC was also reported in terms of \$/gge.

Carbon Intensity of Energy Source (CIES)

The global climate change potential intensity was estimated by calculating the ratio of total GHG to net energy produced for each crop. The CIES was calculated as shown in Equation 35 below:

$$CIES(MT \text{ CO}_2 \text{ e/ha/yr}) = \frac{GHGT(kg \text{ CO}_2/ha/yr)}{MEY_N(GJ/ha/yr)} \tag{eq. 35}$$

Ratio of MHY to Best Reported Yields

In order to place the MHY predicted by FEBEF in a realistic context, we found BRYs in the literature (for the different crops under similar climatic conditions and on plots greater than 10 ha when possible and computed a ratio and reported as a percentage as shown below in Equation 36:

$$RY = \frac{MHY (Mg/ha/yr)}{BRY (Mg/ha/yr)} \quad (\text{eq. 36})$$

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Chapter 4. Pathways forward for biodiesel production from algae

Abstract

Algae have yet to play a major role in addressing human energy needs because of their high costs and low production yields. The most costly, most energy and water consuming, and most greenhouse gas (GHG) producing unit operations are “pinch points” – rate limiting steps in the process where improvements have a potentially high return on investment. Understanding the nature of the barriers associated with those pinch points can accelerate the rate at which algal biofuels become economically viable, because such understanding enables assessment of the impact of potential improvements on the economic and environmental potential of algal biofuels. In this work, the Framework for the Evaluation of Biomass Energy Feedstock (FEBEF) is used to identify pinch-points and examine the impact of proposed improvements for three algal production biofuel systems including Open Raceway Ponds (ORPs), Photobioreactors (PBRs), and a system coupling PBRs to ORPs (PBRs-ORPs). The key metrics examined in FEBEF included Carbon Intensity of Fuel Energy Source, Maximum Fuel Energy Yield including the Co-Product Credit, Energy Return on Investment with Co-Product Credit, Fuel Energy Cost, and Total Energy Cost. Biological improvements such as increases in radiation use efficiency and oil yield led to the greatest improvements for each key metric. Decreases in labor and irrigation costs led to meaningful reductions in Fuel Energy Cost (\$/GJ) and Carbon Intensity of Fuel Energy Source and increases in Energy Return on Investment including Co-Product Credit. We found that with the combined improvements of increased radiation use

efficiency to 15% and oil yields to 70% along with decreased labor costs relatively low Fuel Energy Costs could be attained, 19 \$/GJ for biodiesel from ORPs and PBR-ORPs along with low Carbon Intensity of Fuel Energy Source predictions, 19 kg CO_{2 eq}/GJ for biodiesel from ORPs . Although these results suggests that algal biofuels can, within the bounds of theoretical limits on photosynthesis, become cost-effective contributors to technological civilizations appetite for liquid transportation fuels, the timeframe of such non-trivial improvements is extremely hard to predict.

Introduction

Algae have yet to play a major role in solving the global energy problem. Though algae are viewed as sustainable sources for replacing petroleum (Raja et al. 2008), there are many unresolved challenges in the production of algae for biofuels. Production of algae in open raceway ponds is hampered by infections (viral, bacterial, or other algal species) and low cellular densities, while large scale production of algae in photobioreactors is prohibited by high costs (Shen, 2009, van Beilen, 2010). And for all production systems there is still the challenge of simultaneously maximizing biomass yield and oil content (Jha, 2008).

Biotechnological developments may lead to improvements in algal biomass and oil yields, but such advances alone do not appear sufficient (Wesseler and Kovacevic, 2010) to improve the economic or environmental performance of algae biofuels sufficiently to be competitive with petroleum or other biofuels. Engineering efforts such as system optimization of parameters like temperature, sterilization methods, and nutrient conditions can also lead to yield improvements. Yet there still remain multiple biological and engineering hurdles to overcome before cost-competitive algal biofuels are realized. For example, recently researchers estimated that current algal production

costs need to be reduced by nearly 3.5 times (from 73 \$/GJ to 21 \$/GJ to be competitive with oil (Wesseler and Kovacevic, 2010).

A number of recent peer reviewed life cycle analyses (Batan et al. 2010, Clarens et al. 2010, Sander and Murthy, 2010, Stephenson et al. 2010) and techno-economic analyses (Raman et al., 2010), Kovacevic, and Wesseler, 2010, Norsker et al. 2010, Pokoo-Aikins et al. 2010, Chisti, 2007, Huntley and Redjale, 2007, Benemann and Oswald, 1996) of algae production have illuminated and sought to quantify those biological and engineering hurdles. The most costly, most energy and water consuming, and most greenhouse gas (GHG) producing unit operations are “pinch points” – rate limiting steps in the process where improvements potentially have a high return on investment. Understanding the nature of the barriers associated with those pinch points can help make algal biofuels commercially viable. In a similar fashion to traditional Pinch Analysis, a methodology that use the laws of thermodynamics to systematically analyze chemical processes and the surrounding utility systems in order to minimize energy consumption (Tan and Foo, 2007), these process pinch points can be scrutinized to reveal the chemical, physical, or biological processes that underlie the barrier.

Employing a what-if analysis, by manipulating the inputs and assumptions in the model, Framework for the Evaluation of Biomass Energy Feedstocks (FEBEF), could provide such an understanding of pinch points. The model was developed to compare feedstocks in an understandable and transparent manner, to gain insights into the differences, and sources of difference, between them (Raman et al., 2010). It is possible using FEBEF to compares energy costs, production costs, and energy return on

investment (EROI) from hypothetical feedstock production and fuel conversion scenarios. The spreadsheet based model links basic biological and physical assumptions with economic and environmental factors. FEBEF's structure has compartmentalized inputs such a way that offers a unique opportunity to examine tradeoffs with capital cost, biological components, and processing steps. Based on such an analysis, we aim to provide realistic estimates of the potential improvements in cost, energy return, and greenhouse gas emission yielded by such improvements.

Methodology

Pinch-Points Analysis

The first step in the analysis was to identify the pinch-points based on life cycle analyses (LCAs) and techno-economic analyses (TEAs) results for the three algal production scenarios analyzed in FEBEF: Open Raceway Ponds, Tubular Photobioreactors (PBRs), and a system that couples PBRs to ORPs (PBR-ORPs). Table 1 lists the unit operations classified as pinch-points along with literature that identified the unit operation/characteristic a hurdle.

The next step in the analysis was to connect pinch-points to proposed solutions that could be investigated by manipulating inputs and assumptions in FEBEF. Proposed solutions examined are listed in Table 1, along with potential targets and/or approaches for each solution, and anticipated impacts of each proposed solution. The value or range assigned as the potential was based on literature and/or company press releases suggesting or supporting the listed gain.

Table 1. Pinch-Points Identified from Literature LCAs and TEAs and Proposed Solutions and Potential Impacts

Manipulated in FEBEF.

Unit Operation/ Characteristics	Study	Proposed solutions	Target	Effect
Production – Efficiency	Batan et al 2010	Increased Radiation Use Efficiency	RUE reaches 15%	Increased biomass
Production-Oil Yield	Clarens et al 2010, Sander & Murthy 2010	Increased Oil Content	Algal Oil Content=70%	Increased oil recovered per algal cell
Separation and Extraction	Sander &Murthy 2010, Batan et al 2010	Secreting Oil- alkanes (here multiple inputs and assumptions can be changed)	Reduced capital investment by eliminating centrifugation costs	Easier harvesting &separation and avoids destroying algal biomass and may even skip conversion
Labor	Raman et al., 2010	Robust algal systems	Reduce operating costs by 50%	Reduce labor demands by ½
Irrigation	Raman et al., 2010	Recycle Water or use “free waste water”	Reduce clean water use by 50%	Reduce clean water use
Cultivation-PBR	Stephenson et al. 2010	Low cost PBR	Reduce photobioreactor capital costs 75%	Lower capital cost

FEBEF Key Metric Calculations

Five key metrics were monitored in order to assess the improvements to pinch-points in FEBEF. The key metrics included Energy Return on Investment, Maximum Fuel Energy Yield, Fuel Energy Cost, Total Energy Cost, and Carbon Intensity of Fuel Energy Source, an estimate of GHG emissions on a unit energy delivered basis. A percent change in each metric was also calculated (new value-base case value)/base case value. To understand the sensitivity of changes to key metrics to model inputs we calculated sensitivity coefficients (e.g., Hamby 1994). Given previous assessments that suggest algal biodiesel needs at least a 2/3 reduction in cost to be cost competitive with petroleum fuels (Wesseler and Kovacevic, 2010), we also calculated the impact of a combination of improvements to key metrics including energy cost.

Explanation of Key Metrics in FEBEF

Carbon Intensity of Fuel Energy Source

The Carbon Intensity of Fuel Energy Source is an indication of the total GHG emissions of the fuel per unit energy delivered. Lower values are clearly desirable, and a value of 96kg CO_{2 eq}/GJ represents fossil-based gasoline and 95 kg CO_{2 eq}/GJ for diesel (California ARB, 2009) and is a hurdle which any viable biofuel should clear. To compute it, the sum of the conversion and production GHG direct and indirect emissions term gave the total GHG on an areal basis. The CIFES was then calculated by using the GHG total (areal basis) and Total Energy Fuel Yield (TFEY) as shown in equation 1:

$$CIFES \left(\frac{kg \ CO_2e}{GJ_{out}} \right) = \frac{GHGT \left(\frac{MT \ CO_2}{ha \ yr} \right)}{TFEY \left(\frac{GJ_{out}}{ha \ yr} \right)} * 1000(kg/Mg) \quad (eq. 1)$$

Maximum Fuel Energy Yield with Co-Product Credit

The Maximum Fuel Energy Yield with Co-Product Credit (MFEY_{CPC}) is a representation of the total fuel energy plus energy embedded in the co-product credit produced by the system on an areal basis. Higher values are preferred and can be compared to corn to ethanol which has estimated MFEY_{CPC} 200 GJ_{out}/ha/yr (Raman et al. 2010). To compute MFEY_{CPC}, TFEY, Total Energy Use (direct and indirect) for Production (TEUP), and Total Energy Use for Conversion with Co-Product Credit (TEUC_{CPC}) were used as shown in equation 2, where all terms are in units of GJ ha⁻¹ yr⁻¹.

$$MFEY_{CPC} = TFEY - TEUP - TEUC_{CPC} \quad (eq. 2)$$

Energy Return on Investment (EROI) with Co-Product Credit

The Energy Return on Investment with the Co-Product Credit (EROI_{CPC}) is an important indicator of benefits for the fuel production technology and can be compared to EROI values for fuel and energy sources listed in Table 2. In order to compute EROI_{CPC} in FEBEF, Co-Product Credit (CPC) and Total Energy Use for Production and Conversion (TEUPC) along with TFEY were used as shown in equation 3, where all terms are in units of GJ ha⁻¹ yr⁻¹.

$$EROI_{CPC} = \frac{TFEY + CPC}{TEUPC} \quad (eq.3)$$

Table 2. Energy Return On Investment (EROI) for Fuel and Energy Sources in the United States (source: Murphy & Hall, 2010)

Fuel/Energy Source	EROI
Imported oil	12
Shale oil	5
Natural gas	10
Coal (mine-mouth)	80
Hydropower	>100
Wind turbines	18
Photovoltaic	6.8
Ethanol (sugarcane)	1 to 10
Ethanol (corn)	0.8 to 1.6
Biodiesel (soybeans)	1.3*

* Pradhan et al. (2008) reported a range of EROIs from past studies for biodiesel from soybeans to be 0.79 to 3.21.

Fuel Energy Cost

The Fuel Energy Cost (FEC) is assessment of the economic expense acquired during fuel production in relation to the energy content of the fuel. For reference Table 3 lists US energy prices from various sources. To compute the FEC for the different algal biodiesel production scenarios the Conversion of Fuel Energy Produced (CCFEP) and the TFEY were used FEC as shown in equation 4:

$$FEC \left(\frac{\$}{GJ} \right) = CCFEP \left(\frac{\$}{ha} / yr \right) / TFEY \left(\frac{GJ}{ha} / yr \right) \text{ (eq. 4)}$$

Table 3. Energy Price Comparison Short Term Energy Outlook as of March 31st, 2011. (EIA, 2011).

Energy Source	Unit Energy Price (\$/GJ)
West Texas Intermediate-Crude Oil	17.45
Gasoline (retail)	27.18
Diesel (retail)	26.10
Coal	2.11
Natural Gas (retail)	10.34
Electricity (retail)	32.47
Ethanol (corn) (retail)	31.94
Biodiesel (soybeans) (retail)	37.84

Total Energy Cost (production, conversion (fuel and co-product credit)

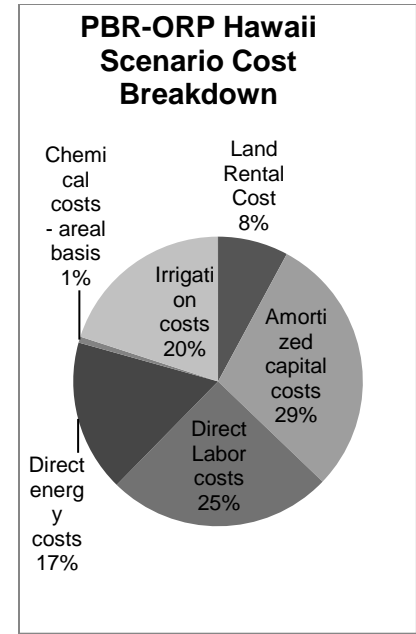
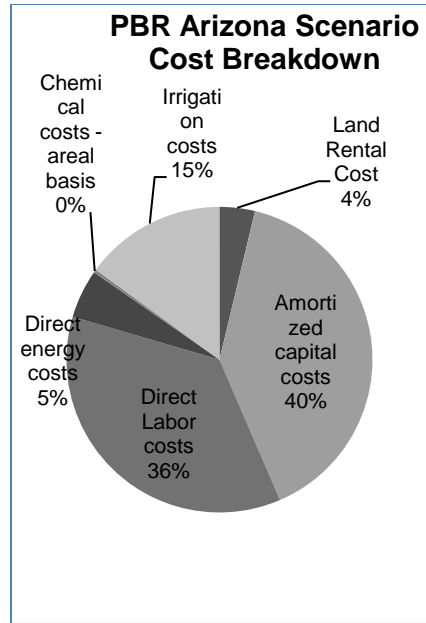
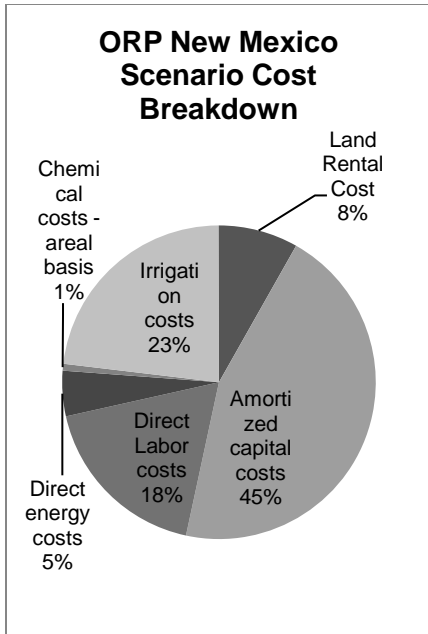
Total Energy Cost (TEC) is the ratio of the economic expense incurred during the production of a fuel to all energy produced which includes energy in the fuel and in the co-product. The TEC is comprehensive as it does include all energy gains it may understate the true cost. The TEC which includes the co-product energy ignores the difference in quality of the co-product credit energy to the liquid fuel product; for example diesel, higher quality energy is more valueable than coal, a lower quality energy source (Mulder and Hagens, 2008). The TEC including fuel and co-product credits from production to conversion was estimated as shown in equation 5:

$$TEC \left(\frac{\$}{GJ_{out}} \right) = TCFEP \left(\frac{\$}{ha} \right) / \left(TFEY \left(\frac{GJ_{out}}{yr} \right) + CPC \left(\frac{GJ_{out}}{yr} \right) \right) \text{ (eq.5)}$$

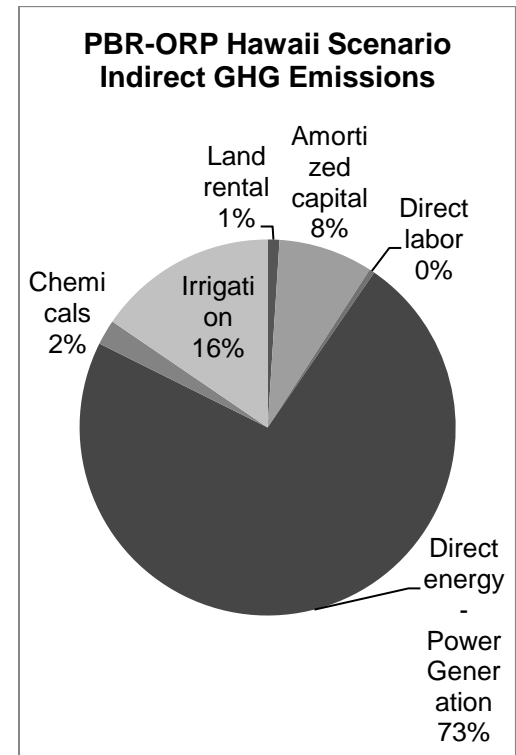
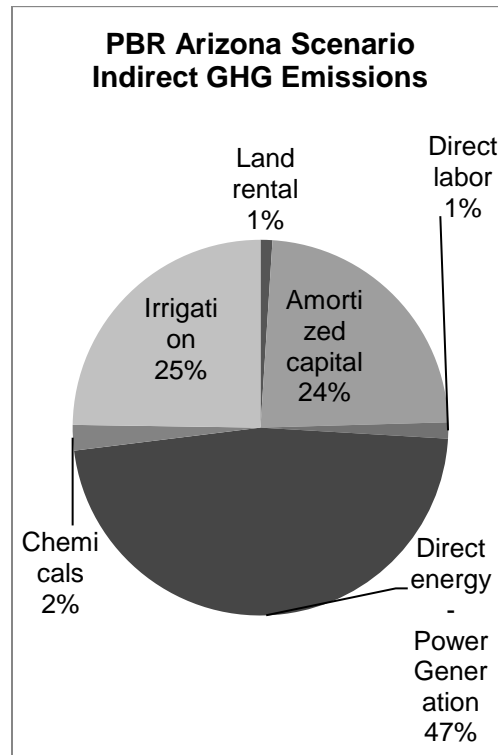
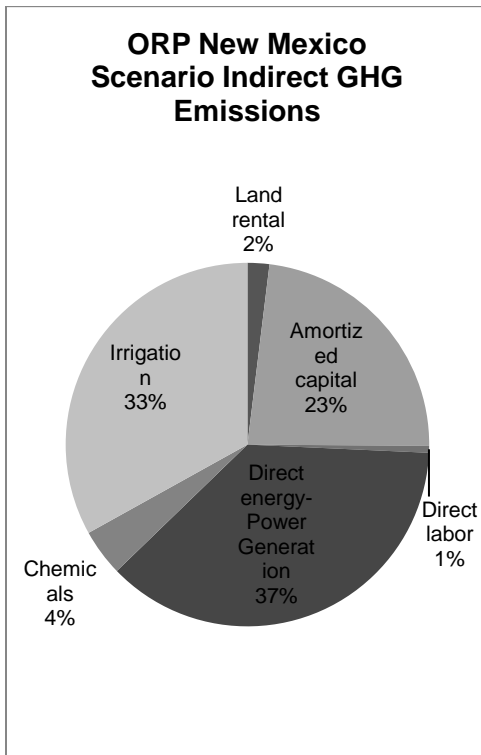
Results and Discussion

Pinch Analysis

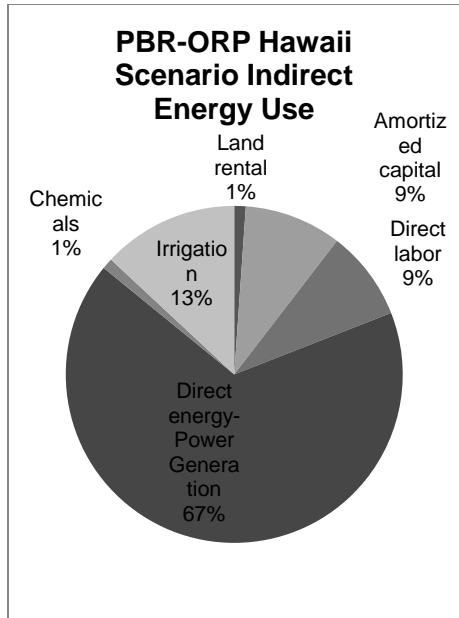
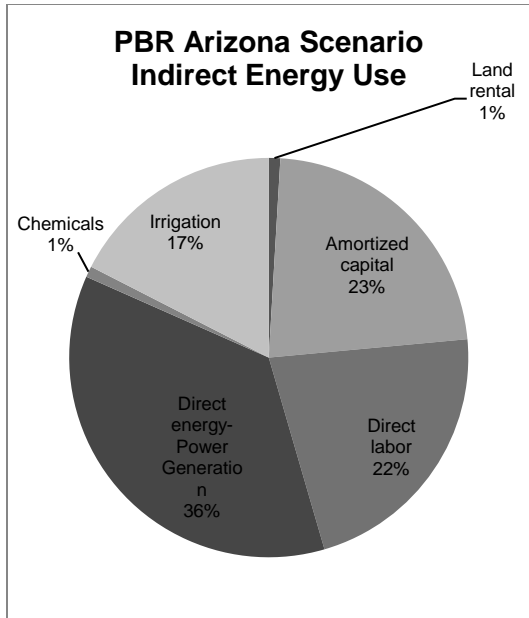
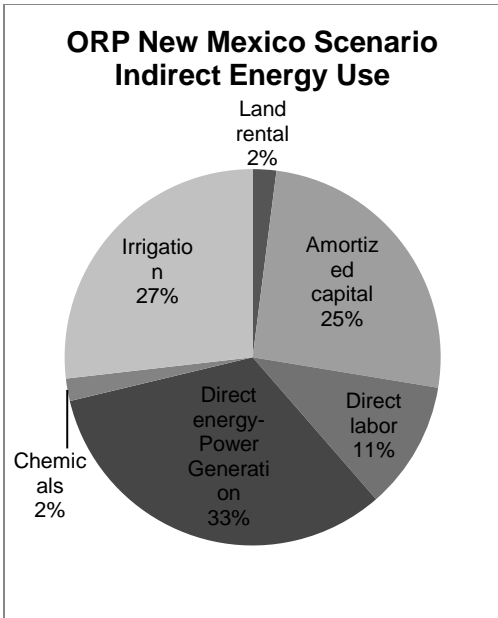
The greatest cost components for the scenarios were predicted to be amortized capital costs, labor costs and irrigation costs. The greatest indirect GHG emissions were predicted to be associated with energy, amortized capital, and irrigation for the three scenarios. The greatest indirect energy use associated with the different algal production scenarios were energy, amortized capital, irrigation and labor. These results suggest efforts should be focused on reducing capital, labor, and irrigation costs to improve the economic and environmental potential of biofuels from algae. In addition to directly reducing the cost of these pinch-points, increasing the biomass and oil yield of algal production scenario could serve to offset the costs of those pinch-points and improve the economic and environmental potential of biofuels from algae. The most costly, most energy consuming, and most greenhouse gas (GHG) producing components, the “pinch points” for each algal production scenario are shown in Figures 1 a through i



Figures 1 (a, b, c). Cost Component Breakdown for ORP New Mexico Algal Production Scenario, PBR Arizona Algal Production Scenario and PBR-ORP Algal Production Scenario.



Figures 1 (d, e, f). Indirect Greenhouse Gas Emissions Component Breakdown for ORP New Mexico Algal Production Scenario, PBR Arizona Algal Production Scenario and PBR-ORP Algal Production Scenario.



Figures 1 (g, h, i). Indirect Energy Use Component Breakdown for ORP New Mexico Algal Production Scenario, PBR Arizona Algal Production Scenario and PBR-ORP Algal Production Scenario.

A sensitivity analysis examining key metrics response to perturbations in FEBEF inputs supports the pinch-points identified and examined. Sensitivity Coefficients were calculated as shown in Equation 6.

$$\text{Sensitivity Coefficient} = \frac{\frac{\text{Perturbed Key Metric Value} - \text{Original Key Metric Value}}{\text{Original Key Metric Value}}}{\frac{\text{Perturbed Input} - \text{Original Input}}{\text{Original Input}}}$$

(eq. 6)

Select inputs in FEBEF with calculated sensitivity coefficients that negatively and positively affect key metrics are shown in Table 4. The key metric in FEBEF, Carbon Intensity of Fuel Energy Source was most sensitive to changes in inputs Radiation Use Efficiency and Oil Content. Maximum Fuel Energy Yield with Co-Product Credit was most sensitive to changes in inputs: Biomass Moisture Content at Harvest, Oil Content, and Radiation Use efficiency. The Energy Return On Investment with Co-Product Credit was most sensitive to changes in the inputs Biomass Moisture Content at Harvest and Oil Content. Fuel and Total Energy Costs were most sensitive to changes in inputs Oil Content and Radiation Use Efficiency.

Table 4. Sensitivity Coefficients for Key Metrics in Response to Perturbations to FEBEF Inputs.

Metrics	FEBEF Inputs						
	Radiation Use Efficiency	Biomass Moisture Content @ Harvest	Amortized Capital Costs	Direct energy costs	Direct Labor costs	Irrigation costs	Oil Content
Carbon Intensity of Fuel Energy Source (production and conversion)	-0.89	0.00	0.18	0.01	0.50	0.23	-0.94
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit	1.42	14.78*	0.53	0.34	1.04	0.53	1.56
EROI (Refined Oil with Co-Product Credit)	0.5	-2.31	-0.1	0.08	-0.24	-0.09	0.86
Fuel Energy Cost (production & conversion costs included)	-0.78	0.06	0.34	0.24	0.08	0.17	-0.88
Total Energy Cost (fuel and co-product energy: production & conversion costs included)	-0.78	0.06	0.34	0.24	0.08	0.17	-0.88

*Average value over three scenarios

Addressing Pinch-Point 1: Radiation Use Efficiency Increase to 15%

Algal biomass production is directly proportional to the efficiency with which algae convert carbon dioxide to fixed carbon. Photosynthetic efficiency is greater for algae than higher plants; with the theoretical maximum calculated using Photosynthetically Active Radiation (PAR) to be around 17%. Yet reports of the best case algal productivities achieved are only 40% of the theoretical maximum productivity (Melis, 2009). Melis (2009) and others have suggested that bioengineering could lead to higher photosynthetic efficiencies.

Per Melis's (2005) demonstration that algae can achieve 15% radiation use efficiency (RUE), increasing the algae RUE from 10.6% to 15% in FEBEF led to a noticeable improvements in key metrics. The increase in RUE led to a 26% reduction in Carbon Intensity of the Fuel Energy Source ($\text{kg CO}_2\text{ eq/GJ}$) (CIFES) and 23% or more reduction in Fuel Energy Cost (FEC) and Total Energy Cost (TEC) for all three scenarios considered in FEBEF. The lower FEC estimates, as shown in Table 5a, are impressive for algae grown in ORPs and suggest that the biodiesel produced from algae grown in ORPs is competitive with 5.90 \$/gal petroleum diesel. Additionally, the TECs suggest that biodiesel from algae grown in ORPs and PBR-ORPs systems might actually achieve the label of "cheap" biofuels, "cheap" being defined as a value equivalent or less than gas and diesel prices listed in Table 3. Equally impressive are the new estimates of CIFES for the ORP systems: at 42 $\text{kg CO}_2\text{ eq/GJ}$ they represent a 56% reduction compared to gasoline, and are competitive with corn ethanol. The increase in RUE led to over a 106% increase in Maximum Fuel Energy Yield including the Co-Product Credit (MFEY_{CPC}) for ORPs,

but only 42% and 26% for PBRs and PBR-ORPs Scenarios; only the ORPs scenario $MFEY_{CPC}$ moved into positive territory. However, the increase in RUE only led to a 12%, 23%, and 18% increase in Energy Return on Investment including the Co-Product Credit ($EROI_{CPC}$). These increases in $EROI_{CPC}$ led to relatively low new EROIs. These results corroborate those from the sensitivity analysis, which suggested that increases in RUE leads to small changes in CIFES, FEC, and TEC, greatest changes in $MFEY_{CPC}$ and the smallest changes in $EROI_{CPC}$ (Table 5b).

Given the success of Melis (2009), photosynthetic efficiency improvements are likely for algae in commercial systems, leading to greater biomass productivity for commercial systems, providing that the genetically modified organisms can dominate the algal slurry, and provided that other aspects of the system, such as CO_2 supply, can be designed to keep up.

Table 5a. New predictions of six key metrics in FEBEF given changes in radiation use efficiency for three algal production scenarios, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion) ($kg\ CO_{2\ eq}/GJ$)	42	76	78
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit($GJ/ha/yr$)	11	-540	-676
EROI (with Co-Product Credit)	1.01	0.84	0.80
Cost for Fuel Energy Produced (production and conversion costs included) ($$/GJ$)	40	79	42
Cost for all Energy (fuel and co-product) Produced (production & conversion) ($$/GJ$)	23	46	24

Table 5b. Sensitivity Coefficients of six key metrics to changes in Radiation Use Efficiency for three algal production scenarios, Open Raceway Pond-ORP,

Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs. (A sensitivity coefficient of 1.0 indicates that a 1% change in the RUE causes a 1.0% change in the metric.)

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion)	-0.65	-0.68	-0.68
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit	2.61	1.03	0.62
EROI (with Co-Product Credit)	0.30	0.55	0.44
Cost for Fuel Energy Produced (production and conversion costs included)	-0.57	-0.64	-0.57
Cost for all Energy (fuel and co-product) Produced (production & conversion)	-0.57	-0.64	-0.57

Addressing Pinch-Point 2: Oil Yield increases to 70% (w/w)

The oil yield for algae is a pinch point because it is limited by the cellular mechanisms that convert glucose to oils; the maximum theoretical stoichiometry for the conversion of glucose to triacylglycerol is 33% and derated to 22% when cellular metabolism are included (Ratledge and Cohen, 2008). Algae begin to accumulate oil when deprived of nitrogen but at the expense of reproducing: fast growth rates and high lipid contents are mutually exclusive (Ratledge and Cohen, 2008). Chisti (2007) presented evidence that lipid contents of algae can reach as high as 77% (dry weight basis) and assumed that 70% oil content can be achieved in commercial scale production facilities while Ratledge and Cohen (2008) argue that 40% is the optimum algae oil content to maximize the overall biomass yield.

Assuming that researchers are able to consistently produce algae that can achieve 70% oil content, increasing the algae oil content from 30% to 70% in FEBEF led to a noticeable improvement in key metrics. The increase in oil content led to a

55% reduction in CIFES, 50% (or greater) reductions in FEC, and at least a 33% reduction in TEC for all three scenarios considered in FEBEF. The lower FEC estimates, as shown in Table 6a, are impressive for algae grown in ORPs and suggest that the biodiesel produced from algae grown in ORPs is competitive with 3.80 \$/gal petroleum diesel. Additionally, the TEC suggest that biodiesel from algae grown in ORPs might actually achieve costs lower than present day fossil fuels. .

Equally impressive are the new estimates of CIFES as shown in Table 3a are all improvements over gasoline and diesel at 96 and 95 kg CO_{2 eq}/GJ (California ARB, 2009), respectively and competitive with corn ethanol estimated to be 42 kg CO_{2 eq}/GJ (Raman et al., 2010). The Maximum Fuel Energy Yield including the Co-Product Credit (MFEY_{CPC}) led to over a 400% increase for ORPs but only 105% and 100% for PBRs and PBR-ORPs Scenarios. This difference can be understood by the 15% difference in Total Energy Use for production and conversion between ORPs and the PBRs and PBR-ORPs scenarios. The 40% increase in algae oil content resulted in pushing the MFEY_{CPC} for the ORPs and PBRs I scenarios into positive territory. However, the 40% increase in oil content while leading to over a 90% increase in EROI_{CPC} for the ORPs, PBRs and PBR-ORPs scenarios only lead to relatively low new EROIs compared to a soybean biodiesel EROI of 3.21 (Pradhan et al. 2008). These results correspond to the sensitivity analysis suggested that increase in algae oil content leads to noticeable changes in CIFES, FEC, and TEC, greatest changes in MFEY_{CPC} and the smallest changes in EROI_{CPC} as shown in Table 6b.

Table 6a. New predictions of six key metrics in FEBEF given changes in oil yield for three algal production scenarios, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion) (kg CO ₂ eq/GJ)	25	46	47
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit(GJ/ha/yr)	509	48	-1
EROI (with Co-Product Credit)	1.27	1.01	1.00
Cost for Fuel Energy Produced (production and conversion costs included) (\$/GJ)	26	49	27
Cost for all Energy (fuel and co-product) Produced (production & conversion) (\$/GJ)	20	38	21

Table 6b. Sensitivity Coefficients of six key metrics in FEBEF to changes in Oil Yield for three algal production scenarios, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion)	-0.41	-0.42	-0.42
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit	3.14	0.79	0.75
EROI (with Co-Product Credit)	0.31	0.36	0.36
Cost for Fuel Energy Produced (production and conversion costs included)	-0.38	-0.41	-0.38
Cost for all Energy (fuel and co-product) Produced (production & conversion)	-0.25	-0.29	-0.25

This pinch-point analysis only changed one parameter, algae oil content, and assumes that all others remain the same, which is an oversimplification of the biological, physical, and economic systems and their relationships. The synthesis of lipids, high energy molecules, from the products of photosynthesis results in loss of mass and energy. Williams and Laurens (2010) use a combination of thermodynamic and metabolic pathway analysis to estimate the biomass and energy

losses associated with making lipids. Assuming a protein to carbohydrate ration of 3:2, the yield of biomass (Y) in mass per mass of hexose produced is shown in equation 7 where L is the algal lipid content.

$$Y = 1/(1.46 + 1.14 * L) \quad (\text{eq. 7})$$

When the tradeoff between lipid production and biomass reduction is accounted for in FEBEF while simultaneously increasing the algae oil content from 30% to 70%, the Maximum Harvested Yield for algae biomass per Williams and Laurens (2010) calculation should be reduced by 25%. Based on the increase in oil content and the decrease in biomass the key metrics discussed above changed slightly suggesting that the CIFES would actually only decrease by 43%, the FEC and TEC decrease by more than 40% and 20%, respectively while the $EROI_{CPC}$ increased by more than 25%. The increase in oil content and decrease in biomass resulted in the $MFEY_{CPC}$ increasing by 250% for ORPs but only 50% and 60% % for PBRs and PBR-ORPs scenarios, respectively. The 40% increase in algae oil content resulted in pushing the $MFEY_{CPC}$ for only the ORPs scenario into positive territory.

Given the biological constraints (i.e. 100 g glucose gives 33 g oil) there is likely a ceiling to the gains that can be made in oil productivity. Researchers suggest that while increasing lipid content comes with expense of biomass productivity there is the possibility with a two-stage culture system to optimize for biomass productivity in the first stage and then optimize for oil content in the second stage (Griffiths and Harrison, 2009).

Addressing Pinch Point 3: Reduced capital investment via elimination of centrifugation

Centrifugation capital cost account for nearly 20% of the total capital costs for the PBR-ORPs system, and 12% and 6% of total capital costs of the ORP and PBR system. The electrical costs associated with centrifugation are estimated to account for nearly 30% of the direct energy costs of commercial systems. Research by Schirmer et al. (2010) and researchers at Synthetic Genomics (Fehrenbacher, 2010) suggest that it may be possible to modify algae to synthesize and secrete hydrocarbons that can serve as fuel replacements. Producing algae that secrete hydrocarbons could allow for only needing a primary settling tank and no need for centrifugation to separate algae and water from oil.

Reducing the capital costs by removing centrifuge costs while assuming the oil yield (g oil/g biomass) and the co-product credit (GJ/liter biodiesel) remains the same in FEBEF resulted in small improvements to key metrics. The decrease in capital costs led to 12% and 1.5% reduction in CIFES for the ORPs and both PBRs and PBR-ORPs scenarios, respectively and 6.5%, 2.6%, and 4.6% reduction in FEC and TEC for the ORPs, PBRs, and PBR-ORPs scenarios, respectively. The lower FEC estimates, as shown in Table 7a are impressive for algae grown in ORPs and suggest that the biodiesel produced from algae grown in ORPs is competitive with 7.20 \$/gal petroleum diesel. Again, the TEC for ORPs is suggestive that biodiesel from algae grown in ORPs could be less than other liquid fuels. These results correspond to the sensitivity analysis suggested that decrease in capital costs only lead to minor changes in FEC, and TEC. The change in harvesting costs resulted in a 5% increase for the ORPs $EROI_{CPC}$ and approximately a 1% increase for both the PBRs and PBR-ORPs scenarios $EROI_{CPC}$ and nearly a 45%, 3.4%, and, 2.7%

increase in $MFEY_{CPC}$ for ORPs, PBRs, and PBR-ORPs scenarios. The decrease in harvesting costs was not enough to move $MFEY_{CPC}$ to positive levels for any of the scenarios. Nor was the decrease in harvesting costs was not enough to move $EROI_{CPC}$ above 1.0 for any of the scenarios. These results correspond with the sensitivity coefficients shown in Table 7b, all minor coefficients.

Table 7a. New predictions for six key metrics in FEBEF to reduction centrifugation capital costs for three algal production scenarios, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion) (kg CO ₂ eq/GJ)	50	103	106
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit(GJ/ha/yr)	-87	-899	-882
EROI (with Co-Product Credit)	0.94	0.69	0.68
Cost for Fuel Energy Produced (production and conversion costs included) (\$/GJ)	49	105	52
Cost for all Energy (fuel and co-product) Produced (production & conversion) (\$/GJ)	28	60	30

Table 7b. Sensitivity Coefficients of six key metrics in FEBEF to reduction centrifugation capital costs for three algal production scenarios, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion)	0.88	0.23	0.08
Maximum Fuel Energy Yield (Net-converted with Co-Product Credit)	3.29	0.47	0.15
EROI (with Co-Product Credit)	0.36	0.15	0.05
Cost for Fuel Energy Produced (production and conversion costs included)	0.47	0.37	0.26
Cost for all Energy (fuel and co-product) Produced (production & conversion)	0.47	0.37	0.26

Given biotechnology advancements (Schirmer et al. 2010; Fehrenbacher, 2010) it seems feasible that algae be modified to secrete hydrocarbons, though such an improvement alone is insufficient to make algal-biofuels economical. However, questions remain about the operation of this type of system. It is likely that the above assumption that the oil yield (g oil/g biomass) would remain the same is not likely, it could be much greater. Contrastingly, given that there is no centrifugation to separate oil from algae biomass would likely result in a much lower co-product credit. It is difficult to predict the overall impact hydrocarbon secreting algae would have on biofuels production from algae.

Addressing Pinch-Point 4: Reduction in Labor Costs by 50%

FEBEF estimates that labor accounts for more than 18%, 36%, and 25% of the total annual cost, 11%, 22%, and 9% of the indirect energy use, but only a small fraction of the indirect greenhouse gas emission of algae production in ORPs, PBRs

and PBR-ORPs scenarios, respectively. The PBR and PBR-ORPs systems are more complex than the ORPs and require greater monitoring and a skilled.

Researchers at Sandia National Laboratories (Janes, 2010) are trying to make open algae more robust to infection which in turn would make the systems more reliable, increasing the reliability of systems reduces labor needs. Additionally, automation of PBRs systems and increasing robustness of algae in those systems to higher temperatures and oxygen levels which in turn increases the reliability of the system and reduces the need for labor.

Reducing labor costs in FEBEF by 50% lead to only minor improvements in key metrics. The decrease in labor costs lead to negligible reductions, all less than 1%, in Carbon Intensity of the Fuel Energy Source ($\text{kg CO}_2 \text{ eq/GJ}$) (CIFES) and larger reductions of 8%, 17%, and 11% reduction in FEC and TEC for ORPs, PBR, and PBR-ORPs scenarios respectively. The lower FEC estimates, as shown in Table 5a, are impressive for algae grown in ORPs and suggest that the biodiesel produced from algae grown in ORPs is competitive with 280 \$/bbl of crude oil. Additionally, the TEC again suggest that biodiesel from algae grown in ORPs might actually achieve the label of “cheap” biofuels. The Maximum Fuel Energy Yield including the Co-Product Credit (MFEY_{CPC}) lead to only a 20% and 22% increase for ORPs and PBRs, respectively but only 7% for PBRs and PBR-ORPs Scenarios; none of those increases pushed the MFEY_{CPC} any scenario into positive territory. The decrease in labor costs only lead to a 2%, 8%, and 2% increase in EROI_{CPC} for the ORPs, PBRs, and PBR-ORPs scenario respectively. These increases in EROI_{CPC} led to relatively low new EROIs as shown in Table 8a. These results

correspond to the sensitivity analysis suggested that a decrease in labor costs only leads to very small changes in CIFES, FEC, and TEC, MFEY_{CPC} and EROI_{CPC} as shown in Table 8b.

Table 8a. New Predictions for six key metrics in FEBEF to changes in Labor Costs for three algal production scenarios, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion) (kg CO ₂ _{eq} /GJ)	56	104	107
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit(GJ/ha/yr)	-127	-719	-842
EROI (with Co-Product Credit)	0.92	0.74	0.69
Cost for Fuel Energy Produced (production and conversion costs included) (\$/GJ)	48	89	48
Cost for all Energy (fuel and co-product) Produced (production & conversion) (\$/GJ)	28	51	28

Table 8b. Sensitivity Coefficients of six key metrics in FEBEF to changes in Labor Costs for three algal production scenarios, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion)	0.01	0.01	0.00
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit	0.41	0.45	0.14
EROI (with Co-Product Credit)	0.04	0.15	0.05
Cost for Fuel Energy Produced (production and conversion costs included)	0.16	0.34	0.22
Cost for all Energy (fuel and co-product) Produced (production & conversion)	0.16	0.34	0.22

It is important to point out that reductions in labor would lead to increases in capital costs, particularly for the PBRs and PBR-ORPs; though if the reduction in

labor is greater enough the increase in capital costs may still allow for large reductions in FEC and TEC. It is difficult to predict the success of researchers producing more resilient algae given that bioengineering techniques are much better known than 30 years ago, it seems more likely now.

Addressing Pinch Point 5: Reduced Irrigation by 50%

Studies (Aresta et al., 2005, Mulbry et al. 2009, Mulbry et al. 2008, Mata et al. 2010) suggest that it is possible to produce algae using brackish and/or waste water instead of freshwater for biofuels production. Researchers report that algae remove nitrates and phosphates from the wastewater while at the same time producing an oil-rich biofuel feedstock (Gawlowicz, 2011).

Reducing freshwater consumption by 50% in FEBEF led to a small improvement in key metrics. The decrease in freshwater use led to nearly a 16%, 11%, and 7% reduction in Carbon Intensity of the Fuel Energy Source ($\text{kg CO}_2 \text{ eq/GJ}$) (CIFES) for ORPs, PBR, and PBR-ORPs scenarios. The reduction in freshwater use led to small reductions in Fuel Energy Cost (FEC) and Total Energy Cost (TEC) about 10%, 7%, and 9% for ORPs, PBRs, and PBR-ORPs scenarios. The lower FEC estimates, as shown in Table 9a, are mildly impressive for algae grown in ORPs and suggest that the biodiesel produced from algae grown in ORPs is competitive with 260 \$/bbl of crude oil. Additionally, the TECs scenarios respectively suggest that biodiesel from algae grown in ORPs might become cost competitive with other fuels. Only the estimate of CIFES for ORPs was lower than gasoline but not corn ethanol while the CIFES for PBRs, and PBR-ORPs scenarios were not

much different than gasoline. The Maximum Fuel Energy Yield including the Co-Product Credit (MFEY_{CPC}) lead to over a 50% increase for ORPs but only 18% and 11% for PBRs and PBR-ORPs scenarios and none of those increases pushed the MFEY_{CPC} any scenario into positive territory. The decrease in freshwater use only lead to tiny increases of 6%, 3% increase in EROI_{CPC} for the ORPs, PBRs, and PBR-ORPs scenario respectively. These increases in EROI_{CPC} lead to relatively low new EROIs. These results correspond to the sensitivity analysis suggested that increase in algae oil content leads to small changes in CIFES, FEC, and TEC, greatest changes in MFEY_{CPC} and negligible changes in EROI_{CPC} as shown in Table 9b.

Table 9a. New Predictions for six key metrics in FEBEF to changes in Irrigation Costs for three algal production scenarios, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion) (kg CO ₂ eq/GJ)	48	92	99
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit(GJ/ha/yr)	-79	-762	-809
EROI (with Co-Product Credit)	0.95	0.73	0.70
Cost for Fuel Energy Produced (production and conversion costs included) (\$/GJ)	47	100	50
Cost for all Energy (fuel and co-product) Produced (production & conversion) (\$/GJ)	27	57	29

Table 9b. Sensitivity Coefficients of six key metrics in FEBEF in changes to Irrigation Costs for three algal production scenarios, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion)	0.31	0.24	0.15
Maximum Fuel Energy Yield (Net-converted with Co-Product Credit)	1.01	0.36	0.22
EROI (with Co-Product Credit)	-0.11	-0.12	-0.07
Cost for Fuel Energy Produced (production and conversion costs included)	0.20	0.14	0.18
Cost for all Energy (fuel and co-product) Produced (production & conversion)	0.20	0.14	0.18

It is likely that utilizing wastewater could result in decreased chemical costs, but even if it could, the economic impact of such fertilizer offsets are likely small since irrigation costs are more than 30 times the chemical costs for all scenarios considered. Utilizing brackish or wastewater could result in lower biomass productivities due to lack of/reduced control over nitrate and phosphate concentrations and competition for nutrients and sunlight from bacteria and or other algal species already present in the wastewater.

Addressing Pinch Point 6: Capital Cost reduction for PBRs by 75%

PBRs account for the largest percentage of capital costs for the PBR and PBR-ORPs scenarios, 21% and 17% respectively. Baton et al. (2010) suggest that polyethylene bags can be used in place of glass or heavy plastic based PBRs leading to large reductions in capital costs. However, reducing the capital costs of PBRs in FEBEF lead to only lead to small improvement in key metrics for PBRs and

the PBR-ORPs scenario. The decrease capital costs lead to minor decreases in CIFES for PBRs and PBR-ORPs scenarios, nearly 3.5% and 1.0%, respectively. Similarly, the reduction in capital costs only resulted in a 6% reduction in FEC and TEC for PBRs and 3.5% for PBR-ORPs scenarios considered in FEBEF. The lower FEC and TEC estimates, as shown in Table 10a are still greater than the ORP predictions of FEC and TEC, 49 and 28 \$/GJ without any system improvements. The reduction in capital costs lead to improvements in $EROI_{CPC}$ and $MFEY_{CPC}$, but only small ones, around 2% for $MFEY_{CPC}$ and 1% for $EROI_{CPC}$. These results suggest that algal biodiesel from PBRs and PBR-ORPs systems need more than a reduction capital costs before achieving costs competitive with gasoline or other biofuels. Cheaper PBRs are not the panacea for cheap biofuels from algae without improvements in biomass and oil yields and reductions in labor costs. These results are also reflected in the small sensitivity coefficients shown in Table 10b.

Table 10a. Sensitivity Coefficients of six key metrics in FEBEF for three algal production scenarios to changes in PBR capital costs, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion) (kg CO_2_{eq} /GJ)	-	101	106
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit(GJ/ha/yr)	-	-861	-888
EROI (with Co-Product Credit)	-	0.70	0.68
Cost for Fuel Energy Produced (production and conversion costs included) (\$/GJ)	-	101	53
Cost for all Energy (fuel and co-product) Produced (production & conversion) (\$/GJ)	-	58	30

Table 10b. Sensitivity Coefficients of six key metrics in FEBEF for three algal production scenarios to changes in PBR capital costs, Open Raceway Pond-ORP, Photobioreactors-PBR, ORP-PBR combined system-PBR-ORPs.

	ORP	PBR	PBR-ORPs
Carbon Intensity of Fuel Energy Source (production and conversion)	-	0.22	0.23
Maximum Fuel Energy Yield (Net-converted) with Co-Product Credit	-	0.96	0.47
EROI (with Co-Product Credit)	-	-0.11	-0.15
Cost for Fuel Energy Produced (production and conversion costs included)	-	0.40	0.37
Cost for all Energy (fuel and co-product) Produced (production & conversion)	-	0.40	0.37

Two Thirds Reduction in Cost

None of the solutions examined in FEBEF singularly provide a two thirds reduction in FEC. A number of different combinations of solutions examined could lead to the two thirds reduction needed to make algae oil competitive with petroleum diesel. The increase in algae oil content and RUE combined would result in much lower FEC and TEC for the ORPs, PBRs and PBR-ORPs scenarios. The combined solutions impacts are shown in FEC and TEC shown in Table 11a and the new lower CIFES and higher $EROI_{CPC}$ are shown in Table 11b. The ORP production scenario is predicted to produce biodiesel from algae with the lowest FEC and TEC and highest EROI and lowest CIFES, put with decreased labor costs, an increase in RUE and oil yield, the PBR-ORPs system also is predicted to have similar FEC and TEC costs.

It is nearly impossible to estimate the probabilities concerning the likelihood of any one of these solutions coming to fruition and then estimate the combined probability of any of the combined solutions happening. While the lower PBR costs

appear to be a commercial reality (Batan et al. 2010) it is not enough to contribute to a 2/3 reduction in costs. Given the current state of technology it seems less likely that such large reductions in labor costs and harvesting costs will occur than it does to have biotechnology successes of increased RUE and Oil Yield given literature reports of successes with biotechnology.

Table 11a. Adjusted FEC and TEC for Algal Production Scenarios Reflecting Combined Reduction

Algal Scenarios	ORP		PBR		PBR-ORPs	
	FEC (\$/GJ)	TEC (\$/GJ)	FEC (\$/GJ)	TEC (\$/GJ)	FEC (\$/GJ)	TEC (\$/GJ)
Increase in Oil Yield (70%) and RUE (15%)	21	16	37	29	21	16
Decrease in Labor Costs (50%) and Increase in Oil Yield (70%)	24	19	42	32	24	19
Decrease in Harvesting Capital costs (~15%) and Increase in Oil Yield to 70%	24	19	48	37	26	20
Decrease in Labor Costs (50%), Increase in RUE (15%) and Oil Yield (70%)	19	16	32	29	19	16

Table 11b. Adjusted Carbon Intensity of Fuel Energy Source (CIFES) ($\text{kg CO}_2\text{eq/GJ}$) and Energy Return on Investment with Co-Product Credit (EROI_{CPC})

Algal Scenarios	ORP		PBR		PBR-ORPs	
	CIFES	EROI_{CPC}	CIFES	EROI_{CPC}	CIFES	EROI_{CPC}
Increase in Oil Yield (70%) and RUE (15%)	19	1.88	34	1.63	34	1.55
Decrease in Labor Costs (50%) and Increase in Oil Yield (70%)	25	1.29	46	1.08	47	1.02
Decrease in Harvesting Capital costs (~15%) and Increase in Oil Yield to 70%	22	1.32	45	1.02	46	1.03
Decrease in Labor Costs (50%), Increase in RUE (15%) and Oil Yield (70%)	19	1.39	34	1.20	34	1.15

Conclusions

Manipulating the inputs and assumptions in FEBEF in light of claims and evidence discussed in literature we were able to discern the individual contribution of pinch points. The key metrics responded differently to changes in inputs: EROI_{CPC} was most sensitive to changes in RUE for PBRs and PBR-ORPs with a sensitivity coefficient (SC) of 0.55 and 0.44 but for ORPs was more sensitive to changes in oil yield with a SC of 0.31. The CIFES metric was most sensitive to changes in RUE with a SC of -0.68; MFEY_{CPC} for ORPs was most sensitive to changes in harvesting costs with a SC of 3.29 while MFEY_{CPC} for PBRs and PBR-ORP was most sensitive to changes in RUE with SCs near 1.0. Similarly, the FEC and TEC were most sensitive to changes in RUE with SCs around 0.6. These results suggest that the focus of future research efforts (i.e. improving RUE or reducing fresh water use) would vary depending on the objective (i.e. cheap energy versus low GHG intensity).

We were also able to assess the impact of improvements to the pinch-points to the overall economic and environmental potential of algae to biodiesel production systems. Specifically, we were able estimate that with the combined improvements of increased RUE and oil yields along with decreased labor costs relatively low FECs could be attained, 19 \$/GJ for biodiesel from ORPs and PBR-ORPs. Additionally, we were able to show that significant decreases in capital costs including eliminating centrifugation costs and reducing PBR cost did not result in large enough improvements to make algal biodiesel competitive with gasoline or biofuels.

These results indicate that the most promising opportunities to improve the economics and environmental benefits gained from producing biodiesel from algae produced in ORP, PBR, and PBR-ORPs are biotechnology solutions; increasing RUE and oil yield. Not one solution considered here appeared to be sufficient to reduce the cost of fuel energy from algae to a competitive level with petroleum diesel prices (2.65\$/gal, ca. \$18/GJ). The combined gains in the solutions presented, increases in RUE and oil content, decreases in irrigation, harvesting, labor and PBR costs can lead to low FEC and TEC, ranging from 48 to 11 \$/GJ.

Wijffels and Babarosa (2010) concluded following a similar feasibility analysis that biodiesel production from algae would only be possible if algae were produced to make bulk chemicals, food, feed, and also oil for biodiesel. These results reflect the conclusion made by Wijffels and Babarosa (2010): “production technologies are immature and need biotechnological and engineering gains before these systems can compete with other mature fuel production systems like oil and corn ethanol.”

Terms

TFEY -Total Fuel Energy Yield ($\text{GJ}_{\text{out}}/\text{ha}/\text{yr}$)
 CPC- Co-Product Credit ($\text{GJ}_{\text{out}}/\text{L}$ biodiesel)
 TEUP-Total Energy Use for Production ($\text{GJ}/\text{ha}/\text{yr}$)
 TEUC_{CPC}-Total Energy Use for Conversion with Co-Product Credit ($\text{GJ}/\text{ha}/\text{yr}$)
 TEUPC-Total Energy Use for Production and Conversion ($\text{GJ}/\text{ha}/\text{yr}$)
 CCFEP-Cost for Conversion of Energy Produced ($\$/\text{ha}/\text{yr}$)
 TCFEP-Total Cost for Fuel Energy Produced ($\$/\text{ha}/\text{yr}$)
 ORPs-Open Raceway Ponds
 PBRs-Photobioreactors
 PBR-ORPs-Photobioreactors coupled to Open Raceway Ponds
 MFEY_{CPC} -Maximum Fuel Energy Yield –Net Converted with Co-Product Credit ($\text{GJ}/\text{ha}/\text{yr}$)
 EROI_{CPC} -Energy Return on Investment with Co-Product Credit (dimensionless)
 CIFES-Carbon Intensity of Fuel Energy Source ($\text{kg CO}_2 \text{ eq}/\text{GJ}$)
 FEC-Fuel Energy Cost ($\$/\text{GJ}$)
 TEC- Total Energy Cost (production, conversion (fuel & Co-Product Credit)) ($\$/\text{GJ}$)

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Chapter 5. Conclusions

Discussion

The successful development of biofuels from algae has been promoted as a cheaper, more environmentally friendly, non-food source alternative to biofuels derived from terrestrial crops such as corn and sugar cane. Biofuels from algae is presently limited to small- (mostly bench) scale production. There is a disconnect between the highly, promoted yet unrealized potential of algae and the current state of algal biofuels production. Estimating the costs and life cycle impacts of proposed algal biofuel production systems was crucial not only to enlighten researchers, policy makers and investors, but helps to fix the disconnect. Reports of direct TEA and LCA comparisons between algae to biofuel production systems are limited as noted in Chapter 3. These limited reports also suffer from varying assumptions and system boundaries that confound comparisons across studies. Furthermore, cost and life cycle estimation allow for the identification algal production technologies' pinch points and then subsequent the quantification of impacts of proposed technological advancements thought to remedy pinch points. We sought to address these challenges in this work by 1) assessing Cost Growth and Plant Performance, 2) cost and life cycle impacts and 3) identifying pinch-points and quantifying impacts on cost and environmental metrics of specific improvements to pinch-points.

In Chapter 2, "*Comparison of Algae Production Scenarios' Cost Growth And Plant Performance*," two models were employed to predict pioneer plant Cost Growth and Plant Performance along with the subsequent unit Cost Growth for three algal production technologies. The three production technologies were Open

Raceway Ponds (ORPs), Photobioreactors (PBRs), and a coupled system of PBRs to ORPs (PBR-ORP). The predictions for Cost Growth, Plant Performance and unit Cost Growth for the scenarios were far from precise, given the error in the model parameter estimates and the uncertainty around the inputs related to the algal production technologies. Although these analyses had significant uncertainty, the results highlight the risks associated with implementing algal biofuel systems, as all scenarios examined were predicted to have Cost Growth, ranging from 1.2 to 1.8, and Plant Performance was projected as less than 50% of design performance for all cases. As a result of low Plant Performance and Cost Growth, unit costs for first plants will be much higher than estimates which supports the argument for the production of high-value compounds from algae instead of biofuels to build a technical knowledge base that can be scaled to make biofuels in the future with lower unit costs. More refined models and better statistical tools could improve predictions of various algal technologies' Cost Growth and Plant Performance.

In Chapter 3, "*EIO-LCA Based Comparison of Algal Production Technologies using the Framework for the Evaluation of Biomass Energy Feedstocks Suggests Cheap Algal Biofuels Distant Hope*," we employed the Framework for the Evaluation of Biomass Energy Feedstocks (FEBEF) to examine the economic and environmental potential of biofuels from three algal biofuel production scenarios. The analysis indicated that biodiesel from algae produced in ORPs, PBRs, and PBR-ORP are more expensive and are not necessarily more environmentally friendly than other biofuel feedstocks. The biodiesel produced for the ORP and the PBR-ORP

system was estimated to cost 7 \$/gge. The biodiesel from algae produced in PBR and PBR-ORP release more GHG emissions, 105 and 107 kg CO₂ eq/GJ, respectively, than gasoline and ethanol from corn. Yet, the biodiesel produced from algae in ORPs has a Carbon Intensity, 56 kg CO₂ eq/GJ, which is lower than gasoline but not ethanol from corn. Adding to the bad news for algae were the disappointingly low estimates for EROIs which were all below one.

In Chapter 4, “Pathways forward for biodiesel production from algae,” we completed a pinch point analysis to understand impact of proposed advancements and solutions on the economic and environmental potential of biofuels using FEBEF for three algal production systems: ORPs, PBRs, and PBR-ORPs. The results from this analysis indicated that are tremendous opportunities to improve the economics and environmental benefits gained from producing biodiesel from algae produced in ORP, PBR, and PBR-ORPs. Not one solution considered in Chapter 4 appeared to be enough to reduce the cost of fuel energy from algae to a competitive level with current oil prices (100\$/bbl). The combined gains in the solutions presented, increases in RUE and oil content, decreases in irrigation, harvesting, labor and PBR costs could lead to low biodiesel costs of near 3 \$/gge. Again there is no structured uncertainty available surrounding the value of the improvements studied for each pinch point. Employing a more complicated Monte Carlo simulation could produce meaningful distributions of model outputs that better describe the potential impact of suggested improvements.

Recommendations

Future work that attempts to address and assess algal biofuels economics and life cycle impacts, particularly if the work is to be used for decision making purposes (i.e. investment in research, pilot plant construction of bench-scale technologies) must attempt to deal with the vast uncertainty surrounding each of the technologies being proposed. While it is difficult to quantify the uncertainty surrounding FEBEF predictions using traditional methods (probability), FEBEF offers users flexibility and transparency that is not likely to be found with other economic assessment-LCA tools. Structured uncertainty (i.e. means, standard deviations, and distribution forms (normal)) is not available for data concerning the algal production technologies analyzed in FEBEF nor is there for the EIO-LCA, biological and economic data that FEBEF is built upon. Future work that desires the flexibility offered with FEBEF may instead need to employ other tools like possibility based analysis or information gap analysis in order to make investment decisions given such challenging uncertainties.

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