Algal Research 4 (2014) 96–104

Contents lists available at ScienceDirect

Algal Research

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

A financial assessment of two alternative cultivation systems and their contributions to algae biofuel economic viability

James W. Richardson [a,*], Myriah D. Johnson [a], Xuezhi Zhang [b], Peter Zemke [b], Wei Chen [c], Qiang Hu [b,*]

[a] Agricultural & Food Policy Center, Department of Agricultural Economics, Texas A&M University, College Station, TX 77843, USA
[b] Laboratory for Algae Research and Biotechnology, College of Technology and Innovation, Arizona State University, Mesa, AZ 85212, USA
[c] Institute of Hydrobiology, Chinese Academy of Sciences, No. 7 Donghu South Road, Wuchang District, Wuhan, Hubei 430072, China

ARTICLE INFO

Article history:
Received 31 May 2013
Received in revised form 9 December 2013
Accepted 15 December 2013
Available online 8 January 2014

Keywords:
Photobioreactor
Open raceway ponds
Cost of production
Monte Carlo simulation
Farm-level Algae Model (FARM)
Net cash income

ABSTRACT

The Farm-level Algae Risk Model (FARM) is used to simulate the economic feasibility and probabilistic cost of biomass and bio-crude oil production for two projected algae farms. The two farms differ in their cultivation system: an open raceway pond (ORP) and a photobioreactor (PBR). The economic analysis incorporates production, price, and financial risks the farms will likely face over a 10-year period. Current technology for both cultivation systems is assumed with an emphasis on the differences in biomass production, lipid content, culture crashes, and dewatering and extraction costs. Results of the analysis indicated that with current prices and technology neither cultivation system offers a reasonable probability of economic success. The total costs of production for crude bio-oil is 109 \$ $gal^{-1} \pm 45$ $(\bar{x}, \sigma)$ for an ORP and 77 $gal^{-1} \pm 25$ $(\bar{x}, \sigma)$ for a PBR. Further analysis revealed that for every 1% increase in biomass production annual net cash income is increased 0.21% for an ORP and 0.10% for a PBR.

1. Introduction

Microalgae are being heavily researched as an alternative feedstock for renewable biofuels. In the production process there are several key steps that affect the cost of biofuel production and profitability, but the single most critical step is involved in the cultivation system and process to produce biomass feedstock [1–4]. There are two predominate cultivation systems employed in the microalgal industry, i.e., open raceway ponds (ORPs) and closed photobioreactors (PBRs) [5]. Due to their initial costs and maintenance and energy requirements, as well as their determination on final cell population density, cellular biochemical composition, and biomass productivity, the cultivation system used on a microalgae farm determines to a large extent the economic viability of microalgae-based biofuels and bioproducts.

Most available biomass productivity data have been obtained from lab-scale or outdoor small-/pilot-scale trials over a brief period of time (days or weeks), and are extrapolated to commercial-size facilities. Only a few publicly available data exist for larger size facilities or a longer time period of operation. Norsker et al. determines the production costs to be 4.95, 4.16, and 5.96 € kg^{-1} of biomass for ORPs, horizontal tubular PBRs and flat panel PBRs, respectively, for a 100 hectare facility [6]. Chisti estimates the cost per gallon of production to be \$2.95 and \$3.80 for PBRs and ORPs, respectively, for a facility producing 100,000 kg of biomass annually [7]. Alternatively, Davis et al. find minimum selling prices for algal lipid of 8.52 \$ gal^{-1} for ORPs and 18.10 \$ gal^{-1} for PBRs to achieve a 10% internal rate of return in a facility producing 10 MG yr^{-1} [3]. Richardson et al. also evaluate a production facility producing 10 MG yr^{-1} and find that ORPs have a lower cost of production at 12.74 \$ gal^{-1} as compared to PBRs, which have a cost of production of 32.57 \$ gal^{-1} [8]. However, in each of these studies and others [9–11], optimistic productivities were assumed that did not accurately reflect the actual productivities and the cellular lipid content currently achievable in the existing ORPs and PBRs. For example, Davis et al. [3], Richardson et al. [8], and Delrue et al. [11] assumed equal areal productivities of 25 g m^{-2} d^{-1} and 25% lipid content, for both ORPs and PBRs. However, recent studies have reported that considerably higher lipid productivities are achievable in PBRs than in ORPs. Quinn et al. reported a two-year average of 7.4 g biomass m^{-2} d^{-1} and 35% lipid content of *Nannochloropsis* sp. grown in the Solix PBR system [12]. Previously, Rodolfi et al. [13] reported average outdoor productivities of 11 g biomass m^{-2} d^{-1} and 40% lipid content for *Nannochloropsis* sp. in green wall photobioreactors [13]. Short-term productivities of *Nannochloropsis* sp. in ORPs have been 3–4 g biomass m^{-2} d^{-1} with lipid contents of 15–25% [14]; Hu et al.

Abbreviations: OPR, open pond reactor; PBR, photobioreactor; PDF, probability density function; NCI, net cash income; CAPEX, capital expenses; OPEX, operating expenses; Es, sensitivity elasticity.

* Corresponding authors.
E-mail addresses: jwrichardson@tamu.edu (J.W. Richardson), huqiang@asu.edu (Q. Hu).

http://dx.doi.org/10.1016/j.algal.2013.12.003
2211-9264/

Table 1
Summary of biomass productivities, lipid contents, and biomass loss due to algal grazers assumed for the analysis based on published literature.

	Biomass productivity (g m^{-2} d^{-1})	Lipid content (%)	Harvesting biomass concentration (g L^{-1})	Grazer biomass loss (%)
ORP	6.8 ± 3.0	20 ± 5	1.5	20 ± 10
PBR	9.3 ± 2.0	40 ± 10	3.0	8 ± 3

achieved productivities of 10 g biomass m^{-2} d^{-1} and 18% average lipid content in a PBR [15].

When the capital and operational costs of PBRs and ORPs are compared in isolation, the costs of PBRs are higher than those of ORPs. When the comparison is made in the context of the entire algal biofuel production supply chain, however, it is not known which system would be more cost-effective. For example, greater stability and sustainability of microalgal mass culture, and higher biomass density and lipid content are achievable in PBRs while having considerably less water demand and associated energy consumption per kg of biomass obtained. These differences have significant economic implications for overall biomass feedstock production and subsequent harvesting, dewatering and extraction processes. However, the influence of cultivation systems and processes on the individual steps up- and down-stream has not been recognized in the previous techno-economic analyses, let alone quantitative assessments of the cultivation systems and processes on overall production cost.

As further research is done on algal cultivation systems, especially at a larger scope than lab, bench, or small outdoor-scale with a longer period of time (months or years), it needs to be analyzed to determine which technologies may be more financially feasible for use in commercial production systems. The Farm-level Algae Risk Model (FARM) developed by researchers at Texas A&M University for use in the National Alliance for Advanced Biofuels and Bio-products (NAABB) Consortium was used for this analysis [8]. Productivity data (algae growth rates, lipid contents, biomass concentrations) was based on productivities published in the literature. For PBRs, the productivities and lipid contents were based on the results of Quinn et al. [12] and Rodolfi et al. [13] while the results of Hu et al. [15] and Crowe et al. [14] were used for ORPs. These values, given in Table 1, were selected as they are representative of annual productivities observed by the authors. Product lost to algal grazers has not been well quantified, but the authors estimate that it is 5–10% for PBRs and 10–30% for ORPs. Currently, at this time there are no well documented mitigation strategies for pond predation and crashes. So, the probability of pond crashes and grazer biomass loss does not decrease over the 10 year horizon for the business.

The stochastic variables listed in Table 1 were simulated using the GRKS distribution using the Excel add-in, Simetar [16]. The GRKS[1] distribution is suited to this application because it requires minimal parameters (minimum, middle, and maximum) and provides a 2.28% probability of outliers beyond the minimum and maximum parameters. Simetar is an Excel add-in for estimating parameters of probability distributions for random variables and simulating Monte Carlo models. Simetar has been used extensively for risk analysis of business models and prospective businesses [17].

GRKS probability distributions for the following stochastic production variables were based on values in the literature: biomass productivity (g m^{-2} d^{-1}), percent lipid content, harvesting biomass concentration (g L^{-1}), percent grazer biomass loss, and number of harvests per month were specified. Combing stochastic production values listed above with total facility pond volume, the model simulates total annual biomass and lipid production.

The objective of this paper is to compare the economic feasibility of biofuel production in the two alternative cultivation systems, ORPs and PBRs, with the consideration of different algal density, cellular lipid content, biomass productivity, production loss due to grazers and parasites, and their influence on the harvesting and extraction processes. The two cultivation systems are compared as to their impacts on the revenues, expenses, and cost of production for an algae farm. While neither cultivation system is expected to result in economically feasible biofuel production at present productivities, this work will provide insight into the kinds and magnitudes of technical improvements and cost reductions required for each production step to produce economically competitive biofuels.

2. Material and methods

The data for the two algae farms with alternative cultivation systems was analyzed using the FARM to project changes in their economic viability. FARM is a Monte Carlo firm level simulation model designed to simulate the annual production and economic activities of an algae farm. The model was designed to facilitate researchers' analysis of the economic returns and costs of production for an algae farm under alternative management systems. The model can be thought of as a systems compilation of many techno-economic models for different phases of an algae farm.

2.1. FARM programming

FARM is programmed in Microsoft® Excel and depends upon the Simetar© add-in to incorporate risk. The Excel workbook model is divided up into multiple worksheets that include: Input, Model, SimData, Prices, and others.

All inputs for an algae farm are entered in the INPUT worksheet and most calculations are in the MODEL worksheet. Simetar is used to simulate the model by randomly drawing annual stochastic prices, production, and costs from known probability distributions. The parameters for price probability distributions are estimated from historical data provided as input by the researchers. Parameters for algal biomass production are estimated from actual production data for ORPs and PBRs.

The FARM model is simulated recursively for 10 years. This means that the ending cash position of the business in year 1 is the beginning cash flow position for year 2, and so on. The 10 year planning horizon is repeated 500 times (iterations) using different stochastic prices and production values for each year. By simulating the 10 year planning horizon for 500 iterations, the model is able to simulate most combinations of the stochastic variables (i.e., the best and worst cases and those in between) based on their respective probabilities of being observed. The resulting 500 values for the key output variables are estimates of the empirical probability distributions for these variables and are used to calculate probabilities of financial and economic sustainability [8].

Analysts enter all of the data to describe the scenario to be simulated for a farm. Input data include information for: the type of cultivation, final cell density, lipid content, biomass productivity, harvesting, lipid extraction, and use of co-products. A base scenario is usually defined and copied multiple times with slight variations in the many management

[1] The GRKS distribution assumes that 50% of the observations are greater than the model value. Also, the distribution draws 2.28% of the values from above the maximum and 2.28% from below the minimum. Random values from outside the minimum and maximum values account for low frequency, rare observations, i.e., Black Swans.

control variables. For the present analysis two input data sets were used representing the biomass production in ORP and in PBR. Simetar simulated both scenarios at once using the same risk for all of the stochastic variables. In this manner one can be guaranteed that the scenarios can be compared directly and that the only difference between scenarios is the input data for the ORP and the PBR.

The model simulates the stochastic monthly production of algae biomass and uses those values to simulate the lipid production. Based on the stochastic culture volume at harvest and the unit throughput of the harvesting and dewatering systems, the model calculates the number of harvesting and dewatering units. The capital costs of harvesting and dewatering processes were then calculated. The operational costs in harvesting and dewatering processes include electricity, chemicals, labor and maintenance. Extraction costs are a function of the system used, the quantity and type of biomass and its concentration (percent solids), electricity and solvent requirements and labor costs. Annual maintenance, overhead, management, and fixed costs are calculated by inflating the initial costs for these variables using stochastic annual rates of inflation.

The economic variables (such as: receipts, expenses, interest, taxes, dividends, and principal payments) are used to calculate the key output variables: net cash income, ending cash reserves, and net worth each year of the 10 year planning horizon. The overall net returns to the farm are summarized in net present value which reflects the overall returns to the business in today's dollars. If the net present value is positive the farm's internal rate of return exceeds the discount rate and the business is an economic success.

By simulating an algae farm for 500 iterations, the model estimates 500 points for an empirical probability distribution of each key output variable (KOV). In this manner FARM estimates the probability distributions for annual net cash farm income, cost of production for a gallon of crude bio-oil, ending cash reserves, and net present value. The estimated probability distributions show the mean for the KOVs as well as the range or risk associated with the KOVs. For instance, the model provides an estimate of the 95% confidence interval about the estimated average cost of production for a gallon of crude bio-oil. Additionally, the probability distributions show the skewness associated with the KOVs so scientists and investors have an estimate of the risk associated with alternative algae oil pathways.

2.2. Description of the two cultivation systems

Fig. 1 illustrates the overall production process. The farms are located on land in the Southwestern U.S. and each produces 50,000 MT per year of crude lipid. Both farms use brackish water or saline aquifers for production of the marine alga *Nannochloropsis* sp. This genus of algae was assumed because of its relatively high resistance to disease and predation and wide tolerance of environmental conditions (e.g., salinity and temperature) compared to other algae that may have higher lipid productivities under ideal conditions. Each farm uses a batch growth process to mitigate microbial contamination as well as to maximize lipid content [18].

Each batch increases the biomass concentration by a factor of 10 from seed to finished biomass (0.15 to 1.5 g L^{-1} for ORP, 0.3 to 3 g L^{-1} for PBR). As a result, an additional 11% of land is needed for seed cultivation in addition to land for biomass production.

The ORPs are assumed to be lined and circulated with paddlewheels. Eighty percent of the farm is assumed to be covered by ORPs, with the remaining 20% being access and utility routes. The ORP depth varies seasonally from 20 to 30 cm. Currently, in the Southwestern United States algal production facilities with ORPs are regulated by the same policies as wastewater treatment facilities, which require liners. This policy does not appear likely to change in the near future. Thus, unlined ORPs were not considered for this analysis.

The PBRs are assumed to be thin vertical plate reactors similar to those described by Sierra et al. [19], composed of a thin-film polymer bag compressed between rigid “fencing.” The capital cost is estimated between 40 and 100 \$ m^{-2}. They have an optical path length (mean thickness) of 4 cm. The PBRs are assumed to be 1 m high and spaced 1 m apart. Mixing is provided by aeration, and cooling is achieved by circulating water from an underground aquifer through cooling lines in the PBRs, as necessary.

Algal biomass is harvested using dissolved air flotation (DAF), followed by membrane ultrafiltration and centrifugation. The effluents from DAF and centrifuge pass through a membrane ultrafiltration unit to further recover algal biomass while at the same time purifying the culture medium for recycling. With a staggered cultivation and harvesting strategies (24 h d^{-1}), the biomass in the PBR and OPR was harvested every day and the daily harvesting volumes (m^3 d^{-1}) were calculated using annual biomass production amount, plant operation time (330 days per year), and final dry weights. The number of harvesting units was then selected based on the daily harvesting volume and the throughput of the harvesting unit. The solids content after DAF is 10%, and is increased to 25% after centrifugation. Cationic polymer is used for the DAF pre-treatment for the generation of algal flocs at a concentration of 30 g kg^{-1} for both ORP and PBR, which is the typical dosage used at ASU's Laboratory for Algae Research and Biotechnology outdoor culture site. The overall harvesting efficiency is 95%, with the membrane ultrafiltration process recovering any remaining algae in DAF and centrifuge effluents. The average flux of membrane ultrafiltration of DAF residual is selected as 40 L m^{-2} h^{-1}. The lifetime of the membrane filtration unit is 20 years. The membrane is cleaned with 400 mg L^{-1} NaClO after each batch harvesting. Annual maintenance cost of membrane ultrafiltration units is 10% of the capital investment, including the membrane module replacement cost.

After harvesting with centrifugation, the wet biomass (25% solids) is hydrothermally pre-treated (HTT), followed by solvent extraction (SEP), lipid fractionation and oil refining. The number of extraction units was calculated based on the biomass flow rates. The subcritical hydrothermal pretreatment of algal biomass is conducted at pressures of 1.0 MPa and temperatures of 150 °C. Hydrothermal pretreatment can use high moisture biomass (>80% moisture) as feedstock directly without water evaporation, and this process can efficiently breakdown the thick algal cells and accelerate the subsequent lipid extractions significantly. This eliminates the need for drying of algal biomass after the

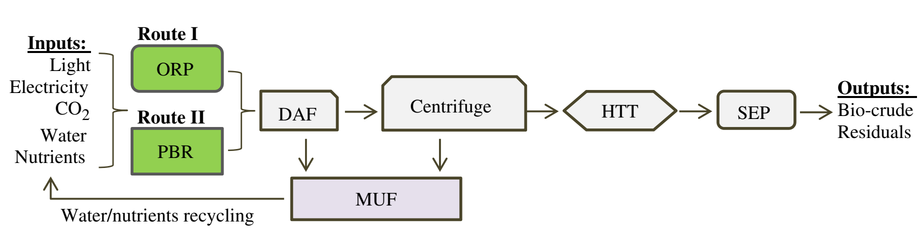

Fig. 1. Process flow diagram of open pond and closed photobioreactor-based microalgal feedstock production for biofuels. PBR, photobioreactor; DAF, dissolved air flotation; HTT, hydrothermal treatment; SEP, solvent-based extraction and purification; MUF, membrane ultrafiltration.

DAF process [20]. Lipid extraction is a semi-continuous process with an extraction efficiency of 95%.

2.3. Assumptions

The following farm system options are assumed — evaporation and precipitation weather for Pecos, Texas, batch process, and 90% recycled water. DAF, centrifugation, and membrane ultrafiltration (MUF) are used for harvesting, and extraction is done with a solvent based system. The final product is crude bio-oil.

Construction on the farm is started in 2013 and it takes one year for the farm to have any production to sell. Values for the debt financing came from Marc Allison's study [21]. Specific assumptions not included in Appendix A are listed below:

- Dividends as fraction net cash income	0.05
- Dividends as initial equity	0.05
- Discount rate	0.04
- Beginning cash	$1,000,000
- Fraction year operating loan	0.10
- CAPEX debt interest rate	0.07
- Loan length	20 years
- Year loan started	2013
- Fraction of cost financed	0.75
- Fraction machinery replace financed	0.80
- Number years for machinery loans	5
- Interest rate for machinery loans	0.08

To produce 50,000 MT of crude algal oil, the ORP farm requires 27,350 ha, while the PBR farm requires only 5730 ha. The water depth is 0.25 m for the ORP and the average thickness of each PBR is 0.04 m. The facility operates 330 days per year. Each day 738,400 m^3 cultures are harvested from the ORPs while 152,000 m^3 cultures are harvested from the PBRs.

Three steps are used in the harvesting system, including dissolved air flotation (DAF), centrifugation, and membrane ultrafiltration. Membrane ultrafiltration is used to clean and recycle the water back to cultivation while recovering any remaining algal biomass from the effluents of the DAF and centrifugation processes. Eleven DAF units, 4 centrifuges and 4 membrane ultrafiltration units are needed for the ORP system. Four DAF, 3 centrifuges and 1 membrane ultrafiltration unit are required for the PBR. The lower number of harvesting units required for the PBR results in lower CAPEX than for the ORP. Extraction is done by solvent extraction. The lipid extraction system has a 20 year life and has an effective extraction rate of 95%. Because it is more difficult to extract lipids from the biomass produced from ORPs than from PBRs, due to lower lipid content and higher amounts of membrane polar lipids in ORP produced biomass, it is assumed that 50% more time or 50% greater extraction system capacity is needed for the ORP-based algae farm than the PBR-based algae farm to achieve the same lipid extraction rate. Ninety-two percent of the solvent is recovered and recycled in the lipid extraction process. Large amounts of solvent are required relevant to the biomass that is processed. Per unit cost for the solvent cost is also expensive, resulting in high operating costs for the extraction system.

A land cost of $2000 per hectare is assumed along with a liner cost of $3.55 per m^2. The CAPEX for the PBR is 6% higher than for the ORP. OPEX costs are calculated on an annual basis or with a ratio of product required for an amount of biomass production. For example, 2.52 tons of CO_2 are required per ton of biomass production at a price of $40 MT^{-1}. The nitrogen and phosphorus costs are 2012 U.S. annual averages from the United States Department of Agriculture (USDA). The cost of water is $0.10 per cubic meter and 90% of the water is recycled. The property tax rate is 4% and unemployment tax is 8%. A complete list of assumptions is available in Appendix A.

3. Results and discussion

The objective of this paper was to compare the economic feasibility of biomass and crude oil production in the two alternative cultivation systems, ORP and PBR. The results for analyzing the two cultivation systems over a 10 year planning horizon are summarized by key output variables from FARM. Table 2 contains the key output variable annual biomass production, annual lipid production, annual total revenue in year five, annual total expenses in year five, annual net cash income in year five, net present value, and the total cost ($ gal^{-1}) of oil for both ORP and PBR. Both farms produce 50,000 MT of crude oil per year.

Both cultivation systems have negative average net cash incomes (NCI) and net present values (NPV). Neither system has a positive probability of economic success. However, the NCI and NPV for the PBR are less negative than for the ORP farm, indicating that in comparison, PBR is a better cultivation system than the ORP. The PBR is a better economic platform for growing algae because the reduced water, increased cell concentration and higher cellular lipid content more than offset the lower CAPEX and OPEX for the ORP system.

Fig. 2 shows that the NPV probability density function (PDF) is much more negative for the ORP than for the PBR. Additionally, the PDF shows there is greater variability in the ORP PDF, indicating that there is more risk associated with the ORP scenario than there is with the PBR. The PBR has less risk for NPV due to the reduced incidence of culture crashes and the lower variability associated with biomass production and lipid concentration.

Table 2
Summary statistics of key output variables for ORP and PBR.

	Open pond	PBR
Biomass production (MT/yr)		
Mean	341,602	161,223
StDev	121,927	36,086
Min	59,211	31,397
Max	858,533	251,102
Oil production (MT/yr)		
Mean	49,554	49,950
StDev	19,949	11,906
Min	8988	10,188
Max	138,037	83,966
Total revenue (M$s) year 5		
Mean	42.63	42.96
StDev	18.98	12.76
Min	5.68	6.94
Max	144.30	114.67
Total cash expenses (M$s) year 5		
Mean	1182.67	818.45
StDev	105.06	53.69
Min	901.82	659.52
Max	1622.80	938.76
Net cash income (M$s) year 5		
Mean	(1140.04)	(775.49)
StDev	95.08	50.48
Min	(1513.40)	(889.81)
Max	(896.15)	(652.58)
Net present value (M$s)		
Mean	(9957.09)	(7272.96)
StDev	376.63	230.26
Min	(11,190.83)	(8058.76)
Max	(8927.43)	(6626.56)
Total cost ($/oil of lipid) year 5		
Mean	109.12	76.98
StDev	45.85	25.70
Min	37.00	42.34
Max	421.01	312.92

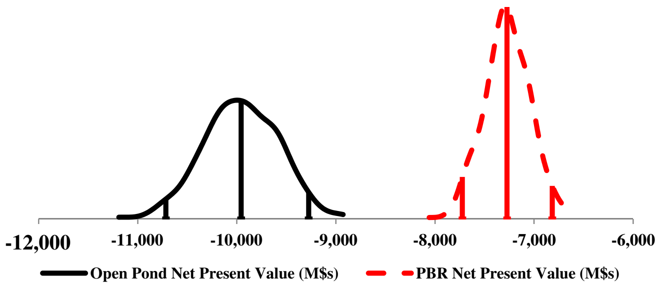

Fig. 2. Probability density function (PDF) approximations for net present value comparing the ORP and the PBR (M$s).

The average total cost ($ gal^{-1} of oil) is 109.12 and 76.98 for ORP and PBR, respectively. Fig. 3 contains the PDFs of the total costs ($ gal^{-1} of oil). Both the ORP and PBR PDFs are positively skewed, indicating that the total cost of production could be quite high. The PBR PDF has greater density at the lower costs and is less variable when compared to the PDF for the ORP's total cost of production. Again, there is more risk associated with lipid production by ORP than by PBR, thus owing to the greater risk for total costs. The PDFs also show that the PBR has a lower cost of production than ORP. The results indicated that under the assumed conditions, the PBR is a lower cost and less risky cultivation system than the ORP.

PDFs for the annual biomass and lipid production under the two cultivation systems are presented in Figs. 4 and 5, respectively. The greater variability in ORP production of biomass is largely due to the increased probability of pond crashes. Additionally, the lipid content of biomass produced in ORPs is about half the lipid content for biomass produced in a PBR. For an ORP to produce the same amount of lipid as a PBR, much more biomass must be produced by the ORP than the PBR, which explains why the ORP biomass PDF is further to the right than the PBR's biomass PDF (Fig. 4). The PDFs for biomass and lipid production in ORPs have a very small probability of achieving high amounts of production. The high levels of production depicted in the PDFs could only be obtained if there is no production loss in production caused by pathogens, parasites, and predators, i.e., the best case scenario for ORPs. There is a 2.5% chance that biomass production would be greater than 625,000 MT per year for the ORPs.

As expected, the costs of production for both ORP and PBR are far too high to be economical. This analysis offers a head to head comparison of ORP and PBR cultivation systems, with all other variables held constant. Substantial cost reductions will be necessary on all fronts for algae production to become a viable source of crude oil to compete with fossil fuels. A sensitivity elasticity analysis was calculated for NCI in the fifth year of production for key parameters to the algal production systems. The sensitivity elasticities show percentage change for NCI in year 5 for both ORP and PBR (Tables 3 and 4) for a 1% increase in each of the exogenous variables. Because NCI is inversely related to increases in costs, the sensitivity elasticities are negative. Therefore if costs are decreased, the sensitivity elasticities reflecting the percentage increases in NCI can be expected. The order of the sensitivity elasticities is very similar for both ORP and PBR.

For ORP decreasing the pond reactor cost will have the greatest impact on NCI. If the reactor cost is decreased by 1% NCI will increase by 0.46% (Table 3). The amount of extraction solvent and its cost also have a big impact on ORP NCI. Reducing these two things alone by 1% would increase ORP NCI by 0.38%. Other variables having a large impact on ORP's NCI are non-harvesting and extraction maintenance and biomass production. The reactor CAPEX also has the largest impact on the profitability for the PBR system (Table 4). If the PBR reactor CAPEX was decreased by 1% the NCI would increase 0.69%. Like ORP, the

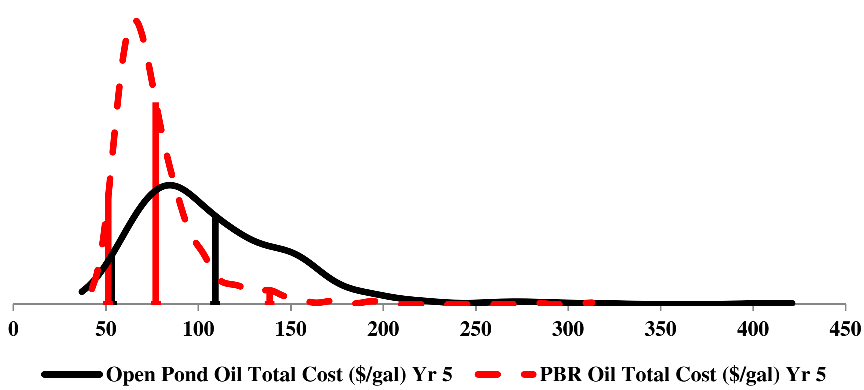

Fig. 3. Probability density function (PDF) approximations for ORP and PBR algae system's total cost of oil production, $ gal^{-1}.

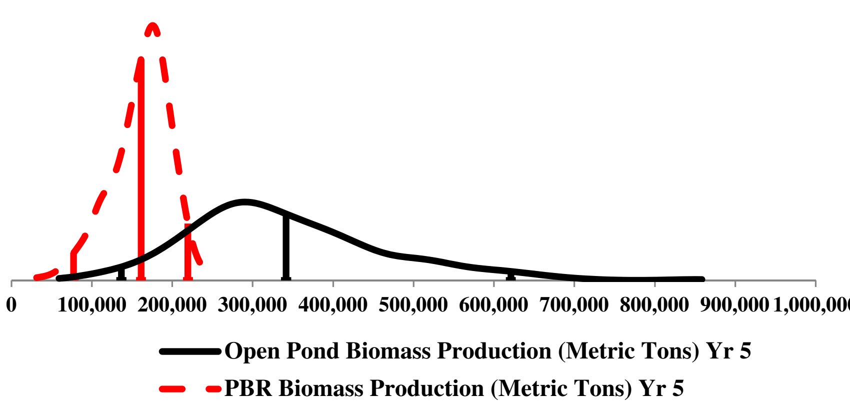

Fig. 4. Probability density functions of biomass production for ORP and PBR algae systems (MT yr^{-1}).

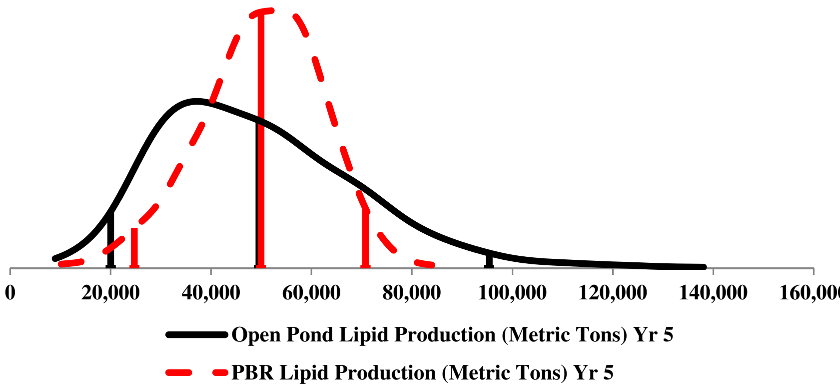

Fig. 5. Probability density function (PDF) of lipid production for ORP and PBR algae systems (MT yr^{-1}).

amount of extraction solvent and its cost are also critical to the profitability of the PBR system, with an increase of 0.25% in NCI if they were decreased by 1%. The other important variables affecting NCI are non-harvesting and extraction maintenance and biomass production. The biomass production sensitivity elasticity is negative in both cases because as biomass production increases, the cash expenses are increasing more than the revenue from the additional production. If the largest five cost categories for each cultivation system could be reduced by 1% the NCI would increase by 1.30% for ORP and 1.36% for PBR. There are also several cost categories that have negligible effects on NCI for both ORP and PBR. Research efforts should be concentrated in these five areas where returns to investment made in research will be the greatest.

For the ORP, decreasing OPEX for extraction will have the greatest impact on NCI. For ORP, if extraction OPEX is decreased by 1% NCI will increase by 0.39% (Table 3). For the PBR, decreasing the OPEX for cultivation will have the greatest impact on NCI. If the PBR cultivation OPEX is decreased by 1% NCI will increase by 0.44% (Table 4). If the largest three cost categories for both ORP and PBR (extraction OPEX, cultivation CAPEX, and all non-harvesting and extraction OPEX) could be reduced by 10%, NCI would be predicted to increase by 98% and 83%, respectively.

In Table 5 the CAPEX and OPEX values are reported for lipid production. Reporting the costs on a per unit basis shows which cost areas are contributing the most to the overall cost of production. Between the four primary operating cost areas (cultivation, harvesting, extraction, and all other OPEX), All Other OPEX is the largest proportion of the total costs followed by cultivation, extraction and harvesting (Table 6). The largest component in the All Other OPEX section is interest cost.

Table 3
Net cash income sensitivity elasticities for ORP show the percentage change in net cash income for a one percent change in selected exogenous variables.

Variable	OPR Es	OPR StDev Es
Reactor CAPEX	−0.46345	0.02765
Extraction solvent cost	−0.25340	0.05327
Non-H&E maintenance	−0.23955	0.01434
Biomass production	−0.21242	0.04681
Extraction solvent tons required	−0.13239	0.02783
DAF chemical required	−0.08232	0.01731
DAF chemical price	−0.08232	0.01731
DAF CAPEX	−0.04830	0.00288
Membrane ultrafiltration maintenance	−0.04295	0.00257
CO_2 required	−0.03705	0.00783
CO_2 price	−0.03705	0.00783
DAF maintenance	−0.02497	0.00149
Membrane ultrafiltration CAPEX	−0.02007	0.00125
Cultivation electricity kwh	−0.01716	0.00102
Property tax	−0.01292	0.00077
Water treatment price	−0.00585	0.00037
Extraction electricity	−0.00449	0.00093
Centrifuge CAPEX	−0.00376	0.00022
Unemployment tax	−0.00304	0.00018
Nitrogen price	−0.00290	0.00061
Price of water	−0.00222	0.00014
Centrifuge maintenance	−0.00194	0.00012
Membrane ultrafiltration electricity	−0.00101	0.00021
Phosphorous price	−0.00063	0.00013
Lipid extraction CAPEX	−0.00056	0.00003
Membrane ultrafiltration chemical price	−0.00040	0.00008
Membrane ultrafiltration chemical required	−0.00040	0.00008
Extraction maintenance	−0.00032	0.00002
Centrifuge electricity	−0.00022	0.00005
DAF electricity	−0.00013	0.00003
Subcritical-hydrothermal pretreatment CAPEX	−0.00006	0.00000
Lipid fractionation/separation CAPEX	−0.00004	0.00000
Labor & overhead	0.00000	0.00000
Phosphorous required	0.00060	0.00012
Nitrogen required	0.00276	0.00058

Table 4
Net cash income sensitivity elasticities for ORP show the percentage change in net cash income for a one percent change in selected exogenous variables.

Variable	PBR Es	PBR StDev Es
Reactor CAPEX	−0.69327	0.01535
Non-H&E maintenance	−0.31974	0.00771
Extraction solvent cost	−0.16545	0.02588
Biomass production	−0.10417	0.01958
Extraction solvent tons required	−0.08644	0.01352
Cultivation electricity kwh	−0.05914	0.00136
DAF chemical required	−0.05375	0.00841
DAF chemical price	−0.05375	0.00841
CO_2 required	−0.02583	0.00406
CO_2 price	−0.02583	0.00406
DAF CAPEX	−0.02398	0.00053
Membrane ultrafiltration maintenance	−0.01466	0.00035
DAF maintenance	−0.01239	0.00030
Membrane ultrafiltration CAPEX	−0.00685	0.00018
Property tax	−0.00631	0.00015
Water treatment price	−0.00441	0.00031
Centrifuge CAPEX	−0.00385	0.00008
Extraction electricity	−0.00293	0.00045
Centrifuge maintenance	−0.00199	0.00005
Nitrogen price	−0.00191	0.00030
Price of water	−0.00168	0.00012
Unemployment tax	−0.00087	0.00002
Membrane ultrafiltration electricity	−0.00066	0.00010
Lipid extraction CAPEX	−0.00058	0.00001
Phosphorous price	−0.00041	0.00006
Extraction maintenance	−0.00033	0.00001
DAF electricity	−0.00019	0.00003
Centrifuge electricity	−0.00014	0.00002
Membrane ultrafiltration chemical price	−0.00011	0.00002
Membrane ultrafiltration chemical required	−0.00011	0.00002
Subcritical-hydrothermal pretreatment CAPEX	−0.00006	0.00000
Lipid fractionation/separation CAPEX	−0.00006	0.00000
Labor & overhead	0.00000	0.00000
Phosphorous required	0.00040	0.00006
Nitrogen required	0.00182	0.00029

Table 5
Costs of oil production in dollars per gallon for ORPs and PBRs.

	ORP	PBR	ORP	PBR
CAPEX ($/gal)				
Cultivation			20.53	24.75
Reactor cost	20.1918	24.6753		
Land cost	0.3365	0.0705		
Harvesting			4.08	1.34
DAF units	2.1046	0.7653		
Centrifuge units	0.1638	0.1228		
Membrane ultrafiltration units	1.8101	0.4525		
Extraction			0.03	0.02
Sub-hydrothermal pretreatment	0.0025	0.0018		
Lipid extraction	0.0246	0.0185		
Lipid fractionation/separation (F/S)	0.0037	0.0037		
CAPEX sub-total ($/gal)			24.64	26.11
OPEX ($/gal)				
Cultivation			24.51	18.78
Electricity	0.8825	2.2275		
Nutrients	0.1857	0.0887		
CO_2	1.9699	0.9927		
Water	0.1173	0.0655		
Wastewater treatment	0.3048	0.1702		
Chemicals for cleaning/disinfection	0.0025	0.0032		
Chemicals for crop protection/disinfection	0.0999	0.0064		
Maintenance	12.5939	12.3122		
Labor	8.3546	2.9171		
Harvesting			8.13	3.23
Electricity	0.0711	0.0375		
Chemicals	4.3709	2.0572		
Maintenance	3.6727	1.1184		
Labor	0.0170	0.0128		
Extraction			7.40	3.54
Electricity	0.2348	0.1108		
Make up solvent	6.1625	2.9083		
Solvent recovery	0.8337	0.3935		
Maintenance	0.0169	0.0127		
Labor	0.1534	0.1193		
All Other OPEX			36.40	32.03
Insurance	0.4945	0.5241		
Unemployment taxes	0.6820	0.2439		
Property taxes	0.1603	0.0336		
Operating interest	0.3233	0.2059		
Carryover debt interest	20.1281	15.5371		
Interest on machinery debt	–	–		
Interest on initial debt	11.5339	12.2233		
Dividends as a fraction of beg. equity	3.0828	3.2669		
OPEX sub-total ($/gal)			76.45	57.59

Table 6
Percentage of costs for each phase of algal crude production and percentage of total CAPEX and OPEX.

	ORP	PBR	ORP	PBR
CAPEX ($ gal^{-1})				
Cultivation	% of cultivation		% of total CAPEX	
Reactor cost	98.36%	99.72%	81.96%	94.50%
Land cost	1.64%	0.28%	1.37%	0.27%
Harvesting	% of harvesting			
DAF units	51.60%	57.08%	8.54%	2.93%
Centrifuge units	4.02%	9.16%	0.66%	0.47%
Membrane ultrafiltration units	44.38%	33.75%	7.35%	1.73%
Extraction	% of extraction			
Sub-hydrothermal pretreatment	8.00%	7.69%	0.01%	0.01%
Lipid extraction	80.00%	76.92%	0.10%	0.07%
Lipid fractionation/separation (F/S)	12.00%	15.38%	0.01%	0.01%
OPEX ($ gal^{-1})				
Cultivation	% of cultivation		% of total OPEX	
Electricity	3.60%	11.86%	1.15%	3.87%
Nutrients	0.76%	0.47%	0.24%	0.15%
CO_2	8.04%	5.28%	2.58%	1.72%
Water	0.48%	0.35%	0.15%	0.11%
Wastewater treatment	1.24%	0.91%	0.40%	0.30%
Chemicals for cleaning/disinfection	0.01%	0.02%	0.00%	0.01%
Chemicals for crop protection/disinfection	0.41%	0.03%	0.13%	0.01%
Maintenance	51.38%	65.55%	16.47%	21.38%
Labor	34.09%	15.53%	10.93%	5.07%
Harvesting	% of harvesting			
Electricity	0.87%	1.16%	0.09%	0.07%
Chemicals	53.75%	63.77%	5.72%	3.57%
Maintenance	45.17%	34.67%	4.80%	1.94%
Labor	0.21%	0.40%	0.02%	0.02%
Extraction	% of extraction			
Electricity	3.17%	3.13%	0.31%	0.19%
Make up solvent	83.26%	82.05%	8.06%	5.05%
Solvent recovery	11.26%	11.10%	1.09%	0.68%
Maintenance	0.23%	0.36%	0.02%	0.02%
Labor	2.07%	3.37%	0.20%	0.21%
All Other OPEX	% of All Other OPEX			
Insurance	1.36%	1.64%	0.65%	0.91%
Unemployment taxes	1.87%	0.76%	0.89%	0.42%
Property taxes	0.44%	0.10%	0.21%	0.06%
Operating interest	0.89%	0.64%	0.42%	0.36%
Carryover debt interest	55.29%	48.50%	26.33%	26.98%
Interest on machinery debt	0.00%	0.00%	0.00%	0.00%
Interest on initial debt	31.68%	38.16%	15.09%	21.23%
Dividends as a fraction of beg. equity	8.47%	10.20%	4.03%	5.67%

Carryover debt interest costs makeup the largest share of OPEX at roughly 26% and 27% for ORP and PBR, respectively (Table 6).

In Table 6 the costs are listed on a percentage basis for their contribution to the sub-category areas as well as overall production. For extraction OPEX, solvent costs account for more than 80% of the extraction costs (Table 6). In harvesting, chemicals and maintenance also account for over 90% of the harvesting OPEX. Maintenance and labor are cost drivers in the cultivation operating costs, accounting for over 80%. Maintenance costs are calculated based on engineering handbook costs (5% of CAPEX). If actual maintenance costs were available, maintenance costs most likely would represent a smaller portion of the OPEX. In All Other OPEX the carryover debt interest and interest on initial debt interest cost account for over 85% of the costs in that category.

For extraction, the lipid extraction units account for over 75% of the CAPEX, while in harvesting the DAF units and membrane ultrafiltration units comprise more than 90% of the CAPEX (Table 6). However, the reactor cost is the single largest cost in all CAPEX, accounting for 81% of the ORP total and 94% for PBR (Table 6).

4. Summary and conclusions

The objective of the paper was to provide a head to head comparison of the costs to produce crude bio-oil with ORPs and PBRs. The biomass and crude bio-oil production in the two cultivation systems were modeled using published research data on outdoor cultivation of *Nannochloropsis* strains. Data to define probability distributions for biomass production, lipid content, and culture crashes for both cultivation systems are used as the primary differences in risk between the systems. The same harvesting and extraction methods are assumed to be used for both cultivation systems, but with different levels of efficiency. The cultivation systems were scaled to produce the same amount of crude bio-oil. CAPEX and OPEX for harvesting and extraction are scaled for the two systems based on required throughput of water and biomass.

The results of the analysis show that with current costs neither system is economically profitable, however the PBR system has a much greater NCI and lower cost per gallon of crude bio-oil. The risk analysis shows that on a relative risk basis NCI for the ORP cultivation system is 26% more variable (riskier) than the PBR system. The increased risk for the ORP system causes over investment in pond area to ensure meeting the annual biomass production requirement, which leads to even greater volumes of water having to be harvested which inflates harvesting and extraction OPEX costs (7.40 $ gal^{-1} vs. 3.54 $ gal^{-1}). Cultivation OPEX costs for the ORP system are 30% greater than the PBR due largely to greater maintenance and labor costs associated with a larger farm.

Biomass production is 59% more variable for the ORP than the PBR due to a greater probability of crashes and the over investment in production capacity to ensure observing the assumed average annual oil production of 50,000 MT. The increased relative risk for biomass production coupled with higher relative risk in lipid content for ORPs leads to greater absolute and relative risk for total annual lipid production. The results show that relative risk associated with producing 50,000 MT of lipid per year is 69% greater for ORPs. These results indicate that a PBR algae farm will have a much higher reliability factor than an ORP farm for producing a fixed amount of algae crude each year.

The average total cost of production for crude bio-oil is 109.12 $ gal^{-1} for the ORP and 76.98 $ gal^{-1} for the PBR system. The range of costs simulated for the two systems is much wider for the ORP due to the greater risk of production. The relative risk for the estimated probability distribution of total costs per gallon is 42.0% for ORPs and 33.4% for PBRs. The PBR system has a 26% lower relative risk for total costs which again is a function of the reduced risks for biomass production and lipid concentration.

The PBR cultivation system has a significantly lower risk of producing a targeted level of lipid each year than an ORP and the total cost per gallon of oil will be lower. The reactor is the major capital investment for both cultivation systems, and interest costs account for the majority of the crude bio-oil operating cost. At present, the costs for either existing cultivation system are too high and any incremental improvement in the current cultivation systems and processes won't dramatically change the estimated cost structure. For biofuels from microalgae to be an economically viable industry, next generation cultivation systems and processes will have to be developed that can increase biomass productivity by an order of magnitude greater than what has been achieved today while at the same time reducing substantially CAPEX and OPEX. These will be the greatest challenges and opportunities to the microalgal research community and algal industry for many years to come.

Acknowledgments

Funding for this project was provided in part by the US Department of Energy through contract DE-EE0003046 to the National Alliance for Advanced Biofuels and Bioproducts (NAABB) and Texas A&M University as well as the US Department of Energy contract DE-EE0003372 to the Sustainable Algal Biofuels Consortium.

Appendix A. Summary of input values for the ORP and PBR analysis

Harvesting assumptions	
DAF	
- Throughput (L h^{-1})	1,816,800
- Harvest (h d^{-1})	24 h
- Capital cost ($ unit^{-1})	$31,098,236
- Effective recovery	97.5%
- Percent solids of output	10%
- Percent of yearly production harvested with DAF	100%
- Life of machine	20 years
- Maintenance cost	5% of total CAPEX per yr.
- Number of units needed for PBR farm	4 units
- Number of units needed for ORP farm	11 units
- Electricity (kwh kg^{-1} of algae)	PBR 0.00948, ORP 0.0217
- Chemical cost ($ MT^{-1})	8000
- Chemical (polymer) consumption (ton chemical ton^{-1} biomass)	PBR 0.03; ORP: 0.03
- Total CAPEX for 4 units	$124,392,944
- Total CAPEX for 11 units	$342,080,596
- Centrifugation	
- Throughput (L h^{-1})	68,130
- Harvest (h d^{-1})	24 h
- Capital cost ($ unit^{-1})	$6,655,835
- Effective recovery	97.5%
- Percent solids of output	25%

Appendix A. (*continued*)

Harvesting assumptions	
- Percent of yearly production harvested with DAF	100%
- Life of machine	20 years
- Maintenance cost	5% of total CAPEX per yr
- Number of units needed for PBR farm	3 units
- Number of units needed for ORP farm	4 units
Electricity	PBR 16.5 kwh MT^{-1}; ORP 16.5 kwh MT^{-1}
- Total CAPEX for 3 units	$19,967,505
- Total CAPEX for 4 units	$26,623,340
Membrane ultrafiltration	
- Throughput (L h^{-1})	6,000,000
- Harvest (h d^{-1})	24 h
- Capital cost ($ unit^{-1})	$73,552,695
- Life of machine	20 years
- Maintenance cost	10% of total CAPEX per yr
- Number of units needed for PBR farm	1 unit
- Number of units needed for ORP farm	4 units
- Electricity	PBR 76.9 kwh ton^{-1}; ORP 76.9 kwh ton^{-1}
- Chemical (chlorine) cost	$400 ton^{-1}
- Chemical consumption (ton chemical ton^{-1} biomass)	PBR 30.3; ORP: 69.4
- Total CAPEX for 1 unit	$73,552,695
- Total CAPEX for 4 units	$294,210,780

Extraction assumptions	
Subcritical hydrothermal pretreatment	
- Throughput (L h^{-1})	300,000
- Harvest (h d^{-1})	24 h
- Capital cost ($ unit^{-1})	$50,000
- Effective extraction	97.5%
- Life of machine	20 years
- Maintenance cost	5% of total CAPEX per yr
- Number of units needed for PBR farm	6 units
- Number of units needed for ORP farm	8 units
- Electricity (kwh MT^{-1} of algae)	PBR 300 kwh ton^{-1} biomass; 300 kwh ton^{-1}
- Total CAPEX for 6 units	$300,000
- Total CAPEX for 8 units	$400,000
Lipid extraction and solvent recovery	
- Throughput (tons d^{-1}), lipid	100
- Capital cost ($ unit^{-1})	$500,000
- Life of machine	20 years
- Maintenance cost	5% of total CAPEX per yr
- Number of units needed for PBR farm	6 units
- Number of units needed for ORP farm	8 units
- Electricity	PBR 20 kwh ton^{-1}; ORP 20 kwh ton^{-1}
- Total CAPEX for 6 units	$3,000,000
- Total CAPEX for 8 units	$4,000,000
Lipid fractionation/separation	
- Throughput (L h^{-1})	300,000
- Harvest (h d^{-1})	24
- Capital cost ($ unit^{-1})	$300,000
Life of machine	20 years
- Maintenance cost	5% of total CAPEX per yr
- Number of units needed for PBR farm	2 units
- Number of units needed for ORP farm	2 units
- Electricity	PBR 20 kwh ton^{-1}; ORP 20 kwh ton^{-1}
- Total CAPEX for 2 units	$600,000
- Total CAPEX for 2 units	$600,000

CAPEX assumptions	
The capital costs per hectare include land preparation, cost of the ORP or PBR, piping, CO_2 delivery, and the cooling system	
- ORP land cost	$2000 ha^{-1} for 27,350 ha
- PBR land cost	$2000 ha^{-1} for 5730 ha
- ORP capital cost	$150,000 ha^{-1} for 21,880 ha
- PBR capital cost	$4,66,667 ha^{-1} for 5730 ha

OPEX assumptions	
CO_2	
- ORP tons of CO_2 required ton^{-1} of biomass	2.52

(*continued on next page*)

Appendix A. (*continued*)

Harvesting assumptions	
- PBR tons of CO_2 required ton^{-1} of biomass	2.70
- Efficiency of CO_2	99%
- Contract cost (\$ ton^{-1})	\$40
Nutrients	
- ORP ratio of biomass to nitrogen	163.13
- PBR ratio of biomass to nitrogen	161.27
- ORP ratio of biomass to phosphorus	842.98
- PBR ratio of biomass to phosphorus	833.33
- Cost of nitrogen (\$ ton^{-1})	\$1328
- Cost of phosphorus (\$ ton^{-1})	\$1594
Labor	
- ORP non-harvesting & extraction labor	\$4300 ha^{-1} for 27,350 ha
- PBR non-harvesting & extraction labor	\$7200 ha^{-1} for 5730 ha
- Dissolved air flotation labor	\$120,000 yr^{-1} for ORP, \$60,000 yr^{-1} for PBR
- Centrifuge labor	\$60,000 yr^{-1} for ORP, \$60,000 yr^{-1} for PBR
- Membrane ultrafiltration labor	\$60,000 yr^{-1} for ORP, \$60,000 yr^{-1} for PBR
- Sub-hydrothermal pretreatment labor	\$120,000 yr^{-1} for ORP, \$120,000 yr^{-1} for PBR
- Lipid extraction and solvent recovery labor	\$120,000 yr^{-1} for ORP, \$120,000 yr^{-1} for PBR
- Lipid fractionation/separation	\$120,000 yr^{-1} for ORP, \$120,000 yr^{-1} for PBR
- Total ORP labor cost	\$88,001,047 yr^{-1}
- Total PBR labor cost	\$52,042,863 yr^{-1}
Water	
- Cost of water (\$ m^{-3})	\$0.10
- Wastewater treatment (\$ m^{-3})	\$0.264
- Percent water recycled	90%
Electricity	
- ORP (kwh acre foot (AF)$^{-1}$yr^{-1})	8108
- PBR (kwh AF^{-1}yr^{-1})	488,459
Property tax rate	4%
Workman's compensation/ unemployment tax rate	8%
Insurance	\$0.00186 × sum of CAPEX costs
Crash frequency	18.3% for ORP, 7.5% for PBR

References

[1] E. Stephens, I.L. Ross, B. Hankamer, Expanding the microalgal industry — continuing controversy or compelling case? Curr. Opin. Chem. Biol. 17 (2013), http://dx.doi.org/10.1016/j.cbpa.2013.03.030.

[2] P. Zemke, M. Sommerfeld, Q. Hu, Assessment of key biological and engineering design parameters for enhanced production of *Chlorella* sp. (Chlorophycease) in an outdoor photobioreactor, Appl. Microbiol. Biotechnol. 97 (2013) 5645–5655.

[3] R. Davis, A. Aden, P.T. Pienkos, Techno-economic analysis of autotrophic microalgae for fuel production, Appl. Energy 88 (2011) 3524–3531, http://dx.doi.org/10.1016/j.apenergy.2011.04.018.

[4] Q. Hu, M. Sommerfeld, E. Jarvis, M. Ghirardi, M. Posewitz, M. Seibert, A. Darzins, Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances, Plant J. 54 (2008) 621–639.

[5] G. Chini Zittelli, N. Biondi, L. Rodolfi, M.R. Tredici, Photobioreactors for mass production of microalgae, in: Richmond, Hu (Eds.), Handbook of Microalgal Culture, 2nd ed., Wiley-Blackwell, West Sussex, UK, 2013, pp. 225–266.

[6] N. Norsker, M.J. Barbosa, M.H. Vermue, R.H. Wijffels, Microalgal production — a close look at the economics, Biotechnol. Adv. 29 (2011) 24–27.

[7] Y. Chisti, Biodiesel from microalgae, Biotechnol. Adv. 25 (2007) 294–306.

[8] J.W. Richardson, M.D. Johnson, J.L. Outlaw, Economic comparison of open pond raceways to photo bio-reactors for profitable production of algae for transportation fuels in the Southwest, Algal Res. 1 (2012) 93–100.

[9] R. Davis, D. Fishman, E.D. Frank, M.S. Wigmosta, Renewable diesel from algal lipids: an integrated baseline for cost, emissions, and resource potential from a harmonized model, NREL/TP-5100-55431, Golden, CO, 2012.

[10] S. Nagarajan, S.K. Chou, S. Cao, C. Wu, Z. Zhou, An updated comprehensive techno-economic analysis of algae biodiesel, Bioresour. Technol. (2012), http://dx.doi.org/10.1016/j.biortech.2012.11.108.

[11] F. Delrue, P.A. Setier, C. Sahut, L. Courna, A. Roubaud, G. Peltier, A.K. Froment, An economic, sustainability, and energetic model of biodiesel production from microalgae, Bioresour. Technol. 111 (2012) 191–200.

[12] J.C. Quinn, T. Yates, N. Douglas, K. Weyer, J. Butler, T.H. Bradley, T.H., P.J. Lammers, *Nannochlorposis* production metrics in a scalable outdoor photobioreactor for commercial applications, Bioresour. Technol. 117 (2012) 164–171.

[13] L. Rodolfi, G.C. Zittelli, N. Bassi, G. Padovani, N. Biondi, G. Bonini, M.R. Tredici, Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor, Biotechnol. Bioeng. 102 (2009) 100–112.

[14] B.C. Crowe, S. Attalah, S. Agrawal, S.P. Waller, R. Ryan, J. Van Wagenen, A. Chavis, J. Kyndt, M. Kacira, K.L. Ogden, M. Huesemann, A comparison of *Nannochloropsis salina* growth performance in two outdoor pond designs: conventional raceways versus the ARID pond with superior temperature management, Int. J. Chem. Eng. (2012), http://dx.doi.org/10.1155/2012/920608.

[15] Q. Hu, M. Sommerfeld, and S. Qin, Methods of using *Nannochloropsis* algal strains to produce hydrocarbons and fatty acids (2012) U.S. Patent No.: US 8227216.

[16] J.W. Richardson, K. Schumann, P. Feldman, Simetar: Simulation for Excel to Analyze Risk, Department of Agricultural Economics, Texas A&M University, College Station, Texas, 2005.

[17] J.W. Richardson, B.K. Herbst, J.L. Outlaw, R.C. Gill II, Including risk in economic feasibility analyses: the case of ethanol in Texas, J. Agribus. 25 (2007) 115–132.

[18] J.C. Weissman, D.M. Tillett, Design and operation of outdoor microalgae test facility, in: L.M. Brown, S. Sprague (Eds.), Aquatic Species Report; NREL/MP-232-4174, National Renewable Energy Laboratory, Golden, Colorado, 1990, pp. 32–57.

[19] E. Sierra, F.G. Acien, J.M. Fernandez, J.L. Garcia, C. Gonzalez, E. Molina, Characterization of a flat plate photobioreactor for the production of microalgae, Chem. Eng. J. 138 (2008) 136–147.

[20] U. Jena, K.C. Das, Comparative evaluation of thermochemical liquefaction and pyrolysis for bio-oil production from microalgae, Energy Fuels 25 (2011) 5472–5482.

[21] M.S. Allison, The Future of Biofuels: An Economic Analysis of the Design and Operation of a Microalgae Facility in Texas and the Southwestern United States, Department of Agricultural Economics, Texas A&M University, August 2010. (Master of Science Thesis).