Applied Energy 88 (2011) 3524–3531

Contents lists available at ScienceDirect

Applied Energy

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

# Techno-economic analysis of autotrophic microalgae for fuel production

Ryan Davis *, Andy Aden, Philip T. Pienkos

*National Renewable Energy Laboratory, 1617 Cole Blvd, Golden, CO 80401, United States*

ARTICLE INFO

*Article history:*
Received 18 February 2011
Received in revised form 6 April 2011
Accepted 6 April 2011
Available online 17 May 2011

*Keywords:*
Algae
Autotrophic
Pond
Photobioreactor
Techno-economic
Green diesel

ABSTRACT

It is well-established that microalgal-derived biofuels have the potential to make a significant contribution to the US fuel market, due to several unique characteristics inherent to algae. Namely, autotrophic microalgae are capable of achieving very high efficiencies in converting solar energy into biomass and oil relative to terrestrial oilseed crops, while at the same time exhibiting great flexibility in the quality of land and water required for algal cultivation. These characteristics allow for the possibility to produce appreciable amounts of algal biofuels relative to today's petroleum fuel market, while greatly mitigating "food-versus-fuel" concerns. However, there is a wide lack of public agreement on the near-term economic viability of algal biofuels, due to uncertainties and speculation on process scale-up associated with the nascent stage of the algal biofuel industry.

The present study aims to establish baseline economics for two microalgae pathways, by performing a comprehensive analysis using a set of assumptions for what can plausibly be achieved within a five-year timeframe. Specific pathways include autotrophic production via both open pond and closed tubular photobioreactor (PBR) systems. The production scales were set at 10 million gallons per year of raw algal oil, subsequently upgraded to a "green diesel" blend stock via hydrotreating. Rigorous mass balances were performed using Aspen Plus simulation software, and associated costs were evaluated on a unit-level basis. Upon completing the base case scenarios, the cost of lipid production to achieve a 10% return was determined to be \$8.52/gal for open ponds and \$18.10/gal for PBRs. Hydrotreating to produce a diesel blend stock added onto this marginally, bringing the totals to \$9.84/gal and \$20.53/gal of diesel, for the respective cases. These costs have potential for significant improvement in the future if better microalgal strains can be identified that would be capable of sustaining high growth rates at high lipid content. Given that it is difficult to maximize both of these parameters simultaneously, it was determined that the near-term research should focus on maximizing lipid content as it offers more substantial cost reduction potential relative to an improved algae growth rate. Additional economic sensitivity studies were established to identify other important cost drivers, and a resource assessment comparison was made to evaluate parameters such as water and $CO_2$ requirements.



## 1. Introduction

Microalgae exhibit great versatility as an energy source, as algal cells can be used either directly as a biomass feedstock in many biochemical (e.g., fermentation) or thermochemical (e.g., gasification, pyrolysis, and liquefaction) conversion pathways, or can be exploited specifically for their relatively high oil content [1]. In the latter case, algal oil can be extracted and upgraded into infrastructure-compatible fuels with a high energy density, while a variety of co-products can simultaneously be produced from other algal constituents. Algal growth is divided into two main classes, autotrophic and heterotrophic. Autotrophic algae utilize $CO_2$ as the carbon source, while heterotrophic algae utilize sugars derived from other biomass sources. Each category has its own advantages; for example, autotrophic growth directly consumes $CO_2$ which on a large scale would typically be supplied from an upstream power plant or other emissions source, thereby providing for an effective carbon capture and recycle opportunity. While the same carbon recycle indirectly takes place in the heterotrophic pathway ($CO_2$ is utilized for growing the biomass sugar source), it does so less efficiently as it relies on terrestrial biomass growth which exhibits lower photosynthetic efficiency relative to autotrophic algae [2]. However, the heterotrophic pathway utilizes currently available and proven fermentation technology for algal cultivation, and typically exhibits higher cellular lipid content [1,3]. The autotrophic pathway has generally received more public attention, as attributable to the large number of companies dedicated either in whole or in part to pursuing autotrophic algal biofuels, relative to a smaller number of entities in the heterotrophic field. As such, there is a much larger amount of public data on autotrophic growth

* Corresponding author. Tel.: +1 303 384 7879.
*E-mail address:* ryan.davis@nrel.gov (R. Davis).

0306-2619/\$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.04.018

currently available. Due to these two considerations, we have limited the scope of this analysis to autotrophic algae pathways.

Autotrophic algae convert solar energy into biomass via photosynthesis, according to the generic growth equation:

$$[a]\ CO_2 + [b]\ \text{nutrients} + \text{sunlight} \rightarrow [c]\ O_2 + \text{biomass} \quad (1)$$

In the above equation, the coefficients *a*–*c* depend on the molecular composition of the algae biomass. Autotrophic algae can be grown either in an open pond system or a closed photobioreactor (PBR). Again, each approach has its own advantages and drawbacks. Open ponds are simple and relatively low-cost to construct, but are more amenable to culture crashes as they are open to the environment and the introduction of invasive algal species as well as predators and pathogens. PBRs mitigate this risk as they are largely closed monoculture systems (though they cannot be sterilized and are not designed to be operated axenically for long periods), and also achieve a higher algal cell density due to higher surface area-to-volume ratio; however, they are usually seen as being too costly and as such very few techno-economic studies have been conducted on PBR systems [4,5]. A high-level comparison between the open pond and PBR options is provided in Table 1. This brief summary is far from exhaustive, and a more thorough discussion can be found in [2,4,6].

It is the goal of this overall study to evaluate the economics of both the pond and PBR options, in order to better understand the current state of algal biofuel technology as it stands today, and to identify the most significant opportunities for cost reduction in the future. For all cases in this study, a microalgal facility producing raw oil on a basis of 10 MM gal/yr was modeled using Aspen Plus software, in order to obtain more accurate mass balance information than what is typically assumed. Additionally the model was used to estimate key requirements (such as hydrogen demand) associated with hydrotreating the oxygen-laden triglycerides into diesel-range hydrocarbons. The model was also used to estimate the power required by the overall process as well as the power generated by utilization of the biogas produced by anaerobic digestion of the spent algal biomass. Using the resulting flow rates, the cost of each process unit was estimated based on vendor information, cost equations, or previous studies to determine the cost of lipid and fuel production. It is important to note at the outset that algal biofuel technology is still in an early stage of development, and there are numerous opinions on the optimal configuration and conditions at each stage of the production process; as such, the estimated cost of production varies in other studies from \$1 to > \$40/gal [7]. Thus, in order to establish "near-term" costs as objectively as possible, the unit operations assumed here for each process were chosen on the merit of what could plausibly achieve the goal of each step using currently available technology.

## 2. Approach and assumptions used for analysis

### 2.1. Lipid production

The key input assumptions with respect to the algal growth stage are summarized in Table 2. To meet the 10 MM gal/yr target for lipid production, the assumption was made that the algal facility receives adequate solar radiation to achieve the respective productivity values shown in Table 2 and that the facility operates 330 days per year. The latter assumption implies that a site location is chosen which receives high year-round solar exposure; a number of such locations which could sustain 85–90% operating factor are concentrated in the Southwestern US [8]. Several studies have been published that investigate the influence of location on the algae growth potential; while this is beyond the scope of this report, a thorough analysis is provided by Weyer et al. [9]. The baseline algal productivity and lipid content for both cases were selected based on currently achievable data as reported in literature [2,10–12]. The systems were assumed to achieve a steady-state algae cell density of 0.5 g/L for the ponds and 4 g/L for the PBR, a self-limiting value where cell shading impedes further growth [2,6]. While 0.5 g/L for the pond case is fairly standard, there is typically a much larger range of reported cell densities associated with PBR production due to the variety of PBR configurations. For tubular PBRs, cell density can range from 2 g/L to 6 g/L or more [2,11,13]; thus 4 g/L was chosen as the base case, and is later varied over this range as a sensitivity analysis. The superior cell density from the PBR system is achieved due to higher surface area-to-volume ratio and consequently shorter light path length versus ponds. However, the areal productivity per square meter of solar radiation was set equal to the open pond case, thus at 1.25 g/L/day the corresponding areal footprint of the PBR tube system would be 200 $m^3$/hectare of land.

After conducting an extensive literature search as well as an optimization study in Aspen to determine optimal processing steps (for example, number of concentration stages that best minimize cost), a process configuration was chosen again with an emphasis on establishing a baseline analysis. It is important to note that the selected approach is not claimed to be the best or most optimized process, but is one of the more likely options to be feasible on a large scale using technology currently used in industrial processes today. The selected process configuration as modeled in Aspen Plus is shown in the block flow diagram in Fig. 1. Pure $CO_2$ is concentrated out of flue gas from a nearby power plant or other flue gas source and delivered to the facility. A $CO_2$ delivery cost of \$40/metric ton accounts for all upstream operations required to concentrate $CO_2$ out of the flue gas stream; the technical and cost details of such operations are outside the scope of this analysis, but \$40/metric ton is intended to serve as an average value for

**Table 2**
Baseline algal growth assumptions.

| | Open pond | PBR |
|---|---|---|
| Scale (MM gal/yr algal oil) | 10 | 10 |
| Algae productivity[a] | 25 ($g/m^2$/day) | 1.25 ($kg/m^3$/day) |
| Algal cell density (g/L) | 0.5 | 4 |
| Lipid yield (dry wt.%) | 25% | 25% |
| Operating days/yr | 330 | 330 |

[a] Productivity is on an areal basis ($g/m^2$/day) for open ponds and a volumetric basis ($kg/m^3$/day) for PBRs.

**Table 1**
Comparison of open pond versus PBR systems.

| Metric | Pond | PBR |
|---|---|---|
| Capital investment | Low | High |
| Ease of scale-up | Good | Variable (depends on PBR type) |
| Availability of technology | Readily available | Not demonstrated on large-scale |
| Downstream processing cost | High (very dilute culture) | Low (higher density culture) |
| Flexibility to strain selection | Low (open to invasive species) | High (closed system) |
| Water use | High (evaporation) | Lower |

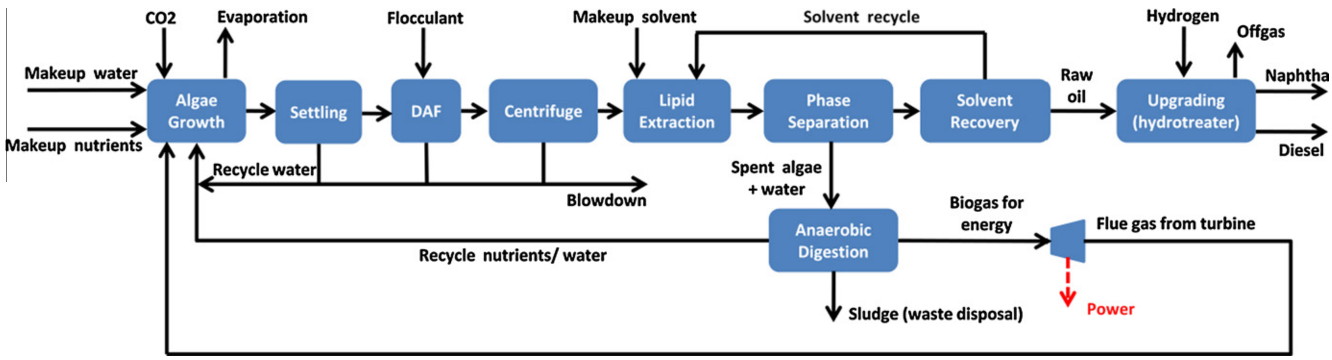


**Fig. 1.** Schematic of algal biofuel process modeled in Aspen.

**Table 3**
Algal oil hydrotreater conditions and yields.

| Parameter | Value used in Aspen model | Reference/notes |
|---|---|---|
| Temperature | 350 °C | [34] |
| Pressure | 500 psig | [34] |
| Hydrogen consumption | 1.5 wt.% of feed | Deduced from [34–36] |
| Hydrogen feed ratio | 6000 standard cubic feet/barrel of feed | [34] |
| Feed TAG carbon number composition | C10 1%<br>C12 2%<br>C14 15%<br>C16 35%<br>C18 41%<br>C20 6% | "Average" TAG composition from [37]. Note: this is not intended to be strain-specific. |
| Feed TAG saturation | 45% | [37]; See note above. |
| Product slate from hydrotreater (wt.% composition) | Naphtha 2%<br>Diesel 78%<br>$H_2O$ 2%<br>$CO_2$ 11%<br>CO 1%<br>Offgas 6% | 80% fuel yield from [34,36,38] Offgas is mostly propane (C3 backbone of TAG molecule) |

carbon capture using standard technology such as MEA amine scrubbing [5,14]. The $CO_2$ is transferred to the ponds via 1.5 meter deep sumps with baffles to limit outgassing (the design and cost for this system was based on Benemann and Oswald's 1996 analysis, and appears to support very high $CO_2$ retention [5]). $CO_2$ is directly injected to the PBRs. The ponds have a liquid depth of 20 cm to maximize light utilization [4,15], and are unlined and mixed using paddle wheels. The pond inputs were also based on the above-mentioned Benemann report, which stipulates that adding a liner to the ponds would be a significant economic detriment [5]. Water evaporation from the ponds was assumed to occur at a rate of 0.3 cm/day [16]. The PBR system consists of rows of parallel tube passes, with each tube measuring 8 cm ID × 80 m length [13,17]. Between each 80 m tube section is a degassing station consisting of airlift columns, which serve a dual purpose to strip out accumulated oxygen as well as provide circulation without damaging cells as traditional pumps might [17–19]. The PBRs are cooled using a sprinkler system to spray water on the tube surface; the design and cost of this system was based on prior PBR studies [20,21]. Nutrient demands for algal growth are met using diammonium phosphate (DAP) and ammonia. $CO_2$ and nutrient requirements were set stoichiometrically based on Eq. (1), assuming an algal composition of $[C_{106}H_{181}O_{45}N_{15}P]$ based on the Redfield Ratio [22].

The microalgae grow to the steady-state concentrations shown in Table 2, and are continuously harvested at a rate equal to the growth rate. Harvesting is accomplished first in a simple settling tank that concentrates the algae to 1% (10 g/L) [5,23] via autoflocculation, where any algae carryover into the clarified effluent is recycled to the growth stage. The next step consists of flocculation with chitosan and collection by dissolved air flotation (DAF) [24–26], which thickens the material to 10% (100 g/L). The slurry is further concentrated to 20% (200 g/L) using a centrifuge [12,27], to minimize downstream costs as much as possible. Extraction is accomplished by a combination of mechanical methods using high pressure homogenizers to disrupt and lyse the cell [2,12,28], followed by solvent extraction with butanol [29]. These two steps together were assumed to achieve 90% extraction efficiency. The oil/solvent phase is separated from the water and spent biomass material using disk stack centrifuges (private vendor discussion), and the spent biomass plus water is sent to anaerobic digestion to produce biogas for power production [30–33]. Beyond the 10% extraction efficiency loss, an additional 5% of the extracted oil was assumed to be lost through entrainment in the water phase. Next, the butanol solvent is separated from the oil in a stripping column and recycled, leaving a 99.5% pure lipid stream. The liquid effluent from anaerobic digestion is recycled to the growth stage to minimize fresh nutrient makeup, and the flue gas from the turbine is also recycled to minimize fresh $CO_2$ demand.

### 2.2. Oil upgrading

After producing the purified algal oil product, the oil is upgraded via hydrotreating to a finished fuel product by removing oxygen and saturating double bonds present in the fatty acid chains of the triglyceride (TAG) components. Hydrotreating employs hydrogen addition to remove heteroatoms (oxygen in this case), saturate double bonds, and crack large molecules into smaller components. Process assumptions for the hydrotreating section

**Table 4**
Summary of operating cost assumptions.

| Material | Cost | Reference/Notes |
|---|---|---|
| $CO_2$ | $40/metric ton[a] | [5,14]; Not location-specific |
| Ammonia | $407/ton[a] | NREL in-house value |
| DAP | $442/ton[a] | [43] |
| Chitosan for flocculation | $4.84/lb | [44] |
| Butanol for solvent extraction | $0.94/lb | [45] |
| Water | $0.05/1000 gal | [39]; Note: This cost only applies to fresh water makeup for PBR sprinkler system. All process water supplied to ponds + PBRs is pumped from underground [5] |
| Hydrogen | $1.50/kg | [46] |
| Waste disposal | $1000/hectare cultivation area (1996 dollars) | [5] |
| Power | $0.08/kW h (net import); $0.065/kW h (net export) | [47]; Electricity price varies depending on whether the overall power balance results in net demand or net excess power |

[a] Fresh $CO_2$ requirements are decreased due to recycle of flue gas from anaerobic digestion, as well as undigested carbon in the liquid effluent from digestion [30]. Likewise, fresh nutrient requirements are also decreased due to recycle of digester effluent.

were based largely off of a UOP study for hydrotreating of "vegetable oils" and brown grease [34]. In addition to the primary upgraded diesel product, a small amount of naphtha-range material is also produced from the hydrotreater. The assumed conditions for the hydrotreating section are summarized in Table 3.

### 2.3. Economic assumptions

The resulting mass and energy balance outputs from the Aspen models were used to evaluate all capital and operating costs in order to establish an overall cost of production value. All capital costs for algal oil production were estimated based on vendor quotes, prior literature studies, or standard engineering estimates [5,20,21,32,33,39,40]. Capital costs for the hydrotreater facility were based on a report by Larson et al. [41]. One cost reference used in select areas was Benemann and Oswald's 1996 widely-cited report [5], which at the time of publication provided an unprecedented level of analysis on equipment costs for algal cultivation and processing. However, the Benemann study presented all cost results based on "dollars/hectare" of growth ponds for simplicity. Many subsequent economic analyses have adopted this basis for every process stage, but with varying input parameters such a method of cost estimating loses its accuracy for downstream units. Thus this basis was avoided in the present study except for directly applicable instances. Specifically, the Benemann report was used to estimate costs for the pond and paddle wheel systems, $CO_2$ delivery and distribution systems, and "outside battery limit" costs for items such as electrical systems and water delivery pumps. A land cost of $3000/acre was used as appropriate for low-value land; this is a conservative estimate for both the southwest US as well as the Gulf States [42], which are both attractive candidate sites for an algae growth facility.

Likewise, all operating costs were also based on public literature. The operating cost assumptions are listed in Table 4. All items are self-explanatory with the exception of makeup water. For the pond case, makeup water is required to replace losses in evaporation, as well as water removed from the recycle circulation loop to control buildup of salts and other contaminants in the system; this material is referred to here as blowdown. 5% of the circulated water is removed as blowdown and sent to off-site treatment, which also must be replaced with makeup water. Likewise, 5% of the recycle water in the PBR system is also removed as blowdown. These losses are all assumed to be made up with water pumped from an underground saline or brackish aquifer, so to avoid further straining freshwater resources in water-limited regions such as the Southwestern US [5]. Even though this makeup water would contain some level of salts, as long as a blowdown stream is removed from circulation the system will reach a steady-state salt concentration rather than increasing indefinitely (in a practical application, the blowdown rate would be varied to achieve a salinity that can be tolerated by the algal strain). Thus the only costs associated with makeup process water are embodied in capital expense for the pumping equipment as well as associated pumping power requirements [5]. However, fresh (non-saline) water is required to make up for evaporative losses in the sprinkler system used for PBR cooling, to avoid scaling on the tubes.

Finally, the financial assumptions applied in the present study are summarized below.

- Fixed operating costs
  - Labor: 50 ponds per operator (pond case); 25 hectare per operator (PBR case).
  - All other labor costs: based on NREL's Aden et al. ethanol model [33].
  - Overhead = 60% of labor [33].
  - Maintenance = 2% of installed equipment cost [33].
  - Insurance and taxes = 1.5% of total installed cost [33].
- Indirect capital costs: based on NREL's Aden et al. ethanol model [33]
  - Contingency = 30% (due to inherent uncertainties in scale-up for algae production).
  - Working capital = 25% of operating costs [5].
- 10% IRR (internal rate of return).
- 20 year plant life.
- 35% tax rate.
- MACRS (Modified Accelerated Cost Recovery System) 7-year depreciation schedule.

## 3. Results and discussion

### 3.1. Baseline economics

The resulting production costs for both the intermediate oil (TAG) and the upgraded diesel products are shown in Fig. 2 for the input conditions presented in Table 2. For consistency with NREL's recent techno-economic studies, all costs are presented in year 2007 US dollars.

The raw oil production cost for the open pond case was found to be $8.52/gal, while PBR production was found to be roughly twice this cost at $18.10/gal. The upgrading step adds marginally to these costs, at $9.84 and $20.53/gal of diesel, respectively. The refined diesel prices are equivalent to $9.30/GGE (gallon gasoline equiva-

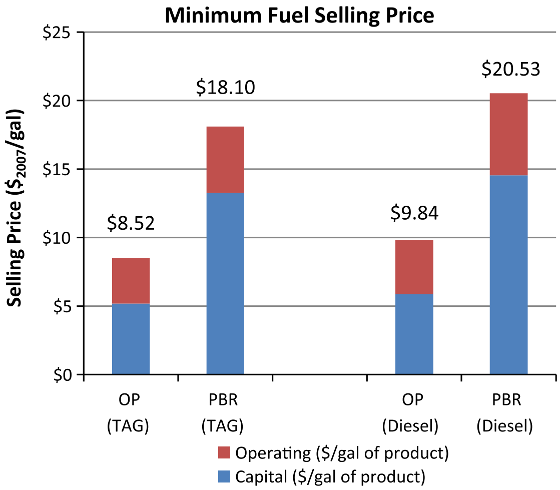


**Fig. 2.** Minimum selling price required to achieve 10% rate of return for algal TAG and diesel production (OP = open ponds, PBR = photobioreactors).

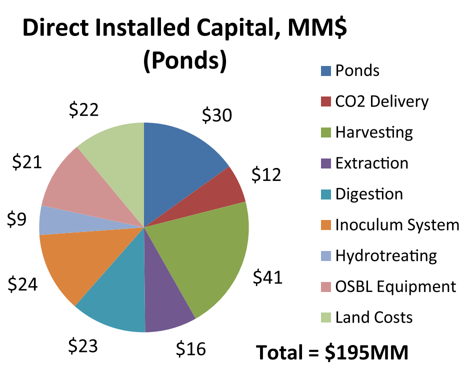


**Fig. 3.** Capital cost allocation, pond.

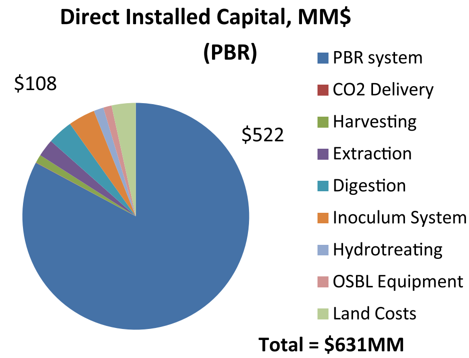


**Fig. 4.** Capital cost allocation, PBR.

**Table 5**
Process, economic, and resource assessment for the pond and PBR pathways.

| | Base case | |
|---|---|---|
| | OP | PBR |
| *Production scale* | | |
| Lipid production (MM gal/yr) | 10.0 | 10.0 |
| Diesel production (MM gal/yr) | 9.3 | 9.3 |
| *Land use* | | |
| Pond/PBR land use (acre) | 4820 | 4820 |
| Total plant land required (acre)[a] | 7190 | 7190 |
| *Resource assessment* | | |
| Net water demand (MM gal/yr) | 10,000 | 3000 |
| – Water evaporated (gal/gal lipid)[b] | 570 | 250 |
| – Water blowdown to treatment/discharge (gal/gal lipid)[b] | 430 | 50 |
| Fresh $CO_2$ demand (ton/yr)[c] | 145,000 | 145,000 |
| Fresh $NH_3$ required for algae growth (ton/yr)[d] | 5100 | 5100 |
| Fresh DAP required for algae growth (ton/yr)[d] | 4800 | 4800 |
| Power coproduct exported to grid (MM kW h/yr)[e] | 80 | 100 |
| Naphtha coproduct (gal/yr) | 340,000 | 340,000 |
| *System cost* | | |
| Total capital cost (direct + indirect) ($MM) | $390 | $990 |
| Net operating cost ($MM/yr) | $37 | $55 |
| Total coproduct credits ($MM/yr) | $6 | $7 |

[a] Total facility footprint including downstream operations; assumes that growth step = 2/3 of total land area.
[b] Includes makeup for evaporation losses + blowdown stream removed from recycle loop (to off-site treatment), NOTE: for LCA purposes, consumptive use is typically only the evaporation portion (blowdown can be treated and returned to a water body downstream). This analysis assumes that brackish water from underground replaces OP evaporation, OP blowdown, and PBR blowdown, while fresh water replaces PBR evaporative losses in the sprinkler cooling system.
[c] After recycling turbine flue gas + carbon in digester effluent.
[d] Net nutrient requirements after recycling digester effluent.
[e] After considering all facility power demands; includes $CO_2$ capture step.

lent) for open ponds and $19.39/GGE for PBRs, calculated according to lower heating value ratios presented in Argonne National Laboratory's GREET model [48]. Fig. 2 shows that the economics for both cases are driven more by capital costs, especially in the PBR case. The specific capital allocations for each scenario are shown in Figs. 3 and 4. The plots show that while the capital costs for the pond case are fairly evenly allocated across a number of systems, the PBR costs are dominated by the capital cost of the PBR tube system itself, being several times higher than the total capital cost of the open pond process.

A summary of important process results and resource considerations is presented in Table 5.

Table 5 highlights several important points. First, it demonstrates the advantage of PBRs over open ponds with respect to water use, with PBRs requiring 30% of the water demand for the open pond scenario (more than half of which is lost to evaporation from the ponds in the base case). Still, the water demand for PBRs is roughly 300 gallons per gallon of algal oil produced, not an insignificant result in water-limited areas such as the desert southwest where solar radiation is ideal for autotrophic production. $CO_2$ and nutrient requirements are essentially the same between the open pond and PBR cases since the conversion efficiency of $CO_2$ to lipid is the same in either case. Additionally, the land footprint is the same, again due to the fact that algal productivity per unit area of solar radiation is a constant; and although PBR production allows for higher cell densities due to shorter light paths, PBRs do not necessarily increase areal productivity (on an areal basis, both the pond and PBR cases achieve a productivity of 25 $g/m^2/day$). For both cases, there was a net electricity export after considering all facility power demands (including $CO_2$ capture as well as the hydrotreating section). However it is important to note that additional assumptions had to be made in the Aspen models (which otherwise had no effect on the mass balances) in order to estimate power usage. Thus the electricity balance shown in Table 5 should be viewed as a qualitative estimate more than an absolute quantitative basis.

### 3.2. Sensitivity analysis

A sensitivity study was run for several alternative growth scenarios, to evaluate the effect of potential future strain improvements on the overall economics. In these scenarios, both the growth rate and oil content were improved simultaneously beyond the baseline values, in an "aggressive" case and "maximum growth" case. The open pond assumptions for these alternative scenarios were based on a

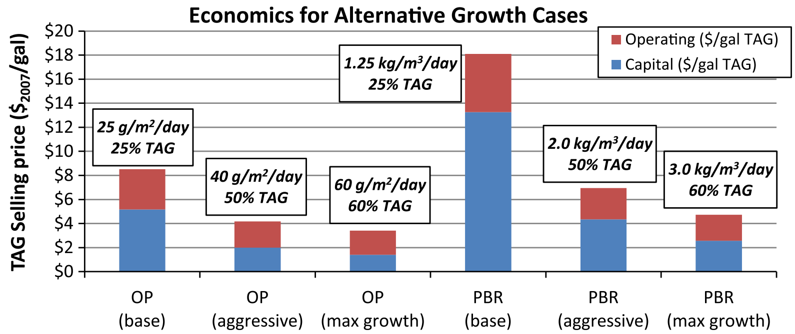


**Fig. 5.** Algal oil production costs for alternative growth scenarios.

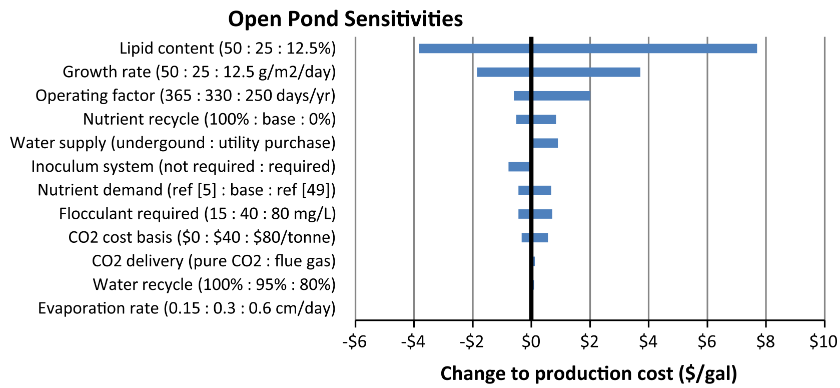


**Fig. 6.** Open pond sensitivity analysis. (See above mentioned reference for further information.)

previous NREL report to the US Congress [23], where the "aggressive" case is intended to represent feasible longer-term research advancements in strain improvement, while the "max growth" case is set near the theoretical maximum growth rate and lipid content that could possibly be achieved based on photosynthetic efficiency limitations. The PBR productivity assumptions were scaled in each case according to the surface area-to-volume ratio for the PBR and pond dimensions outlined previously. The cost results are presented in Fig. 5; for conciseness, only the raw oil (TAG) costs are presented here, but the upgraded diesel results would follow the same trend as the base case results, at a roughly 15% increase over the raw oil costs.

Fig. 5 shows that there is room for substantial improvement in algal oil economics for both the open pond and PBR cases, if a strain can be identified or engineered to sustain a high growth rate while also maintaining a high lipid content. The majority of the cost improvement is due to reductions in capital expenses. To put these figures into a larger context, it is important to note that "max" in this case merely means the maximum algae growth and oil content (based on efficiency limits) applied to this specific configuration and associated assumptions. Thus, while $3–5/gal appears to be the "future potential" cost range for this study, this does not imply that these are the absolute lowest costs that can ever be achieved as there are numerous other process options and even unforeseen additional improvements that could be realized as the technology develops, as well as the potential for higher-value co-products.

While it is important to understand the cost reduction potential for future scenarios, it is equally important to evaluate how a single process parameter influences the overall result. This is best captured through tornado plots. Individual parameters were varied from the established base case over a reasonable range, and the results are shown in Figs. 6 and 7.

The tornado diagrams show that the overall economics are by far the most sensitive to growth rate and lipid content (biological parameters specific to the algae strain). Another key result is that the lipid content more strongly impacts the economics than the growth rate does: for the open pond case, when lipid content is either doubled or divided in half, the net cost impact is twice as large as a similar adjustment in growth rate. This is because increasing the areal growth rate merely decreases the size of the growth system (and associated costs) relative to the amount of algal biomass being grown, while an increase in the oil content actually decreases the amount of algal biomass that must be produced to achieve a set oil production target (thereby reducing all downstream processing costs due to lower equipment throughputs). Although the PBR case also shows greater cost sensitivity to oil content than to the algae growth rate, the cost savings is less pronounced; this is due to the PBR growth system exhibiting a much larger fraction of the overall cost and thus less savings opportunity to be seen with lower downstream throughputs. In either case, the key implication for research going forward is that it is more economically beneficial to target improvements in lipid content than algal growth rate given that in reality there is typically a tradeoff between the two parameters.

While the inputs with the largest cost sensitivity (lipid content and growth rate) are strain-specific biological parameters, most other items shown in Figs. 6 and 7 are parameters more related to engineering aspects that can be adjusted through improvements to the process rather than the algal biology. This demonstrates another important result, that although the engineering aspects appear to exhibit a lower degree of control over the cost outcome, there are many more "handles" that can be turned through such process engineering improvements, many of which are still far from insignificant (a $1/gallon adjustment in a single parameter is still more than 10% of the overall cost in the pond case). Of the remaining sensitivity parameters examined, the items with the strongest cost impact were operating days per year and degree of

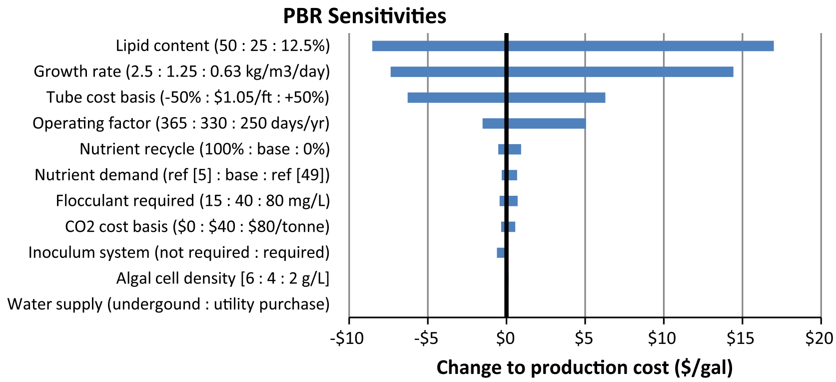


**Fig. 7.** PBR sensitivity analysis.

nutrient recycle. Additionally, the PBR tube cost exhibited a very strong cost sensitivity, again due to its large contribution to overall capital expenses (Fig. 7 implies that the tube cost alone accounts for 70% of the base case production cost). Further compounding the large uncertainty here is that the price assumed in other studies varies even more than this 50% range. For example, applying the tube cost basis from two other sources would result in a cost as low as $8/gal or as high as $25/gal [20,24], while using a separate vendor quote for a different tube material would result in a cost of $80/gal. Such drastic variations highlight the challenge in determining a credible baseline production cost for PBRs at this point in time. Another interesting result is the small sensitivity impact of the algal cell density assumed for the PBR case. As stated previously, the reported cell density achieved using tubular PBRs varies widely across literature studies [2,11,13]. To address this point, the basis of 4 g/L was varied between 2 and 6 g/L, and the cost impact was marginal. This is because the PBR system volume is set by the volumetric growth rate which is unchanged; thus the only impact is on downstream harvesting costs, which while important for the open pond case, are a very small fraction of PBR costs as shown in Fig. 4.

Finally, while assumptions on water recycle and evaporation rate do not appear to show a significant cost sensitivity, it is important to reiterate the underlying assumption that water was not assumed to incur a cost beyond capital and power expenses for pumping from underground. If water demand increased while also being purchased as a utility, the cost impact would be noticeably higher (as suggested by the $1/gal increase for fresh water shown in Fig. 6). Furthermore, even if large variations in the water balance parameters show a low-cost sensitivity, the impact on water resources would be much more dramatic, raising the issue of sustainability and impacted economics based on changes in supply and demand.

A final note should be mentioned regarding economies of scale. Although 10 MM gal/yr oil production is not excessively large, the total system throughput is considerably higher due to the dilute nature of the processes. Thus even at the scale evaluated here, the associated flow rates are higher than the largest wastewater treatment plants in the US (private discussion with vendor). Consequently, all of the equipment would already be modular and multiple units would be required to accommodate the flow rate in excess of any given unit's maximum capacity. Therefore, it is not expected that economies of scale would play a significant role in reducing the production cost at larger plant scales. However, as noted above if the equipment itself could be improved and tailored specifically to microalgae production, significant cost improvements could result (i.e. developing a low-cost material that could be produced in bulk for PBR use, and developing more efficient extraction methods).

## 4. Conclusions

To achieve a 10% rate of return, the required product selling prices were found to be $8.52 and $18.10/gal of TAG for open pond and PBR production, respectively; hydrotreating to a diesel product did not add significantly to this cost, at $9.84 and $20.53/gal diesel. Given the current petroleum diesel production cost of $2.60/gal (January 2011 [50]), these results reiterate that the economics of microalgal biofuel production would not be competitive with traditional fossil fuels if a large scale facility were to be built today. While this conclusion is in line with other reports [7,24], the present analysis highlights several more important results, namely (1) there is room for significant cost reduction potential through both biological and engineering improvement opportunities; (2) from an economic standpoint, near-term research should focus on maximizing lipid content versus algal growth rates, given the tradeoff traditionally observed between the two parameters; and (3) there is more room for cost improvement through capital cost reductions (namely establishing novel low-cost equipment for a certain process stage) than through operating cost reductions (for example, optimizing nutrient or $CO_2$ requirements), especially in the PBR case. The PBR results presented here are specific to a rigid tube system, and lower-cost options may exist such as thin films or hanging bags which were not considered here. A caveat should also be noted that operating costs were minimized to a large extent in the present analysis by employing a high degree of carbon and nutrient recycle, as well as assuming that water is delivered at low-cost from an underground aquifer. Regardless of economic impacts, from a sustainability standpoint it is important to consider such metrics as carbon, nutrient, and water balances, recycle opportunities, and delivery sources, all of which are location-specific.

Algal biofuel economics could be further improved in the near-term through means such as utilizing the spent algal biomass for more valuable co-products beyond biogas for power generation. However, the market sustainability of such co-products must be considered in the context of the envisioned commercial production volume. At the vast production quantities associated with the fuel market, it is not easy to find a value-added coproduct with comparable scale; but in the near-term at the level of a 10 MM gal/yr production facility, co-products could drive the economics. Finally, it is important to reiterate that the selected process is not intended to represent the best or most optimized approach, but represents one of the more likely options to be feasible if such a process were built on a commercial scale today. Given that no such large-scale process exists and a number of process steps have not even been demonstrated on an appreciable scale, the results presented here intrinsically carry a relatively high degree of uncertainty in both the process steps as well as costing methods. However, both the assumptions and results correspond well to typical ranges presented in other studies [7,15,24].

## Acknowledgements

This work was supported by the US Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory (NREL). All results are representative of analysis done by NREL, and do not represent any claims made by the Department of Energy.

## References

[1] DOE 2010. National algal biofuels technology roadmap. US Department ofenergy, office of energy efficiency and renewable energy. Biomass program <http://www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf> [accessed January 2011].
[2] Brennan L, Owende P. Biofuels from microalgae – a review of technologies for production, processing, and extractions of biofuels and co-products. Renew Sust Energy Rev 2010;14:557–77.
[3] Miao X, Wu Q. High-yield bio-oil production from fast pyrolysis by metabolic controlling of chlorella protothecoides. J Biotechnol 2004;110:85–93.
[4] Shen Y, Yuan W, Pei ZJ, Wu Q, Mao E. Microalgae mass production methods. Trans ASABE 2009;52:1275–87.
[5] Benemann JR, Oswald WJ. Systems and economic analysis of microalgae ponds for conversion of $CO_2$ to biomass. Final report to the Department of Energy, Pittsburgh Energy Technology Center; 1996, DOE/PC/93204-T5.
[6] Bowles D, editor. Micro- and macro-algae: utility for industrial applications. Outputs from the EPOBIO project. University of York: CNAP; 2007.
[7] Sun A. Techno-economic analysis of algae biofuel deployment. In: Proceedings to the 2009 algae biomass summit. San Diego, CA; October 2009.
[8] NOAA data on annual solar exposure in select US cities. <http://www.ncdc.noaa.gov/oa/climate/online/ccd/pctposrank.txt> [accessed January 2011].
[9] Weyer K, Bush D, Darzins A, Willson B. Theoretical maximum algal oil production. Bioenergy Res 2010;3:204–13.
[10] Griffiths MJ, Harrison STL. Lipid productivity as a key characteristic for choosing algal species for biodiesel production. J Appl Phycol 2009;21:493–507.
[11] Eriksen NT. The technology of microalgal culturing. Biotechnol Lett 2008;30:1525–36.
[12] Molina Grima E, Belarbi EH, Acién Fernández FG, Robles Medina A, Chisti Y. Recovery of microalgal biomass and metabolites: process options and economics. Biotechnol Adv 2003;20:491–515.
[13] Chisti Y. Biodiesel from microalgae. Biotechnol Adv 2007;25:294–306.
[14] IEA greenhouse gas R&D programme. Leading options for the capture of $CO_2$ emissions at power stations; 2000, report number PH3/14.
[15] Benemann J. Growth and productivity of algae biomass. In: Proceedings to the 2009 algae biomass summit. San Diego, CA; October 2009.
[16] Eichinger WE, Nichols J, Prueger JH, Hipps LE, Neale CMU, Cooper DI, et al. Lake evaporation estimation in arid environments. Final report to the US Bureau of reclamation; 2003. IIHR report no. 430.
[17] Chisti Y. Biodiesel from microalgae beats bioethanol. Trends Biotechnol 2007;26:126–31.
[18] Molina E, Fernández J, Acién FG, Chisti Y. Tubular PPR design for algal cultures. J Biotechnol 2001;92:113–31.
[19] Wurts W, McNeill SG, Overhults DG. Performance and design characteristics of airlift pumps for field applications. World Aquacult 1994;25:51–5.
[20] Tapie P, Bernard A. Microalgae production: technical and economic evaluations. Biotechnol Bioeng 1988;32:873–85.
[21] Tredici M, Zittelli GC, Benemann JR. A tubular integral gas exchange photobioreactor for biological hydrogen production: preliminary cost analysis. BioHydrogen. New York: Plenum press; 1998. p. 391–401.
[22] Clarens AF, Resurreccion EP, White MA, Colosi LM. Environmental life cycle comparison of algae to other bioenergy feedstocks. Environ Sci Technol 2010;44:1813–9.
[23] DOE 2008. Microalgae feedstocks for biofuels production. Report to congress (EISA 2007 – section 228).
[24] Abayomi A, Tampier M, Bibeau E. Microalgae technologies & processes for biofuels/bioenergy production in British Columbia: current technology, suitability, and barriers to implementation. Final report submitted to the British Columbia innovation council; 2009.
[25] Divakaran R, Sivasankara Pillai VN. Flocculation of algae using chitosan. J Appl Phycol 2002;14:419–22.
[26] Heasman M, Diemar J, O'Connor W, Sushames T, Foulkes L. Development of extended shelf-life microalgae concentrate diets harvested by centrifugation for bivalve molluscs – a summary. Aquacult Res 2000;31:637–59.
[27] Leung W. Industrial centrifugation technology. New York: McGraw-Hill; 1998.
[28] EPA 2006. Emerging technologies for biosolids management. US environmental protection agency, office of wastewater management. <http://www.docstoc.com/docs/585772/Emerging-Technologies-for-Wastewater-Biosolids-Management> [accessed January 2011].
[29] Nagle N, Lemke P. Microalgal fuel production processes: analysis of lipid extraction and conversion methods. Extract from NREL aquatic species program annual report; 1989, SERI/SP-231-3579. <http://www.nrel.gov/docs/legosti/old/3579.pdf> [accessed October 2010].
[30] Weissman JC, Goebel RP. Design and analysis of open pond systems for the purpose of producing fuels. NREL subcontract report; 1987, SERI/STR-231-2840. <http://www.nrel.gov/docs/legosti/old/2840.pdf> [accessed October 2010].
[31] Davis M, Cornwell D. Introduction to environmental engineering. Boston: WCB/McGraw-Hill; 1998.
[32] Dean J, Braun R, Munoz D, Penev M, Kinchin C. Analysis of hybrid hydrogen systems: final report. NREL technical report; 2010, NREL/TP-560-46934. <http://www.nrel.gov/docs/fy10osti/46934.pdf> [accessed September 2010]..
[33] Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, et al. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. NREL technical report; 2002, NREL/TP-510-32438. <http://www.nrel.gov/docs/fy02osti/32438.pdf> [accessed September 2010].
[34] Marker T, Petri J, Kalnes T, McCall M, Mackowiak D, Jerosky B, et al. Opportunities for biorenewables in oil refineries. Final technical report submitted to the US Department of Energy; 2005, contract no. DE-FG36-05GO15085.
[35] Donnis B, Egeberg RG, Blom P, Knudsen KG. Hydroprocessing of bio-oils and oxygenates to hydrocarbons. understanding the reaction routes. Top Catal 2009;52:229–40.
[36] Sotelo-Boyas R, Liu Y, Minowa T. Production of green diesel by hydrocracking of canola oil on Ni–Mo/$\gamma$-$Al_2O_3$ and Pt-Zeolitic based catalysts. <http://www.nt.ntnu.no/users/skoge/prost/proceedings/aiche-2008/data/papers/P134226.pdf> [accessed October 2010].
[37] Hoekman SK, Gertler A, Broch A, Robbins C. Investigation of biodistillates as potential blendstocks for transportation fuels. Coordinating research council; 2009, CRC report no. AVFL-17.
[38] $(S\&T)^2$ Consultants, Inc. The addition of NRCan's supercetane and ROBYS™ processes to GHGenius. Prepared for National Resources, Canada; 2004.
[39] Seider WD, Seader JD, Lewin DR. Product and process design principles. New York: John Wiley and Sons; 2004.
[40] Wang LK, Shammas NK, Hung YT. Handbook of environmental engineering: biosolids treatment processes. New Jersey: Humana Press; 2007.
[41] Larson ED, Jin H, Celik FE. Large-Scale gasification-based coproduction of fuels and electricity from switchgrass. Biofuels, Bioprod Biorefining 2009;3:174–94 [electronic version with supporting info].
[42] Based on performing a statistical analysis of land prices in Louisiana and Arizona, according to prices in <http://www.landwatch.com/> [accessed August 2010].
[43] University of Tennessee Extension. Farm management newsletter, Spring; 2009. <http://www.utextension.utk.edu/managecamp/spring09.pdf> [accessed November 2009].
[44] Bough WA, Landes DR. Treatment of food-processing wastes with Chitosan and nutritional evaluation of coagulated by-products. In: Proceedings of the first international conference on Chitin/Chitosan; 1978. p. 218–230.
[45] SRI report on Oxo chemical prices. <http://www.sriconsulting.com/CEH/Public/Reports/682.7000/> [accessed September 2009].
[46] Wright MM, Satrio JA, Brown RC, Daugaard DE, Hsu DD. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. NREL technical report; 2010, NREL/TP-6A20-46586. <http://www.nrel.gov/docs/fy11osti/46586.pdf> [accessed February 2011].
[47] US Energy Information Administration, average wholesale electricity prices. <http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html> [accessed September 2010].
[48] US DOE, Hydrogen Analysis Resource Center. Lower and higher heating values of fuels. <http://hydrogen.pnl.gov/cocoon/morf/projects/hydrogen/datasheets/lower_and_higher_heating_values.xls> [accessed November 2010].
[49] Hassannia J. Algae biofuels economic viability: a project-based perspective. <http://www.biofuelreview.com/content/view/1897/1> [accessed September 2010].
[50] US Energy Information Administration, regional petroleum prices. <http://eia.gov/emeu/steo/pub/cf_tables/steotables.cfm?tableNumber=11&loadAction=Apply+Changes&periodType=Monthly&startYear=2009&endYear=2012&startMonth=1&startMonthChanged=false&startQuarterChanged=false&endMonth=12&endMonthChanged=false&endQuarterChanged=false&noScroll=false> [accessed February 2011].