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Comparative cost analysis of algal oil production for biofuels

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ABSTRACT

Economic analysis is an essential evaluation for considering feasibility and viability of large-scale, photoautotrophic algae-based, biofuel production. Thus far, economic analysis has been conducted on a scenario-by-scenario basis which does not allow for cross-comparisons. In 2008, a comparative study was carried out using a cross-section of cost analyses consisting of 12 public studies. The resulting triacylglyceride cost had a spread of two orders of magnitude excluding two studies which were intended for specialty chemicals. The cost spread can be largely attributed to disparate assumptions and uncertainties in economic and process inputs. To address this disparity, four partners from research, academia, and industry collaborated on a harmonization study to estimate algal oil production costs based on a common framework. The updated cost comparison based on a normalized set of input assumptions was found to greatly reduce economic variability, resulting in algal oil production costs ranging from \$10.87 gallon^{-1} to \$13.32 gallon^{-1}.

1. Introduction

Realization of large-scale algae cultivation for biofuel production requires a combination of technical innovations and feasible implementation. Commercial deployment involves practical considerations of sustainable feedstock resources, large-scale economics, and operational logistics. Techno-economic assessment is a necessary component to study the economic and technical challenges to make algae an attractive feedstock for biofuels.

Historical technoeconomic assessments for large-scale production of photoautotrophic algae had focused on carbon sequestration, wastewater treatment, and high-value nutraceutical production. More recent studies focus on the technology development for algal oil production such as novel extraction techniques or compatibility of algae oil methyl ester to conventional diesel engines [1,2]. Benemann and Oswalds' 1996 report to the National Energy Technology Laboratory gave a comprehensive assessment of the research, technologies, commercial applications, and economics of open pond algal biomass production for biodiesel [3]. Funded by the United States Department of Energy Aquatic Species Program [4], Benemann and Oswalds' report is by far one of most cited references on cost estimations for algae production for carbon sequestration. In a separate study, Life Cycle Assessment methodology was applied to understand the feasibility of CO_2 sequestration using algae in coal-fired power plants, by comparing the impact of energy and environmental footprints with and without algae co-production [5]. Another study conducted scenario-based feasibility analyses of algae co-production in wastewater treatment plants on a large-scale [6].

In December 2008, the DOE/EERE Office of Biomass Program hosted a workshop with the support of SNL (Sandia National Laboratories) and NREL (National Renewable Energy Laboratory) to create an Algae Biofuels Technology Roadmap. To meet the objectives of the workshop and establish a common basis for later discussion among the participating experts during the road-mapping process, cost analysis based on published data was initially carried out based on twelve references [7]. The analysis was limited to consideration of biomass and TAG (triacylglyceride) oil production from photosynthetic microalgae only, and did not include heterotrophic microalgae or autotrophic macroalgae. Table 1 categorizes the twelve sources of information used, and this includes inputs from all four organizations represented by the authors of this report. Table 1 is categorized by the institutions where the authors conducted their studies as well as a number of

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Table 1
Sources of Information for 2008 Historical Cost Overview.

Source	Contributors
National Laboratory	
NREL	Phil Pienkos, David Humbird
Sandia	Ben Wu, Amy Sun
Industry	
Solix	Bryan Willson
NBT	Ami Ben-Amotz, Israel
Seambiotic	Ami Ben-Amotz, Israel
Bayer	Ulrich Steiner
General Atomics	David Hazlebeck
Academia	
New Mexico State University	Meghan Starbuck
California Polytechnic State University	Tryg Lundquist
Literature	
Biotech Advances v20 pgs.491–515	Grima et al. (2003)
Biotech & Bioengineering, 1988	Tapie & Bernard (1998)
PETC	Benemann & Oswald(1996)

others. Data were gleaned from sources spanning academia, where hypothetical cases were proposed based on pilot studies, to industry estimates, based on proprietary information. The estimates based on disparate sources had to be re-adjusted to 2008 dollars.

Fig. 1 shows the range of TAG production cost excluding two outlier studies that extrapolated from nutraceutical production for TAGs[1]. While the sampling size is small relative to the available public information, the selected studies represent a reasonable cross-section of more recent information that includes assessment of both open and closed algae cultivation system approaches. The resulting range of cost estimates for processes proposed for biofuel production span nearly two orders of magnitude from \$0.92 gallon^{-1} to \$42.6 gallon^{-1}. The average cost per gallon is \$19.3 gallon^{-1} with a standard deviation of \$28.8 gallon^{-1}. If estimates include cost of TAG recovery in traditionally nutraceutical production, the cost uncertainty expands by another two orders of magnitude. These estimates include both actual and hypothesized values that span more than ten years of reported results from various individuals and groups across three continents. They also span several technologies (open pond, closed photobioreactors, etc.), and are based on a wide range of productivity assumptions.

The range of values yielded doubts about the competitiveness of algal-based triacylglyceride relative to other biomass derived lipids and pointed to barriers in establishing an algae-based transportation fuel industry. Compared to a 2007 cost review by Chisti, the range of uncertainties was much wider than anticipated [8]. Nevertheless, this analysis achieved our goal of motivating interdisciplinary discussions during and subsequent to the workshop. While the comparative cost assessment contributed to the background analysis, these results were not included in the DOE Algae Technology Roadmap Report [9]. The report laid out the short-term and long-term technical challenges for algae-derived transportation fuel and summarized recommendations for research and development effort.

Renewed interests from private industry as well as non-profit organizations were met with increased government funding. In 2009 and 2010 alone, the Department of Energy announced three major multi-year awards toward accelerating advanced biofuel research and commercialization, calling out algal biofuels for the first time [10–13]. The purpose of this paper, therefore, is to capture the information presented at the workshop and to use that as a foundation to describe more recent progress.

[1] Cost referred throughout this paper is based on 2008 US dollars.

Since the initial assessment of twelve open sources, more cost studies have been published. Campbell and others conducted life cycle analysis and greenhouse gas balance of algal biodiesel production coupled with CO_2 sequestration [14]. In terms of the life cycle fuel cost required by a 30-tonne articulated truck, the study estimated a cost of \$0.033–0.040 tonne-km^{-1}, though the authors did not provide a volumetric algal productivity and so direct comparisons with other works cannot be made. Several recent studies were also presented at the 2009 Algal Biomass Summit. A preliminary economic analysis was given by David Lewis of the University of Adelaide [15], who estimated a current cost of \$5.30 gallon^{-1} of oil based on pilot scale performance (although several cost components were unknown and thus left out). Another analysis presented by Lundquist et al. estimated the production cost around \$300 barrel^{-1} (\$7.10 gallon^{-1}) for a wastewater application [16]. A presentation was also given by John Benemann who used updated cost estimates to project that an optimistic value of \$7.60 gallon^{-1} could be achievable in the future [17]. This shows a continued lack of agreement regarding production cost, although the amount of variation across these recent studies appears smaller than in earlier estimates. Diversified Biofuel presented a methodology using net present value to gauge profitability of algae biofuel production. Diversified Energy has also conducted its own sensitivity analyses showing areas of improvement needed for commercialization [18,19].

To address these variations, the authors of this report jointly reconsider their earlier models and assumptions in a harmonization study. All of the sources for the 2008 analysis will be described in the next section. Cost parameters, reactor geometries, and cultivation/isolation processes that distinguish each study are given. This is followed by more recent work which provides a more consistent set of assumptions and cost categorization to establish a methodology that can be applied across different algae production scenarios.

2. Methodology of 2008 comparative cost analysis

2.1. Assumptions

Production costs estimates for the Roadmap workshop are defined as the sum of capital and operating costs minus the credits derived from all co-products.

$$C_{\text{production}} = \sum_i C_{\text{capital},i} + \sum_j C_{\text{operating},j} - \sum_k C_{\text{co-products},k}$$

where $C_{\text{production}}$ = Total cost of production, $C_{\text{capital},i}$ = Capital cost, including direct and indirect capital costs, of sub-category *i*. $C_{\text{operating},j}$ = Operating cost of sub-category *j*. $C_{\text{co-products},k}$ = Cost of *k*th co-product.

Capital cost is further broken down into cost of land, equipment, facilities, and indirect expenditures while operating cost includes items such as labor, maintenance cost, raw material cost, and utility cost. Depending on the scenario posed by each source, each cost sub-category may or may not be further broken down into more details. Table 2 summarizes the range of assumptions used in the 2008 analysis. First, the type of cultivation system is not categorized, which leads to differences in biomass yields for closed photobioreactors compared to open pond. Second, the range of oil content can be as low as 10% and as high as 60% depending on the scenario. Similarly, areal dry mass yield ranges from 2 gm m^{-2} day^{-1} to 110 gm m^{-2} day^{-1}. While no timeline actualization is noted in the equation above, it is considered in all of the studies. The loan period, which causes a shift in annualized cost calculations, varies widely in each study from five to twenty years.

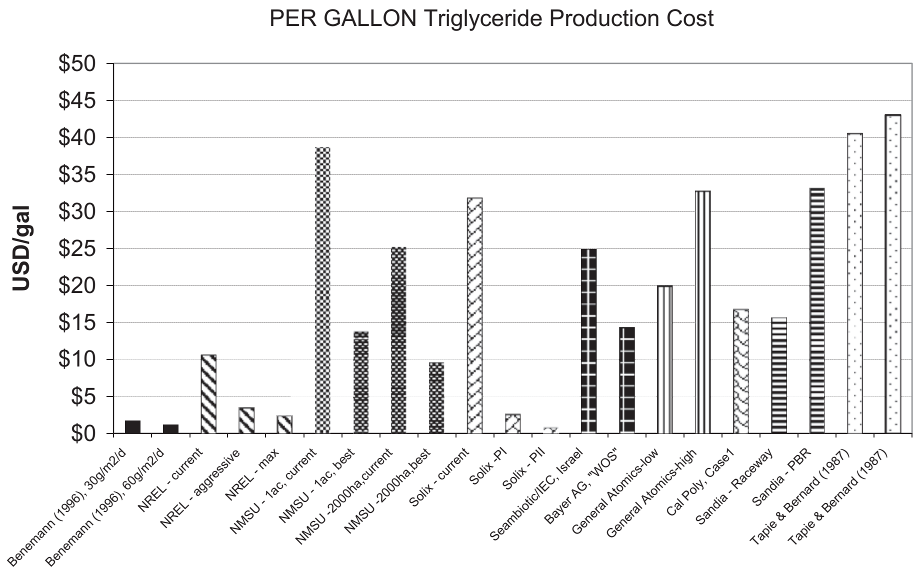

Fig. 1. Per gallon TAG cost from different publically available estimates adjusted to 2008 cost basis. Benemann (1996); NREL & NMSU (private communications); Solix; Bayer; General Atomics; Cal Poly (2008); NBT Ltd., Israel (2007); Seambiotic, Israel, (2008); Tapie & Bernard (1987); Sandia (2007).

The wide range of assumptions and end use, therefore, resulted in a deviation of two orders of magnitude in total product cost per gallon of triacylglyceride. The results with highest costs originated from studies that were targeted for specialty chemicals, such beta-carotene (NBT, Israel) and eicosapentaenoic acid (Molina-Grima); hence, TAG only exists in small quantities as a byproduct. Low production costs were associated with scenarios that have optimistic productivity assumptions. The Benemann and Oswald 1996 study projected the lowest production cost out of all other more recent studies, even with costs adjusted to 2008 dollars.

For our comparative study we determined that it would be most appropriate to focus on TAG as the final product. Although the technology for conversion of TAGs to biodiesel (fatty acid methyl esters or FAMEs) is mature and conversion costs and yields are well modeled, biodiesel is not the only fuel product that can be made from TAGs. In 2008 progress was being made in the conversion of algal lipids to hydrocarbons through the standard refinery processes of hydrotreating, catalytic cracking, and reforming to allow TAGs to be converted to more conventional, renewable-based fuel such as diesel or jet fuel. Because these TAG-based processes are not as well established as the conversion to biodiesel, but are of great interest to a growing number of end users, we determined that our models should focus on the production cost of TAGs, the feedstock common to all fuel producers. Furthermore, the TAG feedstock production costs will represent the dominant cost of the final fuel product, regardless of the conversion process used.

2.2. Sandia 2008 analysis

Sandia conducted technoeconomic calculations for algae TAG production in both open pond and closed photobioreactors. Other than the differences in cultivation systems, harvesting methods,

Table 2
Summary the 2008 evaluations for DOE EERE algae technology roadmap shown in Fig. 1. Current or baseline scenario refers to the estimated productivity and lipid yield in 2008.

Source	Scenario	Cultivation	Cost (USD gal^{-1})	Lipid yield (wt.% of dry mass)	Areal Dry Algae Mass Yield (gm m^{-1} day^{-1})	Loan Period (yrs)
Benemann	Baseline	Open pond	$1.7	50%	30	5
Benemann	Maximum growth	Open pond	$1.2	50%	60	5
NREL	Current	Open pond	$10.6	25%	20	15
NREL	Aggressive	Open pond	$3.5	50%	50	15
NREL	Maximum growth	Open pond	$2.4	60%	60	15
NMSU	Current, 1 acre	Open pond	$38.7	35%	35	20
NMSU	Highest yield, 1 acre	Open pond	$13.9	60%	58	20
NMSU	Current, 2000 hectare	Open pond	$25.2	35%	35	20
NMSU	Highest yield, 2000 hectare	Open pond	$9.7	60%	58	20
Solix	Current	Hybrid	$31.8	16–47%	0–25	unknown
Solix	Phase I	Hybrid	$2.6	16–47%	30–40	unknown
Solix	Phase II	Hybrid	$0.9	16–47%	30–40	unknown
Seambiotic/IEC, Israel	Best yield	Open pond	$24.9	35%[a]	20	unknown
Sandia	Current	Open	$15.7	35%	30	10
Sandia	Current	PBR	$33.2	35%	30	10
Bayer Tech Services	Optimistic	PBR	$14.3	33%	52	10
General Atomic	Low	Open/hybrid	$20.0	unknown	unknown	unknown
General Atomic	High	Open/hybrid	$32.8	unknown	unknown	unknown
California Polytech, Pomona	Waste treatment + digester	Open pond	$16.8	25%	20	8
Tapie & Bernard	Tubes on ground	PBR	$40.6	35%[a]	20	5
Tapie & Bernard	Double tubular bioreactor	PBR	$43.1	35%[a]	20	5

[a] Assumed quantity required to convert from weight-basis to oil basis.

and production volumes, the two cases are identical in downstream separation systems. The open pond design was based on an annual 50 million gallon production target of algal TAG coupled with a CO_2 feed stream from flue gas derived from natural gas fired power plants. The PE (purchased equipment) cost was first obtained from Benemann's report [3]. In addition to purchased equipment, however, additional cost was considered for basic infrastructure. These include buildings, service facilities, instrumentation, piping, electrical, and yard improvement. Estimates for contingency, legal expense, and working capital were also included. The additional considerations tripled the cost estimated by Benemann and Oswald's earlier evaluations.

The closed PBR (photobioreactor) design was based on an areal requirement (assuming the productivity listed in Table 1) to sequester CO_2 produced by a 756 MW natural gas power plant. This land requirement is multiplied by \$10 m^{-2} as an optimistic estimate for the cost of a PBR system. The estimate is approximately an order of magnitude lower than the other cost estimates that used PBR as the cultivation system, namely, Solix and Bayer. The unit cost of equipment downstream from cultivation was identical to that used in the open pond case. Given all the other assumptions being equal, the per gallon production cost doubled in the PBR case compared with the open pond case. Hence, the initial capital investment for PBR equipment is an added burden to the overall production cost.

2.3. NREL 2008 analysis

In 2007, at the request of the U.S. Congress, a report on the current status of commercial development of algal biofuels was prepared by NREL [20]. This report included a technoeconomic assessment based on an updating of a hypothetical process by Benemann and Oswald noted above. This process was meant to combine the lowest possible capital and operating cost components into an integrated process. These components consisted of:

- Raceway ponds for cultivation
- Flocculation for biomass concentration
- Extraction with hot algal lipid stream
- Three phase (solids, water, oil) separation using continuous centrifuge
- Recycle of water back to cultivation
- Conversion of extracted solids via anaerobic digestion to generate power for overall process operation.

The TE model constructed for the Congressional report was further modified to provide information for the DOE Algal Biofuels Roadmapping Workshop in December 2008 to allow for determination of a unit cultivation facility based on the production of 10 Mgal lipid per year. The size of this unit facility was calculated as a function of areal productivity and lipid content. Water usage was calculated both as a function of inputs of evaporation rate and water lost due to assumed inefficiencies of separation and water deliberately discarded (blowdown). The inefficiencies were used along with an assumed continuous cell density to calculate (along with the growth rate) the amount of water that needed to be processed every day. Separate inputs for these two water recharge costs were included to allow for a cost calculation for both freshwater and saline inputs to replace evaporation and process losses. Table 3 provides the values for various input parameters used to calculate the NREL TAG production costs included in Fig. 1.

As shown in Fig. 1, the preliminary analysis from NREL suggested that increases in productivity can have a significant impact on the overall cost of lipid production, reducing the calculated cost from approximately \$11 $gallon^{-1}$ for the "current" scenario to \$3 $gallon^{-1}$ for the "maximum" scenario. Even this is not sufficient to bring the cost down to a point where it can compete with petroleum (\$2 $gallon^{-1}$ = \$84 $barrel^{-1}$ in May, 2010), indicating that biological productivity, alone, may not be sufficient to achieve economic viability.

Table 3
Input Assumptions for NREL 2008 Model.

Input Category	Value		
	Current	Aggressive	Max
Areal Productivity (gm m^{-2} day^{-1} dry cell weight)	20	40	60
TAG content (% dry cell weight)	25%	50%	60%
Target Cell Density (gm L^{-1} dry cell weight)	0.5		
CO_2 Cost (\$ ton^{-1})	\$50		
Water Cost (\$ $gallon^{-1}$)	\$0.00008		
Land Cost (\$ $acre^{-1}$)	\$5000		
Nutrient cost (\$ $acre^{-1}$)	\$400		
Flocculant cost (\$ $acre^{-1}$)	\$440		
Power cost (\$ kWh^{-1})	\$0.065		
Pond depth (cm)	20		
Daily evaporation rate (cm)	0.3		
Water lost from extraction (%)	20		
Harvest efficiency (%)	80		
Lipid recovery (%)	80		

One other area of potential cost improvements can come from co-products. The choice of anaerobic digestion of extracted biomass to provide energy to run the plant is shown in Fig. 2 to provide a relatively small reduction in cost, and that value is reduced in the higher productivity scenarios as less of the biomass becomes available for digestion. Many proposals for economic production of algal oil have identified higher value co-products as a means to reduce overall costs [21]. The challenge for following this path is to identify co-products with markets scalable with biofuels.

2.4. Industry

Five of the twelve sources were obtained from industry in the form of presentations. They are General Atomic, Solix, Bayer, NBT Limited, and Seambiotic [22–26]. Without considering the production example of β-carotene (NBT Ltd.), the references provided by this group estimated a per gallon TAG cost ranging from \$1.57 $gallon^{-1}$ to \$32.80 $gallon^{-1}$.

All of the industry reference sources provided very few details, with the exception of commercial productions in Israel [25,26]. This is not surprising given that private producers want to maintain their competitive advantage and cannot disclose proprietary information. Nevertheless, analyses associated with Seambiotic and

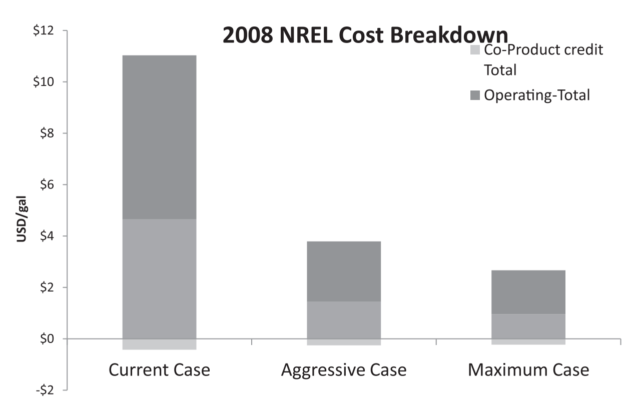

Fig. 2. Cost breakdown for NREL 2008 model.

NBT Ltd. of Israel were broken down into subcategories. Table 4a and b list the categories and cost estimates used for the Israel case studies. The large cost difference between NBT Ltd. operation for beta-carotene production and Seambiotic for algal lipid production were attributed to Seambiotic's co-location with a power plant, the use of flue gas for CO_2 demands, and plant cooling seawater for cultivation. Seambiotic extrapolated the data from its 1000 m^2 pilot plant cultivation unit to a large-scale footprint.

Similarly, a future cost reduction by one order of magnitude was also projected by Solix, based on the implementation of improved system integration and control for lower energy costs and technical advances in harvesting, dewatering, and extraction. Fig. 3 shows the breakdown of production by category. Capital cost for facility construction is greatly reduced between the Solix 2008 estimate and its later phase I or phase II estimates. Such drastic reductions in facility costs are due to a cost reduction in harvesting, dewatering, and extraction steps.

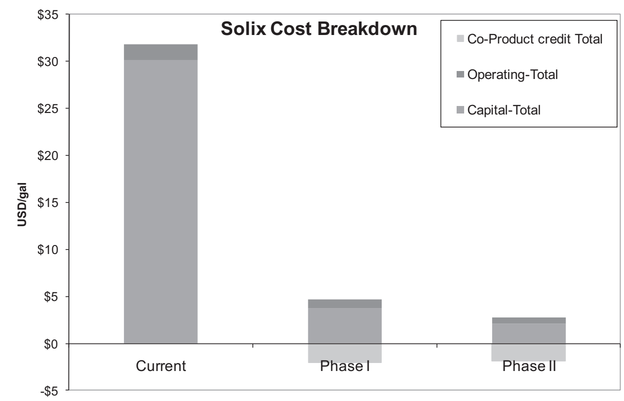

Fig. 3. Cost comparison of solix production estimated in 2008.

2.5. Academia

The 2008 study also included participations from academia. New Mexico is situated in the Southwestern region of the U.S. characterized by clear and arid climate conditions with some of the highest solar resource available in the country. Meghan Starbuck at NMSU (New Mexico State University) initially assessed the cost of large-scale open pond operation based on an existing 0.25 acre open pond operation in southeastern New Mexico. This work was carried out as part of statewide effort to map out innovative energy technologies in New Mexico [27]. It is worth noting that Roswell, New Mexico was chosen as the site for the large-scale production facility used for the Aquatic Species Program. Dewatering and harvesting equipment are sized to process 12,500 gallons of open pond culture twice a week. In addition, water is added to make up the loss due to pond evaporation assuming 70 inches of water loss per year. Two growth scenarios at two different pond sizes were assessed for cost estimates. The base case assumed 35% extractable TAG oil and 35 gm m^{-2} day^{-1} biomass productivity and a high yield case assumed 60% TAG oil and 58 gm m^{-2} day^{-1} productivity. The extracted TAG oil cost ranged from \$38.72 $gallon^{-1}$ to \$13.90 $gallon^{-1}$ of TAG. Applying a scale-up factor of 0.90 for a 2000 hectare facility, the cost estimate dropped to \$25.22 $gallon^{-1}$ and \$9.65 $gallon^{-1}$ of TAG for the two productivity scenarios.

Tryg Lundquist at California Polytechnical University had estimated the cost of constructing an algae biofuel facility that is coupled to a large-scale wastewater treatment facility in southern California [28]. The wastewater treatment design included primary solid separation clarifier and secondary clarifier where algae cultivation takes place. Downstream steps included harvesting and extraction equipment that also recycled residual biomass for anaerobic digestion and power generation. The total investment for such a design based on 25% oil yield and 20 gm m^{-2} day^{-1} areal productivity was estimated to be \$39 million. On a per gallon TAG basis, the cost of cultivating algae and biocrude production was estimated to be \$16.78 $gallon^{-1}$.

Table 4
a) Difference in annual production cost between NBT Ltd. existing production of β-carotene from *Dunaliella* versus Seambiotics's algal biodiesel plant. b) Difference in initial capital investments between NBT Ltd. production of β-carotene from *Dunaliella* versus Seambiotics's algal biodiesel plant.

	NBT Ltd. Eilat	Seambiotic/IEC Plant
a)		
	2008 (US\$/yr)	Estimated 2008 (US\$/yr)
Microalgae	*Dunaliella*	*Nannochloropsis*
Product	*beta-carotene*	*biodiesel*
Manpower	500,000	120,000
Electricity	180,000	30,000
Fertilizers	36,000	36,000
Domestic Land Taxes	50,000	10,000
CO_2	150,000	5000
Sea Water	200,000	5000
Fresh Water	20,000	10,000
Other Supplies/Misc.	30,000	20,000
Total	1,166,000	236,000
Biomass production	70 tons	700 tons
(gm/m^2/day)	(2 g/m^2/day)	(20 g/m^2/day)
Cost/kg dry biomass	*\$17.00*	*\$0.34*
b)		
Product	*beta-carotene*	*biodiesel*
Land	0	0
Seawater pumping/piping	200,000	30,000
Centrifuge	2,000,000	200,000
Groundwork/lining	1,500,000	150,000
CO_2 containers	150,000	50,000
Spray Drier	450,000	unknown
Infrastructure	1,000,000	~200,000
Building	1,000,000	500,000
Other	300,000	300,000
Total	6,600,000	~1,430,000
Biomass production	70 tons	700 tons
(gm/m^2/day)	(2 g/m^2/day)	(20 g/m^2/day)
Cost/kg dry biomass	*\$94.00*	*\$2.00*

Reprint from Ben-Amotz, 2008. Algae Biomass Summit.

2.6. Literature

Three of the twelve sources for cost comparison were derived from published reports and journals that date as far back as 1988. One of the sources was based on Benemann and Oswalds' 1996 report renormalized to 2008 cost basis [1]. The estimates for open pond operations, compared to other sources used in this study, were surprisingly low after adjustment to 2008 cost basis. The cost difference between low and high yield was \$0.50 $gallon^{-1}$. Benemann and Oswalds' estimates represented the lowest in the range of production cost for this comparison study.

Tapie and Bernard reviewed process economics of various published research and estimated the production cost for algal biomass using two types of closed tubular bioreactor designs [29]. Their analysis focused on algal biomass production and harvesting, and no cost was included for extraction of bio-oil from the biomass. For this comparison, two assumptions were made to this data. The first assumption was that the cost of supplying supplemental CO_2 to enhance algae biomass production would be averaged between the two CO_2 supply options listed in the paper. Secondly, an extractable TAG oil content of 35% was assigned to the biomass in order to derive a per gallon TAG cost estimate. After correcting for inflation and currency exchange, this configuration resulted in a cost between \$40.6 gallon^{-1} and \$43.1 gallon^{-1} of TAG production.

This cost comparison also enlisted the process economics conducted by Molina-Grima [30]. This report, like that of NBT Ltd., was not targeted for biodiesel. Instead, the economics were carried out for the production of EPA (eicosapentaenoic acid) from the marine diatom *Phaeodactylum tricornutum*. The technoeconomics were based on an annual production of 430 kg of EPA, or total production of 26.2 dry tons of algae biomass per year based on 2.5% by weight EPA content and various process efficiencies (96% purity and 70% recovery rate). For a hypothetical application of this algal system for TAG production, a 10% oil content was reported. Even with total recovery of all lipids in this system, the cost of such operation amounted to \$1127 gallon^{-1} TAG, the highest in this comparison.

2.7. Observations

In all analyses, the costs, on a per gallon TAG basis, were still prohibitively high relative to the cost of fossil-fuel production, thus leading to the conclusion that there would be serious challenges to achieving economic feasibility for algal biofuels, even in cases of extremely optimistic productivity assumptions. The models discussed also did not account for the costs for transport of TAGs or conversion to biofuel. It is, however, difficult to make conclusions on critical path elements for economic process improvements when so many assumptions varied from model to model. Therefore, to compare cost information more effectively, a more consistent set of assumptions and definitions are needed. Through this comparison, the analysis can be improved in areas of units of measure and cost categorization.

For example, units of measure adopted in each of the twelve sources were disparate enough to require great care to harmonize volumetric or mass basis for comparative cost information. While some analyses may indicate that the estimated cost of biomass production is very attractive, the conversion to a cost based on TAG production may provide a different outlook. Hence, the extractable oil content represents one of the most important parameters in studying economic feasibility of algal biofuel production. The measure of algal TAGs also remains a challenge in research laboratories and many of the standard methods (especially extraction and gravimetric analysis) give rise to materials of uncertain purity and therefore even experimentally generated productivity numbers must be considered with caution. It is much easier to assume a pure TAG product stream for modeling considerations than it is to actually produce one.

The cost categories defined in each of the sources were more variable than anticipated initially. For example, indirect costs were allocated differently between the NREL and Sandia studies. As the algal biodiesel industry considers novel processes that require new categories, more work is needed to organize the cost information with more consistency.

It is with these criticisms in mind that we set out to review our cost models (employing technological advances whenever possible) and to use uniform inputs so that the range of outputs would reflect differences in the models themselves rather than differences in assumptions. In this way we hope to better reflect the current state of economic potential for the production of algal TAGs. That exercise is summarized in the next section.

3. Development of a common framework for comparative cost analysis

As demonstrated above, cost categories, when applied subjectively without agreed-upon definitions, can result in large uncertainties in a comparative study. Without a consistent framework, it is difficult to identify measures to reduce production cost or draw constructive conclusions. A common framework consisting of uniform metrics, assumptions and cost categories is proposed and applied theoretically by a subset of the original sources in the 2008 cost assessment for the Technology Roadmap. Namely, Sandia, NREL, NMSU, and Seambiotic have revised their cost assessments of TAG production based on an agreed-upon framework.

3.1. Assumptions

Table 5 lists the metrics and assumptions that have been established for a harmonized cost comparison. Rather than the disparate yields used in the 2008 study, the assumptions here are applied uniformly to eliminate variability in oil yield and in areal productivity. We also focus solely on open pond operation targeting algal oil production, further avoiding the potential misalignment in cost comparisons.

In open pond operation, scaling up to large volume operation can vary by geo-location and by technology. Hence, the scale-up factor is not harmonized and is left to each individual author to unitize their own pond module and define their production scale.

The financial terms are defined and applied uniformly to each source across the board to further eliminate cost uncertainties. In this modified study, these include plant life, depreciation period, rate of return. Financing a large-scale production requires parameters and accounting measures that span a broader set than what is stated in Table 5, [31]. This study is based on engineering economics rather than a more stringent accounting estimate for commercial construction and operation, thus should be viewed as a “feasibility” level analysis.

3.2. Scenarios

Other than described in Section 2, the main features of each of the four sources are listed in Table 6. NREL, SNL, NMSU, and Seambiotic all have different target production levels, water and power management strategies, and co-products. These are attributes that reflect the diversity of commercial strategies for algae cultivation for fuel production. While the variation in this new study is not as expansive as the projects now funded by DOE for construction of algae-based biorefineries (which include open pond phototrophic algae cultivation, heterotrophic algae cultivation, and direct algae to ethanol processes), it focuses on using a common cost framework using a representative set of sources. Sandia, NMSU, and NREL operations pertain to open pond cultivation and on-site harvesting and extraction. NREL and Sandia models additionally include an anaerobic digester in its operation that processes lipid-extracted biomass residue into a power co-

Table 5
Assumptions defined in the new comparison.

Assumptions	Unit	Value
Oil content	%	25%
Areal yield	gm/m^2/day	20
Pond cell density	g/L	0.7
% return	%	10
Operating factor	days/year	330
Plant life	years	15
Depreciation	years	10
Electricity cost	\$/kWh	\$0.08
Natural gas cost	\$/MM Btu	\$8
Price Index	year	2008
GDP deflator	year	2008
Tax rate	%	35%
TAG end use		transportation fuel

Table 6
Operation scenarios of Sandia, NREL, NMSU, and Seambiotic.

Operations	NREL	SNL	NMSU	Seambiotic
Target Fuel Production	10 MGY	50 MGY	50 MGY	10 ha
CO_2 source	CO_2 gas	Flue Gas	Air	Flue Gas
Water Make Up	Groundwater	Unspecified	Groundwater	Ocean
Water Management	Recycle	Recycle	Recycle	Recycle
Harvest	Settling/Flocculation/ Centrifuge	Membrane	Proprietary	Proprietary
Anaerobic Digester	Yes	Yes	No	No
Power Management	Electricity	Electricity & NG	Electricity	Electricity
Annual Operating Days	330	330	330	330
Co-products	Feedstock for anaerobic digester	Feedstock for anaerobic digester	Animal feed	Nutraceutical

product and nutrient-rich effluent for recycle. Ten hectares is the current industrial scale footprint for algae production. In addition, Seambiotic utilizes flue gas from a coal-fired power plant and turbine cooling seawater to offset the cost of carbon dioxide and water for algae cultivation.

3.3. Cost categories

Table 7 lists the cost categories defined in the modified study. Most of these are drawn from the 2008 cost comparison. These categories are defined and applied uniformly by Sandia, NREL, NMSU, and Seambiotic.

The direct capital cost includes costs associated with land, facilities, and equipment. The indirect capital cost includes buildings/offices, permitting, field expense, and other contingencies. Operating cost includes charges associated with materials, utilities, water, disposal, labor, debt service, and maintenance.

The last broad cost category is the contribution of co-products. In 2008, all but two sources had considered the values of co-products besides biofuel. This has been called out frequently as the critical path to economic production of algal biofuels, and yet the ideal co-product (in terms of market size, selling price, and consistency with overall process constraints) has yet to be clearly identified. In the present analysis, the co-product is not constrained to be the same across the four studies, as each study is not necessarily optimized with the same co-production pathway.

Table 7
Cost categories defined in the comparative study based on common framework.

Capital-Direct	*Operating Cost*
Land	Electricity
Ponds	Natural Gas
Mixing (paddle wheels)	Petroleum
Plumbing	Flue gas
CO_2 delivery	Nutrients (N,P,Fe)
Decanter	CO2 (pure or flue gas)
Harvesting	Flocculant
Centrifuge	Waste Disposal
Extraction	Water Make-up
Drying	Labor and Overhead
Water infrastructure	Laboratory
Pumps	Maintenance
Anaerobic digestion	Chemicals
Storage	Administrative/marketing
Instrumentation	Transportation
Analytical	Tax and insurance
Buildings/offices	OTHER
OTHER	
Capital-Indirect	*Co-products (Credit)*
Buildings/offices	Power generation
Electrical supply/distribution	Biomass
Permit	Nutraceuticals
Field expense	Animal feed
Working capital	OTHER
Contingency	
OTHER	
Cost Definitions	*Unit*
Cost/biomass	USD/kg
Cost/TAG	USD/gal or USD/liter

4. Results and discussion

Table 8 lists the cost summary from NREL, Sandia, NMSU, and Seambiotic based on the new baseline assumptions described in Table 5. Table 9 summarizes the cost per gallon before and after the cost harmonization. Compared to the 2008 study, the range of cost per gallon of TAG is much tighter. On a per volume basis, NREL, Sandia, and Seambiotic are all within one dollar of each other while the NMSU study is approximately \$2 higher. The variability is significantly lower than that obtained by the 2008 exercise, even if only a subset of previously reported sources are considered. Specific notes for each study are included below.

4.1. NREL analysis

NREL utilizes process engineering software AspenPlus to conduct mass and energy balances to estimate material throughput. The NREL analysis is based on 10 Mgal yr^{-1} TAG production. The basic process for the NREL model is as follows: CO_2 is purified from a nearby flue gas source using the same implicit cost assumptions as described in the Benemann and Oswald report [3]. The purified CO_2 is delivered to the open ponds via sumps and spargers configured to limit outgassing. The algae grow according to the parameters defined in Table 5, using stoichiometric amounts of CO_2 and N/P fertilizer nutrients, and are harvested at a rate equal to the growth rate (steady-state operation). Harvesting is accomplished in three stages: first by natural settling, followed by flocculation and dissolved air floatation, and finally by centrifugation. This series of steps concentrates the algae biomass from 0.7 gm L^{-1} to 200 gm L^{-1}.

The concentrated material is sent to extraction, which consists of mechanical cell disruption using high-pressure homogenizers followed by solvent extraction at elevated temperature [32]. The resulting mixture of water and spent biomass is split from the TAG/solvent phase using disk stack centrifuges. The solvent is stripped out from the TAG and recycled, leaving a purified algal oil product at 99.5% purity. Extraction efficiency was assumed at 90% (i.e., 90% of the produced oil is recovered from the algal cells), combined with 95% oil recovery (i.e., 5% of the extracted oil is subsequently lost due to entrainment in the water phase). The water phase and spent biomass are sent to anaerobic digestion to produce biogas burned in a turbine for electrical power generation, and the resulting flue

Table 8
Results of Cost Comparison applying the Common Cost Framework.

	NREL	SNL	NMSU	Seambiotic
Target Fuel Production (gal yr^{-1})	10 million	50 million	50 million	47,380
Capital Direct	$227 million	$873.4 million	$426.7 million	$0.6 million
Capital Indirect	$216 million	$458.6 million	$249.2 million	$0.8 million
Operating Cost	$43.2 million	$304.3 million	$383.5 million	$0.2 million
Co-product (Credit)	($5 million)	($16 million)	($28.5 million)	
Total cost/biomass (USD kg^{-1})	$0.79	$0.80	$0.96	$0.79
Total cost/TAG (USD gal^{-1})	$10.87	$11.10	$13.32	$11.02
Total cost/TAG (USD liter^{-1})	$2.87	$2.93	$3.51	$2.91

gas is recycled to the growth stage along with the digester effluent material to mitigate fresh CO_2 and nutrient demands. The produced power is sold as a co-product, after subtracting the various power demands required throughout the facility.

After modeling the process in AspenPlus, the associated capital and operating costs were calculated using a combination of factors from literature, vendor quotes, and the Benemann and Oswald report [3,33,34]. Additional cost elements such as labor, indirect capital, and nutrient costs were calculated based on the same approach utilized in NREL's biochemical and thermochemical ethanol models [35,36], with contingencies increased to 25% to account for the inherent uncertainties associated with the state of algae technology. The resulting production cost required to achieve a 10% rate of return was found to be $10.87 gallon^{-1} TAG. This corresponds relatively well with the 2008 NREL "current case" result shown in Fig. 1, even though the approach and methodology was different between the two NREL studies. See Table 8 for a breakdown of the cost results.

4.2. Sandia analysis

Sandia estimated the production costs of a large-scale production facility with an annual capacity of 50 million gallons. As described earlier, Sandia's 2008 estimate originated from Benemann and Oswalds' 1996 cost estimate adjusted for inflation and expanded to include more cost categories as described in Section 2.2. The process basis per the Benemann study is described in Sections 2.2 and 2.3, from which several modifications were made as follows.

For this study, Sandia restricted the categories to those defined in Table 7. In order to conform to the definitions, some of the items that were considered as direct costs were shifted into indirect costs, such as electrical, field expense, and working capital. Overall, per gallon TAG cost estimate is lower in this study than in 2008. The cost differential between the 2008 and 2010 estimates was mostly attributed to fewer cost categories for this study. In Sandia's 2008 estimate, categories were added to the ones suggested in Benemann and Oswalds' 1996 report. Each additional cost was estimated as a percentage of purchased equipment (PE). These additional expenses amounted to a 279% increase relative to nominal purchased equipment cost. Examples of the additional burden were service facilities (45% of PE), engineering and supervision (32% of PE), construction expenses (34% of PE), and contractor fees (19% of PE). These were dropped and realigned in the current study such as field expense (15% of PE), and buildings/offices (29% of PE). The ancillary fix-capital services for the current study amounted to 110% of PE, which is substantially less than those considered in 2008. The cost factor adjustments resulted in a production cost of $11.10 gallon^{-1} TAG (see Table 8).

Table 9
Results before and after Cost Harmonization.

	NREL	SNL	NMSU	Seambiotic
Before (USD gal^{-1})	$10.61	$15.67	$25.22	$24.89
After (USD gal^{-1})	$10.87	$11.10	$13.32	$11.02
Percentage change (%)	+2.45%	−29.16%	−27.18%	−55.73%

4.3. NMSU Analysis

NMSU estimated the production costs of a large-scale production facility with an annual capacity of 50 million gallons, unlike its 2008 estimate based on a 2000 open pond hectare facility. The current model uses a wet solvent continuous batch extraction system with a flocculent/centrifuge process for harvesting from the ponds. The open pond configuration is based on ponds that are approximately 0.5 acre in surface area, using two paddles per pond, lined with plastic, and air sparging for mixing and adding ambient CO_2 to the culture. Nutrient costs are limited due to recycling of culture from the harvest and extraction processes. Notably, this model excludes costs for inoculation systems and assumes some simplistic infrastructure for the ponds and facility. There is also no attempt to predict actual harvest quantities adjusted for 'crash' events and other impacts to production. This model is a first generation view of a standard system scaled up to 50 million gallons, and it is likely actual facility costs would be larger than reported here. Once the cost categories are renormalized according to the standard list, plus updated cost estimates based on pilot data, the 2010 assessment results in lower cost on a per volume basis. The resulting baseline production cost was found to be $13.32 gallon^{-1} TAG.

4.4. Seambiotic analysis

Accordingly, Seambiotic TAG production cost and capital investment are both re-assessed based on the assumptions given in Table 5. As noted in Table 6, Seambiotic is using a fixed, planned footprint for its large-scale production. Hence, the volumetric throughput is different from the hypothetical scenarios used by NREL, Sandia, and NMSU. Since the cost categories are similar under the new framework, total capital or operating costs shown in Table 6 are no different from those presented in Table 4. On the other hand, the loan period and interest assumptions in the new analysis establish a new annualized fixed charge for the 10-hectare facility. This illustrates the importance of setting consistent financial terms when comparing different scenarios. Due to this realignment, Seambiotic cost per weight of biomass and per gallon of TAG is very similar to the other three estimates, at a baseline of $11.02 gallon^{-1}.

4.5. Sensitivity analysis

In addition to the base case evaluated above, two alternative algae growth and oil yield scenarios were examined to understand

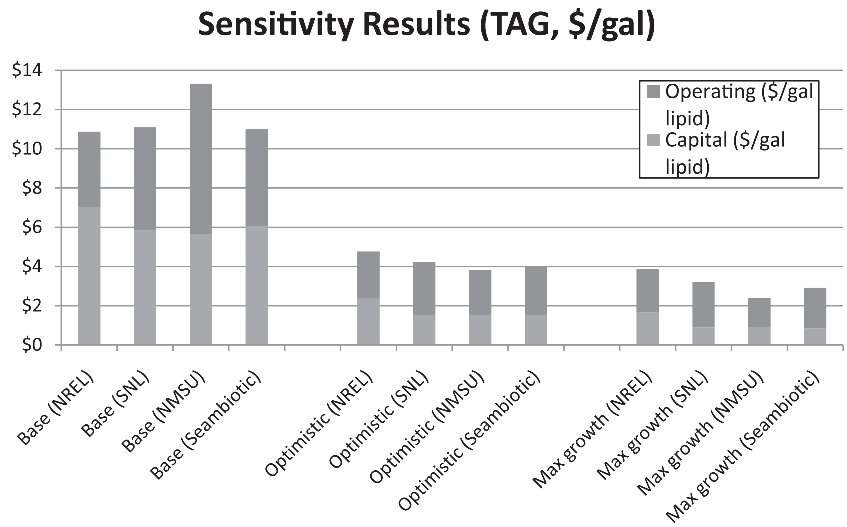

Fig. 4. Baseline and sensitivity results for all studies.

how potential future strain improvements could impact the economics. The results from this sensitivity analysis are shown in Fig. 4. Each alternative case study is based on future improvements in daily areal productivity (averaged over a year) and in oil yield with a constant algae concentration in the pond. These parameters are presented in Table 10, along with the original baseline scenario. Areal or volumetric productivity is correlated to algae concentration in the pond if the footprint of the pond is known. Appendix-A describes the relationships amongst common productivity parameters.

The parameters for the two alternative cases were based on the same NREL congressional report discussed previously [20], where the "optimistic" case represents feasible longer-term research advancements and the "max growth" case is based on the theoretical maximum growth rate and lipid content that could possibly be achieved based on photosynthetic efficiency limitations. The sensitivity results presented below are essentially an "update" to the 2008 costs shown in Fig. 2. It is important to note that while the NREL, SNL, and NMSU studies all adjusted their models to accommodate the alternative scenarios; the Seambiotic costs for the alternative cases were projected by adjusting expected operating cost differences associated with producing more biomass and oil through a fixed-scale facility.

The results presented in Fig. 4 show that there is room for substantial improvement to the algal oil production cost, if a strain can be identified or engineered to sustain a high growth rate while also maintaining a high lipid content. All four analyses show this dramatic effect that improving the biological aspects of the organism can have on the overall economics. The improvement from baseline to "optimistic" productivity and lipid yield is substantially larger than the subsequent cost improvement from the "optimistic" to the "max growth" case. This is advantageous as the "optimistic" growth parameters are practically achievable,

Table 10
parameters used in sensitivity analysis.

	Base case	Optimistic case	Max growth case
Algae productivity [gm m^{-2} day^{-1}]	20	40	60
Lipid yield [dry wt.%]	25%	50%	60%
Cell density [gm L^{-1}]	0.7	0.7	0.7

while the "max growth" parameters would be much more difficult to achieve as they are associated with near-maximum theoretical limitations.

Additionally, the NREL, SNL, and Seambiotic studies are in agreement that the capital cost is higher than operating costs; thus, reductions in capital cost are responsible for the majority of overall cost improvements for the alternative scenarios, due to lower equipment throughputs and sizes. NMSU shows a slightly lower capital cost allocation but a substantially larger operating cost improvement with improved growth scenarios. To put these results into a larger context, it is important to note that "max" in this case merely means the maximum algae growth and lipid content as applied to *these specific* configurations and associated assumptions. Thus it does not imply that these are the absolute lowest costs that can be achieved, as evidenced by the large uncertainties highlighted throughout this report.

Based on these four case studies, the cost of algal oil production does not appear to exhibit a strong correlation with production scale. This is does not imply that algal oil production is *independent* of production scale, but that growth rate and lipid content are the primary pathways to capturing economies of scale. Due to the dilute nature of algal cultivation, it is difficult to capture economies of scale simply by scaling up cultivation capacity. As cultivation increases so does the need for capital, which prevents the dilution of capital cost, i.e., the capturing of economies of scale.

5. Conclusions

Algae-based biofuel has gained wide interests as a promising option for replacing fossil-based transportation fuel. Estimating the investment for large-scale facilities combines small-scale technical data for algae growth with traditional engineering economics. In 2008, a preliminary audit of twelve sources for cost estimates reflected a 50-fold range of cost for producing a gallon of TAG. The range was wider when cost literature targeted for nutraceuticals was included. As we have shown, this disparity arose mainly from differences in algae growth assumptions, different cultivation systems, and baseline economic investment terms.

A consistent set of growth assumptions and cost basis values was established in this work to re-assess the economic variability associated with producing algal oil from open ponds. Based on the updated harmonization work performed by NREL, SNL, NMSU, and Seambiotic, the variability is considerably reduced with a mean value of \$11.57 gallon^{-1} (or \$3.05 L^{-1}) and a standard deviation of \$1.17 gallon^{-1} (or \$0.31L^{-1}). This cost is envisioned to be associated with a "near-term" scenario for algal growth, with potential for significant improvement in the future if growth rate and lipid content can be improved.

The sensitivity study shows that doubling the algae productivity and lipid yield can improve cost structure by more than 50%. Thus, at a baseline of around \$11.57 gallon^{-1} TAG which is clearly not competitive with petroleum-based transportation fuels, the near-term economic viability of algal biofuel production will likely be dependent on combined yield and process improvements.

Both the NREL and SNL models assumed digestion of the spent biomass and subsequent co-production of power while NMSU and Seambiotic have other uses for their biomass residues. Although an attractive option from a sustainability standpoint, the digestion pathway only marginally improved economics. The costs across the four studies show no discernible sensitivity to production volume. The high volume handling for algae cultivation may attribute to the limited scalability, though finer resolution studies and process data are required to ascertain the scale-up factor for large-scale deployment.

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Appendix A

Definitions of algal biofuel production target, productivity, and biomass concentration for open pond cost estimation are interdependent. We first define the volume of open pond as area A times depth h. Areal and volumetric productivities are related by the factor h.

$$V_{\text{pond}} = A_{\text{pond}} h_{\text{pond}} \tag{A.1}$$

$$AP_{\text{day}} = h_{\text{pond}} \left(VP_{\text{day}} \right) \tag{A.2}$$

The annual biomass target BT has to be greater or equal to the production target PT that each facility is operating. The target can also be written in terms of the volumetric or areal productivity if volume or area of the facility is already known. Another definition for the annual biomass target is obtainable by biomass concentration in the pond and the targeted harvesting rate.

$$BT_{\text{yr}} \geq \frac{(PT_{\text{yr}})(\rho_{\text{oil}})}{(\%_{\text{oil}})\left(\eta_{\text{process}}\right)} \tag{A.3}$$

$$BT_{\text{yr}} = \left(VP_{\text{day}}\right)\left(V_{\text{pond}}\right)\left(N_{\text{days}}\right) = \left(AP_{\text{day}}\right)\left(A_{\text{pond}}\right)\left(N_{\text{days}}\right) \tag{A.4}$$

$$BT_{\text{yr}} = \left(\xi_{\text{pond}}\right)(V_{\text{harvest}})(N_{\text{yr}})(f_{\text{unit}}) \tag{A.5}$$

where, PT_{yr} = yearly TAG production target [gal/yr]; BT_{yr} = yearly biomass production [gm/yr]; VP_{day} = daily biomass volumetric productivity [gm/m^3/day]; AP_{day} = daily biomass areal productivity [gm/m^2/day]; η_{Process} = efficiency of the entire cell-to-TAG conversion process; ξ_{pond} = algae biomass concentration in the pond [gm/liter], ρ_{oil} = TAG density [gm/gal], $\%_{\text{oil}}$ = oil content = mass TAG/mass biomass [%], h_{pond} = pond depth [m], A_{pond} = pond area [m^2], V_{pond} = pond volume [m^3], V_{harvest} = harvest volume [m^3/harvest], N_{yr} = # harvests per year [1/yr], N_{days} = days of harvestable growth per year [day/yr], f_{unit} = unit conversion [1000 L/m^3]

Eq. (A.3) is used to set a requirement for biomass production when an annual production target is established. Eq. (A.4) or Eq. (A.5) is used to set a requirement for pond footprint given algae productivity on either volumetric or areal basis. The footprint leads to land and basic pond construction cost estimation. Eq. (A.5) is related meeting the target as well, but it is used for estimating harvesting volumes. Such formulation is important for estimating operating throughput of the scale-up operation that leads to cost information on operating equipment. These conventions are used interchangeably in different cost estimation publications.

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