Techno-Economic Analysis for the Production of Algal Biomass via Closed Photobioreactors: Future Cost Potential Evaluated Across a Range of Cultivation System Designs

Jennifer Clippinger and Ryan Davis
National Renewable Energy Laboratory

Techno-Economic Analysis for the Production of Algal Biomass via Closed Photobioreactors: Future Cost Potential Evaluated Across a Range of Cultivation System Designs

Jennifer Clippinger and Ryan Davis
National Renewable Energy Laboratory

Acknowledgements

Nomenclature

AFDW	ash-free dry weight
CIP	clean-in-place
CO_2	carbon dioxide
DCFROR	discounted cash flow rate of return
ha	hectare
IRR	internal rate of return
LDPE	low-density polyethylene
MBSP	minimum biomass selling price
MM	million
NREL	National Renewable Energy Laboratory
PBR	photobioreactor
PNNL	Pacific Northwest National Laboratory
RE $\approx$	Reynolds number
TEA	techno-economic analysis
VVM	volume of gas per minute per reactor volume

Executive Summary

In this assessment, we have evaluated future economic potential for algae biomass production across four photobioreactor (PBR) designs, as quantified by minimum biomass selling price (MBSP). We utilized techno-economic analysis (TEA) modeling to quantify PBR algae farm economics reflective of "best-case" cultivation performance that may plausibly be achievable in the future through research and development, and implementation of the technology advancements in an "n^{th}-plant" scenario, as may be required in the context of low-cost commodity fuels production. In the process, algal biomass is produced in each of the four cultivation options, including horizontal tubes (large diameter), vertical helical tubes (small diameter), and two vertical bag/panel designs (termed in this study as "GWP-II flat panels" and "Leidos hanging bags" attributed to two discrete system designs furnished to the National Renewable Energy Laboratory [NREL]). The asserted target cultivation productivity for each PBR design was set based on available literature data presenting PBR and open pond cultivation performance on a directly comparable basis, and then extrapolating out to a future value by scaling from prior-established open pond research targets of 25 g/m^2/day. Resulting PBR best-case future productivity projections on an areal basis were estimated to range from 25 to 52.5 g/m^2/day (cultivation area). The analysis includes considerations for CO_2, nutrient, and inoculum supply, storage and CO_2/water piping, and dewatering of harvested biomass to 20 wt% solids.

TEA models were run for each PBR case; for reference, a comparison was also included based on NREL's previously established TEA targets for open pond cultivation by adjusting each farm size to achieve the same annual biomass output rate as the open pond basis. Resulting MBSP projections were estimated at $639/ton ash-free dry weight (AFDW) for the Leidos hanging bag system (reflecting a vertical bag design with design/cost inputs furnished by Leidos), $708/ton for horizontal tubes (set as large volume reactors made of flexible plastic), $1,737/ton for helical tubes (based on a glass tubular design configured in a fence-type array), and $1,793/ton for the GWP-II design (vertical flexible plastic flat-panel system) with all costs in 2014$. For reference, NREL's previous open pond algae farm design case established an MBSP *target* of $494/ton AFDW. These highlight that PBR economics can vary widely, and additional analysis is required to understand the underlying reasons for such disparities. To help in this understanding and highlight critical cost drivers, a sensitivity analysis was run for key parameters across all design scenarios, with some of the larger drivers identified as material of construction for helical tubes (glass versus plastic), plastic lifetime for the flexible plastic PBR designs, and the necessity for external cooling of the system.

While none of the PBR cases were seen to achieve biomass cost projections that match open pond research goals, a sensitivity case on the open pond basis found that if open pond cultivation only operated productively for 230 days per year (versus the assumed target at 330 days/year for all scenarios) due to more frequent contamination events than may occur in PBRs, the open pond MBSP would increase to equal the lowest-cost PBR case. Like ponds, MBSPs for PBRs follow an exponential cost curve as a function of productivity, with MBSP reducing more gradually as productivity increases. Recognizing the above findings for *plausible future* techno-economic potential, it is also important to acknowledge that PBR systems offer other benefits over current open pond limitations, including less contamination, lower water, nutrient and CO_2 retention losses, and better control over compositional quality (key for higher-value product applications); these can translate to favorable economics through the overall chain for end-use products.

Table of Contents

Introduction

To promote the production of liquid biofuels from renewable feedstocks including algae biomass, the U.S. Department of Energy's Bioenergy Technologies Office sponsors scientific research related to algae cultivation and conversion into fuels. The National Renewable Energy Laboratory (NREL) supports the Department of Energy's goals with an algae platform focused on various research avenues including: improving algae biological characteristics (e.g., algae productivities, strain robustness, and composition); understanding the current state of technology in the research space; studying dewatering technologies; developing algae biomass conversion technologies; and investigating the economics for the current and target cultivation and conversion technologies. Besides understanding a base case for the economics of algae biomass production, techno-economic analysis (TEA) is an advantaged tool that can guide research by understanding the largest economic drivers from which research advances would benefit.

In 2016, NREL developed a design case model along with a full report documenting the process and cost targets for open pond algae growth, harvesting, and dewatering [1]. This "algae farm" design case solicited four independent cost sources to provide a more comprehensive survey of cultivation inputs and costs. Notably, it was found that among the different pond sizes considered (2-acre, 10-acre, and 50-acre) there was reasonable agreement between the sources on cultivation system capital costs. The scope of the design case was to determine the specific algae feedstock parameters and targets needed to achieve a biomass cost that could support future economical algal fuel production. Of note, the design case assumed a target productivity of 25 g/m^2/day for a large-scale commercial system of 5,000 cultivation acres ("wetted acres") [1]. This resulted in a minimum biomass selling price (MBSP) of $494/ton (ash-free dry weight [AFDW] basis) (2014$) for individual ponds sized at 10 acres [1]. In comparison, state-of-technology cultivation performance in opens ponds has been demonstrated at 8.5 g/m^2/day resulting in a MBSP of $1,227/ton AFDW (2014$) in 2015 (based on publicly available data) [2]. While the design report TEA considered several open pond designs in detail (e.g., raceway ponds driven by paddlewheel mixing, serpentine ponds, and gravity flow raceway ponds) the scope did not include closed photobioreactors (PBRs). In part, this was because at the time there was little credible public data available on commercial PBR cultivation systems and associated design/cost/process details. However, based on subsequent collaborations and discussions with experts in the PBR domain that have recently provided NREL with such details, this study serves to supplement the previous open pond design case by establishing similar TEA projections for plausible future MBSPs that may be possible through PBRs.

The open pond analysis considered three types of pond designs that were treated similarly in the cultivation and harvesting/dewatering models aside from unique mixing energies, footprint/piping layouts, and capital costs. In contrast, PBR design options are more highly varied. For example, one review of PBRs [3] describes over 30 designs, with more to have likely developed since the time of that work in 2012. Because there is such a diversification of designs, some PBRs will have advantages that others do not, making it difficult to outline the advantages and disadvantages of "all" PBRs without choosing a specific design. In general, PBRs have several advantages when compared to open ponds. For example, with the majority of PBRs designed as enclosed systems, there is less likelihood of a single monoculture algae strain to become contaminated with competing organisms [4]. This advantage can translate to: (1) a continuously running system or longer run times before cleaning and reseeding from a culture

crash, (2) the ability to choose a target strain that is less robust against competitors, but may have other advantages such as a more specific targeted composition, and (3) the capability to run the growth media in milder growth conditions (e.g., saline tolerance, temperature, and pH) without competitors. As a second example, some PBRs are vertically oriented (extending up from the ground) including: flat panels, hanging bags, tubular fences, helical systems, and bubble columns, to name a few [4]. These vertical PBRs can have higher solar irradiance absorption, light scattering effects, and shorter light paths compared to the two-dimensional plane for open ponds. More light absorption can translate to higher areal productivities in these PBRs. Additionally, some PBRs (e.g., helical systems) lend themselves well to cleaning and clean-in-place regimens that could allow for a pure production of algae for food or nutraceutical applications [3]. Some PBRs may possess better automation translating to less labor per ton of algal biomass grown [5]. Other benefits also include greater temperature control, reduced water evaporation losses, higher CO_2 utilization efficiency, and higher harvest densities with lower dewatering costs for specific PBR designs compared to ponds [4]. Further, PBRs may be able to more quickly implement nutrient depletion and compositional shifts within the culture [5].

Between individual PBRs, a number of design factors influence variances in achievable productivities. Accordingly, a literature review was conducted on three major classes of PBRs (horizontal, helical tubular, and flat panel) to compare productivity gains against open ponds. Figure 1 compiles this information based on both measured outdoor productivity data [6-10] as well as modeled productivity [8-14]. Each point in Figure 1 indicates the reported PBR areal productivity compared to that for open ponds, constrained only to studies that evaluated both PBRs and ponds in the same location and grown with the same algal strain at the same time. This better isolates the productivity differences to the design, orientation, and spacing of the PBR. Although it is recognized that different strains may perform differently from each other in PBRs or ponds, there were too few data points for a single strain in a single location to provide a comprehensive dataset. Thus, the data shown in Figure 1 include subsets of data for various algal strains (most commonly *Nannochloropsis* sp. and *Phaeodactylum tricornutum*) and locations.
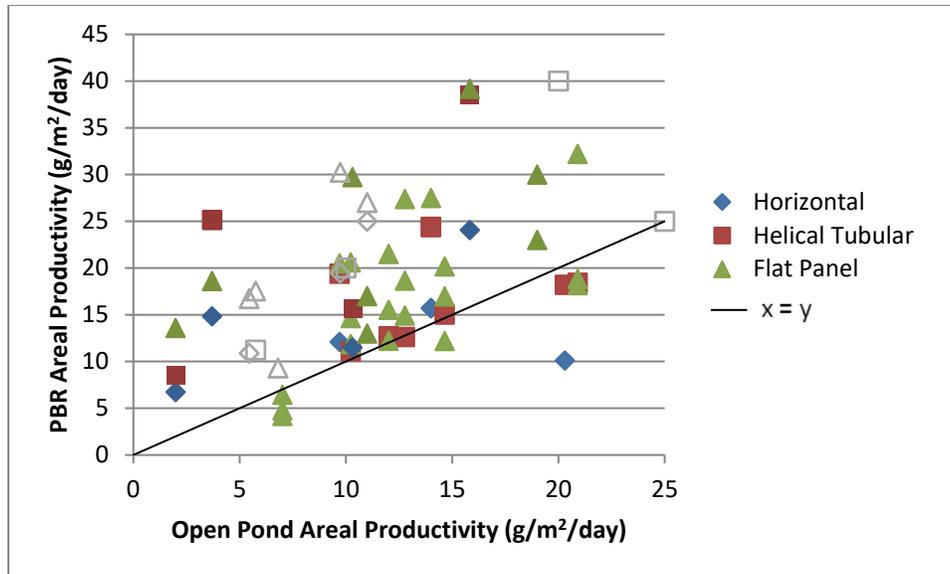
Figure 1. Areal productivity of horizontal, vertical (helical), and flat panel PBRs versus open ponds [6-13,15-20,14]. Grayscale/hollow points indicate additional values that have been considered in prior published studies but were deemed less credible; these points are shown for reference but were not included in calculations done with these data in this study.

Of the algae growth models reflected in Figure 1, the series of papers by San Pedro et al. [8-10] have been validated with two years of observational data for helical tubes, flat panels, and open ponds. Additionally, the papers by Slegers et al. [11-13] discuss a highly detailed growth model for four cultivation systems (horizontal tubular, helical tubular, flat panel, and raceway ponds) in three locations (Netherlands, France, and Algeria). Finally, a growth model by Pacific Northwest National Laboratory's (PNNL's) Biomass Assessment Tool team considers flat panel PBRs compared to open ponds situated in Kansas and Florida [14]. Although another growth model exists in the literature [21], it is not included in Figure 1 because the model has not been validated, assumes optimal growing temperatures at all times, and predicts a very high occupied areal productivity of 110 $g/m^2/day$ (other models predict 12–40 $g/m^2/day$ for similar PBR designs [10,13,14]). Actual operational data that compare PBRs to open ponds are rare and sometimes only include short time frames (<2 months) [6,7], or provide data without time/season specification [8-10]. The actual data that could be found are included in Figure 1. Figure 1 also includes grayscale points that represent values presented in other studies, but are based on less clear or verifiable assumptions [15-17,20,18,19], for example, assumed photosynthetic efficiencies or indirect extrapolations from other published data that did not constrain comparisons to the same location or time of year. Those points are included in Figure 1 for reference (and in many cases they correspond with the other selected data points) but were excluded from any calculations in this report. On a high level, it is clear from the figure that all three types of PBRs uniformly should be expected to achieve areal productivities *at least* as high as open ponds, even when they are not fully optimized (as is the case for some of the data).

Understanding that PBRs can produce comparable or (often) better productivities than open ponds elicits a question on what the associated cost tradeoffs would be for PBR cultivation designs in translating to overall biomass production costs. In this study, four individual PBR designs and costs are evaluated on a comparable basis to each other, along with the algae farm

3

open pond design case, to understand plausible *target* PBR parameters and economics for each PBR design considered, and how those might compare to the *target* open pond basis. The four PBRs considered in this study include:

1. Horizontal tubes – large diameter (0.38 m), high volume-to-cultivation-area ratio (0.24 m^3/m^2), and made of flexible plastic culture chambers that lay in a "trench" along the ground (design reflects details published by Beal et al. [2], based on additional consultation with the author of that study)

2. Helical tubes – an array of horizontal tubes stacked vertically in a helical fence-like arrangement around a support structure, made of glass with a 0.065 m diameter (design/cost inputs furnished by industry)

3. Green Wall Panel-II (GWP-II) – a "standing bag" flat panel type system with a short light path (0.045m), made from flexible plastic culture chambers (reflective of the pilot design operated by Fotosintetica & Microbiologica S.r.l. and published TEA [3], based on additional consultation with the developers of that system)

4. Leidos hanging bags – hanging bags made from flexible plastic, similar to Algenol's PBR system (all design/cost inputs furnished by Algenol via Leidos, an engineering subcontractor consulted by NREL).

It should be noted that while this work focused on future aspirational parameters, the relative amount of research efforts required to achieve those parameters is not considered. For example, compared to PBRs, open ponds may be further away from achieving culture robustness reflective of 330 days-per-year operating time. Similar to the challenges that were seen in the open pond design case, credible PBR cost data and design details are limited, and for many of the PBR designs considered, the systems have not reached full-scale commercialization. This adds uncertainty to the target economics. Finally, as noted in prior NREL TEA reports, we stress that this study serves to describe a limited number of feasible production and processing scenarios to transparently document the assumptions and details that went into their designs, based on either publicly available information or information otherwise furnished to NREL with the intent to be incorporated into a public analysis. This report is not meant to provide an exhaustive survey of all process alternatives or cost sensitivity analyses.

Modeling Inputs

The following sections summarize the four individual PBR designs and key assumptions in the TEAs alongside the baseline algae farm design case (using 10-acre open ponds). The limited availability for both cost and process parameter information confines the PBR options that can be evaluated. Similar to the approach taken for the algae farm design case, baseline cost estimates for the PBRs are derived from external design information developed by others either in published literature (Beal et al. [22] and Huntley et al. [23]) or furnished to NREL by engineering subcontractors (Leidos) and experts in the field (the company Fotosintetica & Microbiologica S.r.l. and other industry inputs). Examples of the four discrete PBR designs listed above as evaluated in this study are depicted in Figure 2. Although many other PBR systems exist, these four generally represent the designs most often discussed in literature [3].

Figure 2. Representative pictures for the four PBR designs considered [24-27]. (A) Horizontal tubular system based on [22,23], photo from Cellana [24]. (B) Helical tubular system (fence-type, TEA base case reflects glass tubes without indoor enclosure based on industry inputs), example image of tubular fence array, photo from AJCespedes/Shutterstock.com [26]. (C) Flat-panel standing bag system (known as the GWP-II system, quote provided by the University of Florence/Fotosintetica & Microbiologica S.r.l. who operates a 1-ha pilot plant), modified image from Tredici et al. 2016 [25]. (D) Flat-panel hanging bags (design/cost details from Leidos Engineering using primary cost information from Algenol), modified image from Algenol [27].

Figure 3 shows the overall process diagram for the modeled facilities. Briefly, algae inoculum, CO_2, water, and nutrients feed into the biomass production area, or PBRs. The systems are modeled under continuous steady-state conditions with biomass harvesting occurring at a fixed culture density. Harvested biomass then undergoes three stages of dewatering (settlers, membranes, and centrifugation) to reach 20 wt% solids. Finally, the process stores the dewatered algae paste in a short-term surge tank before sending it downstream to biomass conversion (outside the scope of this work). The process includes piping and power for clarified water

recycle and water make-up. Aside from the replacement of open ponds with PBRs for primary biomass production, all process areas and model framework are identical to the details described in NREL's open pond algae farm design report.
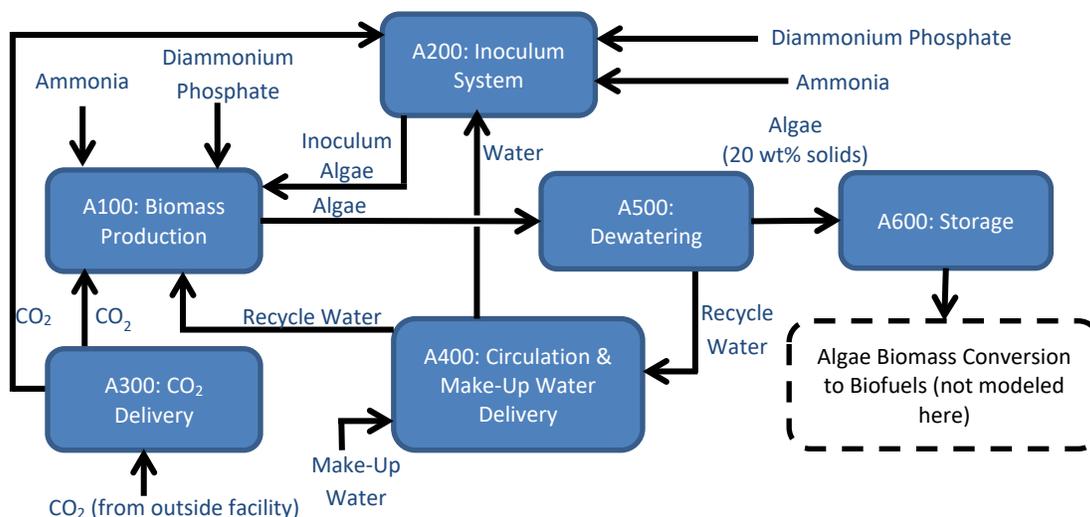

Figure 3. Simplified flow diagram of overall process

Facility Design and Layout

The open pond design case analyzed a hypothetical commercial-scale facility containing 5,000 cultivation acres that produce 190,000 dry tons per year of algae biomass (AFDW) [1]. As a general note, all biomass cost, yield, productivity, and concentration data are on an AFDW basis unless noted otherwise. In this analysis, we maintain the same biomass production output as the open pond design case at 190,000 tons per year (including inoculum) for all cases, such that downstream implications on biomass conversion to fuels would not be impacted by economy-of-scale differences in biomass throughputs. The fixed biomass production rate is achieved here by varying the facility size and layout across the different PBR design options (set in turn by the asserted productivity rates for each design). Figure 4 shows the facility layout for the open pond reference case, maintained similarly for the horizontal tubular PBR, helical tubular PBR, and the GWP-II systems, while the Leidos hanging bag system is based on a different facility layout (based in turn on the design and cost information furnished by Leidos) as shown in Figure 5.

In Figure 4, the cultivation systems are grouped into module units of 100 "occupied" acres. Previous designs referred to the occupied area as "wetted acres," but they are renamed here to also refer to the occupied area of the vertical PBR systems. Each module includes allowances for piping, in-ground settling ponds, and roads and fences, making the total area larger than 100 acres. Pumps and pipelines internal to the 100-acre modules are discussed later in each PBR-specific design. The site is assumed to have a 1% continuous slope, and the modules form a "terraced" layout with level sections. Table 1 includes an overview of the module dimensions (A and B), facility dimensions (C and D), and corresponding underground pipeline lengths required to service individual modules. Each facility footprint includes additional area for downstream

6

conversion and considers the price of the dewatered algae as a "transfer price" to the conversion facility. The dashed orange line in Figure 4 represents the facility layout for the open pond reference case and the horizontal tubular PBRs. Both require ~5,000 acres of cultivation area and use 50 modules for the design. The horizontal tubes are spaced 0.38 m apart and require much more total area (13,702 acres) for a full facility compared to the open ponds (7,176 acres). Reducing spacing between the horizontal tubes thus reduces the land requirement. The helical tubular system requires 3,000 acres of cultivation area (outlined in Figure 4 with a green dashed line). Finally, the red dashed line in Figure 4 outlines the facility boundary of the GWP-II PBR at 2,428 cultivation acres.
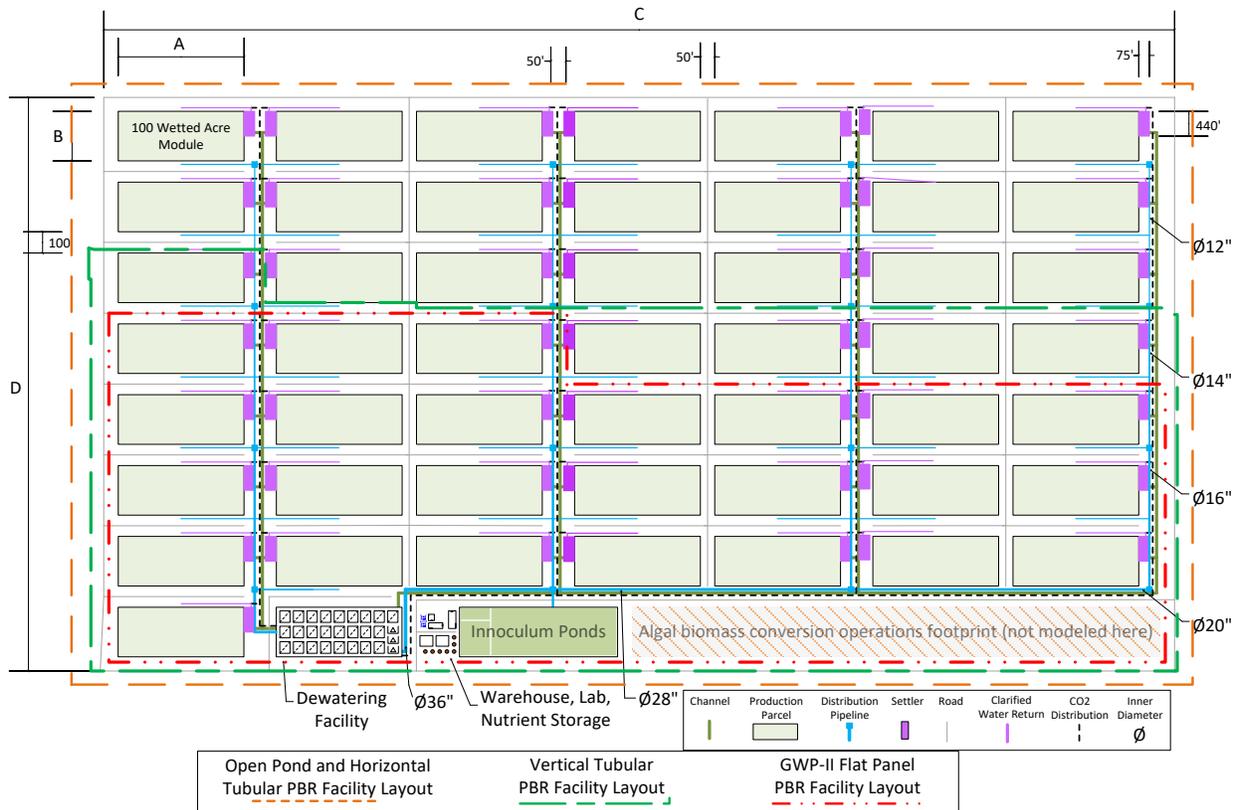
Figure 4. Facility layout denoting boundaries for open pond, horizontal tubular, helical tubular, and GWP-II flat panel PBR systems

Table 1. Effect of Cultivation System Choice on Facility/Module Dimensions and Pipeline Lengths

Pond or PBR Type	Open Ponds (10 acres)	Horizontal Tubular	Helical Tubular	GWP-II Flat Panel	Leidos Hanging Bag
Facility and module dimensions (see Figure 4 for "A–D" labels)					
A (ft)	4,588	5,597	4,588	4,588	NR
B (ft)	1,070	1,305	1,070	1,070	NR
C (ft)	33,041	40,107	33,041	33,041	NR
D (ft)	9,460	11,343	6,920	5,750	NR
Cultivation Area (acre)	5,000	5,148	3,000	2,428	2,428
Facility Size (acre)	7,176	10,444	4,807	4,139	3,168
Distribution pipeline requirements (ft)					
34" ID	5,883	7,128	5,883	5,883	NR
26" ID	9,426	11,445	9,426	9,426	NR
20" ID	9,991	12,127	9,991	9,991	NR
16" ID	9,360	11,243	9,360	9,360	NR
14" ID	9,360	11,243	9,360	7,020	NR
12" ID	9,360	11,243	1,170	0	NR

NR = not reported.

For each scenario shown in Figure 4, capital is included for CO_2 and water recirculation underground piping. Four vertical pipelines with decreasing diameters serve as the main trunk lines for water recirculation, and the required lengths for these pipelines are shown in Table 1. Gravity settling ponds (depicted as purple rectangles in Figure 4 and Figure 5) within the 100-acre modules concentrate the harvested biomass from the PBRs and open ponds to 10 g/L (AFDW). If harvest density is already above 10 g/L the settling ponds are removed and not included as a capital cost. After settling, the partially dewatered biomass travels via an aqueduct to the central dewatering facility. Circulation pumps to send recycle water, make-up water, and nutrients to the modules are included with power requirements calculated in Aspen Plus [28]. Support buildings and nutrient storage are also included in the facilities footprints.

Separate from the other cases, the Leidos hanging bag design has a different layout (Figure 5). Rather than assuming a continuous 1% slope, the land for this facility design is assumed level (note that we have demonstrated in the prior algae farm design case that the continuous slope assumption does not weigh heavily into overall economics or power demand relative to a flatter site, i.e., outside of areas that are graded for pond construction). Each module within the design constitutes 65 acres of occupied area for the PBRs instead of 100 acres. Like the previous cases, the modules include additional land allowances for roads, piping, and dewatering. There is no additional land for algae conversion, although this could still be nominally located directly outside of the indicated facility footprint. Gravity settling ponds are located between two modules, and because of the higher harvest density and smaller modules, one settling pond can handle harvests from two modules. The facility footprint is shown in Figure 5 and considers pipelines for recirculation water and CO_2, inoculum systems, valves and fittings, field equipment, weed control, and some electrical. In all, the facility has 2,428 acres of cultivation and 3,169 acres of total land area. Note that this is only an example of what the commercial facility could plausibly look like for this system.
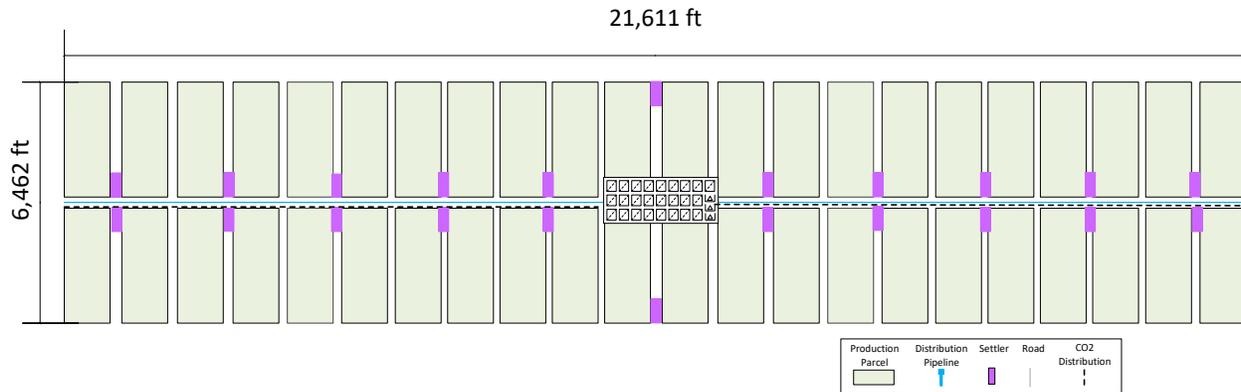
Figure 5. Facility layout for Leidos hanging bag case

Biomass Production Process Assumptions

Biomass productivity is a key parameter and cost driver for algal systems, with important influence from both the annual biomass productivity (g/m^2/day) and the seasonal variability (the shape of the productivity curve and resulting peak and minimum points). Not all PBRs are able to achieve the same productivity. In fact, productivity can vary for the same PBR by changing spacing, directional orientation, and culture conditions such as pH, temperature, aeration rates, and culture velocity. Additionally, unlike open ponds that are constrained to a two-dimensional light input, vertically oriented PBRs benefit from light scattering, partial shading, and three-dimensional light absorption over shorter light path lengths. Combined, these factors translate to higher achievable productivities as presented in Figure 1. However, quantitatively predicting specific productivity values for future targets attributed to each discrete PBR design would be very challenging without sophisticated physics/biological growth models, which is outside the intended scope of this work. Rather, future projected PBR productivity potential is estimated by scaling from the previously established open pond design case targets of 25 g/m^2/day, using a ratio of currently demonstrated PBR productivity versus open pond productivity, as previously presented in Figure 1 based on published literature utilizing the same algae strain in the same location at the same time of year. In other words, this approach assumes that if open pond cultivation can ultimately achieve the targeted 25 g/m^2/day goal, then growing the same strain in a PBR would yield comparatively higher areal productivity results as has been demonstrated at present on lower productivity ranges (depending on the PBR design).

Using the data from the literature survey, Table 2 compiles the optimum cases for each source in Figure 1 (excluding the grayscale points as described previously) and the resulting ratio applied to estimates of targeted areal productivity in each PBR case. Optimum cases are defined as cases that have (1) reasonable open pond productivity for a strain (>10 g/m^2/day) and (2) optimized PBR productivity for the operating conditions considered (i.e., spacing between PBRs, dilution rate, and chemostat versus turbidostat operation).

9

Table 2. Literature Productivity Comparison between Open Ponds, Horizontal, Helical Tubular, and Flat Panel PBRs

Open Pond	Horizontal PBR		Helical Tubular PBR		Flat Panel PBR		Source
Prod. g/m²/day	Prod. g/m²/day	Ratio to Ponds	Prod. g/m²/day	Ratio to Ponds	Prod. g/m²/day	Ratio to Ponds	
9.7	12.1	1.2	19.4	2.0	20.5	2.1	[6][a]
14.0	15.7	1.1	24.4	1.7	27.5	2.0	[6,7][b]
12.8	-	-	12.6	1.0	27.4	2.1	[8-10][c]
11.0	-	-	-	-	13.0	1.6	[14][d]
19.0	-	-	-	-	30.0	1.5	[14][e]
10.3	11.5	1.1	15.6	1.5	29.7	2.9	[11-13][f]
15.8	24.1	1.5	38.5	2.4	39.2	2.5	[11-13][g]
	Ratio Average	1.2[h]	Ratio Average	1.7	Ratio Average	2.1	

[a] Actual pilot-scale productivity data for *Nannochloropsis* sp. CCAP 211/78 during July 2013 to August 2013 in the Netherlands. Data is for the **average** values seen in the open ponds and the PBRs.

[b] Actual pilot-scale productivity data for *Nannochloropsis* sp. CCAP 211/78 during July 2013 to August 2013 in the Netherlands. Data is for the **maximum** values seen in the open ponds and the PBRs.

[c] Actual pilot-scale productivity data for *Nannochloropsis gaditana* in Almería, Spain. Experiments occurred over 2 years with changes to operating conditions. The data in the table is for a dilution rate of 0.31–0.5 1/day and 0.5 m spacing between the flat panels.

[d] Productivity growth model for Kansas at a constant biomass concentration of 1 g/L at optimal orientation and spacing.

[e] Productivity growth model for Florida at a constant biomass concentration of 1 g/L at optimal orientation and spacing.

[f] Simulation model that predicts productivity for *P. tricornutum* in the Netherlands.

[g] Simulation model that predicts productivity for *P. tricornutum* in Algeria.

[h] After conversations with authors of the horizontal system modeled in literature [22,23], the ratio was conservatively adjusted to 1.0 rather than 1.2 for designs with a large light path length.

Limiting the data in Table 2 to cases that have reasonable productivity in open ponds allows for more readily stipulating that the performance could reach the open pond future target productivity of 25 g/m²/day, thus reducing any undue benefit for PBRs by excluding extremely low-performing pond cases. For example, some algae only grow (or grow well) in PBRs, and their corresponding ratios to open ponds would be too large for this method of scaling future productivities to be practical or realistic. As indicated in the footnotes for Table 2, although a marginal benefit in areal productivity versus ponds may still be possible for the horizontal PBR case (though less dramatic than vertically oriented designs), the specific horizontal system design/dimensions/costs applied in this study were based on the PBR design as published by Beal et al. (implied to be representative of Cellana's PBR system) [22]. That particular design is for a large-diameter reactor with higher light path length than the open pond basis, and upon further discussions with the authors, it was determined that it would be most appropriate to assume a 1.0 ratio for that case (i.e., no benefit for areal productivity compared to open ponds). The resulting target productivity values for PBRs thus range from 25 g/m²/day for horizontal tubes to 42.5 g/m²/day for vertical/helical tubes to 52.5 g/m²/day for flat panels/hanging bags. We note that productivities as high as 52.5 g/m²/day are approaching theoretical limits [29], but are still under. The maximum theoretical efficiency for photosynthesis is 12.4% of total solar irradiation, but when accounting for photosaturation, photoinhibition, and other losses this number is reduced to 5% (50–60 g/m²/day depending on the location and corresponding total solar irradiance) [29].

PBRs are closed systems and can exhibit different seasonal variabilities than open ponds. Seasonal variability is dictated by location, algae strain optimal temperature regimes, and external heating/cooling (if used). Preliminary PBR growth modeling work furnished by PNNL (noted above) predicted the variability of *Chlorella* throughout the year in Florida, grown in vertical panel PBRs [14,30]. The model predicted a maximum swing in productivity of roughly 1.7:1 between the summer and winter cases when the harvest density is maintained at 1 g/L with the flat panels aligned in a north-south orientation, without any inclusion of external heating or cooling [14]. In different locations, similar variability swings (summer:winter) have been noted from literature including: 1.7:1 in Almería, Spain for flat panels [10]; 2.1:1 in Almería, Spain for vertical tubes [31]; 1.2:1 in Algeria for flat panels (modeled) [13]; 2.4:1 in Algeria for vertical tubes (modeled) [11]; and 1.4:1 in Algeria for horizontal tubes (modeled) [11]. The PNNL model basis is therefore used for all PBR cases to account for the location-specific aspect of seasonal variability, asserted here to be located in the U.S. Gulf Coast region consistent with prior NREL studies [32,33]. Compared to the 3:1 maximum target variability for open ponds, this reduced range at 1.7:1 for PBRs appears to be a reasonable future projection. The full "shape of the curve" from the PNNL model was also used to determine the spring (1.1:1) and fall (1.5:1) variability assumed here.

The resulting seasonal areal and volumetric productivity values for each PBR case are shown in Table 3. As discussed above, the horizontal PBR case is assumed to achieve an annual average areal productivity of 25 g/m^2/day (not including spacing between tubes), which means there is no additional benefit for this parameter compared to ponds. The horizontal system evaluated is a wide flexible tube 0.38 m in diameter. This is a much larger light path than the other vertically oriented PBRs in Table 2 and is expected to achieve comparatively lower areal productivity.

Table 3. Assumptions for Seasonal Cultivation Areal Productivities and Corresponding Volumetric Productivities Used for the Base Case Models

	Summer	Fall	Winter	Spring	Annual Average	Ratio to Ponds
Open Pond						
Areal Algae Productivity (g/m^2/day AFDW)	35	24.9	11.7	28.5	25	-
Volumetric Productivity (g/L/day AFDW)	0.18	0.13	0.06	0.14	0.13	-
Productivity Variance versus Summer Peak	NA (1:1)	1.4:1	3.0:1	1.2:1	NA	NA
Horizontal PBR						
Areal Algae Productivity (g/m^2/day AFDW)[a]	31.6	21.1	18.6	28.7	25	1.0
Volumetric Productivity (g/L/day AFDW)	0.13	0.09	0.08	0.12	0.10	0.8
Productivity Variance versus Summer Peak	NA (1:1)	1.5:1	1.7:1	1.1:1	NA	NA
Helical Tubular PBR						
Areal Algae Productivity (g/m^2/day AFDW)[b]	53.7	35.8	31.6	48.8	42.5	1.7
Volumetric Productivity (g/L/day AFDW)	1.87	1.25	1.10	1.70	1.48	11.8
Productivity Variance versus Summer Peak	NA (1:1)	1.5:1	1.7:1	1.1:1	NA	NA
Flat Panel PBR						
Areal Algae Productivity (g/m^2/day AFDW)[b]	66.4	44.2	39.0	60.3	52.5	2.1
Volumetric Productivity (g/L/day AFDW)	2.29	1.52	1.34	2.08	1.81	14.5
Productivity Variance versus Summer Peak	NA (1:1)	1.5:1	1.7:1	1.1:1	NA	NA

[a] Areal productivity for horizontal process does not include spacing between tubes.
[b] Areal productivity is for occupied area of the PBR; this includes spacing between rows.

Unlike open ponds, PBRs are less subject to seasonal water losses from evaporation and blowdown. PBRs are closed systems and only incur evaporation losses from aeration or degassing of the culture. For the present effort, we estimated evaporation loss by modeling the water mass balance of inlet air (at humidity) that is used for airlifting, aeration sparging, and/or degassing and the saturated outlet gas. Blowdown is affected by evaporation rate; therefore, the lower evaporation in PBRs results in a smaller blowdown. We estimated blowdown demands by taking the ratio of PBR evaporation loss to the open pond evaporation loss, and multiplying by the blowdown in open ponds for the corresponding season (see [1] for more information on blowdown for open ponds).

All PBR cases assume the same targeted algae composition as previously set for the open pond design case, namely mid-harvest *Scenedesmus* comprised of 54.0% carbon, 8.2% hydrogen, 1.8% nitrogen, 35.5% oxygen, 0.2% sulfur, and 0.22% phosphorous by weight (component composition approximately 27% lipids as fatty acid methyl esters, 53% carbohydrates, 13% protein, 2% ash, and 5% other) [1]. The model utilizes diammonium phosphate and anhydrous ammonia to meet the phosphorus and nitrogen requirements for this composition. Similar to the open pond design, the models allow for 20% excess nutrients beyond stoichiometric demands, but the large majority of that excess is recirculated through the internal recycle loops across the dewatering stages [1]. CO_2 is provided based on specific PBR designs for aeration and sparging, with a 10% excess beyond stoichiometric demands to account for outgassing losses during gas stripping in the PBRs [1]. An outside plant (envisioned as a coal- or natural gas-fired power plant) captures CO_2 from flue gas and concentrates it to a >99% purity. The concentrated stream is then sent via pipeline to the algae facility boundary and is stored in a pressurized sphere. Similar to the open pond design case, the cost of CO_2, including purification, compression, and transportation via pipeline, is set at $45/metric ton CO_2 ($41/ton) [1].

Process Design Scenarios

Open Ponds (Reference Case)

A full description of the open pond design is available in the algae farm design report [1]. Briefly, the open pond system applies an average cost of four discrete 10-acre pond designs, which includes three raceway paddlewheel ponds and one pond circulated by pumps and gravity. The ponds are assumed to have minimal lining for erosion control but are otherwise compacted soil with sufficient clay content to minimize percolation and operate with a 20 cm water depth. To keep the algae from settling, paddlewheels or pumps are used for circulation, with an average power demand of 55.1 kWh/ha/day. The ponds are projected to achieve a target annual productivity of 25 g/m^2/day based on the pond cultivation area. Additionally, the ponds are continuously harvested at a fixed steady-state harvest density of 0.5 g/L. Based on prior PNNL Biomass Assessment Tool models for open ponds located along the Gulf Coast, we set the annual pond evaporation to 0.087 cm/day (annual average) and the corresponding average annual blowdown to 6.3 MM L/day [1]. Sumps within the ponds sparge CO_2 to meet the algae carbon demand plus an additional 10% for outgassing losses. Aqueducts and piping within the 100-acre modules transport harvested media, clarified water, and make-up water and nutrients to and from the ponds and dewatering areas. Pond costs include civil work, minimal lining, piping, electrical, and other pond costs (e.g., concrete and paddle wheels).

Horizontal Tubular PBR

The comprehensive journal articles published in 2015 by Beal et al. [22] and Huntley et al. [23] consider the economics of a 111-ha hybrid cultivation system that employs horizontal tubular PBRs for algae inoculum production (shown in Figure 2A) and open raceway ponds for algae cultivation. The analysis presented a thorough cost model for expanding the Cellana Demonstration Facility. For this analysis, we contacted the authors of these journal articles for additional details on the PBR system, specifically with respect to cost breakouts, PBR lifetimes, achievable future productivities, and foreseeable harvest densities.

In-depth PBR design information and accompanying discussions are presented in the above cited articles [22,23], but will be briefly summarized here. Each horizontal tubular PBR contains a volume of 50 m^3 and is circulated by an airlift system. The culture chambers, made from 10–15 mil polyethylene, span 0.38 m in diameter. The authors project the polyethylene tube lifetime at 2 years before required replacement. Individual PBRs utilize two parallel rows of tubes (spaced 0.38 m apart) with each row running 245 m in length and connecting to a 180° U-bend (made of roto-molded polyethylene). Tube ends not connected to the U-bends attach to a 2.5 m airlift column (also made of roto-molded polyethylene) that also turns the culture 180°. In all, each PBR covers 186 m^2 of cultivation area and 372 m^2 of land with the algae culture occupying 90% of the PBR volume and the remainder as back-pressured headspace. Cultivation area-to-culture volume ratio resulting from the PBR dimensions is 4.13 m^2/m^3. Additionally, the airlift column circulates the culture media within the tubes at a fluid velocity of 0.4 m/s and cycle time of 20 minutes, and it imparts gas transfer to strip out produced oxygen and to supply CO_2. Although the airlift efficiency (compressor efficiency to inject gas into the airlift column and impart circulation through the PBR) was 25% in Beal et al. [22], here, to keep efficiencies consistent between all cases, an airlift efficiency of 60% is used based on calculations from [34,35]. The GWP-II system uses an airlift efficiency of 60%. Furthermore, Verrecht et al. [35] confirms that a 60% efficiency for a blower is typical for the blower outlet pressure of 106,300 Pa and has been confirmed with data from blower manufacturers.

Based on conversations with the above authors, the horizontal tubular system is expected to perform similar to an open pond for both productivity and harvest density [36]. This horizontal tubular design has a wide diameter of 0.38 m, which translates to a larger depth and longer light path than the open pond 0.2 m depth. With the airlift column creating turbulent flow at a Re ≈ 50,000, we assume the algae is a homogenous mixture. Thus, even with a large tube diameter, the culture is anticipated to achieve a similar areal productivity as open ponds. Moreover, the PBR case is fully enclosed, which provides for better temperature control particularly in cold seasons and thus is likely able to achieve better productivities during these periods. The target productivity of the horizontal tubular PBR is thus set at 25 $g/m^2/day$ for the area directly under the tubes. The PBR tubes flatten out to be wider (0.51 m) than a set circular diameter (0.38 m) because of the flexible plastic used. Thus, the area under the PBRs relates to the product of the total length of PBRs and the wider 0.51 m diameter [37]. Any spacing area between tubes does not benefit the PBRs and is not counted (aside from increasing total facility footprint and land costs). Because the PBR has a large volume-to-area ratio, the algae cannot reach high concentrations; thus, the harvest density is maintained at 0.5 g/L to be consistent with the open pond basis. The process requires 5,148 acres (including inoculum) of cultivation area, and the whole facility uses 83,392 individual PBRs to produce the target biomass production of 0.19 MM tons algae biomass (AFDW) per year.

Huntley et al. [23] followed Beal et al.'s [22] study and provided more cost breakouts for PBR-specific equipment. PBR costs include the PBR reactor, internal fittings within the reactor, and plumbing that connects the PBR to the main supply or discharge system. Huntley et al. [23] provided costs on a $/acre basis of PBR areal coverage, and included the spacing between PBRs that translated to $6.47/acre (including spacing). We assume that the 100-acre module includes pipeline costs from Huntley et al. [23] (pipelines outside the 100-acre module for overall facility circulation are priced separately). Finally, operating costs for clean-in-place (CIP) chemicals are based on information provided for the Leidos hanging bag case (described below), which is also applied to the GWP-II panels.

Helical Tubular PBR

Although we considered tubular PBRs with a vertically stacked fence design in a prior TEA [19], the older model for this design was based on using plastic for the tubes and optimistic cost assumptions for couplings, fittings, and the support structure. Additionally, the past model optimistically assumed that the plastic tubes would last for the full 30-year facility lifetime without requiring replacement beyond standard maintenance costs. Here, we consider glass tubing with design and cost guidance for the helical tubes and fittings based on inputs from industry, as a potentially more optimal material than plastic for this particular design. Unlike other PBR designs all utilizing plastic that must be frequently replaced, PBRs made from glass were quoted to achieve a lifetime exceeding 30 years (barring a catastrophic weather event, which may be an important consideration in the Gulf Coast). This, combined with the fact that the tubes allow >99% light transmission, are rigid and withstand sagging, and can resist corrosion from cleaning chemicals, make glass tubes an interesting option to examine [38]. Glass tubes are used in commercial production facilities. Recently, Varicon Aqua Solutions built glass tubular pilot plants in Iceland and Sweden for algae production [38,39].

Algae in this PBR travel from the base of an attached degassing column through 400 m [31] of 6.28-cm (inner diameter) glass tubes (0.22 cm thick) before re-entering the degassing column. The 400 m of tubes loop around a support structure in a helix design employing multiple U-bends for directional changes (see Figure 2B). Each 400-m tube PBR stacks 10 vertical rows of tubes and covers 42 m^2 of area [31]. This tube design translates to an area-to-volume ratio of 35 m^2/m^3. In the sensitivity analysis we further examine the configuration and area-to-volume ratio of the tubes by considering the option of multiple 400-m loops per PBR module. The algae culture circulates through the tubes at a velocity of 0.6 m/s with flow from a centrifugal pump [40].The degassing column is a bubble column 3.5 m high and 0.4 m in diameter, and it supports the gas transfer of CO_2 and oxygen through the media. Using a similar volume of gas sparged to volume of the PBR culture per minute (VVM) as Acien et al. [31] (0.07 VVM) and assuming a 60% efficiency for the blower [34,35], the aeration power requirement is calculated at 6.7 kW/acre (occupied area). The target areal productivity is 42.5 g/m^2/day, based on the PBR versus pond scaling factor shown in Table 2 and Table 3. To produce 0.19 MM tons algae AFDW annually, the facility requires 3,000 cultivation acres, equating to a total of 289,039 individual PBRs and a corresponding culture volume of 349,000 m^3. The PBRs can produce a high harvest density of 2 g/L, consistent with published literature operating this system at a 1-ha scale [31].

The helical tube system is assumed to require seasonal cooling to maintain culture temperatures. This represents a deviation from the other PBR designs that are otherwise not assumed to require cooling. For example, the Leidos hanging bag case (described below) was described to NREL as

not utilizing an external cooler at any point during the year, as the air sparged directly to the bags stripped water from the culture to provide sufficient evaporative cooling. GWP-II bags are similar in design to the Leidos hanging bags, thus are also assumed to be sufficiently cooled through direct gas transfer in the PBR chamber. Additionally, the airlift system of the horizontal tubes follows the same principle while also incurring lower temperature swings given much larger culture volume-per-area ratios for the large-diameter tube design. However, the helical tubes are glass with high transparency, have less shading between each other, and use pumps for mixing, while not allowing for the same direct air stripping/gas exchange to occur within the PBR chamber (length of the glass tube run). It is not anticipated that gas sparging will provide enough water evaporation for heat transfer and cooling, thus the helical tubes are cooled at least during the hot summer months for the base case. Based on temperature models for PBRs in New Orleans, a total cooling requirement of 500 MJ/m^2/year is assumed [41]. Assigning this only to the summer, the heat removed is 5.47 MJ/m^2/day and zero for the rest of the year. The culture in the PBRs is cooled via a chiller system, which is in turn connected to a cooling tower. The power requirement for cooling is 695 kWh/ha/day averaged over a year, or 2,781 kWh/ha/day during the summer. Several sensitivity analyses consider scenarios with and without cooling for the GWP-II, horizontal tubes, and helical tubes.

A lower 1.1 installation factor is assumed for the glass tubes, couplings, and fittings, given their modular design with fitted couplings. Other costs, including the support structure, pumps, blowers, and the bubble column, are based on previous vertical fence tube models [19] or calculated using Aspen Capital Cost Estimator [42]. Cost for the cooling tower and chiller are included in the capital costs [43]. Operating expenses (power) for cooling are also added to this analysis. Rigid tubular PBRs like the helical tubes analyzed here can use plugs known as "pigs" or plastic particles to effectively control fouling on the inside of the tubes (one advantage of the helical system with more certainty on effective low-cost capability to keep the PBR clean over extended time periods). Given the simplicity of this cleaning mechanism, the costs are assumed to be marginal for this design.

GWP-II PBR

Fotosintetica & Microbiologica S.r.l. holds several patents for a vertical PBR design known as the Green Wall Panel-II. The capital costs of this system have been presented in public literature as $50/m^2 (lumped cost for the PBR) [3]. To further understand the elements included in this cost, we contacted a member of the company who authored a follow-up paper on TEA analysis on the system [25]. The GWP-II PBR, a vertical system comprised of supported panels of LDPE film (0.3 mm thick), utilizes 0.7-m-high, 48-m-long, and 4.5-cm-wide panels (when fully filled) [25]. Vertical stainless steel bars connected at the top with two U-bars driven into a wood base provide support for the flexible panels [25]. Additional support is provided by two vertical bars placed in parallel on either side of the panels. A perforated pipe within and at the bottom of the panels accomplishes gas transfer to bubble CO_2, as well as mix the culture [25]. A blower (assumed 60% efficiency [34]) delivers compressed air and CO_2 (0.12 bar) to the perforated pipe at 0.22 VVM during the day and 0.12 VVM at night. Although one linear meter of panel can hold 45 L of culture, the shorter panel height combined with 1-m spacing between panels translates to an area-to-volume ratio of 34.4 m^2/m^3.

A PBR unit equals 24 panels connected with PVC manifolds, and the unit covers 1,250 m^2 of land with spacing for the manifolds [25]. Panels can be isolated from each other with valves. In

all, eight panel units, attached with piping, cover 1 ha of land. A circulation pump services eight panel units and circulates the culture media for harvesting. The process also has the option for circulation through cooling/heating. To maintain consistency with the Leidos hanging bag design given a similar sparging system through the bags and out of the headspace, cooling and heating is not included in the base case for this design and all costs directly relating to those elements are removed. The option of cooling the culture with a chiller is considered as a sensitivity case.

The GWP-II system follows the flat panel configuration, translating to a resulting target annual areal productivity of 52.5 g/m^2/day based on the 2.1 times scaling factor for PBR versus pond performance presented earlier in Table 2. This translates to a target volumetric productivity of 1.8 g/L/day (Table 3). The process needs 2,428 acres of cultivation area to produce 0.19 MM tons of biomass annually (AFDW). This equates to 189,000 PBR panels or 7,861 PBR units. The harvest density for a continuous system is set at 2 g/L based on published data [34].

Since the original published costs were for a 1-ha demonstration facility [25], extrapolating to large commercial scales and target capital costs is challenge, and can increase uncertainties around the final cost numbers. Similar to Tredici et al. [25], we assume that the 1-ha system can benefit from economies of scale up to 10 ha, with costs scaled using a 0.85 scaling exponent ("*n*") according to the expression *[new cost = base cost x (new scale/base scale)^n]*. Beyond 10 ha, we assume the process scales linearly. All capital costs include a 10% installation factor [25]. In the above-cited TEA, the facility lifetime was set to 25 years, but it is assumed in this analysis that this can be extended to a standard 30-year lifetime. Lifetimes of specific pieces of equipment were also specified in the above TEA [25]. Some equipment, such as the wood base, has a shorter lifetime and would need to be replaced. To account for shorter equipment lifetimes, any item with less than a 20-year lifetime is multiplied by the number of times it will need to be replaced.

We assume that the pipeline costs described in the cited study are for smaller diameter pipelines that would be located within the 100-acre modules. Again, additional piping for CO_2 and water recirculation between the central dewatering facility and each 100-acre module is included separately, with costs described in the algae farm design report [1]. The low-density polyethylene (LDPE) bag plastic must be replaced once every year for this particular system, based on discussions with the above-cited study's author. Further discussion on this cost is described below. The provided cost for CIP from Leidos is also applied to the GWP-II system to account for cleaning of the panels. Although this GWP-II system is shown as a target case, further potential cost improvements have been discussed with the authors and could lead to a lower MBSP than shown here as the base case.

Leidos Hanging Bags

In the algae farm design case, NREL consulted with Leidos Engineering to provide a number of the pond designs and cost estimates. In the present effort, Leidos was again consulted to provide similar guidance for a hanging bag PBR system, in turn based on discussions with Algenol (the developer of this design). Two different sets of costs were provided for this system, one based on more near-term, smaller scale estimates and a second more reflective of envisioned commercial "nth-plant" target estimates, with the latter utilized in this study for consistency with the other cases (including the open pond reference basis).

Because the costs for this PBR are reflective of a commercial industry design, more specific design details (e.g., for bag materials of construction, specific dimensions, and cleaning protocols) were considered proprietary and were not furnished to NREL but were provided on a higher level with less granularity. Instead, a general description of the process is given as background. Flexible plastic bags hang from metal support structures. Each bag is sparged with air and CO_2. The sparged gases leave the system saturated with water, which was described to provide all required cooling without the need for dedicated external cooling. The life of the facility was originally noted to be 24 years, but it is assumed here that this can be extended to the standard 30-year lifetime. This lifetime is for all capital except the hanging bags, which are an operating cost for ongoing replacement after the initial installment (as is the case for the other scenarios with plastic replacement as well). The provided costs include the PBR arrays and installation, field equipment, variable operating costs, and labor. The central processing and all dewatering steps are maintained consistent with the algae farm design case [1]. Like the GWP-II system, the target productivity of the Leidos hanging bags is set at 52.5 $g/m^2/day$ based on the 2.1 times factor for PBRs versus ponds shown in Table 2. At the same productivity, both the GWP-II and Leidos hanging bags require 2,428 acres of cultivation area, but due to different facility layout configurations, the GWP-II system requires more total land. The harvest density for this process is also different than the GWP-II, set in this case at 1 g/L based on inputs from Leidos.

All costs furnished by Leidos for this system were rolled up to a $/acre basis. However, the capital costs were broken out by categories and include the PBR bags, the installation cost of the PBR, the support structure, any piping before central dewatering, valves and fittings, field equipment, the inoculum system, electrical, and weed control. Additionally, operating costs include operations labor, maintenance, weed control, CIP costs, power consumption, and nutrients. To keep the TEA designs consistent, we account for nutrients using the same methodology described in the algae farm design report across all scenarios, as described above [1]. Importantly, the base case Leidos hanging bag scenario assumes a 6-year bag lifetime before needing replacement, based on information provided to Leidos from commercial experience, with longer-term targets of up to 12 years (with the latter considered as a sensitivity case).

Cost Estimation for Individual Design Scenarios

Table 4 shows the capital costs attributed to cultivation for each design on a $/acre (cultivation area) basis. Among the scenarios evaluated, the horizontal tubular design is the least capital-intensive PBR system, whereas the GWP-II system is the most, and the open pond reference case is less capital-intensive than all the PBR systems. For the horizontal tube system, some of the costs are included in a total value and cannot be broken out based on the details presented in the source study [22]. Between all cases, the main cultivation costs are the largest expenses for open ponds, horizontal tubes, helical tubes, and the Leidos hanging bags. Conversely, the GWP-II system's support structure is the highest capital contributor. The helical tubular system uses glass with a high initial installed cost, but also benefits from a long lifetime of the system, >30 years without requiring frequent material replacement, as is the case of the other plastic system designs. The helical tubular system and the horizontal tubular system are comparatively different with the former made from a rigid material with a short light path diameter of 0.065 m, and the latter made from flexible plastic with a long light path diameter of 0.38 m. If the helical design

was made of plastic tubes of a similar diameter instead of glass, the balance between higher initial installed glass cost versus shorter lifetime and higher plastic replacement cost would translate to higher overall biomass costs (shown in the sensitivity analysis). Table 4 also provides the capital cost of the open pond liners and the first year's installment of PBR plastic for the bags, panels, and tubes as applicable. After the first year, any replacement of plastic becomes an ongoing operating expense. Although the costs are shown on a $/acre basis, it is important to keep in mind that some facilities require less cultivation area than others to produce the same amount of biomass, thus overall facility installed capital cost is not exclusively dictated by $/acre system costs, but the combined effect of $/acre and total acreage (i.e., cultivation productivity).

For the cost and footprint of inoculum, the inoculum PBRs are assumed to be of the same design as those used for primary production across each case (e.g., if horizontal tubes are used in the main production facility, then this design is also used to grow the inoculum). The inoculum trains achieve the same productivity as the corresponding production trains. Additionally, any biomass produced for inoculation is included toward the target biomass production of 0.19 MM tons/year AFDW. Because the inoculum train design is identical to the main production PBR design for each case and also is assumed to achieve the same productivity (with both inoculum and main cultivation biomass counted toward the total 0.19 MM tons/year basis), no separate acreage is explicitly set aside for inoculum versus primary biomass production, and inoculum costs are rolled into the total cultivation costs. The only exception to this is the Leidos hanging bag design, which includes separate accounting for the inoculum train both in the capital and operating costs based on the information furnished by Leidos.

Table 4. Capital Cost Details Attributed to Cultivation for all Designs Considered in TEA Model

	Installed Capital for Cultivation System in $/acre (2014$)				
	Open Pond	**Horizontal Tubular**	**Helical Tubular**	**GWP-II Flat Panel**	**Leidos Hanging Bag**
Main Cultivation Costs + Inoculum (PBRs or Ponds)	$7,600	$39,010	$233,240	$9,250	$31,971
Support Structure	$0	$0[a]	$118,937	$255,148	$22,186
Piping System	$8,625	Incl.	Incl.	$25,811	$19,376
Valves & Fittings	$0	Incl.	Incl.	$60,983	$9,688
Field Equipment	$0	Incl.	$25,715	$5,665	$11,841
Electrical Equipment	$2,150	Incl.	$0	$97,406	$512
Open Pond Liner or PBR Plastic (Bag/Panel/Tube) for Initial Installation[b]	$2,400	$4,738	$0	$6,529	Incl.
Other Costs for PBR	$12,267	Incl.	$0	$49,825	$1,550
Total	$33,042	$43,748	$377,892	$510,617	$97,124

Incl. = Included in main cultivation row.
[a] The horizontal tubes are placed on the ground without the need for a support structure. The land excavation costs for the overall facility are assumed in this case to include digging trenches for the horizontal tubes to be placed in.
[b] The capital cost of the PBR plastic for the first year of the plant is shown for horizontal tubes and the GWP-II PBR, but is included in the main cultivation costs of the Leidos hanging bags. PBR plastic replacement for all subsequent years is handled as an operating cost for all relevant systems (shown in Table 7).

After cultivation, an in-ground gravity settling pond within the 100-acre modules dewaters the harvested material to 10 g/L. The stream is then sent via aqueduct or pipeline to a central dewatering facility. A hollow fiber membrane further concentrates the material to 13 wt% solids, followed by centrifugation to concentrate the material to 20 wt% solids. Other considerations included in the analysis are CO_2 delivery, on-site circulation, and storage. The design and costing of all these operations is consistent with the open pond design report with further details available in that report.

Table 5 provides the estimated power demands broken out for all cases on an areal basis. The power usage for some of the PBRs has been provided on an areal basis without providing the volume-to-area ratio. Leidos provided power demand values on an areal basis for the hanging bag system. The areal basis is therefore more accurate for direct comparison across these specific designs, but the power usage is more universal to PBR systems and reflective of actual processing conditions, such as power for circulation and aeration attributed to a given volume of culture. PBRs include spacing between rows that can be varied, which alters the volume-to-area ratio depending on the spacing.

The power usage for the cases varies widely from 12,967 kW for Leidos hanging bags to 83,155 kW for helical tubes (compared to 9,753 kW for the open pond reference case). The helical tube power demand is driven in part by the power requirements to run the chiller (only used for that design in the base case), as noted earlier. Power to run the chiller translates to 695 kW/acre/day or 42% of the total power demand for the helical tube case. Additionally, the helical tubes use air and CO_2 gas sparging in a degasser column while using pumps to circulate the culture. Other PBR designs use the gas sparging for both degassing and mixing (GWP-II, horizontal tubular, and Leidos hanging bags) and thus reduce the total power requirement dedicated to mixing (although a similar airlift circulation design implemented for the horizontal tube case could also potentially be used for the helical tube case, depending on the required pressure to drive circulation). Horizontal tubes use an airlift column to both mix and aerate the culture, but because of that case's larger facility size and volume, it uses more power than either the GWP-II or the Leidos hanging bag cases. In all the PBR cases, the mixing power is higher than for open pond paddlewheel circulation, which is an important consideration particularly for LCA given known LCA dependencies on circulation power demand even for open ponds [32].

Table 5. Summary of Power Requirements for Each Case Based on Occupied Area Coverage

Power Demand (kWh/ha/day)	Open Ponds	Horizontal Tubular	Helical Tubular	GWP-II	Leidos Hanging Bags
Mixing	55.2	135.5	488.1	407.4	301.4
Pumps in Modules	21.2	21.0	6.0	7.3	0.0
Inoculum	2.4	0.0	0.0	0.0	0.0
CO_2 Delivery	21.6	21.5	36.6	45.2	0.0
Aeration	0.0	0.0	399.1	0.0	0.0
Make-Up Water Delivery	3.4	0.4	2.4	1.1	0.8
On-Site Circulation	4.7	6.8	4.6	6.4	0.0
Dewatering	7.3	6.9	11.8	14.6	14.6
Cooling	0.0	0.0	695.4	0.0	0.0
Total	116	192.2	1,644	482	317
Cultivation Area (acres)	5,000	5,148	3,000	2,428	2,428
Total Power for Facility (kW)	9,753	16,681	83,155	19,732	12,967

Economic Assumptions

In the economic analysis, a process model developed in Aspen Plus [28] feeds into setting capital and operating costs, which in turn are used by a discounted case flow rate of return (DCFROR) analysis to estimate the MBSP that produces a net present value of zero for the nth-plant at an internal rate of return (IRR) of 10%. Capital equipment is subject to an exponential scaling expression for sizing and installation factors and leads to a total capital investment for the facility. Percentage allocations for direct and indirect costs for cultivation, dewatering, and outside boundary limits remain consistent with the algae farm design report. Many of the economic assumptions for the DCFROR are consistent with the algae design report—and all costs are indexed to 2014\$—but assumptions that differ are noted here. In addition to the variable operating costs used in the algae farm design report [1], PBRs can require CIP chemicals (although pond cleaning is also required for the open pond case, CIP was not explicitly considered in that prior work), cooling tower chemicals, weed control (i.e., to prevent weeds from growing in between rows of PBRs), and inoculum costs (in the Leidos case inoculum operating expenses were provided explicitly). Table 6 provides chemical and utility costs used in all cultivation cases. CIP processes for PBRs have not been well documented in the literature, so the guidance provided from the Leidos hanging bag estimation is also used for the other plastic-based cultivation systems (horizontal tubes and GWP-II).

Table 6. Chemical/Utility Costs and Sources

Component	Cost (2014$)	Source
CO_2	$0.0218/lb	[44-46] ($45/metric ton)
Ammonia	$0.4123/lb	[47] (average of 2011–2014)
Diammonium Phosphate	$0.3364/lb	[47] (average of 2011–2014)
Power	$0.0682/kWh	[48]
Chilled Water Utility Price	$5.34/GJ	[49]
Process Water	NA	Water is sourced from a nearby local water resource; costs are accounted for via pipelines, pumps, and pumping power to bring make-up water on site.
CIP Chemicals	$750/acre (cultivation area)	Estimation from Leidos hanging bag case
Cooling Tower Chemicals	$1.77/lb	[43]
Weed Control	$340/acre (cultivation area)	Estimation from Leidos hanging bag case
Inoculum Costs	$500/acre (cultivation area)	Estimation from Leidos hanging bag case[a]

[a] Inoculum costs are only explicitly included for the Leidos hanging bag case; all other cases include inoculum rolled into the total cultivation operating costs.

Table 7 provides the operating costs for periodic plastic replacement in all relevant cases (all PBR scenarios except the helical tubular design). Each case has a specified bag/tube lifetime based on the plastic and additives/coating used. Replacement schedules are assumed to be spread throughout the year and labor for plastic replacement is accounted for in the fixed operating costs. The helical tubes have a lifetime of 30 years; it is assumed that, barring any major weather events (this could be an important factor for glass tubes in the Gulf Coast), the tubes are sufficiently robust to not need major ongoing replacement beyond standard maintenance cost

factors for the facility. Coincidentally, the GWP-II and Leidos hanging bag operating costs are very similar when translated to an annual basis, even though the Leidos hanging bags have a much longer lifetime. The plastic costs for the Leidos hanging bags are $32,502/acre (replaced every six years), whereas the plastic for the GWP-II costs $5,739/acre (replaced every year).

Table 7. Operating Costs for PBR Plastic Replacement on an Annual Basis

	Open Pond	Horizontal Tubular	Helical Tubular	GWP-II Flat Panel	Leidos Hanging Bag
PBR Plastic Replacement: Cost of Bags/Panels/Tubes ($/acre/year)	$0	$2,211	$0	$5,739	$5,417
PBR Lifetime (years)	30	2	>30	1	6

Fixed operating costs are higher for the PBR systems compared to open ponds, in most cases tied to substantially more maintenance employees dedicated to replacing or servicing the PBR reactors. Table 8 presents the different cultivation systems with the number of required employees and total labor. A 90% labor burden is added to all employee salaries, except for the "Field and PBR Employees for Leidos Hanging Bags," which is already fully burdened. The horizontal tubes are assumed to need 172 maintenance technicians for PBR replacement, based on the following logic: the facility has 83,392 PBRs and the PBR lifetime is assumed to be 2 years, i.e., each year 41,696 PBRs are replaced and we assume that it takes two people 4 hours to replace one PBR. The GWP-II PBR also requires maintenance labor for PBR replacement. The GWP-II PBR has a 1-year lifetime, and because of its smaller size is assumed to take one person 2 hours to replace, translating to 193 maintenance technicians. The helical tubes have labor similar to open ponds as they have a long 30-year lifetime and require much less intensive labor for ongoing PBR replacement. The Leidos design includes estimations for a fully burdened labor force that would work on the PBR and field side of the facility based on estimates furnished by Leidos. Because of the 6-year lifetime of the hanging bags, less labor is needed to be dedicated to PBR replacement, which translates to a smaller labor force of 141 people. Additional labor is counted for operators dedicated to dewatering as well as other labor positions noted in Table 8.

Table 8. Summary of Labor Cost Assumptions

Position	2014 Salary		# Required				
			Open Pond	Horizontal Tube	Vertical Tube	GWP-II	Leidos Hanging Bag
Plant Manager	$	155,617	1	1	1	1	1
Plant Engineer (civil)	$	82,050	2	2	2	2	2
Plant Engineer (environmental)	$	83,360	2	2	2	2	0
Maintenance Supervisor	$	60,341	1	1	1	1	1
Maintenance Technician	$	42,345	12	172	20	193	Incl.
Lab Manager	$	59,283	1	1	1	1	0
Lab Technician	$	42,345	1	1	1	1	0
Shift Supervisor	$	50,814	4	4	4	4	0
Module Operator – Production	$	26,910	56	56	56	56	Incl.
Module Operator – Inoculum[a]	$	44,100	8	0	0	0	0
Module Operator – Dewatering	$	38,590	9	9	9	9	9
Clerks & Secretaries	$	38,110	3	3	3	3	3
Field and PBR Employees for Leidos Hanging Bag	$ 3,500/acre[b]		-	-	-	-	125 ($3,500/acre)
Labor Total			100	252	100	273	141

Incl. = Included in the field and PBR employees lump sum for Leidos hanging bags.

[a] Inoculum personnel are included in the Module Operator – Production row for horizontal tubes, helical tubes, and the GWP-II system.

[b] Fully burdened labor for the field and PBR employees for Leidos hanging bag scenario.

Results

Table 9 summarizes the results for the four PBR designs considered, as well as the open pond reference case from the algae farm design report [1]. Unless otherwise noted, all costs presented here are updated to 2014$. As mentioned previously, this analysis is intended to be forward-looking toward plausible future target projections for the cultivation systems, with the projected areal productivity varied depending on the type of design, and does not consider the degree of research advances that may be needed to reach these goals. Different areal productivities influence the total area required, the number and total volume of PBRs to reach that facility size, the total power demand, and ultimately, the total capital investment for a facility. Based on assumptions described above, the target cases for the PBRs all translate to higher MBSPs than the open pond reference case, i.e., the asserted relative improvements in productivities over the open pond goal of 25 g/m^2/day do not outweigh the increase in facility capital and operating costs. All PBR cases have a higher $/acre capital cost than open ponds as seen in Table 4. While the higher $/acre cost is partially counteracted by the smaller facility size (in the case of helical tubular, GWP-II PBRs, and Leidos hanging bags), it is not enough to reach the same or lower overall installed costs than open ponds for the given biomass output rate. The Leidos hanging bag case translates to a 15% higher total installed system cost than open ponds, whereas the GWP-II and helical tubular systems are more than 5 times larger than open ponds. Figure 6, which shows the cost breakouts for the MBSP, highlights that the capital costs of the cultivation system (and inoculum equipment) dominate the higher MBSP PBR cases. In fact, the capital cost of any cultivation system (open ponds and PBRs) is the largest contributor to the MBSP.

Beyond the installed costs, all PBR options also translate to higher variable operating costs than open ponds. The PBRs use more power for mixing, aeration, and cooling (if applicable) than the open ponds. Additionally, three of the four PBR options (horizontal tubular, GWP-II, and Leidos hanging bags) make use of disposable plastic culture chambers with a set lifetime. The replacement cost of these culture chambers is applied as a variable operating cost but is not applicable for either open ponds or helical tubes. Some of the PBRs also require CIP chemicals to reduce biofilm buildup and increase the plastic lifetime. Finally, each PBR case reflects a higher fixed operating cost than open ponds, in part due to higher labor costs for all cases other than helical tubes (discussed above) and also driven by higher maintenance costs (tied to higher capital expenses, not including plastic replacement, which is included as a variable cost).

Among the PBR cases, the MBSP results vary widely from $639/ton (AFDW) for the Leidos hanging bags to $1,793/ton (AFDW) for GWP-II, i.e., a spread of 281%. Within this range, horizontal tubes were estimated at $708/ton and helical tubes at $1,737/ton. This is a much larger variation in modeled biomass costs than were seen for the open pond design report across discrete pond designs, but this is to be expected given that the systems considered here are much more different from one design to another. However, the two systems that are closest in design to each other, Leidos hanging bags and GWP-II, fall on the opposite ends of the full range, tied to widely varying estimates received for capital cost elements (namely support structures, valves and fittings, and electrical) that otherwise may be expected to be similar; to some degree, this may reflect differences in the degree of technology development and optimization for commercial scale-up and associated projections for what reasonably may be achievable for n[th]-plant designs. Of course, another key driver in MBSP costs is the asserted productivities and how they may vary between each design and in comparison to open ponds (discussed more below).

23

Finally, another important driver is the capital intensity of the system. The GWP-II and helical systems incur considerably higher initial installed costs than the other designs, although for different reasons (support structures and other cost elements in the case of the GWP-II, versus the cost of glass tubes and fittings in the case of helical tubes). Higher capital costs in turn also cascade to higher cost penalties tied to the 10% IRR metric (rate of return on capital investment), whereby higher initial installation costs for glass tubes in the helical case subsequently require more return on that higher capital investment than the plastic PBR cases with a lower initial capital expense, and then subsequent operating expenses for continual PBR plastic replacement (not subject to IRR). At higher IRR rates, those differences would become further magnified.

Table 9. Summary of Yields, Rates, and Processing Costs (2014$)

Parameter	Open Ponds	Leidos Hanging Bags	Horizontal Tubes	GWP-II	Helical Tubular
Annual Average Productivity (g/m²/day)[a]	25.0	52.5[b]	25.0[c]	52.5[b]	42.5[b]
Cultivation Area (acres)	5,000	2,428	5,148	2,428	3,000
Total Area (acres)	7,176	3,169	10,444	4,139	4,807
Annual Power Usage (MMkWh/yr)	77.2	102.7	132.1	156.3	658.6
Cooling Included in Power Usage	No	No	No	No	Yes
Installed Capital Costs ($MM)	$233	$269	$276	$1,280	$1,209
Variable Operating Costs ($/ton AFDW)	$152	$249	$249	$263	$363
Fixed Operating Costs ($/ton AFDW)	$62	$91	$128	$215	$134
Minimum Biomass Selling Price ($/ton AFDW)	**$494**	**$639**	**$708**	**$1,793**	**$1,737**

[a] Based on the operating area (i.e., cultivation area) of the PBRs and ponds, except where specified.
[b] Spacing between rows is included in cultivation area.
[c] Does not include spacing between tubes as cultivation area.
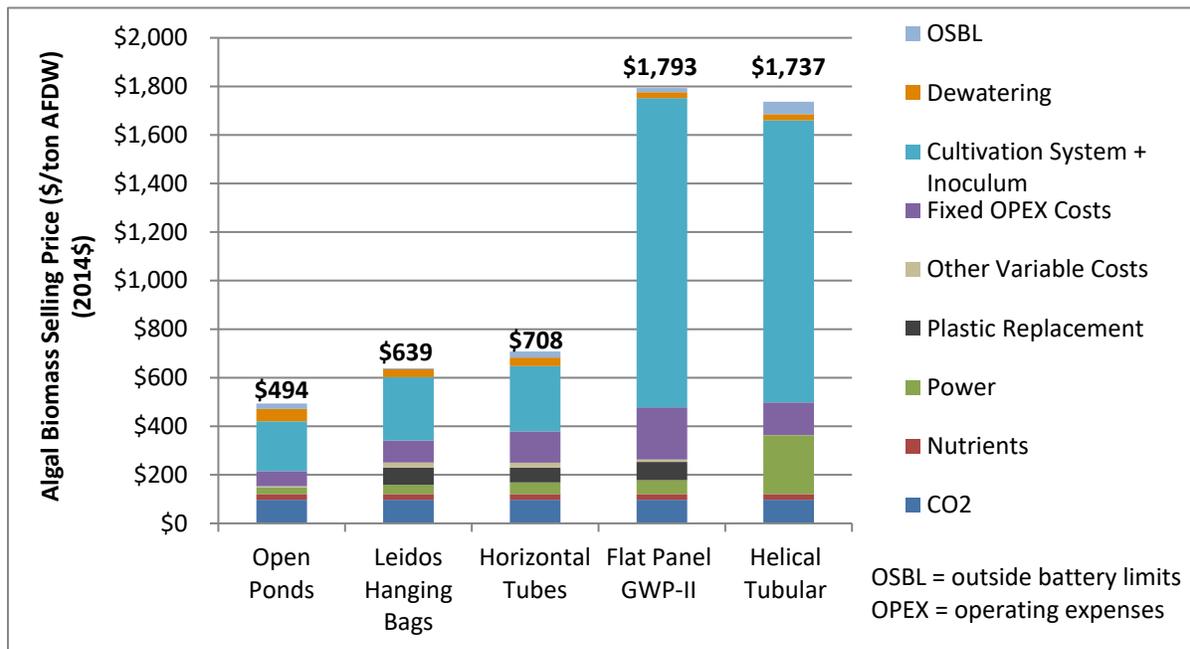
Figure 6. MBSP results for each PBR scenario (as well as open pond reference case) broken out by major contributions

Single-Point Sensitivity Analysis

Beyond the base cases presented above, Figure 7 considers the implications on MBSP for alternative sensitivity scenarios. PBRs can generally resist culture crashes more than open ponds because they are closed systems. The algae farm design report had assumed a sufficiently robust future target strain that minimized open pond culture crashes once every 20 days, which in part fed into the targeted 90% process uptime (i.e., 35 days/year allowed for downtime between crashes/restarts, planned maintenance, and extraneous events such as freezes). If pond crashes occur more often, more inoculum area is required and the MBSP increases. Assuming ponds instead crash every 5 days increases the open pond MBSP to $529/ton. Alternatively, if culture contamination, weather events, pond freezes, or other factors translated to a higher downtime than the targeted 35-days-per-year allowance, the open pond algae farm system could be down for 135 days of the year (37% of the year) to yield a MBSP comparable to the lowest-cost Leidos hanging bag PBR case at 10% (35 days/year) downtime. Importantly, if the ponds required full liners, the open pond MBSP would increase to $617/ton in the algae farm design case at the base 90% uptime, which is close to the target Leidos hanging bag case at $639/ton.

Three alternative scenarios are considered for the Leidos hanging bag base case. The costs of valves and fittings were still considered to be poorly understood for very large-scale implementation and not provided. As seen in Table 4, valves and fittings for the GWP-II system equal $60,983/acre. The GWP-II capital costs are higher than the Leidos hanging bags; therefore, this cost for valves and fittings is viewed as the maximum for the Leidos hanging bags at small scale. The GWP-II system could have more fittings and valves than the Leidos hanging bags because of the number of entry points and various pipelines used, including air and flue gas supply, culture circulation, culture harvesting, and culture preparation and supply. To account for the larger number of fittings and valves the cost of the fittings and valves for one of the Leidos hanging bag sensitivity cases is increased to $40,000/acre (between the $10,000/acre target case and the $60,983/acre GWP-II case). The increased costs for valves and fittings results in an MBSP of $713/ton. Leidos also provided a range of PBR operating costs and envisioned PBR lifetimes, which are also examined in Figure 7. Overall, expanding the PBR lifetime to 12 years only reduces the MBSP by $36/ton, whereas increasing the plastic replacement costs to $60,800/acre over 6 years increases the MBSP by $62/ton.

PBR lifetime is also a consideration for the horizontal tubular process and the GWP-II PBR, as both designs use plastic for the culture chamber. Discussions with the authors of Beal et al. [22] and Huntley et al. [23] established the horizontal tubular lifetime target at 2 years, but this value had not been demonstrated. As a sensitivity case for the horizontal system, this is varied between 0.5 and 6 years, with a resulting MBSP of $1,105/ton and $620/ton, respectively. The GWP-II process assumes a plastic lifetime of 1 year for the base case, but for the sensitivity case, a range of .5 to 2 years is assumed, translating to an MBSP of $1950/ton and $1,714/ton for those scenarios, respectively.

As noted previously, unlike ponds, which are cooled by evaporation, closed system PBRs can require external cooling in order to keep non-heat tolerant algae strains from crashing. PBR design, location, and the temperature tolerance of the algae strain play a role in determining if a PBR requires cooling. Leidos was provided guidance based on commercial operations that algae grown year-round do not require external cooling for the Leidos hanging bag design. Because

this design and the GWP-II system are similar, it was assumed that the base case GWP-II PBR does not require cooling either. A sensitivity is considered here with cooling of the GWP-II system at a total cooling requirement of 500 MJ/m^2/year, assumed to occur only in the summer [41]. After adding a chiller system to achieve this cooling load [43], cooling adds $109/ton to the GWP-II case. This cooling scenario is also considered for the horizontal tubes and results in an increase of $218/ton. Finally, the helical tubular system is considered *without* cooling, which would reduce MBSP by $232/ton in this case. For the base case GWP-II PBR, the capital cost of the PBR includes $237 MM of electrical equipment. Comparatively, the Leidos hanging bag system estimates electrical equipment far lower at $528/acre or $1.2 MM. Given that this element is not expected to vary so dramatically for a similar system design, replacing the GWP-II electrical equipment costs with the Leidos scenario electrical costs results in a savings of $255/ton.

Next, for the helical tube case, a sensitivity was considered to replace glass with plastic. Unlike glass, which has a long lifetime, plastic helical tubes are assumed to only last 10 years. Although the costs per unit volume for thin flexible plastic bags are shown to be fairly low, the costs for rigid UV-protected plastic tubes are estimated to be substantially higher (even higher per linear foot than the glass system for a similar diameter rigid pipe, based on cost inputs from industry). This, combined with the need to replace the full PBR array every 10 years, incurs a significant penalty on overall economics. The plastic tubes are also assumed to need the same number of couplings, fittings, and support structures. Changing the helical design from glass to rigid plastic translates to an estimated MBSP of $2,425/ton or a $688/ton increase from the glass basis. Of that $688/ton increase, $274/ton is due to plastic replacement costs, and the other $414/ton is attributed to the increased capital cost of the plastic.

Beyond material choice (glass or plastic), helical tubes can vary in configuration. A sensitivity case considered an optimized configuration that allows for one PBR module to contain multiple 400 m long tube loops that circulate to and from the degassing column. This change in configuration reduces the number of U-bends required for each 400 m loop from 20 down to 3, which reduces the MBSP by $97/ton. Another choice for design configuration is the spacing between PBR modules, impacting the area-to-volume ratio. As this ratio decreases, areal productivity would generally be expected to increase (to a limit), although this would also add to the number of PBRs required and the cost. Strictly reducing the area-to-volume ratio to 16 m^2/m^3 without any allowance for higher productivity would increase the MBSP significantly to $2,832/ton; if productivity were also increased to 55.1 g/m^2/day (5% higher than the maximum case with hanging bags), MBSP would be $2,079/ton (still higher than the base case configuration/productivity). The final sensitivity case evaluated for helical tubes considers the high mixing and aeration power estimates. To reduce the power requirement, the velocity of the culture is reduced to 0.3 m/s and the air sparging rate is reduced to 0.007 VVM based on a different helical tubular system described in Muller-Feuga et al. [50]. This change in the mixing power and sparging inputs translates to a reduction of $133/ton.
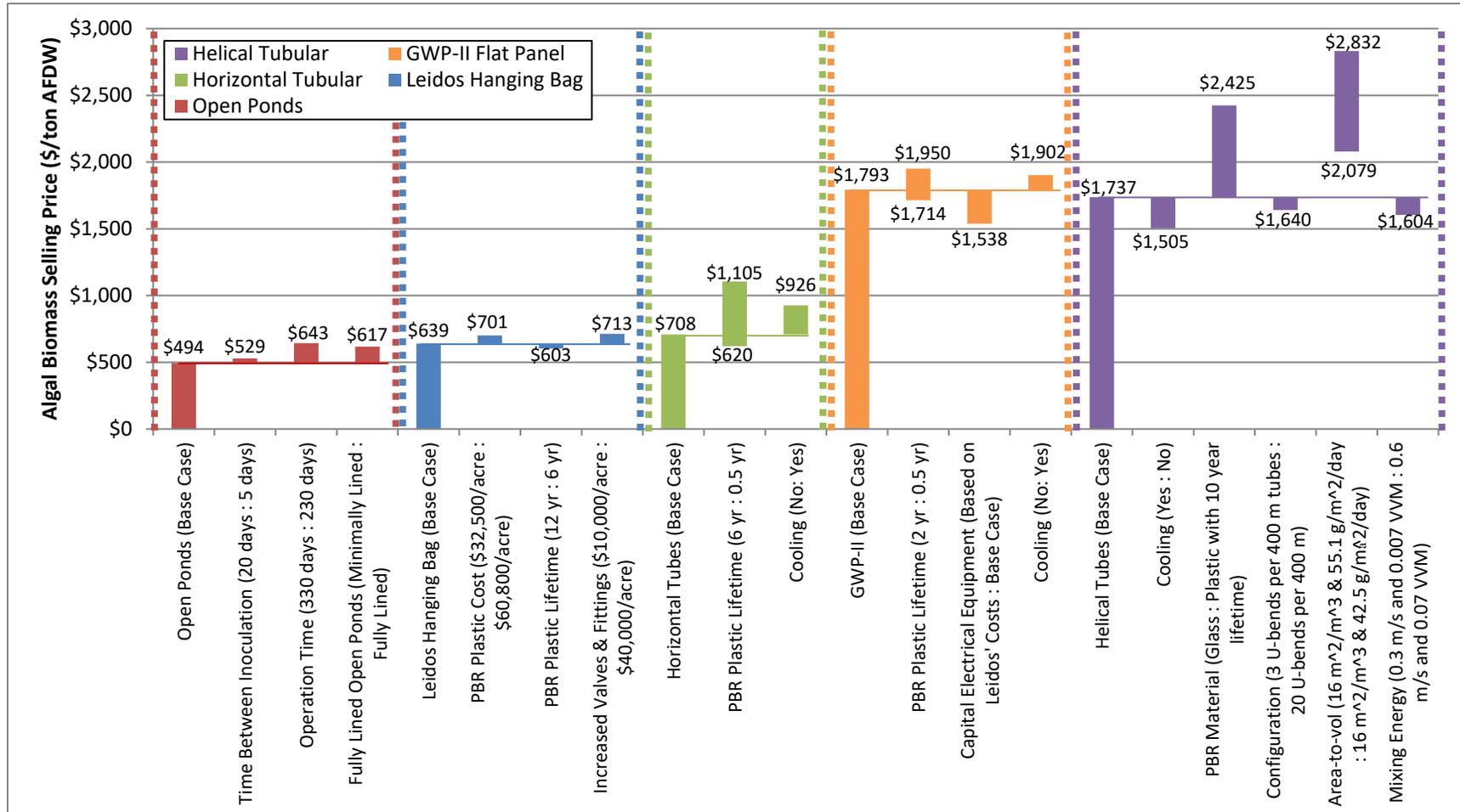
Figure 7. MBSP implications for alternative scenarios. Note: Helical tubular case considers decreasing the area-to-volume ratio, thereby increasing the number of PBRs per area and overall costs. Sensitivity scenario assumes decreasing the ratio from 35 to 16 m²/m³ while first maintaining the basis areal productivity (higher MBSP) and then increasing it (lower MBSP).

Productivity Sensitivity Analysis

Figure 8 provides a scan plot of the relationship between MBSP and productivity for all cases. If all cases could equally achieve the same areal productivity (which is not likely realistic), then the horizontal tubes would come out as the lowest cost option of PBR systems, and the GWP-II panel would emerge as the highest cost option (followed closely by helical tubes). However, for a more realistic case reflective of the target productivities asserted here (yellow markers in Figure 8), the MBSP trends are different as shown in Figure 6. Another important point is that relative to today's state-of-technology performance, which is closer to 8–12 $g/m^2/day$ for open ponds ($824–$1,227/ton MBSP) [2], if, for example, PBR current performance was at 25 $g/m^2/day$ in the Leidos hanging bag design, current MBSPs would be more comparable at $1,190/ton. What is also noteworthy from this plot is the shift where the asymptote occurs for the cases. When capital cost is "low" for the system (e.g., horizontal tubes, open ponds, and Leidos hanging bags), the facility reaches a point where increased productivity translates to a clear diminishing return. Comparatively, systems with high capital costs do not reach this asymptote until productivity becomes much higher than the other cases, with dramatic cost reductions observed until at least 30 $g/m^2/day$.
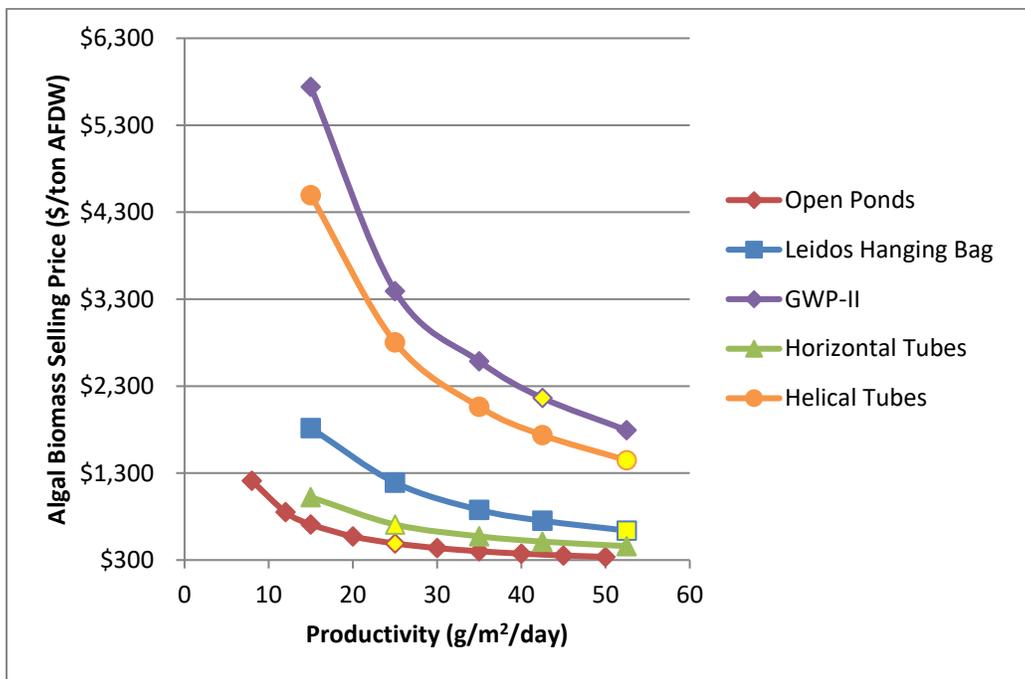
Figure 8. Scan of MBSP versus productivity for the open ponds and PBRs. All points in yellow denote the corresponding productivity for each design's targeted base case.

Conclusions

A comparison on growing algae in different cultivation systems requires both qualitative understanding of the benefits of the systems and quantitative understanding of the economic potential of each system. The focus of this report is on the quantitative results from TEA modeling for four PBR target cases as well as a previously established open pond reference case. In the process, algae production follows several sequential operations. First inoculum algae, CO_2, and nutrients are fed into the selected cultivation system (either open ponds or PBRs) to grow the biomass. After cultivation, the algae undergo a three-step dewatering process to concentrate the biomass to 20 wt% AFDW. Mixing for each cultivation system is different and can include paddlewheels (for ponds), pumps, gas sparging, or airlift columns. Throughout the facility, culture and clarified water are transferred by aqueducts and pipelines.

This report leverages inputs and cost values garnered from published literature, engineering subcontractors, and experts in the field to develop four algae production and dewatering scenarios using different PBRs. The target annual productivity for each PBR is estimated based on published literature data for the performance of the PBR compared to an open pond reference growing the same strain at the same location. Additionally, the target seasonal variability is based on modeling predictions for PBRs located in the Gulf Coast. The analysis considers a comparatively large (in diameter) horizontal tubular PBR made of LDPE, a glass helical tubular PBR, an LDPE GWP-II PBR, and a flexible plastic hanging bag PBR. The base case MBSPs are estimated at \$494/ton for open ponds, \$639/ton for Leidos hanging bags, \$708/ton for horizontal tubular, \$1,793/ton for GWP-II, and \$1,737/ton for glass helical tubes. The wide variability between the PBR MBSPs highlights that PBR economics are still wide ranging (but also quite different in design and resultant capital- and operating-cost intensity). One of the largest contributing factors to the high variability seen in the MBSPs is the initial installed capital cost of the cultivation system. For the PBRs with lower MBSPs the cultivation capital cost ranges between \$269 MM and \$276 MM, whereas the higher MBSP systems' capital costs range between \$1,209 MM and \$1,280 MM.

Beyond the base cases, several alternative sensitivity scenarios were considered to understand MBSP impacts. Some sensitivity cases considered the cost impacts of cooling and plastic replacement lifetime. Two sensitivities were run for open ponds to understand the ramifications that pond downtime or culture crashes (inoculum system sizing) would exhibit on the open pond MBSP. A comparable MBSP between open ponds and the lowest-cost PBR case (Leidos hanging bags) was shown to occur if open pond operational downtime increased to 135 days/year, versus 35 days/year assumed in the base cases. Another conclusion found was that when capital costs are high for a system, it takes higher productivities before reaching a point of diminishing economic return (flattening MBSP curve), although such asymptotic cost curves apply for all cultivation cases considered. As algae production processes are still in relatively early stages of development, the cost values established in this analysis have a higher degree of uncertainty.

Finally, we emphasize that while the PBR systems evaluated here all translated to a higher biomass cost than for open pond cultivation (and also varied considerably amongst themselves), this is not to conclude that PBRs will not play an important role in algae production or that one PBR design will always be better-suited in all instances than another. On the contrary, closed PBR systems play a key role in producing biomass or inoculum seed under more controlled

conditions with less susceptibility to contamination, as well as lower nutrient and CO_2 retention losses, all of which are more challenging for open ponds, particularly based on current performance, i.e., relative to the future n^{th}-plant projections considered here. In addition, PBR systems offer important advantages in applications requiring specific algal compositional characteristics, e.g., for isolating desired components such as carotenoids, pigments, and fatty acids for use in high-value food, nutraceutical, or other products, which constitute a major fraction of the current algae market. Additionally, as shown in this study, many PBRs are more space-efficient with respect to total land footprint requirements than open ponds per unit of produced biomass, which can be important in processes constrained by low land availability (for example, wastewater treatment using algae in highly populated/developed areas). Finally, given better temperature control and more efficient utilization of available light, PBRs offer opportunities to cultivate algae in more northern areas of the United States that may not be practical with open ponds, which in turn could open up additional opportunities for exploration, such as integration with waste CO_2 from ethanol facilities and power plant carbon capture.

References

1. R. Davis, J. Markham, C. Kinchin, N. Grundl, E. Tan, and D. Humbird, *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*, (Golden, CO: National Renewable Energy Laboratory, NREL/TP-5100-64772, 2016), http://www.nrel.gov/docs/fy16osti/64772.pdf.

2. Bioenergy Technologies Office, *Multi-Year Program Plan March 2016*, (Washington, DC: U.S. Department of Energy Bioenergy Technologies Office, 2016), http://energy.gov/sites/prod/files/2016/03/f30/mypp_beto_march2016_2.pdf.

3. G. C. Zittelli, N. Biondi, L. Rodolfi, and M. R. Tredici, "Photobioreactors for Mass Production of Microalgae," in *Handbook of Microalgal Culture: Applied Phycology and Biotechnology*, 2nd Edition, ed. Amos Richmond and Qiang Hu (Hoboken, NJ: John Wiley & Sons, Ltd., 2013), 225-266.

4. M. R. Tredici, G. C. Zittelli, and L. Rodolfi, "Photobioreactors," in *Encyclopedia of Industrial Biotechnology: Bioprocess, Bioseparation, and Cell Technology*, (Hoboken, NJ: John Wiley & Sons, Ltd., 2010), 1-15.

5. L. Rodolfi, G. Chini Zittelli, N. Bassi, G. Padovani, N. Biondi, G. Bonini, and M. R. Tredici, "Microalgae for Oil: Strain Selection, Induction of Lipid Synthesis and Outdoor Mass Cultivation in a Low-Cost Photobioreactor," *Biotechnology and Bioengineering* 102, no. 1 (2009): 100-112.

6. J. H. de Vree, R. Bosma, M. Janssen, M. J. Barbosa, and R. H. Wijffels, "Comparison of four outdoor pilot-scale photobioreactors," *Biotechnology for Biofuels* 8, no. 1 (2015): 1-12.

7. J. H. de Vree, R. Bosma, R. Wieggers, S. Gegic, M. Janssen, M. J. Barbosa, and R. H. Wijffels, "Turbidostat operation of outdoor pilot-scale photobioreactors," *Algal Research* 18 (2016): 198-208.

8. A. San Pedro, C. V. González-López, F. G. Acién, and E. Molina-Grima, "Outdoor pilot production of *Nannochloropsis gaditana*: Influence of culture parameters and lipid production rates in raceway ponds," *Algal Research* 8 (2015): 205-213.

9. A. San Pedro, C. V. González-López, F. G. Acién, and E. Molina-Grima, "Outdoor pilot-scale production of *Nannochloropsis gaditana*: Influence of culture parameters and lipid production rates in tubular photobioreactors," *Bioresource Technology* 169 (2014): 667-676.

10. A. San Pedro, C. V. González-López, F. G. Acién, and E. Molina-Grima, "Outdoor pilot production of *Nannochloropsis gaditana*: Influence of culture parameters and lipid production rates in flat-panel photobioreactors," *Algal Research* 18 (2016): 156-165.

11. P. Slegers, P. Van Beveren, R. Wijffels, G. Van Straten, and A. Van Boxtel, "Scenario analysis of large scale algae production in tubular photobioreactors," *Applied Energy* 105 (2013): 395-406.

12.   P. M. Slegers, M. B. Lösing, R. H. Wijffels, G. van Straten, and A. J. B. van Boxtel, "Scenario evaluation of open pond microalgae production," *Algal Research* 2, no. 4 (2013): 358-368.

13.   P. M. Slegers, R. H. Wijffels, G. van Straten, and A. J. B. van Boxtel, "Design scenarios for flat panel photobioreactors," *Applied Energy* 88, no. 10 (2011): 3342-3353.

14.   M. Huesemann, B. Crowe, P. Waller, A. Chavis, S. Hobbs, S. Edmundson, and M. Wigmosta, "A validated model to predict microalgae growth in outdoor pond cultures subjected to fluctuating light intensities and water temperatures," *Algal Research* 13 (2016): 195-206.

15.   R. Slade, and A. Bauen, "Micro-algae cultivation for biofuels: cost, energy balance, environmental impacts and future prospects," *Biomass and Bioenergy* 53 (2013): 29-38.

16.   J. W. Richardson, M. D. Johnson, X. Zhang, P. Zemke, W. Chen, and Q. Hu, "A financial assessment of two alternative cultivation systems and their contributions to algae biofuel economic viability," *Algal Research* 4 (2014): 96-104.

17.   M. S. Chauton, K. I. Reitan, N. H. Norsker, R. Tveterås, and H. T. Kleivdal, "A techno-economic analysis of industrial production of marine microalgae as a source of EPA and DHA-rich raw material for aquafeed: Research challenges and possibilities," *Aquaculture* 436 (2015): 95-103.

18.   O. Jorquera, A. Kiperstok, E. A. Sales, M. Embiruçu, and M. L. Ghirardi, "Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors," *Bioresource Technology* 101, no. 4 (2010): 1406-1413.

19.   R. Davis, A. Aden, and P. T. Pienkos, "Techno-economic analysis of autotrophic microalgae for fuel production," *Applied Energy* 88, no. 10 (2011): 3524-3531.

20.   N.-H. Norsker, M. J. Barbosa, M. H. Vermuë, and R. H. Wijffels, "Microalgal production — A close look at the economics," *Biotechnology Advances* 29, no. 1 (2011): 24-27.

21.   M. Marsullo, A. Mian, A. V. Ensinas, G. Manente, A. Lazzaretto, and F. Marechal, "Dynamic Modeling of the Microalgae Cultivation Phase for Energy Production in Open Raceway Ponds and Flat Panel Photobioreactors," *Frontiers in Energy Research* 3, no. 41 (2015).

22.   C. M. Beal, L. N. Gerber, D. L. Sills, M. E. Huntley, S. C. Machesky, M. J. Walsh, J. W. Tester, I. Archibald, J. Granados, and C. H. Greene, "Algal biofuel production for fuels and feed in a 100-ha facility: A comprehensive techno-economic analysis and life cycle assessment," *Algal Research* 11 (2015): 375-378.

23.   M. E. Huntley, Z. I. Johnson, S. L. Brown, D. L. Sills, L. Gerber, I. Archibald, S. C. Machesky, J. Granados, C. Beal, and C. H. Greene, "Demonstrated large-scale production of marine microalgae for fuels and feed," *Algal Research* 11 (2015): 379-380.

24.   "Cellana Media Resources," Cellana, accessed September 29, 2016, http://cellana.com/news-events/media/.

25.   M. R. Tredici, L. Rodolfi, N. Biondi, N. Bassi, and G. Sampietro, "Techno-economic analysis of microalage biomass production in a 1-ha Green Wall Panel (GWP) plant," *Algal Research* 19 (2016): 253-263.

26.   AJCespedes, "Photo of Photobioreactor Closed for the Cultivation of Microalgae Inside a Greenhouse," 2019.

27.   Published with permissions from Algenol, "Photo of Algenol Hanging Bags," 2019.

28.   "Aspen Plus Release 7.2," Aspen Technology Inc., Cambridge, MA, accessed August 20, 2016, https://www.aspentech.com/en/products/engineering/aspen-plus.

29.   M. R. Tredici, "Photobiology of microalgae mass cultures: understanding the tools for the next green revolution," *Biofuels* 1, no. 1 (2010): 143-162.

30.   M. Wigmosta, personal communication, May 2016.

31.   F. G. Acién, J. M. Fernández, J. J. Magán, and E. Molina, "Production cost of a real microalgae production plant and strategies to reduce it," *Biotechnology Advances* 30, no. 6 (2012): 1344-1353.

32.   R. Davis, D. Fishman, E. D. Frank, M. S. Wigmosta, A. Aden, A. M. Coleman, P. T. Pienkos, R. J. Skaggs, E. R. Venteris, and M. Q. Wang, *Renewable Diesel from Algal Lipids: an Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model,* (Golden, CO: National Renewable Energy Laboratory, ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437, 2012), https://www.nrel.gov/docs/fy12osti/55431.pdf.

33.   R. E. Davis, J. N. Markham, C. M. Kinchin, C. Canter, J. Han, Q. Li, A. Coleman, M. Wigmosta, and Y. Zhu, *2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling,* (Golden, CO: National Renewable Energy Laboratory, ANL-18/12; NREL/TP-5100-70715; PNNL-27547, 2018), https://www.nrel.gov/docs/fy18osti/70715.pdf.

34.   M. R. Tredici, N. Bassi, M. Prussi, N. Biondi, L. Rodolfi, G. Chini Zittelli, and G. Sampietro, "Energy balance of algal biomass production in a 1-ha 'Green Wall Panel' plant: How to produce algal biomass in a closed reactor achieving a high Net Energy Ratio," *Applied Energy* 154 (2015): 1103-1111.

35.   B. Verrecht, T. Maere, I. Nopens, C. Brepols, and S. Judd, "The cost of a large-scale hollow fibre MBR," *Water Research* 44, no. 18 (2010): 5274-5283.

36.   C. Beal, and M. Huntley, personal communication, June 10, 2016.

37.   C. Beal, and M. Huntley, personal communication, September 29, 2016.

38.   F. Wintersteller, "Crystal clear benefits of tubular glass photobioreactors," presented at Algae Europe, Lisbon, Portugal, December 1-3, 2015.

39.   "References of Complete Tubular PBR Systems," Schott, accessed September 29, 2016, http://microsites.schott.com/us-pbr/english/references/references.html.

40.   R. Bosma, J. H. de Vree, P. M. Slegers, M. Janssen, R. H. Wijffels, and M. J. Barbosa, "Design and construction of the microalgal pilot facility AlgaePARC," *Algal Research* 6, part B (2014): 160-169.

41.   C. H. Endres, A. Roth, and T. B. Brück, "Thermal Reactor Model for Large-Scale Algae Cultivation in Vertical Flat Panel Photobioreactors," *Environmental Science & Technology* 50, no. 7 (2016): 3920-3927.

42.   "Aspen Capital Cost Estimator Release 8.6," Aspen Technology Inc., Cambridge, MA, accessed August 20, 2016, https://www.aspentech.com/en/products/engineering/aspen-capital-cost-estimator.

43.   R. Davis, L. Tao, E. C. D. Tan, M. J. Biddy, G. T. Beckham, C. Scarlata, J. Jacobson, K. Cafferty, J. Ross, J. Lukas, D. Knorr, and P. Schoen, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbon*s, (Golden, CO: National Renewable Energy Laboratory, NREL/TP-5100-60223, 2013), http://www.nrel.gov/docs/fy14osti/60223.pdf.

44.   K. Gerdes, J. Black, J. Haslback, A. P. Jones, W. Lundberg, V. Shah, A. Kyle, and E. Lewis, *Cost and Performance of PC and IGCC Plants for a Range of Carbon Dioxide Capture*, (Pittsburg, PA: National Energy Technology Laboratory, DOE/NETL-2011/1498, 2011).

45.   H. Jilvero, N.-H. Eldrup, F. Normann, K. Andersson, F. Johnsson, and R. Skagestad, "Techno-economic evaluation of an ammonia-based post-combustion process integrated with a state-of-the-art coal-fired power plant," *International Journal of Greenhouse Gas Control* 31 (2014): 87-95.

46.   D. Keairns, R. Newby, and V. Shah, *Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture*, (Pittsburgh, PA: National Energy Technology Laboratory, DOE/NETL-2012/1557, 2012),

47.   "National Agricultural Statistics Service: Quick Stats," U.S. Department of Agriculture, accessed 2015, http://quickstats.nass.usda.gov/.

48.   "Electricity Retail Price to Consumers," U.S. Energy Information Administration, accessed July 2013, http://www.eia.gov/electricity/data.cfm#sales.

49.   W. D. Seider, J. D. Seader, and D. R. Lewin, *Product and Process Design Principles: Synthesis, Analysis, and Evaluation*, 2nd ed. (New York, NY: John Wiley and Sons, 2004).

50.   A. Muller-Feuga, M. Lemar, E. Vermel, R. Pradelles, L. Rimbaud, and P. Valiorgue, "Appraisal of a horizontal two-phase flow photobioreactor for industrial production of delicate microalgae species," *Journal of Applied Phycology* 24, no. 3 (2012): 349-355.