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Pacific Northwest NATIONAL LABORATORY

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Algae Farm Cost Model: Considerations for Photobioreactors

Y Zhu
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October 2018

U.S. DEPARTMENT OF ENERGY

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Executive Summary

Cost estimates and assumptions for a vertical hanging-bag type photobioreactor (PBR) system are reported here for a preliminary model developed to elucidate major cost drivers and opportunities for reducing the costs of algae cultivation. The design inputs and assumptions for this system are described in the report. A baseline case is presented, and alternative cases with differing areal algal productivities are used to compare to an open-pond case. The baseline algae production cost is estimated to be $1,137/short ton (st) algae, on an ash-free dry weight (AFDW) basis (2016 US$). Sensitivity analyses probe the areal productivity, support structure cost, and PBR bag replacement cost and life as significant impact factors affecting the system cost. A preliminary comparison of the PBR system and an open pond system is also developed to indicate the cost difference between these two systems. The baseline economic summary is shown in Table ES.1.

Table ES.1. Summary Economics

Algal Biomass Production - Photobioreactor

Minimum Algae Selling Price (MFSP)	**1,137**	$/st AFDW algae (delivered at 20 wt% solids (AF basis)
Algae annual productivity	**36.8**	kst/yr AFDW
Internal Rate of Return (After-Tax)	10%	
Equity Percent of Total Investment	40%	
Cost Year	2016	

CAPITAL COSTS		
PBR structure structure	$67,700,000	79.7%
CIP systems	$5,640,000	6.6%
Inoculum system	$4,510,000	5.3%
CO2 Delivery	$1,030,000	1.2%
Makeupwater delivery + On-site circulati	$470,000	0.6%
Dewatering	$4,300,000	5.1%
Storage	$1,260,000	1.5%
Missing Equipment	$0	0.0%
Total Installed Capital Cost	$84,900,000	100%
Building, site development, add'l piping	$3,200,000	
Indirect Costs	$29,900,000	
Working Capital	$5,900,000	
Land	$9,507,000	
Fixed Capital Investment (FCI)	$118,000,000	
Total Capital Investment (TCI)	$133,400,000	
Installed Capital per Annual st AFDW Alga	$2,307	
TCI per Annual AFDW st algae	$3,625	
Loan Rate	8.0%	
Term (years)	10	
Capital Charge Factor (computed)	$0.00	

MANUFACTURING COSTS		
Plant Hours per year	7920	
	$/st Algae	**mm$/year**
Natural Gas	0.00	$0
CO2	93.7	3.45
Nutrients (Ammonia and DAP)	95.3	3.51
CIP	27.0	0.99
PBR Replacement	194	7.14
Electricity	41.5	1.53
Makeup Water	0.00	0.00
Fixed Costs	167	6.13
Capital Depreciation	0.00	3.93
Average Income Tax	43.0	1.58
Average Return on Investment	476	17.5
	1,137	45.8

PERFORMANCE	
Total Electricity Usage (KW)	2,851
Electricity Produced Onsite (KW)	0
Electricity Purchased from Grid (KW)	2,851
Electricity Sold to Grid (KW)	0
Net Electricity Use (KWh/st product)	614

Note: CIP = clean in place.

Acknowledgments

The authors wish to thank the U.S. Department of Energy Bioenergy Technologies Office for funding this work. We also wish to thank our industrial partners who provided invaluable feedback and guidance.

Acronyms and Abbreviations

AFDW	ash-free dry weight
CIP	clean in place
DOE	U.S. Department of Energy
HTL	hydrothermal liquefaction
MBSP	minimum biomass selling price
NREL	National Renewable Energy Laboratory
PBR	photobioreactors
PVC	polyvinyl chloride
SOT	state of technology

Unit Abbreviations

g/L	grams per liter
$g/m^2/d$	grams per square meter per day
ft	feet
L	liter
$L/m^2/d$	liters per square meter per day
st	short ton
t	ton
W/m^3	watts per cubic meter
yr	year

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1.0 Introduction

Development of renewable energy provides value to the country by making use of domestic natural resources and deriving economic gains through jobs, infrastructure development, and technical competitiveness. Different biomass feedstocks (e.g., wood, switchgrass, and algae) have been investigated for liquid fuels production (Xu and Lad 2008, Mullen and Boateng 2008, Biller and Ross 2011). Liquid fuels and products from microalgae do not compete with food or fiber when sustainable water and land use are considered (Efroymson et al. 2017). Further, microalgae exhibit higher photosynthesis efficiency (compared with agricultural and forest crops), which enables faster conversion of CO_2 and water into biomass, and thus improves CO_2 mitigation ability (Brennan and Owende 2009). This efficient use of solar energy enables microalgae to produce up to 30 times more lipids per unit area than oilseed crops (Luque et al. 2011). These advantages have prompted extensive research into algae cultivation in order to reduce the cultivation cost and increase the productivity of microalgae for use in the production of fuels and chemicals.

Algae cultivation methods include open, closed, and hybrid cultivation systems (IEA Bioenergy 2017, DOE 2016a, 2016b). A typical open system, such as a raceway pond, consists of a closed-loop channel with circulation pumps and underground distribution pipelines. A closed photobioreactor (PBR) system consists of closed transparent reactors, which can be tubes, flat panels, bags, or columns, or flat-plate, floating-bag, vertical flat-bag, or vertical or horizontal tubes or columns (Beal et al. 2015, Borowitzka and Moheimani 2013, Algasol Renewables 2015, OriginClear Group 2014, Jorquera et al. 2010, Luque et al. 2011, Kotrba 2015, Menetrez 2012, National Research Council 2012, Woods 2015). Open-pond and PBR systems have been tested at the laboratory and commercial scales (IEA Bioenergy 2017, White and Ryan 2015). Compared to the open pond systems, a PBR system features better control of the cultivation environment because of the closed reactor design, with respect to nutrient feed, water supply, gas mixing, protection from external contamination, and evaporation loss. In addition, PBRs have higher algae harvest concentration and higher algae productivity, and therefore the potential for significant productivity improvements when compared to open pond systems for the same algal production yields (Richardson et al. 2014). Recent modeling efforts indicate that productivity improvements per unit of top surface area can be realized, but that production per land surface area is highly dependent upon PBR spacing and orientation (Wigmosta 2017). PBR systems can use natural or artificial light. The costs presented here are for a natural-light system.

The first-generation cultivation method were types of large-scale open-pond production of microalgae, and these predominated in the market over PBR systems. In recent years, commercial-scale production using PBR or hybrid (raceway combined with PBR) systems have undergone great development (IEA Bioenergy 2017). Although some literature estimated that PBR systems have higher production costs than open pond systems, more recent studies show potential for cost improvements (Davis et al. 2011, Richardson et al. 2014, Kotrba 2015). The economic features of open pond systems have been extensively reported (DOE 2016a). However, for PBRs, little analysis of economic risks and benefits exists. Considering the advantages of PBRs in algae cultivation, this study reports the development of a preliminary PBR cost model to provide economic evaluation for a large-scale PBR system.

Plastic-bag type PBRs receive more attention than other types in the literature. This is because of their lower material cost for commercial-scale production. Additionally, they offer good sterility at start-up because of their high film-extrusion temperatures (Wang et al. 2012, Algasol Renewables 2015, Woods 2015). Floating-bag PBR systems have application in ocean environments, while vertical flat-bag PBR systems are best suited for land-based operations (Kotrba 2015). Considering the land use flexibility of vertical hanging flat-bag PBR systems and their smaller cultivation area requirement compared to floating-bag PBRs, the vertical hanging flat-bag PBR is chosen for this initial study.

This report is divided into three sections:

- design basis for a plastic bag PBR system
- preliminary economic considerations and key sensitivity factors associated with the cost of production
- conclusions

2.0 Design Basis

A typical plastic bag PBR is shown in Figure 2.1. The PBR system consists of plastic bags, frame (which supports the plastic bag), and aeration systems (Huang et al. 2017, Han et al. 2017).

Figure 2.1. Vertical Plastic Bag PBR Example (Huang et al. 2017)

The PBR cost model is developed in an Excel format. The design for the PBR system is based on open literature (Woods 2015, Kotrba 2015, Jessen 2015) and the results have been reviewed by an industrial expert with commercial PBR operating experience. The major input parameters for the PBR cost model are listed in Table 2.1. These include cultivation related parameters (algae areal productivity, biomass harvesting concentration, water loss, etc.) and PBR unit parameters (bag dimensions, number, and lifetime). The cultivation area is assumed to be 1000 acres, which is reasonable for a PBR based commercial algae farm operation based on industrial input. The areal productivity for plastic bag PBR systems greatly varies depending on different culture conditions (temperature, whether indoor or outdoor, seasonal variations, location, bag dimensions, etc.) and algae strain types. Han et al. (2017) and Zittelli et al. (2013) claim that the areal productivity of plastic bag PBR systems can be very high. Similarly, a flat-plate PBR system is reported to have a productivity ranging from 5 to 35 g/m^2/d (Acién et al. 2017). Based on the above literature information, an annual average cultivation areal productivity of 25 g/m^2/d on an AFDW (ash-free dry weight) basis is selected and assumed for this study. With the specified areal productivity and the assumed hydraulic retention time of 3 days, the resulting biomass harvesting concentration is 2 grams/liter (g/L). A range of 1 to 4 g/L for PBR systems has been reported in the literature, and this range is used in this study for sensitivity analysis. PBR systems generally have higher harvesting concentration than that of open pond systems because PBRs function like settlers, which can lead to higher harvest concentration and thus lower costs for algae dewatering (Jorquera et al. 2010, Menetrez 2012, Davis et al. 2016). The PBR energy consumption mainly includes (1) water circulation, which is specified based on literature values for flat-panel vertical PBR systems (Borowitzka and Moheimani 2013, Jorquera et al. 2010); (2) aeration, which is based on industrial experts' inputs; and (3) algae dewatering (Davis et al. 2016).

Table 2.1. PBR Cost Model Parameters

Parameters	Unit	Values
Algae farm type		Vertical flat-bag PBR
Algae farm cultivation area	acre	1,000
Annual average areal productivity	$g/m^2/d$ AFDW	25
Area per PBR module	acre	5
PBR bags per module		18,000
PBR bag size		
Length	feet	10
Height	feet	4
Depth	inch	2
Working volume	liter	50
Hydraulic retention time	day	3
Energy consumption		
Water circulation	W/m^3	287
Aeration	kWh/st AFDW	340
Algae dewatering	kWh/m^3	0.04 for membrane and 1.35 for centrifuge
Coolant		cooling water
Evaporation loss of cooling water	$L/m^2/d$	1
Evaporation loss from PBR	$L/m^2/d$	0.02 to 0.07
CO_2 and nutrients utilization efficiency	percentage of stoichiometric demands	10% for CO_2 and 20% each for diammonium phosphate (DAP) and anhydrous ammonia (NH_3)

The major capital cost components include PBR support structure, inoculum, and clean-in-place (CIP) systems. Other capital costs are the systems for CO_2 delivery, makeup water delivery, and algal dewatering. The PBR bag costs are estimated as a variable operating cost based on the bag life specification. Key costs are shown in Table 2.2 and in the Appendix.

The PBR bag cost is specified based on review by an industrial practitioner in the field, and also compared to the cost derived from literature information (Algasol Renewables 2015). The capital cost for the inoculum system is estimated from literature information for a 5 acre PBR module (Scott et al. 2015). It is assumed that for every 5 acres of PBR, there is an associated inoculation system required and its major equipment includes inoculum tanks, drip emitters, and surge tanks. The capital costs for CO_2 delivery, makeup water delivery, and dewatering systems are based on information from the National Renewable Energy Laboratory (NREL) open pond farm report (Davis et al. 2016). Algae compositions reported in Jones et al. (2014) for *Chlorella*, a freshwater strain, are assumed for this study and used to estimate the CO_2 and nutrient requirements.

Table 2.2. Key Capital and Operating Cost Inputs

Parameters	Values	Note
Cost per PBR Bag	$10 (2014 US$)	per industrial review
PBR bag life	5 years	3 to 8 years per industrial review
PBR support structure	$20/PBR bag (2014 US$)	$10–30 per industrial review
CIP chemicals	1000 $/acre/yr (2014 US$)	$500 to 1500 $/acre/yr per industrial review
PBR related labor cost	$3500/acre (2014 US$)	per industrial review

Additional cost assumptions include

- 2016 US$
- 30 year plant life, Modified Accelerated Cost Recovery System (MACRS) depreciation, and 330 operating days/year
- 40% equity, with 10 year loan at 8% interest
- 10% internal rate of return
- 21% income tax rate
- warehouse, site development, piping, and indirect cost estimates based on the installed capital cost for cultivation and dewatering areas
- $3000/acre for land
- working capital is 5% of fixed capital investment.

3.0 Results and Discussion

This section summarizes the analysis results for the initial PBR system algae cultivation Excel-based cost model. A baseline case was developed, and the major cost results are shown in Table 3.1.

Table 3.1. Major Cost Estimation Results

Installed costs (2016$)	**million US$**	**Percentage of total installed cost**
PBR support structure	67.7	78%
CIP system	5.64	6.5%
Inoculum system	4.51	6.8%
CO_2 delivery system	1.03	1.2%
Makeup water delivery and onsite circulation	0.47	0.6%
Dewatering to 20 wt% solids	4.30	5.0%
Storage	1.26	1.5%
Total installed cost	84.9	100%
Warehouse and site development	3.22	
Total direct cost	88.1	
Total indirect cost	29.9	34% of installed costs
Fixed capital investment (FCI)	118	
Total capital investment (TCI)	133	
Production cost breakdown	**$/st AFDW**	**% in total**
Cultivation and inoculum system	539	47.4%
PBR bag replacement	194	17.1%
CO_2 and nutrients	198	17.4%
Dewatering	31.8	2.8%
Storage	7.70	0.7%
Fixed operating cost	167	14.6%
Minimum biomass selling price (MBSP)	1,137	

The PBR cultivation and inoculum system's capital costs represent over 90% of the total cost. The PBR bag replacement costs are treated as variable operating costs, and the initial set of bags is not included in the capital costs. For the production cost breakdown based on each major area, the cost in unit of $/st AFDW (short ton, ash free dry weight) was estimated. The total cost of the PBR cultivation and inoculum system and bag replacement represents about 65% of the total production cost. Figure 3.1 depicts the operating cost breakouts for the PBR system. The PBR bag replacement and fixed costs together represent about 60% of the operating cost, and the PBR bag cost is the most significant one.

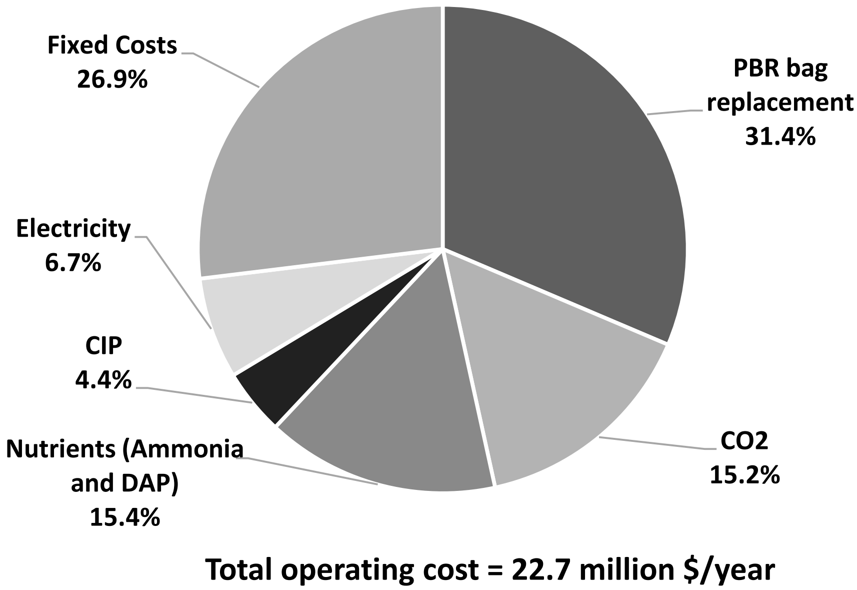

Figure 3.1. Operating Cost Allocation for PBR System

Because the PBR algae cultivation technologies are still in the early development stage, there are many uncertainties related to the process parameters. To understand the effects of the variations in key parameters on the PBR system cost, the values for the cultivation areal productivity, PBR support structure costs, CO_2 and nutrient costs, PBR bag replacement cost, PBR bag life, CO_2 and nutrients cost, algae cultivation area, and CIP capital cost are varied for sensitivity analysis. The baseline values and variation ranges for the selected parameters and their potential effects on the system are presented in Table 3.2.

Table 3.2. Selected Parameters for Sensitivity Analysis

Parameter	Values	Impacts	Notes
Cultivation areal productivity	Base case: 25 g/m^2/day Range: 5 to 50 g/m^2/day	Annual average production rate, harvest rate, and costs for circulation and dewatering processes	for a given cultivation area and harvesting concentration; productivity of 50 g/m^2/day represents a potential future target
PBR support structure cost	Base case: \$20/bag Range: ±50% of base case	Capital costs	Per input from industry review
PBR bag replacement cost	Base case: \$10.5/bag Range: ±50% of base case	Variable operating costs	Range is estimated
PBR bag life	Base case: 5 years Range: 3 to 8 years	Variable operating costs	Per input from industry review
CO_2 and nutrients cost	Base case: \$7.0 million/year Range: ±30% of base case	Variable operating costs	Range is estimated based on potential changes in CO_2 and nutrients' unit prices
Algae cultivation area	Base case: 1000 acres Range: 500 to 3000 acres	Annual algae production rate, fixed operating cost	Range is estimated
CIP system capital cost	Base case: \$6000/acre Range: ±50% of base case	Capital costs	Per input from industry review
Biomass harvesting concentration	Base case: 2 g/L Range: 1 to 4 g/L	Capital and operating cost related to dewatering and circulation	Range is based on literature values

The sensitivity analysis results are depicted in Figure 3.2 and Figure 3.3. The cultivation areal productivity has the most significant impact on the MBSP of the PBR system, as shown in Figure 3.2. In addition, a decrease in the productivity has a relatively greater effect on the cost than an increase in the productivity. The MBSP decreases by about 38% when the productivity increases from 25 to 50 g/m^2/d AFDW, while the cost increases about 300% when the productivity decreases from 25 to 5 g/m^2/d AFDW. The productivity change directly affects the annual algae yields and thus the operating cost in units of \$/st algae biomass. Productivity change also affects the capital cost for CO_2 delivery, circulation, dewatering, and storage. For operating cost, productivity affects the CO_2 and nutrients cost, as well as power consumption. The combined effects lead to significant changes in the final production cost.

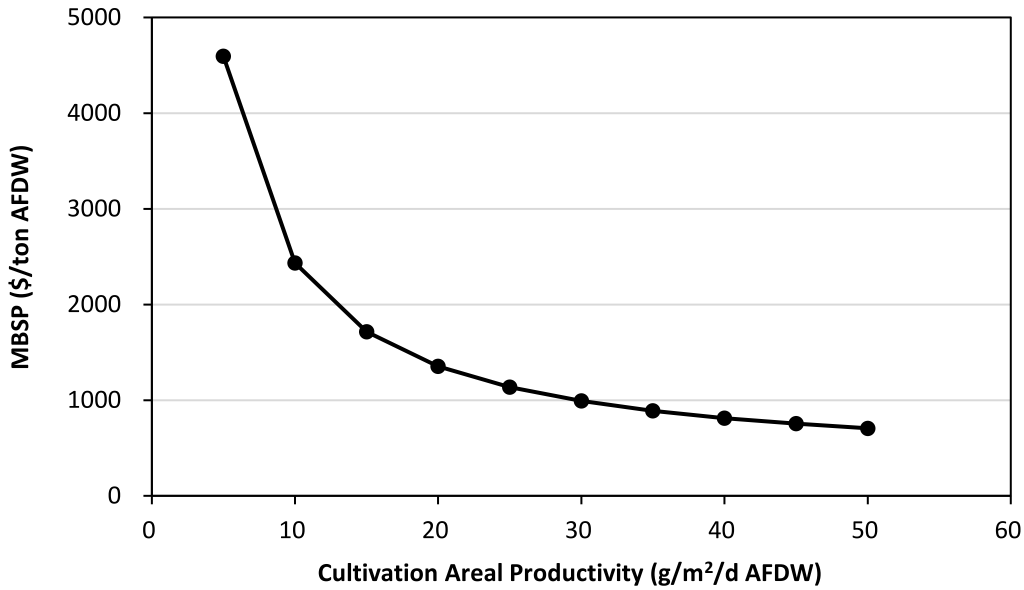

Figure 3.2. Effects of Cultivation Areal Productivity on the PBR Algae Farm Cost

The effects of other selected parameters on the MBSP of the PBR system are shown in Figure 3.3. The PBR support structure also significantly affects the algae production cost. Variation by ±50% leads to the MBSP changing by ±15% or, in absolute terms, from 961 to 1,312 $/ton AFDW algae. Although the support structure is a large cost component for the vertical-bag type PBR system investigated in this study, other types of PBR systems, such as floating bags, are likely to have different cost drivers that may be worth considering in future studies. Comparing Figure 3.2 and Figure 3.3, changing the cultivation areal productivities has much greater cost impacts than other selected parameters.

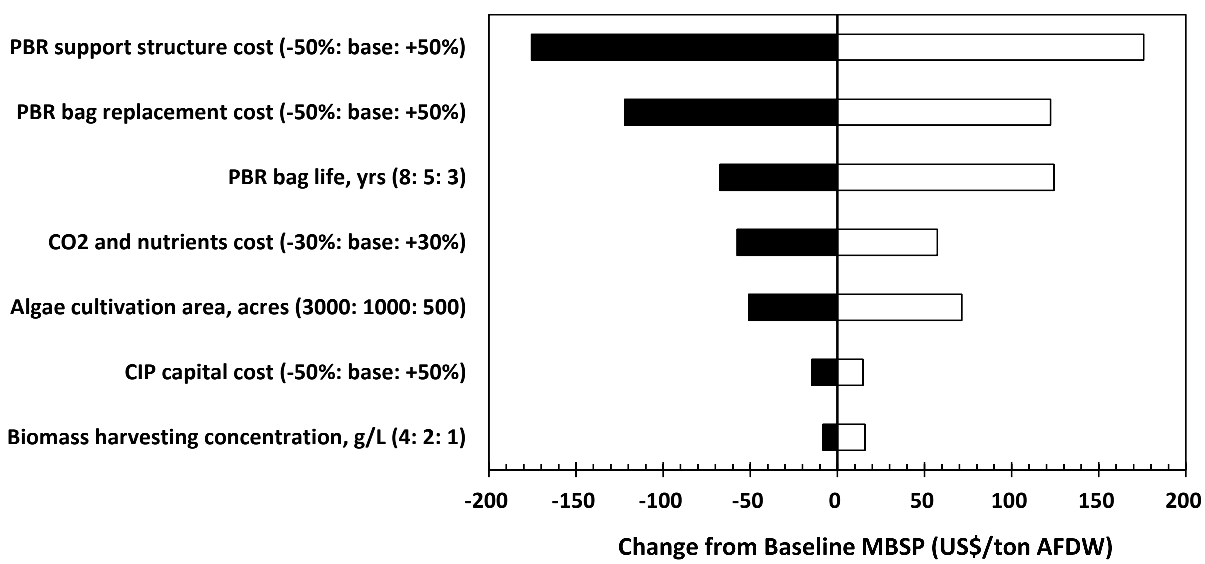

Figure 3.3. Effects of Selected Parameters on the PBR Algae Farm Cost

Other significant factors leading to more than a 10% production cost change include the PBR bag replacement cost and PBR bag life. The ±50% change in the PBR bag replacement cost leads to about

±11% change in the production cost. Therefore, reducing the PBR bag replacement cost is an important consideration towards lowering costs. Decreasing the PBR bag life from 5 to 3 years increases the production cost by 11%. Although the plastic bag reactors used in this PBR system are less expensive than other PBR materials such as glass or thick polyvinyl chloride (PVC), their replacement rate is still an important cost driver.

The algae cultivation area and the CO_2 and nutrients cost moderately affect the production cost within the specified variation range. In the PBR model of this study, the capital and operating costs related to the PBR cultivation and inoculum systems are linearly proportional to the cultivation area with scaling exponents of 1. When the areal productivity is a constant number, these costs are also linearly proportional to the annual algae yields. Therefore, the sensitivity analysis results do not demonstrate obvious economic benefits resulting from large plant scale or cultivation area. More pilot-scale or commercial-scale PBR systems need to be developed to provide information about the effects of large plant scale. Decrease in the CO_2 and nutrients cost can be realized by improving their utilization efficiencies and decreasing unit prices, such as obtaining CO_2 from lower cost sources. The effects of CIP capital cost and biomass harvesting concentration on the MBSP are minor, with less than 5% relative change, compared to other factors.

A preliminary comparison of the PBR system in this study and a typical open pond system was conducted to investigate the cost difference between these two systems. The comparison results are presented in Table 3.3. The open pond system cost information is from the 2016 Multiple-Year Program Plan (MYPP) (DOE 2016a). The same algae production scale, 188 ton/d AFDW, is assumed for the two types of algae farms as a consistent comparison basis. As mentioned earlier, many factors affect the productivity of PBR systems. Considering this and limited commercial-scale PBR operating data, three cases with different productivities are considered. Case A represents a highly optimistic, high productivity case based on literature suggestions for PBRs, which that have not been demonstrated. For Case B, the productivity and area are adjusted to match the same MBSP as for the open pond. Case C matches the same productivity of the open pond case (i.e., 8.5 g/m^2/day). The open system is based on a 5000 acre algae farm. For the comparison purpose, the cost analyses of PBR cases are adjusted to use consistent cost assumptions consistent with the open pond case, including the same cost year, 2014 US$, and income tax rate at 35%.

Table 3.3. Case Comparison of PBR and Open Pond Systems

Algae Farm Types	PBR			Open Pond (2015 SOT) [a]
Cases	Case A - high productivity	Case B - MBSP of open pond	Case C - productivity of open pond	
Algae production scale, ton AFDW/d	188	188	188	188
Productivity, g/m^2/day	50	21.7	8.5	8.5
Cultivation area, acres	845	1,945	5,000	5000
Production cost breakdown, $/ton (2014 US$)				
Cultivation and inoculum systems	407	873	2,145	945
CO_2 and nutrient demands	132	131	131	124
Other costs	137	223	467	158
MBSP	676	1,227	2,743	**1,227**

[a] SOT = state of technology

At very high PBR productivity, Case A results in a 45% lower MBSP than that of the open pond case. The major cost advantage for this case is the lower cultivation and inoculum system cost, which is about 57% lower than the open pond case. The high productivity of Case A leads to lower cultivation area and thus lower cost. The CO_2 and nutrient costs are mainly dictated by the algae composition and the efficiency of carbon and nutrient utilization. Therefore, the two systems have similar cost for the CO_2 and nutrient demands when the same algae composition is assumed. The other costs include the fixed operating costs (essentially manpower and associated overhead) and dewatering costs. Dewatering costs for PBR systems are typically lower than for open pond systems because PBR-grown algae can be harvested at higher concentrations, 1 to 4 g/L, than that from an open pond, 0.5 g/L (Jorquera et al. 2010, Menetrez 2012, Davis et al. 2016). For Case B with the same MBSP as the open pond case, the PBR system has higher productivity than the open pond case, and thus a smaller cultivation area. Although the higher productivity leads to 8% lower cultivation and inoculum cost, the other costs are 41% higher than the open pond case, mainly because the fixed operating costs (mainly labor) are higher. Because of the smaller cultivation area, the labor cost for the PBR system per acre of cultivation area is much higher than for the open pond system. For Case C with the same algae productivity and cultivation area, the MBSP is 124% higher than for the open pond case, mainly resulting from the higher cultivation and inoculum costs and the fixed operating cost.

The cost advantage of the PBR system mainly results from its potentially higher areal productivity and thus lower cultivation area than the open pond system. When the productivity of the PBR system is lower than approximately 20 g/m^2/day, there appears to be no cost advantage over the open pond system with 8.5 g/m^2/day productivity and other 2015 SOT assumptions. A target case for the open pond system is also documented by DOE (2016a), where an algal productivity of 25 g/m^2/day and other improvements are assumed. For appropriate comparison to the open pond target case, a PBR case with projected optimal productivity and design assumptions must be developed based on industrial inputs and comments, but is out of scope for this work. This should be considered for future work in this area. Alternative PBR designs have wide ranges in the productivities and capital costs, and thus the conclusions for comparison to the open pond systems may be different. In addition, because of the lack of technical and cost information for very large-scale PBR, this study is limited to not including the potential effects of scale change on biomass productivity as reported by Wigmosta et al. (2017). The effect of areal change on the PBR structure and CIP capital cost are based on the assumption that they vary linearly with the cultivation area. Future efforts should incorporate alternative PBR designs, scales, and productivity effects for a more robust comparison. When more field data for PBR systems becomes available, a more comprehensive comparison between PBR and other algae cultivation technologies can be conducted.

4.0 Conclusions

A preliminary cost model has been developed for a vertical hanging-bag PBR algae cultivation system based on industrial input and literature information. The largest cost contribution is from the PBR cultivation and inoculum systems. Sensitivity analysis demonstrates that the areal productivity, support structure cost, PBR replacement cost, and PBR bag life have significant effects on the PBR system economics. A simplified comparison of the PBR system to an open pond system at the same algae production scale with different productivities and areas was conducted. The PBR system modeled here potentially has a land use advantage relative to open pond systems. However, because of the potentially wide variations in the PBR system productivities, the PBR system must have much higher productivity than the open pond system at the projected large scale of the open ponds in order to have clear cost advantages.

Data Gaps

PBR algae cultivation systems are still in the early development phase, and different designs lead to significant variability and cost uncertainty. As such, the following data gaps have been identified:

1. Limited published information regarding PBR systems is available. More information is needed, for example, on long-term, large-scale PBR areal productivity and long-term robustness of PBR materials (bags, structures, etc.).
2. The PBR model reported here considers algae production only. PBR application for hybrid production of both algae and chemicals, such as ethanol, has been demonstrated, and the cost model for such a system could be developed to evaluate the advantages and risks of the hybrid production.
3. The PBR cost model would be more useful if integrated with a conversion facility model, such as hydrothermal liquefaction (HTL) and upgrading, to investigate the cost effects of recycling wastewater from conversion systems to the PBR cultivation system. Consideration could also be given to
    a. incorporating the co-feeding of other renewable feedstocks, such as dry terrestrial biomass, or wet wastes, to the conversion system, and investigating the effects of recycling streams on the PBR systems
    b. incorporating alternative HTL aqueous treatment methods and investigating the effects of recycling the effluent streams to the PBR systems.
4. PBR farm configurations, shading, and other factors that potentially increase areal land use are under investigation, and should be included in future evaluations of PBR systems.
5. Emerging approaches to CO_2 and nutrient utilization (via algal strain improvements), techniques for facilitating CO_2 transport, and farm operational approaches are under investigation, and should be included in future studies.

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Appendix

Equipment Cost Details
for Baseline Case

Area	Number Required	Number Spares	Equipment Name	Scaling Stream	Original Equipment Stream Flow	New Flows	stream flow units	Size Ratio	Original Equip Cost (per unit)	Base Year	COST BASIS: installed (i) or	Total Original Equip Cost (Req'd & Spare) in Base	Scaling Exponent	Scaled Cost in Base Year	Installation Factor	Installed Cost in Base Year	Installed Cost in 2016$	Scaled Uninstalled Cost in 2016$	source	CE Index base year	CE Index 2016
A001	1	0	PBR support structure	bags	1	3,600,000	units	3,600,000	$20	2014	i	$20	1	72,000,000	1.2	72,000,000	67,700,746	$56,417,289	1	576.1	541.7
	1	0	CIP system	Area	1	1,000	acres	1,000	$6,000	2014	i	$6,000	1	6,000,000	1.2	6,000,000	5,641,729	$4,701,441	1	576.1	541.7
A002	1	0	Inoculum system	Area	5	1,000	acres	200	$19,987	2014	b	$19,987	1	3,997,400	1.2	4,796,879	4,510,449	$3,758,707	2	576.1	541.7
A003			**CO2 Delivery**																		
	1	0	Pipeline CO2 storage sphere	CO2 requirement	68,550	8,303	kg/h	0.12	$1,400,800	2014	b	$1,400,800	0.6	394,741	1.25	493,427	463,963	$371,170	3	576.1	541.7
	1	0	Storage tank immersion vaporizers	CO2 requirement	68,550	8,303	kg/h	0.12	$70,500	2014	b	$70,500	1	8,539	1.76	15,029	14,132	$8,029	3	576.1	541.7
	1	0	Trunk line	CO2 requirement	68,550	8,303	kg/h	0.12	$1,661,900	2014	b	$1,661,900	1	201,295	1.0	201,295	189,275	$189,275	3	576.1	541.7
	1	0	Branch line	CO2 requirement	68,550	8,303	kg/h	0.12	$912,300	2014	b	$912,300	1	110,501	1.0	110,501	103,902	$103,902	3	576.1	541.7
	7	0	Injection fittings	CO2 requirement	1,371	1,186	kg/h	0.87	$44,200	2014	b	$309,400	1	267,682	1.0	267,682	251,698	$251,698	3	576.1	541.7
	1	0	Supply to Inoculum area	CO2 requirement	68,550	8,303	kg/h	0.12	$59,300	2014	b	$59,300	1	7,183	1.0	7,183	6,754	$6,754	3	576.1	541.7
	1	0	circulation	Makeup water	2,575	390	MMgal/y	0.15	$5,421,935	2014	b	$5,421,935	1.4	386,608	1.3	502,590	**472,579**	**$363,522**	3	576.1	541.7
A004			**Dewatering**																		
	1	0	Clarified water return pipe	Clarified water	66,420,622	2,475,516	kg/h	0.04	$11,329,058	2014	b	$11,329,058	1	422,237	1.0	442,133	415,733	$397,025	3	576.1	541.7
	2	0	Pump for clarified water pipeline	Clarified water	6,653	5,507	gpm	0.83	$121,905	2012	b	$243,810	0.8	209,592	1.15	241,031	223,344	$194,212	3	584.6	541.7
	3	0	Settler	Biomass harvesting	1,000	833	m3/h	0.83	$34,300	2014	b	$102,900	1	85,750	1.0	85,750	80,630	$80,630	3	576.1	541.7
	1	0	Membrane	1% wt% solid inlet	20,000,000	2,673,071	gal/d	0.13	$12,864,000	2014	b	$12,864,000	0.75	2,843,553	1.0	2,977,543	2,799,748	$2,673,759	3	576.1	541.7
	1	0	Centrifuge	13wt% solid inlet	463	32	m3/h	0.07	2,242,500	2013	b	$2,242,500	0.6	454,910	1.8	818,839	781,888	$434,382	3	567.3	541.7
A005	1	0	Storage	Algae biomass to	152,336	21,077	kg/h 20wt%	0.14	$3,982,119	2014	b	$3,982,119	0.7	997,296	1.3	1,336,376	**1,256,579**	**$937,745**	3	576.1	541.7
												Total Equipment cost				**$90,296,257**	**$84,913,148**	**$70,889,542**			

Source References

1 Correspondence with industrial experts

2 Estimated based on PBR inoculum system information in US 9,121,012 B2

3 NREL/TP-5100-64772, Process Design and Economics for the Production of Algal Biomass, Feb. 2016

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