ANL/ESD-17/13

# Greenhouse Gas Emissions, Energy and Water Use of Photobioreactors for Algal Cultivation and Biofuels Production

Energy Systems Division

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# Greenhouse Gas Emissions, Energy and Water Use of Photobioreactors for Algal Cultivation and Biofuels Production

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June 2017

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# 1. INTRODUCTION

The Department of Energy's Bioenergy Technology Office (BETO) collaborates with a wide range of institutions towards the development and deployment of biofuels and bioproducts (DOE BETO 2016). To facilitate this effort, BETO and its partner national laboratories develop detailed techno-economic assessments (TEA) of biofuel production technologies. The National Renewable Energy Laboratory (NREL) recently completed an algal cultivation photobioreactor (PBR) study as part of an internal BETO milestone (Davis et al., 2017, the PBR study henceforth), which used a techno-economic analysis (TEA) to estimate the minimum biomass-selling price (MBSP) of algae biomass at the farm gate. The biomass cost projections considered the design and operation of a culture inoculum system, biomass production, $CO_2$ storage and delivery, onsite circulation of cultures and clarified water, makeup water delivery, and biomass dewatering.

The goal of this analysis is to expand the GREET model and determine greenhouse gas (GHG) emissions, fossil energy consumption, and water use from the algal biomass production and dewatering operations as modeled in the PBR study. To obtain the well-to-wheel (WTW) life-cycle GHG emissions, energy and water use from PBR study (biomass production and dewatering) were added to the combined algae process (CAP). CAP produces renewable diesel and naphtha from lipids, ethanol from sugars, and heat-power-nutrient recycles from anaerobic digestion of the protein residue (Frank et al. 2016).

# 2. METHODOLOGY

## 2.1 LIFE CYCLE ANALYSIS SYSTEMS BOUNDARY AND FUNCTIONAL UNIT

The system boundary for the LCA in this study encompasses all operations related to the biomass growth and dewatering, biomass conversion to fuel, fuel transportation and distribution, and fuel combustion in vehicles (Figure 1). In addition, the system boundary also includes the indirect GHG emissions, energy and water use associated with the nutrients, materials, and energy production. The indirect GHG emissions, energy and water use associated with the PBR materials are included in the system boundary, but those associated with the infrastructure materials and equipment used elsewhere in the algae farm are not included.

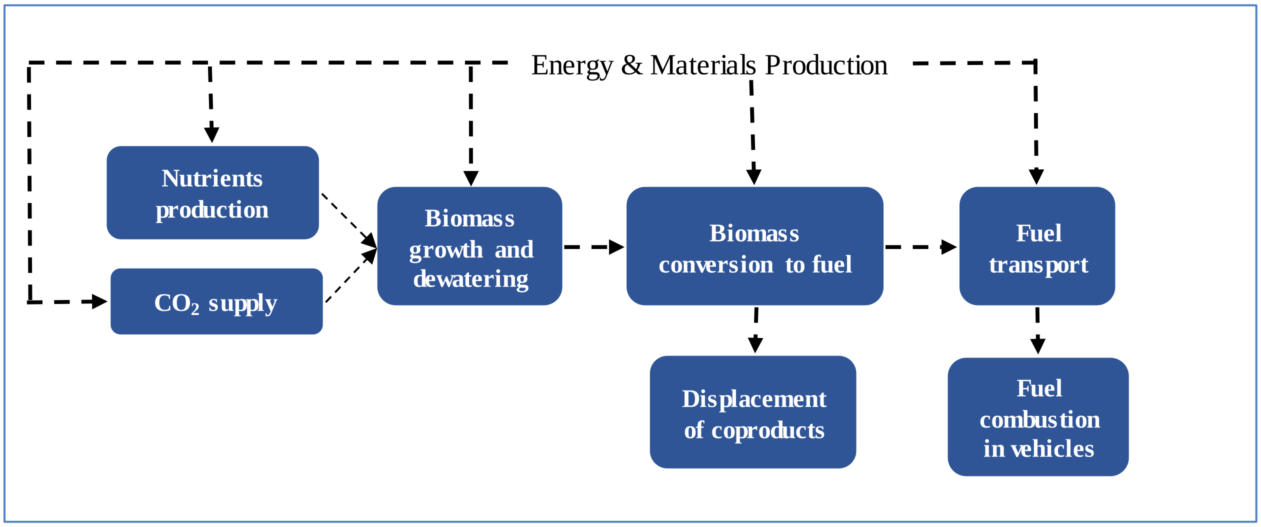


**Figure 1. Life cycle analysis (LCA) system boundary: biomass growth and dewatering, biomass conversion to fuel, fuel transportation and distribution, and fuel combustion in vehicles**

The functional unit of this LCA is one mega joule (MJ) of total fuels based on the lower heat value (LHV). GHG emissions, energy and water use are reported per MJ of fuels. To simplify the analysis and avoid technical questions regarding allocation methods, the LHV of the renewable diesel (RD), ethanol, and naphtha were combined into a total fuel output, which is referred here as "RD equivalent ($RD_e$)" (Pegallapati and Frank 2016).

The life cycle GHG emissions, water and energy use are computed using Argonne National Laboratory's GREET® (The Greenhouse gases, Regulated Emissions and Energy Use in Transportation) model (GREET 2016). The GREET model includes various feedstocks, conversion technologies and fuels. In addition, the GREET model includes all transportation subsections, including road, rail, marine, and air transportation (GREET 2016). Frank et al. (2011) developed the Algae Process Description (ADP) platform to explore algae biofuel productions options. The ADP is an excel file with several worksheets, including $CO_2$ sourcing, nutrients, algae biomass growth and dewatering, and fuel production. The ADP exchanges data with the GREET model through the GREET-APD interface. In this project, we expanded the GREET model for PBR, including algae growth and dewatering and algae fuel process. The expanded model eliminated data exchange between the GREET model and the ADP, which improves the speed and efficacy of algal fuel LCA development. Additionally, the expand GREET provides clear and consistent algal biofuel modeling approach and structure with other pathways.

## 2.2 PHOTOBIOREACTOR DESIGN AND MATERIALS

The PBR study considered four different PBR designs: a horizontal tubular system (PBR1-HT) (Beal et al. 2015, Huntley et al. 2015), a flat-panel hanging bag system (PBR2-HB) (Markham and Davis 2017b), a flat-panel standing bag system (PBR3-SB, also known as the GWP-II system) (Tredici et al. 2016, Zittelli et al. 2013), and a glass helical tubular system (PBR4-GT) (Acien et al. 2012, Wintersteller 2015). The PBR1-HT system is made of low-density polyethylene (LDPE) with total volume of 4,169,601 $m^3$, the tubular diameter is 0.38 m, and its target lifetime is 2 years (Table 1) (Markham and Davis 2017a). Total plastic material weight is 12,922,484 kg, the daily material consumption rate is 17,702 kg/day, and the material consumption per unit algal biomass is 0.0343 kg/kg afdw (ash free dry weight). Both PBR2-HB and PBR3-SB were based on design details furnished to NREL by Leidos Engineering and the University of Florence, respectively. These two PBRs were assumed to be made of LDPE and have the same volume of 285,261 $m^3$. The developers furnished details of the PBR3-SB system. Details were not available for the PBR2-HB design, thus it was assumed to be the same as the former basis (Markham and Davis 2017a). They have different target lifetimes of 6 years and 1 year (PBR2-HB vs PBR3-SB respectively, Table 2). For PBR2-HB and PBR3-SB, the daily material consumption rates are 1,713 and 10,275 kg/day, and material consumptions per unit algal biomass are 0.0034 and 0.0201kg/kg afdw, respectively. PBR4-GT is a fence-type reactor with total volume of 285,261 $m^3$ and the lifetime of 50 years (Table 1) (Acien et al. 2012, Wintersteller 2015). Amortization of the total material weight (141,876,660 kg) results in a glass consumption of 0.0152 kg/kg afdw.

**Table 1. The horizontal tubular system (PBR1-HT) and the glass helical tubular system (PBR4-GT) design, dimensions and material requirements**

| | PBR1-HT | PBR4-GT | Data source |
|---|---|---|---|
| Volume ($m^3$) | 4,169,601 | 348,986 | NREL[a] |
| Diameter (m) | 0.38 | 0.0628 | NREL |
| Thickness | 12.5 mil (plastic) | 0.22 cm (glass) | NREL |
| Inner cross-section area ($m^2$) | 0.1130 | 0.0027 | NREL |
| Length (m) | 36,888,424 | 130,284,404 | NREL |
| Density | 0.925 g/$cm^3$ (LDPE) | 2600 kg/$m^3$ (glass) | GREET[b] |
| Lifetime (yr) | 2 | 50 | NREL |
| Material volume ($m^3$) | 13,970 | 54,568 | Calculation |
| Material weight (kg) | 12,922,484 | 141,876,660 | Calculation |
| Material consumption (kg/day) | 17,702 | 7,774 | Calculation |
| Material consumption (kg/kg afdw) | 0.0343 | 0.0152 | Calculation |

[a]Markham and Davis (2017a), and [b]GREET (2016).

**Table 2. The flat-panel hanging bags (PBR2-HB) and the flat-panel standing bag system (PBR3-SB) design, dimensions and material requirements**

| | PBR2-HB[a] | PBR3-SB | Data source |
|---|---|---|---|
| Volume ($m^3$) | 285,261 | 285,261 | NREL[b] |
| Plastic thickness (mm) | | 0.39 | NREL |
| Height (m) | | 0.7 | NREL |
| Length (m) | | 48 | NREL |
| Width when fully filled (cm) | | 4.5 | NREL |
| Plastic density (g/$cm^3$) | | 0.925 | GREET[c] |
| Lifetime (yr) | 6 | 1 | NREL |
| Total section number (n) | | 188,665 | Calculation |
| Material volume ($m^3$) | | 4,055 | Calculation |
| Material weight (kg) | | 3,750,751 | Calculation |
| Material consumption (kg/day) | 1,713 | 10,276 | Calculation |
| Material consumption (kg/kg afdw) | 0.0034 | 0.0201 | Calculation |

[a]Assumed to have similar dimensions and material as the PBR3-SB (GWP-II), [b]Markham and Davis (2017a), and [c]GREET (2016).

## 2.3 BIOMASS PRODUCTION

The biomass growth and dewatering model used in this analysis was provided by Markham and Davis (2017a) . The fresh water algae strain, *Scenedesmus* (LRB-AP-0401), was assumed in this study to maintain consistency with NREL's previously-published open pond design case (Davis et al. 2016). Table 3 shows the composition of high-carbohydrate *Scenedesmus* ("HCSD") with carbon and ash contents of 54% and 2.4%, respectively (Davis et al. 2016). The biomass production model, Figure 2, included algal cultivation in PBRs and dewatering to 20% solids. The first step of the dewatering is in-ground gravity settlers, followed by hollow fiber membranes, and then centrifugation (Davis et al. 2016). The NREL PBR model accounted for higher biomass harvest densities typical for most of the PBR systems considered, which resulted in lower harvest volume rates routed to the primary dewatering step. In order to promote high biomass growth rates, supercritical $CO_2$ ($scCO_2$) is delivered to the cultivation system. The $CO_2$ outgassing is assumed to be 10% of $scCO_2$ inputs. Because separation of $CO_2$ from coal-fired power plant flue gas *via* monoethanolamine (MEA) absorption requires heat to release the captured $CO_2$, additional coal must be consumed to maintain the base power plant output. Each kilogram of $scCO_2$ increased the heat rate of the power plant by 0.176 kWh of electricity (GREET 2016). Alternative "second-generation" carbon capture technologies are also possible (as were assumed in NREL's TEA modeling), but their life-cycle energy burdens and GHG emissions are not yet well understood (Markham and Davis 2017a). GHG emissions, energy and water use, and associated additional power plant fuel demands (increased heat rate) were burdened to the algal biomass (Frank et al. 2016). Nutrient requirements for the algal seed inoculum and algal growth are assumed to be met using diammonium phosphate (DAP) and anhydrous ammonia ($NH_3$), after accounting for the amount of nitrogen available in DAP (Davis et al. 2016). Total cultivation water use includes water lost to blowdown and evaporation, as well as cooling evaporation (in the case of the PBR4-GT system, as the only design currently assumed to require supplemental cooling in the base cases), and remaining water in the biomass sent to conversion. The water recycle from the CAP conversion process is also accounted for downstream. For PBR1-HT, PBR2-HB, and PBR3-SB, the PBR study assumes that no external cooling is required, and PBR4-GT has external cooling by a chiller. To ensure algal biomass applicability to any downstream conversion process, no credit is taken as part of the biomass production step for recycle of nutrients or $CO_2$ from downstream conversion operations back to the production ponds. For a specific selected conversion technology and operating sequence (the CAP process in this study), recycle nutrients and $CO_2$ credits are applied to the back-end process to reduce conversion process GHG emissions, energy and water use.

**Table 3. Elemental and component composition for mid-harvest high-carbohydrate *Scenedesmus* strain (HCSD)[a]**

| Elements | Element (% of afdw) | Component | % |
|---|---|---|---|
| C | 54.0 | Ash | 2.4 |
| H | 8.2 | Protein | 13.2 |
| O | 35.5 | Lipids as FAME | 27.4 |
| N | 1.8 | Non-fuel polar lipid impurities | 2.7 |
| S | 0.2 | Fermentable carbohydrates | 47.8 |
| P | 0.22 | Other carbohydrates | 5.0 |
| **Total** | 100.0 | Cell mass | 1.6 |
| | | Total | 100.0 |

[a]Davis et al. (2016)

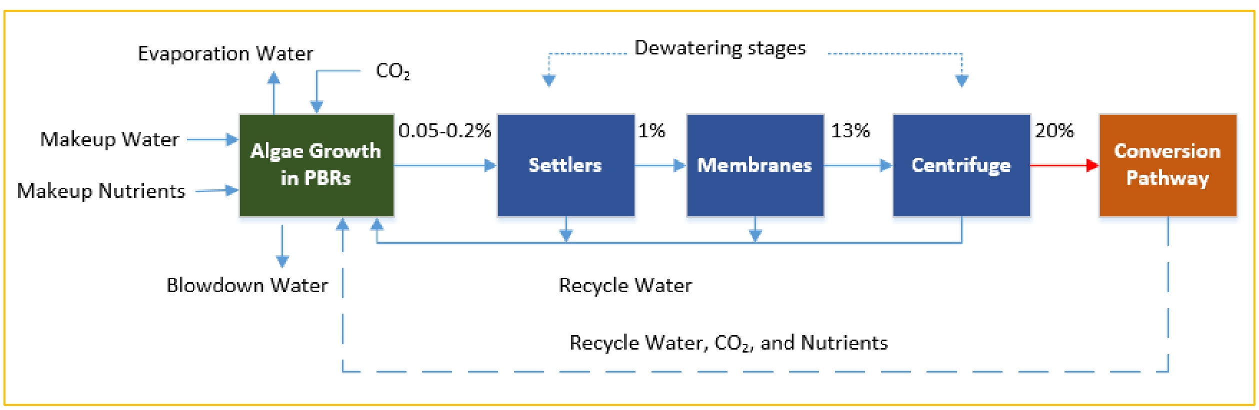


**Figure 2. Algae biomass production in PBRs and dewatering stages: growth, settlers, membranes, and centrifuge**

The material and energy requirements for algae cultivation and dewatering in PBRs are presented in Table 4 (Markham and Davis 2017a). The PBR study assumed that PBRs have the same annual algae biomass production output, $CO_2$ and nutrients requirements as open ponds (Markham and Davis 2017a). PBRs have higher electricity use than open ponds, and the electricity energy uses which include mixing, sparging, and cooling, are 4.0, 45, 69, and 238 W/m$^3$ of reactor volume for PBR1-HT, PBR2-HB, PBR3-SB, and PBR4-GT, respectively. However, a caveat must be noted that the mixing, aeration, and cooling demands for each system were generally based on inputs from the various sources (furnished to NREL) or otherwise taken from literature for similar systems, which may not represent fully-optimized conditions and further room for improvement to reduce power demands may be possible (Markham and Davis 2017a).

**Table 4. General input and output inventories (yearly average) for the four PBR cases[a] compared to the open ponds**

| | Open ponds | PBR1-HT | PBR2-HB | PBR3-SB | PBR4-GT |
|---|---|---|---|---|---|
| Algae (Tonne afdw/day)[b] | 516 | 516 | 516 | 516 | 516 |
| Resources (Tonne/day) | | | | | |
| Carbon dioxide | 1,148 | 1,148 | 1,137 | 1,137 | 1,137 |
| Ammonia | 10 | 10 | 10 | 10 | 10 |
| Diammonium phosphate | 5 | 5 | 5 | 5 | 5 |
| Total process water | 26,790 | 2,994 | 2,691 | 3,679 | 10,846 |
| Electricity (kWh/day)[c] | 234,084 | 400,344 | 311,346 | 473,568 | 1,995,750 |
| Output streams (Tonne/day) | | | | | |
| Water in biomass | 2,083 | 2,083 | 2,062 | 2,062 | 2,062 |
| Water lost to blowdown | 6,272 | 278 | 269 | 664 | 320 |
| Water lost to evaporation | 18,060 | 632 | ND | 953 | 690 |
| $CO_2$ outgassing | 114 | 115 | 113 | 114 | 114 |
| Cooling water evaporation[d] | 0 | 0 | 0 | 0 | 7,773 |

[a]PBR1-HT: horizontal tubular system, PBR2-HB: flat-panel hanging bags (Leidos), PBR3-SB: flat-panel standing bag system (GWP-II), and PBR4-GT: glass helical tubular system; [b]afdw-ash free dry weight; [c]The energy includes mixing, dewatering, and other requirements of the system; [d]For PBR1-HT, PBR2-HB, and PBR3-SB, NREL assumes that no external cooling is required, and PBR4-GT has external cooling by a chiller.

## 2.4 BIOMASS CONVERSION

Figure 3 shows the process to fractionate algal biomass into carbohydrate, lipid, and protein-rich fractions that can be converted into fuels and co-products based on NREL's CAP pathway (Davis et al. 2014). Detailed descriptions of the engineering process design was presented in Davis et al. (2014). The algal biomass (20 wt%) is first treated with steam and dilute sulfuric acid at elevated temperature to hydrolyze carbohydrates to sugar. Ammonia is used to adjust the pH to 5 for sugar fermentation to ethanol, and $CO_2$ from the fermentation step is recycled to upstream algae cultivation. The ethanol product is distilled, then the distillation stillage is extracted using hexane solvent. The distilled oil product goes through a series of purification steps consisting of degumming, de-metallization, and beaching with addition of phosphoric acid, wash water, silica, and clay. The purified algal oil is upgraded to produce a diesel-range paraffinic product suitable as a diesel blendstock (RDB) with a small naphtha coproduct. The protein-rich residue left after lipid extraction is combined with the oil cleanup waste stream and sent to anaerobic digestion (AD). The AD is utilized as a means to reclaim carbon via biogas production as well as enable nutrient recycle coproduct credits that are intended to be routed back to upstream algal cultivation. The methane-rich biogas is combusted in a gas turbine to generate electricity. If it is produced in excess of facility power demands and then sold to the grid. Flue gas heat is recovered by generating steam to satisfy process and utility steam demands. The digester effluent water contains nitrogen and phosphorus nutrients which garner additional coproduct credit, as does the solids digestate cake which is sold for the nitrogen content as a land-application fertilizer. To be consistent with the harmonization report (Davis et al. 2012) and the TEA study (Davis et al. 2014), the elemental components (N and P) were translated to equivalent ammonia ($NH_3$) and diammonium phosphate (DAP), with 1:1 displacement of upstream $NH_3$ and DAP. The bioavailable nitrogen in the digestate cake steam is also translated to equivalent $Ca(NO_3)_2$, with 1:1 displacement of the commercial fertilizer. Table 5 lists major inputs and outputs of the biomass conversion process, which are based on a mass- and energy-balanced Aspen Plus models (Davis et al. 2014). Inputs and outputs are the same for algal biomass produced from open pond and PBRs. In the PBR study, the seasonality variabilities were assumed to be 1.7:1 between summer and winter for the PBR cases, compared to 3:1 for the open pond case. So we consider the possible 40% reduction of nature gas use for biomass drying for the PBRs cases in this study. To be consistent with the algal farm study (Davis et al. 2016) for the CAP conversion, excess electricity, recycle water, nutrients and $CO_2$ are counted as credits and applied to the CAP process to reduce conversion process water and energy use.

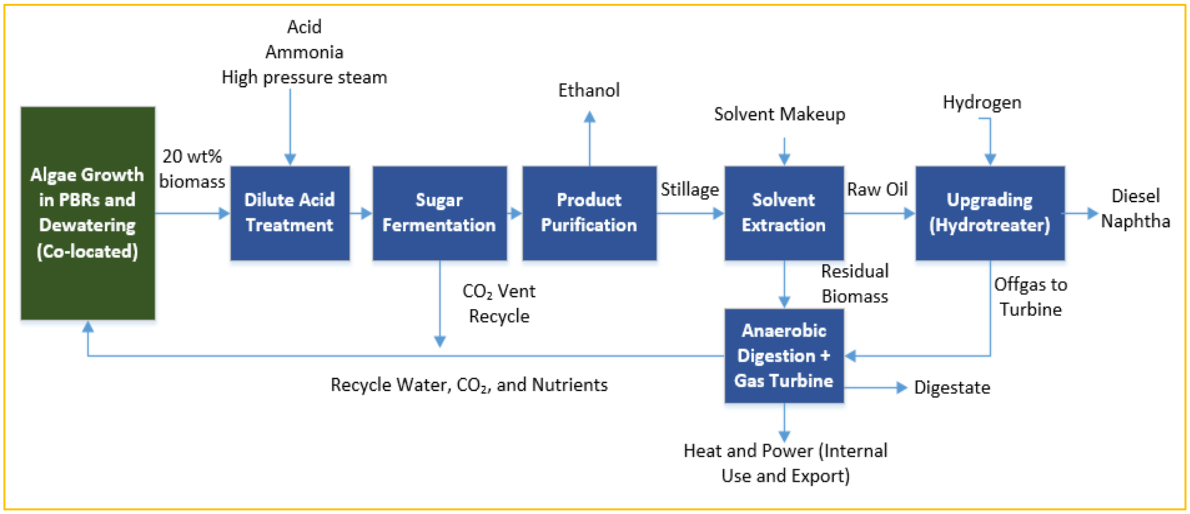


**Figure 3. Combined algal process (CAP) to fractionate algal biomass into carbohydrate (sugar), lipid, and protein-rich components. The carbohydrate-rich stream is fermented to ethanol. Lipids are extracted and upgraded to renewable diesel (RD). The protein-rich residue is converted to biogas by anaerobic digestion (AD) and this biogas is used for co-generation of heat and power on-site.**

**Table 5. The major inputs and outputs of combined algal process (CAP)**

| Category | Items | Values |
|---|---|---|
| Fuel products | Renewable diesel (MJ/MJ) | 0.600 |
| | Naphtha (MJ/MJ) | 0.013 |
| | EtOH (MJ/MJ) | 0.387 |
| | Total (MJ Fuels) | 1.000 |
| Algae (HCSD) biomass | kg afdw/MJ | $6.26\times10^{-2}$ |
| Energy inputs | Natural gas for utility (MJ/MJ) | $3.20\times10^{-2}$ |
| | Natural gas for algae drying (MJ/MJ) | $5.51\times10^{-2}$ |
| | Total natural gas (MJ/MJ) | $8.71\times10^{-2}$ |
| Chemicals use | Sulfuric acid (kg/MJ) | $2.76\times10^{-4}$ |
| | Ammonia (kg/MJ) | $8.92\times10^{-4}$ |
| | $(NH_4)_2HPO_4$ (kg/MJ ) | $1.19\times10^{-4}$ |
| | Hexane (kg/MJ) | $9.62\times10^{-4}$ |
| | Phosphoric acid (kg/MJ) | $3.21\times10^{-5}$ |
| | Silica (kg/MJ) | $1.75\times10^{-5}$ |
| | Clay (kg/MJ) | $3.50\times10^{-5}$ |
| | Hydrogen (kg/MJ) | $4.11\times10^{-4}$ |
| Water use | Process water (gal/MJ) | $2.80\times10^{-2}$ |
| Recycled nutrients and $CO_2$[a] | AD effluent (kg $NH_3$/MJ) | $9.38\times10^{-4}$ |
| | AD effluent (kg $(NH_4)_2HPO_4$ /MJ) | $3.67\times10^{-4}$ |
| | AD bioavailable N (kg $Ca(NO_3)_2$ /MJ) | $5.29\times10^{-4}$ |
| | Recycled $CO_2$ (kg/MJ) | $4.35\times10^{-2}$ |
| Recycled water | gal/MJ | $7.51\times10^{-2}$ |

| | | |
|---|---|---|
| Process excess electricity | kWh/MJ | $8.79\times10^{-3}$ |
| Intermediate AD $CH_4$ | g/MJ | 4.10 |
| AD fugitive $CH_4$ emission | (%) | 2% |

[a]AD: anaerobic digestion.

# 3. RESULTS AND DISCUSSION

## 3.1 WTW GHG EMISSIONS OF PBRS

In this study, the algal farm and the conversion plant are assumed to be collocated, and nutrients and $CO_2$ are recycled to the algal farm from the conversion plant. Figure 4 shows the carbon balance of PBR4-GT for algal cultivation and fuel production. In the algal farm-biomass conversion processes, 89% of carbon source was photosynthesized into algal biomass, then 52% of carbon source was converted into algal biofuels and utilized for vehicle operation. With the collocation of the conversion plant with the algal farm, 31% of carbon could be recycled and utilized, which is counted as credits and applied to the process.

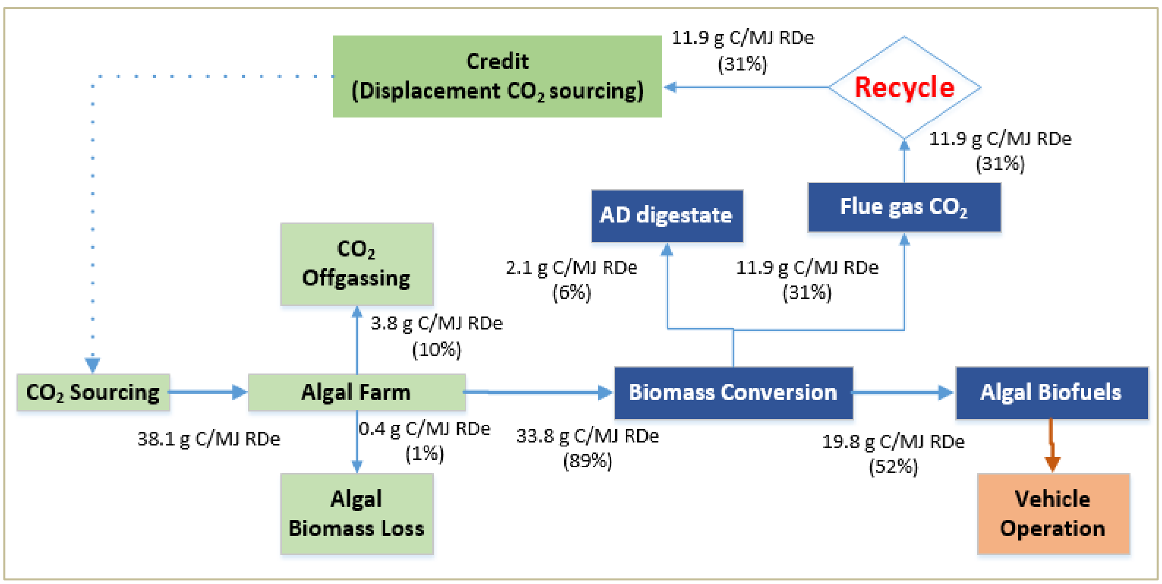


**Figure 4. Carbon balance of photobioreactor (PBR4-GT) for algal cultivation and renewable diesel production**

The WTW GHG emissions of PBRs, compared with open ponds, are shown in Figure 5. With the exception of farm energy and PBR materials, GHG emissions from other processes are the same for open ponds and four PBRs. Overall, all four PBRs have higher WTW GHG emissions than open ponds, and PBRs' GHG emissions ranged from 55 to 168 g $CO_{2e}$/MJ (compared to the open pond case at 49 g $CO_{2e}$/MJ). Compared to low sulfur petroleum diesel (94 g $CO_2$e/MJ), PBR1-HT, PBR2-HB and PBR3-SB reduce WTW GHG emissions by 30%, 43%, and 27%, respectively. However, PBR4-GT increases WTW GHG emissions by 75% due to high farm energy use (driven by high circulation, aeration, and cooling energy demands). The carbon in algal fuels represents a natural carbon captured from the coal power plants, so the net fuel combustion $CO_{2e}$, which equals to total combustion $CO_{2e}$ emissions subtract biogenic $CO_2$, contribute less than 2% of total WHW GHG emissions (Figure 5). Algae farm energy and $CO_2$ sourcing are two largest contributors to WTW GHG emissions. The farm energy use of PBR1-HT, PBR2-HB, PBR3-SB, and PBR4-GT contributes 40%, 38%, 46% and 80% of WTW GHG emissions, respectively. In this study, the U.S. mixture electricity for stationary use is assumed to be used in algae farming and fuel process, and its GHG intensity is 550 g $CO_{2e}$/kWh (fuel-cycle only) (GREET 2016). If different electricity mixtures are used, GHG emissions from the farm energy would be different. For example, if electricity from coal power plants is used, its GHG intensity is 1,080 g $CO_{2e}$/kWh (fuel-cycle only) (GREET 2016), WTW GHG emissions of PBR1-HT, PBR2-HB, PBR3-SB, and PBR4-GT would increase by 22, 16, 26, and 126 g $CO_{2e}$/MJ $RD_e$, respectively. Again as noted previously, these results should be interpreted with caution as the underlying energy use estimates were based on inputs furnished to NREL by the various sources and/or extrapolated from literature for similar PBR designs, and thus may not be fully-optimized with respect to minimizing circulation, aeration, or cooling energy use as much as possible (Markham and Davis 2017a). Additionally, PBR4-GT is the only case to assume that there is external cooling required by a chiller, which is a primary driver of high energy use. The sc$CO_2$ sourcing of PBR1-HT, PBR2-HB, PBR3-SB, and PBR4-GT contributes 29%, 38%, 38% and 16% of WTW GHG emissions, respectively. An alternate $CO_2$ sourcing is the short-distance low-pressure pipeline delivery of flue gas (GREET 2016, Frank et al. 2016). As compared with sc$CO_2$, low-pressure pipeline $CO_2$ sourcing could reduce WTW GHG emissions significantly (Frank et al. 2016). However, low-pressure flue gas $CO_2$ imposes stringent constraints on farm sizing and siting possibilities that must be collocated with $CO_2$ point sources. The alternate $CO_2$ sourcing will be revisited in the ongoing harmonization modeling efforts by ANL, NREL, PNNL, and ORNL. The GHG emissions related to PBR materials are not a major contributor, which contributed 11% (7.5 g$CO_{2e}$/MJ), 1.3% (0.7 g$CO_{2e}$/MJ), 6.3% (4.4 g$CO_{2e}$/MJ), and 0.5% (0.2 g$CO_{2e}$/MJ) of WTW GHG emissions of PBR1-HT, PBR2-HB, PBR3-SB and PBR4-GT, respectively. However, the upper end of those values are significantly higher than what typically in open ponds (Canter et al. 2014). Frequent PBRs replacement would be a big penalty on LCA, compared to other biofuel processes when accounting for infrastructure. Biomass drying and conversion NG contributed 10%, 12%, 9% and 4% of WTW GHG emissions of PBR1-HT, PBR2-HB, PBR3-SB and PBR4-GT, respectively. With the 40% reduction of nature gas use for spring and summer biomass drying for the PBRs cases in this study, WTW GHG emissions of PBRs decreased by 1.5 g $CO_{2e}$/MJ $RD_{e,}$ .

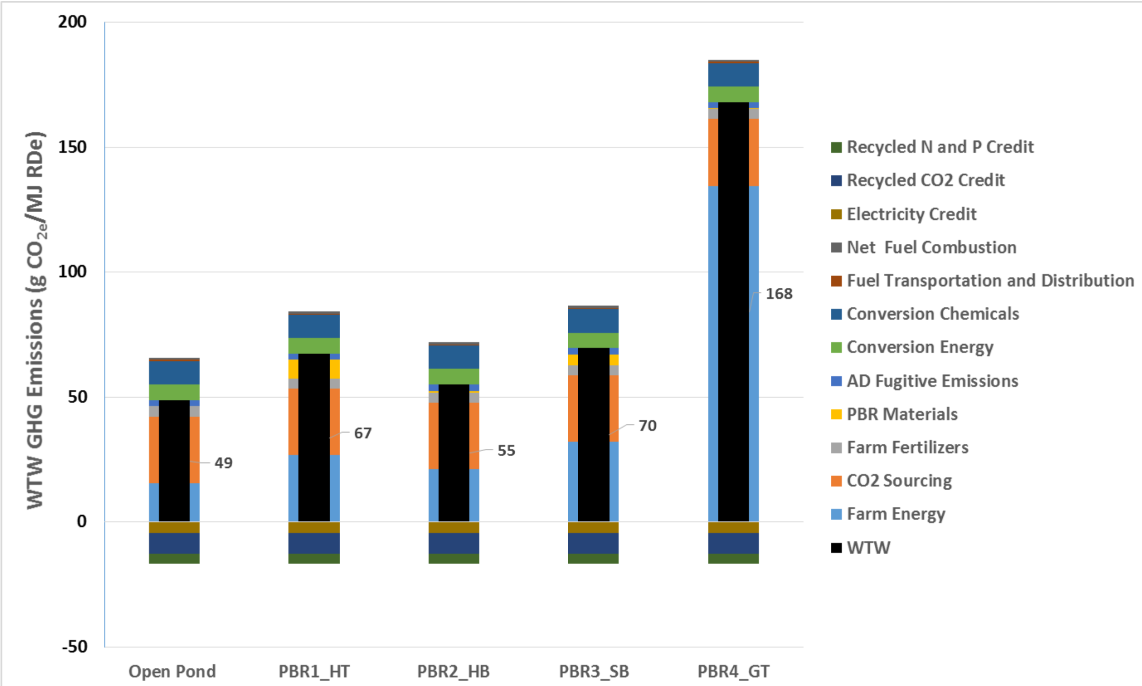


**Figure 5. Greenhouse gas emissions (GHG) of photobioreactors for algal cultivation and renewable diesel production. PBR1-HT: horizontal tubular system, PBR2-HB: flat-panel hanging bags, PBR3-SB: flat-panel standing bag system, and PBR4-GT: glass helical tubular system.**

## 3.2 WTW FOSSIL FUEL USE OF PBRS

Figure 6 presents the fossil fuel use of PBRs. It includes the process direct energy required during algal cultivation and fuel production as well as indirect energy use such as for electricity and natural gas, fertilizers and materials manufacturing, and fuel transportation and distribution. The fossil energy use of the four PBRs are 0.93, 0.69, 0.91 and 2.03 MJ/MJ $RD_e$, respectively. Compared to the open pond basis, the fossil energy uses of PBR1-HT, PBR2-HB, PBR3-SB and PBR4-GT increased by 51%, 14%, 50%, and 232%, respectively. The algae cultivation electricity use is the major contributor to the increase of fossil use. PBRs need higher mixing and gas sparging energy than open ponds. As noted above, PBR4-GT is the only case to assume that there is external cooling by a chiller, which drives high energy use. The indirect fossil energy use related to PBR materials contributed 20%, 3%, 12% and 0.1% of WTW fossil fuel use of PBR1-HT, PBR2-HB, PBR3-SB and PBR4-GT, respectively. The exported electricity, recycled nutrients and $CO_2$ credits reduce fossil fuel energy use by 9-27%. Overall, farm energy use, $CO_2$ supply, and conversion chemicals are the top three contributors to fossil fuel uses in PBRs.

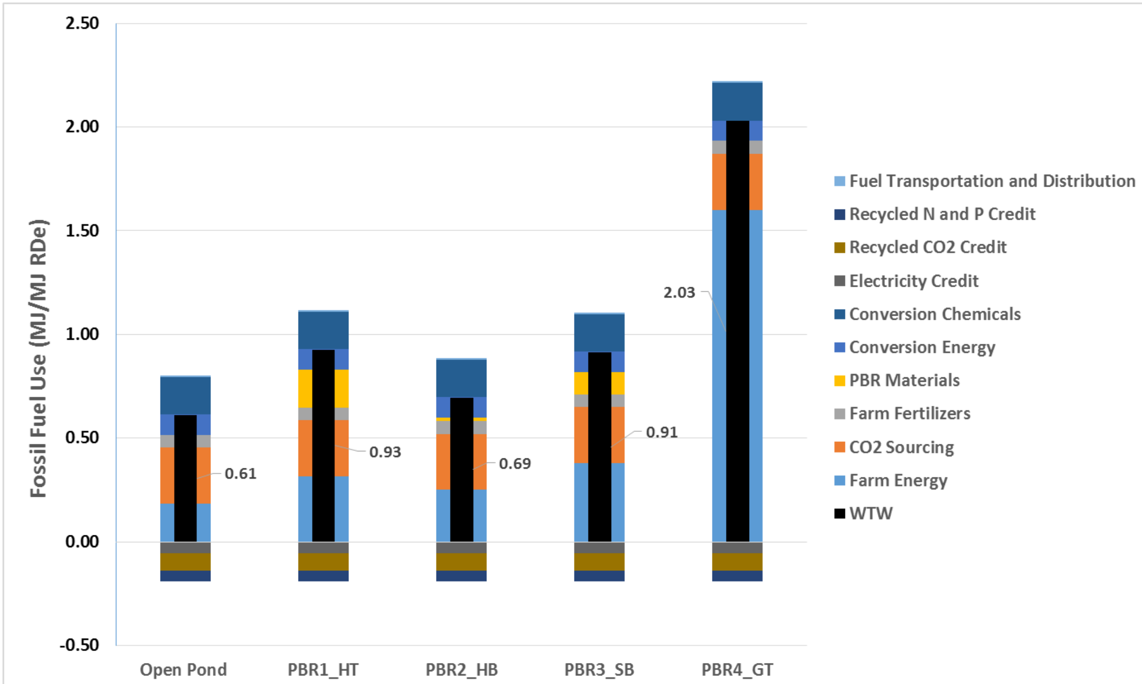


**Figure 6. Fossil fuel use of photobioreactors for algal cultivation and renewable diesel production. PBR1-HT: horizontal tubular system, PBR2-HB: flat-panel hanging bags, PBR3-SB: flat-panel standing bag system, and PBR4-GT: glass helical tubular system.**

## 3.3 WTW WATER USE OF PBRS

Figure 7 shows an example direct water balance of algal cultivation in open ponds and PBRs. In open ponds, pond evaporation and blowdown are the two largest contributors to the total water consumption, accounting for 65% and 23% of the direct water use (Figure 7A). As compared with open ponds, PBRs could reduce evaporation water loss significantly, only accounting for 6% of the direct water use (Figure 7B); however, the PBR water losses e.g. being stripped out during sparging are more uncertain in the current NREL models, given uncertainties around aeration rates and seasonal culture temperatures (Markham and Davis 2017a). Actual evaporative water losses may err on the conservative side and in fact be higher than those estimated here for the PBR cases (Markham and Davis 2017a). As shown in Figure 7, water recycle from the conversion plant back to the algal farm ranged from 8% to 20% in open ponds and PBRs. Water recycle could reduce wastewater treatment cost and decrease fresh water use for algal cultivation, so water recycle is important for both economics and life cycle water performance. Figure 8 shows estimated WTW water consumption for PBRs. PBRs have much less water use than open ponds. Cultivation makeup water use to offset evaporation and blowdown is the key contributor to the total water consumption. Indirect water use from electricity consumption of PBRs during the cultivation stage is also a significant contributor to WTW water use in PBRs.

Using saline water to culture algae is currently under consideration, which would result in zero freshwater consumption for algae growth activities (ANL et al. 2016). Saline water sources will be constrained to underground water with an appropriate salinity range. As shown in Figure 9, water demand could reduce significantly for open ponds, however using non-fresh water has limited benefit for PBRs water use. In the case of using non-fresh water, electricity consumption is the dominant contributor to the total water consumption. This alternate scenario will be revisited as additional harmonization modeling efforts continue between ANL, NREL, PNNL, and ORNL.

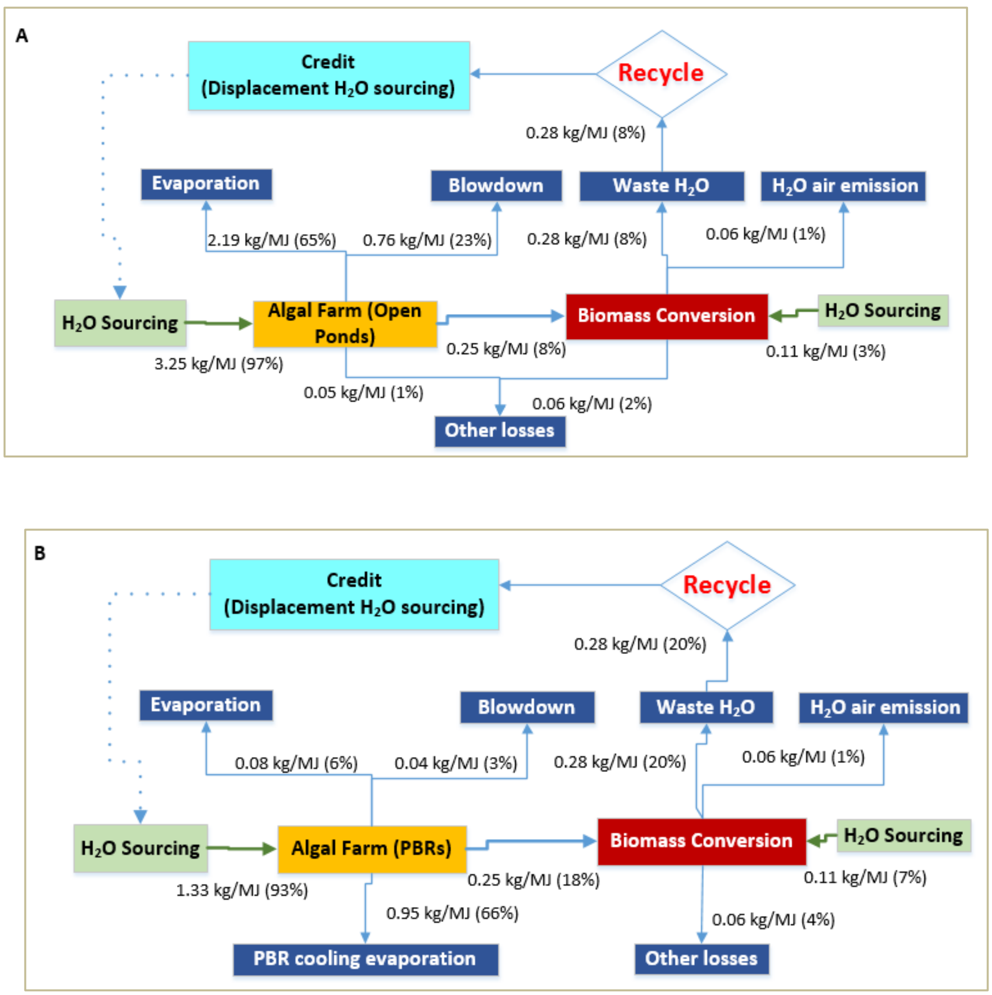


**Figure 7. Direct water use balance of algal cultivation and fuel production. A: open pond and B: PBR4-GT: glass helical tubular system**

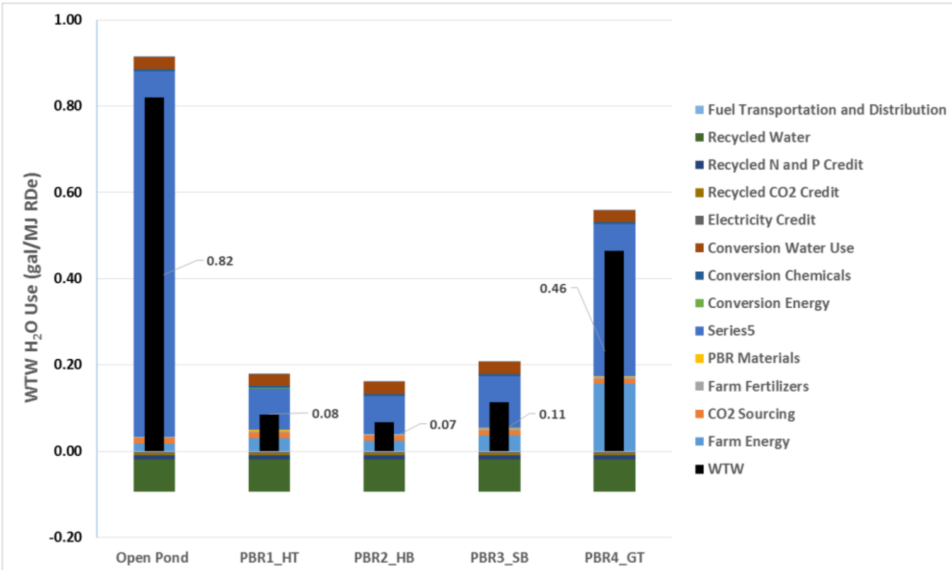


**Figure 8. Water use of photobioreactors for algal cultivation and fuel production. PBR1-HT: horizontal tubular system, PBR2-HB: flat-panel hanging bags, PBR3-SB: flat-panel standing bag system, and PBR4-GT: glass helical tubular system.**

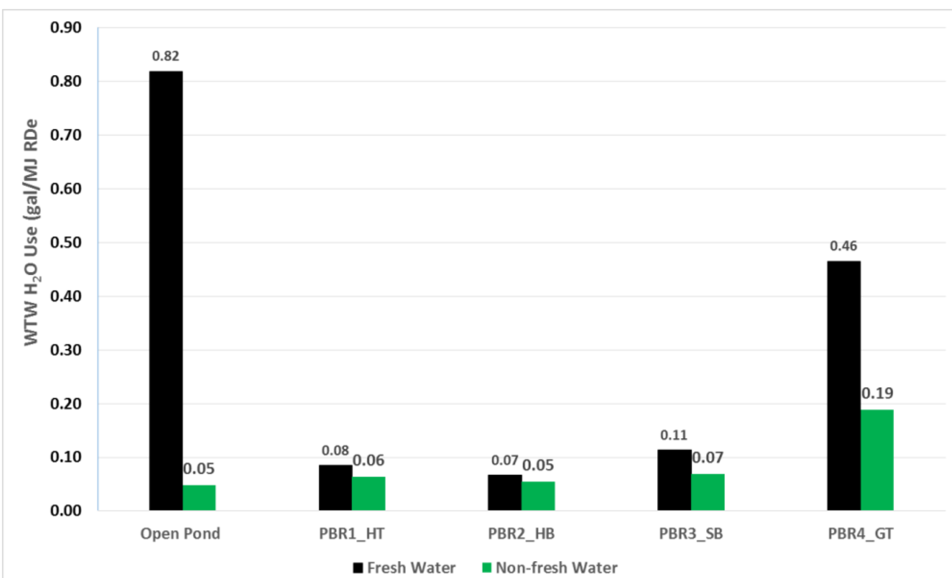


**Figure 9. Fresh water vs non-fresh water (saline water) scenarios for algal cultivation and fuel production. PBR1-HT: horizontal tubular system, PBR2-HB: flat-panel hanging bags, PBR3-SB: flat-panel standing bag system, and PBR4-GT: glass helical tubular system.**

# 4. CONCLUSIONS

Given high biomass productivities of photobioreactors (PBR) over open ponds, a good number of PBR designs have been proposed. The design of photobioreactors for maximum production and minimum environmental impact is important. In this assessment, we examined the environmental sustainability of four PBR designs through life-cycle analysis (LCA). PBRs for algal cultivation become unfavorable with additional energy (e.g. circulation, aeration, and cooling) needed for operation. Compared to open ponds (0.61 MJ/MJ RDe), the fossil energy use of the four PBRs are 0.93, 0.69, 0.91 and 2.03 MJ/MJ $RD_e$, respectively. Higher energy use in PBRs leads to higher GHG emissions than those of open ponds. PBRs' GHG emissions ranged from 55 to 168 g $CO_{2e}$/MJ (compared to the open pond case at 49 g $CO_{2e}$/MJ). Although the design of PBRs in commercial scale has made some progress in recently years, existing PBRs have not been proven to be environmentally favorable alternatives to open ponds. Research and development efforts should focus on optimizing PBR engineering designs to reduce energy consumption and increase algae biomass production. Research and development efforts should also focus on PBR materials with respect of price, life span, and tendency for fouling.

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