



## Algae biodiesel life cycle assessment using current commercial data



Howard Passell<sup>a</sup>, Harnoor Dhaliwal<sup>b,\*</sup>, Marissa Reno<sup>a</sup>, Ben Wu<sup>a</sup>, Ami Ben Amotz<sup>c</sup>,  
Etai Ivry<sup>c</sup>, Marcus Gay<sup>d</sup>, Tom Czartoski<sup>e</sup>, Lise Laurin<sup>b</sup>, Nathan Ayer<sup>b</sup>

<sup>a</sup>Sandia National Laboratories, Box 5800, MS 1137 Albuquerque, NM, USA

<sup>b</sup>EarthShift LLC, 830 Taft Road, Huntington VT 05462, USA

<sup>c</sup>Seamiotic, Inc., 1 Azrieli Tower, 132 Menachem Begin Blvd., Tel Aviv 67021, Israel

<sup>d</sup>GAIA Consulting Services, 67 Baldwin St, Unit 1, Boston, MA 02129, USA

<sup>e</sup>Solution Recovery Systems, Inc., 7455 Newman Blvd., Dexter, MI 48130, USA

### ARTICLE INFO

#### Article history:

Received 6 March 2013

Received in revised form

15 June 2013

Accepted 26 June 2013

Available online

#### Keywords:

Life cycle assessment

LCA

Microalgae

Biodiesel

Environmental impacts

### ABSTRACT

Autotrophic microalgae represent a potential feedstock for transportation fuels, but life cycle assessment (LCA) studies based on laboratory-scale or theoretical data have shown mixed results. We attempt to bridge the gap between laboratory-scale and larger scale biodiesel production by using cultivation and harvesting data from a commercial algae producer with  $\sim 1000 \text{ m}^2$  production area (the base case), and compare that with a hypothetical scaled up facility of  $101,000 \text{ m}^2$  (the future case). Extraction and separation data are from Solution Recovery Services, Inc. Conversion and combustion data are from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET). The LCA boundaries are defined as “pond-to-wheels”. Environmental impacts are quantified as NER (energy in/energy out), global warming potential, photochemical oxidation potential, water depletion, particulate matter, and total  $\text{NO}_x$  and  $\text{SO}_x$ . The functional unit is 1 MJ of energy produced in a passenger car. Results for the base case and the future case show an NER of 33.4 and 1.37, respectively and GWP of 2.9 and 0.18 kg  $\text{CO}_2$ -equivalent, respectively. In comparison, petroleum diesel and soy diesel show an NER of 0.18 and 0.80, respectively and GWP of 0.12 and 0.025, respectively. A critical feature in this work is the low algal productivity ( $3 \text{ g/m}^2/\text{day}$ ) reported by the commercial producer, relative to the much higher productivities ( $20\text{--}30 \text{ g/m}^2/\text{day}$ ) reported by other sources. Notable results include a sensitivity analysis showing that algae with an oil yield of 0.75 kg oil/kg dry biomass in the future case can bring the NER down to 0.64, more comparable with petroleum diesel and soy biodiesel. An important assumption in this work is that all processes are fully co-located and that no transport of intermediate or final products from processing stage to stage is required.

© 2013 Elsevier Ltd. All rights reserved.

### 1. Introduction

Autotrophic microalgae are a potential future feedstock for transportation fuels that might produce lower greenhouse gas emissions and provide similar or lower net energy ratios (NERs) (energy in/energy out) when compared to petroleum diesel or other biodiesels. Algae may also provide useful and valuable co-products in various forms (e.g., biomass or animal feeds) that will further offset environmental burdens. All these advantages might occur at least partly because of high solar energy yields in the algae and the potential for higher yields with hybrid or genetically modified algae; the potential for large-scale, year-round algae

cultivation using impaired waters inappropriate for direct human consumption or other agriculture (e.g., wastewater or brackish water); use of land inappropriate for other agriculture; co-location with fossil-fuel burning power plants or other industries as a sources for waste  $\text{CO}_2$  and other nutrients; and co-location with wastewater treatment plants as sources of water and nutrients (U.S. DOE, 2010; Brune et al., 2009).

Although numerous large-scale, commercial algae cultivation, harvesting and processing facilities exist around the world, most are used for the production of high value food additives rather than for low cost transportation fuels. Data on algae cultivation and harvesting capabilities and technologies from those commercial facilities are mostly proprietary and difficult to obtain for life cycle assessment (LCA) studies. Also, many new technologies for extraction and separation of algal oils and the transformation of those oils into biodiesel are unproven at scale. These conditions

\* Corresponding author.

E-mail address: [harnoor@earthshift.com](mailto:harnoor@earthshift.com) (H. Dhaliwal).

have made it difficult to estimate what the future environmental burden of large-scale biodiesel production from algae will be.

Many efforts have been made to experimentally and theoretically explore different pathways that might allow the economical and energy efficient production of biofuels from algae (Weyer et al., 2010; Cooney et al., 2010; Sun et al., 2011). Co-location of algal production with wastewater and waste CO<sub>2</sub> sources has received special attention (Smith et al., 2009; Johnson and Wen, 2010; McGinn et al., 2011; Sturm and Lamer, 2011). So far, however, algal pathways are considered theoretical rather than mature (Frank et al., 2011), and major and transformative breakthroughs are believed to be required to make algal biofuels viable both economically and energetically (Cooney et al., 2010). In a uniquely comprehensive study, Pate et al., 2011 suggest that significant resource supply challenges (including land, water, CO<sub>2</sub>, nitrogen, and phosphorus) can be expected to emerge as regional algae biofuel production capacity in the United States approaches the level of about 10 billion gallon per year, which is relatively low when compared to U.S. total annual liquid fuel consumption of about 300 billion gallon per year. Wigmosta et al., 2011, suggest that algae cultivated in optimal geographic locations may be able to help meet U.S. alternative fuel goals, but with considerable water demand. Pate, 2013 directly addresses general geomorphological, geographical and atmospheric requirements, along with other resource requirements (water, space, nutrients), and potential co-location issues, all with a special focus on the U.S. but which are also acknowledged as having global relevance.

Numerous useful LCA studies for algal biodiesel have been reported, with varying results. Kadam (2001) found that using flue gases from fossil fuel powered electricity production as a CO<sub>2</sub> source and then co-firing algal biomass with coal for electricity production offered potential benefits for power production. Lardon et al. (2009) found that algae cultivation (including use of fertilizers), harvesting, and oil extraction brought high energy costs to algae relative to more traditional fuels production. Batan et al. (2010) considering a pond-to-pump system boundary, found a NER for microalgae biodiesel of less than 0.93, indicating a barely net positive energy balance. They found net greenhouse gas (GHG) emissions comparable to the net GHG emissions for soy biodiesel, and much more favorable than the net GHG emissions for conventional diesel. Sander and Murthy, 2010, also using the pond-to-pump system boundary, found NERs greater than 1 across a range of analyses, and GHG emissions both greater and lesser than those for conventional gasoline depending on different algae processing steps. Jorquera et al. (2010) analyzed algae biomass production (but not extraction, separation, or conversion to biodiesel) and found positive energy balances for production in both flat plate photobioreactors and open ponds. Clarens et al. (2010) found that energy use, GHG emissions, and water use, mostly in the cultivation stage, were much greater than for canola, corn, and switchgrass feedstocks, although algae production using waste CO<sub>2</sub> and wastewater nutrients can reduce those burdens. Clarens et al. (2011) built upon their earlier study and found a net positive energy balance for various combinations of algae biodiesel production coupled with use of waste CO<sub>2</sub> and wastewater nutrients, and found lower land use impacts for algae when compared to terrestrial feedstocks. Finally, Frank et al. (2011) used an expanded version of the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model on an algal biofuel pathway to derive an unfavorable NER of 2.58, and found algal fuels consume more fossil fuel and have higher GHG emissions than other biofuels. For comparison, petroleum diesel and soy biodiesel NERs are 0.18 and 0.80, respectively (GREET, 2011).

All these studies use data from bench-scale or laboratory-scale research, theoretical studies, and/or other literature. An LCA with

data from current commercial cultivation, harvesting, and processing methods will be useful for showing the current state of the industry, and for providing a baseline against which future LCA results from larger algae production facilities, and future technological improvements can be measured.

## 2. Goal and scope of the study

The goal of the current study was to conduct a pond-to-wheels (cultivation to consumption) LCA (ISO 14040, 2006) of algae biodiesel by using data from commercial partners to capture the impacts from current commercial capabilities. To further examine the results, they were compared with soy biodiesel and low sulfur diesel. The reference unit (also known as the functional unit) was defined as production of 1 MJ of energy by combusting the fuel in a compression-ignition direct-injection (CIDI) passenger car.

Two scenarios for algae production were examined: the base case in which commercial data were used and the estimated future case in which the data were extrapolated to examine the impacts with a larger scale production.

### 2.1. Data sources

Data for cultivation and harvesting were supplied by Seambiotic, Inc., ([www.seambiotic.com](http://www.seambiotic.com)) a commercial algae production company based in Israel. Seambiotic produces algae for high value dietary supplements at its ~1000 m<sup>2</sup> facility in Ashkelon, Israel. The algae facility is co-located with a 4 GW fossil fuel burning electricity generation plant (Fig. 1). Another data source was Solution Recovery Services (SRS) Inc., based in Dexter, Michigan, USA, which specializes in fluid separation technologies. SRS provided data and information on algal oil extraction and separation based upon performance of SRS's AlgaFrac™ wet fractionation technology, currently in commercial use for algae biodiesel production. Transesterification data for oil to biodiesel conversion were obtained from the GREET 1\_2011 model (GREET, 2011). Conversion of soy oil to soy biodiesel was used as a surrogate for conversion of algal oil to algal biodiesel, as no data for conversion of algal oil to biodiesel were available. Data for combustion of biodiesel in a compression-ignition direct-injection (CIDI) passenger car were also obtained from GREET. For modeling all the upstream



Fig. 1. Algae ponds at Seambiotic, Inc. in Ashkelon, Israel. Parts of a 4 GW fossil fuel burning power plant are in the background.

secondary processes, Ecoinvent Life Cycle Inventory data (Frischknecht et al., 2007) were used. Petroleum diesel and soy biodiesel data, for comparison, were taken from GREET.

## 2.2. Impact assessment method

Seven impact categories were considered in this analysis (Table 1). Global warming potential (GWP) is based on International Panel on Climate Change (IPCC) characterization factors. It is reported as kg CO<sub>2</sub>-equivalents by normalizing the impact of different greenhouse gases to that of CO<sub>2</sub>. Energy is measured as NER (total primary energy input/energy output, or in other words, well-to-pump energy input/pump-to-wheels energy output), such that a favorable energy balance would be reflected by a value smaller than 1. Particulate matter formation measures the human health impacts of emissions such as PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>x</sub>, and SO<sub>x</sub>. Water depletion measures the total freshwater consumption (direct and indirect use) throughout the life cycle. It does not include sea water. Photochemical oxidation potential measures the health impacts of photochemical oxidants due to the emissions of non-methane volatile organic compounds (VOCs). NO<sub>x</sub> and SO<sub>x</sub> results provide the total emission of the two pollutants.

## 2.3. System boundaries

The studied system includes algae cultivation, harvesting and dewatering, algae oil extraction, conversion into biodiesel, and finally combustion of biodiesel in a CIDI vehicle. Fig. 2 depicts the unit processes included at each of these life cycle stages.

Transport of materials was excluded from the current analysis as co-location is assumed for all processes from production to combustion. Materials and energy associated with the construction of any infrastructure have also been excluded.

## 2.4. System description

Two scenarios for algae production are examined: the base case and estimated future case. In both cases algae are cultivated in open raceway ponds with paddlewheels for circulating water and mixing nutrients. The base case is modeled after Seambiotic's 1000 m<sup>2</sup> commercial facility that produces *Nannochloris* sp. and *Nannochloropsis* sp., and which is co-located with a fossil fuel burning electricity generation plant as a source of waste CO<sub>2</sub> in abundance far greater than can be used by Seambiotic. The flue gas is brought in at 180 m<sup>3</sup>/hour rate with 13–14% CO<sub>2</sub> concentration. According to Symbiotic, about 2 kg of CO<sub>2</sub> is absorbed per kg of biomass produced, and the remainder is released by the algae during its growth. Based on this, the model includes an input of 181 kg of CO<sub>2</sub> and a release of 179 kg CO<sub>2</sub> per kg biomass leading to an environmental credit of 2 kg of CO<sub>2</sub> (Table 4). The future case in our study is an estimated scenario with higher production efficiency as a result of a larger facility and potential improvements in algae cultivation technology and methods. In the future case, the 1000 m<sup>2</sup> facility is

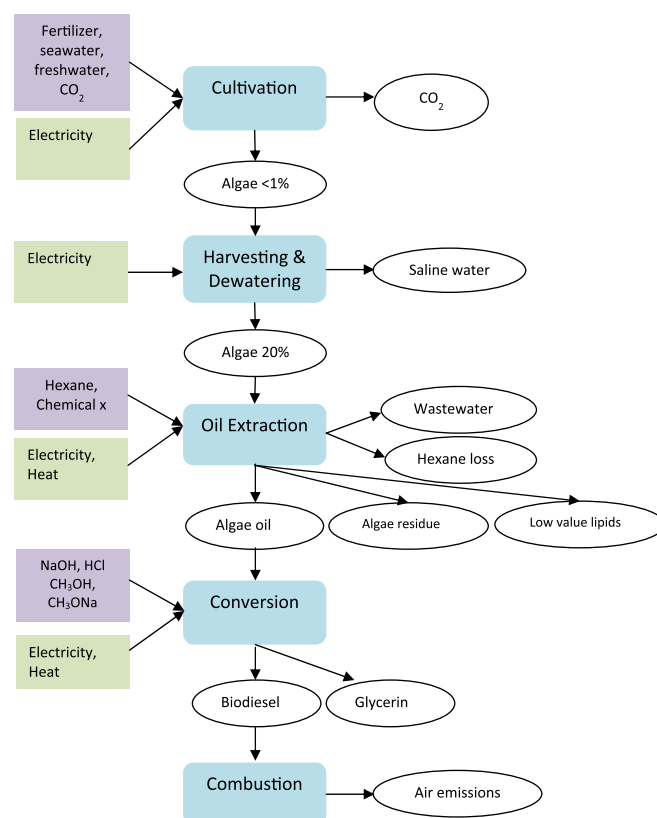


Fig. 2. System boundaries depicting the unit processes considered in the study.

treated as the inoculant ponds for a 100,000 m<sup>2</sup> total production area. The total pond area, then, is assumed to be 101,000 m<sup>2</sup>, with fifty 2000 m<sup>2</sup> ponds plus the 1000 m<sup>2</sup> inoculation facility, resulting in a ratio of inoculant ponds to the total pond area of 1:100. This is a much greater ratio than the current industry standard of 1:10.

The future scenario assumes 1:100 for the ratio of inoculant ponds to production ponds, rather than the current approximate industry standard and Seambiotic ratio of about 1:10. Following this scaling the total future case pond was 10 ha, or 100 times greater than Seambiotic's 0.1 ha. We felt that increasing that ratio in the future case to 1:100 would not only be achievable within the next decade but may also be a requirement for viable future production. We believe it can be achieved with improvements in pond maintenance (i.e., reductions in pond population crashes and re-inoculation).

The inoculum for the ponds at the Seambiotic plant is started indoors, sequentially transferred to ponds of increasing size and finally to production ponds. Waste sea water (salinity ~35 g/L) from the adjacent power plant is used for cultivation and is available in much greater quantities than Seambiotic can use. The high salinity helps inhibit the growth of algae predators. Freshwater pumped from groundwater is used to mediate pond salinity. The waste flue gas from the co-located power plant is bubbled into the ponds using a blower. Algae are extracted from the production ponds at a rate of ~10% of pond volume/day. A centrifuge reduces the solution to a paste of ~20% solids. The plant further reduces the paste to dry biomass for shipping as a food additive, but the LCA described here does not include that drying. The annual average algae productivity at this facility is about 3 g/m<sup>2</sup>/day, which is considered low by most theoretical studies and anecdotal reports, but is the measured productivity for this year-round, outdoor, open pond system. This value will be discussed more below.

Table 1

Impact categories considered in the analysis.

Impact category	Unit of measure
GWP	kg CO <sub>2</sub> -equivalents
NER (net energy ratio, energy in/energy out)	MJ/MJ
PM (particulate matter) formation	kg PM <sub>10</sub> -equivalents
Water depletion <sup>a</sup>	m <sup>3</sup>
PCOP (photochemical oxidation potential)	kg NMVOC-equivalents
NO <sub>x</sub> (oxides of nitrogen)	kg NO <sub>x</sub>
SO <sub>x</sub> (oxides of sulfur)	kg SO <sub>x</sub>

<sup>a</sup> GREET data do not include water consumption.



The 20% paste is modeled as the input to the SRS extraction and separation technology. This process uses a wet extraction method that includes six main steps: pretreatment, extraction, solvent recovery, oil separation, belt filter press, and feed dryer (Table 4). The pretreatment step involves addition of an unidentified proprietary chemical that is modeled by using a generic process for organic chemicals. The extraction step involves addition of hexane that dissolves the oil and strips it from the algae. The solvent recovery phase recovers the hexane from the oil. The leftover biomass is dewatered and dried using the belt filter press and dryer. The values used to represent the SRS process are derived from the existing batch-scale AlgaFrac™ technology but estimated by SRS to reflect greater efficiencies when the batch-scale evolves to larger scale continuous processing. Most of the hexane added during oil extraction is modeled as recovered and reused but a small amount of it is lost as emissions to air and water. In our model the wastewater produced during the oil extraction is sent to a treatment plant. Transesterification is assumed for the conversion of algae oil into biodiesel. The future scenario uses data from all the processes described above, but with some assumptions for added efficiency due to scaling. These assumptions are presented later in Section 3.1 and 3.2.

### 2.5. Co-products

Co-products are produced during two processes: the SRS process for algae oil extraction and the transesterification process for converting the oil into biodiesel. The SRS process produces high value lipids (algal oil), low value lipids, and residual dry biomass (oilcake). Transesterification yields glycerin as a co-product. Allocation based on the energy content of the co-products was used to allocate impacts to the co-products. This allocation method is consistent with the GREET data. Table 2 and Table 3 present the allocation ratios based on the energy content. Sensitivity of the results to the energy based allocation is tested by using the displacement method.

## 3. Life Cycle Inventory

The Life Cycle Inventory (LCI) consists of the energy and material inputs and outputs for the process involved in algae biodiesel production and consumption. The LCI data and data sources for the base case are summarized in Table 4. Full LCI data are available as Supplemental Information. The oil extraction and conversion data for the future case are the same as the base case. Assumptions for the entire study, both base case and future case, are summarized in section 3.1 and 3.2. LCA software SimaPro (Pré Consultants, 2011) was used for modeling the data and generating results.

### 3.1. General assumptions

- The SRS oil extraction process uses a belt filter press to separate the algae solids from the water. Due to unavailability of belt press energy data, we have used 2 kWh/kg oil (same as the feed dryer energy).

**Table 2**  
Energy based allocation ratios per kg crude algae oil.

Co-product	Percent allocation
Crude algae oil	42%
Hydrocarbons	28%
Algae residue	30%

**Table 3**  
Energy based allocation ratios per kg algae biodiesel.

Co-product	Percent allocation
Algae biodiesel	90%
Glycerin	10%

- Transesterification process is assumed for the conversion of algae oil into biodiesel. GREET data for soy oil to biodiesel conversion was used as a surrogate.
- HHV for the low value lipids (co-product of algae oil) is assumed to be comparable to algae oil.
- All the electrical power requirements in the base case scenario are modeled using the average U.S. electricity grid from the Ecoinvent database.
- Co-location is assumed for all processes from production to combustion for both the scenarios; therefore the impacts associated with the transport of materials have been excluded from the current analysis.
- Materials and energy associated with the construction of any infrastructure have been excluded.

### 3.2. Future case assumptions

- The paddlewheel energy consumption is assumed to scale from 7.5 kW (for 8 paddlewheels) in the 1000 m<sup>2</sup> facility to 5.8 kW (for each paddlewheel in each of the fifty 2000 m<sup>2</sup> ponds in the 100,000 m<sup>2</sup> production facility). This scaling follows the actual pond size to paddlewheel power consumption ratios in Seabiotic's variously sized ponds – two 5 m<sup>2</sup> ponds with a 0.5 kW pump each, two 20 m<sup>2</sup> ponds with a 0.75 kW pump each, two 100 m<sup>2</sup> ponds with a 1.0 kW pump each, and two 350 m<sup>2</sup> ponds with a 1.5 kW pump each, and assumes that the efficiencies gained at Seabiotic as pond size scales up will continue when scaling up to the future case. The water pump and blower energy is assumed to scale linearly (i.e., no efficiency gains) and is 100 times greater, since pump and blower efficiencies generally do not increase with scale. We assumed the entire facility would scale up by a factor of 100 from Seabiotic's 0.1 ha facility to a future case of 10 ha. See more on this in the discussion. Algae productivity is assumed to increase from 3 g/m<sup>2</sup>/day to 25 g/m<sup>2</sup>/day. This is within the range of productivities currently reported in the literature.
- We assumed that autoflocculation will reduce water volume for centrifugation by a factor of 20, so if 1 centrifuge at 4 kW is required for every 1000 m<sup>2</sup> (as in the base case) we would need 100 for 100,000 m<sup>2</sup>; 100,000 m<sup>2</sup>/20 = 5000 m<sup>2</sup>, requiring 5 centrifuges at 4 kW each, or 20 kW. Sensitivity of the results to this assumption is tested by doubling the energy input (Fig. 5 and Fig. 6).
- The base case uses 0.24 kg oil/kg dry algae biomass. In the future, large scale algae production will likely use algae species with much higher oil content. The future case scenario therefore assumes 0.50 kg oil/kg dry algae biomass.
- A cleaner source of electricity is assumed to be supplying power in the future case. The average German electricity grid from Ecoinvent was used to model this electricity. The share of fossil fuels in this grid mix is about 55% (i.e., 15% less than the average U.S. grid).

## 4. Results

The results of this analysis indicate that the base case production (1000 m<sup>2</sup> pond area) compares very poorly across all criteria (NER, GWP, PM10, PCOP, NO<sub>x</sub>, and SO<sub>x</sub>) with industrial scale petroleum

**Table 4**

LCI data for the base case scenario.

Process/inputs	Value	Unit	Data source	Comment
Cultivation: inputs (kg <sup>-1</sup> dry biomass)				
Nitrogen fertilizer	0.26	kg	Seamiotic	52 g of nitrogen fertilizer is used per kg algae slurry at 20% solids.
Phosphorus fertilizer	0.045	kg	Seamiotic	9 g of phosphate fertilizer is used per kg algae slurry at 20% solids.
Freshwater	1.67	m <sup>3</sup>	Seamiotic	Added to offset evaporation and maintain salinity.
Electricity (paddlewheels)	30	kWh	Seamiotic	8 paddles wheels of increasing size (0.5 kW, 0.5 kW, 0.75 kW, 0.75 kW, 1.0 kW, 1.0 kW, 1.5 kW, 1.5 kW) are used for 12 h/day.
Electricity (flue gas blower)	12	kWh	Seamiotic	A 3 kW blower used to bubble the CO <sub>2</sub> into the ponds for 12 h/day.
Electricity (water pump)	3.33	kWh	Seamiotic	A 1 kW water pump used 10 h/day.
Electricity (algae inoculant prep)	6.77	kWh	Seamiotic	Florescent light (0.846 kW) used 24 h/day.
Electricity (algae inoculant prep)	14.9	kWh	Seamiotic	Air conditioner (0.746 kW) used 24 h/day.
Flue gas pumped in	-181	kg	Seamiotic	Flue gas at 180 m <sup>3</sup> /hr for 12 h/day with a CO <sub>2</sub> concentration of 13–15%. This input is modeled as an environmental credit.
Cultivation: outputs (kg <sup>-1</sup> dry biomass)				
CO <sub>2</sub> emitted	179	kg	Seamiotic	The ratio of CO <sub>2</sub> absorbed by the algae to dry biomass assumed to be 2:1.
Harvesting & dewatering: inputs (kg <sup>-1</sup> dry biomass)				
Electricity	2	kWh	Seamiotic	A 0.5 kW harvesting pump is used for 12 h/day.
Electricity	16	kWh	Seamiotic	A 4 kW centrifuge is used for 12 h/day for producing algae slurry.
Oil extraction: inputs (kg <sup>-1</sup> algae oil)				
Electricity	0.21	kWh	SRS	Electricity used per kg oil.
Heat (pretreatment and extraction)	4933	BTU	SRS	Energy input for the pretreatment and extraction of the oil.
Heat (solvent recovery)	6278	BTU	SRS	Energy input for recovery of hexane.
Heat (oil separation)	1805.57	BTU	SRS	Energy input for processing of the oil to separate the oil and other lipids.
Electricity (belt filter press)	2.0	kWh	Assumed	Energy input for belt filter press to dewater the biomass. Energy needed for this process is assumed to be comparable to the feed dryer energy.
Heat (feed dryer)	6417	BTU	SRS	Energy input for drying the biomass.
Hexane	0.33	kg	SRS	Solvent extraction method is used to extract the oil. Hexane is used as the solvent.
Chemical A	0.08	kg	SRS	Unidentified chemical. It is modeled by using a generic Ecoinvent process for organic chemicals.
Oil extraction: outputs (kg <sup>-1</sup> algae oil)				
Algae oil	1	kg	SRS	Primary output of the process. Allocated based on the high heat value (HHV) of 16,200 BTU/lb.
Algae residue (oilcake)	1.87	kg	SRS	Co-product of algae oil production. Allocated based on the HHV of 6107 BTU/lb (21)
Low value lipids	0.67	kg	SRS	Co-product of algae oil production. Allocated based on the HHV of 16,000 BTU/lb (assumed to be comparable to biodiesel).
Wastewater	17.35	l	SRS	The slurry contains 80% water and 20% solids. The water is sent to a treatment facility. Out of the 20% solids, about 3% remain in the water and are also sent to wastewater treatment. Chemical A is removed as wastewater also.
Hexane losses	0.0038	kg	SRS	A small amount of hexane is lost during the oil extraction as fugitive emissions.
Conversion to biodiesel: Transesterification from GREET 1_2011 (GREET, 2011).				
Biodiesel combustion: Combustion in a CIDI vehicle from GREET 1_2011 (GREET, 2011).				

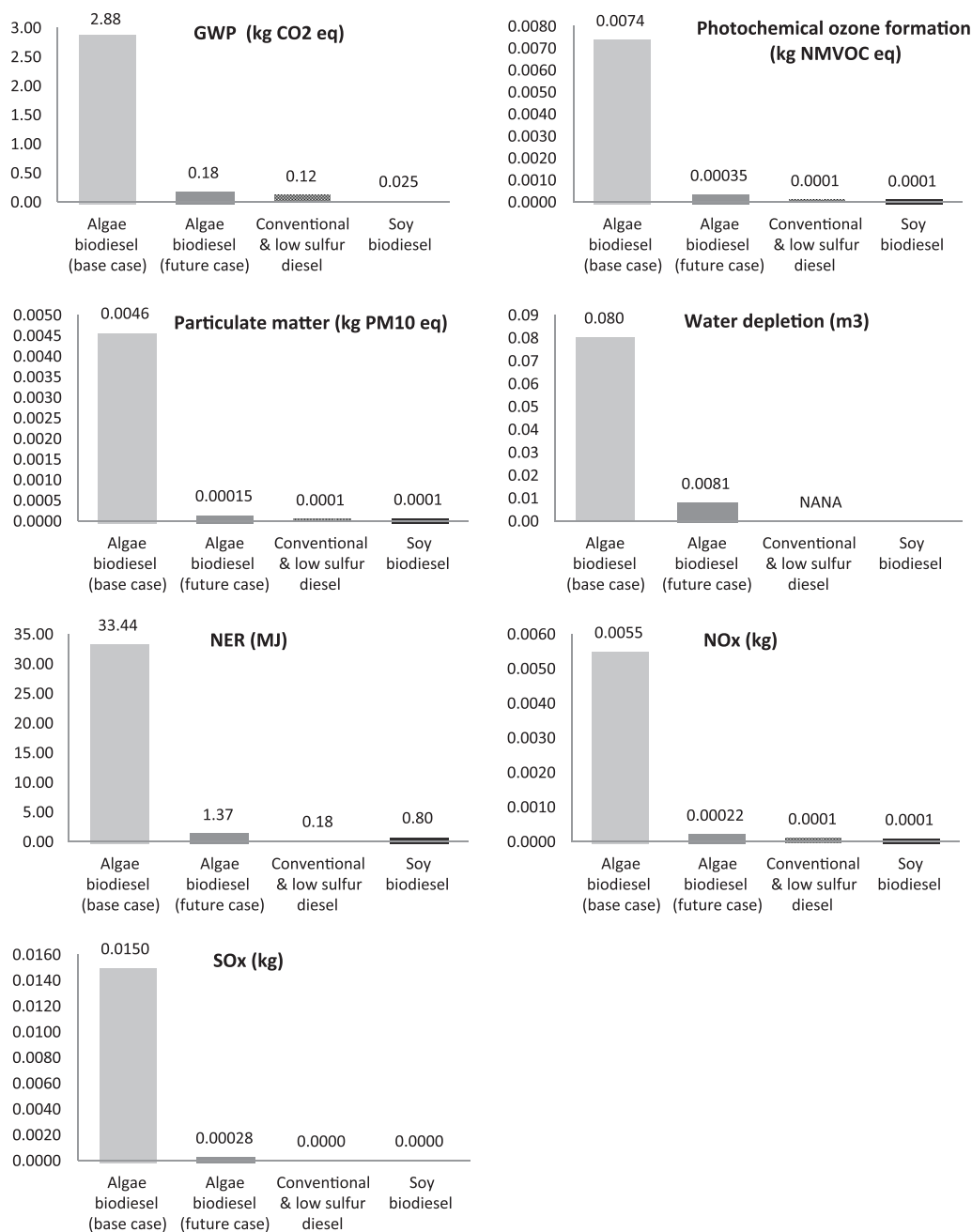
diesel and soy biodiesel (Fig. 3). This should be expected, because in the base case we are comparing algae biodiesel production at a very small scale relative to production of petroleum diesel and soy biodiesel at large, technically mature, industrial scales. Significant improvement is seen in the environmental impacts for the future case, in which the NER reduces to 1.37 (from 33.4 in the base case) and GWP reduces to 0.18 kg CO<sub>2</sub>-equivalents from 2.9 kg CO<sub>2</sub>-equivalents in the base case. The NERs for petroleum diesel and soy biodiesel are 0.18 and 0.80, respectively (GREET, 2011). These improvements can be attributed to the assumed gains in productivity and harvesting efficiency in the future case.

A contribution analysis was conducted to examine the breakdown of the impacts for the base and the future case. The results indicate that the largest impacts across all categories come from the

energy use in the pumps, blowers, paddlewheels, and centrifugation in the cultivation and harvesting stage, underlining the need for technical improvements in these areas (Fig. 4).

Scaling up algae production in the future case led to improvement across all criteria, but the impacts are still predominantly from the power requirements associated with cultivation (Fig. 4). With cultivation and harvesting playing a smaller role in the future case, the extraction and separation phases play a relatively larger role.

Sensitivity analyses were conducted to examine the sensitivity of the future case to the allocation method, to the electricity grid, to the assumed energy usage in the belt press process during the oil extraction, and assumed energy usage for the paddlewheel and the centrifuge (Fig. 5). Displacement method was used to evaluate



**Fig. 3.** Comparison of algae biodiesel with conventional and low sulfur diesel and soy biodiesel per functional unit (1 MJ of fuel combusted in a CIDI vehicle). Note that GREET data does not include water depletion.

sensitivity to the allocation method. The co-products of the algae oil production—algae residue and low value lipids—are assumed to displace fish feed (Aresta et al., 2005 and Kadam, 2002) and light fuel oil, respectively. The sensitivity to the electricity source was conducted by replacing the average German electricity grid with the average U.S. grid, which contains about 15% more fossil energy. The sensitivity to the energy utilized by the belt filter press, paddlewheel and centrifuge was conducted by assuming twice the current amount. Another sensitivity test was done for the assumed oil content in the algae by using 0.25 kg oil/kg dry biomass and 0.75 kg oil/kg dry biomass – bracketing the future case value of 0.50 kg oil/kg dry biomass. Finally, sensitivity of the results to the daily biomass productivity in the base case was examined by using 25 g/m<sup>2</sup>/day as most of the studies referred to for this work have

used a productivity between 20 and 30 g/m<sup>2</sup>/day (Lardon et al., 2009; Batan et al., 2010; Frank et al., 2011) (Fig. 6).

The results showed little sensitivity to the choice of allocation, and to the assumed belt filter press, paddlewheel and centrifuging energy. In the case of the electricity source, the impacts are slightly higher with the average U.S. grid. Considering that the U.S. grid mix has only 15% more fossil fuels, we conclude that if the energy source has much higher fossil fuels, the NER can increase significantly, and vice versa. The sensitivity test for the oil content and the biomass productivity shows that the results are strongly sensitive to these variables. Most notably, increasing oil yield in the future case to 0.75 kg oil/kg dry biomass brings the NER down to 0.64 and into the range of petroleum diesel and soy biodiesel (0.18 and 0.80, respectively).

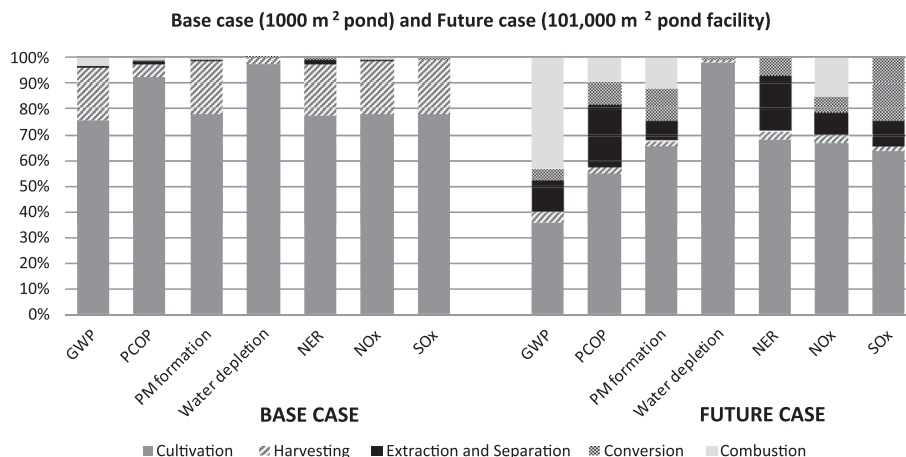


Fig. 4. Contribution analysis for the algae biodiesel base case (1000 m<sup>2</sup> pond) and future case (101,000 m<sup>2</sup> pond facility) per functional unit (1 MJ of fuel combusted in a CIDI vehicle).

5. Discussion

The results suggest that significant improvements and efficiencies will have to be realized in algae production for it to become a competing feedstock for transportation fuels. The LCA results for the commercial facility (base case) compare poorly with soy biodiesel and petroleum diesel. The results in the base case are at least an order of magnitude higher than the soy biodiesel and petroleum diesel across all categories, with most of that impact coming from cultivation and harvesting. A large difference like this should be expected, since in this case we are comparing relatively immature, small-scale algae production and processing for high value food additives with very large-scale, technically mature, farming and industrial processes used for soy biodiesel and petroleum diesel. The future case with improved efficiencies provides lower impacts across all categories compared to the base case, although even in the future case more energy is required to produce algal biodiesel than is embodied in it. In other categories the future case results are closer to soy biodiesel and petroleum diesel but are still notably higher – except in the test of the model’s sensitivity to increasing oil yield to 0.75 kg oil/kg dry biomass, in which case the algae impacts compare well with soy biodiesel and petroleum diesel.

The base case NER results (33.4) are found to be significantly higher when compared to some of the existing algae biodiesel LCA

studies. For example, Lardon et al. (2009) provide NER values of 1.96, 1.04, 1.47, and 0.744 for four algae production and oil extraction scenarios, and Frank et al. (2011) provide an NER of 2.58 (all with NER values calculated as energy in/energy out). One of the reasons for the difference in the results is the higher productivity (20–30 g/m<sup>2</sup>/day) assumed by most of the authors. This study uses 3 g/m<sup>2</sup>/day for the base case, which is the annual average productivity of the algae facility studied. Furthermore, the total energy input in the base case scenario (28 MJ/kg oil) is considerably higher than what has been used in most of the previous studies. For example, Stephenson et al. (2010) used 1.8 MJ/kg oil and Lardon et al. (2009) used 8.6, 30.8, 3.9, and 14.1 MJ/kg oil for their four algae production scenarios. According to Seambiotic, both the low productivity and high energy input per kg oil are reasonable for outdoor, open ponds in year-round commercial production. More LCAs of actual small- and large-scale production pond facilities will help resolve these issues.

Sensitivity analyses were conducted to examine the sensitivity of the results to certain variables in the base and the future case. Sensitivity test for biomass productivity in the base case shows that the environmental impacts reduce considerably with a higher productivity. NER with 25 g/m<sup>2</sup>/day productivity reduces from 33.4 to 4.32, which is much more comparable to the past studies. Sensitivity testing for the future case for variables shows that the

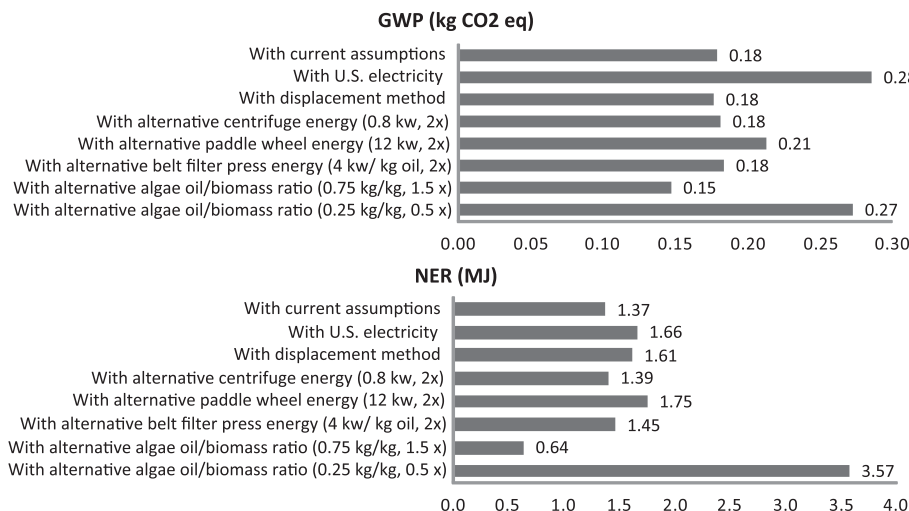


Fig. 5. Sensitivity analysis for future case.

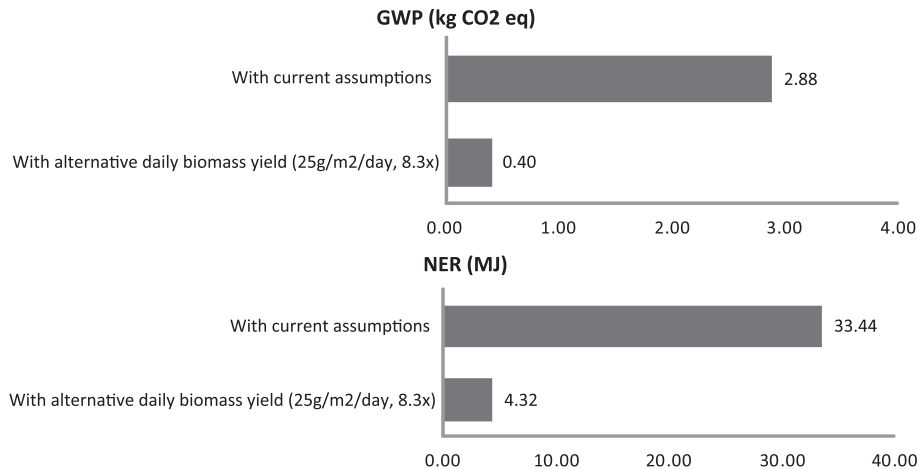


Fig. 6. Sensitivity analysis for base case.

results are most sensitive to the source of electricity and oil content per kilogram biomass. Based on these results, we can conclude that if algae cultivation in the future utilizes a clean source of energy, such as wind or hydropower, and algae species with high biomass productivity and much higher oil content, then considerable reductions in NER and other impacts associated with fossil fuel consumption can be achieved. Notably, the NER in the future case with a biomass productivity of 50 g/m<sup>2</sup>/day and an oil yield of 0.75 kg oil/kg dry biomass is only 0.64, placing it favorably in comparison to the NER for soy biodiesel at 0.80. This suggests that increasing productivity and oil yield may be the most important technological advances in this field.

Results in both the base case and the future case represent a kind of “best case” with regard to impacts because full co-location of all resources and processes is assumed. Any transport of resources, such as water or nutrients, from sources to production facilities, or the transport of products from one process stage to another, were not included in either scenario.

Breakthroughs that may allow algae to play an important role in meeting future energy demand will include improved cultivation and harvesting methods and the use of renewable energy to drive them, higher biomass productivities, higher oil yields, nutrient recycling, and other similar kinds of advances. However, an important breakthrough at a larger scale will be the intentional physical co-location of new industrial processes and facilities so that wastewater, waste nutrients, and waste CO<sub>2</sub> can all be used as feedstock for algae production.

Achieving the 1:100 inoculant to pond ratio (rather than the current industry standard of about 1:10) will require advances in the ability to prevent the crash of pond populations, which may be due to pathogens, predators, or other ecological dynamics. Hybridization or molecular modification of algal species aimed at making them more resilient to disease or other kinds of disruptions may help achieve the longevity in ponds that can help increase the ratio. Genetic modification may also be promising in improving biomass and oil productivity (Beer et al., 2009; Radakovits et al., 2010). However, the release to marine and freshwater ecosystems of genetically modified highly resilient algae species could have very important and negative impacts on native algal species and to marine and freshwater ecosystems in general.

The historic monopoly held by fossil fuels in the human energy economy may not persist long into the future, and the future energy demands may be met by a mosaic of sources, each filling different needs in the marketplace. Algae may meet some set of those needs. In any case, a critically important part of that mosaic should include

not only efforts in science and technology to provide for current consumption and to meet future demand, but also to reduce both through significant conservation and other demand reduction approaches.

#### Acknowledgments

This work was performed under funding support to Sandia National Laboratories from the Office of Biomass Program within the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. The authors specifically wish to thank staff from Seabiotic, Inc., and from SRS, Inc., who generously provided data and information, and to the project's DOE coordinators Joanne Morello and Joyce Yang. We appreciate a review of the paper provided by Dr. Ed Frank at Argonne National Laboratory, and by three anonymous reviewers. Sandia National Laboratories is a multiprogram laboratory managed and operated by Sandia Corporation, a wholly-owned subsidiary of Lockheed Martin Corporation, for the US Department of Energy's National Nuclear Security Administration under contract DEAC04-94AL85000.

#### References

- Aresta, M., Dibenedetto, A., Barberio, G., 2005. Utilization of macro-algae for enhanced CO<sub>2</sub> fixation and biofuels production: development of a computing software for an LCA Study. *Fuel Processing Technology* 86 (14–15), 1679–1693.
- Batan, L., Quinn, J., Willson, B., Bradley, T., 2010. Net energy and greenhouse gas emission evaluation of biodiesel derived from microalgae. *Environmental Science and Technology* 44 (20), 7975–7980.
- Beer, L.L., Boyd, E.S., Peters, J.W., Posewitz, M.C., 2009. Engineering algae for biohydrogen and biofuel production. *Current Opinion Biotechnology* 20 (3), 264–271.
- Brune, D.E., Lundquist, T.J., Benemann, J.R., 2009. Microalgal biomass for greenhouse gas reductions: potential for replacement of fossil fuels and animal feeds. *Journal of Environmental Engineering* 135 (11), 1136–1144.
- Clarens, A.F., Resurreccion, E.P., White, M.A., Colosi, L.M., 2010. Environmental life cycle comparison of algae to other bioenergy feedstocks. *Environmental Science and Technology* 44 (5), 1813–1819.
- Clarens, A.F., Nassau, H., Resurreccion, E.P., White, M.A., Colosi, L.M., 2011. Environmental impacts of algae-derived biodiesel and bioelectricity for transportation. *Environmental Science and Technology* 45 (17), 7554–7560.
- Cooney, M.J., Young, G., Pate, R., 2010. Bio-oil from photosynthetic microalgae: case study. *Bioresource Technology* 102 (1), 166–177.
- Frank, E.D., Han, J., Palou-Rivera, I., Elgowainy, A., Wang, M.Q., 2011. Life Cycle Analysis of Algal Lipid Fuels with the GREET Model. Energy Systems Division. Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439.
- Frischknecht, R., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hirschler, R., Jungbluth, N., Nemecek, T., Rebitzer, G., Spielmann, M., 2007. Overview and Methodology. Final Report, Ecoinvent V2.0 No. 1, Swiss Centre for Life Cycle Inventor.



- REET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model), 2011. Argonne National Laboratory, U.S. Department of Energy. <http://greet.es.anl.gov/> (accessed 10.08.12.).
- ISO 14040, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework.
- Johnson, M.B., Wen, Z., 2010. Development of an attached microalgal growth system for biofuel production. *Applied Microbiology and Biotechnology* 85 (3), 525–534.
- Jorquera, O., Kiperstok, A., Sales, E.A., Embirau, M., Ghirardi, M.L., 2010. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. *Bioresource Technology* 101 (4), 1406–1413.
- Kadam, K., 2001. Microalgae Production from Power Plant Flue Gas: Environmental Implications on a Life Cycle Basis. Technical Report NREL/TP-510-29417. National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO, 80401.
- Kadam, K.L., 2002. Environmental implications of power generation via coal-microalgae cofiring. *Energy* 27 (10), 905–922.
- Lardon, L., Helias, A., Sialve, B., Steyer, J.-P., Bernard, O., 2009. Life-cycle assessment of biodiesel production from microalgae. *Environmental Science and Technology* 43 (17), 6475–6481.
- McGinn, P.J., Dickinson, K.E., Bhatti, S., Frigon, J.C., Guiot, S.R., O'Leary, S.J.B., 2011. Integration of microalgae cultivation with industrial waste remediation for biofuel and bioenergy production: opportunities and limitations. *Photosynthesis Research* 109 (1–3), 231–247.
- Pate, R., 2013. Resource requirements for the large scale production of algal biofuels. *Biofuels* 4 (4), 409–435.
- Pate, R., Klise, G., Wu, B., 2011. Resource demand implications for US algal biofuels production scale-up. *Applied Energy* 88 (10), 3377–3388.
- Pré Consultants, 2011. SimaPro 7.2. Amersfoort, The Netherlands. <http://www.prestustainability.com/> (accessed 05.05.12.).
- Radakovits, R., Jinkerson, R.E., Darzins, A., Posewitz, M.C., 2010. Genetic engineering of algae for enhanced biofuel production. *Eukaryotic Cell* 9 (4), 486–501.
- Sander, K., Murthy, G., 2010. Life cycle analysis of algae biodiesel. *International Journal of Life Cycle Assessment* 15 (7), 704–714.
- Smith, V.H., Sturm, B.S.M., deNoyelles, F.J., Billings, S.A., 2009. The ecology of algal biodiesel production. *Trends in Ecology and Evolution* 25 (5), 301–309.
- Stephenson, A.L., Kazamia, E., Dennis, J.S., Howe, C.J., Scott, S.A., Smith, A.G., 2010. Life-cycle assessment of potential algal biodiesel production in the United Kingdom: a comparison of raceways and air-lift tubular bioreactors. *Energy and Fuels* 24 (7), 4062–4077.
- Sturm, B.S.M., Lamer, S.L., 2011. An energy evaluation of coupling nutrient removal from wastewater with algal biomass production. *Applied Energy* 88 (10), 3499–3506.
- Sun, A., Davis, R., Starbuck, M., Ben-Amotz, A., Pate, R., Pienkos, P.T., 2011. Comparative cost analysis of algal oil production for biofuels. *Energy* 36 (8), 5169–5179.
- U.S. DOE (U.S. Department of Energy), 2010. National Algal Biofuels Technology Roadmap. U.S. DOE, Office of Energy Efficiency and Renewable Energy, Biomass Program.
- Weyer, K.M., Bush, D.R., Darzins, A., Willson, B.D., 2010. Theoretical maximum algal oil production. *Bioenergy Research* 3 (1), 204–213.
- Wigmosta, M.S., Coleman, A.M., Skaggs, R.J., Huesemann, M.H., Jane, L.J., 2011. National microalgae biofuel production potential and resource demand. *Water Resources Research* 47. <http://dx.doi.org/10.1029/2010WR009966>. W00H04.