

Life cycle analysis of algae biodiesel

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Abstract

Background, aim, and scope Algae biomass has great promise as a sustainable alternative to conventional transportation fuels. In this study, a well-to-pump life cycle assessment (LCA) was performed to investigate the overall sustainability and net energy balance of an algal biodiesel process. The goal of this LCA was to provide baseline information for the algae biodiesel process.

Materials and methods The functional unit was 1,000 MJ of energy from algal biodiesel using existing technology. Systematic boundary identification was performed using relative mass, energy, and economic value method using a 5% cutoff value. Primary data for this study were obtained from The USLCI database and the Greenhouse Gases, Regulated Emissions and Energy use in Transportation model. Carbohydrates in coproducts from algae biodiesel production were assumed to displace corn as a feedstock for ethanol production.

Results and discussion For every 24 kg of algal biodiesel produced (1,000 MJ algae biodiesel), 34 kg coproducts are also produced. Total energy input without solar drying is 3,292 and 6,194 MJ for the process

with filter press and centrifuge as the initial filtering step, respectively. Net CO₂ emissions are –20.9 and 135.7 kg/functional unit for a process utilizing a filter press and centrifuge, respectively. In addition to the –13.96 kg of total air emissions per functional unit, 18.6 kg of waterborne wastes, 0.28 kg of solid waste, and 5.54 Bq are emitted. The largest energy input (89%) is in the natural gas drying of the algal cake. Although net energy for both filter press and centrifuge processes are –6,670 and –3,778 MJ/functional unit, respectively, CO₂ emissions are positive for the centrifuge process while they are negative for the filter press process. Additionally, 20.4 m³ of wastewater per functional unit is lost from the growth ponds during the 4-day growth cycle due to evaporation.

Conclusions and recommendations This LCA has quantified one major obstacle in algae technology: the need to efficiently process the algae into its usable components. Thermal dewatering of algae requires high amounts of fossil fuel derived energy (3,556 kJ/kg of water removed) and consequently presents an opportunity for significant reduction in energy use. The potential of green algae as a fuel source is not a new idea; however, this LCA and other sources clearly show a need for new technologies to make algae biofuels a sustainable, commercial reality.

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1 Introduction

About 28% of the 99.3 quads of total energy demand in the USA in 2008 (EIA 2008) was used in the

transportation sector. The world needs alternatives to provide transportation energy needs (Dale 2008), and biofuels from renewable bioresources provide one such alternative. Although other automobile technologies using plug-in electric, natural gas, and hydrogen may provide alternatives to terrestrial transport, presently there is no such alternative for the air transportation sector.

Due to limitations in production capacity, first-generation feedstocks such as corn and soybeans cannot meet all the transportation fuel needs. Additionally, food vs. fuel issues, requirement of intensive agricultural inputs, land use, and freshwater use are some of the limitations for large-scale production of the first generation of biofuels. Second-generation feedstocks, using cellulose in nonedible plant biomass, address some of the concerns such as food vs. fuel. Though (ligno)cellulosic feedstocks do not use human food resources, they still require arable land, freshwater, and some agricultural inputs for their production. Long-term impacts of sustained biomass harvest on soil quality, nutrient management are still being studied. Additionally, infrastructure for large-scale production, transportation, and processing is in the initial stages of development.

Biofuels from algae feedstock are the “third generation” of biofuel feedstocks as they can potentially address most of the concerns about first- and second-generation fuels. Algae are autotrophs that utilize CO₂ and sunlight through photosynthesis. Algae can be used to obtain the essentials of life such as oxygen, organic carbon, and vital nutrients (Hills and Nakamura 1978; Borowitzka and Borowitzka 1988; Lembi and Waaland 1989; Shelef and Soder 1980). Some strains of algae accumulate high lipid/starch content; thus, algae can be used as a feedstock for producing liquid biofuels. Algae have shorter growth cycles as compared to other terrestrial plants, and hence, the biofuel productivity potential from algae is orders of magnitude higher than terrestrial crops such as soybeans (Chisti 2007). Algae can be grown in wastewater unfit for crop irrigation or municipal use. Versatility of algae to grow in diverse climatic conditions and wastewaters as well as their heavy metal sequestration capacity has been well documented (Sheehan et al. 1998b; Mehta and Gaur 2005; Grima et al. 2003; Ceron et al. 2008). Many processes have been proposed for growing single-celled algae and converting it into liquid fuels (Chisti 2007; Aresta et al. 2005; Sheehan et al. 1998b). Algae biofuels is a rapidly advancing area with many studies focusing on production, harvesting, and processing technologies. However, there are relatively few studies on the long-term sustainability and life cycle analysis of the algae

to biofuels pathways (Aresta et al. 2005; Clarens et al. 2010; Lardon et al. 2009).

As with any potential new technology, the long-term sustainability of algae production as well as its impacts on the environment are critical concerns. These questions deserve special consideration because such questions have been raised in the case of other biofuels. It is prudent to answer these questions before any large-scale production of biofuels from algae biomass.

A well-to-pump LCA is a general descriptive term used in transportation fuel LCA to indicate an LCA including processes from the extraction of resources from the earth to delivery of fuel at refueling station.

Many of the contrasting conclusions from several LCA's and resulting debates can be traced to less rigorous system boundary definition (Wang 2005). Relative mass, energy, and economic value (RMEE) is a system boundary selection protocol proposed by Reynolds et al. (2000). RMEE method is a systematic method that is objective, repeatable, and quantitative to ensure fair comparison between systems with very different configurations. In the RMEE method, the information about individual system processes is compiled before the system boundary is drawn making this process less prone to subjectivity. This information is then used to delineate the system boundary. Using this system, individual unit process data cannot be left out arbitrarily which is contrary to typical LCA practice.

Presently, there are no large-scale commercial operations that produce and process algae feedstock into biodiesel, so a complete industrial scale algal biodiesel processes is not readily available to model. The process technology for the algae-based biodiesel process used in this LCA is based on current state-of-the-art industrial technology. Such component technologies are well characterized and used in other industries, or have been used in large-scale algae culture for other purposes such as wastewater remediation. Different aspects of algae technology have been studied for decades, yet a detailed LCA of a practical whole algae system has not been done to enable an analysis of energy input and environmental impact. The goal of this LCA is to establish baseline information for the process of making algal biodiesel, to which other transportation fuel LCA's can be compared. Understanding the environmental burdens of the algal biodiesel production will allow insight into inherent sustainability. Information from this LCA will be useful in identifying energy and emission bottlenecks in the process. This information can be used to provide impetus for further technological advancement of algal biodiesel and reduce overall energy use and environmental impact of a future algal biodiesel process.

Therefore, the specific objectives of this paper are to:

1. Perform well to pump LCA for the production of 1,000 MJ energy from algal biodiesel
2. Establish baseline information for algal biodiesel process
3. Assess sustainability of algae biodiesel by characterizing energy use and emissions

2 Scope of this study

The goal of this LCA is to provide baseline information for the algae biodiesel process. The system analyzed is typical of what the authors believe an algae system would look like if it were implemented today. This model proposes using currently existing industrial technology (both in algae processing and other industries). This approach was taken for two reasons: If algae is to be grown large scale as a fuel source, early systems will most likely use already existing technology components. Data for such component technologies is readily available and verifiable. The functional unit for the LCA analysis is 1,000 MJ of energy from algae biodiesel “well-to-pump.”

2.1 Data organization and display

The data were organized in a Microsoft Excel spreadsheet. Efforts were made to make these data compilation/model as transparent and user friendly as possible. The data which are deemed variable are listed on a separate worksheet and can be changed. Changing these values will result in a spreadsheet recalculation. This feature increases transparency, allows for a multitude of calculation scenarios and model sensitivity analyses.

2.2 Data specificity

Data used in this report, in all cases where a distinction is appropriate (such as electricity prices, efficiency values), are specific to the USA. All attempts were made in using the most up-to-date data available; however, some data were chosen over newer data because of its greater specificity and usefulness.

3 Life cycle inventory

3.1 Relative mass energy and economic value method

In choosing a complete system boundary, the RMEE method was employed (Raynolds et al. 2000). The

RMEE method uses a predefined “cut off ratio” to the functional unit on the basis of mass, energy, and economic value. For a process input, a relative ratio of that input to the functional unit is determined for all three values (mass, energy, and economic value). Starting with the unit process closest to the functional unit, the three RMEE ratios are calculated for each input. If any of the three RMEE ratios are larger than the predefined cut off ratio for a given input, the upstream process of that input is included in the system boundary. This is done until all upstream processes are below the cut off threshold. A cutoff ratio of 5% was chosen for this LCA. Therefore, all processes which contribute >5% mass, energy, or economic value with respect to the functional unit are included.

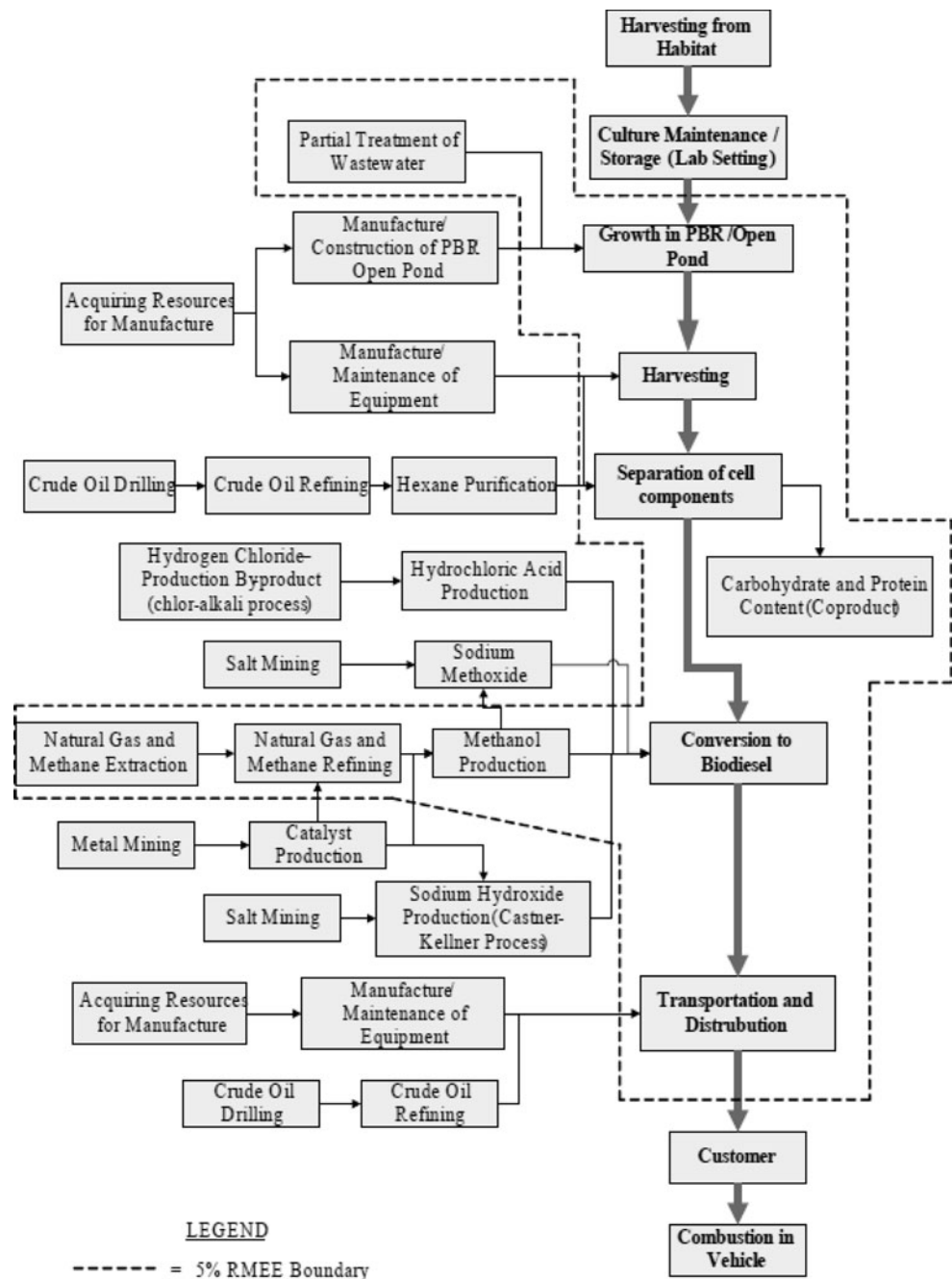
3.2 System boundary

Algal biodiesel conversion process (Fig. 1) analyzed in this LCA is similar to a process which may be implemented if a plant were to be built today. It must be noted that the analysis will be significantly different if new technologies lead to radically different process layouts.

The process starts with culturing a strain of algae in photobioreactors/indoor ponds to prepare inoculum. The inoculum will be used as a seed culture for the open ponds. Open ponds, based on standard design (Borowitzka and Borowitzka 1988), consist of a lined, shallow raceway (0.18 m deep and 1,115 m length) in which water containing algae is circulated by paddle wheels. Wastewater after secondary treatment is used as nutrient medium, and the wastewater is assumed to have all nutrients necessary for algal growth except carbon. Carbon dioxide may be supplied from external sources such as flue gases from boilers, furnaces, or power plants to stimulate the growth of algae in the open ponds, although flue gas sparging is not considered in this LCA. Typical harvest–growth–harvest cycle is assumed to be 4 days (Borowitzka and Borowitzka 1988).

After the growth of algae to their harvest concentration, they are separated from the wastewater by one of two processes, filtered through a chamber filter press or centrifuged in a self-cleaning plate separator centrifuge followed by drying in a natural gas fired dryer. The algae are dried to 9% moisture, the required moisture content for the hexane extraction step (Sheehan et al. 1998a).

After the harvesting and drying steps, lipids present in the algae are extracted using a solvent (hexane) extraction process. Growth, harvest, and oil extraction from algae are assumed to be performed at the same

Fig. 1 Process flow diagram

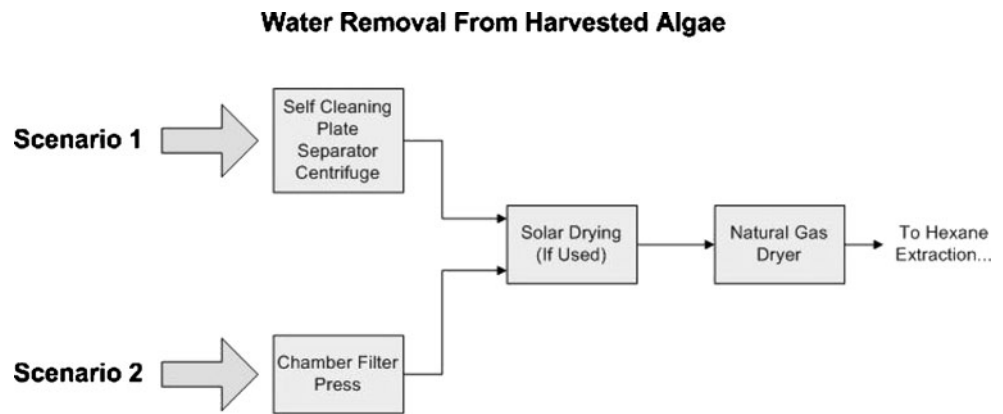
site. Algal oil is then transported 150 km to a separate facility for conversion to algae biodiesel. Hexane extraction process and transesterification of resulting algal oil into biodiesel were modeled based on a previous soybean biodiesel LCA (Sheehan et al. 1998a).

The final process included in this LCA is the transportation and distribution of the biodiesel as described by the Greenhouse Gases, Regulated Emissions and Energy use in Transportation (GREET) model (GREET 2008). This involves transporting the biodiesel from a conversion plant through a distribu-

tion chain to a refueling station. The functional unit is described as 1,000 MJ of biodiesel at a refueling station. Since this is a well-to-pump LCA, this LCA does not capture the emissions created resulting from the use of algae biodiesel in the vehicles.

3.3 Algae dewatering

Algae dewatering is the most significant energy sink in the process, and therefore, a more detailed analysis was performed for this step. Dewatering freshly harvested

Fig. 2 Water removal process flow

algae slurry can be accomplished in two alternate pathways (Fig. 2).

Both scenarios have three distinct steps to take the algae/wastewater mixture from a dilute $5 \times 10^{-2}\%$ (w/w ; 0.5 g algae/L) to 91% algae. Only the first step of the two pathways is different. In the first process, a self-cleaning plate separator centrifuge is used while in the second process, chamber filter press is used as a first dewatering step.

Both scenarios allow for user-defined amounts of solar drying as the second step so as to reduce the amount of water to be removed (and subsequent energy

use) in the drum drying step. It is assumed that there are no energy inputs (beyond the pumping requirements) to be accounted for in the solar drying process, no air emissions created, and no mass lost. The third step in both scenarios is a natural gas fired dryer.

3.4 Data quality indicators and notable assumptions

3.4.1 Data sources

Two primary data sources used to compute LCI environmental outputs and energy inputs were the US

Table 1 Summary of data sources

Unit process	Data source	Data gathered from source
RMEE analysis	GREET (2008)	Natural gas boiler efficiency
	Akers et al. (2006)	Density of diesel fuel, biodiesel Heat of combustion diesel fuel, biodiesel
Growth	Borowitzka and Borowitzka (1988)	Electricity requirements Paddle wheel and pond design, 1988
Harvest and drying	Shelef and Soder (1980)	Operating parameters of separations Unit process equipment, 1980
	Sheehan et al. (1998a)	Natural gas dryer efficiency, 1998
Separation	USLCI (2008)	Natural gas dryer emissions
	Sheehan et al. (1998a)	Hexane extraction process information, 1998
	Borowitzka and Borowitzka (1988)	Dry algal cell components
Algal oil transportation	USLCI (2008)	Natural gas boiler inputs and emissions
	USLCI (2008)	Diesel truck transportation information
Biodiesel conversion	Sheehan et al. (1998a)	Base catalyzed transesterification
MeOH production and transportation	USLCI (2008)	MeOH production and transportation Missing CO ₂ emission information
	GREET (2008)	Transportation and distribution of biodiesel
Biodiesel transportation and distribution	GREET (2008)	Inputs and emissions
Natural gas extraction and processing	USLCI (2008)	Natural gas extraction and Processing inputs and emissions
	GREET (2008)	Inputs and emissions
Coproduct allocation	Nielsen and Wenzel (2005)	Density of raw corn

LCI database (created and maintained by ACLCA) (USLCI 2008) and the GREET model version 1.8 (GREET 2008).

Data sources for process parameters and energy inputs are shown in Table 1. Since transesterification of algal oil is yet to be practiced on a large scale, little data exist. Data for the growth and harvest portions of the LCA were taken from Borowitzka and Borowitzka (1988), Shelef and Soder (1980), Richmond (1986), and Lembi and Waaland (1989).

Data for the soybean crushing (oil separation) and biodiesel conversion processes were obtained from Sheehan et al. (1998a). Some of the steps such as grinding, hull cracking, flaking, and other pre-extraction processing steps specific to soybean feedstock were omitted due to the differences between algal biomass and soybeans. Also, data were specified in terms of outputs per mass of whole beans delivered to the processing plant. Therefore, reported values were adjusted to units of outputs per “mass processed” rather than per “mass delivered”.

Additional assumptions (Table 2) were made in regard to use of the soybean biodiesel model developed by Sheehan et al. (1998a). Hexane-extracted algal oil was assumed to have similar composition as soy-

bean oil. The lipid percentage of the algal feedstock and working volume in the separation process were adjusted for typical algal values (Borowitzka and Borowitzka 1988).

3.4.2 Coproduct allocation

One of the largest input and output values (depending on parameter settings) in this LCA is the coproduct allocation. In the USA, 97% of ethanol produced is made using corn as a feedstock (Shapouri et al. 2006). Typical algae biomass has a substantial fraction of carbohydrate, particularly after the lipid has been removed. The carbohydrate fraction can be further converted to simple sugars and fermented into ethanol using a process similar to a dry grind corn ethanol conversion process. Thus, this LCA supposes that algae carbohydrate byproduct will become a feedstock for an ethanol conversion process, offsetting the currently used corn feedstock. Algae meal was chosen to have the same ethanol yield as wheat straw since residual algae meal and wheat straw have similar glucan content (Kim and Dale 2003). Since algae do not contain lignin, it is anticipated that the ethanol conversion process involving algae meal will not require a harsh lignocellulosic

Table 2 Summary of assumptions

Process	Assumptions
Growth	Wastewater substrate has ample nutrients for algal and bacteria growth Raceway pond operated to maximize algal growth Wastewater taken after secondary treatment
Harvest	Algae are 30% lipids, 37.5% protein, 31% carbohydrates and 1.5% nucleic acids Dryer requires 3,556 kJ/kg (850 kcal/kg) water removed (Sheehan et al. 1998a) Dry algae has a density of 1 g/mL Filter press capture is 90% No mass loss in dryer or during solar drying
Separation	Filter cloth replacement not included LCA due to lack of reliable data No energy input or emissions from solar drying Algae delivered to hexane extraction at 9% moisture Overall extraction process is 92.5% efficient Hexane extraction is 96% efficient Algae residuals leaving hexane extraction are at 12% moisture (Sheehan et al. 1998a)
Biodiesel conversion	Distance traveled from extraction to conversion site = 150 km Overall mass yield = 96.4% MeOH to algal oil molar ratio 6:1 Transesterification reaction yield 99% Density of algal oil = 0.93 g/L No losses in glycerin settling tanks Counter-current biodiesel washing utilizes water equal to 20% <i>w/w</i> of biodiesel feed
RMEE	Default GREET model assumptions Density of algal biodiesel = 0.87 g/mL
Coproduct allocation	Algae meal converted to fuel ethanol Algae meal displaces corn as feedstock in a fuel ethanol plant Additional corn production required to replace DDGS market

pretreatment. Based on preliminary studies (Sander and Murthy 2009), algae “pretreatment” would consist of a process similar to corn dry grind ethanol liquefaction process.

The allocation was done using the system expansion method of allocation (Fig. 5; Kim and Dale 2002). A theoretical yield was calculated for the algae meal, based on the assumption that 30% of the carbohydrates are cellulose (Ververis et al. 2007). It is assumed that hemicelluloses are not fermented in such a process. A cellulose to ethanol yield of 85% was assumed, resulting in 6.28 L (1.66 gal) of ethanol per 1,000 MJ of algal biodiesel. Assuming a corn dry grind ethanol yield of 0.387 L/kg corn (2.6 gal/bushel), the algae meal coproduct from one functional unit would replace 16.25 kg of corn (15% moisture) input.

Protein matter made up the bulk of the remaining algae meal. If algae were to replace the corn input into the ethanol process, 5.22 kg of DDGS would not be produced. Kim and Dale (2002) state a displacement ratio of 1.077 U of corn for 1 U of DDGS. This would necessitate adding 5.62 kg of corn back into the system and bringing the net amount of corn displaced to 10.63.

Residual algae meal, consisting mostly of protein and minerals, has not been evaluated as a replacement for other products. It is not definitively known at present whether residual algae meal can replace DDGS or other protein rich products. For this reason, the residual algae meal was not assigned a displacement value nor were any of the inputs and emissions from algal biodiesel allotted to it. However, on a protein *w/w* basis, one functional unit of algae residual meal could replace 93.7 kg of DDGS (with a 30% (*w/w*) protein content) or 2.2 kg of urea fertilizer (assuming 50% bioavailability of the nitrogen in algae meal).

The coproduct allocation from corn farming used from the GREET model was considered as one data (i.e., energy use and emissions for the entire process of corn farming using GREET assumptions as one data set). Since the boundary was not selected in accordance to RMEE, the coproduct allocation is a violation of the RMEE boundary selection process. A past LCA utilizing the GREET model (Wang et al. 2007) as well as the GREET model itself provides some insight into the processes included in the corn farming. Corn farming processes in GREET include the processes of farming and collection of corn. The process also includes the application of fertilizers and pesticides. The production of farming equipment is not included. A portion of the CO₂ emissions (195 g/bushel corn) are calculated based on potential land use changes. Total energy input into corn farming and collection is 145.61×10^{-3} kJ/kg of corn (12,635 BTU/bushel of corn). This is an estimate

in the GREET model for corn farming practices in the year 2010. Despite the efforts to quantify the individual processes, the extent of deviation is difficult to quantify, and therefore, this may cause the results reported to be different than those of the RMEE defined system boundary.

4 Results and discussion

4.1 Overall energetics and sensitivity analysis

The base case for all results reported in this LCA is calculated for the algae composition of 30% lipids, 31% carbohydrates, 37.5% proteins, and 1.5% nucleic acids. The model allows for the algae compositions to be varied, resulting in different scenarios. Overall energetics can be described in terms of total energy and net energy input to the process as defined below.

$$\text{Total energy input} = \sum \text{Subprocess energy inputs}$$

$$\begin{aligned} \text{Net energy input} &= \text{Total energy input} \\ &\quad - \text{Coproduct allocation} \end{aligned}$$

$$\begin{aligned} \text{Net energy balance} &= \text{Net energy input} \\ &\quad - \text{Energy in functional unit, 1,000 MJ} \\ \text{Net energy ratio} &= \frac{\text{Net energy input}}{\text{Energy in functional unit, 1,000 MJ}} \end{aligned}$$

Sensitivity of total and net energy input to algae lipid composition at constant carbohydrate to protein ratio is shown in Table 3. The lipid content of algae varies between species and with growing conditions (Borowitzka and Borowitzka 1988). In most algae species, there is typically a larger percentage of carbohydrates than lipids in an algae cell. With such a large percentage of the algae cell being carbohydrates, algae’s potential as an ethanol feedstock cannot be ignored. Every 24 kg of algal biodiesel produced (one functional unit, 1,000 MJ algae biodiesel), 28.1-kg carbohydrates and cellulose coproduct are also produced. With less than 2% lignin (Ververis et al. 2007), algae also circumvent

Table 3 Total energy sensitivity

Algal lipid content (%, <i>w/w</i>)	Total energy input (MJ/1,000 MJ algae biodiesel)	Net energy input (MJ/1,000 MJ algae biodiesel)
40	2,500	−3,982
30	3,292	−6,680
20	4,878	−12,073
15	6,470	−17,462
10	9,665	−28,228
5	19,347	−60,427

Table 4 Energy and CO₂ emissions for each unit process

Unit process	Energy demand (MJ)	CO ₂ emissions (kg)
Filter press primary dewatering		
Growth	15.43	0.00
Harvest	2,915.27	241.87
Separation	165.03	6.33
Transportation	8.79	0.65
Biodiesel conversion	36.02	3.18
Methanol prod. and transport	72.24	0.06
Biodiesel transport and dist.	9.66	0.66
Natural gas production	69.52	0.00
Coproduct allocation	−9,971.77	−273.60
Process total	−6,679.81	−20.90
Centrifuge primary dewatering		
Growth	15.43	0.00
Harvest	5,743.32	398.48
Separation	165.03	6.33
Transportation	8.79	0.65
Biodiesel conversion	36.02	3.18
Methanol prod. and transport	72.24	0.06
Biodiesel transport and dist.	9.66	0.66
Natural gas production	143.65	0.00
Coproduct allocation	−9,971.77	−273.60
Process total	−3,777.63	135.71

the issue of processing a lignin-laden material. As the lipid content of algae decreases, a larger amount of residual algae mass is processed into ethanol resulting in larger coproduct credits. Therefore, total energy increases due to increased processing energy, as algae

lipid content decreases. However, net energy also increases due to higher coproduct credits as algae lipid content decreases (Table 3).

Total energy input with no solar drying is 3,292 and 6,194 MJ for the process with filter press and centrifuge as the initial filtering step, respectively. Overall net energy input for the process with no solar drying was −6,680 and −3,778 MJ when a filter press and centrifuge were used as the initial filtering step, respectively (Table 4). To achieve zero net energy balance without coproduct allocation for a filter press process, the algal slurry would have to be solar dried to 19% (*w/w*) moisture. The solar drying process is well documented and has been used for many years in Asia for drying food-quality algae and in agriculture (Kadam 2001; Hills and Nakamura 1978). Although not infeasible, this process relies on the sun as its driving force and would be too slow for large-scale commercial applications.

The largest energy input is in the natural gas drying of the algal cake. This process comprises 69% of the entire energy input into the process. Algae carbohydrates displace corn, which require petroleum intensive farming practices. Huo et al. (2008) report a net energy ratio 0.15 for soybean biodiesel using the displacement method for allocating coproducts. For an algal biodiesel process using a filter press, this ratio is −6.7 (−6,680 MJ total process energy/1,000 MJ functional unit).

Overall results of this well-to-pump LCA for a functional unit produced using two types of harvesting processes are presented in Figs. 3 and 4 and Table 4.

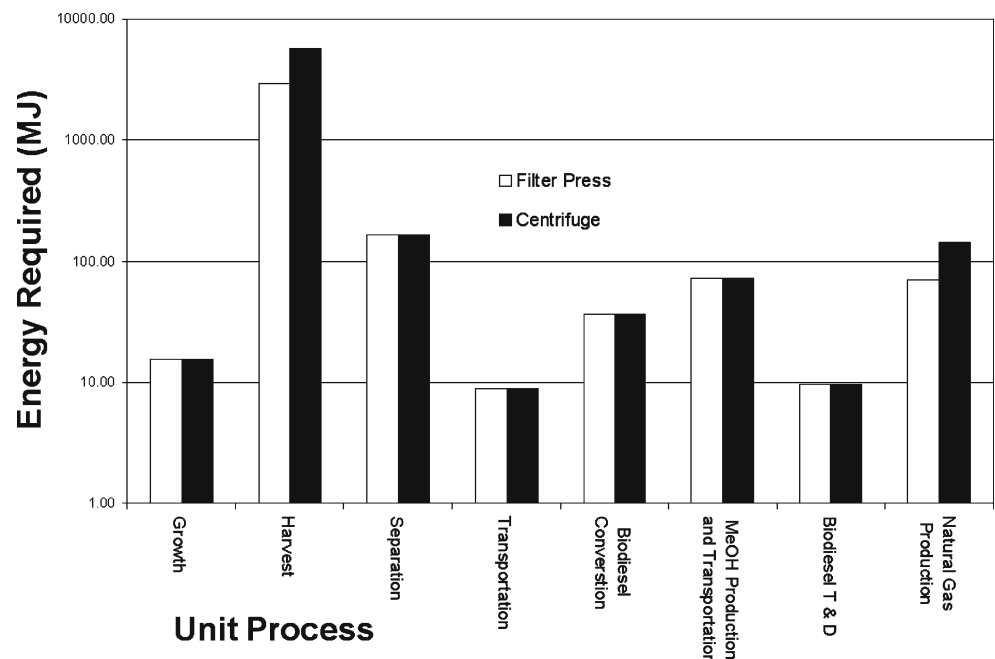
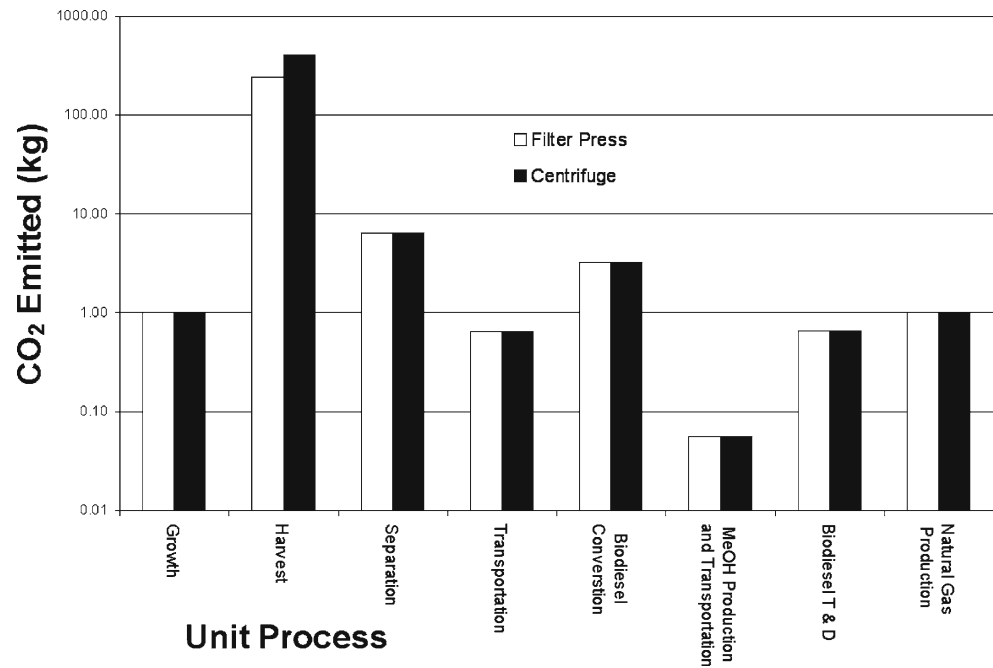
Fig. 3 Energy use in unit processes

Fig. 4 CO₂ emissions for unit processes

A well-to-pump GHG emission (measured as CO₂ equivalents of CO₂, CH₄, and N₂O) of −0.074 kg CO₂ equivalent/1,000 MJ of soybean biodiesel was reported by Huo et al. (2008). Well-to-pump GHG emissions for conventional gasoline is 119.0 kg of GHG per 1,000 MJ of gasoline in GREET model (GREET 2008). Equivalent GHG emissions for a filter press algae biodiesel process with coproduct allocation would be −18.4 kg GHG/1,000 MJ of algal biodiesel. Net CO₂ emissions are −20.9 and 135.7 kg/functional unit for filter press and centrifuge case, respectively. The natural gas drying process alone accounts for 45% and 39% of the CO₂ emissions (excluding the coproduct credits) from the filter press and centrifuge process, respectively (Fig. 4). It is interesting to note that, although net energy for both filter press and centrifuge processes are −6,680 and −3,778 MJ/functional unit, respectively, CO₂ emissions are positive for the centrifuge process while they are negative for the filter press process (Table 4). This reinforces the need for a comprehensive analysis of all impact categories when assessing sustainability of bio-fuels using LCA and not simply relying on net energy arguments. No credits were assigned to the CO₂ input during the growth of algae, as the algal biofuels system is in steady state and there is no net sequestration of carbon. Energy and emissions credits were, however, assigned to corn displaced by algae meal for ethanol production. Other criteria pollutants which are created (per functional unit) during the process utilizing a filter press are VOC's, NO_x, CO, particulate matter, and SO_x resulting in a net −13.96 kg of total air emissions,

18.6 kg of waterborne wastes, 0.28 kg of solid waste, and 5.54 Bq per functional unit (Table 5). Solid waste in both processes is waste oil and grease skimmed during the biodiesel conversion process. These are the only solid waste streams generated in the entire process. The solid wastes from wastewater treatment are not included in this LCA. Radioactive species is a byproduct of steam generation in a natural gas boiler (USLCI 2008).

Evaporative water loss during algae growth is the largest quantity of water consumption. Evaporative loss of 0.137 m/month was estimated based on evapora-

Table 5 Well-to-pump algae biodiesel net emissions

Dewatering process ⇒	Centrifuge	Filter press
Emissions (kg) ↓		
VOC	−0.12	−0.16
CO	−0.90	−0.92
NO _x	−1.51	−1.65
Particulate matter (PM 10 μm)	−0.14	−0.15
Particulate matter (PM 2.5 μm)	−0.10	−0.11
SO _x	2.64	1.34
CH ₄	0.90	0.15
CO ₂	135.71	−20.90
Other air emissions	8.44	8.44
Total air (kg)	144.91	−13.96
Total waterborne (kg)	18.62	18.60
Total solid (kg)	0.28	0.28
Total radioactive species (Bq)	5.54	5.54

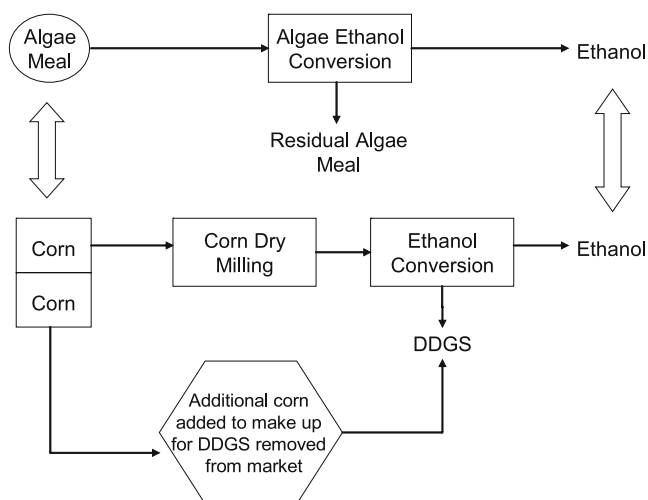


Fig. 5 Coproduct allocation strategy

tion tables from Bakersfield, CA, USA (CDWR 2007). Evaporative water loss accounts for 10% of the total volume (201.42 m³ algae culture) which is lost during 4 days of growth. This water was not included in the LCA totals for freshwater use because wastewater was assumed to be used as the water source. This volume of wastewater can be produced in 4 days by 34 people with an estimated wastewater output of 0.375 m³/person-day (Kenny et al. 2009).

This result indicates that if algae are grown in open pond systems with thousands of acres of surface area and utilize wastewater, the evaporation make-up demands must be considered in the design phase and sourced appropriately (Fig. 5).

One process improvement which might be made to reduce overall energy use and GHG emissions would be to degrade the algal biomass enzymatically in aqueous solutions (Sander and Murthy 2009). This would eliminate the need for an energy intensive dewatering/dehydration process. In addition, CO₂ emissions would be reduced by 45% as well. Another processing method that may be used is the anaerobic digestion of algae biomass. The algae drying step will not be necessary if it is to be anaerobically digested; however, the prefilter step will still be necessary.

5 Conclusions

This LCA has quantified one major obstacle in algae technology, the need to efficiently process the algae into its usable components. Thermal algal dewatering requires high amounts of fossil fuel derived energy (3,556 kJ/kg (850 kcal/kg) of water removed) and consequently presents an opportunity for process improve-

ments to reduce energy use. Advances in processing technology are imperative for the success of algal bio-fuels. The removal of water is an intermediate step in the final separation of algae components and ultimately may not be necessary. If there is a separations process capable of separating the algae into its components without having to undergo the energy intensive process of water removal, this would fulfill the needs of sustainable algae bioprocessing. Enzymes may provide a pathway to developing such a process. The potential of using algae as a feedstock for biofuels is not a new idea (Sheehan et al. 1998b); however, this LCA and other sources clearly show a need for new technologies to make algae biofuels a sustainable, commercial reality.

References

- Akers SM, Conkle JL, Thomas SN, Rider KB (2006) Determination of the heat of combustion of biodiesel using bomb calorimetry. *J Chem Edu* 83(2):260–262
- Aresta M, Dibenedetto A, Barberio G (2005) Utilization of macro-algae for enhanced CO₂ fixation and biofuels production: development of a computing software for an LCA study. *Fuel Proc Technol* 86:1679–1693
- Borowitzka M, Borowitzka L (eds) (1988) *Micro-algal biotechnology*. Cambridge University Press, Cambridge
- CDWR (2007) Evaporation pan data. Tech. Rep., California Department of Water Resources. <http://www.sjd.water.ca.gov/landwateruse/evaporation/>. Accessed Oct 2009
- Ceron MC, Campos I, Acien JSF, Molina E, Fernandez-Sevilla J (2008) Recovery of lutein from microalgae biomass: development of a process for *Scenedesmus almeriensis* biomass. *J Agric Food Chem* 56:11761–11766
- Chisti Y (2007) Biodiesel from microalgae. *Biotechnol Adv* 25:294–306
- Clarens A, Resurreccion E, White M, Colosi L (2010) Environmental life cycle comparison of algae to other bioenergy feedstocks. *Environ Sci Technol* 44:1813–1819
- Dale B (2008) Biofuels: thinking clearly about the issues. *J Agric Food Chem* 56:3885–3891
- EIA (2008) Annual energy review 2008. Tech. Rep. 0384, Energy Information Administration, U.S. Department of Energy
- REET (2008) The greenhouse gases, regulated emissions and energy use in transportation model. Tech. Rep., Argonne National Laboratory, U.S. Department of Energy. http://www.transportation.anl.gov/modeling_simulation/REET/. Version 1.8. Accessed Dec 2008
- Grima EM, Belarbi E, Fernandez FA, Medina AR, Chisti Y (2003) Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnol Adv* 20:491–515
- Hills C, Nakamura H (1978) *Food from sunlight; planetary survival for hungry people*. University of the Trees Press, Boulder Creek
- Huo H, Wang M, Bloyd C, Putsche V (2008) Life-cycle assessment of energy and greenhouse gas effects of soybean-derived biodiesel and renewable fuels. Tech. Rep. ANL/ESD/08-2, Argonne National Laboratory, U.S. Department of Energy

- Kadam K (2001) Microalgae production from power plant flue gas: environmental implications on a life cycle basis. Tech. Rep. NREL/TP-510-29417, National Renewable Energy Laboratory
- Kenny J, Barber N, Hutson S, Linsey K, Lovelace J, Maupin M (2009) Estimated use of water in the united states in 2005. Tech. Rep. Circular 1344, U.S. Geological Survey
- Kim S, Dale B (2002) Allocation procedure in ethanol production system from corn grain. *Int J LCA* 7:237–243
- Kim S, Dale B (2003) Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenergy* 26:361–375
- Lardon L, Helias A, Sialve B, Steyer J, Bernard O (2009) Life-cycle assessment of biodiesel production from microalgae. *Environ Sci Technol* 43:6475–6481
- Lembi C, Waaland J (eds) (1989) *Algae and human affairs*. Cambridge University Press, Boulder Creek
- Mehta SK, Gaur JP (2005) Use of algae for removing heavy metal ions from waste water: progress and prospects. *Crit Rev Biotechnol* 25:113–152
- Nielsen P, Wenzel H (2005) Environmental assessment of ethanol produced from corn starch and used as an alternative to conventional gasoline for car driving. Tech. Rep., The Institute for Product Development, Technical University of Denmark
- Raynolds M, Fraser R, Checkel D (2000) The relative mass-energy-economic (RMEE) method for system boundary selection. *Int J LCA* 5:37–46
- Richmond A (ed) (1986) *Handbook of microalgal mass culture*. CRC, Boca Raton
- Sander K, Murthy G (2009) Enzymatic degradation of microalgal cell walls. ASABE paper no: 096054. 2009 ASABE annual international meeting
- Shapouri H, Salassi M, Fairbanks J (2006) The economic feasibility of ethanol production from sugar in the United States. Tech. Rep., U.S. Department of Agriculture
- Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H (1998a) Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. Tech. Rep. NREL/SR-580-24089, U.S. Department of Energy and U.S. Department of Agriculture
- Sheehan J, Dunahay T, Benemann J, Roessler P (1998b) A look back at the US Department of Energy's aquatic species program-biodiesel from algae. National Renewable Energy Laboratory, Golden CO. Report: NREL/TP-580-24,190
- Shelef G, Soder C (eds) (1980) *Algae biomass; production and use*. Elsevier, Amsterdam
- USLCI (2008) The U.S. life-cycle inventory database. Tech. Rep., National Renewable Energy Laboratory. <http://www.nrel.gov/lci/database/>. Accessed Dec 2008
- Ververis C, Georgiou K, Danielidis D, Hatzinikolaou D, Santas P, Santas R, Corleti V (2007) Cellulose, hemicelluloses, lignin and ash content of some organic materials and their suitability for use as paper pulp supplements. *Biores Technol* 98:296–301
- Wang M (2005) Updated energy and greenhouse gas emission results of fuel ethanol. In: *The 15th int symp alcohol fuels*
- Wang M, Wu M, Huo H (2007) Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environ Res Lett* 2:1–13