Life Cycle Assessment of Algae-based Transportation Fuels in Thailand and Comparison with Petroleum Equivalents

Wilton Burns, Ty Fenton, Emily Love, Mary Katherine McKenzie, Lauren Riedle

A B S T R A C T

The purpose of this study is to assess the practicality of algal biofuel production and consumption in Bangkok, Thailand based on the environmental impacts of algal biofuels as compared to petroleum equivalents and the ability of algal biofuels to offset Bangkok's petroleum fuel use. A life cycle assessment was conducted to determine the environmental impacts of three algal biofuels - biodiesel, ethanol, and compressed biomethane. These biofuels replace low-sulfur diesel, standard gasoline, and compressed natural gas (CNG), respectively. Three possible scenarios for the production of the algal biofuels were evaluated and compared based on net energy ratio (NER) and vehicle kilometers traveled (VKT). The growth of two strains was considered. For *B. braunii*, a high lipid content strain, the scenario that produced both biodiesel and compressed biomethane from algal feedstocks had the highest VKT of 1,220,000 and an NER of 1.26. For an averaged "generic" strain, the production of biodiesel and methane also produced the highest VKT of 1,200,000 with a NER of 1.25. For both *B. braunii* and generic strains, the production of only methane showed a higher NER of 1.45 and 1.50 respectively, but a decreased VKT of 936,000 and 976,000 respectively. The life cycle environmental impacts from algal biofuels produced in the biodiesel-methane scenario are found to be higher than from comparative petroleum fuels in all impact categories considered. The ability of algal biofuels to offset petroleum fuels is primarily limited by the land area available for the cultivation of algae grown in wastewater. Available land area around Bangkok's wastewater treatment plants was found to be 20.7 ha, which would yield enough algal biofuels, according to the selected algae production scenario, to replace 0.60% of Bangkok's petroleum fuel usage. Based on the findings of this study, production of transportation fuels from algae is not recommended for Bangkok.

1. Introduction

As the world's supplies of fossil fuels diminish and greenhouse gas emissions grow to be a pressing issue, nations across the globe are working to provide sources of alternative energy. In Thailand, nearly all of the energy used for transportation comes from petroleum products. Such little fuel diversification leaves the country vulnerable to possible supply constraints and price increases in the future (World Bank & NESDB, 2009).

To counter these effects, Thailand aims to increase its production and consumption of renewable fuels. Current Thai policy mainly focuses on biodiesel and ethanol production, but natural gas and methane are also growing in prominence as a cheaper, alternative transportation fuel (Preechajarn & Prasertsri, 2012). Thailand's newly implemented biodiesel and ethanol policies call for the expansion of current biodiesel and ethanol feedstock production. Most biodiesel in Thailand is made from palm oil, while ethanol comes from sugarcane molasses and cassava. Attempts to increase the production of these feedstocks have been challenged by competition over Thailand's limited supply of suitable farmland (Preechajarn & Prasertsri, 2011).

In this respect, biofuels from algae offer great promise. Algae could prove to be superior to terrestrial crops as a fuel source due to its higher photosynthetic capabilities, higher lipid and starch yields, higher growth rate, and lower land use requirements than conventional biofuel feedstocks (Lakaniemi et al., 2011). Algae can be grown in freshwater, saltwater, or wastewater and therefore do not require arable land or freshwater to grow. Growing algae in wastewater can reduce the need for fertilizers and can provide the added benefit of wastewater treatment (IEA, 2010).

Thailand has an ideal climate for growing algae on a large scale. However, further research is needed to demonstrate the feasibility of algal biofuel production in Thailand. There are uncertainties that should be addressed including the method in which the algae should be grown, the biofuels that should be produced, and the potential impacts from the replacement of fossil fuels.

2. Methodology

2.1 Goal and Scope

This study aims to (1) select the best strategy for algal transportation fuel production in Bangkok, Thailand, based on vehicle kilometers traveled (VKT) and net energy ratio (NER); (2) compare the algal biofuels produced from the selected scenario to petroleum fuel equivalents in respect to life cycle environmental impact potentials, including global warming, acidification, photochemical ozone creation, and eutrophication potentials; (3) gauge the ability of biofuels to offset Bangkok's petroleum fuel use given the available land area for algae cultivation in Bangkok.

This study focuses on the production of three algal biofuels: biodiesel produced by transesterification to be blended into a 95% diesel, 5% biodiesel blend (B5) and combusted in a conventional diesel engine, ethanol produced by yeast fermentation to be blended into a 90% gasoline, 10% ethanol blend (E10) and combusted in a conventional gasoline engine, and biomethane produced by anaerobic digestion that is compressed and used for combustion in dedicated compressed natural gas (CNG) vehicles. Since commercial scale production of algal biofuel is not yet available in Thailand, production data was found in academic literature and adapted to reflect the growth model. Due to the uncertainty involved in adaptations, all data is reported to three significant figures. Data is calculated using all available significant figures are available in the Supporting Information.

2.2 System Boundaries

A "well-to-wheel" life cycle assessment is performed for biodiesel, ethanol, and biomethane produced from algae (**Fig. 1**). The steps included are: cultivation of algae, harvesting, conversion of algae biomass to biofuels, and the combustion of the produced biofuels in a passenger vehicle. The life cycle inventory analysis in this study quantifies the life cycle energy usage from scenarios of various algal biofuel production, described in Section 3.2. The life cycle air emissions and environmental impacts of algal biofuels are calculated and compared to life cycle environmental impacts from conventional transportation fuels, including diesel, gasoline, and CNG. This study does not account for the energy and resources necessary to build the infrastructure to grow algae, harvest biomass, or produce algal biofuels due to the long lifetime of the required infrastructure.

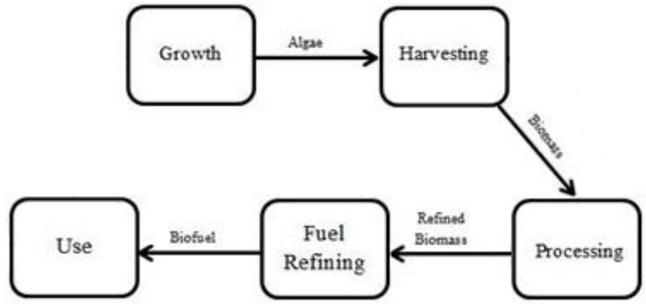

Fig. 1: *"Well-to-wheel" life cycle for algal biofuel production*

2.3 Functional Unit and Reference Flows

The functional unit of the study is to move a passenger vehicle 1,000 km based on standardized driving behavior in city traffic measured in Bangkok, Thailand (Tamasanya et al., 2006). Reference flows were calculated using the gasoline equivalent of each fuel type, normalizing for engine efficiency and energy density of fuels (**Table 1**).

Gasoline engines are assumed to be 30% efficient, while diesel and CNG engines are assumed to be 40% efficient (Reitz, 2010). The energy densities used are 29.7 MJ/L for gasoline, 36.1 MJ/L for diesel, 9.18 MJ/L for CNG, and 8.96 MJ/L for compressed biomethane gas (CBG) (GREET, 2012). E10 fuel usage is assumed to increase of 1.5% from 100% gasoline combustion, and B5 is assumed to be a 0.4% increase from pure diesel combustion (ACE, 2005; Anderson, 2012).

Table 1: *Reference flows for each fuel type*

Fuel	Reference Flow (L per 1000 km)
Gasoline	84.8
Diesel	57.1
Compressed Natural Gas (CNG)	225
Compressed Biomethane Gas (CBG)	230
E10	86.1
B5	57.3

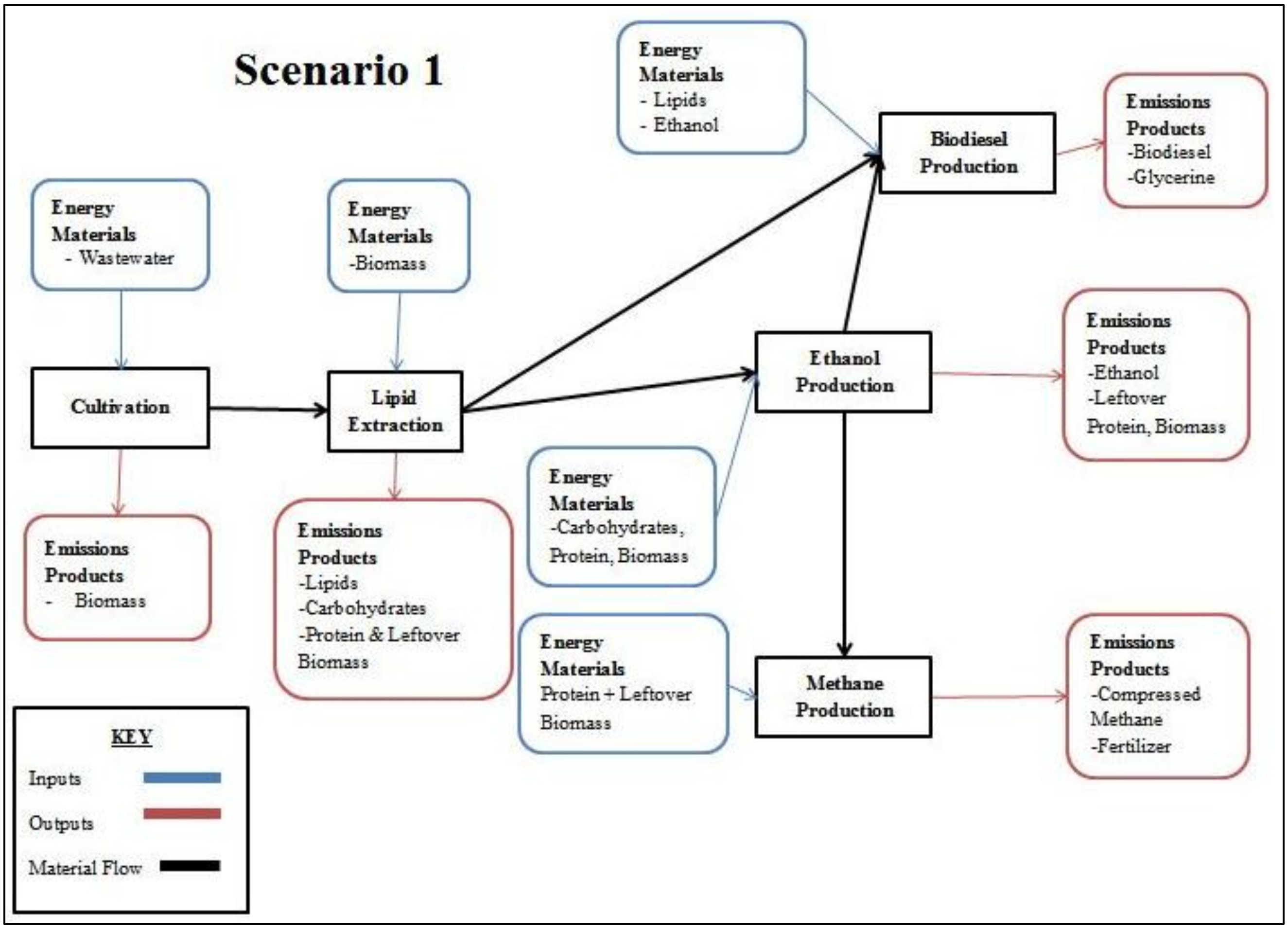

Fig. 2: *Scenario 1 process diagram. Scenarios 2 and 3 follow similar processes, but Scenario 2 excludes "Ethanol Production", and Scenario 3 excludes "Lipid Extraction," "Biodiesel Production," and "Ethanol Production."*

3. Life Cycle Inventory

3.1 System design

The assumed pond design is consistent with industrial standards: a 10-m wide x 100-m long x 0.3-m deep, oval-shaped pond built with concrete blocks, on a 10-cm thick sole. A PVC liner covers the concrete to decrease roughness and to avoid biomass attachment. Each pond spans a growth area of 0.1 hectare (ha). Thus, 1 ha of algae accommodates 10 ponds. Algae is grown in Bangkok wastewater having a nutrient content of 184 mg/L nitrogen and 18.6 mg/L phosphorus (Sreesai & Pakpain, 2007). The wastewater is provided from a nearby municipal wastewater treatment plant, thereby limiting algae cultivation to locations adjacent to wastewater treatment plants for the purposes of this study.

3.2 Biofuel Production Scenarios

Three fuel production combinations are modeled in the present study for the purpose of finding the scenario with a positive net energy ratio (NER) and the maximum usable energy output in the form of vehicle kilometers traveled (VKT) for Bangkok, Thailand.

- **Scenario 1:** Lipids are extracted from the algae biomass and used to make biodiesel. The carbohydrates are then extracted from the remaining biomass and put towards ethanol production. A portion of the ethanol produced in this process is recycled for use in biodiesel production. The final biomass content, containing mostly proteins, is converted into biomethane via anaerobic digestion. Scenario 1 is illustrated in **Fig. 2**.
- **Scenario 2**: Lipids are extracted from the biomass and used to make biodiesel. The remaining biomass, consisting of mostly carbohydrates and proteins, is converted into biomethane via anaerobic digestion.
- **Scenario 3**: All of the biomass is converted to biomethane via anaerobic digestion

3.3 Estimating Algae Growth and Composition

Two strains were selected for this study. *Botryococcus braunii* was considered as the ideal case for biodiesel production due to its high growth rate and high lipid content. The other strain was an average of several algae strains, representing a potential "generic" strain likely to be found in Bangkok. The biomass productivities and compositions of both strains are determined in the following sections.

3.3 a. B. braunii

The present study bases growth off of an Indian strain, *B. braunii* AP103, cultured in CHU 13 medium and grown in a pilot scale raceway pond (Ashokkumar and Rengasamy, 2012). One of the most important aspects of *B. braunii* that sets it apart from other fast-growing, lipid-producing strains is its high hydrocarbon content. Hydrocarbons can be extracted from the algae along with lipids and used to produce biodiesel. The present study considers the effects of using wastewater as a medium on the growth of algae. In When the nitrogen content of CHU 13 is adjusted to the Bangkok wastewater level, the biomass concentration of algae has been shown to increase by 2.9%, hydrocarbon content by 47%, and lipid content by 32% (Ruangsomboon, 2012; An et al., 2003). *B. braunii* is modeled as grown in 2% carbon dioxide. The addition of 2% CO_2 leads to a 22% increase in biomass concentration, 48% increase in hydrocarbon content, and 5.1% increase in lipid content (Ranga Rao et al., 2007; Ge et al., 2011). After accounting for these increases, the final biomass content of *B. braunii* is 0.15 g/L-d, consisting of 39% lipids and hydrocarbons, 33% carbohydrates, and 18% protein.

3.3 b. Generic Strain

The biomass productivity and composition of the generic strain were calculated by averaging values of 14 algae strains from Wenguang et al. (2011) and 17 algae strains from Singh & Gu (2010). In these studies, the algae was cultivated in wastewater under otherwise natural growth conditions. The algae strains are, therefore, assumed to exhibit natural growth, comparable to that of an average strain grown in Bangkok without intensive cultivation requirements. Because the generic strain is assumed to be grown under natural conditions, carbon dioxide is not added. For the averaged generic strain, the resultant biomass productivity is 0.21 g/L-d, composed of 28% lipids, 23% carbohydrates, and 44% protein.

Table 2: *Final Biomass Productivities and Compositions for B. braunii and Generic Strain*

Final Algae Content	*B. braunii* (Mg/ha-year)	Generic Strain (Mg/ha-year)
Biomass	174	195
Lipids & Hydrocarbons	66	50
Carbohydrates	56	45
Protein	31	86

3.4 Cultivation

The pond has several energy requirements related to the water that must be pumped to and from the pond and stirred by paddle wheels, and the 2% CO_2 that is assumed to be compressed at a nearby power plant and delivered to the algae pond. All energy values for cultivation, harvesting, and biofuel conversion as well as credits from co-products are summarized in **Table 3**.

3.5 Harvesting

Algae biomass is harvested to achieve a low water content using flocculation from alum followed by gravity thickening. In flocculation, the addition of alum causes algae to clump by neutralizing the electrode double layer surrounding them (Becker, 1994). Once clumped, the algae will settle to the bottom and be directed to a collection point via gravity thickening. The final algal concentration is approximately 140 g/L, which is assumed to be a suitable concentration for subsequent steps without the need of further dewatering (Clarens et al., 2011).

3.6 Biofuel Conversion

3.6 a. Biodiesel

The biodiesel production process consists of homogenization, thermal pretreatment, lipid extraction, transesterification, and blending. Homogenization is required to break the algae cell walls to allow hexane to extract the lipids (Clarens et al., 2011). Before lipid extraction, *B. braunii* must undergo thermal pretreatment to fully extract the available hydrocarbons. Thermal pretreatment involves heating the algae biomass up to 60°C for 10 minutes (Magota et al., 2012). Lipids and hydrocarbons are extracted using hexane and are refined into biodiesel by the process of transesterification. The final yield of biodiesel can be calculated using the total lipid yield and considering 4% loss in homogenization, 15-20% loss through lipid extraction with hexane, and 3.6% loss of lipids entering the transesterification reaction. The biodiesel is then transported to refineries in Rayong, Thailand, where it is mixed with 95% diesel by volume and transported back to Bangkok for distribution.

3.6 b. Ethanol

Carbohydrates from algae can be converted into ethanol via yeast fermentation. Lipid extraction prior to ethanol conversion is not necessary but is ideal, as demonstrated in a study by Harun et al. (2010) in which lipid-extracted algae yielded 60% higher ethanol concentrations than dried, intact algae. The ethanol conversion process follows lipid extraction for biodiesel production and consists of the following steps: saccharification, fermentation, distillation, refining, and blending. Saccharification, also known as hydrolysis, converts the complex carbohydrates into simpler sugars that can be fermented by yeast into a dilute ethanol solution (10-15% ethanol).This solution is subjected to distillation in which water and impurities are removed to produce 95% concentrated, liquid ethanol. Refining removes more water, so that the final product is 99.5% ethanol. Finally, the concentrated ethanol is transported to an oil refinery where it is blended to the desired ratio. This report examines ethanol in the form of E10, a blend that is 10% ethanol, 90% gasoline by volume.

The theoretical ethanol yield can be calculated based on the chemical equation relating the fermentation of hexose to the production of ethanol and CO_2: $C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$. It is assumed that 75% of the carbohydrate content can be hydrolyzed into fermentable hexose, and that the obtained ethanol yield is 80% of the theoretical yield (VangerGheynst, 2008).

3.6 c. Biomethane

Algae biomass goes through multiple steps to be processed into biogas that is upgraded into 96% biomethane gas and then compressed to be utilized in vehicles as a transportation fuel. Algal biomass is loaded into an anaerobic digester where microorganisms break down the biomass to produce a biogas that is 70% biomethane and 30% CO_2. The biogas is then bubbled through pressurized water, where the carbon dioxide and particles are separated from the methane, leaving a 96% concentration of biomethane gas (Collet et al., 2011). The biomethane is compressed at the pump from a pressure of 0.1 mPa to a pressure of 25 mPa. The theoretical biomethane yield is modeled from the relation between biomethane yield and respective carbohydrate, protein, and lipid contents as reported in Angelidaki and Sanders (2004). Based on findings by Chen (1987) and Foree & McCarty (1970), it is assumed that obtained methane yield is 60% of theoretical methane yield.

3.7 Co-products

3.7 a. Treated Wastewater

The majority of the wastewater in Bangkok goes through secondary treatment. However, without a subsequent tertiary treatment, the wastewater is not clean enough to reach government standards in terms of pH, total nitrogen, total phosphorus, suspended solids, and chemical oxygen demand. Sreesai and Pakpain (2007) show that growing algae in wastewater as a tertiary treatment can significantly reduce the amount of total nitrogen and total phosphorous in the wastewater effluent, thereby meeting the standards outlined by the Thai government. Submerged membrane bioreactors coupled with activated sludge provide similar treatment results as algal tertiary treatment, in terms of percent reduced total nitrogen and chemical oxygen demand (Visvanathan et al). Algae growth is assumed to replace this method of tertiary treatment. Visvanathan et al. reports the energy consumption of this tertiary treatment method to be 0.0252 MJ/m^3. The volume of water treated in the ponds is calculated to be 91,250 m^3/ha-year, based on the system design of 3,000 m^3/ha and 12 day growth cycles.

3.7b. Glycerol

Glycerol is obtained as a by-product of biodiesel production. The yield of glycerol is 213 kg per Mg of biodiesel (Sheehan, 1998). Based on current market prices, the glycerol co-product would represent 7.74% of the total economic potential if the products were sold at market prices (Alibaba, 2012; "The Nation"). Based on glycerol's properties and uses, economic allocation seems the most appropriate way to allocate and is used for the remainder of the study.

3.7 c. Fertilizer

Following biomethane production, a digestate high in nitrogen, phosphorus, and potassium is left, which can be sold as fertilizer. This digestate is assumed to replace fertilizer produced in Thailand, which requires energy inputs of 35.3 MJ/kg N, 36.2 MJ/kg P, and 11.2 MJ/kg K (Kraatz, 2008). Transportation of digestate fertilizer is assumed to be comparable to transportation of inorganic fertilizers, as both will be produced and consumed within Thailand. Therefore, transportation of fuels are considered equal and are not counted in energy offsets.

Table 3: *Summary of energy inputs for biofuel production*

	Electricity Input	Unit	Sources
Cultivation			
Pumping	40,800	MJ/ha-yr	[1]
Stirring	1,170	MJ/ha-yr	[1]
CO2 aeration	38,700	MJ/ha-yr	[1]
Harvesting			
Alum upstream production	78,000	MJ/ha-yr	[2]
Gravity thickening	11.0	MJ/ha-yr	[1]
Biodiesel			
Homogenization	825	MJ/Mg biomass	[1]
Thermal pretreatment	115	MJ/Mg algae	[3]
Lipid extraction	123	MJ/Mg biomass	[1,4,5]
Hexane upstream production	880	MJ/Mg biomass	[1]
Methanol production	1.11	MJ/L biodiesel	[6]
Steam production	0.561	MJ/L biodiesel	[6]
Electricity production	0.111	MJ/L biodiesel	[6]
Sodium methoxide production	0.296	MJ/L biodiesel	[6]
Sodium hydroxide production	0.0143	MJ/L biodiesel	[6]
Hydrogen chloride production	0.0499	MJ/L biodiesel	[6]
Transport for blending	0.33	MJ/L biodiesel	[6]
Ethanol			
Saccharification	0.41	MJ/L ethanol	[7]
Fermentation	0.99	MJ/L ethanol	[7]
Distillation	14.2	MJ/L ethanol	[7]
Membrane refining	0.69	MJ/L ethanol	[7]
Transport for blending	0.29	MJ/L ethanol	[6]
Biomethane			
Mixing	389	MJ/Mg biomass	[8]
Centrifugation of digestates	90.7	MJ/Mg biomass	[8]
Internal biogas used	2,450	MJ/Mg biomass	[8]
Purification	1.1	MJ/m^3 gas	[8]
Compression	0.453	MJ/L gas	[9]
Credits			
Wastewater treatment	2,300	MJ/ha-yr	[10]
Fertilizer production	186	MJ/m^3 gas	[1,11]
Glycerol production *			[6]

* Glycerol production is assigned 7.4% of the energy inputs of biodiesel production based on economic allocation.

Sources: [1] Clarens et al., 2011; [2] Becker, 1994; [3] Joaquín et al., 2012; [4] Yamaguchi et al., 1986; [5] Magota et al., 2012; [6] Sheehan et al., 1998; [7] Anudit, 2001; [8] Collet et al., 2011; [9] López et al., 2011; [10] Visvanathan et al.; [11] Kraatz, 2008

Table 4: *Fuel production per scenario*

	Scenario	Biomethane (L/ha-yr)	Biodiesel (L/ha-yr)	Ethanol (L/ha-yr)
B. braunii	1	23,600	57,800	13,800
	2	66,800	57,800	--
	3	215,000	--	--
Generic Strain	1	78,200	43,900	10,900
	2	112,000	43,900	--
	3	225,000	--	--

5. Results

5.1 Scenario Results

The fuel production (**Table 4**), NER, energy output, and VKT for each scenario are compared (**Table 5**). Net energy ratio (NER) is reported as total fuel energy output divided by the primary energy input. Vehicle kilometers traveled (VKT) are the total number of kilometers a passenger vehicle can travel given the combustion of all the fuel produced in a given scenario. VKT allow for the fair comparison of fuels with different calorific contents and burning characteristics and are calculated using the reference flows from **Table 1**.

5.1 a. B. braunii

Scenario 1 shows the lowest NER value. Ethanol production yields negative energy, requiring 843,000 MJ for production and supplying only 295,000 MJ of fuel energy. Scenario 3 shows the highest NER, representing the greatest process efficiency, however the total yield of energy is lower than for scenario 2.

5.1 b. Generic strain results

Consistent with *B. braunii*, Scenario 1 again shows the lowest NER value. Ethanol production yields less energy than needed for production, requiring a primary energy input of 665,000 MJ for the conversion process, and yielding 232,000 MJ of fuel energy. Similar to *B. braunii*, scenario 3 shows the highest NER, but lower net energy output compared to Scenario 2. All NER values in Scenarios 1 and 3 obtained with the generic strain are higher than those obtained with *B. braunii*. *B. braunii* shows a higher VKT in all scenarios excluding scenario 3.

Table 5: *Energy inputs, energy outputs, NER, and VKT for all biofuel production scenarios*

	Scenario	Primary Energy Input (MJ)	Fuel Energy Output (MJ)	NER	VKT
B. braunii	**1**	2,420,000	2,430,000	1.00	1,160,000
	2	2,000,000	2,520,000	1.26	1,220,000
	3	1,230,000	1,920,000	1.56	936,000
Generic Strain	**1**	2,330,000	2,400,000	1.03	1,140,000
	2	1,970,000	2,470,000	1.25	1,200,000
	3	1,230,000	2,010,000	1.63	976,000

5.2 Comparison to Conventional Fuels

The most promising scenario for each strain was selected to compare to conventional fuels. As the functional unit relates to distance traveled and the purpose of this study is to assess petroleum offset, the scenario which resulted in the highest VKT with a positive NER (greater than 1.00) was chosen. For both strains, this is Scenario 2.

The algal biofuels produced in Scenario 2, biodiesel and compressed biomethane gas (CBG), were compared to diesel and natural gas, based on environmental impacts. Because the algal biodiesel is blended with diesel the combustion emissions of biodiesel are mostly attributed to diesel combustion. With the addition of 95% diesel to the produced biodiesel, the total volume of B5 is 1,160,000 L for *B.braunii*. The energy content of the total scenario is 98.6% B5 and 1.4% CBG for *B.braunii.* The conventional diesel within the B5 blend represents 94.1% of the total energy. Biodiesel from the generic strain is blended to produce 878,000 L of B5. The total energy content is 97.1% B5 and 2.1% CBG, and conventional diesel represents 92.7% of the total energy in the generic strain fuel mix. Calculations were performed using the heating values of biodiesel, biomethane, and diesel as 35.97 MJ/L, 8.96 MJ/L, and 36.14 MJ/L respectively (GREET, 2012).

The emission data for each conventional fuel are reported as life cycle emission from production and combustion specific to Thailand. Data on the life cycle of natural gas and diesel is taken from Phumpradab et al (2009), Sheehan et al (1998) and Argonne GREET (2012), and adapted to Thailand when necessary.

As shown in **Figs. 3-6**, algal fuels and their equivalent conventional fuels are compared by Global Warming Potential (GWP) in kg CO2-eq, Acidification Potential (AP) in kg SO2-eq, Photochemical Ozone Creation Potential (POCP) in kg C2H4-eq and Eutrophication Potential (EP) in kg PO4-eq based on the most recent CML LCIA method (CML 2 Baseline Method).

6. Land Available for Algae Cultivation

Using aerial photography, the seven existing wastewater treatment plants (WWTPs) in Bangkok were analyzed for undeveloped surrounding land area that could be used for algae cultivation in raceway ponds. Of the seven WWTPs in Bangkok, only two have sufficient area available for algae production: Nong Khaem (12.2 ha of undeveloped land) and Thung Khru (8.5 ha of undeveloped land). Therefore, the total potential land area for algae production in Bangkok was estimated to be 20.7 ha.

The petroleum fuel displaced by algal biofuel production utilizing these 20.7 ha is given in **Table 6**. It is assumed in this study that current diesel and CNG usage is the same as 2007 usage. The percentage of petroleum fuels displaced are less than 1% for all fuels from either strain of algae.

Because the land area available within Bangkok can only produce enough algae fuel to offset a small percentage of Bangkok's petroleum fuel use, it is more reasonable to use land area outside of Bangkok. The present study assessed the available land at WWTPs in all of Thailand and applied that potential area to production values. It was assumed that the potential area surrounding WWTPs outside of Bangkok was two times that of those found within the city limits. Using this assumption, the potential available hectares for all of Thailand is 512 ha. The present study assumes that the algal biofuels produced outside of Thailand will be transported to Bangkok and used within the city since majority of transportation fuels are used in Bangkok. Applying this potential land area to production of algal biofuels, the liters and percentage of diesel and CNG displaced in Bangkok are reported in **Table 6**.

The percentage of diesel that can be replaced using available land in all of Thailand is still less than 1% so the present study assessed the necessary land needed to replace 20% of diesel and CNG use in Bangkok. For 20% of Bangkok's diesel use to be displaced, 3,740,000,000 L of biodiesel would need to be produced. This amount of biodiesel would require about 65,000 ha of land if produced from *B. braunii,* or 87,900 ha if produced from the generic strain. To replace 20% of CNG use, 76,600,000 L of CBG are needed, requiring 1,170 ha of land for *B. braunii,* or 698 ha for the generic strain.

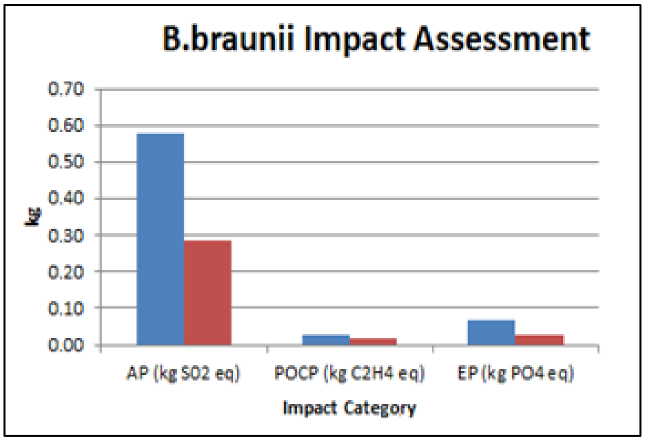

Fig. 3: *AP, POCP, EP of B. braunii-derived B5 and CBG and conventional diesel and CNG*

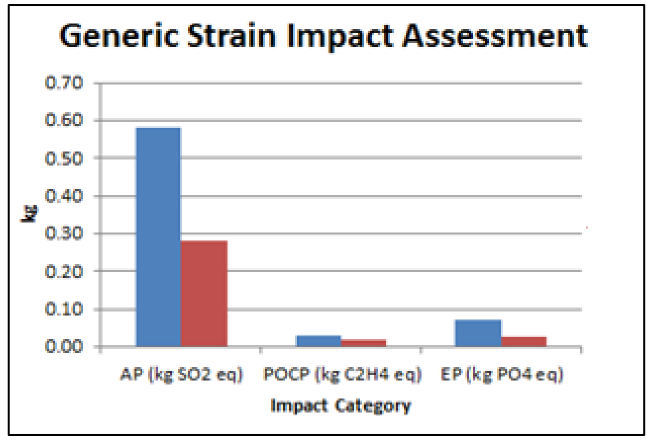

Fig. 5: *AP, POCP, EP of generic Strain-derived B5 and CBG and conventional diesel and CNG*

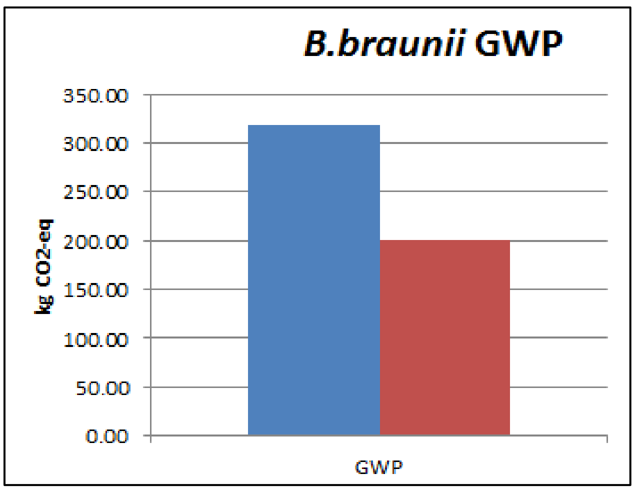

Fig. 4: *GWP of B. braunii-derived B5 and CBG and conventional diesel and CNG*

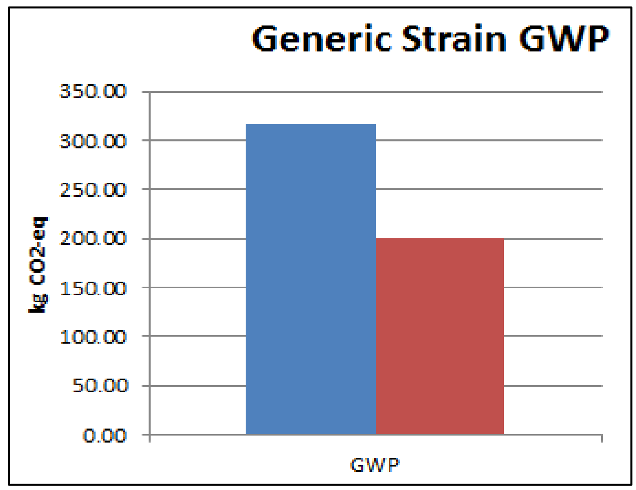

Fig. 6: *GWP of generic strain-derived B5 and CBG and conventional diesel and CNG*

Table 6: Bangkok fuel displacement using available land around wastewater treatment plants in Bangkok versus all of Thailand

	Fuel Type	Fuel Use (million L)	Fuel Displaced by S2, BB (million L)	% Fuel Displaced by S2, BB	Fuel Displaced by S2, GS (million L)	% Fuel Displaced by S2, GS
Bangkok Only	**Diesel**	18,700	1.20	0.00640	0.955	0.00510
	CNG	383	1.40	0.350	2.27	0.590
All of Thailand	**Diesel**	18,700	29.6	0.15	22.5	0.12
	CNG	383	34.2	8.7	57.3	14.0

7. Discussion and Conclusions

The purpose of this study was to determine the feasibility of displacing conventional transportation fuels with algae produced fuels in Bangkok and to compare various biofuel production pathways. The fuel production pathways were first compared based on their NER and VKT. The results for both strains showed the highest VKT from the production of biodiesel and biomethane. The highest NERs were obtained from the production pathway involving only biogas production. As the purpose of the study was to displace conventional fuels, VKT was determined to have a higher significance, however, the lower NER is important for production considerations. The energy intensive process for biodiesel production shows significant room for improvement in terms of energy reduction, specifically in the harvesting and lipid extraction stages. As improvements are made, biodiesel production should be reevaluated to determine NER improvements which would make it more feasible for production.

Algal biomethane has an efficient conversion process, requiring low input energy. Biomethane production shows room for improvement primarily in actual yield of theoretical methane production. Options such as codigestation with proven feedstocks should be considered to improve methane yield.

The primary energy input in the production of ethanol was lower than the fuel energy yield with both *B.braunii* and the generic strain. Ethanol production is, therefore, not recommended with algae strains containing carbohydrate contents similar to that found in the strains used in the present study.

The present study noted no significant differences between the chosen strains. This suggests a local strain grown with minimally intensive cultivation has the potential to have similar yields as a specific strain chosen for biodiesel cultivation. This is due to the increase in growth rate seen in strains that do not favor lipid production.

In comparison to conventional fuels, B5 and biomethane produced in Scenario 2 showed an increase in total process emissions. The algae biofuels had higher impact potentials for all the given categories, showing a decrease in overall environmental benefit from algal biofuels. The increase in pollutants is due to the high process energy demand of algae biofuel production, which is significantly higher than that of conventional diesel. The energy demanded is supplied primarily by the Thai grid which lacks pollution control or efficient technologies and thus contributes large amounts of pollutants per kWh. These results are extremely important and show that although algae biofuels yield more energy than is input, they are not currently an environmentally friendly alternative to conventional transportation fuels.

Land use constraints in Bangkok suggest that algae fuels would have a minimal impact on overall fuel consumption. There is more land available outside of Thailand, but as wastewater treatment plants are only available in urban areas, available land will likely be a problem in any location. While there may be sufficient land to offset 10% of Bangkok's diesel or CNG usage, land close to wastewater treatment plants is a limiting factor for algal biofuel production.

Based on the findings of this study, production of transportation fuels from algae is not recommended for Bangkok.

8. References

Alibaba. Thailand, Glycerine suppliers. Retrieved December 2, 2012 from http://www.alibaba.com/countrysearch/TH/glycerine. html

American Coalition for Ethanol (ACE). Comparing performance and cost of various ethanol blends and standard unleaded gasoline. Paper. (2009).

An, J., S Sim, J.S. Lee, B.W. Kim. (2003). Hydrocarbon production from secondarily treated piggery wastewater by the green alga Botryococcus braunii. Journal of Applied Phycology. 15 (2-3), 185-191.

Anderson, L.G., "Effects of Biodiesel Fuels Use on Vehicle Emissions." (2012). Journal of Sustainable Energy & Environment 3: 35-47.

Angelidaki I, Sanders W. (2004) Assessment of the anaerobic biodegradability of macropollutants. Rev Environ Sci Biotechnol 3:117–129.

Ashokkumar, V. and R. Rengasamy, 2012. Mass culture of Botryococcus braunii Kutz under open raceway pond for biofuel production. Bioresource Technology: 104, 394–399.

Becker, E. W., 1994. Microalgae: Biotechnology and Microbiology. Cambridge University Press, Cambridge Studies in Microbiology: Part VII, 293.

Chen, P. H., 1987. Factors influencing methane fermentation of microalgae, PhD thesis. University of California: Berkeley, California.

Clarens, A.F., Resurrection, E.P., White, M.A., Closi, L.M., 2010. Environmental life cycle comparison of algae to other bioenergy feedstock. Environ. Sci. Technol: 44, 1813–1819.

Clarens, A.F., H. Nassau, H.P. Resurreccion, M.A. White, L.M. Colosi. Environmental impacts of algae-derived biodiesel and bioelectricity for transportation. Environ. Sci. Technol., 45 (2011). pp. 7554-7560.

Collet, P. Hélias, A., Lardon, L., Ras, M., Romy-Alice, G., Steyer, J., 2011. Life-cycle assessment of microalgae culture coupled to biogas production. Bioresource Technology:102, 207–214.

Foree, E.G. and M. McCarty, 1970. Anaerobic decomposition of algae. Environmental Science Technology: 4, 842–849.

Ge, Y., J. Liu, and G. Tian, 2011. Growth characteristics of Botryococcus braunii 765 under high CO2 concentration in photobioreactor. Bioresource Technology: 102, Issue 1, 130-134.

Goedkoop, M., M. Oele, A. Schryver, and M. Vieira, 2008. Sima Pro Database Manual, CML 2001. PRe Consultants.

Harun, R., M.K. Danquah, & G.M. Forde (2010). Microalgal biomass as fermentation feedstock for bioethanol production. Journal of Chemical Technology and Biotechnology, 85(2), 199-203.

IEA (2010). Algal biofuels status and prospects. IEA Bioenergy: Annual Report 2010, Retrieved from http://www.ieabioenergy.com/libItem.aspx?id=6780

"Imports of palm oil are not a good solution". The Nation. Retrieved December 2, 2012 from http://www.nationmultimedia.com/opinion/Imports-of -palm-oil-are-not-a-good-solution-30187718.html

Kraatz, S., Reinemann, D. J., & Berg, W. E. (2008, June).*Energy inputs for corn production in wisconsin and germany*. Written for presentation at 2008 asabe annual international meeting, Providence, RI. Retrieved from http://fyi.uwex.edu/uwmril/files/2011/05/08-ASABE-Kraatz-Corn-Energy-Inputs.pdf

Lakaniemi, A.M., Hulatt, C.J., Thomas, D.N., Tuovinen, O.H., and J.A. Puhakka, 2011. Biotechnol Biofuels: 34, Issue 4.

Magota, A., Saga, K., Okada, S. Atobe, S., and K. Imou, 2012. Effect of thermal pretreatments on hydrocarbon recovery from Botryococcus braunii. Bioresource Technology: 123, 195-198.

Phumpradab, K. S. Gheewala, M. Sagisaka. (2009). *Life cycle assessment of natural gas power plants in Thailand. 14*354-363. International Journal Of Lifecycle Assessment.

Preechajarn, S., Prasertsri, P. United States. USDA Foreign Agricultural Service. Thailand: Biodiesel Demand and Supply Outlook. 2011.

Preechajarn, S., Prasertsri, P. United States. USDA Foreign Agricultural Service. Thailand: Biofuels Annual. 2012.

Ranga Rao, A., Sarada, R., and G.A. Ravishankar, 2007. Influence of CO2 on growth and hydrocarbon production in Botryococcus braunii. Journal of Microbiology Biotechnology: 17, 414–419.

Reitz, R. (2010). High efficiency fuel reactivity controlled compression ignition (rcci) combustion. (Academic presentation). Retrieved from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2010/tuesday/presentations/deer10_reitz.pdf

Ruangsomboon, S., 2012. Effect of light, nutrient, cultivation time and salinity on lipid production of newly isolated strain of the green microalga, Botryococcus braunii KMITL 2. Bioresource Technology: 109, 261-265.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., & Shapouri, H. (1998). Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. Final report (No. NREL/SR--580-24089, 658310). Retrieved from http://www.osti.gov/servlets/purl/658310-vEJMIM/webviewable/

Singh, J., S. Gu, Commercialization potential of microalgae for biofuels production, Renewable and Sustainable Energy Reviews, Volume 14, Issue 9, December 2010, Pages 2596-2610, ISSN 1364-0321, 10.1016/j.rser.2010.06.014.

Sreesai and Pakpain, 2007. Nutrient Recycling by Chlorella vulgaris from Septage Effluent of the Bangkok City, Thailand. Department of Environmental Health Science, Faculty of Public Health, Mahidol Unveristy, Thailand. Science Asia: 33, 293-299.

Tamasanya, S., Chunpaibulpattana, S., Attajariyakul, S., 2006. Development of automobile Bangkok driving cycle for emissions and fuel consumption assessment. Second Joint International Conference on Sustainable Energy and Environment, Bangkok.

VangerGheynst, J. (2008). The future of microalgae in clean technologies. Unpublished manuscript, University of California, Davis, Retrieved from VangerGheynst, J. (2008, April 03). The future of microalgae in clean technologies. Retrieved from http://www.ucop.edu/ott/industry/documents/VanderGheynst-CleanTech.pdf

Visvanathan, C., D. Pokhrel. "Role of Membrane Bioreactors in Environmental Engineering Applications." Urban Environmental Engineering and Management Program, Asian Institute of Technology, Pathumthani, Thailand.

Wang M. GREET 1 2012 transportation fuel cycle model. Argonne, IL: U.S. Dept. of Energy, Argonne National Laboratory; 2006.

Wenguang Zhou, Yecong Li, Min Min, Bing Hu, Paul Chen, Roger Ruan, Local bioprospecting for high-lipid producing microalgal strains to be grown on concentrated municipal wastewater for biofuel production, Bioresource Technology, Volume 102, Issue 13, July 2011, Pages 6909-6919, ISSN 0960-8524, 10.1016/j.biortech.2011.04.038.

World Bank & NESDB. 2009, March. Thailand: making transport more energy efficient.