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An updated comprehensive techno-economic analysis of algae biodiesel

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ABSTRACT

Algae biodiesel is a promising but expensive alternative fuel to petro-diesel. To overcome cost barriers, detailed cost analyses are needed. A decade-old cost analysis by the U.S. National Renewable Energy Laboratory indicated that the costs of algae biodiesel were in the range of \$0.53–0.85/L (2012 USD values). However, the cost of land and transesterification were just roughly estimated. In this study, an updated comprehensive techno-economic analysis was conducted with optimized processes and improved cost estimations. Latest process improvement, quotes from vendors, government databases, and other relevant data sources were used to calculate the updated algal biodiesel costs, and the final costs of biodiesel are in the range of \$0.42–0.97/L. Additional improvements on cost-effective biodiesel production around the globe to cultivate algae was also recommended. Overall, the calculated costs seem promising, suggesting that a single step biodiesel production process is close to commercial reality.

1. Introduction

The world energy consumption has increased rapidly and will continue to increase due to an annual projected population increase of about 1%. Fluctuations of oil prices have worsen the situation and further decreased oil supply due to political pressure. It is estimated that the seriousness of the depletion of oil and other fossil fuels along with the climate change effects will be felt by the beginning of 2030–2050 (Wigley et al., 1996), stressing the need for alternative fuels. As a result, a large amount of money is being invested on the research and development of alternate energy resources, such as solar, wind, hydro and biofuels. Solar, wind, and hydro energy can be used to produce electricity, but the only alternative to liquid transportation fuel is liquid biofuel.

Liquid biofuels are classified into three generations based on the substrate raw materials and processing or production technology. First generation liquid biofuels – bioethanol and biodiesel – were produced from food crops such as corn, sugarcane, wheat, maize and vegetable oils. Due to the use of food crops for fuel production, first generation liquid biofuels were criticized for conflicting with the food supply and increasing the costs of food crops. The conflicts with food crops paved the way for second generation liquid biofuels, which were manufactured using corn cob wastes, palm kernels, lingo-cellulosic wastes, non-edible plant seed oil, waste cooking oil, waste vegetable oil and animal fats. Although second generation liquid biofuels overcame the problems faced by their first generation counterparts, consistent feedstock supply became a challenge. This difficulty led to the development of third generation liquid biofuels – biobutanol and algae biofuels (Cheng et al., 2012; Jones and Mayfieldt, 2012). Biobutanol is a promising gasoline alternative that is being intensively studied while algae biofuel is relatively mature.

Algae cultivation has been developed for decades with the initial purpose of providing food supplements and animal feeds. During the energy crisis in 1970s, the U.S. National Renewable Energy Laboratory's (US NREL, formerly SERI) Aquatic Species Program (ASP) started to utilize algae biofuels as alternative energy sources (Sheehan et al., 1998). Although the high cost of algae biofuels during that time put a halt to the program in 1996, extensive amount of data on cultivation, harvesting, extraction, and transesterification of algae published throughout the period of ASP serves as foundations for modern studies of algae biofuels.

Algae were cultivated as biofuel feedstock mainly due to their high productivity of oil and less land requirement. The production of oil from algae range from 5.87 L/m^2 to 13.69 L/m^2, which is 10–23 times higher than that of the highest oil producing terrestrial oil crop – palm (Demirbas, 2011). The required land space is 10–340 times smaller than that of their terrestrial counterparts. Physicochemical characterization of algal oils have been studied recently with a reported pH in the range of 6–7, density in the range of 0.85–0.89 g/cm^3, and viscosity in the range of 3.8–4.4 mm^2/s (Pankaj Kumar et al., 2011).

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Biodiesel is produced from algal oils by transesterification and has similar properties as petro-diesel. Additionally, biodiesel is more suitable for vehicles than bioethanol because biodiesel can be used in vehicles without significant engine modifications.

Although algae biodiesel is a promising alternative to petro-diesel due to its high productivity and comparable physicochemical properties to petro-diesel, it is more expensive than petro-diesel because of high costs of processing steps and scaling up difficulties. In 2008, the U.S. Department of Energy (DOE) published a report to summarize the challenges faced by algae biofuels for commercialization, which indicates that the algae biodiesel cost of $2.11/L is too high when compared with $1.05/L soy oil biodiesel (in 2008 USD) (EERE, 2008). The report also mentioned that extensive research and development, system integration, and detailed cost analysis are necessary in the near future to reduce biodiesel costs (EERE, 2008). The optimization of algal biofuel production through the analysis of net energy gain, costs, resource needs, and productivity were further investigated in recent studies (Arudchelvam and Nirmalakhandan, 2012; Beal et al., 2012).

To overcome the cost barriers, detailed analysis on costs and technology alternatives are needed. The results of a decade-old cost analysis on algal biofuels by NREL (Benemann and Oswald, 1996) have been used as baseline data by many researchers for cost preditions. The costs of algae biodiesel estimated for both open ponds and photobioreactor (PBR) systems in the literature are summarized in Table 1, where all costs were updated to 2012 USD values. The results in Table 1 indicated that the costs of algae biodiesel produced from open pond systems were lower than other systems.

In the NREL study, cost analysis was conducted based on an algae biodiesel production process involving centrifuge for simultaneous biomass harvesting and oil extraction, as well as subsequent transesterification. However, detailed cost analysis on transesterification was not performed and only roughly estimated ($0.092/L) in the original NREL study (Benemann and Oswald, 1996). An updated cost analysis is needed to evaluate the feasibility and profitability of algae biodiesel and to determine if it is competitive enough to be commercialized.

With the recent development of optimized processes and improved cost estimation on transesterification, an updated comprehensive techno-economic analysis was conducted in this study. The major process improvement in this study is the utilization of a highly efficient one-step biodiesel production process with high power dual-frequency ultrasonicator available in the market during the last few years. After primary settling, algal slurry is mixed with alcohol and alkali, and then directly converted to biodiesel through simultaneous oil extraction and transesterification (SOET) with high power dual-frequency ultrasonicator. Additionally, latest quotes from vendors, government databases, and other relevant data sources were used to calculate the updated algal biodiesel costs. The cost analysis presented in this paper is an order of magnitude cost estimation with an accuracy of ±30% (Coker, 2010). This estimation utilizes a SOET process using ultrasonication to produce biodiesel and compares it with the costs from the previous NREL study (Benemann and Oswald, 1996). To the best of our knowledge, cost analysis for SOET using ultrasonication has not been reported in the literature.

2. Methods

2.1. Production process for algae biodiesel

The production of biodiesel from algae involves four steps: cultivation, harvesting, oil extraction, and transesterification. There have been various efforts to cut down the final biodiesel price, such as reduction or modification of process steps and system integration. Reducing the number of process steps can greatly reduce biodiesel cost and one of the latest developments in process optimization is to combine oil extraction and transesterification steps into a single step, such as SOET, which can significantly reduce chemical usage, time for extraction/transesterification, and post process waste treatment. Most existing algae biodiesel production processes use dry algae for oil extraction, whose efficiency is relatively low because extraction is energy-intensive and usually large volume of solvents have to be used. However algal biodiesel production from wet algal slurry instead of dry algal powder has been reported (Levine et al., 2012). In this study ultrasonication of wet algal slurry with solvent is used for SOET. SOET has been developed in the last few years and no detailed cost analysis has been reported. An updated cost analysis integrating SOET are reported and compared with the previous NREL study conducted by Benemann and Oswald (1996). All cost data are converted to 2012 USD values.

2.2. NREL cost analysis

The NREL cost analysis of algal biodiesel systems was a derivative estimate from previous studies. An open pond system with paddle wheels for mixing was assumed for the cost analysis. Total area of the system was 4×10^6 m^2 with the land cost assumed to be $0.2/m^2. The productivity was assumed to be 30 g/m^2/day and 60 g/m^2/day. Deep brackish ground water was assumed to be the water source. Two gas sources – CO_2 from flue gas and pure CO_2 – were considered for the cultivation of algae. An oil content of 50% and an extraction efficiency of 100% were assumed (556.5 L oil/MT biomass). Primary harvesting was achieved by settling assisted by flocculation. Secondary harvesting was done by a three phase centrifuge that performed simultaneous harvesting and oil extraction, which was a major innovative step of cost estimate

Table 1
Cost comparison of algae biodiesel from literature.

Cultivation system	Details	Cost of Biodiesel ($/L)	Reference
Open pond (333.3 ha)	Monte Carlo sampling method	1.68	Delrue et al. (2012)
PBR	Monte Carlo sampling method	2.80	Delrue et al. (2012)
Raceway + PBR	Monte Carlo sampling method	2.69	Delrue et al. (2012)
Solar lit PBR (500 ha)		21.72	Amer et al. (2011)
Open pond (500 ha)	Solvent extraction of oil is eliminated	3.55	Amer et al. (2011)
Integrated PBR	Carbon credits and biogas production credits included	49.46–75.77	Harun et al. (2011)
Open pond (1950.58 ha)		2.73	Davis et al. (2011)
PBR (1950.58 ha)		5.70	Davis et al. (2011)
Open pond	Monte Carlo financial feasibility model	3.91	Richardson et al. (2012)
PBR	Monte Carlo financial feasibility model	9.89	Richardson et al. (2012)
Open pond (400 ha)	Anaerobic digestion lagoon used to produce biogas as co-product for the production of electricity	0.50–0.82	Benemann and Oswald (1996)

Table 2
Algae biodiesel cost estimates (2012 \$/ha) (Benemann and Oswald, 1996).

Operations items	Productivity assumptions							
	30 g/m^2/day or 109 MT/ha/yr		60 g/m^2/day or 219 MT/ha/yr		30 g/m^2/day or 109 MT/ha/yr		60 g/m^2/day or 219 MT/ha/yr	
	Flue gas	% Of total cost	Flue gas	% Of total cost	CO_2	% Of total cost	CO_2	% Of total cost
Capital cost (\$/ha)								
Site prep, grading, compaction	4302.9	3.9	4302.9	2.8	4302.9	3.7	4302.9	2.5
Pond levees, geotextiles	6024.0	5.4	6024.0	3.9	6024.0	5.1	6024.0	3.5
Mixing (paddle wheels)	8605.7	7.7	8605.7	5.6	8605.7	7.3	8605.7	5.1
CO_2 sumps, diffusers	8605.7	7.7	8605.7	5.6	6884.6	5.9	6884.6	4.0
CO_2 supply, distribution	8605.7	7.7	13,769.2	9.0	516.3	0.4	516.3	0.3
Primary harvesting (settling)	12,048.0	10.8	12,048.0	7.9	12,048.0	10.2	12,048.0	7.1
Flocculation	3442.3	3.1	5163.4	3.4	3442.3	2.9	5163.4	3.0
Centrifugation, extraction	21,514.3	19.3	43,028.7	28.2	21,514.3	18.3	43,028.7	25.3
Anaerobic digestion lagoon	5593.7	5.0	11,187.5	7.3	5593.7	4.8	11,187.5	6.6
Gen-set (power generation)	–	0.0	–	0.0	14,974.0	12.7	29,948.0	17.6
Water and nutrient supply	8950.0	8.0	8950.0	5.9	8950.0	7.6	8950.0	5.3
Waste treatment (blow down)	1721.1	1.5	1721.1	1.1	1721.1	1.5	1721.1	1.0
Buildings, roads, and drainage	3442.3	3.1	4302.9	2.8	3442.3	2.9	4302.9	2.5
Electrical supply and distribution	3442.3	3.1	4302.9	2.8	3442.3	2.9	4302.9	2.5
Instrumentation and machinery	860.6	0.8	860.6	0.6	860.6	0.7	860.6	0.5
Subtotal of all the above	97,158.7	87.0	132,872.5	87.0	102,322.2	87.0	147,846.5	87.0
Engineering & contingency (15% of above)	14,573.8	13.0	19,930.9	13.0	15,348.3	13.0	22,177.0	13.0
Total direct capital	111,732.5	100.0	152,803.4	100.0	117,670.5	100.0	170,023.5	100.0
Land costs	3574.5		3574.5		3574.5		3574.5	
Working capital (25% net op. cost)	4337.9		5935.4		6091.7		6893.5	
Total capital investment	119,644.9		162,313.2		127,336.7		180,491.5	
Operating cost (\$/ha/yr)								
Power, mixing	953.8	5.5	953.8	4.0	953.8	3.9	953.8	3.5
Power, harvesting, processing	–	0.0	–	0.0	681.3	2.8	1362.5	4.9
Power, water supply	776.6	4.5	776.6	3.3	776.6	3.2	776.6	2.8
Power, flue gas supply	1362.5	7.9	2725.0	11.5	–	0.0	–	0.0
Power, other	136.3	0.8	136.3	0.6	136.3	0.6	136.3	0.5
Nutrients, N, P, Fe	1272.8	7.3	2545.6	10.7	1272.8	5.2	2545.6	9.2
CO_2 (@\$40/MT)	–	0.0	–	0.0	10,465.4	42.9	10,465.4	38.0
Flocculant	1414.2	8.2	2828.5	11.9	1414.2	5.8	2828.5	10.3
Labor + overheads	5561.6	32.1	7415.5	31.2	5561.6	22.8	7415.5	26.9
Waste Disposal	1853.9	10.7	1853.9	7.8	1853.9	7.6	1853.9	6.7
Maintenance, tax, insurance, (@5% total direct cap)	5586.6	32.2	7640.2	32.2	5883.5	24.1	8501.2	30.8
Credit for power or fuel	−1566.9	−9.0	−3133.8	−13.2	−4632.5	−19.0	−9265.0	−33.6
Total net operating costs	17,351.4	100.0	23,741.5	100.0	24,366.8	100.0	27,574.2	100.0
Capital charge (15% of total cap invest)	17,946.7		24,347.0		19,100.5		27,073.7	
Total annual cost	35,298.1		48,088.5		43,467.3		54,647.9	
Biomass cost (\$/MT)	323.8		219.6		398.8		249.5	
Oil cost (\$/barrel)	92.5		62.7		113.9		71.3	
Biodiesel cost (\$/barrel)	113.3		83.5		134.7		92.1	
Biodiesel cost (\$/L)	0.71		0.53		0.85		0.58	

compared with previous studies. Power cost of \$0.065/kW h was used for the calculations. An engineering and contingency ratio of 15% was assumed. Another highlight of the NREL study was the utilization of spent biomass for the production of electricity through biogas produced from an anaerobic digestion lagoon. By doing this, a part of the electricity costs required for the production of biodiesel can be offset. The details of cost analysis conducted by Benemann and Oswald (1996) are summarized in Table 2, with costs converted to 2012 USD values based on the construction cost indices, skilled labor cost indices, and material cost indices from Engineering News-Record (ENR, 2012) and land prices in the U.S. (Lincoln Institute of Land Policy, 2012). These costs will be used as the base line costs for comparison with the updated cost analysis in this study.

Although the NREL study included detailed cost analysis on most production processes for algae biodiesel, it had several drawbacks. For example, the transesterification cost (\$0.092/L) and land cost (\$0.2/m^2) were only roughly estimated without detailed cost analysis, and an unrealistic oil extraction efficiency of 100% was assumed.

2.3. Updated cost analysis

The updated cost analysis assumes a 4×10^6 m^2 open pond design with paddle wheels, biomass productivities and gas sources similar to the NERL study conducted by Benemann and Oswald (1996). Brackish water was assumed to be the water source for algal growth. Nitrogen (3.15% of dry weight of algae) and phosphorus (0.85% of dry weight of algae) required for algal growth were determined by taking the average values of nitrogen and phosphorus reported by Alabi et al. (2009) and Norsker et al. (2011). The costs of nitrogen (ammonia) and phosphorus (super phosphate) were \$783/MT and \$665/MT, respectively (ERS, 2012). An algal oil content of 50% and transesterification efficiency by ultrasonication of 90% was assumed (Stavarache et al., 2007). One limit of the NREL study by Benemann and Oswald (1996) is that a 100% oil extraction efficiency was assumed, while a recent study on *Scenedesmus* sp. indicated an ultrasonication assisted oil extraction efficiency of 75% (Ranjan et al., 2010), which was used in this study for the updated cost analysis. Algal biomass was harvested with the assistance of organic cationic polyelectrolytes. Organic cationic polyelectrolytes at 10 mg/L are used to harvest biomass as slurries (final volume reduced to 10% of total volume) as suggested in the NREL comparative study (Benemann and Oswald, 1996). Sodium carboxyl methyl cellulose (CMC) with a cost of \$550/MT was considered as an organic cationic polyelectrolyte for flocculation. The slurry was assumed to be mixed with methanol and sodium hydroxide in the ratio of 4:1 (Ma et al., 1999) in a 316 stainless steel mixer with a capacity of 5000 L. The cost of the mixer was estimated as \$0.16/m^2 (Matches, 2007). Costs of methanol and sodium hydroxide were taken as \$239.4/MT and \$5320/MT respectively (Grima et al., 2003). A 24 kW DFR-9624 ultrasonicator with a 5% shipment charge was considered for the ultrasonication assisted SOET process. Two units of ultrasonicators were required to process 30 g/m^2/day biomass with a cost of \$0.099/m^2 and the cost doubled for 60 g/m^2/day biomass. Decantation centrifuge was used for the separation of biodiesel with a cost of \$0.234/m^2 (Gumerman et al., 1979). Engineering cost of 5% was retained from the NREL study, but contingency cost was reduced to 5% from 10% mentioned in the NREL study based on the new construction facility data provided by California's State Administrative Manual (DGS, 1998). Non-farm labor costs of \$19.42/h was obtained from USDA and inflated to 2012 values (NASS, 2011a). Power cost of \$0.0989/kW h was used for all the calculations (E.I.A., 2012a). A similar anaerobic digestion lagoon as mentioned in the NREL study was assumed in this study and the credit for fuel production was calculated with an electricity cost of \$0.0989/kW h.

The roughly estimated cost of \$0.2/m^2 in the NREL study in 1996 is equivalent to \$0.36/m^2 in 2012 USD values. However, recent studies indicated much higher land costs, such as \$0.78/m^2 (Davis et al., 2011), and \$13.78/m^2 (Norsker et al., 2011). In this study, a land cost of \$0.91/m^2 was used, which was obtained from the land values for non-irrigated lands reported by the U.S. Department of Agriculture (NASS, 2011b) and inflated to 2012 USD values.

2.4. Solar radiation and algal cultivation

Solar radiation is an important factor for determining the efficiency of algal cultivation. The theoretical maximum efficiency is estimated as 10%, which was calculated from the visible light of the solar spectrum at 45% and algae's efficiency of converting visible light at 22% (Benemann and Oswald, 1996). In an idealistic case, the photosynthetic efficiency is calculated to be 11.9% (Beal et al., 2012). The methods of calculating theoretical maximum efficiencies are different among several studies as some researchers used the heating value of the whole biomass while others only used the oil's heating value for the calculations (Norsker et al., 2011; Weyer et al., 2010). Photosynthetic efficiencies can be calculated with on Global Horizontal Irradiation (GHI) data obtained from the Solar and Wind Energy Resource Assessment database (SWERA, 2012), which was launched in 2001 to collect solar and wind energy resource data sets and analysis tools from a number of international organizations.

Photosynthetic efficiency based on biomass productivity with flue gas as the gas source is calculated using Eq. (1) shown below (Norsker et al., 2011).

$$\mathrm{PE} = \frac{P_a \times \mathrm{HV}}{I} \tag{1}$$

where PE is the photosynthetic efficiency (%), P_a is the productivity of algal biomass (g/m^2/day), HV is the heating value of algal biomass (MJ/g) and I is the global horizontal solar irradiation (kW h/m^2/day).

The photosynthetic efficiencies based on biodiesel mediated by ultrasonication (SOET) were also calculated with flue gas as the gas source.

3. Results and discussion

3.1. Cost comparison

The results of updated algae biodiesel cost estimates are shown in Table 3 and compared with the results in the NREL study in Table 2. The results in this study indicate that the cost of biodiesel is reduced by 40.7–42.3% when the biomass productivity is doubled, which was larger than the cost reduction in the NERL study (26.3–31.6%) for doubled biomass productivity. The results also indicate that flue gas is a better gas source than pure CO$_2$ as the biodiesel production costs drops by 24.8–26.8% with flue gas in this study and drops by 9.3–15.9% with flue gas in the NREL study.

The comparison of algae biodiesel costs in the updated cost analysis and previous NREL cost analysis by Benemann and Oswald is shown in Fig. 1. Compared with the NREL cost estimates, the reduction of biodiesel cost in the updated cost analysis ranges from 0.8% to 20.2%. One exception is the case with CO$_2$ as gas source and biomass productivity at 30 g/m^2/day, where the biodiesel cost in the updated cost analysis is 14.0% higher than the estimates in the NREL study, which is mainly due to a more accurate estimation of transesterification cost, land cost, and realistic extraction efficiency.

Table 3
Updated algae biodiesel cost estimates.

Operations items	Productivity assumptions							
	30 g/m^2/day or 109 MT/ha/yr		60 g/m^2/day or 219 MT/ha/yr flue gas		30 g/m^2/day or 109 MT/ha/yr		60 g/m^2/day or 219 MT/ha/yr	
	flue gas ($)	% Of total cost	flue gas ($)	% Of total cost	CO_2 ($)	% Of total cost	CO_2 ($)	% Of total cost
Capital cost ($/ha)								
Site prep, grading, compaction	4302.9	4.9	4302.9	3.9	4302.9	4.6	4302.9	3.4
Pond levees, geotextiles	6024.0	6.8	6024.0	5.5	6024.0	6.4	6024.0	4.8
Mixing (paddle wheels)	8605.7	9.7	8605.7	7.8	8605.7	9.1	8605.7	6.8
CO_2 sumps, diffusers	8605.7	9.7	8605.7	7.8	6884.6	7.3	6884.6	5.5
CO_2 supply, distribution	8605.7	9.7	13,769.2	12.5	516.3	0.5	516.3	0.4
Primary Harvesting (settling)	12,048.0	13.6	12,048.0	11.0	12,048.0	12.8	12,048.0	9.5
Flocculation with 10% polyelectrolytes	3442.3	3.9	5163.4	4.7	3442.3	3.6	5163.4	4.1
Mixer (for transesterification)	1628.9	1.8	3257.9	3.0	1628.9	1.7	3257.9	2.6
Ultrasonication (1 step conversion to Biodiesel)	993.6	1.1	1987.2	1.8	993.6	1.1	1987.2	1.6
Decanter centrifuge	2337.9	2.6	4675.7	4.3	2337.9	2.5	4675.7	3.7
Anaerobic digestion lagoon	5593.7	6.3	11,187.5	10.2	5593.7	5.9	11,187.5	8.9
Gen-set (power generation)					14,974.0	15.9	29,948.0	23.7
Water and nutrient supply	8950.0	10.1	8950.0	8.2	8950.0	9.5	8950.0	7.1
Waste treatment (blow down)	1721.1	1.9	1721.1	1.6	1721.1	1.8	1721.1	1.4
Buildings, roads and drainage	3442.3	3.9	4302.9	3.9	3442.3	3.6	4302.9	3.4
Electrical supply and distribution	3442.3	3.9	4302.9	3.9	3442.3	3.6	4302.9	3.4
Instrumentation and machinery	860.6	1.0	860.6	0.8	860.6	0.9	860.6	0.7
Subtotal of all the above	80,604.8	90.9	99,764.7	90.9	85,768.2	90.9	114,738.7	90.9
Eng. & conting (10% above)	8060.5	9.1	9976.5	9.1	8576.8	9.1	11,473.9	9.1
Total direct capital	88,665.3	100.0	109,741.1	100.0	94,345.1	100.0	126,212.5	100.0
Land Costs	9148.0		9148.0		9148.0		9148.0	
Working Capital (25% net op. cost)	3442.1		4009.8		5788.8		6150.8	
Total Capital Investment	101,255.4		122,899.0		109,281.9		141,511.4	
Operating cost ($/ha/yr)								
Power for paddle wheels	1065.1	7.7	1065.1	6.6	1065.1	4.6	1065.1	4.3
Power (ultrasonic + centrifugation + mixer)	361.5	2.6	723.0	4.5	361.5	1.6	723.0	2.9
Power, water supply	867.3	6.3	867.3	5.4	867.3	3.7	867.3	3.5
Power, flue gas supply	1362.5	9.9	2725.0	17.0				
Power, other	156.6	1.1	156.6	1.0	156.6	0.7	156.6	0.6
Nutrients, N, P	3304.6	24.0	6639.4	41.4	3304.6	14.3	6639.4	27.0
CO_2 (@ 40 $/MT)					10,465.4	45.2	10,465.4	42.5
Methanol (@225 $/MT with inflation)	10,437.8	75.8	20,971.4	130.8	10,437.8	45.1	20,971.4	85.2
NaOH (@5000 $/MT with inflation)	2319.5	16.8	4660.3	29.1	2319.5	10.0	4660.3	18.9
Polyelectrolyte	203.5	1.5	416.1	2.6	203.5	0.9	416.1	1.7
Labor	4331.7	31.5	4331.7	27.0	4331.7	18.7	4331.7	17.6
Waste disposal	1853.9	13.5	1853.9	11.6	1853.9	8.0	1853.9	7.5
Maintenance, tax, insurance, (@5% total direct cap)	4433.3	32.2	5487.1	34.2	4717.3	20.4	6310.6	25.6
Credit for power or fuel	−16,928.8	−123.0	−33,857.5	−211.1	−16,928.8	−73.1	−33,857.5	−137.6
Total net operating costs	13,768.4	100.0	16,039.3	100.0	23,155.3	100.0	24,603.3	100.0
Capital charge (15% total cap invest)	15,188.3		18,434.9		16,392.3		21,226.7	
Total annual cost	28,956.7		34,474.2		39,547.6		45,830.0	
Biomass cost (S/MT)	265.7		157.4		362.8		209.3	
Biodiesel cost ($/barrel)	112.4		66.63		153.58		88.58	
Biodiesel cost ($/L)	0.71		0.42		0.97		0.56	

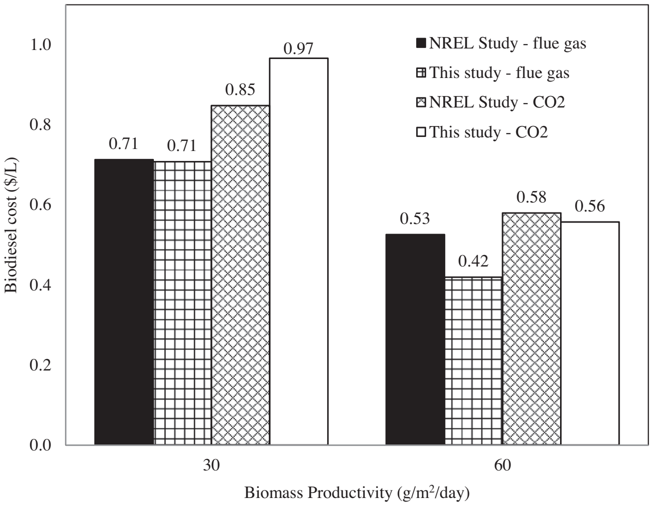

Fig. 1. Comparison of biodiesel costs in the NREL study (Benemann and Oswald, 1996) and this study.

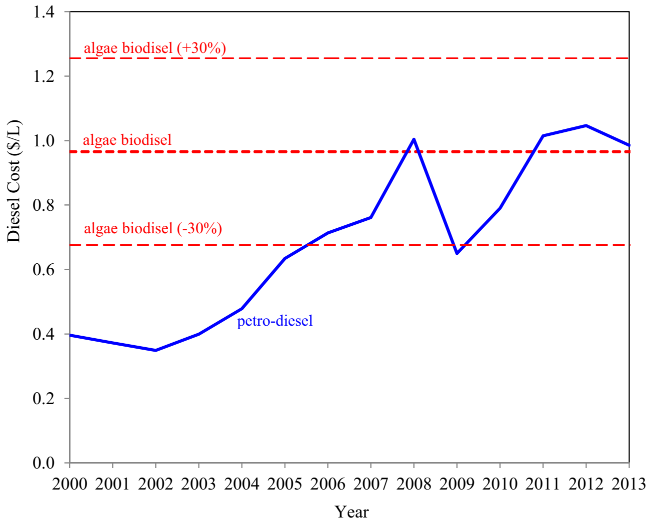

Fig. 2. Cost comparison of petro-diesel (E.I.A., 2012b) with algae biodiesel.

The updated cost analysis with SOET has suggested several improvements on the overall efficiency of biodiesel production. For the algal biomass productivity of 30 g/m^2/day, the ultrasonicator, decanter, and mixer in SOET contribute to about 5.6% of the total direct capital cost when compared to a 19.3% cost for a centrifuge for oil extraction alone as mentioned in the NREL study. The use of polyelectrolytes reduces the flocculation operating costs by almost 85.6%. Electricity generation from biogas produced from spent biomass helps significantly reduce the cost of biodiesel by almost 36.9%.

The highest cost of algae biodiesel ($0.97/L) was obtained with pure CO$_2$ as gas source at a biomass productivity of 30 g/m^2/day. A ±30% accuracy of the cost estimate gives cost range of $0.68–1.26/L, which were subsequently compared with historical retail diesel price from EIA's Short Term Energy Outlook and projected cost of diesel in 2013 (E.I.A., 2012b), as shown in Fig. 2. The calculated algae biodiesel cost seems promising and suggests that a single step biodiesel production process is close to commercial reality.

3.2. Solar radiation and algal cultivation

Photosynthetic efficiencies based on both biomass and biodiesel at locations around the world are calculated. For example, a GHI value of 5.25 kW h/m^2/day at California (SWERA, 2012) was used as the radiation value for the calculation of photosynthetic efficiency in California-based algal cultivation systems in both the NERL study and this study. If the heating value of 26.9 MJ/kg for algal biomass with 50% lipids is used (Weyer et al., 2010), the photosynthetic efficiencies based on biomass are calculated as 15.4% and 30.7% for biomass productivity of 30 g/m^2/day and 60 g/m^2/day, respectively. If an oil content of 50%, an oil extraction efficiency of 75%, and an ultrasonication mediated transesterification efficiency of 90% are used, the photosynthetic efficiency based on biodiesel mediated with SOET are calculated as 7.5% and 15.3%, for biomass productivity of 30 g/m^2/day and 60 g/m^2/day, respectively. The photosynthetic efficiencies at other representative locations around the world are calculated and summarized in Table 4.

Due to the difference among GHI data, the photosynthetic efficiencies at various locations around the world are different. Therefore, photosynthetic efficiencies have to be considered for an accurate biodiesel cost analysis and the results in Table 4 can be used as a guideline to convert the biodiesel costs at California, which were used in both the NREL study and this study, to the biodiesel costs at other locations. The results suggest that the optimum locations for algal biodiesel production are in East Asia and parts of central North America and the biodiesel costs will be lower than California-based studies.

Table 4
Photosynthetic efficiency calculations based on global horizontal irradiation data.

Location	Average GHI (kW h/m^2/day)	Photosynthetic efficiency[a]	
		Based on biomass[b] (%)	Based on biodiesel (SOET)[c] (%)
Western South America/Parts of Middle East/Parts of Central Africa/North West Coast of Australia	6.75	12.0	5.8
North and Central Africa/South Western Coast of North America/Middle East/North and North West Australia	6.25	12.9	6.3
Central Australia/North Pacific Ocean/Southern North America/North Eastern South America/Rest of Africa/Parts of SEA/Parts of Middle East	5.75	14.0	6.8
Indian Subcontinent/South Australia/Eastern South America/South Western North America/Rest of Middle East	5.25	15.4	7.5
Rest of Asia/Rest of South America/Parts of Central North America	4.75	17.0	8.2
East Asia/Parts of Central North America	4.25	19.0	9.2

[a] Algal production is calculated based on a 50% lipid, a biomass productivity of 30 g/m^2/day, flue gas as gas source, and global horizontal irradiation (GHI) data (SWERA, 2012).

[b] Biomass produced for 30 g/m^2/day is calculated as 38,114.9 g/m^2.

[c] Biodiesel produced with SOET is calculated as 12.86 kg/m^2, heating value of biodiesel is 35.08 MJ/L, energy content based on biodiesel is 0.392 kW h/m^2/day, and heating value for algae with 50% lipid is 26.9 MJ/kg (Norsker et al., 2011).

The results in Table 4 also indicated that increased solar irradiance does not necessarily improve the overall photosynthetic efficiency, which is consistent with published literature (Benemann and Oswald, 1996; Norsker et al., 2011) and can be explained by light saturation effect in algal photosynthesis.

Both the efficiency calculations are based on productivity, heating value, and irradiance, but not temperature, which has been reported to play an important role in determining the algal productivity in a previous study (Norsker et al., 2011). The accuracy of cost estimation for biodiesel can be further improved when the effect of temperature is considered.

4. Conclusion

This study elaborates on the commercialization potential of algae biodiesel by a simultaneous oil extraction and transesterification process. Accurate land costs, realistic oil extraction efficiencies, polyelectrolytes for flocculation, and solar irradiance based photosynthetic efficiency have been used for the techno-economic analysis of algae biodiesel. Based on the calculations, it is predicted that algae biodiesel production based on a simultaneous oil extraction and transesterification mediated by ultrasonication could be considered as a possible technique to make biodiesel cost competitive to petro-diesel and close to commercial reality.

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References

Alabi, A.O., Tampier, M., Bibeau, E., 2009. Microalgae Techonologies and Processes for Biofuels/Bioenergy Production in British Collumbia: Current Technology, Suitability and Barriers to Implementation. The British Columbia Innovation Council, Canada.

Amer, L., Adhikari, B., Pellegrino, J., 2011. Technoeconomic analysis of five microalgae-to-biofuels processes of varying complexity. Bioresource Technology 102 (20), 9350–9359.

Arudchelvam, Y., Nirmalakhandan, N., 2012. Optimizing net energy gain in algal cultivation for biodiesel production. Bioresource Technology 114, 294–302.

Beal, C.M., Hebner, R.E., Webber, M.E., Ruoff, R.S., Seibert, A.F., King, C.W., 2012. Comprehensive evaluation of algal biofuel production: experimental and target results. Energies 5 (6), 1943–1981.

Benemann, J.R., Oswald, W.J., 1996. Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass. DOE/PC/93204 – T5.

Cheng, C.-L., Che, P.-Y., Chen, B.-Y., Lee, W.-J., Lin, C.-Y., Chang, J.-S., 2012. Biobutanol production from agricultural waste by an acclimated mixed bacterial microflora. Applied Energy.

Coker, A.K., 2010. Ludwig's Applied Process Design for Chemical and Petrochemical Plants: Volume 2: Distillation, Packed Towers, Petroleum Fractionation, Gas Processing and Dehydration. Elsevier Science.

Davis, R., Aden, A., Pienkos, P.T., 2011. Techno-economic analysis of autotrophic microalgae for fuel production. Applied Energy 88 (10), 3524–3531.

Delrue, F., Setier, P.A., Sahut, C., Cournac, L., Roubaud, A., Peltier, G., Froment, A.K., 2012. An economic, sustainability, and energetic model of biodiesel production from microalgae. Bioresource Technology 111, 191–200.

Demirbas, A., 2011. Biodiesel from oilgae, biofixation of carbon dioxide by microalgae: a solution to pollution problems. Applied Energy 88 (10), 3541–3547.

DGS, 1998. State administrative manual – chapter 6800. In: 6854 – Construction. California Department of General Services, Sacramento, CA, USA.

E.I.A., 2012a. Electric Power Monthly August 2012. Washington, DC, USA.

E.I.A., 2012b. Short-Term Energy Outlook, U.S. Energy Information Administration.

EERE, 2008. Algae biofuels. In: E.E.R.E. U.S. Department of Energy (Ed.), Growing America's Energy Future. Alternative Fuels Data Center, Washington, DC, USA.

ENR, 2012. Engineering News-Record. The McGraw-Hill Companies, Inc.

ERS, 2012. Fertilizer use and price. U.S. Department of Agriculture Economic Research Service, Washington, DC, USA.

Grima, E.M., Belarbi, E.H., Fernandez, F.G.A., Medina, A.R., Chisti, Y., 2003. Recovery of microalgal biomass and metabolites: process options and economics. Biotechnology Advances 20 (7–8), 491–515.

Gumerman, R., Culp, R., Hansen, S., 1979. Estimating Water Treatment Costs: Volume 2 - Cost Curves Applicable to 1–200 mgd Treatment Plants. USEPA, Cincinnati, OH, USA, p. 542.

Harun, R., Davidson, M., Doyle, M., Gopiraj, R., Danquah, M., Forde, G., 2011. Technoeconomic analysis of an integrated microalgae photobioreactor, biodiesel and biogas production facility. Biomass & Bioenergy 35 (1), 741–747.

Jones, C.S., Mayfieldt, S.P., 2012. Algae biofuels: versatility for the future of bioenergy. Current Opinion in Biotechnology 23 (3), 346–351.

Levine, R.B., Bollas, A.A., Durham, M.D., Savage, P.E., 2012. Triflate-catalyzed (trans)esterification of lipids within carbonized algal biomass. Bioresource Technology 111, 222–229.

Lincoln Institute of Land Policy, 2012. Land and Property Values in the U.S. Lincoln Institute of Land Policy, Cambridge, MA.

Ma, F.R., Clements, L.D., Hanna, M.A., 1999. The effect of mixing on transesterification of beef tallow. Bioresource Technology 69 (3), 289–293.

Matches, 2007. Reactor cost estimate, http://www.matche.com/EquipCost/Reactor.htm. Accessed on 05.10.12.

NASS, 2011a. A Comparison of U.S. Wage Rates 1981–2011. U.S. Department of Agriculture National Agricultural Statistics Service, Washington, DC, USA.

NASS, 2011b. Land Values 2011 Summary. U.S. Department of Agriculture National Agricultural Statistics Service, Washington, DC, USA.

Norsker, N.-H., Barbosa, M.J., Vermuë, M.H., Wijffels, R.H., 2011. Microalgal production – a close look at the economics. Biotechnology Advances 29 (1), 24–27.

Pankaj Kumar, Suseela, M.R., Toppo, K., 2011. Physico-chemical characterization of algal oil: a potential biofuel. Asian Journal of Experimental Biological Sciences 2 (3), 493–497.

Ranjan, A., Patil, C., Moholkar, V.S., 2010. Mechanistic assessment of microalgal lipid extraction. Industrial & Engineering Chemistry Research 49 (6), 2979–2985.

Richardson, J.W., Johnson, M.D., Outlaw, J.L., 2012. Economic comparison of open pond raceways to photo bio-reactors for profitable production of algae for transportation fuels in the Southwest. Algal Research 1 (1), 93–100.

Sheehan, J., Dunahay, T., Benemann, J., Roessler, P., 1998. Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae; Close-Out, Report. NREL/TP-580-24190.

Stavarache, C., Vinatoru, M., Maeda, Y., Bandow, H., 2007. Ultrasonically driven continuous process for vegetable oil transesterification. Ultrasonics Sonochemistry 14 (4), 413–417.

SWERA, 2012. Renewable Energy Data Exploration, National Renewable Energy Laboratory Solar and Wind Energy Resource Assessment.

Weyer, K.M., Bush, D.R., Darzins, A., Willson, B.D., 2010. Theoretical maximum algal oil production. Bioenergy Research 3 (2), 204–213.

Wigley, T.M.L., Richels, R., Edmonds, J.A., 1996. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. Nature 379 (6562), 240–243.