Microalgal Biomass for Greenhouse Gas Reductions; Potential for Replacement of Fossil-Fuels and Animal Feeds

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Abstract: Microalgal biomass production offers a number of advantages over conventional biomass production including, higher productivities, use of otherwise non-productive land, reuse and recovery of waste nutrients, use of saline or brackish waters, and reuse of CO_2 from power-plant flue-gas or similar sources. Microalgal biomass production and utilization offers potential for greenhouse gas (GHG) avoidance by providing biofuel replacement of fossil fuels and carbon-neutral animal feeds. This paper presents an initial analysis of the potential for GHG avoidance using a proposed algal biomass production system coupled to recovery of flue-gas CO_2 combined with waste sludge and/or animal manure utilization. A model is constructed around a 50 megawatt (MW) natural gas fired electrical generation plant operating at 50% capacity as a semi base-load facility. This facility is projected to produce 216 million kWh/240-day season while releasing 30.3 million kg-C/season of GHG-CO_2. An algal system designed to capture 70% of flue-gas CO_2 would produce 42,400 metric tons (dry wt.) of algal biomass/season, and require 880 ha of high-rate algal ponds operating at a productivity of 20 g-dry-wt/m^2-day. This algal biomass is assumed to be fractionated into 20% extractable algal oil, useful for biodiesel, with the 50% protein content providing animal feed replacement, and 30% residual algal biomass digested to produce methane gas, providing gross GHG avoidances of 20%, 8.5% and 7.8% respectively. The total gross GHG avoidance potential of 36.3% results in a net GHG avoidance of 26.3% after accounting for 10% parasitic energy costs. Parasitic energy is required to deliver CO_2 to

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the algal culture and to harvest and process algal biomass and algal products. At CO_2 utilization efficiencies predicted to range from 60% to 80%, net GHG avoidances are estimated to range from 22% to 30%. To provide nutrients for algal growth and to ensure optimal algae digestion, importation of 53 metric tons/day of waste paper, municipal sludge, or animal manure would be required. This analysis does not address the economics of the processes considered. Rather, the focus is directed at determination of the technical feasibility of applying integrated algal processes for fossil-fuel replacement and power-plant GHG avoidance. The technology discussed remains in early stages of development, with many important technical issues yet to be addressed. Although theoretically promising, successful integration of waste treatment processes with algal recovery of flue-gas CO_2 will require pilot-scale trials and field demonstrations to more precisely define the many detailed design requirements.

INTRODUCTION

This paper examines the potential for application of microalgae cultivation systems for reduction of CO_2 greenhouse gas (GHG) emissions from a 50 megawatt (MW) natural gas fired, electrical generation plant proposed to be located near the Salton Sea, in Southern California. The driver for the present analysis is increasingly restrictive regulations on GHG emissions anticipated in California, and elsewhere, in coming years. In March 2008, the California Public Utilities Commission and the California Energy Commission recommended that California Air Resources Board adopt policies and requirements to reduce GHG emissions from the power generation and other industrial sectors in California (Calif Public Utilities 2008). This was done to implement the goals of the California Global Warming Solutions Act of 2006 requiring statewide GHG emissions reductions to 1990 levels by 2020. It is likely that similar drivers will soon affect all economic sectors and all GHG sources in the U.S.

Current U.S. net GHG emissions, after accounting for CO_2 uptake by soils and forests, are 1,720 MMTCE (million metric tons carbon equivalent, or 6,307 $MMTCO_2$) which includes methane and other non-CO_2 GHG components. This represents approximately 25% of global GHG emissions in spite of the fact that U.S. population is only ~5% of world population. Fossil fuel combustion constitutes 91% of U.S. annual GHG emissions with electrical generation contributing 36% of this total (Table 1, U.S.-EPA 2006). Clearly, reduction in GHG emissions from electrical power generation plants represents an important target for U. S. and world GHG reduction efforts.

Reduction of power-plant GHG emissions is well matched to microalgal mass culture GHG remediation strategies. Elevated CO_2 levels in typical power-plant flue-gas (6 to 12%) may be used to directly supply the inorganic carbon requirements of high-rate algal cultures which cannot be recarbonated from atmospheric sources at a rate sufficient to match rapid culture growth. Furthermore, algal biomass can be used to produce biofuels such as methane and biodiesel, the former potentially serving as a direct replacement of natural gas fueling the power-plant.

The analysis presented herein targets the utilization of open-pond microalgae biomass production as a technique to achieve mandated GHG reductions for existing and planned electrical generation plants through capture and recycle of fossil CO_2 emissions with co-production of biofuels and/or bioproducts. Specifically, we examine four microalgal production and utilization scenarios: (1) production of methane from anaerobic digestion of algal biomass for direct power-plant natural gas replacement, (2) production of biodiesel from algae oils for liquid fuel replacement, (3) production of algal biomass for use as an animal feed replacing conventionally produced soybean meal or, (4) co-production of a combination of methane, oil and animal feeds, typically referred to as an algal biorefinery.

MICROALGAL PRODUCTIVITY AND GHG AVOIDANCE

Numerous studies have proposed and examined high-rate photosynthetic systems as applied to biofuels and bioproducts production (Oswald and Golueke, 1960; Benemann et al, 1978, 2003; Weissman and Goebel 1987; Benemann and Oswald 1996; Doucha et al 2004). This present study is based, in part, on these previously presented data and analyses. However, unlike the previous work, this study focuses on a specific proposed power-plant and location currently under development (Raemy 2008). The combination of algal biomass production with recovery of flue-gas CO_2 from semi base-load power plants offers significant advantages which are highlighted in this study.

Microalgae cultivation in open-ponds or enclosed photobioreactors requires the provision of an enriched source of CO_2 such as flue-gas. Application of closed photobioreactors is neither economically feasible nor technically suited to the requirement for low-cost production of fuels, feeds or GHG abatement (Weissman et al 1988), and therefore, not considered in this analysis. Rather, this effort focuses exclusively on the use of "high-rate ponds;" shallow (< 0.5 m deep), raceway-type systems, mixed with low-head, low-RPM paddlewheels at modest velocities of ~30 cm/sec. High-rate ponds are used extensively for production of algal nutritional products and have been field demonstrated to be capable of achieving carbon fixation rates of 6 to 15 g C/m^2-day or, assuming algal biomass as 50% C of ash-free dry wt, 12 to 30 g dry wt/m^2-day, depending on location and algal species cultivated (Sheehan et al 1998; Benemann 2003).

For the purposes of this analysis, a sustainable algal productivity averaging 20 g of ash-free dry wt expressed as volatile solids (VS) per square meter per day (g-VS/m^2-day) biomass production is projected over an eight-month growing season corresponding to the operational schedule of the proposed semi base-load power plant. Even with a shortened eight-month growing season, the algal system would be expected to produce 48 mt/ha-season (metric tons per hectare per season, or ~ 42,000 lb/acre-season) of dry biomass. The required CO_2 would be obtained from a power-plant to be located in southern California, near the Salton Sea, where irrigation-water, agricultural return-water, or saltwater would be available to support the algal culture facility. The algal biomass is projected to average 9% nitrogen at 50% protein, 20% extractable oil, 25% carbohydrate, and 5% other organic materials, such as cell wall polysaccharides, unextractable lipids (oils), and other organic materials. Numerous investigators have suggested algal lipid content to range from 20-80% (Chisti 2007) however, oil content and total oil yields in excess of 20% of dry weight has not yet been demonstrated to be sustainable in field-scale systems. In spite of the lower assumed oil content, this level of algal-oil and protein productivity is 10-20 times greater than protein and oil productivities obtainable from U.S. soybean production, and 5-10 times higher than irrigated conventional agricultural crops grown in similar locations (Burmm et. al 2005).

Currently the only photosynthetic systems providing significant GHG reductions in the U.S. are related to forestry and agriculture, with forests soils and above ground biomass accumulation currently providing a net sink for atmospheric CO_2. In 2004, this carbon sink was estimated to provide a net removal of 213 MMTCE (781 $MMTCO_2$) or 12% of total U.S. GHG emissions (Table 1, U.S.-EPA 2006). Production of biofuel as a fossil-fuel replacement could provide a potential alternative method for GHG reductions. However, current biofuel production from conventional agricultural crops (eg, ethanol from corn and biodiesel from soybean oil) do little to contribute to GHG reductions as net energy production from these sources is modest. Furthermore, these production systems can result in increases in soil carbon releases (Patzek and Pimentel 2005). Although most organic carbon fixed in U.S. agricultural soils and forest biomass will ultimately degrade to CO_2, with a half-life on the order of tens of decades, at the present time the rate of soil carbon biofixation is increasing, representing a net sink for GHG-CO_2. While open-air, paddlewheel-mixed algal systems have the potential to fix carbon at rates five to 10-fold greater than conventional forest or agricultural crops, unlike wood accumulation, algal biomass is readily degradable, and relatively short-lived, as a carbon sink. Theoretically algal biomass could also be used to provide an increasing and sustainable soil organic matter supplement. Unfortunately, energy required to transport, distribute and incorporate algal biomass into soils would likely render such schemes infeasible. Consequently, the greater potential is to use algal production for replacement of fossil-fuels or products requiring fossil-fuel for production. Therefore it is not likely that algal production can be considered as a means of carbon sequestration, but is more correctly described as "GHG avoidance." GHG avoidance may be achieved if algal biomass is used as a source of biofuel or as algal-generated oils for replacement of fossil-generated transport fuels.

Algal biomass could also be used to replace conventionally produced high-protein animal feeds, such as soybeans. GHG benefits accrue from this replacement if less fossil-fuel is required per mass of protein produced, and if soil N_2O emissions are reduced as a result of conventional soy protein replacement. Soybeans are currently produced on 25 million hectares (63 million acres) in the U.S. at an average productivity of 42 bushels/acre or 2192 lbs/ac-yr (almost 2.5 metric tons/ha-yr) with an average wet weight of 60 lbs/bushel (13% moisture). Soybean protein and oil content average about 35% and 18.5%, respectively (Burmm et al 2005). GHG emissions from fossil-fuel used in soybean production range widely depending on geographic location and irrigation and fertilization practices, from 50 to over 240 kg-C/ha (183-880 kg-CO_2/ha), with a national average estimated at 68 kg-C /ha-yr (West and Marland 2001). GHG emissions resulting from N_2O losses from soybean acreage is even more uncertain, with two reports (U.S.-EPA 2006; Rochette et al. 2004; Reay et al 2007) estimating ranges from 38-420 kg-C/ha-yr (140-1540 kg-CO_2/ha-yr), respectively (N_2O GHG potential expressed as equivalents of carbon or carbon dioxide). In this study, the soybean GHG emission value used is based on the U.S. average of 68 kg-C/ha-yr for soybean energy usage and 145 kg-C/ha-yr for N_2O emissions resulting in an estimated combined soybean GHG potential (CO_2 + N_2O) emission of 213 kg-C/ha-yr (781 kg-CO_2/ha-yr) or 87 kg-C/mt (319 kg-CO_2/mt) of soybeans produced. Approximately one third of soybean GHG is due to CO_2 emissions from fossil-fuel usage in soybean production (Table 2).

MICROALGAL POWER-PLANT CO_2 FIXATION

System Design

The analysis presented and discussed herein is built upon the proposed scenario of a semi base-load power-plant; This proposed plant is to be a natural gas fired, combined-cycle, combustion and steam turbine power generation facility operating to supply peak power to southern California, providing an average electrical production 18 hours/day for eight months from March though October, representing 50% of annual electrical production as compared to a base-load plant. This plant is proposed to provide 50-MW electrical generation capacity, providing net annual power generation of:

$$(50{,}000\text{kW})(18\text{ hr/day})(240\text{ d/season}) = 216\text{ million kWh/season} \quad (1)$$

The expected CO_2-C generation rate is calculated as:

$$(216\text{ million kWh/season})(0.1405\text{ kg C/kWh}) = 30.3\text{ million kg-C/season} \quad (2)$$

The 30.3 million kg-C per 240 day season (111,276 mt CO_2/season) is based upon 0.1405 kg-C/kWh (0.515 kg CO_2/kWh) representing the average U.S.-GHG emission rate from natural-gas fired plants (Table 2, US EPA, 2007). The expected algal dry weight generation will depend on the efficiency of transfer of CO_2 from the flue-gas to the algal reactor. The efficiency of CO_2 transfer into the algal growth medium, and losses by out-gassing, depend on many factors, including flue-gas CO_2 content, culture media alkalinity (determining CO_2 storage), water depth, and mixing velocity (Benemann et al 1982; Weissman and Goebel 1987). Other factors affecting CO_2 utilization are the diel growth response of the algal culture vs. power-plant CO_2 generation, daily algal productivity, and biomass composition, among others. During the time period selected (March to October) the algal culture productivity at the proposed location is likely to vary from 15-30 g/m^2-day. However, these projections are based on systems typically no larger than one acre in size. Optimal sizing of the algal culture facility would depend on a combination of economic factors, monthly algal productivity, and overall CO_2 transfer and utilization efficiency. Benemann et al (1982) observed that CO_2 transfer efficiency in properly operated systems ranges between 85-95%. Variations in culture operation and productivity could reduce overall CO_2 utilization to 60-80%. Recovery and recycling of CO_2 from biogas combustion could return as much as 15-50% of algal carbon back to the algal culture, depending on the degree of algal product exportation, or waste cellulose importation to supplement the algal digestion process. In the final analysis, precise estimates of algal production and overall CO_2 utilization will require large-scale field confirmation. For the purpose of this analysis, it is sufficiently accurate to assume an overall average of 20 g-m^2/day, at an overall CO_2 utilization efficiency ranging from 60-80% with an average value of 70%. At 70% utilization efficiency, and with a 30.3 million kg-C/season (126,450 kg-C/day) CO_2 generation rate, the algal production is expected to be:

$$(126{,}450 \text{ kg-C/day})(2 \text{ g VS/g-C})(0.70) = 177{,}030 \text{ kg-VS/day} \times (240 \text{ days}) = 42.4 \text{ million kg-VS/season} \quad (3)$$

The flue-gas generation from the plant is projected (at 6% CO_2) at a total mass flow rate of ~ 322,000 kg/hr. An average algal reactor water-velocity of 0.25 m/s is assumed to be maintained in the algal culture provided by low-RPM paddle-wheels. The channel depth will be 0.3-m, providing a reactor volume of 300 L/m^2. Average algal cell age will be maintained at three days. Average sustained algal productivity is projected at 20 g VS/m^2-day, or 10 g-C/m^2-day average carbon fixation. At CO_2 utilization efficiency of 70% the required algal culture area is calculated as:

$$(176{,}030 \text{ kg-VS/day})(1000 \text{ g/kg}) \div ((20 \text{ g VS/m}^2\text{-day})(10{,}000 \text{ m}^2\text{/ha})) = 880 \text{ ha} \qquad (4)$$

The 880 ha (2,147 acres) algal production system is projected to consist of 220 four-ha high-rate ponds, this size being the largest pond currently considered feasible (Benemann et al 1980). Each pond would nominally be 64-m wide (32-m channel) by 625-m long ponds with one central baffle. This area represents the algal growth area, and does not include additional land for berms, roads, set-backs, harvesting, processing, and inoculum production systems, which would increase land requirements by 25% to approximately 1100 ha (2,717 acres) for the total system.

Microalgal Harvest and Utilization

At an average algal cell age of three days, 20 g VS/m^2 productivity would yield an expected algal standing crop of 60 g VS/m^2 or a volumetric concentration of 200 mg VS/L (at a depth of 0.30 m), and require processing of 100 L/m^2 or 880 million L/day to harvest the algal biomass. Net seasonal algal productivity is expected to average 48,000 kg/ha-season (~ 43,000 lb/acre-season) on the total water area of 880 ha for a net total biomass of 42.4 million kg/season (176,030 kg/day) at 100% harvest efficiency. As harvesting will be less than 100% efficient, a loss factor would need to be included, but that is ignored here, assuming that the stated productivity represents net harvested production. Following algal harvesting, the culture water would need to be recycled to the growth ponds, with sufficient make-up water addition to offset evaporation and seepage, typically averaging 0.5 cm/day or 5% of daily harvest volume or 44 million L/day (11.6 MGD). Such usage is no larger than expected for other crops and is, in fact, less on a water usage per productivity basis. However, because of limited water resources in the region, this flow requirement will necessitate reuse of irrigation return water, or if located close to the Salton Sea, saline water withdrawal from that body. However, salt-water culture would require supplemental water usage for "blow-down" to prevent excessive culture salinity accumulation.

Algae to be cultured will likely be either green algae (e.g., *Scenedesmus, Chlorella*) or cyanobacteria, such as *Spirulina,* which is commercially produced in the region. However, monocultures of *Spirulina* would likely yield lower productivity and oil content than green algae. A key to selecting the microalgae will be harvesting method to be used, with only three techniques currently cost-effective enough to be considered for biofuels production and GHG avoidance. These are: (1) spontaneous flocculation ("bioflocculation") followed by settling, which could be feasible for green algae species but requires further development (Benemann et al 1980), (2) filtration with screens (>30 micron openings), which is suitable for filamentous strains like *Spirulina,* but not unicellular algae and, (3) harvesting and/or consumption by filter-feeding fish or invertebrates, a technique recently developed and discussed (Brune, 2008).

Although the use of filter-feeding invertebrates would reduce dry matter recovery by approximately 50% as a result of metabolic costs (Brune 2008; Brune and Benemann 2007), invertebrate biomass production would likely provide a more consistent and higher value biomass. In addition, for oil or protein recovery, conversion to invertebrate biomass would be more reliable, less costly, and less energy intensive than physical/chemical processes required to concentrate and dry dilute algal slurries (2-4 % dry wt), typically produced by settling and screening methods. However, this design option is not further considered here as detailed system designs remain to be developed and disclosed.

MICROALGAE GHG ABATEMENT PROCESS OPTIONS

The products to be generated from the algal biomass harvested by sedimentation or screening would consist of one or a combination of products including biogas (65% CH_4 and 35% CO_2) obtained from anaerobic fermentation of either whole algal biomass or residuals remaining after algal-oil extraction for biodiesel production, and/or higher-value oil and protein as a potential animal feed replacement of soybeans. The GHG avoidance potential of these products is examined in greater detail next.

Biogas Production

Harvest of algal biomass followed by anaerobic digestion for production of methane gas remains one of the more feasible energy recovery processes. It was also the first algal energy recovery process to be studied in detail (Oswald and Golueke, 1960). Previous research has shown that effective anaerobic digestion of algal biomass is limited by the high N content in the biomass (C/N ratio of 5.5/1), which has been shown to result in inhibition of methanogenesis by ammonia. Possible methods to overcome this limitation includes removal and recovery of protein to reduce N in the residual biomass subjected to anaerobic digestion or, co-digestion of algal biomass with low N-wastes, such as animal manures, sludges, or waste paper. Previous research has shown that effective anaerobic digestion of raw algal biomass requires supplementation of the algal feedstock with additional cellulose to reduce the high nitrogen content of the algal biomass from a C/N ratio of approximately 6/1 to a ratio of 12-20/1 (Yen 2004). Yen further demonstrated that optimum anaerobic digester loading rates averaged five kg VS/m^3-day for a mix of 50% algal biomass and 50% dairy manure (dry wt. basis) or other cellulose sources (e.g., waste paper or sawdust) yielding from 1.0-1.6 m^3 methane/m^3 of reactor volume per day. In the case of co-digestion, a combined digester loading of 5 g VS/m^3-day corresponds to an algal loading of 2.5 kg algal VS/ m^3-day, leading to a required digester volume of:

$$(176{,}030 \text{ kgVS /day}) \div (2.5 \text{ kg algal VS/m}^3\text{-day}) = 70{,}412 \text{ m}^3 \text{ digester volume} \qquad (5)$$

This is twice as large as would be required to digest the algae biomass alone. Also, at 100% algal biomass fermentation, this process would require importation of 176 metric tons per day of dairy manure, sewage sludge, paper waste or other high carbon waste. This would require that the power-plant be located close to a dairy or other animal feedlot, waste treatment plant, or other suitable waste resource. Co-digestion of algal biomass with other wastes provides an additional mechanism for achieving GHG reductions. Improperly managed animal manures contribute significantly to GHG production as a result of methane releases from conventional manure handling processes and systems (USDA, 1995). Anaerobic co-digestion of animal manure with algal biomass offers a substantial improvement in local animal manure treatment, while also providing a low-cost source of nitrogen and phosphorus, required to support the algal biomass production process. Observed biogas yields at 5 kg VS/m^3-day loading rate, range from 1.0-1.6 m^3 biogas/m^3 reactor/day at 65% methane content, with a projected average yield of 1.3 m^3 biogas/m^3-day. The average daily energy yield at this level of methane production is calculated as:

$$(1.3\ m^3\ \text{biogas}/\ m^3\ \text{digester})(70{,}412\ m^3\ \text{digester})(0.65\ CH_4)(33{,}368\ \text{BTU}/m^3\ CH_4) = 1{,}985\ \text{million BTU/day} \tag{6}$$

If the methane is to be used at the power-plant as a natural gas replacement, at 40% efficiency of conversion of gas energy to electrical energy, over a 240-day operational season, the gas production is calculated to provide an energy supplement of:

$$(0.4)(1{,}985\ \text{million BTU/day})(240\ \text{days/season}) \div (3415\ \text{BTU/kWh}) = 55.8\ \text{million kWh/season} \tag{7}$$

The gross digester methane production will vary depending upon the specific blend of algal solids and waste cellulose, and is expected to range from 40-80 million kWh/season. At 216 million kWh per season projected plant electrical production (equation 1), this average energy yield corresponds to a gross reduction in natural gas requirement of 26% and therefore similar avoidance in gross GHG emissions. Net GHG avoidance would be less, as parasitic losses resulting from harvesting and processing of algal biomass and waste solids added to the fermentation process must be accounted for in the final energy yield. In the case of digestion of algal biomass residue after extraction of protein and oil, approximately 30% of the algal biomass residue would be available for gas production. This would result in a natural gas replacement of 7.8% of power-plant energy consumption assuming supplementation of the algal residual with an external organic carbon source. Operation of the anaerobic digester utilizing the 30% algal residue from oil/protein recovery with a 50/50 feedstock consisting of a mixture of algal biomass and carbonaceous waste would require supplementation with 53 metric tons/day of waste paper, municipal sludge, or animal manure to insure optimum digester performance, and to provide a low-cost source of nitrogen and phosphorus fertilization of the algal ponds. This requirement would amount to recycling manure from approximately 9,700 milk cows (USDA, 1995) or activated sludge from a municipal treatment facility serving a population of approximately 500,000 persons (Tchobanoglous et al, 2003). Transportation of animal waste or other solids would require energy input. A truck hauling 35 tons of animal manure at (at 10% solids) 160 km (100 miles) would require a diesel energy fuel equivalent of approximately 5% of gross methane energy yield from a digester fed an algal biomass and manure mixture. However, if the protein content of the algal biomass is removed from the digester feedstock (to be used as animal feed), required external organic carbon loading could be substantially reduced. The extent to which organic supplementation could be reduced cannot be predicted without field-scale digester demonstrations. Consequently, energy cost of manure transport is not factored into this current analysis.

Oswald and Golueke (1960) proposed a electrical generation plant design powered by algal-biomass derived digester gas using municipal wastewater providing make-up nutrients, water and inorganic carbon for an, essentially, recycled-carbon power-plant. Electrical generation costs were projected to compare favorably with nuclear power costs. Although their study underestimated inevitable losses of CO_2, their proposed principles and arguments remain valid, as energy costs have increased and global climate impacts have become more immediate.

Algal Oil Recovery

There is great interest in generating liquid transportation fuels from algae, specifically vegetable oils that can be converted to biodiesel. Oil recovery from algae biomass is limited by the oil content of the biomass, and feasibility and energetics of oil extraction, which presents significant challenges. As previously described, one approach (Brune 2008) would be to convert the algal biomass into aquatic invertebrate biomass with a relatively constant oil content, overcoming many of the current challenges, including algal biomass harvesting. However, for the present analysis, only conventional oil extraction and recovery technology is assumed, specifically an oil or solvent emulsion step followed by centrifugation to recover oil, residual biomass and water fraction (Benemann and Oswald 1996). Although oil (as triglycerides) content in algae as high as 50% is reported in the literature, it remains to be demonstrated that such high oil yields are achievable in sustained outdoor culture. For the purpose of this analysis, it is assumed that realistic near-term recoverable oil content is 20% (Brune and Benemann 2007). For the present case this results in a prediction of annual oil yield of:

$$(42.4 \text{ million kg-VS/season})(20\% \text{ oil}) = 8.5 \text{ million kg oil/season} \qquad (8)$$

At a specific density of 0.85, this corresponds to 10 million L oil/season (2.6 million gallons) or 11,300 L/ha (1,200 gal/acre). At 118,300 BTU/gal biodiesel energy content (NREL, 1998), this oil is equivalent to 312 billion BTU, equivalent to 91 million kWh/season of energy. This volume of algal-oil used to replace fossil transport fuel at an average conventional diesel carbon emission of 0.0683 kg-C/kWh (Table 1,U.S.-EPA 2002) is equivalent to 6.2 million kg-C/season, or a gross GHG emission avoidance equivalent to 20.3% of power-plant CO_2 emissions. Again, parasitic losses for producing, harvesting, and concentrating algal biomass, extracting algal oil and conversion to fuel oil (if needed) must be considered to provide a prediction of net GHG avoidance potential. Conversion efficiency of plant oil to biodiesel is reported to range from 80-98% (Hem, et.al., 2009). In this present analysis, the energy costs of biodiesel conversion is included in a combined parasitic loss term amounting to 14% of algae biomass production and processing energy costs (see section on parasitic energy costs). The residue after oil extraction could still be subjected to anaerobic digestion, but biogas output would be reduced by about one third (due to the removal of the 20% oil in the biomass). In such case the methane production from algal residue after oil extraction would be equivalent to ~ 17% (26% x 0.66) avoidance of gross GHG emissions.

Animal Feed Replacement

The total algal production from 880 ha of high-rate algal ponds is projected to be 42.4 million kg/season. As previously stated, average U.S. soybean dry weight production is 2,192 lb/acre or 2,461 kg/ha (Burmm et.al 2005). If the algal biomass at 50% protein and 20% oil content is used as a direct replacement for soybean meal in animal feeds, then a conventional soybean replacement area (based on 35% soy protein content) can be calculated as:

$$(42.4 \text{ million kg/season})(0.50/0.35) \div (2461 \text{ kg soybean/ha}) = 24{,}612 \text{ ha} \quad (9)$$

In other words, a land area 28 times greater would be required to produce soybean protein and oil yield equivalent to the 880 ha of algal production ponds, at the assumed 70% power-plant CO_2 utilization efficiency. As previously stated conventional soybean production results a net GHG production rate of 213 kg-C/ha-yr (781 kg CO2/ha-yr). Therefore the GHG avoidance resulting from replacement of this soybean production is calculated as:

$$(213 \text{ kg-C/ha-yr})(24{,}612 \text{ ha}) = 5.2 \text{ million kg-C/yr} \quad (10)$$

This corresponds to gross GHG avoidance of 17.3%, at 70% CO_2 utilization efficiency by the algae system. Additionally biogas production of the 30% residue would contribute an additional gross GHG avoidance of 7.8% of power-plant emissions.

Combined Production

The configuration most likely to be employed in actual practice would be a combined, integrated production of biogas, biodiesel, and animal feed replacements. In this case, algal oil used as potential fossil-fuel diesel replacement would be expected to provide a gross GHG avoidance of 20%. This extracted oil content contains approximately 50% of the combined energy content of algal protein and oil. Therefore, algal protein production, alone, is assigned a gross GHG avoidance credit of 8.5%. This is reduced from 17% for protein + oil assigned to the 100% feed replacement case. This adjustment is made to avoid "double counting" GHG credit for oil processed into biodiesel, while also assigning credit to oil used as part of animal feed replacement. In addition, anaerobic digestion of the 30% algal residues is estimated to provide a gross GHG avoidance of 7.8%. These combined values must be further reduced by parasitic energy losses to allow for estimation of net combined GHG avoidance.

CARBON DIOXIDE UTILIZATION AND PARASITIC ENERGY COSTS

The average efficiency of flue-gas CO_2 capture in algal biomass is assumed to be 70%, based on prior analysis (Benemann et al 1982; Weissman and Goebel, 1987; Benemann and Oswald 1996). The actual efficiency of flue-gas CO_2 capture in algal biomass depends on many factors, in particular, the number of sunlight hours compared to power plant operating hours. Although the power-plant will operate 18 hours/day, the daylight growth period will range from 11-14 hours/day over the season. Carbon dioxide storage in the pond growth medium is limited by water chemistry typically to 1-2 hours of production. Other factors potentially reducing CO_2 utilization include the efficiency of CO_2 transfer into the pond and out-gassing from the ponds. In terms of carbon storage and nutrient provision, recycling of digester supernatant to the ponds can provide both. Biogas CO_2 could also be scrubbed directly with the pond water, but this option is not considered here. Seasonal variations in algal productivity add to the complexity of any assessment of CO_2 capture and utilization from the power-plant. Carbon made available from recycle of biogas flue-gas, relaxes the constraint on 70% CO_2 utilization efficiency. Therefore, an overall estimate of 70% CO_2 utilization is considered a reasonable average, and unlikely to differ by more than 10% either way.

The previously calculated GHG avoidance potential considers only gross GHG estimates. Net GHG avoidance is obtained after inclusion of parasitic energy costs required to support the algal process. This consideration is critical as, for example, the case of ethanol from corn, fossil fuel usage for production of corn (fertilizers, seeds, cultivation, pesticides, harvesting, etc.) and conversion to ethanol (processing, fermentation, distillation, by-product drying) is within ±20% of input energy required to produce the ethanol output (Patzek and Pimentel 2005). Furthermore, to replace corn used in fuel production, additional land must be cultivated, leading to increased soil CO_2 and N_2O emissions. As a result, the process of conversion of corn to ethanol may represent a net contributor to greenhouse gas emissions.

Parasitic energy cost of algae biomass production and processing is considered relative to energy required to produce biogas, biodiesel or soybean feed replacements. Benemann and Oswald (1996) arrived at a parasitic energy requirement of approximately

14% of gross algal outputs consisting of, energy inputs to support the processes of; (1) flue gas delivery from the power plant to the ponds, and transfer into the culture, (2) paddle-wheel mixing of ponds to achieve a water velocity of 20-25 cm/sec, (3) harvesting of algal biomass using bioflocculation, or biological means, and recycling of water to the ponds, (4) extraction and conversion of oil from biomass and/or anaerobic digestion of the biomass/residue, (5) fertilizer supply (N, P, K.), water supply and treatment, inoculum addition, and waste treatment of potential discharges, (6) anaerobic digestion, waste treatment and ancillary energy inputs. The energy embodied in the production facilities is not considered in these estimates. While embodied energy inputs are somewhat uncertain, they are known to be relatively small compared to other energy requirements.

The energy cost involved in transporting flue-gas CO_2 to the pond and transferring the gas into solution is not trivial. This input depends on many factors, including distance between power-plant and algal ponds, and concentration of CO_2 in the flue-gas, among others. Assuming the power plant is surrounded by algal ponds, Benemann and Oswald et al (1996) estimated that compressing flue-gas to overcome piping and sparging head-losses will require approximately, 0.2 kWh/kg of algae produced.

Mixing represents another major energy input, and is most sensitive to water velocity used, as well as, paddle-wheel efficiency (hydraulic and electrical). Since mixing impacts culture productivity, mixing energy is also best expressed in terms of energy/biomass generation ratio For the present case, a value of 0.1 kWh/kg of algae biomass produced is used as representative of typical system requirements (Benemann et al 1982). With 24 hr/day mixing, this energy amounts to approximately 1 kW/ha power input.

Harvesting by sedimentation requires pumping of water and settled algal slurry. The associated energy consumption depends primarily upon area topography and depth of setting basins. Typical pumping energy requirement is observed to be approximately kWh/kg of biomass. Further separation steps are required when oil recovery is the objective. Separating oil from water, and solids requires further concentration of a nominally 3% solids algal slurry using an industrial centrifuge. Releasing oil from algal biomass requires additional techniques such as, sonic disruption or pressure disruption. The estimated energy input required for centrifugation is estimated at 0.1 kWh/kg of biomass. Processing of algal biomass for oil extraction and conversion to biodiesel is estimated to require an additional 0.05 kWh/kg of biomass.

Fertilizer, in particular nitrogen supplementation, represents a potential major energy input. The energy input requirement supporting fertilizer manufacture at 9% algal-N content could be as high as 30% of the biogas yield if waste nitrogen is not available or, if digester nitrogen is not recycled. Recycle and reuse of waste or digester nutrients is critical. A high degree (>80%) of algal/digester nutrient recycle is needed to avoid excessive energy input requirements supporting culture fertilization. The best option would be to meet nutrient requirements by combining algal production with treatment of wastes and/or wastewaters. In this analysis it is assumed that waste nutrients are available and therefore energy costs of nutrient supply are neglected. Similarly, the energy cost of the water supply is neglected; such costs are site-specific, ranging 30-fold, from negligible to substantial (Benemann and Oswald 1996) (Weissman and Goeble 1987).

While algal inoculum production (if needed) energy input is not well defined, it does not represent a significant energy input requirement relative to previously defined processes.

The anaerobic digestion process would most likely consist of plastic-lined earthen digesters, with minimal recirculation and negligible energy input requirement. The greatest energy input to anaerobic digestion would be to maintain digester temperature in the mesophilic range of 35 degrees C. However, in the case of combustion of digester-gas for power-plant energy production, it is assumed that sufficient waste heat will be available to maintain digester temperature without requiring addition energy inputs.

In summary, total parasitic energy required to produce, harvest, and concentrate algal biomass is estimated at 0.35 kWh/kg of dry algal biomass. Furthermore, if energy associated with oil extraction/processing and anaerobic digester of residual algal biomass is included, the total parasitic energy requirement is estimated at 0.50 kWh/kg. At a net algal biomass production of 42.4 million kg-VS/season, total parasitic energy costs, is estimated at:

$$(42.4 \text{ million kg-VS/season})(0.5 \text{ kWh/kg}) = 21.2 \text{ million kWh/season} \quad (11)$$

This energy amounts to an overall parasitic loss of 9.8% of total power-plant energy production and GHG avoidance, or 6.9% for digester operation and feed replacement without oil recovery. The projected gross and net GHG avoidance for methane production, animal feed replacement, and biodiesel production, as well as, combination of the three options is summarized in Table 3. At CO_2 utilization efficiencies ranging from 60-80%, the net GHG avoidance is projected to range from 22.3-29.7%, with a mid-range value of 26.3% at 70% CO_2 transfer efficiency.

Net GHG avoidance potential is shown to be most sensitive to algal-oil content and CO_2 utilization efficiency (Figure 2). The combined worse case of 60% CO_2 transfer efficiency, combined with an algal oil content of 10% suggests a net GHG avoidance potential of 13%. At the combination of 80% CO_2 transfer efficiency, with a 30% algal oil content, a 42% net GHG avoidance potential is predicted. GHG avoidance potential is not particularly sensitive to algal productivity. However, total algal culture area and associated system costs are very sensitive to net algal productivity.

SUMMARY AND CONCLUSIONS

This paper presents an analysis of the potential for GHG avoidance employing a high-rate algal biomass production system coupled to recovery and recycle of flue-gas CO_2, combined with waste sludge and/or animal manure utilization. A model is developed around a proposed 50 MW, 50% base-load, natural gas fired, electrical generation plant operating 18 hours per day over a 240-day season. This plant would produce 216 million kWh/season, releasing 30.3 million kg-C/season of fossil-fuel CO_2. An algal process designed to capture 70% of the flue-gas CO_2 would produce 42.4 million kg algal dry wt/season. This algal production would require 880 ha of high-rate algal ponds operating at a productivity of 20 g VS/m^2-day. If 100% of the algal biomass were harvested and fermented in an anaerobic digester, the resulting biogas production could be used to replace 26% of plant natural gas usage. If the 20% oil content of the algal biomass is extracted, it would yield a potential replacement transportation fuel equivalent to 20% of plant gross GHG emissions. Utilizing the entire algal biomass content as a soybean replacement could provide a 17% reduction in gross conventional crop GHG emissions. Net parasitic energy cost to harvest and process the algal biomass is estimated at 7-10% of plant total energy output, depending on specific processes used to recover and process algal biomass.

A combined, multiple-product strategy is projected to provide similar GHG benefits. The combination of 20% extractable algal-oil recovery providing a transportation fuel replacement (representing 20% gross GHG avoidance), combined with 50% algal protein recovered for animal feed replacement (representing 8.5% gross GHG avoidance), and remaining 30% of algal residue digested to produce methane (providing 7.8% gross energy replacement, and GHG avoidance) would yield a total plant gross GHG avoidance potential of 36.3%. Reducing this by an estimated parasitic energy cost of 10% required to deliver CO_2, harvest and process algal biomass and algal oils, results in a net GHG avoidance of 26.3% assuming an overall CO_2 utilization efficiency of 70%. At CO_2 utilization efficiencies ranging from 60-80% the projected net GHG avoidance potential would range from 22.3% - 29.7% respectively.

Operation of the anaerobic digester utilizing the 30% algal residue after oil/protein recovery using a 50/50 algal biomass and waste feedstock mixture would require supplementation with 53 metric tons/day of waste paper, municipal sludge, or animal manure to insure optimum digester performance and to provide a low-cost source of nitrogen and phosphorus fertilization of the algal ponds. This requirement would amount to recycling manure from approximately 9,700 milk cows or activated sludge from a municipal treatment facility serving a population of approximately 500,000 persons. Additionally, the algal reactors would require make-up water addition of approximately 44 million L/day (11.6 MGD), necessitating the reuse of irrigation return waters, wastewaters, or brackish waters.

This analysis does not address the economics of the processes considered. Rather, the focus is directed at a determination of the feasibility of applying integrated algal processes for fossil-fuel replacement and power-plant GHG avoidance. The technology discussed remains in early stages of development with many important technical issues yet to be addressed. A more detailed analysis will be required to determine if these initial conclusions will bear further scrutiny. Ultimately, pilot-scale trials and demonstrations will be needed to define the many detailed design requirements.

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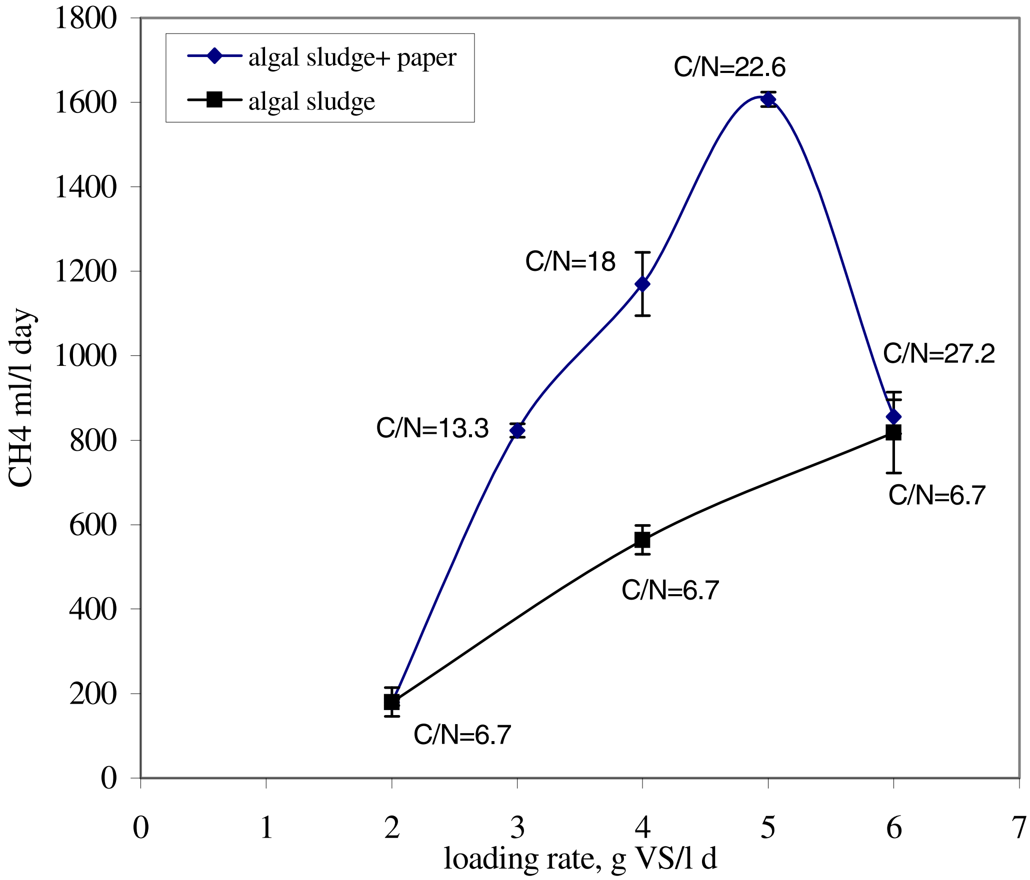
Figure 1. Methane production rate vs. loading rates in digesters fed algal slurry and blends of algal slurry and paper operating at 10 days HRT and at 35 °C (from Yen, 2004).



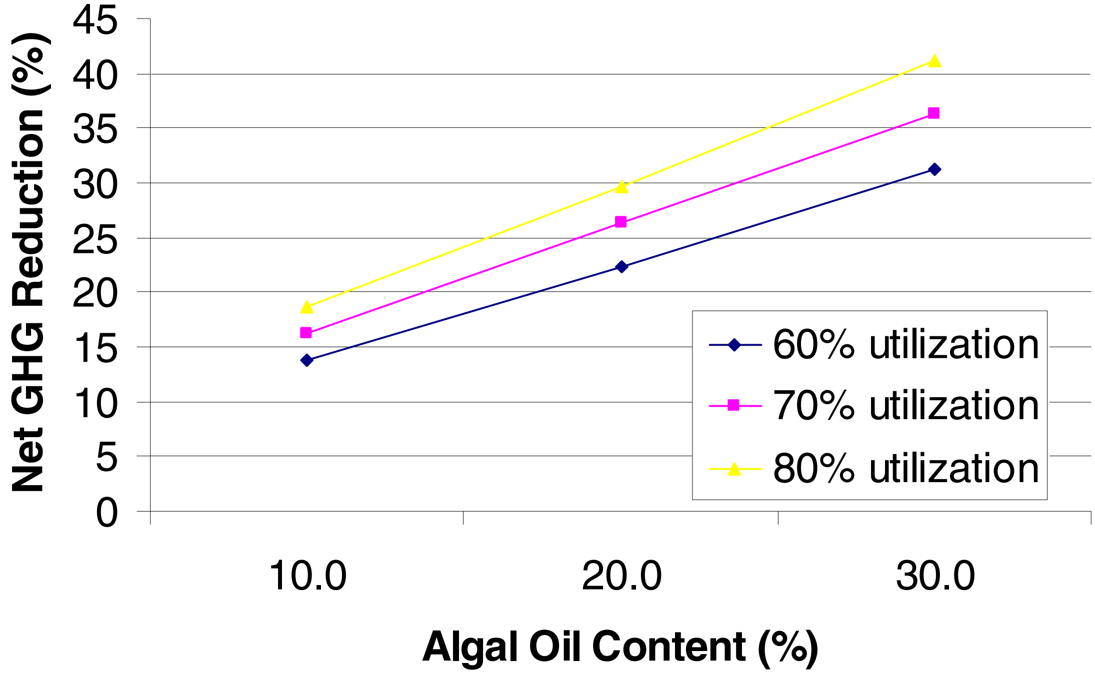


Figure 2; Sensitivity of net GHG reduction to algal oil content and CO_2 utilization efficiency.

Table 1. U.S. annual GHG emissions; Totals, fossil fuel usage and electrical production (as MMTCE, US-DOE, 2004; US-EPA, 2006).

Combined Total Emissions	**1929.0**
Land use change	(-212.8)
Net emissions	1716.6
Fossil Fuels	**1566.5**
Fossil fuel combustion	1524.7
Non energy fossil fuel usage	41.8
Net Electrical Generation	**612.2**
Coal	488.5
Gas	91.9
Petroleum	29.0
Other	2.8
Emissions from Electrical Generation by Fuel Type	
Overall U.S. average	**0.1674 kg-C/kWh**
Coal	0.2625 kg-C/kWh
Petroleum	0.2441 kg-C/kWh
Natural gas	0.1405 kg-C/kWh]
Fuel oil	0.0683 kg-C/kWh

Table 2. U.S. annual crop and animal agriculture GHG emissions (as MMTCE, US-EPA, 2006).

Net Agricultural Emissions	**155.6**
Cropland production	**92.8**
Energy use	30.3
Soil N_2O	64.2
Soil Carbon	(-4.1)
Other croplands	2.4
Livestock production	**62.8**
Enteric fermentation	31.3
Manure CH_4	10.6
Manure N_2O	20.9

Table 3. Projected power-plant GHG avoidance using algal biomass for natural gas replacement, biodiesel production, animal feed replacement, or combination of all three.

	Gross GHG Avoidance (%)	**Parasitic Loss (%)**	**Net GHG Avoidance (%)**
CO2 Utilization (%)	*70%*		*60% 70% 80%*
Algal Product			
Biogas methane[1]	26.0	7	13.7 – 16.0 – 18.3
Soybean Feed Replacement[2]	17.0	7	8.6 – 10.0 - 11.4
Biodiesel[3]	20.0	10	8.6 – 10.0 -11.4
Combination			
Methane	7.8		
Soybean Protein	8.5		
Biodiesel	20.0		
Total (@ 70%)	36.3	10	22.3 – 26.3 – 29.7

1) As power-plant natural gas replacement
2) Soy GHG potential; 33% energy and 66% N_2O emissions
3) As a transport fuel replacement