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ALGACULTURE AS A FEEDSTOCK SOURCE FOR BIODIESEL FUEL – A LIFE CYCLE ANALYSIS

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ABSTRACT

This research investigates algae as a feedstock for producing liquid fuels for the light vehicle sector. It is in the interest of national economic security to investigate alternative sources of transportation energy before the extraction of existing supplies becomes prohibitively expensive. Biofuels are one such alternative liquid fuel supply. The research used the Life Cycle Analysis (LCA) approach for evaluating the production of biodiesel fuel from algae as a feedstock, including processes for growing algae in conventional and accelerated processes in bioreactors. An energy return on investment and comparison with conventional fuels (gasoline, diesel fuel) on an LCA basis and on a resource consumption basis (e.g., land, water, feedstock) is also presented.

The results are reported for required land use, water use, input-to-output energy ratio, and carbon emissions for algacultural biodiesel fuel. From the present study it appears that algae-derived biodiesel fuel requires significantly less land, water and energy than do all other biodiesel fuels. It would appear prudent for the US to vigorously pursue this option since a significant fraction of US light vehicle fuel needs can be addressed.

INTRODUCTION

Our civilization has increasingly come to rely on energy. Everything from transportation to commerce to food supply is heavily dependent on the availability of cheap and plentiful energy supplies. In the past few years, however, many have realized that energy is a finite resource and that the traditional sources of energy – specifically oil and gas – are in limited supply and that we need to prepare for the approaching production maxima. Indeed, in the United States both the proven oil reserves and the annual oil production peaked a couple of decades ago (Figure 1) and we now importing more than half our oil.

It is obviously in the interest of national economic security to investigate alternative sources of energy before the extraction of existing supplies becomes prohibitively expensive. This report investigates the potential of algae-based biodiesel fuel and ethanol production. The concentration in the current study is on transportation needs, although it is recognized that building space conditioning and electricity consumption are also significant demands for energy.

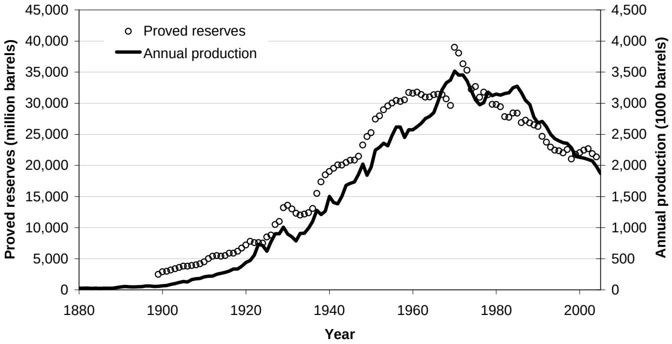

FIGURE 1 HISTORIC OIL RESERVES AND PRODUCTION[1]

Starting in 1978 and continuing for almost 20 years, the National Renewable Energy Laboratory was funded (through the DOE Office of Fuels Development) to research the potential of oil-rich algae for the purpose of removing carbon dioxide from the gaseous effluent of coal-fired power plants. This research concentrated on high lipid-content algae grown in ponds that used waste carbon dioxide from coal fired power plants to enhance the growth rates.[2]

A number of companies performed parallel work in this area. It soon became clear that a proper type of algae would grow whether or not the carbon dioxide used for fertilization was chemically pure or if it was from power plant exhaust gases. It was also observed that the nitrous oxide and sulfur dioxide in the stack's exhaust also could be used to assist in the algae growth. Researchers soon realized that the high oil content of the algae (in some cases over 50 percent) implied that the plants could also be used for producing large quantities of biofuels, notably biodiesel fuel. The rapid growth rates of the algae also supported the idea of harvesting the algae for biodiesel fuel.

It is illustrative at this point to compare the "traditional" biofuel crops to algae. Corn, soybeans, switchgrass, sunflower, rapeseed, and palm oil have all been cited as potential fuel crops. Earlier research has shown that starch and cellulosic ethanol production can achieve yields on the order of 300 to 500 gallons per acre, while biodiesel fuel from standard crops is about 50 to 100 gallons per acre, increasing to perhaps 600 gallons per acre for exotic tropical oils. There are, however, significant problems associated with these yields and the production methods. First and foremost, it is impossible to plant sufficient crops on domestic cropland to satisfy all U.S. transportation energy needs. Even if it were possible, the planting, harvesting, fertilizer, and refining energy inputs are approximately equal – at best slightly less – than the energy inherent in the resulting fuels. Other issues such as large use of petroleum for agriculture and transport machinery, irrigation requirements, land use, and a reliance on monoculture make the use of fuel crops a questionable endeavor at best.

Another serious problem with fuel crops that is rarely considered is the timing of production. At best it may be possible to achieve three harvests a year of corn, soybeans, or palm, while in practice only one or two harvests is realistic. The implication here is that the feedstock arrives at the refineries in large batches that must be securely stored while it is slowly turned into fuels. Likewise, enough fuels must be produced and stored to cover the periods during crop growth. Any perturbation of this process, whether accidental, weather related, or malicious, could cause serious shortages in the fuel supply, not to mention the food supply.

Finally, there is the issue of habitat destruction that accompanies the growing and harvesting of palm oils and sugar cane, particularly in Southeast Asia and South America. In many locations the rainforest and native population are suffering or being lost completely to the significant agricultural pressures being placed on the available land. Should biofuel crop production become more profitable, it is expected that the amount of land taken for agriculture would accelerate. Significant one-time CO_2 emissions from conversion of forests to agricultural crop lands are not included herein.

GROWING AND HARVESTING ALGAE

The process of producing fuels from algae is relatively straightforward. Figure 2 shows the basic process. Algae is grown in an open or closed container such as a pond or a controlled environment. The growth can be promoted by the introduction of carbon dioxide or can rely on the natural presence of carbon dioxide. The algae is then skimmed off or otherwise removed from the growth tank. Next, oils are then removed by any number of methods. The remaining "waste" algae can be used for fertilizer or it can be brewed to produce ethanol using the same method as other fuel crops.

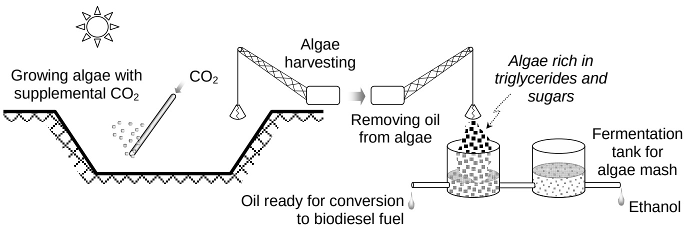

FIGURE 2 PROCESS FOR MAKING FUEL FROM ALGAE

The original NREL (then SERI) algae research (the Aquatic Species Program) concentrated on the use of algae "farms" in sunny, arid areas using shallow saltwater ponds as the growing chambers. This research indicated a possible yield of slightly more than 15,000 gallons of biodiesel fuel produced per acre of desert land.[3] This is at least two orders of magnitude greater than the closest traditional crop competitor. Indeed, as the executive summary of the NREL report states

> *These analyses indicate that significant potential land, water and CO_2 resources exist to support this technology. Algal biodiesel fuel could easily supply several "quads" of biodiesel—substantially more than existing oilseed crops could provide. Microalgae systems use far less water than traditional oilseed crops…Two hundred thousand hectares (less than 0.1% of climatically suitable land areas in the U.S.) could produce one quad of fuel.*

In other words, the original studies concluded that the technology is indeed feasible and in fact could "easily" provide several quads of biodiesel fuel. Considering that the annual transportation energy use of the U.S. is around 20 quads per year[4], the use of algae could play a very meaningful role in supplementing the domestic energy demands. It is also noteworthy that the NREL report – written in July 1998 – indicates that the "*project costs for biodiesel…are two times higher than current petroleum diesel fuel costs.*" If we examine this recent historic on-highway diesel prices as compiled by the Energy Information Agency (see Figure 3) it is clear that this doubling of prices has already occurred since the writing of the original report.

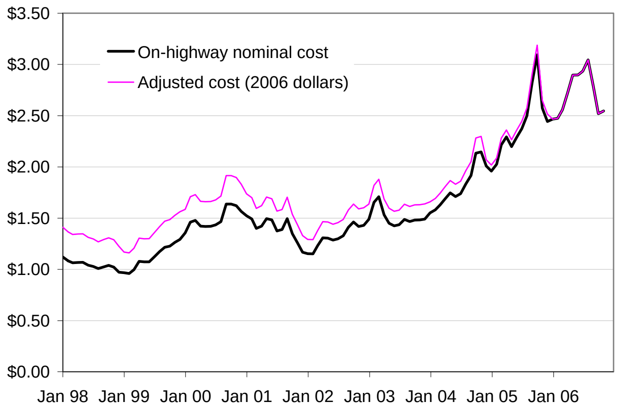

FIGURE 3 INCREASES IN ON-HIGHWAY DIESEL COSTS[5]

It is likely that the costs for algae production of fuels will decrease as the technology matures and as yields increase and uses are found for the waste products. According to studies performed at the University of New Hampshire, algae farms could conceivably use any number of waste streams, including human and animal sources, and thus promote the use of algae around the country. Manufacturing nitrogen- and phosphorous-rich fertilizer from the algae products is an efficient way of recycling the nutrients used in the food cycle and is safer than spreading manure or wastewater bio-solids.[6]

Potential algae species

Current research into algae for oil production of oil is focusing mainly on microalgae (as compared with macroalgae such as common seaweed). Microalgae are small photosynthetic plants generally less than about a tenth of an inch in diameter and include such organisms as diatoms and cyanobacteria. Microalgae have relatively simple structures and grow rapidly. Some species have a high oil content – these are obviously the ones of interest. Ideally, the chosen algae would thrive in environments that can accommodate carbon-rich gases and/or sewage so that the approach not only provides the raw materials for the system, such as CO_2 and nutrients; but it changes those wastes into resources.

The oils in microalgae come from the lipids and fatty acids in the cell membranes. Diatoms and cyanobacteria contain high levels of lipids (over 30 percent), greater than most other kinds of algae. The lipid concentration in algae typically increases when the algae in stressed, for example when it is growth in the absence of food and nutrients.

Chlorophyceae and *Bacilliarophy* algae were used by NREL in their original study. *Chlorophyceae* is green algae, needs nitrogen to grow, and tends to produce starches rather than lipids. *Bacilliarophy* is a diatom algae that needs silicon in the water to grow. When stressed through nutrient deficiency, these algae produce more oils but also do not grow as fast. Another problem is that certain green algae strains are very tolerant to temperature fluctuations but diatoms have a fairly narrow temperature range.[7]

There is now fierce competition to identify proper strains of algae that have high oil content and temperature tolerance. Already there have been patents filed, such as (1) one for a variety of the green alga *Botryococcus* that has a prodigious quantity and quality of produced fuels, (2) for the processes used, such as one for the production of bio-derived hydrocarbon chains of new algae strains and (3) the process that accelerates hydrocarbon production.[8]

Open pond farming

The original studies considered only the use of open ponds for growing algae. Algae need sunlight, nutrients (e.g., carbon dioxide), and water to grow, so open pond cultivation is a simple way to get all three of these components to the algae. However, without some form of subsurface injection of carbon dioxide the algae may grow slowly. Open pond algae growth may also be hampered if the ponds are too deep or too murky and only the algae on the surface is exposed to sufficient sunlight.

It has been suggested that power plant flue emissions would be a good source of carbon dioxide for algaculture. It is important to remember that the algae do not grow at night and that they grow faster in the summer than in the winter due to higher temperatures. For these reasons it has been estimated that a direct pumping of power plant gases to open pond algae farms would lead to only about 30 percent of the carbon dioxide being absorbed, with the remainder still going into the atmosphere.

Land use

While initially considered the easiest and therefore most likely method of algae farming, open ponds have largely been abandoned for the purpose of growing algae with high oil content for the purpose of fuel production. The Aquatic Species Program focused on such ponds and categorized hundreds of species and strains according to their ability to withstand temperature swings, water acidity, and competition from other water organisms. But, it was precisely these complications that led researchers away from the open ponds.

And yet there may be practical uses for uses open pond algae sources, particularly if the main goal is not necessarily to produce fuels. In 2006, a company in New Zealand announced it had produced its first sample of bio-diesel fuel from algae in sewage ponds. This was one of the first instances of commercial production of biodiesel fuel from "wild" algae outside the laboratory. The company predicts they can produce at least one million liters of the fuel each year, although to date the algae-derived fuel has only been tested under controlled conditions with specially grown algae crops.[9]

In any case, it is interesting to examine the land use devoted to algae production required to satisfy specific fractions of the U.S. transportation energy needs. To estimate this, we first need to understand the potential yields. For a properly-maintained open pond, the rate at which algae is produced is taken to be 2 pounds per square foot per year. It is also assumed that it takes about 15 pounds of harvested algae to produce one gallon of oil. The equivalent yield comparable to fuel crops is

$$2\,\frac{\text{lb}}{\text{ft}^2}\times\frac{1\text{ gal}}{15\text{ lb}}\times 43{,}560\,\frac{\text{ft}^2}{\text{acre}}\approx 5800\text{ gallons / acre / year.}$$

Note that this is almost 100 times the best practical yield of 60 gallons per acre from soybeans. At this yield, an algae cultivation area equal to one percent of the active cropland in the U.S. could produce about 12 percent of annual U.S. automotive energy needs. Of course, it would be impractical and unnecessary to devote farm land to algae growth; indeed it would be possible to use normally unproductive desert land for this purpose. It is illustrative to show different fractions of energy production compared to the land area of the United States. Figure 4 shows the relative size of land required to satisfy 10, 25, and 50 percent of the U.S. energy needs compared to the size of the entire country.

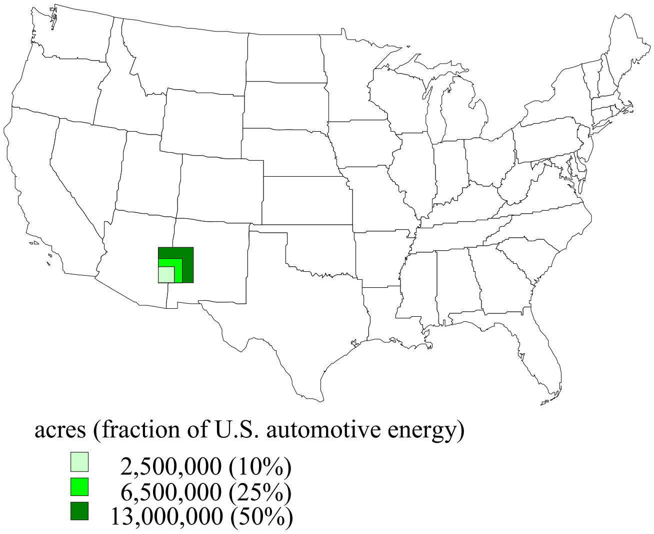

FIGURE 4 OPEN POND SPACE LAND USE FOR VARIOUS ENERGY NEED REQUIREMENTS

Water use

Evaporative water loss may be the biggest issue with open ponds. This effect is compounded if the algae farms are located in desert areas, characterized by high temperatures and sunlight but also by low humidity and correspondingly high evaporation rates. Taking a typical U.S. evaporation rate of about 0.2 inches per day gives an annual evaporation of 73 inches. In other words, the evaporation rate from the ponds is about six cubic feet per square foot of pond area. Adding another 20 percent to account for the water consumed by the algae during photosynthesis and the water lost during the harvesting process gives a total of about seven cubic feet of make-up water required per square foot of pond area, or again to put it in agricultural terms, 7 acre-feet of water per acre of open pond. This is about three to four times *greater* than typical irrigation rates for fuel crops, although the water is required over a much smaller land area. Using the examples from Figure 4 it is calculated that growing enough algae to satisfy 25 percent of the U.S. automotive energy needs would require about 45 million acre-feet of water. This is roughly similar to the water requirements to grow enough corn for ethanol to satisfy a similar percentage of US liquid fuel demands.

Energy use

It is difficult to estimate energy costs for open pond systems due to the lack of operating facilities. The original Aquatic Species Program cites the values of 10,730 kWh per ha for the power mixing, presumably referring to paddle wheels operating to keep the pond raceways in motion. They also cite 7,500 kWh per ha for harvesting and 8,750 kWh per ha for the water supply, apparently for the pumping of the make-up water. Finally, they categorize 1,652 kWh per ha as "other", likely related to issues involving transportation, moving the power plant flue gas to the ponds, etc. The total is then 28,632 kWh per ha, or about 11,600 kWh per acre. Comparing to the energy in the resulting fuel gives an energy input-to-output ratio of

$$\frac{11{,}600\,\dfrac{\text{kWh}}{\text{acre}}\times 3412\,\dfrac{\text{BTU}}{\text{kWh}}}{5800\,\dfrac{\text{gal}}{\text{acre}}\times 130{,}000\,\dfrac{\text{BTU}}{\text{gal}}}\approx 0.05$$

This number does not take into account refining or transportation energy, but it still remarkably low compared to other fuel crops.

Bioreactor farming

As an alternative to open pond growth, algae can be grown in controlled, closed environments called *photobioreactors* or simply *bioreactors*. The initial costs of bioreactors is considerably higher, but the better control of temperatures, sunlight penetration, and nutrient injection can lead to much higher yields which can, in turn, more than compensate for the higher cost. Bioreactors can also be configured to be continuously harvested to provide a constant supply of feedstock for oil production.

GreenFuel Technology has several operating bioreactors in the United States, an example of which is shown in Figure 5. In such a reactor, gas streams rich in carbon dioxide are fed to the bioreactor. Algae are suspended in a medium while nutrients are added to optimize the growth rate. Some of the media is continuously withdrawn from the bioreactor for dewatering and algae harvesting. Water removed during the dewatering steps is returned to the bioreactor. [10]

FIGURE 5 EXAMPLE OF BIOREACTOR

(courtesy of msnbc.com)

The GreenFuel bioreactors use flue gas from power plants (or any combustion process) to provide carbon to the algae. This, along with heat, light, and nutrients mixed in a controlled environment, produces the algae biomass (i.e., starches or glycerins) that can be converted into either ethanol or biodiesel fuel through standard fermentation or esterization processes developed for conventional fuel crops. GreenFuel has pilot projects at the 20 MW power plant at MIT in Cambridge and the 1060 MW combined-cycle Redhawk natural gas power plant in Arizona.

The initial tests at the Redhawk plant showed an average biomass production of 98 grams per day per square meter of bioreactor area, with a peak production of 174 grams per day.[11] This yield is equivalent to approximately 320,000 pounds of raw feedstock per year per acre. Compare this with corn, assuming a corn yield of 150 bushels per acre per year. At 56 pounds per bushel of shelled corn this is about 8400 pounds of feedstock per year, or about 40 times less raw feedstock by weight per acre than algae. The difference is even more extreme compared to soybeans. At a national average soybean yield of around 40 bushels per acre and 60 pounds per bushel, algae produces annually about 130 times more feedstock than soybeans per acre.

These high yields, however, come with a price. GreenFuel has recently had trouble with some of their pilot projects where the algae grew faster than expected. It consequently could not be harvested fast enough and the algae density limited light and nutrient supply, causing a shutdown of the project.[12]

In July 2007, GreenFuels began delivering equipment to the Sunflower Integrated Bioenergy Center in Holcomb, Kansas to begin on-site testing of converting coal flue gas to biofuels. This project will be used, in part, to test which strains of algae work best in the climate of western Kansas.[13]

A combination of the open pond and bioreactor technique is being developed by Solix Bioenergy of Boulder, Colorado. The Solix plan is to use large, sealed pools of algae that are about 20 feet wide and about a foot deep. They expect to have hundreds of these ponds – perhaps encompassing several square miles – using exhaust gas from coal-fired power plants. Solix is currently looking at twenty different species of algae that would be supported in such an arrangement. The yield estimates are between a gallon and two gallons of fuel per square meter per year in addition to carbohydrates and proteins that could be converted to fuel or feed.[14]

Over the next two years, Solix plans to commercialize the technology and to offer biodiesel fuel at competitive costs. They expect to produce a hundred times more oil per acre than conventional fuel crops and have a test program in place with the a brewery in Fort Collins, Colorado.[15]

Also in late 2006, Greenshift Corporation in New Jersey licensed a technology for using algae to consume carbon dioxide using a screen-like algal filter. The prototype can handle about 5000 cubic feet per minute of flue gas, an amount equal to the exhaust from 50 cars or a 3 MW power plant.[16]

Researchers at the University of Minnesota are investigating the potential for growing algae in specialized bioreactors. This line of study is concentrating on finding the right strains of algae and how to most efficiently extract the oil from the algae. The goal of the research is to find the combination of processes to get the ultimate algae oils below $2 per gallon.[17]

Land use

The land use of bioreactors is expected to rival that of conventional oil drilling system in terms of energy yield per area of land. Admittedly there is not much information regarding the long-term performance of bioreactors, however; therefore, land-use estimates must rely on manufacturer's claims for now.

A yield of 100 grams of dried algae per day per square meter of collector can be expected to produce an estimated 12,800 gallons of ethanol, 10,000 gallons of biodiesel fuel, and 3.2 tons of glycerin per acre per year. However, the current pilot projects are at about 60 percent of these values, making them similar to the open pond yields. These numbers are for a sunny environment like Arizona; in a cloudy environment the yields may be 2/3 of the numbers cited above.

In the worst case scenario, the bioreactors produce approximately the same quantity of algae as the open pond techniques. If the future yield predictions are accurate then a 30 to 40 percent reduction of land area per gallon of biodiesel fuel might be expected.

Water use

The main advantage of the bioreactor method is the significant reduction of water use, primarily since evaporation is no longer a real issue. Bioreactors can use treated wastewater and do not require significant inputs of fresh water. A nitrogen fertilizer is added during commissioning of the system and does not require significant refertilization since nitrogen is recirculated in the closed process.

The water inputs are restricted to the section of the system that is open to the environment. This is about ten percent of the whole process and is limited to the evaporation rate in the ambient environment. That is, the water use per acre would be calculated as the evaporation losses in one-tenth of an acre.[18] Under these circumstances, to grow enough algae to provide for approximately 25 percent of the transportation energy needs of the United States would require annual water contributions of four to five million acre-feet. This amount of "irrigation" could easily be supplied by ambient rainfall even in partially arid regions.

Energy use

The optimal algae-growing light levels are on the order of about 10 percent of the available sunlight; as a result bioreactors using natural insolation should work even in relatively overcast regions and there should be no need for artificial lighting.

The current energy input to the GreenFuel process is about 10 percent of the caloric value of the algae produced. The input energy comes from the heat (typically waste heat from the power plant) and from the blower energy used to percolate the flue gas through the algae growing chambers.[19]

The bioreactor energy input is apparently similar or less than that of the open pond techniques, and is extremely low for any fuel crop.

FUEL EXTRACTION FROM ALGAE

Economical extraction of fuels from algae is a key part of whether of not the entire process can be considered beneficial. The costs are related to (1) the collection of raw algae from the growing container, (2) extracting the oil from the wet or dry algae, and (3) any secondary fuel processing (e.g., biodiesel fuel and ethanol from the remaining product).

Once the algae biomass has been produced, conventional techniques are employed to produce fuels. These techniques are currently used to process other biocrops. For example, most biodiesel fuel is refined using a transesterification process that converts soy beans and rapeseed. Likewise, most bioethanol is made from the fermentation of corn sugars. Similar methods work equally well on dewatered algae. In fact, many different processes can be used to convert algae biomass into a number of useful fuel products.

Production of biodiesel fuel

Some of the methods used for separating the oil from algae are similar to those used for extracting oil from seeds[20].

Pressure
A standard oil expeller can be used to squeeze oil from dried algae. This is similar to how many vegetable oil produces use a combination of mechanical pressing and chemical solvents to remove oil from seeds. This method can extract three-quarters of the oils from the algae.

Solvent
Algal oil can also be extracted using chemicals such as benzene, ether, and hexane. Hexane extraction can be used by itself or in subsequent application after an expeller. In the latter, the pulp remaining after pressing is mixed with cyclohexane which dissolves and absorbs any remaining oil. The pulp is then filtered out from the solution and the oil and cyclohexane are separated by means of distillation. The combination of pressing and hexane solvent are typically able to remove more than 95% of the total oil present in algae.

Supercritical carbon dioxide
In this process, carbon dioxide is liquefied under pressure and then heated to a supercritical fluid. The result is a powerful solvent that can extract practically all of the oil present in the algae. This method requires pressure vessels and extraction equipment capable of withstanding these conditions.

Enzymatic extraction
It is possible to use enzymes to break down cell walls of the algae. In this technique, water is the solvent and allows for easy removal of the oil.[21]

Osmotic shock / ultrasonic extraction
These two methods are used to rupture cell walls of algae. The resulting "explosion" of the cell releases the components such as oils and sugars without the need for enzymatic decomposition of the cell wall. Osmotic shock relies on a sudden reduction in osmotic pressure that causes the cells in a solution to rupture. Ultrasonic extraction uses ultrasonic waves to create cavitation bubbles in the solution. Algae cell walls then break apart when bubbles collapse in the vicinity of the cell.

Once the oils from cells are available, they are collected and refined into biodiesel fuel. In the transesterification process, oils react with methanol using potassium hydroxide as a catalyst. Methanol replaces glycerin in the oils so that biodiesel fuel and glycerins are produced. The energy required for the processing stage of the production of biodiesel fuel – this includes all refining actions – is around five to one[22], that is, one unit of refining energy is required for every five units of energy output in the resulting fuel. This is at least twice as much as the estimated 20:1 to 10:1 energy balance for the production of the raw algae biomass.

Overall, biodiesel fuel from algae has a far superior energy balance than from any other fuel crop, and is even more attractive if combined with ethanol production.

POTENTIAL OF ALGAE FOR AUTOMOTIVE FUELS

The open pond and bioreactor techniques discussed earlier assume that carbon-rich power plant flue gas is used for supplementing the growth of algae. One claim is that a 1 GW power plant could produce in the neighborhood of 40 million gallons of biodiesel fuel each year using a 2,000-acre farm of algae bioreactors and that there are perhaps a thousand power plants nationwide with sufficient extra land to construct farms of several hundred to a few thousand acres in size.[23]

How worthwhile is this claim? To verify the numbers it is necessary to investigate the ability of coal power plants in the United States to act as potential suppliers of carbon dioxide to bioreactors. The US Energy Information Administration provides information in their generator-level database that includes specific information about generators in electric power plants owned and operated by both utilities and nonutilities.[24]

Using this database it is possible to calculate the total power production of all operational coal-fired power plants by state (see Figure 6). For the purpose of this study we did not distinguish between the types of coal burned by each generator; instead it was assumed that on average combusted coal has a 60 percent carbon content and that this carbon would be available to the algae farms. Admittedly this is a simplification, but the point of this work is to identify just how much algae could be produced using the existing effluent of carbon power plants (and, of course, how much of this could be converted into biodiesel fuel).

To calculate the gaseous carbon produced by coal incineration, we use the total rated capacity of operational coal power plants in each state to determined the annual energy input,

$$\dot{Q}_{in} = \frac{C_{rated} \times 8760 \times f_{full}}{1000 \times \eta} \text{ in GWh/yr}$$

where C_{rated} is the average of the summer and winter state-wide capacities (in MW), f_{full} represents the equivalent fraction of time the plant is operating at full capacity (set to 50 percent), and η is the state-wide average plant conversion efficiency, assumed to be 35 percent. The result of this equation gives the annual energy input to all coal plants in the state in GWh per year. The amount of carbon in the coal that supplies this input energy is calculated as

$$\dot{m}_{carbon} = \frac{\dot{Q}_{in} \times 3.412 \times f_{carbon}}{1000 \times Q_{coal}} \text{ in } 10^6 \text{ tons of carbon / year}$$

where f_{carbon} is the fraction of the coal that is carbon (assumed to be 60 percent) and Q_{coal} is the energy capacity of the coal (taken as 20 MMBTU per ton). The constant 3.412 converts GWh to MMBTU. The equation result is the total mass of carbon that enters the power plant in the fuel and it is assumed that carbon is available in the flue gas.

Carbon in flue gas is used by algae during photosynthesis and is present in oils produced from algae. As mentioned above, the available solar input also affects the amount of algae that can be grown in a bioreactor. The normalized yield for algae growth was adjusted by state according to the annual average insolation numbers (see Figure 7). Note the mismatch between the sunniest states and those with significant coal-fired power production in Figure 6.

Algae use carbon to synthesize carbohydrates, amino acids, sugars, lipids, and a host of other compounds. The amount of algae that can be supported by available carbon is a function of the species of algae, other available nutrients, sunlight, etc. This is a difficult number to pin down. In this study a mass ratio *MR* of 1 pound carbon per pound of algae is used. Some original estimates for open pond farms give numbers higher than this, but it is assumed that the closed bioreactors will provide greater exposure and efficiency of carbon utilization. The mass of algae that is supported by the available carbon is then calculated as

$$\dot{m}_{algae} = \frac{\dot{m}_{carbon} \times f_{yield} \times 10^6}{MR} \text{ in tons of algae per year}$$

were f_{yield} is the yield ratio given in Figure 7.

The last step is the conversion of algae to biodiesel fuel. The amount of raw biomass required per gallon of final fuel depends on the types of algae used, the extraction methods, etc. Figure 8 shows potential yields based on existing coal plants in the United States accounting for different values of carbon requirements and different amounts of algae fuel stocks.

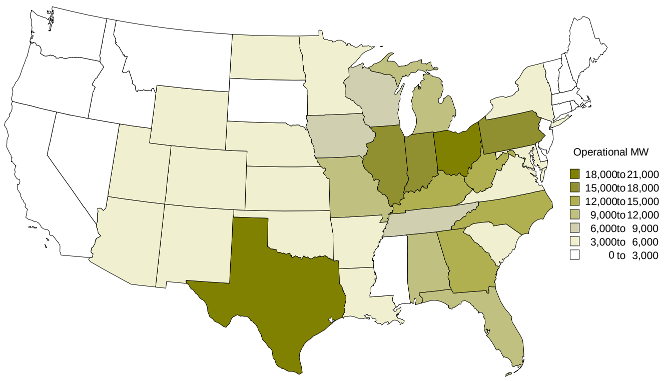

FIGURE 6 ELECTRIC GENERATION CAPACITY FOR OPERATIONAL POWER PLANTS

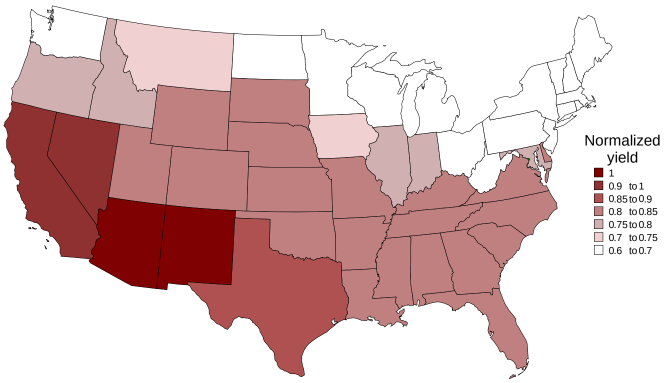

FIGURE 7 ASSUMED ADJUSTED NORMALIZED ALGAE YIELDS BASED ON AVAILABLE SUNLIGHT

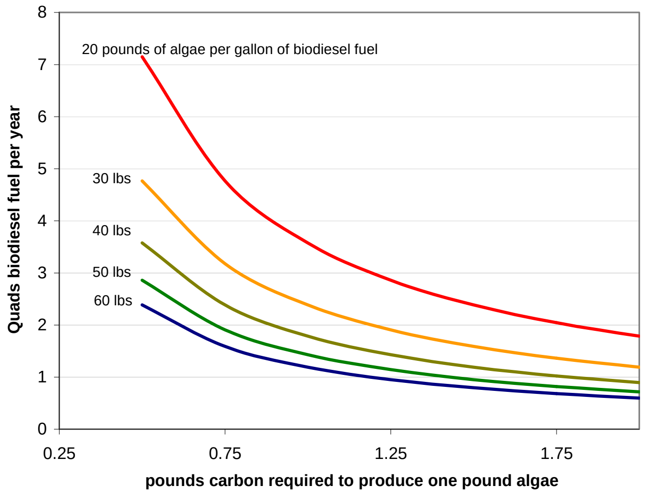

FIGURE 8 POTENTIAL ANNUAL YIELDS OF BIODIESEL ENERGY UNDER DIFFERENT SCENARIOS

We can now return to the previous claim, specifically that a 1 GW power plant could produce 40 million gallons of biodiesel fuel each year using a 2,000-acre farm of algae bioreactors and that a thousand power plants nationwide have sufficient extra land to construct farms of several hundred to a few thousand acres in size. From the previous equations, a 1 GW plant produces about 1.3 millions tons of atmospheric carbon each year. This would imply a potential annual algae yield of just over one million tons using a yield ratio of 0.8, considered an average value for the United States. At 50 pounds of algae per gallon of diesel, the algae could be converted to 41 million gallons of biodiesel fuel, a value very similar to that in the original claim. If we further assume that each of the power plants has, on average, a thousand acres that could be devoted to bioreactors, the annual energy production would be

$$\begin{aligned} &1000\ \textit{power plants} \times 20\ \textit{million gallons} \\ \times\ &130{,}000\ \textit{BTU / gal} \approx 2.6 \text{ quads per year} \end{aligned}$$

Admittedly this is a very approximate calculation, but it matches both the order of magnitude and the overall values in Figure 8.

The production of biodiesel fuel also naturally allows for the production of ethanol and in perhaps greater quantities than the biodiesel fuel. However, the biggest benefit of biodiesel fuel is that the same engines that run on conventional petroleum diesel can run on biodiesel.

> *As biodiesel production continues to ramp up, it can go into the same fuel distribution infrastructure, just replacing petroleum diesel either wholly…or blended in with diesel. Not only does this eliminate the chicken-and-egg problem, making biodiesel a much more feasible alternative than hydrogen, but also eliminates the huge cost of revamping the nationwide fuel distribution infrastructure.*[25]

While the above statement is also partially true for ethanol as it may be used in flex-fuel vehicles, there are problems contingent with the transportation and dispensing of ethanol that may act as a significant initial impediment for this fuel.

Carbon reduction

Finally, it is important to remember that the initial research into algae was not as a fuel source but rather as a method for removing carbon from power plant flue gases. The implication here is that the use of algae for fuel production could also help “short circuit” the carbon cycle by removing CO_2 from stacks, albeit for later emission from automobiles. While this may not seem an improvement at first glance, the overall reduction of greenhouse gases from power plants carries great potential, particularly in light of the reality that the automotive emissions would occur anyway. In describing the MIT demonstration bioreactor, one article points out that

> *…the algae grow quickly even in the wan rays of a New England sun. The cleansed exhaust bubbles skyward, but with 40 percent less CO2 (a larger cut than the Kyoto treaty mandates) and another bonus: 86 percent less nitrous oxide.*[26]

In preliminary tests at the Redhawk power plant in Arizona, specially designed pipes captured and transported the CO_2-rich effluent gases into bioreactors. It is estimated that the production of algae through this process can absorb as much as 80 percent of the CO_2 emissions during the daytime at a natural gas fired power plant.[27] Actual monitored values from this plant showed that the algae was able to absorb between 260 and 450 tons of carbon dioxide per acre of bioreactors.[28]

CONCLUSIONS

Compared to conventional biofuel crops, algae shows tremendous promise in terms of the overall energy balance, fuel use, and water use. Using a technology originally developed for carbon reduction from power plants, algae biofuels also could be beneficial to the reduction of global warming. Using existing available land and power plants, algaculture could potentially supplement an impressively large fraction of automotive energy needs in the United States, perhaps ten to fifteen percent with current technology. As both bioreactor and refineries methods mature, it seems plausible to have fuels from algae reaching and perhaps exceeding fully half of the domestic transportation energy requirements.

Table 1 shows a comparison of the impacts of algae versus those of conventional fuels. The land use is certainly high, although still a small fraction of that used to produce ethanol from other biofuels. The area where algae really makes a difference is in the reduction of carbon emissions. While biodiesel fuel made from algae would of course have carbon emissions from the driving cycle, the double use of the waste carbon makes algae-based fuels an interesting potential replacement for conventional fuels.

TABLE 1 SUMMARY OF IMPACTS OF FUELS

	Land use	**Water use (gallons)**		**Energy ratio**	**CO_2 emissions**[a]
Fuel source	**Acres**	**per gallon of fuel**	**per MMBTU of fuel**	**BTU input per BTU of fuel**	**lb per MMBTU of fuel**
Conventional gasoline	Tens of thousands	5	45	0.05	175
Conventional diesel	Tens of thousands	10	80	0.09	175
Algaculture	~10 million	50	400	0.2	absorbs CO_2 from power plant

[a] includes driving cycle; carbon emissions are calculated from the chemical composition of various fuels and the appropriate stoichiometric combustion equations with the consumption of CO_2 by photosynthesis (for biofuels) not included so that all fuels are compared on an equivalent basis.

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