USING ALGAE TO CAPTURE CO_2 AND AS A FEEDSTOCK FOR BIOFUEL

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ABSTRACT

Using Algae to Capture CO_2 and as a Feedstock for Biodiesel Fuel

Brad Archbold

World economies require a continuous, inexpensive source of hydrocarbons to power their transportation systems. The fuel of choice is oil, a fuel of finite supply. As the demand for oil increases and/or supply disruptions occur, the acute rise in prices will have extremely detrimental effects on oil-dependent economies. Another negative effect of relying on oil as a fuel source is the release of CO_2 during combustion. CO_2 is a major greenhouse gas and its effect on global climate is of worldwide concern.

There is a need for a new fuel source not based on hydrocarbons, which can be utilized with fewer deleterious effects to the environment. Some feel that the leading candidate for the new fuel economy is the hydrogen fuel cell. The problem is that there is a long lead-time before such a new fuel technology can be implemented.

Until then, a stopgap measure needs to be put in place to fuel the economy without adding large amounts of CO_2 into the atmosphere. One of the most promising options is biofuel. The problem with biofuels is that most are based on oils produced from agricultural crops. Wide-scale use of such fuels may cause further environmental degradation as marginal lands are brought into production to meet demand. In addition, there is concern that increased reliance on these commodities may cause food shortages as food prices rise along with crop prices.

Algae can be used as a source of biodiesel. Algae growth can be fed with CO_2 from power generation plants and then harvested as a source of oil. The algal-biodiesel can be utilized to power world economies until an alternative to hydrocarbons as a source of fuel can be implemented. This truly renewable source of fuel can be raised on non-arable land with wastewater providing the nutrients. This fuel would allow people to use existing transportation technology while reducing their overall carbon footprint.

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I want to thank my wife, Leigh, for her extensive support during the writing of this thesis. She was repeatedly required to hang out by herself and to pick up my slack in maintaining our home and our life while I was locked away in the study. I would also like to thank my mother for her support through my entire time through the MES program.

INTRODUCTION

The United States is in a position where it will soon need to reduce its reliance on fossil fuels, for both economic and environmental reasons. Fossil fuels are a non-renewable resource, and finite. Alternative fuels need to be developed to protect the U.S. economy from faltering when fossil fuel supplies run low and/or their use becomes environmentally unacceptable.

Besides being of limited supply, fossil fuels release carbon dioxide (CO_2) when burned. The release of CO_2 into the atmosphere as a result of burning fossil fuels is believed to be a major cause of global climate change. Some fear that if industrialized and industrializing countries continue to release large amounts of CO_2 and other greenhouse gases, the atmosphere may be irreversibly changed for the worse. There are many theories on what climate change may entail, but any markets opened up by the new climate conditions will not likely replace the markets disrupted as changes occur.

It is better to follow the precautionary principle and try to change the factors that are the likely cause of global climate change. A first step towards making the needed changes is to find new ways of producing energy, while recycling CO_2. This step is mandatory to slow the release of this greenhouse gas until a new non-hydrocarbon-based fuel economy, such as hydrogen fuels, can be brought on line.

Extensive use of petroleum fuels by the U.S. transportation sector requires the import of large quantities of oil to meet those needs. The utilization of biomass for the production of a transportation biofuel also meets the CO_2 recycling requirement because plants naturally fix CO_2 through the photosynthetic process (Miyamoto, 1997). Biomass can also be produced in the U.S., thus providing a more secure source of fuel.

Many believe that the production of oil in the world has reached its peak and new sources will be harder to find and more expensive to recover (Roberts, 2004). Many sources of oil are in politically unstable regions and require large military expenditures in foreign countries to protect the resource. The countries of the Middle East produce large quantities of the world's oil supply, and recent U.S. policy decisions and actions in that part of the world may cause an increase in instability of future oil supplies.

This thesis investigates the growth of algae as a biomass fuel source by utilizing carbon dioxide from the flue gases of coal-burning power plants and waste streams of other nutrients such as nitrogen. Oils obtained from the algal biomass can then be processed into biodiesel.

The biodiesel produced would then be utilized in the transportation sector to replace the use of petroleum-based diesel. While still emitting CO_2, the use of biodiesel produced from algae releases CO_2 that would have already been released during power production, thus meeting the requirement of recycling CO_2 and reducing overall emissions.

The algae are able to utilize the CO_2 from the flue gases, nitrogen (N) and phosphorous (P) from wastewaters, and energy from sunlight in the photosynthetic process to create carbohydrates. The stored energy in the carbohydrates is utilized to run cell processes that sequester carbon into tissues in the form of proteins and lipids. The lipids are then processed into oils that replace the animal and plant oils that are traditional feedstocks for the biodiesel production process. These feedstocks are refined to produce biofuels. In the U.S., the main biodiesel feedstock sources are soy oils, animal fats from rendering plants, other plant sources, and used cooking oils (Ginder, 2004).

The use of algae to sequester CO_2 and produce biofuel is still relatively new. The processes were originally investigated in the 1980s in the National Renewable Energy Laboratory's Aquatic Species Program (Sheehan et al., 1998a). Successive projects have worked to establish that algae can successfully sequester CO_2 in both open pond and enclosed bioreactor systems. Now, some researchers are working to develop production methods that are economically feasible on a large scale (Kremer, 2006).

This paper also will investigate the feasibility of using photobioreactor technologies to sequester CO_2 from the coal-fueled power plant in Centralia, WA, owned by the Transalta Corporation. The plant has two 702.5 megawatt production facilities that release over 10,000,000 tons[1] of CO_2 per year (Southwest Clean Air Agency, 2005b). To be feasible, an algal sequestration process would need to be economically practicable, fit within the confines of the property available, meet environmental permitting requirements, and have a market for the end product.

CO_2 AND GLOBAL WARMING

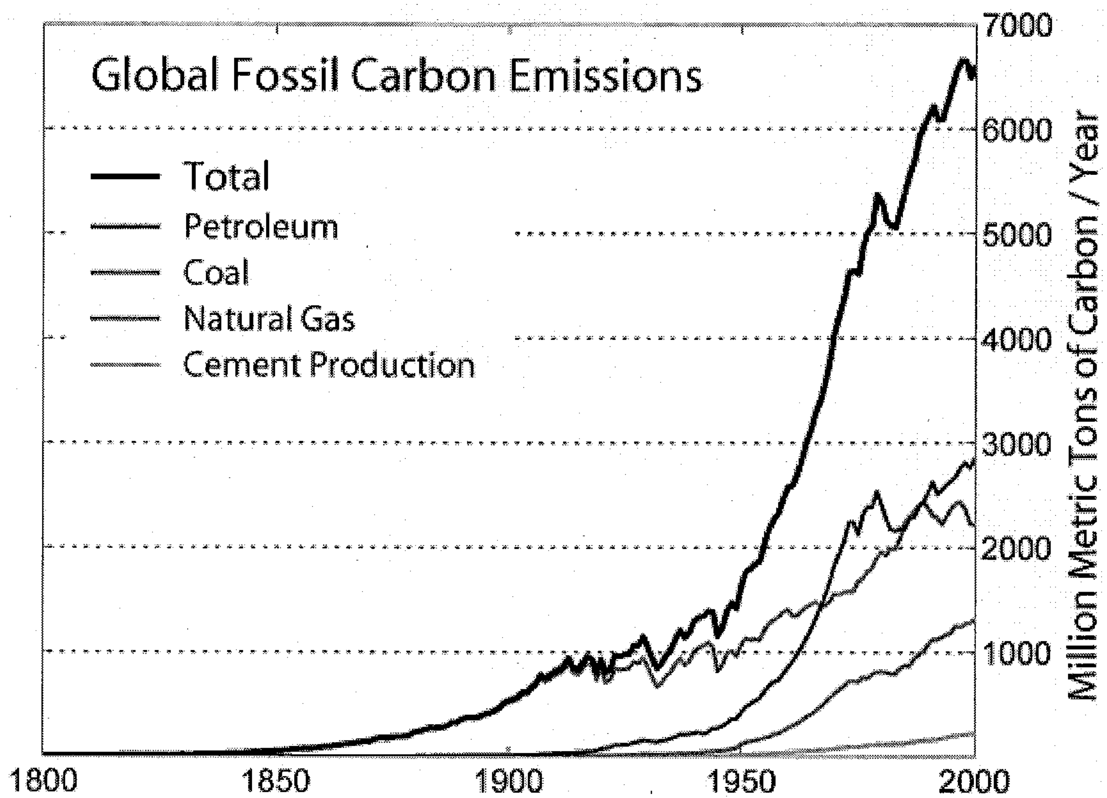
The climate changes associated with the emission of greenhouse gases are beginning to be felt around the world and the theories surrounding the causes, though still repudiated by some, are becoming generally accepted throughout the scientific and political communities.

The main cause of climate change is the release of carbon dioxide from the consumption of non-renewable resources such as fossil fuels. The role of CO_2 in global

[1] I have tried to use metric measurements whenever practicable. For clarity, the use of English units was occasionally deemed more appropriate.

climate change was identified as early as 1979 by the National Academy of Sciences, and a positive correlation between CO_2 in the atmosphere and fossil fuel use has been demonstrated (Speth, 2004; Stepan et al., 2002). These anthropogenic CO_2 emissions have increased sharply in the past 50 years as shown in Figure 1.

Figure 1. – Global CO_2 emissions from fossil fuels and cement production.



Source: Marland, et al, 2003

The most dire temperature-change predictions associated with global warming are that average temperatures will rise between 2.5 to 10.5 degrees Fahrenheit by the end of this century (Speth, 2004). An increase of such magnitude will cause a significant rise in sea level and alter weather patterns, likely resulting in disastrous environmental and societal effects (Speth, 2004).

The rise in both the recorded occurrences of climatic anomalies and an increase in the number of warnings from the international scientific community have brought an increasing awareness of the significance of climate change. Many are calling for reductions of greenhouse gas emissions from industrialized countries. Currently CO_2 levels are approximately 370 ppm, and it is hoped that such reductions would keep atmospheric CO_2 levels from ever reaching 450 ppm. It is believed that beyond this level "dangerous" effects would occur to the planet's ability to support human life, including disastrous increases in sea level and disruption of major ocean currents. Without drastic decreases in current emissions, the 450 ppm-level is projected to be reached by 2030 (Speth, 2004).

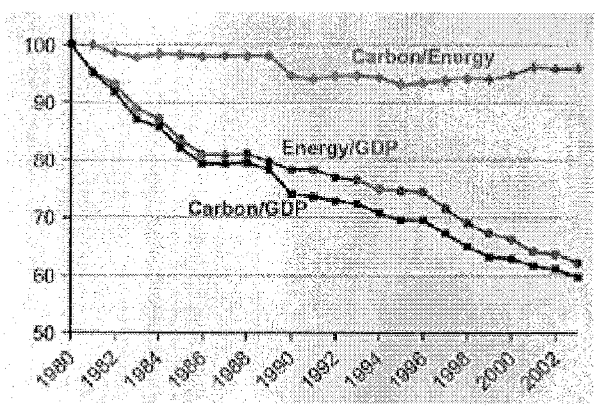
U.S. CO_2 EMISSIONS

The United States is one of the largest emitters of greenhouse gases in the world, averaging around 23 percent of the world's overall output. The country's overall emission rate is growing each year. For example, emissions in 2005 were 17 percent higher than in 1990, despite worldwide calls (e.g. the Kyoto Protocol) for the reduction of emissions by industrialized countries (Energy Information Administration, 2006a).

The yearly increase in rate has continued to decrease with time, but at this time the total amount is still increasing. The yearly increase for 2004 was 0.3 percent compared to the average yearly increase from 1990 to 2004 of 1.2 percent (Energy Information Administration, 2006a). To stem global warming, all industrialized countries need to reduce emissions below their 1990 rates. As the greatest producer of greenhouse gases, the U.S. should take a leading role in reducing emissions.

U.S. increases in energy use, primarily for electricity and transportation, are steadily rising despite the expansion in overall carbon intensity (Energy Information Administration, 2006a). Carbon intensity, the amount of carbon emitted per unit of energy utilized for various uses, is fairly steady or in actual decline through adoption of technologies that are increasingly energy efficient. Figure 2 displays the U.S. carbon intensity over time in the green Carbon/Energy segment. The graph shows that the rate of carbon consumed has dropped by approximately five percent since 1980. This gain is offset by the fact that as people continue to purchase larger homes and fill those homes with an increasing number of electronic goods, the rate of efficiency increase cannot keep up with the increase in demand.

Figure 2. – Intensity ratio of U.S. carbon usage 1980-2005 (1980 = 100%)



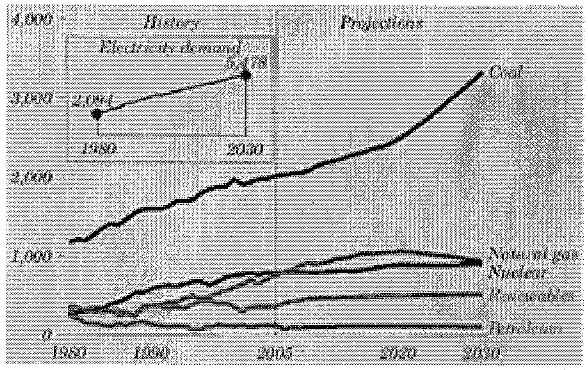
Source: Energy Information Administration, 2006a

The majority of overall U.S. greenhouse gas emissions are in the form of CO_2, making up 84 percent of the total. The largest emitting sectors are the two largest energy sectors, transportation and electricity production. In 2005, 83 percent of U.S. emissions were CO_2 from combustion of coal, petroleum, and natural gas (Energy Information Administration, 2006a). During this year, the actual amount for the transportation sector was 33 percent and the amount for coal-produced electricity was 36 percent (Energy Information Administration, 2006a).

It is projected that natural gas, oil, and coal will grow to 86 percent of the overall energy market, and that this share will stay steady through the year 2030 (Energy Information Administration, 2006b). The increase in the size of this market suggests that CO_2 emissions will continue to expand as the energy market expands, unless steps are taken to reduce emissions. Reduction can come from switching to more carbon-intense fuels, fuels that give more energy per unit of CO_2 emission, cleaning flue or tailpipe emissions, or capturing and sequestering CO_2 as it is released.

The use of fossil fuels for electricity generation is likely to increase as generation from nuclear and other non-fossil fuels are projected to decline, as exhibited in Figure 3 (Energy Information Administration, 2006b; Environmental Protection Agency /Department of Energy, 2000). The major increase in fossil fuel usage for electricity generation will come from coal. All other forms of electric generation from fossil fuels are expected to remain relatively constant, with a slight decrease in the use of natural gas. A significant number of new coal plants are expected to come on line by 2030. By that time, the overall generation level will increase from the current 22.9 quads (quadrillion British thermal units) to 34 quads (Energy Information Administration, 2006b).

Figure 3. - Projected use of fuels for electricity production to 2030 (billion kilowatt hours).



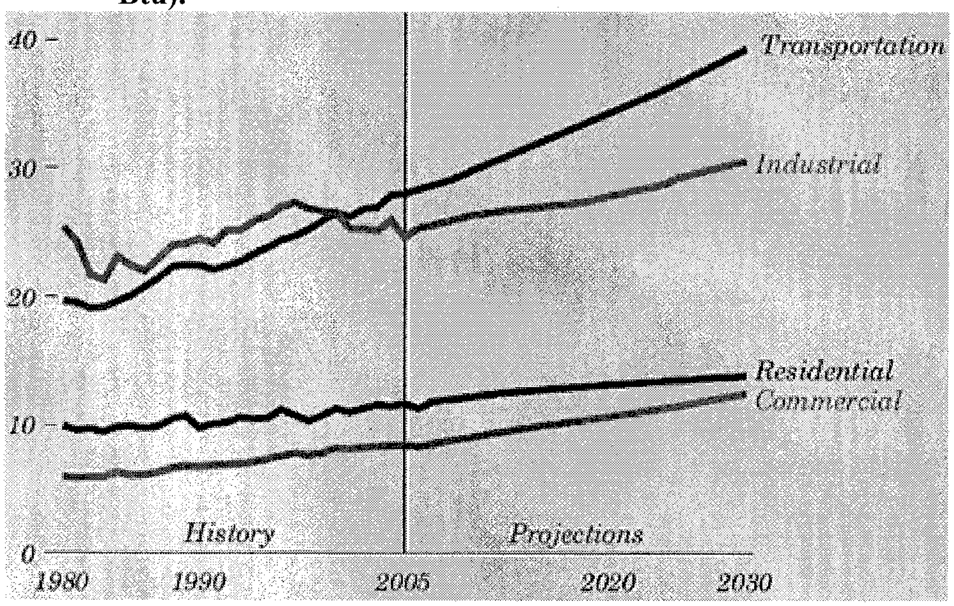
Source: Energy Information Administration, 2006b

The reason for the major increase in coal use is simple; the U.S. has 25 percent of the known coal supply in the world (Sheehan et al., 1998a). Coal is a readily available and relatively cheap source of hydrocarbons for energy production and is likely to remain inexpensive. The price of coal in 2030, adjusted for inflation, is expected to be similar to today's prices (Energy Information Administration, 2006b).

The reliance on coal for an increasing amount of U.S. electricity generation will have negative effects on the environment. Coal has the highest carbon intensity of all the fossil fuels (Energy Information Administration, 2006b). In fact, coal-fired power plants release 80 percent of the CO_2 released during energy production, while only producing 51 percent of the overall electricity output (Environmental Protection Agency/Department of Energy, 2000). In 1999, coal plants produced an average of 1 kilogram of CO_2 per kWh, while the average for all fuels used for energy production was 0.6 kilogram per kWh (Environmental Protection Agency/Department of Energy, 2000). Increased use of coal will drastically raise overall CO_2 output. A decrease in CO_2 released per unit of energy is not likely to occur because CO_2 remediation is prohibitively expensive and CO_2 is not currently regulated under Clean Air Act (Southwest Clean Air Agency, 2007).

While electricity from coal production is expected to increase, this increase will be somewhat tempered by conservation as technology makes electrical devices more energy efficient. On the other hand, consumption of fossil fuels for transportation is expected to rise sharply in contrast to other sectors as shown in Figure 4 (Energy Information Administration, 2006b). The increased use of fossil fuels for transportation means that there will be an increasing market for biofuels.

Figure 4. – Delivered energy consumption by sector, 1980-2030 (quadrillion Btu).



Source: Energy Information Administration, 2006b

CO_2 REDUCTION AND SEQUESTRATION

CO_2 reduction and sequestration schemes need to be implemented immediately if we are to combat the expected global warming that may make life on the planet difficult. The options for reducing CO_2 emissions include: an increase in energy efficiency, a switch to less carbon-intense fuels, a reduction in deforestation, promotion of renewable energy, increased use of nuclear power, and a switch to a non-carbon-based fuel economy (van Harmelen and Oonk, 2006).

For carbon sequestration, there are several options. One option is to capture CO_2 from electricity-production facilities and sequester this CO_2 in oil and gas fields, aquifers, or the ocean. The current cost to sequester a ton of CO_2 is approximately $100 to $300 per ton of emissions avoided (Department of Energy, 2007). The U.S. Department of Energy (DOE) is conducting a research program aimed at finding technologies that will allow CO_2 sequestration at a cost of $10/ton by 2015 (Department of Energy, 2007). Utilization of these techniques is expected to add approximately 10 percent to the cost of electricity (Department of Energy, 2006).

Another option for direct sequestration is biological fixation of CO_2 by plants. Plants utilize CO_2 during photosynthesis and large amounts of that CO_2 are sequestered in plant tissue. The overall rate of sequestration by plants can be enhanced through reforestation, as plants utilize CO_2 directly from the atmosphere. The amount of CO_2 in the atmosphere is approximately 0.036 percent, which means that large areas of land need to be reforested to grow enough plants to sequester a significant amount of CO_2 from low atmospheric levels (Stepan et al., 2002).

A more efficient process of biological fixation is exhibited by algae and cyanobacteria. These aquatic microorganisms can sequester significantly higher rates of CO_2 through direct diffusion from the aqueous solution where they grow. Aqueous solutions can contain much higher rates of CO_2 than the atmosphere (van Harmelen and Oonk, 2006).

Algae biofixation systems have been tested on coal flue gases that were up to 12-13 percent CO_2 (Riesing, no date; Stepan et al., 2002). This percentage of CO_2 can easily be absorbed into the aqueous medium used to grow algae in the biofixation systems. The algae can exhibit growth rates up to 30 times greater than terrestrial plants when such high rates of CO_2 are in the surrounding solution (Sheehan et al., 1998a).

The biofixation systems are comprised of an aqueous solution containing algae that are circulated through an area while CO_2 and nutrients are added. The algae in the system use the CO_2, nutrients, and solar energy in the photosynthesis process. The carbon is sequestered in the algae while oxygen is released. A percentage of the algae is harvested and processed into oils that are used to produce biofuel.

Some strains of algae store the end products of photosynthesis at a higher ratio of lipid content to protein than other strains. The rate of lipid production by algae can also be increased by manipulating the levels of nutrients in the growth medium (Kremer et al, 2006). The lipids are then processed into biodiesel, which can be used to replace petroleum-based diesel. This process has been studied for several decades in both the public and private sectors and will be discussed in depth later in this paper. Prior to that, a history of diesel use and an overview of traditional forms of biodiesel are provided.

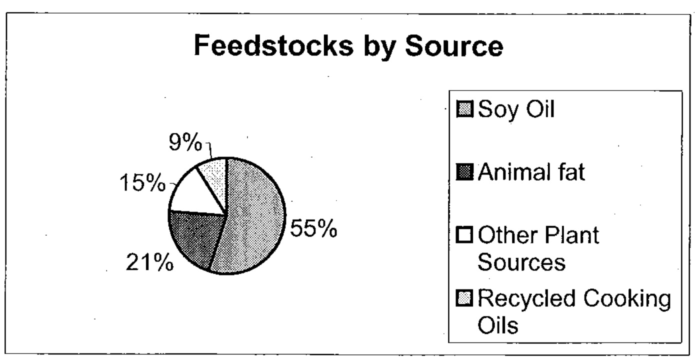
DIESEL USE AND REPLACEMENT

The net U.S. oil imports for transportation needs are projected to increase to 32 percent of total consumption by 2030 from the current rate of 30 percent (Energy Information Administration, 2006b). The amount spent per year on importing petroleum is in between \$110-\$150 billon and accounts for approximately 2/3 of the petroleum used annually in the U.S. (Briggs, 2004). This number is for the cost of the products only and does not include the large expenditures for military bases in foreign countries that protect the flow (Briggs, 2004).

Petroleum fuels (gasoline and diesel) comprise 97 percent of the transportation fuels. Twenty-four percent of the fuel used in the U.S. is diesel, which means an annual import rate of 64 billion barrels (Sazdanoff, 2006). Further steps need to be taken above and beyond the current programs of incentives for producers of alternative fuels, as these fuels are now only projected to replace seven percent of the overall transportation fuels consumed in 2030 (Energy Information Administration, 2006b).

This projection was made based on traditional feedstocks for biofuel production, and includes agricultural products, wood and animal waste. The percentage comprised by each feedstock is shown in Figure 5. New sources for feedstocks, such as algae, need to be investigated and utilized in order to increase the percentage of transportation fuels not manufactured from fossil fuels.

Figure 5. Traditional biodiesel feedstocks.



Source: Ginder, 2004

The biofuel that can be used to replace petrodiesel is biodiesel. Traditional biodiesel is produced from the mono-alkyl esters of fatty acids that are derived from vegetable oils, animal fats, or recycled cooking oil or grease. The oils and fat are commonly referred to as the feedstock for the refining process that produces the fuel.

To produce biodiesel, the feedstock is reacted with an alcohol, most commonly methanol, to produce a compound that is known as fatty acid alkyl ester. The most commonly used catalyst for this reaction is potassium hydroxide and the by-products are a low-quality glycerol, feed quality fat, potassium salts, and methanol. The methanol can be recycled back into the system (Schumaker et al., 2003; Tyson, 2004; Tyson et al., 2004; Van Gerpen, 2004).

The approximate proportions for the conversion process are:

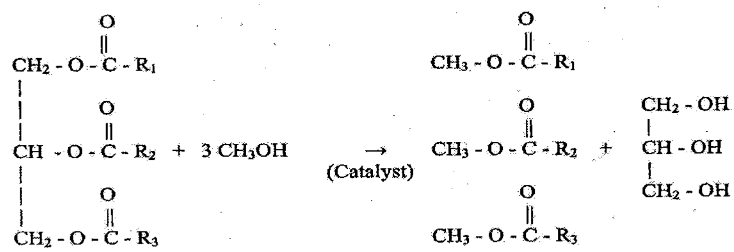
45 kilograms of oil + 4.5 kilograms of methanol = 45 kilograms of biodiesel + 4.5 kilograms of glycerol

or by percentage:

87% oil + 12 % alcohol + 1% catalyst = 86% biodiesel + 9% glycerin + 4% alcohol + 1% fertilizer

A breakdown of the transesterification reaction in the production of biodiesel is the reaction of a triglyceride molecule with an excess of alcohol in the presence of a catalyst to produce glycerin and the mixture of fatty acids known as biodiesel (Figure 6; Tyson et al., 2004; Van Gerpen, 2004).

Figure 6. Biodiesel transesterification reaction.



Source: Van Gerpen, 2004

The United States Environmental Protection Agency (EPA) has legally registered biodiesel as both a fuel and a fuel additive. All biodiesel meeting the international biodiesel specification is included in this registration, independent of the feedstock or process used. The international specification, D6751, is administered by American Society of Testing and Minerals International, a consensus-based standards group recognized in the United States by most governmental agencies. The registration relates to long chain fatty acid esters that contain only one alcohol molecule to one ester linkage (Tyson, 2004).

Biodiesel is considered by many to be a “drop-in technology,” which can be easily incorporated into the current energy system on a large scale. Distribution can utilize the current infrastructure of the petrodiesel companies, as biodiesel is, at first, likely to be consumed as a blended fuel (Schumaker et al., 2003; Van Gerpen, 2004). Blending can take place at a central location before distribution to individual refueling sites (Van Gerpen, 2004).

The blended fuel can then be stored and pumped without any equipment modifications to the individual fueling systems (Schumaker et al., 2003; Van Gerpen, 2004). The most common change reported for storage and maintenance routines is the need for storage tank cleaning before switching to a blended fuel, and an increase in the rate of fuel filter replacement (ASG Renaissance, 2004).

BIODIESEL LIFE CYCLE ANALYSIS

A 1998 analysis of the life cycle of soy-based biodiesel has shown that the production of the fuel returns over three times the energy that is invested in the process (Sheehan et al., 1998b). Biodiesel produced from algae would likely return an even larger energy bonus. An earlier analysis found that biodiesel produced from rapeseed returned less energy than the amount spent producing the fuel, and that the use of the fuel actually had negative environmental effects when compared to diesel use (DeNocker and Spirinckx, 1997).

This 1997 study, conducted in 1997 by DeNocker and Spirinckx, understated the positive environmental effects of large-scale biodiesel use as a replacement for petroleum diesel. The study showed that biodiesel used more fossil fuels and increased greenhouse effects when compared to petroleum diesel. The study also showed that biodiesel usage increased the use of inorganic raw materials, radioactive and non-radioactive wastes, petrochemicals, and water during production, and the fuel usage increased the negative environmental effects of acidification and eutrophication (Van Gerpen, 2000). The study concluded that biodiesel use created more health and environmental problems because it produced more particle matter, pollutants, and waste as compared to petro-diesel use, thus offsetting any positive aspects of using the fuel (Van Gerpen, 2000).

The study also argued that the ratio of energy used to produce biodiesel compared to energy available in the fuel was approximately 1:1 (Van Gerpen, 2000). This means that for every gallon of biodiesel produced, the amount of energy available in a gallon of petroleum fuel would be consumed. This study has been cited by many detractors of biofuels, ignoring the positive aspects of the fuel use.

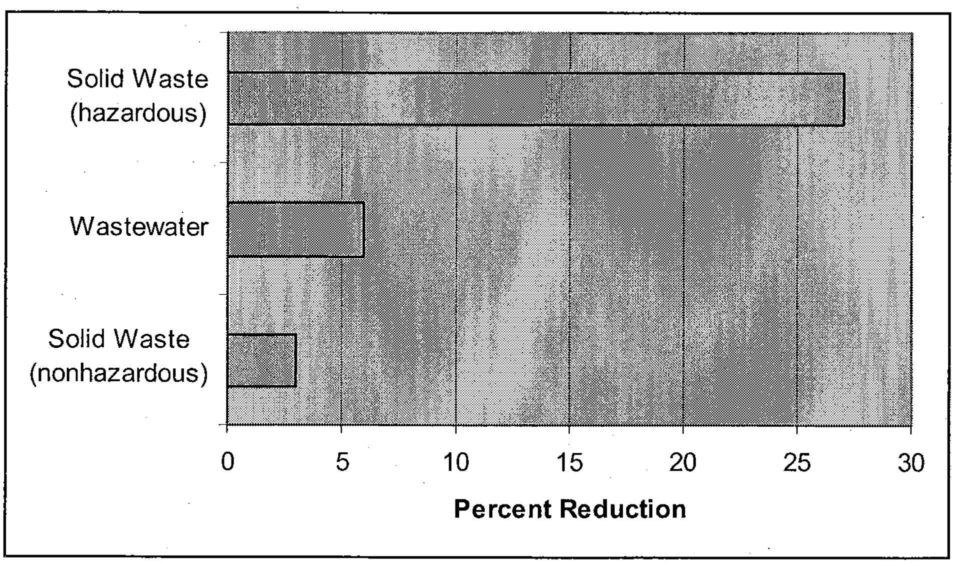
The conclusions reached in this study may be due to the fact that the feedstock used to produce the comparison biodiesel was rapeseed oil. Rapeseed requires relatively high amounts of fertilizer in its production. Rapeseed is one of the main sources of biodiesel feedstock in Europe, but relatively unknown in the U.S. The feedstocks most widely used in the United States require much lower rates of nitrogen inputs, if any at all.

Up to 45 percent of the feedstocks used in the U.S. are waste products and do not require any additional nitrogen input (Ginder, 2004). The feedstock used in the other 55 percent of biodiesel production in the United States is oil from soybeans. Soybeans are nitrogen-fixing plants that require very little input of chemical nitrogen fertilizers. The Flemish study assumed fertilizer inputs of 80 kg/hectare to grow rapeseed, where the average fertilizer input for soybean production in the U.S. is approximately 4.4 kg/hectare (Van Gerpen, 2000).

The amount of chemical fertilizer utilized is a major concern because chemical fertilizers require petroleum in their production and as the fuel for application apparatus, thus lowering the energy efficiency of crops raised in this manner (Van Gerpen, 2000). Using the fertilizer inputs for rapeseed when projecting the lifecycle of fossil inputs for biodiesel produced from soybeans would give skewed results for biodiesel production in the U.S.

The other environmentally based drawbacks of biodiesel use would also be lessened if soybean oil was used in place of rapeseed oil. The large differences in inorganic raw materials, acidification, eutrophication, and wastes used or produced in the Flemish lifecycle analysis would be greatly reduced or eliminated with an analysis conducted with the fertilizer input levels of soybeans. These differences also result from lower amounts of petroleum products with less fertilizer usage. The differences in water usage should also be reevaluated with new biodiesel refining technologies discovered since the 1997 study, as they use less water in the production of biodiesel (Van Gerpen, 2000). Some of these results were exhibited in a Chicago-area lifecycle analysis of switching urban buses to biodiesel as shown in Figure 7 (Sheehan et al., 1998b).

Figure 7. - Analysis of water and solid waste emissions in Chicago buses.



Source: Sheehan et al., 1998b

The overall energy efficiency differences found in lifecycle analysis of biodiesel in U.S. urban buses conducted by U.S. Departments of Agriculture (USDA) and Energy resulted in energy efficiencies of –3.215 for biodiesel and 0.8337 for petroleum diesel (Sheehan et al., 1998b). This means that for every unit of energy used to produce biodiesel, 3.215 units are created. This result is very different from the Flemish study, and the primary factor influencing that difference is the reduction in the amount of fertilizer.

The large positive in efficiency for soy-based biodiesel is a result of the low nitrogen inputs for soybean production and the energy gained through the harvesting of solar energy during photosynthesis by the plants. The average current industry energy efficiencies for soy-based biodiesel are 1:2.42, including an industry best of 1:2.89, with a potential of 1:3.215 to 3.81 (Delucchi and Lipman, 2003). The negative energy available in petroleum diesel is a result of the energy required to turn crude oil into diesel fuel, and transportation of the products (Sheehan et al., 1998b).

Table 1. – Energy efficiency table of different feedstocks.

Feedstock Source	Energy Efficiency
Petroleum	1:0.83
Rapeseed	1:1
Soybean	1:3.215
Algae	1:4.0+

Sources: Sheehan et al., 1998b; Van Gerpen, 2000

The energy efficiency of biodiesel refined from algae oils is likely even higher than those produced from soy oil. No lifecycle analysis has been conducted on biodiesel produced from algae oils, but the inputs of nitrogen in the production of algae are not from petroleum-based products. Thus the energy efficiency of the process will likely be even higher than U.S. soy-based biodiesel.

Most flue gases from coal-fired power plants contain nitric oxides that algae can use as the nitrogen requirements for growth. Any additional inputs of nitrogen and phosphorous can be provided by waste sources, such as those from municipal water systems or farm wastes.

The main energy requirements for the production of algae oil are the electricity used for circulating the water in the system and transporting the oil to refining facilities. This low energy requirement, coupled with the fact that algae-oil-produced biodiesel would have a much greater energy efficiency ratio than traditional biofuels as a result of the use of waste nitrogen, create an even stronger argument for use of this technology (Briggs, 2004). Again, the main difference between the Flemish and USDA/DOE lifecycle analyses are the differences in fossil-fuel-based nitrogen inputs, as those inputs fall to zero with algae production.

This difference creates the large swing in energy efficiencies of the two studies. The swing is large enough that it could be the determining factor for whether or not production of biofuels should be pursued as a transitional alternative to traditional fuels. The resulting energy efficiency of algae-based biodiesel will likely be even more positive than the 1:3.215 exhibited by soy based biodiesel, though this difference will likely be less that the difference between soy- and rapeseed-based biodiesel.

Another difference between using an algae feedstock and traditional feedstocks is the source of carbon dioxide that is eventually sequestered during photosynthesis. Soy beans and other crops produced in agricultural settings obtain CO_2 from the atmosphere. Algae production systems that utilize CO_2 from flue gases sequester CO_2 that has not yet reached the atmosphere. Table 2 compares the amount of CO_2 from fossil and biomass sources for biodiesel and petrodiesel.

Table 2. - Tailpipe contribution to total lifecycle CO_2 in urban buses (g CO2/brake horsepower-hour).

Fuel	Total Life Cycle Fossil CO_2	Total Life Cycle Biomass CO_2	Total Life Cycle CO_2	Tailpipe Fossil CO_2	Tailpipe Biomass CO_2	Total Tailpipe CO_2	% of Total CO_2 from Tailpipe
Petroleum Diesel	633.28	0.00	633.28	548.02	0.00	548.02	86.54%
B100 (100% Biodiesel)	136.45	543.34	679.78	30.62	543.34	573.96	84.43%

Source: Sheehan et al., 1998b

The use of biodiesel fuels releases CO_2 at a rate similar to those of petrodiesel, with a two percent decrease in efficiency (Briggs, 2004). The use of biodiesel essentially gives the same amount of energy per unit of CO_2. The benefit seen by the use of biodiesel is that the CO_2 released was recently sequestered by plants or algae. Petrodiesel use releases CO_2 that has been sequestered in the ground for millennia and that CO_2 adds to the greenhouse effect. The overall rate of CO_2 being released with algal biodiesel is less than if both the transportation and energy activities were powered by fossil fuels. The only biodiesel emission exhibiting a negative impact is NO_X with an increase of 2 percent. (Environmental Protection Agency, 2002).

Biodiesel produced from algae has the added bonus of sequestering CO_2 while it is still in a concentrated form, before it is released into the atmosphere. The process can be more productive than biomass production reliant on atmospheric levels of CO_2. The algae have a much more concentrated source of CO_2 from the flue gases, which allow for high rates of biomass production.

The fact that current algae production systems do not require large inputs of energy for engine fuel or chemical fertilizers means that the incentive towards producing algae-based fuels is even greater than traditional biofuels in terms of energy efficiency. Thus production of these fuels would not cause further eutrophication (the increase in plant growth and decay that negatively effect water quality) of water bodies in agricultural areas, which result from the addition of large amounts of nitrogen.

Waste streams would be reduced through their use as raw inputs to the process of photosynthesis. The major decrease in CO_2 releases when using algal-based biodiesel makes the production and use of the fuel source a positive process for the environment. What remains to be seen is if the fuel can be produced cheaply enough to make sense economically, and not just ecologically.

HISTORY OF ALGAL BIOFUELS

The gasoline crisis in the 1970s created an incentive to investigate ways to produce alternative fuels able to replace gasoline and diesel fuels. The National Renewable Energy Laboratory created a biofuels program to look into options for producing such fuels. A section of the program was titled the Aquatic Species Program (Sheehan et al., 1998a). The Aquatic Species Program investigated different types of aquatic organisms for their potential as the source of biofuel, including commercial algal production systems, which generated much larger amounts of oil from the same amount of biomass than emergent plants. The oils produced were found to be a suitable replacement for the traditional feedstocks of biodiesel (Sheehan et al., 1998a).

Algae were also found to be a better choice for use in biofuel production because the species could be grown in areas of poor soils. Algae don't require good rooting material, and can withstand poor quality water (van Harmelen and Oonk, 2006). Both of these characteristics allow for the construction of production facilities in areas that are currently underutilized for plant production.

In the program, algae strains were collected from all over the country. In all, over 3000 strains were collected, and all strains were investigated for their ability to produce lipids, and for their overall growth potential under the severe conditions encountered in a medium that contained high levels of CO_2. The program utilized flue gases from coal plants as the source of CO_2, with levels as high as 13 percent (Sheehan et al., 1998a). The pond systems investigated were estimated to have the potential to remove hundreds of millions of pounds of CO_2 (Benemann, 2003).

After the original round of experimentation was complete, over 300 strains were found to meet the requirements of the program. The strains are stored in a repository in Hawaii and are available to researchers interested in investigating the potential for the production of biofuels (Sheehan et al., 1998a).

Harvested algae are comprised of three main components; carbohydrates, proteins, and lipids. Each species generates different average levels of each component.

Some of the more economically promising species contain 60-85 percent triglycerol lipids by weight (Miyamoto, 1997).

The program further investigated genetic alteration of the algal strains in order to increase the percentage of lipids that the algae store (Sheehan et al., 1998a). The investigation was the result of the hypothesis that the incidence of a genetic trigger in algae could be manipulated to increase the rate of lipid production (Roessler et al., 1994). Lipids are the part of the algae that are turned into biofuel feedstock, so an increase in lipid production would allow for more oil to be produced from the same amount of algae. The lipid trigger was not found during the experiments, but it was later discovered that nutrient manipulation of the growing medium would increase the rate of lipid production (Kremer et al., 2006).

The program chose to raise algae in outdoor ponds in a manner similar to existing systems designed to raise algae for nutritional supplements, animal feed, and treatment of wastewater (Sheehan et al., 1998a). The total production of these existing systems is approximately 10,000 tons of total biomass per year (van Harmelen and Oonk, 2006). The algae were raised in shallow circular ponds where CO_2 was pumped and circulated by large paddles (Benemann, 2003). The capital costs of raising algae in this manner are approximately \$100,000 per hectare, compared to a cost of \$10,000 per hectare for raising traditional agricultural crops (van Harmelen and Oonk, 2006).

Even with this cost disparity, the production of algae for biofuel was thought to be economically viable, because of the potentially high production rates for algae (Sheehan et al., 1998a). Further economic examination showed that it was not economically feasible at the current rate of production of 50 tons/hectare/year, but with further research it would be feasible to approximately double the rate of production (Benemann, 2003; Giampietro et al., 1997). Production at this doubled rate would be competitive with fossil fuels.

There are several reasons why algae are able to grow at such rapid rates. The first is a remarkably short generation time, one day or less in some species, if the most significant limiting factors for growth are overcome. Algae are also able to use the high rates of fossil CO_2 that are available in the growth medium, which is many times greater than atmospheric levels. For other, emergent, photosynthetic organisms, it is not physically possible to utilize such high concentrations (van Harmelen and Oonk, 2006).

The ability of algae to absorb such high rates of CO_2 is a result of simple diffusion directly through cell walls, allowing for much faster rates than is possible by land plants. As a result of this ability, algae are photosynthetically superior and can sequester carbon at a much faster rate (Sheehan et al., 1998a; van Harmelen and Oonk, 2006). One study showed that one quad of energy could be produced by 202,000 hectares of algae ponds. To produce the same amount of energy by producing rapeseed would require up to 23,200,000 hectares (Riesing, no date).

The algae are able to benefit from the higher CO_2 levels because of the high levels of solar energy the organisms utilize. Research has shown that algae currently use up to five percent of available solar energy, with the potential to use up to 11 percent, while upland plants seldom use over one percent of available solar energy (Miyamoto, 1997; Nakamura, 2004). It is theorized that algae grown under ideal conditions would be able to produce up to 114 kilocalories of biomass for each mole of CO_2, when using the theoretical 11 percent of total solar energy (Miyamoto, 1997). Eleven percent could be reached with the development of better ways to expose increased numbers of algae to solar energy in the production systems.

Under certain limited nutrient conditions, algae do not grow normally, but instead store additional energy as lipids (National Renewable Energy Laboratory, 2006; Roessler et al., 1994). The environmental stress that occurs in the process changes the lipid production in the algae levels that are up to 30 times greater than lipid levels in land plants (Sheehan et al., 1998a). Other limiting factors are temperature, photoperiod, light intensity, light saturation, salinity, and nitrogen levels (Qin, 2005).

Most of the algal strains that were deemed appropriate by the Aquatic Species Program are known extremophiles. Extremophiles are algal species able to tolerate the large range of conditions found in the sequestration production systems. Acidification of the growth medium caused by the addition of high levels of CO_2 is an example of the conditions that must be tolerated (Sheehan et al., 1998a).

Extremophiles are able to grow under conditions such as acidified solutions that would be harmful to many other species. Current systems are producing 50 tons of biomass per hectare per year. The goal of current research using raceway systems is for production rates of up to 100 tons per hectare per year (Benemann, 2003).

To increase production, some research and development is attempting to produce higher algal growth levels by experimenting with different CO_2 aeration techniques (Kremer et al., 2006). An optimal level of pH is also being investigated. When pH is increased to 9, harvest levels increase, while as the growth medium becomes acidic, growth decreases (Matsumoto et al., 1995; Stepan et al, 2002). The pH levels can also be affected by flue gases that contain sulfur and nitric oxides (Stepan et al., 2002).

Light saturation is the greatest limiting factor and is a result of both restrictions of the photosynthetic apparatus and too much light being absorbed by the algae in the layers of water closest to the light source (Benemann, 2003). Algae near the water surface absorb the majority of the light energy, while the algae farther below the surface do not have enough light energy available to photosynthesize at satisfactory levels. The small percentage of algae that do absorb most of the energy are not able to process it because the cellular organelles that conduct photosynthesis cannot use these high levels (Benemann, 2003; Miyamoto, 1997).

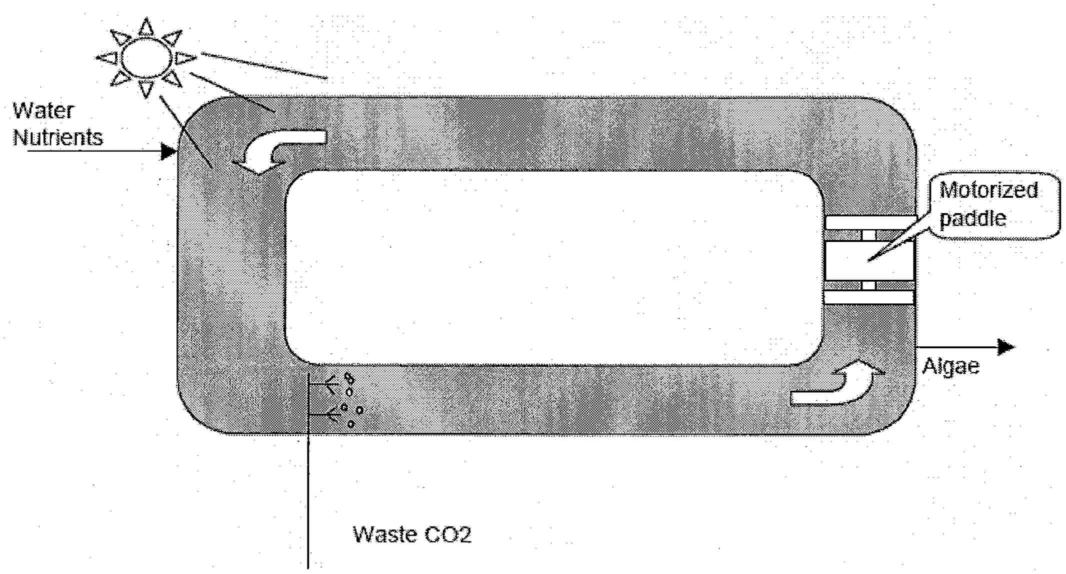
Research has also begun on enclosed photobioreactors that would be able to overcome the geographical limitations of growing algae in outdoor ponds. Light can be added to the bioreactors so that the light limitations imposed by latitudinal position and light saturation are not limiting. The enclosed systems also are able to overcome temperature limitations of northern climates by using the heat normally lost out the flue to heat the water in the system. Thus the production of algae year round in northern climes is no longer insurmountable.

POND ALGAE PRODUCTION

Pond production systems are used to grow algae because the shallow waters in the ponds have high solar conversion efficiencies. These efficiencies result from the large amount of solar energy that is spread throughout the entire water column when the water is sufficiently shallow. The design of the system is such that the limiting factor of light saturation is minimized, while still allowing room for satisfactory production (Benemann, 2003).

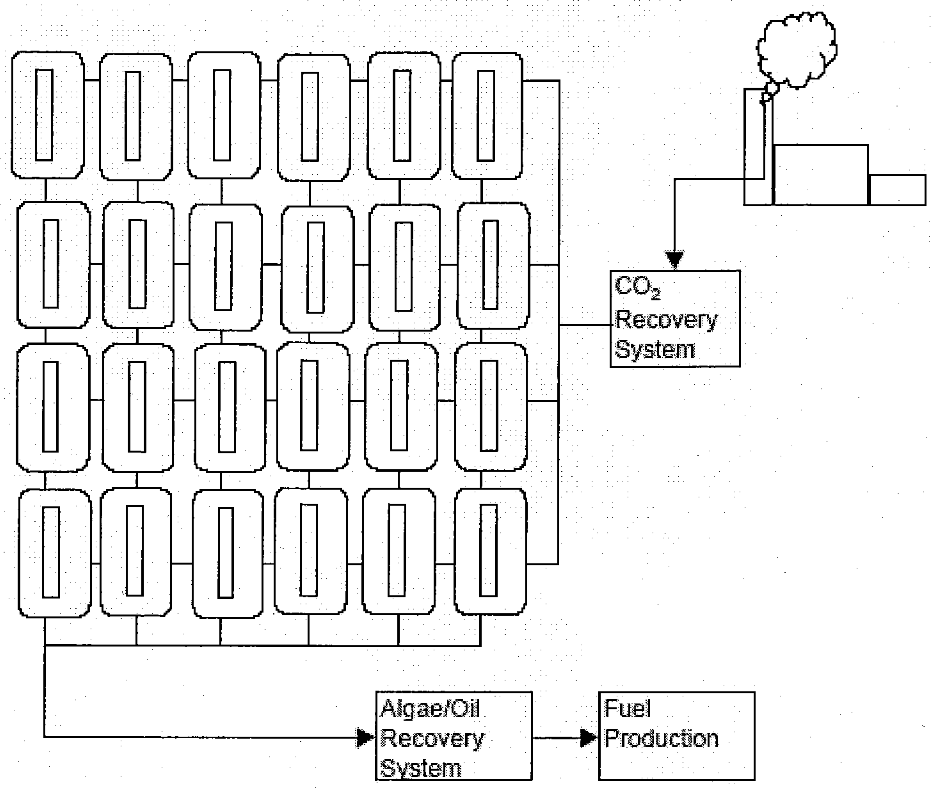
The most suitable size for the individual ponds is between 10 and 100 hectares. (Benemann, 2003). A schematic of a pond is shown in Figure 8. Individual ponds are then connected into a system of appropriate size for the amount of CO_2 to be sequestered as shown in Figure 9. A total of 1400 hectares is required to sequester the CO_2 released by a 500-megawatt power plant (Stepan et al., 2002).

Figure 8. Single raceway pond production schematic.



Source: Sheehan et al., 1998a

Figure 9. - Pond production system overview.



Source: Sheehan et al., 1998a

The systems would use a raceway pond design where water, algae, and nutrients are circulated through the system by motorized paddles. The paddles, in addition to circulating water in the system, continually recirculate the algae throughout the water column so that individuals are frequently exposed to the sunlight hitting the surface (Sheehan et al., 1998a).

Nutrients are continuously pumped into the system, while a percentage of the algae are harvested on a daily basis. The flue gases from coal plants would provide most of the required nutrients, CO_2 and NO_X. Other additional nutrient requirements are nitrogen, phosphorous, and trace minerals (Stepan et al., 2002). These nutrients can be obtained from waste water sources such as municipal water treatment facilities or agricultural sources.

A demonstration project, of two 1000 square meter ponds, conducted by the Aquatic Species Project in Roswell, New Mexico from 1988-1990 proved the practicality of the pond algae system (Sheehan et al., 1998a). The project produced 10 percent more energy than the energy needed to run the system (Sazdanoff, 2006). The experiment ran at 90 percent efficiency, with an average use of 3.5 percent total available solar energy, and produced 20 grams of biomass per square meter per day (Pedroni et al., 2002). The main drawback discovered was the expense of harvesting the algae.

It was extrapolated from the Roswell experiment that the southwest United States alone has the resources to consume several hundred million tons of CO_2. With continued research and development, it is estimated that the application will become practical by the year 2015 (Benemann, 2003). Additional research is needed to find a way to protect the high lipid-producing algae strains from competition with other algae strains and finding more efficient harvest systems.

Researchers are concerned that strains that produce the highest amounts of lipids are not able to outcompete native algae strains. The ponds are routinely invaded by other algae strains and the rates of production are subsequently lessened (Benemann, 2003). When the ponds are producing at optimal levels, the harvest systems may not be able to keep up with production, or harvesting may be too expensive to make biofuel production economically feasible.

To replace the total annual amount of petroleum-based fuels consumed in the United States, approximately 3,885,000 hectares of ponds would need to be constructed (Briggs, 2004; Riesing, no date). A 2004 estimate, which used cost estimates double that of current construction costs, for constructing this number of ponds was $308 billion (Briggs, 2004). This estimated cost is relatively cheap when compared to the annual expense of imported petroleum.

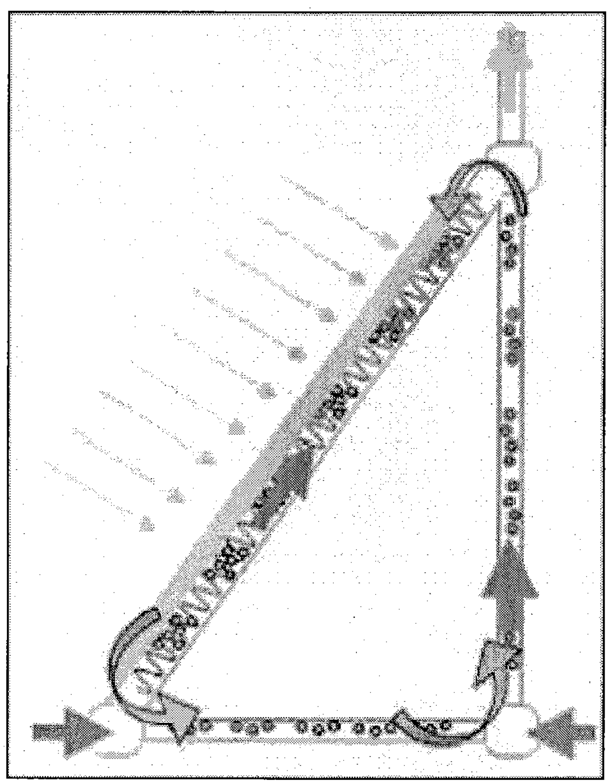
The main restrictions on the implementation of this technology are the limitations of sunlight and heat, thus the highest potential for production is in Asian countries (van Harmelen and Oonk, 2006). The climate restrictions include a minimum average temperature of 15° Celsius and locations between 37° north and south latitude (van Harmelen and Oonk, 2006). An enclosed system is required for economic production of algae for biofuels in latitudes that do not have the sunlight or mean temperatures that meet the minimum requirements for outdoor production. The research to come up with such a system has resulted in development of photobioreactors.

PHOTOBIOREACTOR ALGAL PRODUCTION

A photobioreactor is a system in which the algal growth medium is enclosed in a series of tubes or tanks. The materials that make up the walls of the growth medium enclosure are transparent so that sunlight can pass through and become available to power photosynthesis. The growth medium is circulated through the system so that more of the algae come into contact with both sunlight and CO_2. A schematic of a photobioreactor is shown in Figure 10.

Flue gases are pumped into the growth medium and go into solution, where they are taken up by the algae. Other nutrients and minerals are added as necessary to maintain optimal nutrient levels for the strain of algae being grown. A certain amount of the algae is harvested each day to provide a feedstock for oil production and to provide room for further asexual reproduction by the algae (Greenfuel, 2007c). Oxygen needs to be released from the system as it builds up from algal respiration. If oxygen is not removed, the production rate is dramatically decreased as less CO_2 is diffused into the oxygen-rich growth medium (Pedroni et al., 2002).

Figure 10. - Photobioreactor schematic. The growth medium flows follow the large light arrows in a counterclockwise direction, CO_2 is inserted into the bottom of the system as shown by the dark arrows, the small light arrows show sunlight, and oxygen and nitric oxides are being released from the top.



Source: Suri, 2006

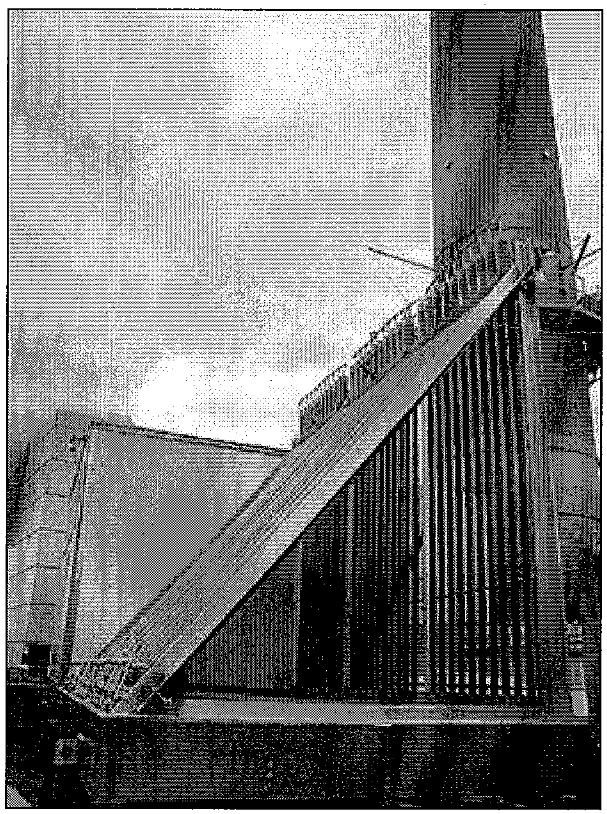
An experiment conducted in Italy and reported on in 2004 compared production levels between open and closed production systems (Pedroni et al., 2004). The results showed that there is not a significant difference between the production levels of the two systems. At the time, the researchers concluded that photobioreactors were not practicable because, although production rates were similar, photobioreactor costs were higher (Pedroni et al., 2004).

The problem with only promoting pond systems is that the total amount of CO_2 that could be sequestered with algae would be artificially limited as there are large numbers of coal-fired power plants in northern climes that would not be able to utilize algal sequestration technologies. The only choice for algal sequestration in these climates is the use of photobioreactors.

Though photobioreactors have been dismissed as uneconomical by many in the algae fuel world during the development of the technologies over the past few decades, certain groups have continued to focus on promoting and improving this technology. Experiments have continued to enhance light transfer rates to increase production, and new low-cost plastics have made photobioreactors more economical to construct (National Renewable Energy Laboratory, 2006). In fact, the photobioreactor at the Massachusetts Institute of Technology (MIT) has exhibited sequestration costs of $5-$8 per ton of CO_2 compared to the U.S. Department of Energy's stated goal of $10 per ton for sequestration (Department of Energy, 2007; Oak Ridge National Laboratory/Ohio University, 2002).

The MIT system of 30 photobioreactors (Figure 11) has run for months at a time and has captured up to 87 percent of the CO_2 and 80 percent of the NO_X in the flue gases released by the adjacent 18 megawatt power plant (The Energy Blog, 2005; Stauffer, 2006; Riesing, no date). Biomass in photobioreactors was shown to increase up to 400 times over a period of five days. This rate is a result of the algae population doubling every 7.5 hours, at an illumination level of 170 micromoles/m^2/sec^{-1} (Kremer et al., 2006).

Figure 11. – Small photobioreactors at Massachusetts Institute of Technology.



Source: The Energy Blog, 2005

The major limiting factor for growth in the enclosed photobioreactors is the amount of light that is available to the algae. The algae at the center of the tubes receive less solar energy then those nearer the edges. Also, the percentage of CO_2 sequestered during cloudy days at the MIT facility can drop to approximately 50 percent (Vunjak et al., 2005). New ways to open up more of the algae to illumination need to be found, including illuminating greater amounts of the growth medium and increasing light transferred to the growth medium during cloudy days.

The problem of illumination in enclosed algae systems is similar to the open pond systems. The light flux decreases exponentially with distance from the irradiated surface (Vunjak et al., 2005). There is a large amount of light energy available near the surface that is taken up by the algae there, but that energy is then unavailable to the rest of the population. In addition, the energy taken up near the surface is too great for the algae to utilize.

There are different groups working to overcome the limiting factors to growth in photobioreactors. Three different companies are currently in the process of bringing enclosed photobioreactor production facilities on line (Ngo, 2007). One of the companies, Greenfuel Technologies Corporation, is expected to have its first large-scale facilities producing fuels by 2008 (Energy Blog, 2005). Another company, Sunflower Electric, is planning to sequester up to 40 percent of the CO_2 expected to be released by a new coal fired power plant outside of Salina, Kansas. The project may be denied necessary permits, however, because the amount of water that needs to be pumped from the Oglalla Aquifer was deemed to be too large (Stineman, 2006).

The area required for photobioreactors is greater that that of raceway ponds. An estimate for the land required for sequestration with photobioreactors is approximately 4-5 hectares per megawatt at a coal-fired power plant (Greenfuel, 2007d). This compares to the estimated 2.8 hectares per megawatt required for the raceway pond system of sequestration.

Greenfuel Technologies, a leading photobioreactor company, has estimated that a 100-hectare facility is the minimum size required to produce enough algae to break even on the expense of constructing and operating the facility (Greenfuel, 2007a). The main source of income would come from the sale of the products of the sequestration process that include proteins for animal feed, carbohydrates for ethanol, and lipids for biodiesel (Greenfuel, 2007a). Another source of income is the sale of carbon credits for each ton of CO_2 that is sequestered. The current value for a ton of carbon is between \$3.30 and \$3.35 and has averaged between \$3-5 per ton over the past two years (Chicago Climate Exchange, 2007). This source of income was not included in the original feasibility study conducted by Greenfuel Technologies (Greenfuel, 2007a).

RESEARCH AND DEVELOPMENT NEEDS

Continued research and development are required to make the process of sequestration of CO_2 with algae economically viable. Some of the original problems have been sufficiently addressed, though continued work on these problems should improve the results. For example, the solution to finding algae strains that produce sufficient percentages of lipids has been solved, but any increase in lipid content per organism will improve the process.

Other problems will require additional work in order for production facilities to improve efficiency. Three main hurdles need to be overcome in both pond and photobioreactor production systems. They include increasing the efficiency of light utilization, finding a way to protect production strains of algae from invasion by other strains, and finding cheaper systems for harvesting algae.

There are a variety options to solve the problem of efficient use of available light. The problem is being approached in two different ways, improving light distribution and increasing the amount of light energy that is utilized.

Improvement of light distribution is being addressed by collecting solar energy and redirecting it to the production systems, instead of relying on passive solar distribution. Large collection facilities are able to gather solar energy and transport that energy to optical materials in the growth medium (Oak Ridge National Laboratory/Ohio University, 2002). This system is more practical for photobioreactors than for large-scale pond systems.

Improving the ability of algae to harness the light that is available can occur in several ways. One way is to devise better methods of mixing the growth medium so that a larger percentage of algae are exposed to the surface of the medium where more light is available (Pedroni et al., 2002). A second way is to genetically alter the algae so that each individual contains less chlorophyll. This will cause each individual alga to catch fewer protons from solar energy so that more energy is available to more individuals (Pedroni et al., 2002). Another alteration that is being investigated is the genetic alteration the algal so that the organelles that are responsible for photosynthesis can utilize solar energy (Pedroni et al., 2002).

In the past, the techniques for harvesting the algae from the production systems have all been deemed too expensive. Schemes have involved centrifuging and chemical flocculation. Centrifuging large amounts of growth medium was found to be hugely expensive and quickly ruled out. Chemical flocculation uses a substance such as lime, which when added to the growth medium causes charge neutralization and subsequent flocculation (Sazdanoff, 2006). The expense of large amounts of flocculants creates a drain on profits.

The current harvesting technique used in pond systems is natural flocculation. Flocculation occurs as algae die and clump together, because of charge neutralization. The clumps then fall out of solution and are collected (Sazdanoff, 2006). New settling systems are being tested that are able to harvest from 90-96 percent of the algae in solution (Nakamura, 2004). This percentage would include both living and dead algae. This would allow for even the dead algae to be utilized for oil extraction before it broke down. The technique is promising for its economic potential, but more work needs to be done to reduce costs.

ECONOMIC ANALYSIS

A 1995 study estimated that a 35 percent blend of soy-based biodiesel would be competitive with petrodiesel if petrodiesel costs were at $3 per gallon (Ahouissoissi et al., 1995). As oil prices have increased in the past few years, biodiesel, at least in blends, is getting close to this level. With increased research and development of both feedstock production and refining techniques, unblended biodiesel cost should be on par with petrodiesel within a decade.

At present, algae sequestration systems cannot yield rates where production of fuel oil alone makes economic sense. With development of certain strains of algae with high levels of biopolymers, valuable co-products could be generated (Benemann, 2003).

Products such as high-value bioplastics and polysaccharides can be produced from the algae before the oil is harvested (Benemann, 2003). These products are much more valuable than the biofuel feedstock oil, now worth approximately $1000/ton. (Benemann, 2003).

A cost consideration that needs to be taken into account is the cost of removing CO_2 from flue gases. There are several technology choices available for CO_2 removal. Algal sequestration would need to be competitive with these technologies before this sequestration technique would likely be considered for use.

The current technology of CO_2 removal from coal plant flue gases is a process of amine-based capture that strips CO_2 from emissions at the smokestack (Simmonds et al., no date). Another carbon sequestration option involves a process whereby CO_2 is absorbed with various substances. The absorbed CO_2 is then compressed and piped to facilities to be injected into either underground wells or into the deep ocean (Department of Energy, 2006). It is yet to be proven that the CO_2 will stay where it is placed.

The cost of amine capture is between $50 and $60 per ton of CO_2 (Simmonds et al., no date). This cost is lower than current estimates for algal sequestration, but much higher than estimated costs for the experimental production techniques. The U.S. Department of Energy is currently funding a program that is looking to bring the costs of sequestration below $10 a ton by 2012 by investigating a variety of new sequestration technologies (Department of Energy, 2007). This program plans to sequester 90 percent of the current level of CO_2 released with a 99 percent rate of permanence. At this level, electricity prices would need to be raised approximately 10 percent to cover the added expense (Department of Energy, 2006). This new process will likely supplant amine capture as the main CO_2 removal technology and be the main competitor with algal bioreactors for the sequestration market.

The production of algae for sequestration and oil production is not currently economically viable in pond systems. Pond systems cost approximately $100-$200 per ton in capital costs, which includes $100,000 to $120,000 dollars per hectare for the initial construction (van Harmelen and Oonk, 2006). Yearly operating costs are estimated to be up to $12,000 for each hectare (Benemann et al., 2002).

The pond systems are only possible in favorable climates, as cold weather and lack of sunlight during northern winters shorten the algal growing season. For production to be feasible at more extreme northern latitudes, closed system photobioreactors need to be improved through continued research and development so that capital and production costs are lowered. The current cost of soybean oil, a comparable oil for use as a feedstock, is approximately $30 (Chicago Board of Trade, 2007). The oil produced by photobioreactors would need to be produced at a cost equal to or lower than this price. The return on investment could be supplemented by selling carbon credits to other emitters. In fact, this aspect is likely to be the main attraction to potential investors (Schulz, 2006).

Current carbon credits in the U.S. are $4 per ton of emissions avoided (Chicago Climate Exchange, 2007). This amount will increase as more attention is paid to greenhouse gas emissions, and rising concerns about global warming increase the demand for reductions of these emissions.

New enclosed photobioreactor systems have been utilizing updated designs and cheaper materials to decrease the costs associated with the process. Tested with flue gases containing 13 percent CO_2, the photobioreactor at the MIT sequestered 50-80 percent of the CO_2 of the school power plant (Riesing, no date). The cost of the process was estimated to be between $5-$8 per ton of carbon sequestered, less than the goal of the Department of Energy sequestration program and 20 percent of amine capture systems (Oak Ridge National Laboratory/Ohio University, 2002).

The MIT program harvested an average of 15-30 percent of the algae produced (Riesing, no date). The algae produced each day were then available for processing into oil. The fact that the process was cheaper than other sequestration techniques and had the additional benefit of being a domestic transportation fuel source makes expansion appear promising. This is especially appealing as the costs of algal sequestration could be turned into a profit for the production companies, and thus reduce the costs to the consumers of the electricity produced at the power plant. An analysis of the MIT program estimated that the photobioreactors would be able to replace approximately 20-25 percent of the total U.S. transportation sector fuel needs (Riesing, no date).

USE OF ALGAL SEQUESTRATION IN WASHINGTON

The Transalta Corporation is a Canadian-based company that has coal-fired power plants throughout the United States and Canada. Since 1990, the company has increased its electrical generation capabilities by 77 percent, while reducing its emissions by 11 percent. The company's main strategy for reducing emissions is to promote production efficiencies and sustainable technologies (Transalta Corporation, 2005).

The main increases in efficiency result from the planning of new facilities that have burning technologies that produce more steam per unit of fuel (Transalta

Corporation, 2005). The sustainable technologies include active management of sulfur dioxide, oxides of nitrogen, mercury, and particulate-matter emissions at production facilities (Southwest Clean Air Agency, 2005b). Active controls are used to manage the particulate matter and sulfur dioxide (Southwest Clean Air Agency, 2005b). The other emissions are controlled through utilization of good combustion techniques that have reduced emissions from past levels.

The company currently does not utilize controls for CO_2 emissions, and CO_2 emissions comprise 99 percent of the company's greenhouse gas emissions (Transalta Corporation, 2005). Emissions credit purchases are proposed to offset the CO_2 from all new plants currently in the planning stage (Transalta Corporation, 2005). There are no plans for active management of CO_2 emissions. Most of the company's current research funding is appropriated for programs focused on reducing mercury emissions (Transalta Corporation, 2005).

Coal-fired power plants are permitted under Section V of the Clean Air Act. The five-year permits provided under this section require continuous monitoring of all emissions that are declared to effect environmental quality (Southwest Clean Air Agency, 2005a). The emissions that are actively limited by the permit include sulfur dioxide, nitric oxides, mercury, and particulate matter emissions.

The CO_2 levels are monitored in accordance with federal rule, 40 CFR part 175, not Title V (Southwest Clean Air Agency, 2005b). Though monitored, CO_2 is not actively limited under the current permit system. The quarterly emissions totals are reported to state or local agencies that have oversight duties granted through the

Environmental Protection Agency, but if the terms of the permits are not followed, the permittees are held accountable according to the Clean Air Act.

Transalta owns a coal-fired power plant in Centralia, Washington operated under Title V as permitted by the Southwest Clean Air Agency in Vancouver, Washington (Southwest Clean Air Agency, 2005a). The facility is comprised of two plants that each are capable of producing approximately 700 megawatts of electricity (Southwest Clean Air Agency, 2005b). Because of the type of coal used, the Centralia plant emits very little mercury. Other emissions require management to lessen the levels released during burning (Transalta Corporation, 2005). The plant has emitted decreasing amounts of NO_X, SO_2, and particulate matter in the past few years, but the plant still releases relatively large amounts of CO_2. The amount of CO_2 released has averaged over twelve million tons per year over the past few years, and there are no plans to limit this type of emission (Southwest Clean Air Agency, 2007; Transalta Corporation, 2005). Recent plant emissions are summarized in Table 3.

Table 3. - Overall Centralia plant emissions in tons.

Year	NO_X	SO_2	PM	CO_2
2003	6,547	181	9,504	13,102,236
2004	4,704	106	8,664	12,150,042
2005	3,776	95	5,879	12,517,501

Source: Southwest Clean Air Agency, 2007

The plant is one of the largest coal-fired plants in the western United States. More coal-fired plants may come on line to meet demand in the area. Washington currently produces approximately 90 percent of its electricity from hydropower (Environmental Protection Agency/Department of Energy, 2000). The creation of any new large-scale hydropower dams is unlikely. More power plants will be needed to meet the rising demand created by both the increase in usage per capita and the annual increase in population that the state is experiencing. A recent state law, WAC 173-401, mandates that new plants control some of the CO_2 emitted, but the Centralia plant will be exempt so it will not be required to reduce its emissions (Southwest Clean Air Agency, 2007).

Since CO_2 emissions at the Centralia plant will not fall under the new state law, and are not yet controlled under the Clean Air Act, there is no financial incentive for Transalta to reduce the emissions. Current CO_2 remediation techniques are not economically feasible and cheap sequestration techniques that may be technologically feasible would still eat into company profits.

An algal photobioreactor, based on the current systems, for sequestering CO_2 could either be financially beneficial to the company or would have the sequestration costs absorbed by another company that would provide the service. Transalta might only need to provide the land required for the photobioreactor facility to efficiently reduce CO_2 emissions at the Centralia plant.

The amount of land that photobioreactors require for sequestration is 4-5 hectares per megawatt (Greenfuel, 2007d). The main requirement for the construction of a photobioreactor system is the land needed for the facility. The process does not require retooling of the power plant facility and can use many types of water including waste or reclaimed water (Greenfuel, 2007a; Greenfuel, 2007b). In addition, once the facility has been set up, most of the process water is recycled after the algal harvesting takes place.

FEASIBILITY AT CENTRALIA

The light and climatic conditions in the area of western Washington where the Transalta Centralia power plant is located preclude the use of a pond sequestration system. Photobioreactors would be required to keep the growth medium at the necessary temperature range of 50-110 degrees Fahrenheit, and the addition of extra light energy through a solar collection facility would be required for sufficient production rates (Greenfuel, 2007b). The size of the power plant and the large amount of CO_2 released will necessitate a large sequestration facility to capture a significant percentage of the CO_2 released.

The amount of land required to sequester the entire amount of CO_2 released at the power plant with photobioreactors would be approximately 5,600 to 6,700 hectares (Greenfuel, 2007d). The current rate of sequestration with existing technology is approximately 80 percent during daylight hours. The overall 24-hour rate of 40 percent would sequester approximately 4,800,000 tons of CO_2 per year, if the facility was built to maximum capacity (Greenfuel, 2007b). The volume of biodiesel that could be produced from a sequestration system covering this area amounts to 70 to 140 million gallons per year (Greenfuel, 2007c).

An abandoned coal mine owned by Transalta adjacent to the power plant property provides a large tract of land that is available for building a sequestration facility. It is not large enough for a sequestration facility sizable enough to sequester all of the CO_2

released by the plant, but enough land is available for a facility that would be much larger than the minimum size estimated to be economically feasible. Transalta currently does not plan to sequester any of the CO_2 released at its plants through amine capture or the sequestration process that the U.S. Department of Energy is investigating (Transalta Corporation, 2005). There are still justifications for a facility that could utilize the available land and sequester some of the available CO_2.

The permitted area of the mine is 5776 hectares (Figure 12). The actual area that has been disturbed is 1,703 hectares (Office of Surface Mining, 2007). The disturbed land is slated to undergo a remediation process as a stipulation of the mine permit if a better use for the land is not found (Office of Surface Mining, 2007). A sequestration facility should fulfill the requirements of "better use" and would be more environmentally friendly than other uses that have been proposed for the property. A sequestration facility would not allow for complete reclamation and revegetation of the mine site, but it would have an environmental benefit by removing CO_2 that is causing wide-ranging environmental problems.

Figure 12. – Photo of Centralia mine permit area (outlined in yellow).

Source: Office of Surface Mining, 2006

The major restriction to using the disturbed area for a sequestration facility is that the slopes in the area are approximately 3:1 (Office of Surface Mining, 2007). Some earthwork would be required to create an area suitable to build sequestration facilities on the disturbed areas. There rest of the area permitted for mining is forested hillsides that are now likely to return to commercial forestry applications (Office of Surface Mining, 2007).

Transalta owns some of this forested area and leases the rest from a forestry company. Much of this land would be available for a sequestration facility. There is also an area of 2,800 hectares adjacent to the area permitted for mining that Transalta owns and is currently working to permit for additional mining. This additional area may not likely to ever be mined, so this area would also be available for sequestration production (Office of Surface Mining, 2007). The area under consideration for new permits is also on forested slopes, but some of the land would be appropriate for construction of algal facilities.

In addition to the land requirement, water availability may be another limiting factor. The ability of algae species to live in water of poor quality allows for the use of wastewater or other sources of previously used water in a photobioreactor (van Harmelen and Oonk, 2006). The sequestration process also recycles most of the water required, so once the original quantity of water is obtained, large amounts of additional water will not be needed as the bioreactor operates.

If reused water sources are not available locally or not allowed under permitting conditions, groundwater would be available. Under Washington State water law, up to 5,000 gallons of water per day for industrial use is exempt from the need to obtain water rights (Gregoire et al., 2000). This amount of water is sufficient for providing water for startup of the photobioreactor process.

Environmental permit requirements for the process would include both State and National Environmental Permit Act (SEPA/NEPA) review, and registration with the Olympic Region Clean Air Agency (Washington State Office of Regulatory Assistance, 2007). The SEPA/NEPA review would be extensive, as the project could impact both slopes and wetlands, but the project would likely be approved through mitigation of local environmental impacts and because of its overall positive environmental benefits for the larger area. Registration with the local clean air agency would just be a formality as the process releases only oxygen and nitrogen gases, which are not known to cause environmental degradation (Greenfuel, 2007b).

There is a market available for the algae oil produced that would create additional environmental benefits from the sequestration process. The largest biodiesel plant in the nation is currently being built on the Washington coast, less than 60 miles from the Centralia power plant (Blumenthal, 2007). That coastal plant is currently depending on future overseas imports of palm oil as the feedstock for the biodiesel to be produced (Verhey, 2006).

Palm oil is produced on plantations in tropical areas of the world, which are often developed on land that was formerly rainforest (Blumenthal, 2007). Importing large amounts of palm oil for the production of biodiesel may create incentives to clear more of those forests. This fact, in conjunction with the fuel used to transport the palm oil from overseas, makes the choice of palm oil for a feedstock environmentally questionable.

Algae produced in Centralia would provide a truly renewable local feedstock for biodiesel production at the coastal facility.

It remains to be seen whether or not the algal oil could be produced at a cost that would be economically competitive with other feedstocks such as palm oil. The overall costs will depend on the expense of building on the available land, the type of photobioreactor used, and the technological improvements created during the continued research and development of the process.

CONCLUSIONS AND RECOMMENDATIONS

The sequestration of CO_2 from coal-fired power plants using algae should not be viewed as the end goal of moving away from petroleum-based fuels. The utilization of biofuels in place of petrofuels should be an intermediate step towards a non-hydrocarbon-based fuel system that hopefully will be more environmentally benign, in both production and emissions, than the fuel systems used to power internal combustion engines.

Until a non-hydrocarbon-based fuel system becomes technologically and economically available, an alternative to petroleum fuels that can be utilized by current engines needs to be readily available. Use of petroleum for transportation fuels will continue to cause a significant increase in greenhouse gases, while continuing our dependence on a finite fuel supply. Also, prices for transportation fuels will continue to rise as supplies decrease and world demand increases.

Biofuels are a drop-in technology that can be transported and distributed with existing infrastructure, and biofuels are readily mixed with petroleum fuels to create blends. These blended fuels can be burned in current engines with no modifications. The main limiting factor for replacing a large percentage of petroleum fuels with biofuels is the availability of feedstocks through the traditional sources of agricultural crops and waste fats.

Algal production of oil for biofuel feedstocks has greater potential for generating larger quantities than traditional feedstock sources. Algae do not have the limiting factors of land and water that restrict agricultural production, as algae can be grown on non-arable land with wastewater or other non-potable water as the growth medium.

Growth of algae on non-arable land allows for large production facilities near already industrialized land, while not taking land out of food production. Using water that has already been employed for human use lessens the impact on already over-utilized water sources. Increased production of agricultural crops for feedstocks either removes land for growing food crops or adds land to production, which reduces wildlife habitat. Both scenarios increase the rates of chemical and water use.

The high rate of growth and the large amount of CO_2 that can be absorbed by algae have the potential for a much higher rate of sequestration per hectare than is possible with terrestrial plants. The potential percentage of overall transportation fuel that algae could supplant is much greater than agricultural crops, because the main market for the oil is the production of biofuels and not for food production.

The fact that algae production systems use waste streams (flue gases and wastewater) for growth instead of chemical fertilizers increases the energy efficiency of the fuel produced. The use of these fuels in the transportation sector gives the greatest energy value per unit of energy used of any oil source. This positive value makes algae oil feedstocks a logical choice for future biofuel production.

Transalta does not currently plan to sequester CO_2 from its power plants. The company's strategy for lessening its CO_2 impacts is through better planning of future facilities and the purchase of carbon credits. It would behoove the company to begin a program of algal sequestration at its facilities. The program would lessen its impact on the environment, and potentially could generate additional profits. Transalta would gain the benefit of a better environmental image while also gaining a possible revenue source.

There is a market for the oil produced through the sequestration process, and the potential carbon credits earned could offset the funds currently being spent on purchasing credits from other sources. The company may not want to build a sequestration facility that would capture all of the CO_2 released, but the company currently owns idle land that would house a facility that would capture a high enough percentage to be profitable.

Currently 70 percent of power facilities in the United States have land available for an algal sequestration facility (Energy Blog, 2005). As the various processes are improved with additional research and development, the cost/benefit ratio will likely improve. If the profitability of the process is proven on a large scale, the technology will proliferate to fill the available market niche. The fact that the end product can be distributed and utilized with current technologies will make the infrastructure costs of its wide-scale introduction relatively cheap compared to other alternatives such as hydrogen fuel cells.

The algal sequestration/biofuel process should be promoted as an interim measure until a non-hydrocarbon-based fuel economy can be brought on line. The process has the potential to benignly replace a significant percentage of the petroleum-based fuel, while still allowing Americans to keep their current lifestyles.

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