Algae Based Biodiesel

Brian Neltner
Jeff Tester, Adviser

April 29, 2008

Abstract

Algae based biodiesel is examined as a potential source for transportation fuel in the United States. Algae has many attractive features — the potential to be grown in regions which are not suitable for food crops, the potential to produce around 14000 gallons of biodiesel per acre of land used as compared to 328 gallons per acre for current corn-based ethanol, and clear routes to improvements in technology.

1 Introduction

As traditional oil prices continue to rise globally, the importance of alternative sources of oil or oil replacements will continue to increase. There are a wide variety of options for replacing our current fuels with biofuels produced from plant matter, including corn, switchgrass, and sugarcane based ethanol, cellulosic ethanol, thermal depolymerization, and biodiesel based on soy and algae. [1, 2]

There are problems associated with each of these fuels, including:

- Energy balance.
- Competition with food crops.
- Economic viability.
- Environmental impact.
- Viability as a direct replacement for current fuels.

Algae based biodiesel has the capacity to successfully meet all of these primary challenges to biofuel adoption. Algae grows extremely quickly, and has a very high lipid content of as high as 77% in wild strains, allowing the production of around 14000 gallons of biodiesel per acre per year. [2–4] For comparison, corn-based ethanol has the potential to produce around 328 gallons per acre of ethanol, or a mere 19 gallons per acre of biodiesel. [2, 5]

Algae can readily grow in salt water unsuitable for use by typical food crops, and can be grown on marginal land with poor soil, or even off of waste products such as sewage or CO_2 emissions from power plants. [2, 6] Algae, due to it's non-competition with food cropland, high growth rate, ability to fixate large amounts of CO_2, and potential to be grown from hazardous contaminants, has a very positive potential environmental impact. [7]

Finally, algae based biodiesel is similar enough to current biodiesel to be used as an immediate replacement. [2, 8] Current vehicles with diesel engines could use the fuel directly with no modification, allowing for the rapid incorporation of the alternative fuel into our existing fuel infrastructure and avoiding the "chicken and the egg" problem with alternative fuels. [9]

2 Energy Balance

There has been a lot of discussion about the thermodynamics of biofuels in the recent past. Much of this discussion has been focused on the viability of corn-based ethanol, which seems to have an energy content of around 1.3:1 (30% more energy than went into growing it).

It is very difficult to estimate the energy content of algae-based biodiesel. This is in large part due to the uncertainties surrounding how best to grow and process it; different methods for growing result in orders of magnitude difference in estimates for energy inputs. Additionally, because the technologies involved are all new, much of the knowledge involved in growing algae economically is secret and has not been peer-reviewed.

For example, a traditional process for producing biodiesel would include growing the algae, harvesting it, drying and breaking up the cells, extracting the oil, and esterizing the oil. This process requires centrifuges or filters, large amounts of hexane or other solvents, and methanol to esterize the lipids extracted. However, simply switching to a press filter versus using a centrifuge can result in wildly different estimates as to the costs involved.

As an even more pronounced alternative, using a gasification process on the undried biomass directly to produce fuels could be much simpler and less expensive energetically than the more complicated machinery in terms of embodied energy. These estimates are extremely difficult to make, and there has been no canonical value used for the actual energy balance. If highly inefficient processing is used, the energy balance could easily be less than 1:1. However, any economically feasible method of processing will also likely be energetically cheap, and should be workable overall.

An interesting note is that at an energy gain of less than around 5:1, an economy (which is fundamentally trading energy), ceases to expand. Thus, if the energy balance isn't sufficiently positive, it will stagnate the economy or even result in a major recession. This is somewhat surprising, as intuitively one would imagine that 1:1 is the limit for making generating energy attractive. Unfortunately, due to fixed costs and general entropic decay, it is necessary to actually generate substantially more energy than the bare minimum. Essentially, the argument is that our economy as a whole is only about 20% efficient. [10]

3 Competition with Food Crops

3.1 Case Study: Corn-based Ethanol

A very serious concern with biofuels is that by growing crops to produce fuel, we grow fewer crops to address the nutritional needs of the world population. In the case of corn based ethanol:

1. Current yields of around 328 gallons per acre. [5]
2. Current transportation energy use of 26.5 quads. [11]
3. Ethanol energy content of 29.67 kJ/gm. [12]
4. Ethanol density is 0.7893 gm/cm^3. [12]
5. The energy balance of corn ethanol is approximately 1.3:1. [13]

From this fairly well established baseline data, it is straightforward to calculate the amount of cropland that is required to use ethanol to replace our fossil fuel usage. First, to meet our total transportation need requires 26.5 quads (approximately $26.5 \cdot 10^{15}$ kJ) of energy, which, if met entirely by ethanol, is equal to $89.3 \cdot 10^{15}$ gm of ethanol. At a density of .7893 gm/cm^3, this works out to around $300 \cdot 10^9$ gallons of ethanol.

From there, it is straightforward to convert to acres of land usage — at 328 gallons/acre, we can produce that $300 \cdot 10^9$ gallons of ethanol using 911 million acres of farm land.

Unfortunately, this isn't the end of the story. Non-cellulosic corn-based ethanol has an energy content of just 1.3 times the energy put into it, mostly in the form of oil. So, while using those 911 million acres of farm land allows us to produce enough ethanol to replace our gasoline as a transport fuel, we will need over 75% of our current transportation fuel usage in order to grow that much corn. Thus, if we want to have a "closed system" where ethanol from corn is used also to grow more ethanol, we need to grow 75% more ethanol than we would think based on a pure productivity calculation. Taking additionally into account the corn required to grow that additional 75% ends up working out to an exponential decay function, the area of which is given by

$$T = \sum_{x=0}^{\infty} (0.75)^x \tag{1}$$

which, using the rules for summing infinite series, gives

$$T = \frac{1}{1 - .75} \tag{2}$$

or T, the total ethanol required, is 4 times the amount needed if a closed system is not enforced.

Thus, with an energy basis of 1.3:1 (which many argue is an overestimate [5]), we would need on the order of 3.6 billion acres of cropland. For comparison, the total current agricultural land in the US amounts to 450 million acres. This is clearly a huge feasibility problem in the case of corn based ethanol, as the plan inherently requires over 3 billion acres of cropland outside the country be used to produce ethanol for the US. It hardly reduces the dependence on foreign sources of fuel, and given that the US is one of the most productive countries in the world for agriculture, is unlikely to ever be plausibly produced by other countries for our use.

Additionally, by converting so much land to fuel production, the cropland remaining for food is very limited — competition is inevitable, with affluent nations purchasing food to turn it into fuel while poor nations are unable to provide nutrition to their citizens. There are already food riots starting all over the world, and pursuing ethanol based on corn will result in disaster.

Cellulosic ethanol has the potential to avoid these issues by using a larger amount of the plant (around 50% as compared to just the sugar-containing seeds), and because the energy balance of cellulosic ethanol could be as high as 36:1. [13] However, it is unavoidable that any terrestrial crop grown for fuel on viable farmland instead of being used for food crops will compete with food and drive the price of food up. Additionally, cellulosic ethanol is not a proven technology, and may not be viable for some time.

3.2 Algae-based Biodiesel

Algae-based biodiesel has the potential to produce over 14000 gallons of biodiesel per acre of land. [2] Additionally, algae can be easily grown in a growth media composed primarily of seawater. [2,4,6,7] Finally, because the algae is grown in liquid, typically inside either a raceway or photobioreactor, the algae can readily be grown on so-called "marginal land" — land where either the nutrient content, salinity, or pH is inappropriate for terrestrial crop growth.

Additionally, the energy content of biodiesel is typically around 33 MJ/L, so to produce the 26.5 quads of transportation energy required in the U.S. will require $803 \cdot 10^9$ L, or $212 \cdot 10^9$ gallons of biodiesel. Thus, using the best current scenario of 14000 gallons per acre for algae based biodiesel, it is possible to completely meet the transportation needs of the United States using 15 million acres of land, none of which needs to be farmland.

The energy balance of algae is less well established than for ethanol, as the total balance will depend in large part on the specific technologies chosen for the production. However, if we assume that algae based biodiesel is the same as for corn-based ethanol, we end up requiring 60 million acres of marginal land to give the United States a completely self-contained transportation fuel infrastructure.

Using any terrestrial crop as a fuel source will inevitably lead to competition for farmland and fresh water with valuable food crops needed for the well-being of the world's population. The use of algae capable of growing on marginal land in water with high salinity is the only practical and close to commercially viable "biofuel" in this respect.

4 Energy Security

There are very serious national security concerns with regard to our energy security. Our current dependence on foreign oil from the Persian Gulf puts us in a very difficult situation economically, politically, and militarily. If a war were to break out which disrupted our ability to import foreign oil, we would be unable to meet our energy needs. [1]

By utilizing modern technology and advanced agriculture techniques, we have the potential to grow our petroleum feedstocks through the use of a small fraction of our land mass. This is an absolutely critical requirement for our future security, especially as we begin to enter into more pronounced competition with China for energy. [14]

Recommendations for mitigating the effect of energy on our foreign policy have included

- A tax on gasoline (with the tax revenue recycled into the economy with a fraction possibly earmarked for specific purposes such as financing of energy technology research and development [R&D]).
- Stricter and broader mandated Corporate Average Fuel Economy standards, known as CAFE standards.
- The use of tradeable gasoline permits that would cap the total level of gasoline consumed in the economy.

Of these proposed possibilities, the first and the third would potentially encourage the use of alternative fuels such as the algae-based biodiesel discussed in this paper. As the price of gasoline becomes larger either through a tax or through regulatory limits to the amount of gasoline allowed to be consumed, the price of biofuels will become more competitive.

5 Environmental Impact

The environmental impact of algae-based biodiesel is projected to be highly beneficial. This is due to a number of factors, including:

- Low land usage. [2, 4, 6]
- Growth on Marginal Land. [2, 4, 6, 7]
- Non-competition with Food Crops. [2, 4, 6, 7]
- Growth on hazardous waste. [7]
- Growth using CO_2 waste from power plants. [15, 16]

All of these are seen as highly desirable in terms of environmental impact. Algae is currently being tested as a method for removing carbon dioxide from the exhaust of power plants, essentially giving the carbon dioxide an extra step of use before being released into the atmosphere and increasing the total energy use per unit of carbon released.

Additionally, and critically from an environmental standpoint, algae based biodiesel can be grown in areas where it will not compete with food crops, or result in the destruction of large areas of forest in order to provide additional farmland. The decreased land usage in general will also encourage better land utilization, and less impact on wildlife.

Algae can also be grown on hazardous waste. It is already in wide use as a way to partially treat wastewater, and has been demonstrated to be usable to remove [7]:

- Polycyclic aromatic hydrocarbons
- Phenolics
- Organic solvents
- Heavy Metals
- Pathogens

In terms of specific chemicals, it has been shown that algae can be used to remove (number in parenthesis is rate of removal in mg/L·day) [7]:

- Acetonitrile (2300)
- Black oil (5.5)
- Phenanthrene (576)
- Phenol (90)
- Phenol Salicylate (2088)
- p-Nitrophenol (50)

In particular, it is highly advantageous to combine CO_2 from power plant waste with wastewater treatment in order to provide an extremely high growth rate, high rate of hazardous chemical consumption, and produces oil at rates which are getting close to economical as well. Finally, algae uses far less water than traditional oilseed crops. [1]

6 Fuel Compatibility

A huge problem with many alternative fuels is that they are not compatible with current vehicles. This incompatibility means that even with substantial government subsidies designed to encourage adoption of alternative fuel, and even with a substantial improvement to fuel efficiency or positive environmental impact, alternative fuels routinely fail. This can be readily understood in terms of the "chicken and the egg" problem. [9]

Ethanol as a fuel source has this problem. Ethanol is a slightly polar, hygroscopic, and corrosive liquid in the case of a steel storage infrastructure. Gasoline, on the other hand, is non-polar, doesn't absorb water, and is non-corrosive. Although a small amount of ethanol can be mixed in with gasoline with no ill effect, a large fraction of ethanol requires a different distribution mechanism, different pumps, and will suffer the problems outlined by Struben et al in attempting to gain adoption.

This problem has also been seen by less controversial alternative fuels such as diesel and liquefied natural gas, which are relatively compatible with current pump technology, competitive with gasoline as a fuel, and utilize technology which is inexpensive and readily available. The lack of adoption has also been readily seen with more complex and divergent technologies such as hydrogen or electric vehicles (although this can also be attributed to the current technical problems surrounding both fuels).

Algae based biodiesel (and biodiesel in general), has a huge advantage over other alternative fuels such as ethanol, hydrogen, and electricity, in that it is compatible chemically with existing diesel fuel. Generally, blends of up to 20% biodiesel with regular diesel (B20) are compatible with existing diesel engines, while some minor engine modifications are required to run on up to 100% biodiesel (B100) to avoid maintenance and performance problems. Biodiesel is sometimes slightly hygroscopic due to incomplete esterification; however, overall it is hydrophobic and should not absorb large amounts of water.

The largest issue with biodiesel is that, due to the esters in it's makeup, it will more rapidly degrade natural rubber gaskets and hoses. However, natural rubber has not been commonly used in engines for about 15 years, and most modern diesel engines will be able to run on B100 without modification.

Although diesel engines are not in widespread use in the United States, the large number of freight trucks and other large trucks which use diesel have resulted in an extensive availability of fuel. Thus, switching to biodiesel has the potential to avoid the chicken and the egg problem of most alternative fuels. The fuel would be easily available all over the country, so the primary barrier to using an alternative fuel car is removed for consumers. Additionally, diesel fuel is widely used already in Europe and in other countries around the world, making the transition to biodiesel in those places extremely simple.

7 Economic Viability

Algae based biodiesel was not economically feasible in 2002, but with the rapidly rising price of oil is very close to feasibility now. [17] At the current oil price of $117/barrel, biodiesel would need to be priced at approximately $0.81/L in order to be competitive. [2] Currently, biodiesel made from corn, soy, palm, and other terrestrial crops in a B20 (20% biodiesel, 80% petrodiesel) mixture are equal in price to pure petrodiesel, while B2 and B5 are less expensive than pure petrodiesel by around 12 cents. This is in large part due to incentives and lower taxes on biofuels, but the costs

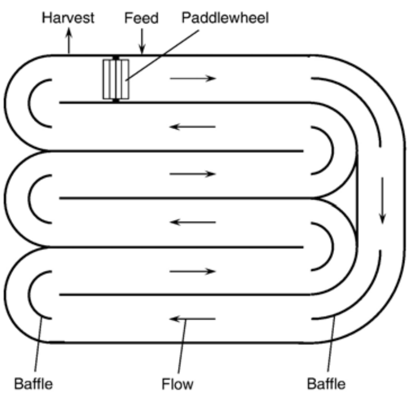

Figure 1: The raceway is an open pond which requires little capital investment and is very simple to operate. The photo is of the Cyanotech Corporation's microalgae production facility in Kona, Hawaii. [2, 7]

involved in producing biodiesel are also decreasing rapidly as more money is invested into research and scaling up current technologies.

7.1 Ways to grow algae

There are two primary ways to grow algae — photobioreactors (PBRs) and raceways. A raceway is an open pond with constant circulation. They are cheap to build, but have a comparatively low productivity per land area used (Fig 1). Previous work has primarily focused on raceways because of their simplicity and low capital expense. [1]

A photobioreactor is a more modern design for growing algae in which the growth area is entirely enclosed (Fig 2). Nutrients are added, cooling is done actively, more elaborate pumping mechanisms are used, and active removal of waste byproducts is accomplished. By using a closed system, PBRs are able to use a mono-culture of algae which allows for higher-lipid content strains to be selectively grown. Finally, PBRs are typically able to have a higher concentration of algae, at approximately 28 times the biomass concentration in the broth. This increased concentration allows for more efficient extraction from solution.

There are many considerations in choosing which technology to use, including [7, 18]

- Contamination with wild, local algae or predatory microorganisms such as *Chytridium* sp.

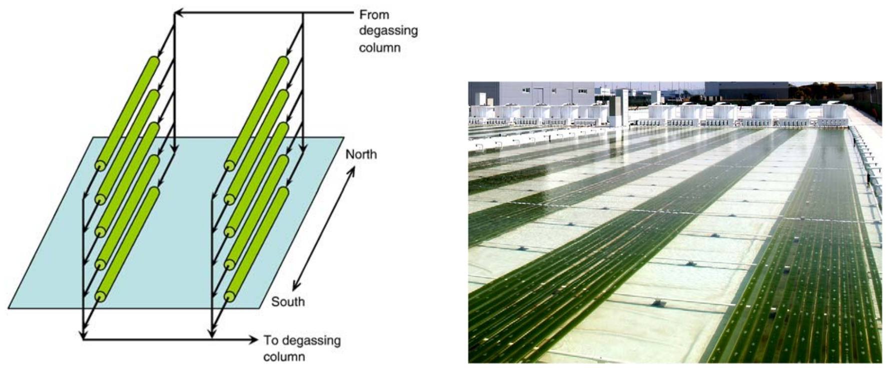

Figure 2: A PBR is a series of fully-enclosed tubes through which growth media flows and algae is grown. The photo is of the Easy Algaes production facility, Cádiz, Spain. [2, 7]

- Temperature Control
- pH control as carbon dioxide is consumed.
- Light supply optimization.
- Dissolved Oxygen content control.

In the case of a raceway, contamination is much more likely. The open nature of the system makes it very difficult to grow a monoculture of algae, so the ability to grow high-lipid content strains is reduced. Additionally, predators can invade the system and reduce yields.

Raceway systems are typically cooled entirely through evaporative cooling, which means that compared to an active system it is much less well regulated. Temperatures could rise during the day and drop during the night enough to damage or reduce growth rate of the algae.

In both the raceway and photobioreactor, rapid consumption of carbon dioxide by the algae can cause the pH to change. This can result in unfavorable conditions for algae growth, and needs to be controlled by the addition of buffers and neutralization agents. This sort of gas transfer requirement is easier to fulfill in a photobioreactor, and such systems typically have a better ability to control pH as well as dissolved oxygen content. [18]

Light supply is easier to optimize in a photobioreactor. Algae prefers to be exposed to very bright light, and then darkness in succession to produce optimal growth. [19] The exact period of the bright and dark stages hasn't yet been completely determined, but photobioreactors readily lend themselves to this sort of switching. [2]

By introducing turbulence into the clear tubes in which the algae grow, algae is alternatively pushed to the boundary of the tube where there is intense light and to the middle of the tube, where biomass blocks much of the light. This effect also allows for photobioreactors to have a much higher algae density in the growth media as darkness in the middle of the tube is desirable and will not result in poor growth rates for any algae. Alternatively, in a raceway any algae at the "bottom" of the pond will receive very little light and be unproductive. Thus, the overall biomass density has to be kept lower in order to ensure acceptable light levels to the bottom.

This increased biomass density means that less volumetric area is needed to grow the same amount of algae, and that harvesting is simplified. In addition, the mixing in a photobioreactor means that all algae is equally productive, and can all be kept relatively close to their optimal light conditions. Thus, a photobioreactor is typically much more productive (13 times more productive per unit volume).

7.2 Refining Costs

There are several options for the processing of algae into biodiesel. The primary involved steps are:

1. Harvesting
2. Drying
3. Extraction
4. Esterification

Harvesting can generally be done either by centrifugation, filtration, or gravity sedimentation. Generally, the best solution produces the lowest water-content biomass, and will thus require the least thermal drying later on. Mechanical water separation is typically less expensive than thermal drying, so this is almost always economically advantageous.

Typically, a self-cleaning disc-stack centrifuge will get you a concentration factor of 120, compared to 20-150 for nozzle discharge centrifuges. Filtration can be done using a variety of methods. A Netzsch chamber filter, belt press, suction filter, or a non-precoat vacuum drum filter will all achieve a concentration factor of over 100. [17]

Based on this data, it seems that the most economical option is probably to use a simple belt press to "squeeze out" all of the water from the algae sludge; especially given the high initial concentration of algae in a photobioreactor (0.4 wt%). If it is desired to keep the cells as intact as possible in order to extract other high-value products from the cells such as eicosapentaenoic acid or other biological products, centrifugation may be the more economical method as it is less likely to damage the cells.

After harvesting, the biomass must be dried to remove all water, and must be dried within hours to prevent spoilage in a hot climate. A number of drying methods include spray drying, drum drying, freeze-drying, and sun drying. [17] Freeze drying is too expensive for use in low-value products like biodiesel. Sun drying is likely the least expensive option, and spray drying is the method of choice in most installations.

In order to actually extract the oil from the microalgae, the cell walls must be disrupted. If freeze drying is used to dry the cells, this will also serve the purpose of disrupting the cell walls, however, mechanical disruption is also very reasonable to do. This would generally be done by taking dried biomass and grinding it using glass or ceramic beads in a large rotating drum. An alternative chemical treatment is to use an alkali to lyse the cell wall. This will generally not be suitable for extracting sensitive proteins, but is reasonable for extracting lipids and free fatty acids for use in biodiesel.

After the cells are disrupted, the oil is extracted. Methods for extraction include solvent extraction using hexane, supercritical CO_2 or other polar solvents. These methods are identical to those used to extract vegetable oil from any other biomass, and are well understood. Similarly, the esterification process will be identical to that of any of the other crops currently used to produce biodiesel such as palm oil or soybean.

Overall, the greatest difference between using algae and using palm oil as a starting material for producing biodiesel is that algae is unicellular, and grows in water. This results in an increased cost as the algae is more difficult to isolate, and is more difficult to dry than similar terrestrial plants.

7.3 Non-traditional Reforming Options

A more current alternative is to use catalytic reforming to convert biomass directly into syngas, and from there into fuels. For example, through steam reforming and the water-gas shift reaction, both readily catalyzed by nickel or iron oxide, you can convert biomass directly into hydrogen gas and carbon dioxide. As a side-benefit, this conversion requires water to be present, and so the drying and harvesting stages of processing are removed.

In this alternative process, the 0.4 wt% biomass is concentrated to a higher fraction on the order of 30-50% using a press. This partially dried biomass can then be directly heated to high temperature where the steam oxidizes the carbon in the biomass, releasing hydrogen and carbon monoxide.

Further, over a nickel or iron oxide catalyst, the water additionally oxidizes the free carbon monoxide to form additional hydrogen and carbon dioxide.

This alternative route is highly desirable, and a great deal of current research is focused on finding suitable low temperature catalysts for this route.

7.4 Economics for Photobioreactors

7.4.1 Biomass Production Costs

A study by Grima suggested that using PBRs would result in a cost of \$32 /kg for the raw algae biomass in a system designed to produce 2620 kg of crude esterified algae oil per year. This raw biomass cost is 13% for the raw materials, 39% for capital expenses, and 48% for other expenses which are primarily labor and plant overhead. For comparison, only 2% of the cost of producing crude oil comes from capital expenses. Thus, it can be seen that the primary cost in producing algae biomass is the large capital investment required to construct the growth pools and purification/drying equipment. [17]

Of these capital costs, the primary contributors are the actual PBRs, the centrifuges to remove the microalgae from the growth medium, installation costs, piping, buildings, engineering costs, and construction expenses.

Utilizing genetically modified algae with higher growth rates, or using our knowledge of the photosynthetic mechanisms in the algae to improve production, we could achieve a substantially reduction in cost. [2,17,19] For example, more current estimates suggest that the actual costs for producing algae biomass are only \$2.95 /kg for a PBR and \$3.80 /kg for a raceway system, and that economies of scale could reduce this cost to as low as \$0.47 /kg in the case of a photobioreactor.

It has been shown that lipid contents up to 77% are achievable using readily available algae. [2] It has also been shown that by taking advantage of the high tolerance to light which algae has in conjunction with pulsed artificial light, it is possible to achieve growth rates of up to 100 $gm/m^2 \cdot hr$. [19] Additionally, engineering progress can improve the efficiency of light collection to further improve the growth productivity.

However, it has also been found that lipid formation is generally preferred when algae are in a "starvation mode" where they do not receive enough nitrogen. The tradeoff of using one of these algae that produces 70+% lipid content is that the growth rate is typically smaller. There should be an optimization point where the lipid production per unit time is maximized, but this point will likely be neither the point with the maximum lipid content per cell, nor the point with the maximum possible growth.

7.4.2 Processing Costs

It is estimated by Grima that Crude Esterified Algae Oil would cost around \$396 /kg to produce. At a density of approximately 0.88 gm/cm^3, this is a price of \$1320 /gal, and is clearly untenable. This estimate is again based on a 2620 kg production quantity for oil. Of this total amount, 81% is the cost of the raw biomass. [17]

Grima suggested a cost of \$32 /kg of algae biomass, compared to the more current estimates of only \$0.47 /kg in the case of a PBR at large scales. Unfortunately, the \$0.47 /kg figure does not take into account the cost of separating the biomass from the broth, and does not go into details as to how the number was developed. However, the more modern study guesses a value of \$1.40 /L for separation and refining algae biomass into biodiesel for a total cost of \$2.80 /L. [2]

To reconcile these two studies, it is necessary to break down the costs further. Grima states that 81% of the cost of the crude esterified algae oil is in the production of biomass. If we assume that the primary difference between the two estimates is that the older study assumes a \$32 /kg cost for biomass whereas the newer study assumes \$0.47 /kg, then that is a clear source of confusion. Additionally, the older study assumes that only 10% of the biomass will be converted into oil while the newer study assumes 30% yields. In fact, 70% yields are possible.

Given this, we can see that a reduction in biomass cost (81% of the total cost) to the numbers used by Chisti results in a new estimate for algae biodiesel of \$266 /gal assuming a density of 0.88 gm/cm^3 (\$70 /L). If we include the additional factor of three due to the difference in assumptions about the lipid content, we get a new price of \$23 /L compared to the modern estimate of \$2.80 /L.

The remaining discrepancy can be accounted for by looking at the capital expenses estimated for processing the algae biomass into biodiesel. Chisti is assuming that refining costs will be 50% of the total cost of the algae based biodiesel while Grima actually looked at the operating expenses of a refinery and suggested closer to 94% of the cost of the oil will lie in the separation and purification steps if the cost of biomass is \$0.47 /kg. This difference very well illustrates the extreme difficulty in getting a good estimate of the costs involved in producing algae-based biodiesel.

Grima also assumed an end-goal of producing high-value pharmaceutical products as opposed to low-value biodiesel. The decreased quality requirements give additional leeway in the costs of purification for Chisti's estimate versus Grima's estimate. For example, Grima used centrifuges for harvesting the algae. This cost amounted to roughly 10% of the total capital costs for producing the biodiesel. Additionally, hexane was used as an extracting agent due to the low temperature of processing. In the case of biodiesel, we care less whether the materials break down, and so the potentially cheaper supercritical CO_2 can be used. While these two specific points are not by themselves enough to make up the difference in the estimates, it becomes clear that design choices can account for the variability in the estimates.

Overall, it is clear that while at one point the cost of biomass appeared to be the largest contributor to the cost of algae-based biodiesel, newer estimates suggest that through genetic manipulation and clever engineering, the biomass cost could be dramatically reduced. The remaining large costs are in separation, drying, and refining the biomass into biodiesel, which are engineering problems that can be solved with enough time and effort.

The impact of switching to a gasification setup instead of a harvesting, drying, and extraction system is more transparent from this point of view. We are now able to grow biomass cheaply enough to be competitive with oil ($0.59 /L based on 70% lipid content). [2] If we were able to process the hydrocarbons into fuel for under $0.22 /L, we would be able to be competitive with gasoline. A complex harvesting, drying, and extraction setup costs a large amount (between 50 and 94% of the total cost), but the ability to use a simple press in combination with either a catalytic gasification or high-temperature gasification reactor (both well-established technologies) would very likely push us close to being competitive with very little further technological development.

7.5 Economics for Outdoor Ponds

In 1998, the Department of Energy's National Renewable Energy Laboratory put out a report entitled "A Look Back at the U.S. Department of Energy's Aquatic Species Program — Biodiesel from Algae". This report looked at a program in which the DOE investigated using open raceway ponds to produce algae for biodiesel.

This study is very different from the two studies mentioned above in that the technology utilized is dramatically different. Both of the above studies look at photobioreactors, whereas this report looked primarily at the open pond systems being investigated in the 1970's and later.

Interestingly, estimates at the time suggested that costs would not vary much by using open pond technology fed by CO_2 from power plants, grown using wastewater as fertilizer, or simply grown naturally. In the case of high pH flue gas fed ponds grown from the waste of power plants, prices as low as \$100/barrel (1997 dollars) were predicted as an optimistic case. For a more conservative case, the cost estimates ere closer to \$200/barrel (1997 dollars). These prices, compared to current oil costs, sound extremely promising.

It is also important to note that these estimates are based on a 40% lipid content in the algae. This continues to be a reasonable number for open systems, but if higher lipid content strains were usable (contents of up to 77% have been reported), the cost per barrel would decrease substantially. A doubling in output for roughly the same amount of equipment would result in estimated prices between \$50 and \$100 per barrel for algae-based biodiesel — lower than the current \$117 per barrel price for imported oil.

7.6 Overall Economics

Even Chisti's more optimistic recent study suggests a cost of \$2.80 /L for algae-based biodiesel using 30% lipid content strains grown in photobioreactors. Similarly, a 70% lipid content strain might have a cost as low as \$1.20 /L. This is still higher than the \$0.81 /L target at which it is directly competitive with gasoline. For comparison, palm oil can produce biodiesel at a cost of around \$0.66 /L, and should be currently competitive with gasoline.

Although palm oil is cheaper than algae-based biomass currently, as a terrestrial crop palm oil has the same problems as corn in terms of competing with food crops and a fundamental limit to the amount of land area available. Algae, due to it's ability to use marginal land, its high productivity, and its high photosynthetic efficiency, remains the only feasible way to replace our entire fuel infrastructure with a closed system that does not require foreign sources of energy.

If the potential price of algae-based biodiesel is actually as low as Chisti estimates, then it is very likely that in the next 5-10 years we could expect that between technological advancements and a continued increase in the price of oil, algae will become a viable direct competitor to oil. In particular, if gasification is proved to be a viable option for converting algae biomass into hydrogen, methane, or directly into liquid fuels, the price of algae-based biodiesel grown in photobioreactors will likely drop below gasoline.

For the case of open pond systems, it seems very likely that due to the immensely lower capital costs that it may already be less expensive to produce than using imported oil. The DOE estimated that open ponds may already be able to produce gasoline at a cost of \$1.70/gallon (\$0.45/L), which is already cheaper than both gasoline and biodiesel farmed using palm oil.

Overall, this suggests that it is inevitable that algae-based biodiesel will become the best available option for growing biofuels. Photobioreactors suffer from high capital costs (in particular, the cost of polycarbonate tubes) while being beneficial in terms of land usage, productivity, and harvesting costs. However, open ponds may already be economically favorable compared to the current price of oil.

Much of the current work being done in the field of algaculture is focused on photobioreactors. Many recent papers have suggested that despite their higher capital costs, photobioreactors are less costly per unit of biomass to grow and harvest than open ponds. [2] However, the DOE report on open ponds suggests that those costs may actually end up being lower. [1] It seems that we should investigate further over the next several years which of these routes will result in lower actual costs when implemented on a large scale. One huge problem with photobioreactors is that the large capital costs are largely in materials costs (polycarbonate, etc). When implemented on a very large scale, it may become impossible to meet those requirements at all, much less meet them economically.

Another serious problem with algae, as well as with all biofuels, is the relience on fertilizers to grow. Algae, for example, has less than 1% phosphate. [20] However, to meet the full needs of our transportation infrastructure in the United States would require (given the best cas 70% lipid content strains) $1 \cdot 10^{12}$ kg of algae biomass. Suddenly, 1% of that mass is an extremely large number — 11 million tons of phosphate fertilizers like ammonia (and this is an optimistically low number). Current US production of phosphate is only 40 million tons, with current thinking being that we are already limiting food production due to a lack of enough phosphate. Thus, it is also clear that on a very large scale, we will have to find a way to recover phosphate from our farming and biofuel systems in order to maintain a closed system.

7.7 Comparison to Solar Power

Compared to solar electricity, biodiesel (regardless of source) is substantially less efficient. Solar cells are commonly available at total conversion efficiencies exceeding 10%, and are projected to reach 40% or higher. Biofuels made from terrestrial crops, on the other hand, have a photosynthetic efficiency of about 3-6%, with a total conversion efficiency of around 1%.

Even in the case of algae-based biodiesel, where the simplicity of the organism is such that much less energy is used in non-recoverable ways, the total conversion efficiency is unlikely to exceed 15%.

From this, it would seem to be advantageous to use solar cells to meet our energy needs instead of biodiesel. However, because of the current limited energy density of batteries, direct electricity is not yet practical for use as a transportation fuel. Additionally, the embodied energy in a solar cell is much higher than that for a comparable algae producing plant. While the most expensive parts of an algae plant are typically the polycarbonate for building the growth tubes and the machines for harvesting the cells, a solar cell requires an entire chain of semiconductor technology utilizing many toxic chemicals, a great deal of energy, and a great deal of time.

Current estimates are that a solar cell takes between one and five years to return it's energy investment. Additionally, the energy return on energy investment (EROEI) is typically in the range of 10-30 over the lifetime of the system. However, given the inefficiency in producing fuels from electricity, biodiesel can get by with a slightly lower EROEI than a solar cell and still be more efficient overall for the specific case of providing transportation fuels.

8 Commercial Ventures

Commercial companies investigating algae based biodiesel include Aquaflow Bionomic, Solix Biofuels, GS Cleantech, and GreenFuel Technologies. [21] Of these, GreenFuel seems to be the closest to implementing their systems, having already built several test facilities. [16] However, there is extensive controversy as to the economic viability of these plants, as well as a great deal of scepticism. [21–24]

As mentioned previously, my analysis suggests that producing biodiesel is not yet viable economically primarily due to the high initial capital costs for equipment and for processing the fuel. This section will give some background on each of these companies, as well as an overview of their technology.

8.1 Aquaflow Bionomics

Aquaflow Bionomics is based in New Zealand and uses open air ponds fed by wastewater as a source of nitrogen, along with wild strains of algae. They have built a proof-of-concept plant, and are in the process of building a second prototype plant expected to be completed by December 2008. They further expect to have enough data to demonstrate economic favorability by the end of 2009. Further, they are investigating producing jet fuel using their algae biomass.

Unfortunately, there are no details readily available as to the economic feasibility of their plants, but they expect to have data available by the end of 2009 from which more accurate estimates as to the feasibility of open pond systems can be developed.

8.2 Solix Biofuels

Solix Biofuels is based on Boulder, Colorado, and claims to be a direct descendant of the Department of Energy Aquatic Species Program outlined above. However, they are primarily investigating the use of photobioreactors as a growth system. They expect to be producing biofuels competitive with the price of crude petroleum commercially within the next two years. However, very little apparent development has occurred since late 2006, so it is questionable if this company is on schedule to make any real progress.

8.3 GS Cleantech

GS Cleantech is a larger company with a more diverse field of technologies ranging from corn based ethanol plants to algae-based biodiesel and gasification. This versatility makes them more attractive as a potential success due to their existing knowledge and success.

GS Cleantech, like Solix and Greenfuel, is focusing on photobioreactors. They expect to have a pilot demonstration plant running by the first quarter of 2008. Additionally, as they are investing in research on biomass gasification, they have the potential to be able to very economically convert the algae biomass into fuel. Their first gasification plant is going into commercial operation now.

8.4 Greenfuel

Whether deserved or not, Greenfuel has attracted the most criticism for their projects. Greenfuel is based in Massachusetts, and is perhaps the furthest along of any company to commercialization of their technology. They utilize photobioreactors fed directly from the CO_2 emissions of power plants in order to simultaneously scrub the flue gasses and produce fuel (Fig 3).

Greenfuel has already done feasibility tests, as well as engineering scale units to assess the possibility of full-scale integration into existing power

Figure 3: A Traditional Bag system for algae growth used by GreenFuel. [16]

plant systems at gas, coal, and oil plants. They are currently in negotiations to build their first full-scale commercial units.

8.4.1 Controversy surrounding GreenFuel

GreenFuel, according to their performance reports, is able to produce 98 $gm/m^2/day$ of dry biomass. If we assume that their algae contains 70% lipid content and that all of that lipid content can be converted into biodiesel, we get a value of 144000 kg/year of biomass, or roughly 100000 kg/year of biodiesel per acre of land used. Using a density of 0.88 gm/cm^3, we find that this is equal to roughly 44000 gallons of biodiesel per year, per acre.

This value is extremely good, and has caused a great deal of controversy. [21–23] Primarily, the controversy comes from the fact that this claim is roughly a factor of two higher than the best estimates generally used.

This difference is brought further into light by comparing it with some of the canonical literature in the field. Chisti, for example, estimated a value of 48 $gm/m^2/day$ of dry biomass by facility area, and a value of 72 $gm/m^2/day$ by PBR projection area. [2] Chisti estimated a production of 14600 gallons of biodiesel per year per acre.

It seems then that GreenFuel is claiming productivity numbers roughly twice as high as all other sources in literature. There have been a number of individuals to object to this value, most notably Dimitrov, who wrote a technical paper outlining his criticisms. [21–23]

By and large, the disagreement between Dimitrov and GreenFuel as to the values seems to come down to a relatively simple difference in their calculations of plant area. GreenFuel uses vertically stacked tubes, which allows them to capture light from a larger projected area during much of the day for a given plant footprint.

Additionally, Dimitrov questions GreenFuel's cost analysis which suggests that they are able to produce biodiesel economically due to the large costs of building a photobioreactor. Essentially, Dimitrov claims that the cost of building the photobioreactors (and principally in building the polycarbonate tubes) will never be paid off by the production of biodiesel at rates he finds reasonable.

It is unclear who is correct in this argument. GreenFuel has actual production data on which they base their claim, and it seems unlikely that Dimitrov's calculations on growth rate are more accurate than experimental data. Additionally, it seems highly unlikely that GreenFuel would attempt to install large scale installations if they didn't find that real costs were low enough to produce biodiesel economically. However, Dimitrov's arguments are compelling, and have not been fully addressed to date.

9 Conclusions

Algae-based biodiesel has a great deal of potential as a biofuel. It does not compete with food crops, requires a very small amount of land, can be used to treat wastewater and absorb CO_2 emissions, remove heavy metals and toxic chemicals from the environment, and is very likely to be competitive with oil in the near future.

The primary issues which remain with algae are finding technical and engineering solutions which allow for lower capital costs in building photobioreactors which have a high productivity, or finding biological and engineering solutions which allow for better protection and processing of algae grown in raceway ponds.

Estimates as to the price of algae-based biodiesel are expected to be $50-$100 per barrel (based on the National Renewable Energy Laboratory report from 1998) or $160 based on Chisti's estimate using raceway ponds. For photobioreactors, the price is estimated to be between $122 (Chisti) and $800 (Dimitrov and Grima) for photobioreactors. It is likely that the substantial difference in estimates for photobioreactors is due to different accounting of capital expenses in the plants, and will likely fall somewhere in between in actual implementation. Additionally, advanced processing methods may reduce the cost of biodiesel manufactured using either technology.

There are a variety of companies actively pursuing algae-based biodiesel. None of these companies have moved beyond the Engineering Study stage, although the next step for both GreenFuel and Aquaflow Bionomics will be to build a commercial plant. It is still unclear whether photobioreactors, with their high capital expense but better productivity and higher quality output, are more or less expensive than open raceway ponds. Aquaflow Bionomics using raceway ponds and GreenFuel using photobioreactors should give some concrete economic and production data from which to make better recommendations in the next two years.

References

[1] J Sheehan, T Dunahay, J. B. "A Look Back at the U.S. Department of Energy's Aquatic Species Program — Biodiesel from Algae", Technical Report, National Renewable Energy Laboratory, 1998.

[2] Y Chisti, *Biotechnology Advances* **2007,** *25,* 294-306.

[3] Gopalakrishnan, *Environment Science & Engineering* **2006,** *4,* 19-24.

[4] Amanda Leigh Haag, *Nature* **2007,** *447,* 520-521.

[5] Pimentel, *Encyclopedia of Physical Sciences and Technology* 159-171.

[6] M Gross, *Current Biology 18,* R46.

[7] R Muñoz, B. G. *Water Research* **2006,** *40,* 2799-2815.

[8] G Knothe, *Journal of the American Oil Chemists' Society* **2006,** *83,* 823.

[9] J Struben, J. S. *Forthcoming, Environment and Planning B* .

[10] Nate Hagens, "At $100 Oil - What Can the Scientist Say to the Investor?", http://www.theoildrum.com/node/3412, 2008.

[11] Energy Information Administration, "Production and end-use data, 2002", Technical Report, Energy Information Administration, 2002.

[12] David Lide, *Handbook of Chemistry and Physics;*.

[13] J Bourne, R. C. *National Geographic Magazine* **2007,** 41.

[14] J Deutch, J. S. "National Security Consequences of U.S. Oil Dependency", Technical Report, Council on Foreign Relations Press, 2006.

[15] M Aresta, A Dibenedetto, G. B. *Fuel Processing Technology* **2005,** *86,* 1679-1693.

[16] GreenFuel Technologies, "Home Website", http://www.greenfuelonline.com/index.html, 2008.

[17] E Grima, E-H Belarbi, F. F. *Biotechnology Advances* **2003,** *20,* 491-515.

[18] A Carvalho, L Meireles, F. M. *Biotechnol. Prog.* **2006,** *22,* 1490-1506.

[19] J Gordon, J. P. *Appl Microbiol Biotechnology* **2007,** *76*, 969-975.

[20] Chris Rhodes, "Could Peak Phosphate be Algal Diesel's Achilles' Heel?", http://ergobalance.blogspot.com/2008/04/peak-phosphate-algal-diesels-achilles.html, 2008.

[21] The Oil Drum, "Has the Algae Cavalry Arrived?", http://www.theoildrum.com/node/2531, 2007.

[22] K Dimitrov, "GreenFuel Technologies: A Case Study for Industrial Photosynthetic Energy Capture", Technical Report, 2007.

[23] K Dimitrov, "GreenFuel Technologies: A Case Study for Industrial Photosynthetic Energy Capture – Followup Discussion", Technical Report, 2007.

[24] M Briggs, "Widescale Biodiesel Production from Algae", http://www.unh.edu/p2/biodiesel/article_alge.html, 2004.