Algae as a Feedstock for Transportation Fuels –

The Future of Biofuels?

A White Paper Prepared for the

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INTRODUCTION:

Events in world energy markets over the past several years have prompted many new technical developments as well as political support for alternative transportation fuels, especially those that are renewable. We have seen dramatic rises in the demand for and production of fuel ethanol from sugar cane and corn and biodiesel from vegetable oils. The quantities of these fuels being used continue to rise dramatically, and their use is helping to create a political climate for doing even more. But, the quantities are still far too small to stem the tide of rising crude prices worldwide. In fact, the use of some traditional crops (corn, sugar, soy, etc.) in making fuels instead of food is apparently beginning to impact the cost of food worldwide. Thus, there is considerable interest in developing alternative biofuel feedstocks for use in making fuels – feedstocks that are not used in the food industries.

Of course, we know that there is a lot of work in developing cellulosic-based ethanol that would be made from woody biomass. Process development is the critical path for this option, and the breakthrough in reducing the cost of the process has been elusive thus far. Making biodiesel from vegetable oils is a well-developed and inexpensive process, but to date there have been few reasonable alternatives for making biodiesel, although advanced processes such as gasification of biomass remain an option.

A New Look at an Old Idea – Algae

Algae fuel (also known as algal fuel) is a biofuel made from algae in which there is much interest today because of the challenges with first generation biofuels as mentioned above. "Algaculture" (farming of algae) can be a route to making vegetable oils, biodiesel, bioethanol, biogasoline, and other biofuels.

Microalgae are one-celled, photosynthetic microorganisms that are abundant in fresh water, brackish water, and marine environments everywhere on earth. The science and principles for making fuels from algae are simple: Algae need water, sunlight, nutrients, and carbon dioxide to grow. Algae thrive in shallow, dirty water, and they grow easily and quickly. They produce oil that can then be harvested and converted into biodiesel or other fuels. Algae's carbohydrate content can be fermented into ethanol. Given the right conditions, algae can double its volume overnight. Research into algae for mass-production of oil is mainly focused on <u>microalgae</u> rather than <u>macroalgae</u>, e.g. seaweed. This is due largely to microalgae's less complex structure, fast growth rate, and high oil content.

Unlike terrestrial crops such as corn and soybean, which require a full growing season to yield crops, algae can be harvested day after day. Up to 50% of algae's weight is comprised of oil, compared with, for example, oil-palm trees (currently the most prolific yields of the most popular vegetable oils) which yields just about 20% of its weight in oil. For comparison, consider the yields of some of the dominant vegetable oil crops: soybeans yield some 78 liters/hectare per year, canola (or rapeseed) 235 liters/hectare, and palm 1,000 liters/hectare per year. But, algae can produce some 16,000 liters/hectare per year, and possibly more. It has been estimated, for example, that the U.S. could replace all of the diesel fuel currently used with an algae-derived fuel using an area of land that is about one-half of 1% of the current farm land now in use. By contrast, to accomplish the same goal by using soybean-based diesel fuel would require an enormous percentage of the available farm land.

Because algae consumes carbon dioxide and produces oxygen through photosynthesis, it is particularly attractive as a means to curtail carbon emissions along with producing fuel. Furthermore, algae can be used to clean up waste by processing nitrogen from wastewater and carbon dioxide from power plants. It can be grown on marginal lands that are useless for ordinary crops.

Given all the obvious attributes of algae as a feedstock for fuel, its production has yet to materialize in any meaningful volume. The reason for this is centered upon the significant capital, operations, and maintenance costs to build and maintain the production and harvesting systems. Algae are easy to grow in small volumes but not easily extrapolated to large-scale production facilities capable of producing consistent yields over long periods of time. The cheapest of all current technologies are still the open architecture approaches, i.e., ponds; which suffer challenges with contamination, evaporation, temperature control, CO_2 utilization, and general maintenance. The preferred approaches are the closed systems, generally known as phtobioreactors, where algae remain in a closed environment to enable accelerated growth and better control over environmental conditions. These glass or plastic enclosures can be mounted in a variety of horizontal or vertical configurations and can take many shapes and sizes. Some of these concepts will be discussed in more detail later.

RECENT HISTORY IN ALGAE FUEL DEVELOPMENTS:

Perhaps the most comprehensive study of algae as a resource for renewable transportation fuels was the "Aquatic Species Program (ASP)" (Sheehan, et al, 1998), conducted by the U.S. National Renewable Laboratory between 1978 and 1996 and funded by the U.S. Department of Energy's Office of Fuels Development. The focus of the program was the production of biodiesel from high lipid-content algae grown in ponds and utilizing waste CO_2 from coal-fired power plants. The double benefit from success of this program would be the development of a viable renewable fuel along with a viable technology for reducing great quantities of CO_2 emissions. During the nearly two decades of this program tremendous advances were made in the understanding of how to manipulate the metabolism of algae and the engineering of microalgae production systems. The program, despite its accomplishments, was terminated in 1996 because gasoline prices had dropped back to only about $1.00 (USD) per gallon. Nevertheless, the program made great contributions to the science during its lifetime. These are summarized below (excerpts are taken from the report):

Applied Biology

<u>A Unique Collection Of Oil-Producing Microalgae.</u>

"The ASP studied a fairly specific aspect of algae – their ability to produce natural oils. Researchers not only concerned themselves with finding algae that produced a lot of oil, but also with algae that grow under severe conditions – extremes of temperature, pH, and salinity. At the outset of the program, no collections existed that either emphasized or characterized algae in terms of these constraints. Early on, researchers set out to build such a collection. Algae were collected from sites in the west, the northwest, and the southeastern regions of the continental U.S., as well as Hawaii. At its peak, the collection contained over 3,000 strains of organisms. After screening, isolation, and characterization efforts, the collection was eventually winnowed down to around 300 species, mostly green algae and diatoms. The collection, now housed at the University of Hawaii, is still available to researchers.". . .

<u>Shedding Light On The Physiology And Biochemistry Of Algae</u>

"Prior to this program, little work had been done to improve oil production in algal organisms. Much of the program's research focused attention on the elusive 'lipid trigger.'" (Lipids are another generic name for TAGs (triacylglycerols), the primary storage form of natural oils.) This "trigger" refers to the observation that, under environmental stress many microalgae appeared to flip a switch to turn on production of TAGs. Nutrient deficiency was the major factor studied. Our work with nitrogen-deficiency in algae and silicon deficiency in diatoms did not turn up any overwhelming evidence in support of this trigger theory.". . .

Breakthroughs In Molecular Biology And Genetic Engineering

. . . "Within the field of plant biotechnology, algae research is one of the least trodden territories. The slower rate of advance in this field makes each step forward in our research all the more remarkable. Our work on the molecular biology and genetics of algae is thus marked with significant scientific discoveries. The Program was the first to isolate the enzyme Acetyl CoA Carboxylase (ACCase) from a diatom. This enzyme was found to catalyze a key metabolic step in the synthesis of oils in algae". . . .

Algae Production Systems

Demonstration Of Open Pond Systems For Mass Production Of Microalgae

"Over the course of the program, efforts were made to establish the feasibility of large-scale algae production in open ponds. In studies conducted in California, Hawaii, and New Mexico, the ASP proved the concept of long term, reliable production of algae. . . . The Roswell, New Mexico tests proved that outdoor ponds could be run with extremely high efficiency of CO_2 utilization. Careful control of pH and other physical conditions for introducing CO_2 into the ponds allowed greater than 90% utilization of injected CO_2. The Roswell test site successfully completed a full year of operation with reasonable control of the algal species grown. Single day productivities reported over the course of one year were as high as 50 grams of algae per square meter per day, a long term goal for the program. Attempts to achieve consistently high productivities were hampered by low temperature conditions encountered at the site. The desert conditions of New Mexico provided ample sunlight, but temperatures regularly reached low levels (especially at night). If such locations are to be used in the future, some form of temperature control with enclosure of the ponds may well be required."

The High Cost Of Algae Production Remains An Obstacle.

"The cost analyses for large-scale microalgae production evolved from rather superficial analyses in the 1970s to the much more detailed and sophisticated studies conducted during the 1980s. A major conclusion from these analyses is that there is little prospect for any alternatives to the open pond designs, given the low cost requirements associated with fuel production. The factors that most influence cost are biological, and not engineering-related. These analyses point to the need for highly productive organisms capable of near-theoretical levels of conversion of sunlight to biomass. Even with aggressive assumptions about biological productivity, we project costs for biodiesel which are two times higher than current petroleum diesel fuel costs."

Resource Availability

Land, Water And CO_2 Resources Can Support Substantial Biodiesel Production And CO_2 Savings.

"The ASP regularly revisited the question of available resources for producing biodiesel from microalgae. This is not a trivial effort. Such resource assessments require a combined evaluation of appropriate climate, land, and resource availability. These analyses indicate that significant potential land, water, and CO_2 resources exist to support this technology. Algal biodiesel could easily supply several 'quads' of biodiesel – substantially more than existing oilseed crops could provide. Microalgae systems use far less water than traditional oilseed crops. Land is hardly a limitation. Two hundred thousand hectares (less than 0.1% of climatically suitable land areas in the U.S.) could produce one quad of fuel. Thus, though the technology faces many R&D hurdles before it can be practicable, it is clear that resource limitations are not an argument against the technology."

CURRENT THRUSTS IN R&D FOR ALGAE AS A FEEDSTOCK FOR RENEWABLE FUELS:

In the 12 years since the close of the Aquatic Species Program there have been significant developments in biotechnologies. New genomic and proteomic technologies make it much easier to understand the mechanisms involved in algae-oil production. One of the challenges is that while some types of algae can produce large amounts of oil, they only do this when they are starved for nutrients. But, they also lose another of their attractive features – their ability to grow quickly and reproduce. The challenge is to understand the molecular switches that cause increased oil production and to turn on those switches without starving the algae at the same time.

Currently, most research into efficient algal-oil production is being done in the private sector. If predictions from small scale production experiments are borne out, then using algae to produce biodiesel, bioethanol, and biobutanol might be the only viable method by which to produce enough automotive fuel to displace the current world gasoline usage.

The least expensive way to grow algae is in open ponds. But, open-pond methods for growing fuel algae have been largely abandoned for the cultivation of algae with high oil content, although there are recent exceptions to this trend. Many believe that a major flaw of the

Aquatic Species Program was the decision to focus their efforts exclusively on open-ponds. In this setting, algae are subject to wide swings in temperature and pH, and competition from invasive algae and bacteria. Plus, open systems using a monoculture are vulnerable to viral infection. The entire effort with an open-pond is dependent on the hardiness of the strain chosen. The strain must be unnecessarily resilient (compared to a closed system) in order to withstand the environmental conditions. For a given amount of photosynthetic energy, an algae strain producing relatively high levels of oil will also produce relatively less protein and/or carbohydrate, usually resulting in the species being less hardy, or having a slower growth rate. Also species with lower oil content have an easier time in the harsher conditions of an open system. But, of course, the goal is to maximize the oil output per unit area.

The alternative is to use closed systems – bioreactors. A photobioreactor is a bioreactor which incorporates some type of light source. Virtually any translucent container could be called a photobioreactor; however the term is more commonly used to define a closed system, as opposed to an open tank or pond. Because these systems are closed, all essential nutrients must be introduced into the system to allow algae to grow and be cultivated. Essential nutrients include carbon dioxide, water, minerals and light. It is possible to introduce a continuous stream of sterilized water containing nutrients, air, and carbon dioxide. As the algae grow, excess culture overflows and is harvested. It can be shown that the maximum productivity for a bioreactor occurs when the "exchange rate" (time to exchange one volume of liquid) is equal to the "doubling time" (in mass or volume) of the algae. Different types of photobioreactors include:

- tanks provided with a light source
- polyethylene sleeves or bags
- glass or plastic tubes

Algae can be harvested using microscreens, by centrifugation, or by flocculation (process where a solute comes out of solution in the form of floc or flakes). Froth flotation is another method to harvest algae whereby the water and algae are aerated into froth, with the algae then removed from the water. Alum and ferric chloride are chemical flocculants used to harvest algae.

Algae oils are extracted through a wide variety of methods. The simplest method is mechanical crushing. Since different strains of algae vary widely in their physical attributes, various press configurations (screw, expeller, piston, etc) work better for specific algae types. Often, mechanical crushing is used in conjunction with chemicals. Of course, crushing is also the typical method of extracting the oil from oil seeds to produce vegetable oils as raw material for the transesterification process to produce biodiesel fuel.

RECENT DEVELOPMENTS IN CULTIVATING ALGAE:

A number of activities are under way worldwide to develop economic means of harnessing the potential for algae fuel. Some of the activities are identified below. Again, development at this time is largely in the private sector.

Canada

International Energy, Inc . (http://www.internationalenergyinc.com)

New Zealand

Aquaflow Bionomic Corporation (http://www.aquaflowgroup.com) Boeing and Air New Zealand announced a joint project with Aquaflow Bionomic to develop algae jet fuel (http://seattletimes.nwsource.com/html/boeingaerospace/2003858756_boeingenergy30.html)

USA

Aurora BioFuels (http://www.aurorabiofuels.com)

Diversified Energy (http://www.diversified-energy.com)

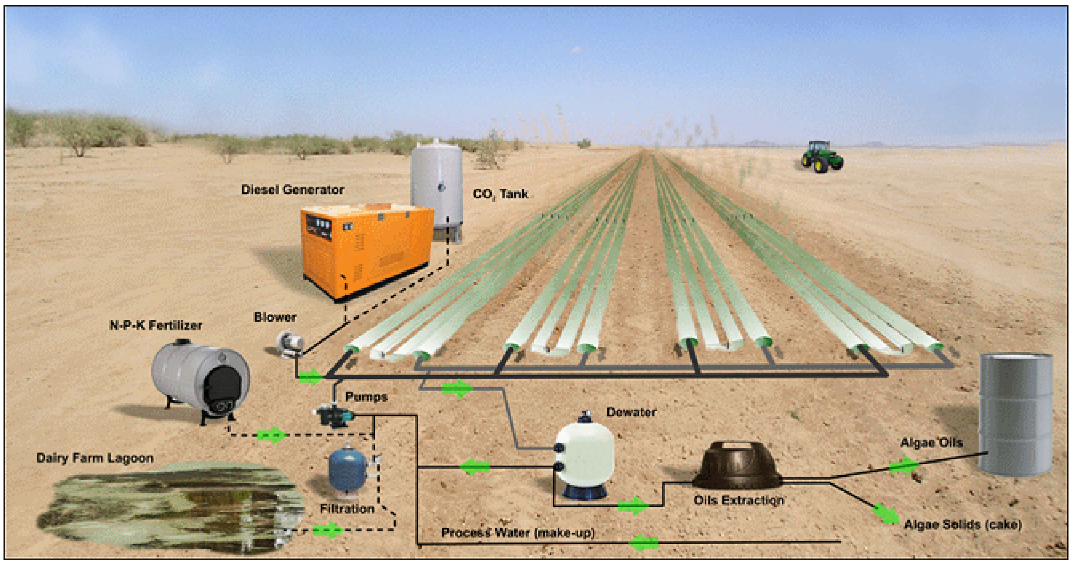
Global Green Solutions (http://www.globalgreensolutionsinc.com/s/Home.asp)

Three of the efforts represented in the above listing are worthy of more details.

International Energy, Inc. announced on January 29, 2008 that they had developed a continuous cyclic growth and hydrocarbon extraction process that can be applied to mass cultures of microalgae for separating the bio-oils from the algal biomass. The process reportedly yields high purity microalgal bio-oils. The company claims that their technology allows the microalgae to be processed for the bio-oil separation and harvesting while preserving the viability and vitality of the cells that produce them. Microalgae are then returned to the growth medium for further growth and hydrocarbon accumulation. This approach should minimize biomass generation time while enhancing yields of hydrocarbon production. They say that challenges must still be addressed as follows:

Identifying the best suitable algal strains
Developing nutrient protocols for the efficient growth of the microalgae
Creating cost-efficient algal harvesting and oil extraction methodologies.

Diversified Energy Company partnered with **XL Renewables** (www.xlrenewables.com), a biorefinery project developer, and have developed an innovative algae production system called Simgae™ (simple algae). Simgae™ is a closed photobioreactor system designed to push yield to its maximum with cost and simplicity the driving principles. The picture below illustrates a concept small-scale implementation at a dairy operation.



The system uses a series of clear, thin-walled polyethylene tubes, called Algae Biotape™, which is similar to conventional drip irrigation tubes, but optimized for diameter and thickness, and treated with UV inhibitors, color schemes, and reflectivity. The tape is laid out in parallel across a field, where the land not only acts as the supporting structure for the system but can also provide a degree of thermal management control. Fertile water containing nutrients and a small portion of algae are pumped into the biotape. As the mix flows along the biotape CO_2 is injected and oxygen is relieved. Sources of CO_2 could be any process whose effluent includes CO_2. After some period of time, the algae leaves the Biotape™ with a greater concentration of algae than at the beginning. Scale-up is achieved by laying more fields of biotape. The system provides a continuous flow of concentrated algae for harvesting, but this concept as is does not include the harvesting process. The partners estimate that the capital cost for the system, including installation but excluding the land, harvesting, and product storage, would be in the range of $25,000 to $35,000 (USD) per acre. The partners, Diversified Energy and XL Renewables, have completed preliminary engineering and modeling of the system and are currently conducting "concept" demonstrations of the technology at a laboratory and at a dairy farm.

Global Green Solutions in a joint venture with **Valcent Products** (http://www.valcent.net/s/Home.asp) have developed a system that they call "High Density Vertical Bioreactor" (HDVB) for making algae fuel. In this case, rather than laying out tubes on the ground, they have arranged flow circuits that go vertical, as shown in the picture below.

In this system algae are grown in a closed loop, continuous process high-density vertical bioreactor. The algae are constantly circulated within the clear plastic reactors, enhancing exposure to sunlight, carbon dioxide absorption, and nutrient delivery. The closed loop system prevents contamination and water evaporation, allows recycling for minimal water consumption, and enables automatic temperature and flow control. The harvesting technology controls harvesting rates to complement daily algae growth rate variations. During the extraction process, the lipids are removed, and the remaining biomass is processed for co-products. Water removed during harvesting and extraction is recycled. The HDVB bioreactor system can be deployed on non-arable land, requires very little water due to its closed circuit process, does not incur significant labor costs, and does not employ fossil fuel burning equipment, unlike traditional food/biofuel crops, like soy and palm oil. The first commercial-scale bioreactor pilot project is under way at Valcent's test facility.

THE CONTRARIAN VIEW OF ALGAE FUEL DEVELOPMENTS

Any new technology program promising great benefits will meet with some skepticism, as well it should. The algae fuel movement is not without its doubters and detractors, all of whom raise good questions that must be answered before the technology can reach a level of legitimacy. The Biopact organization in Europe has raised some interesting questions and criticisms of biofuels from algae that are worthy of attention.

Biopact is a Brussels-based "connective of European and African citizens who strive towards the establishment of a mutually beneficial 'energy relationship' based on biofuels and Bioenergy." It is an entirely volunteer organization of European and African citizens who strive towards the establishment of a mutually beneficial 'energy relationship' based on biofuels and bioenergy. Their goal is to use the potential for the production of bioenergy in the developing world as a lever to create a new development paradigm in which access to energy, energy security and sustainability play key roles.

Biopact issued a report in January, 2007 (Biopact, 2007) that reflected on the work of the Aquatic Species Program and discussed recent developments in light of that previous work and in comparison to much of the other current biofuels developments (biodiesel, ethanol, etc.). They listed the features that the ideal algae would have in the future as:

- It should have a high and constant lipid content
- It must be possible to grow the micro-organism continuously
- It should have a high photosynthetic efficiency resulting in high and constant biomass productivities
- It should be capable of withstanding seasonal climatic differences and daily changes in temperatures
- The physical size must be such that it is easily harvestable by membranes

The authors noted that ALL of the features above were identified during the Aquatic Species Program as being necessary.

They also noted that life cycle analyses are necessary in order to assess the actual energy balances, the greenhouse gas balance, and the costs involved in manufacturing and operating photobioreactors but that press releases from algae-biofuel companies never disclose any such information. Clear comparisons with other biofuels technologies are not possible in the absence of such analyses for algae fuels.

In their final word, the authors noted that "the claims that algae yield enormous amounts of useable biomass have never been demonstrated or substantiated. Algae production in photobioreactors has never left the laboratory or pilot phase, and no energy balance and greenhouse gas balance analyses exist for biofuels obtained from such systems. The only real data we can rely on, so far, are those of the projects carried out under the Aquatic Species Program."

BARRIERS:

In order for algae-based fuels to be commercialized to any great extent, a number of imposing barriers must be overcome. Just a few of those barriers are detailed here.

Notably, one of the major barriers to commercialization of algae is the huge capital cost of facilities which will maximize the productivity and minimize susceptibility of microalgae to contamination while also maintaining a highly efficient process. But, to put this challenge into context and perspective, look at an excerpt from an article written in **2005** (Danielo, 2005):

> *"In 1998, a barrel of petroleum sold for $13; today the price can exceed $50 per barrel. If the production of algal biodiesel has not already been widespread at an industrial scale, it's simply on account of concerns about profitability and competition. In 1982, it was estimated by Benemann that the cost of production for a barrel of algal biodiesel was, on average, $94 (the hypothetical base was $61 and hypothetical high was $127, depending on the mode of production.)*

Obviously, the world has changed considerably since these words were written in 2005. Oil is selling at the time of this writing at $124 per barrel. If oil stays at that price for a long period of time, then many alternatives begin to look attractive, including algae fuel.

NREL chose to focus their Aquatic Species Program on cultivating algae in open ponds, partly because they knew that bioreactor setups would be very expensive as well as unproven. Plus, their focus was on identifying strains of algae that would perform well as oil producers, and that kind of activity did not necessarily require bioreactors. But, common sense dictates that to produce huge quantities of algal oil will require as much mass production processing as possible, and to reach this point will require a great amount of research and development on bioreactor processes.

The characteristics desired in strains of microalgae that will be productive and cost-effective include high-productivity, high lipid content, minimum susceptibility to contamination, and tolerance to fluctuations temperature and salinity. NREL found a number of promising algae strains but not one was found to possess all of the desirable features. Typically, they found that desirable characteristics in algae were mutually exclusive, that is, for example, one strain might have high algae productivity and rapid growth but not have high lipid accumulation, and vice versa. Thus, considerable algae strain development is still needed. As stated in their report (Sheehan, 1998):

> *"Any future R&D program for microalgae CO_2 capture and biofuels production must start with the development of the microalgae "biocatalysts." The goal will be to construct strains via genetic engineering or other strain improvement methods that achieve very high solar conversion efficiencies and yield high lipid microalgal biomass, as required by the economic analyses."*

In the U.S. recently it's been said (for example) that "algae fuels could replace all fuel currently consumed in the U.S. by using only 10% of the land area of the State of New Mexico" (about 31,000 km^2). While such a statement is dramatic and draws a lot of attention, it is also greatly misleading. Practical reality dictates that huge algae bioreactors (or even open ponds) would have to be co-located with huge, traditional industrial centers that are the sources of CO_2. While New Mexico and other desert environments might be nearly ideal locations - on non-arable land, with high insolation levels and moderate temperature fluctuations, that certainly is not the case with much of the rest of the U.S. and much of Europe. It's hard to imagine, for example, a bioreactor operating efficiently and productively in northern climates, in places such as Minnesota, North Dakota, and northern Europe with their lower insolation levels and harsher climate extremes. Yet, the northern areas are where a lot of CO_2 is generated. Therefore, one must conclude that even if the technical barriers can be overcome, the practical barriers such as location, land use, etc. will take many years to overcome and that this will be an evolutionary commercialization, not revolutionary.

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