National Renewable Energy Laboratory

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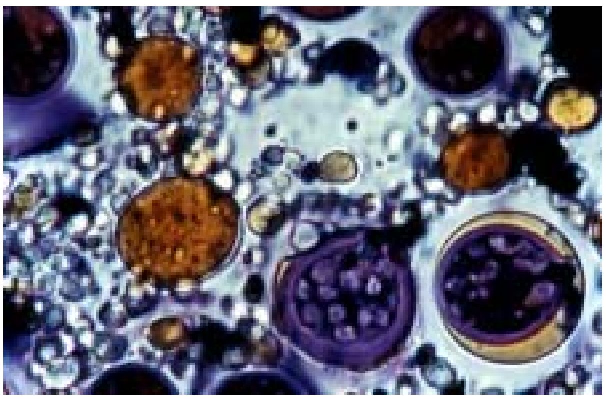
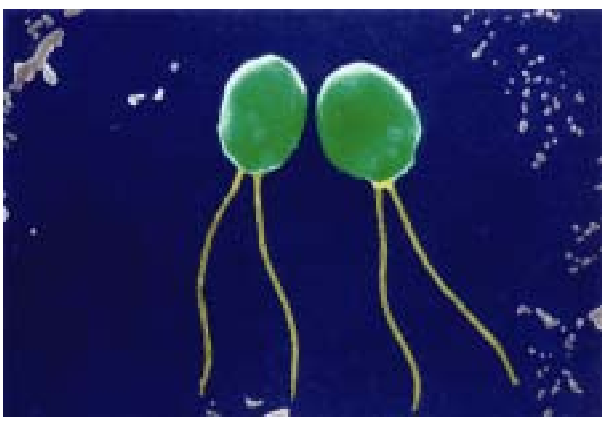
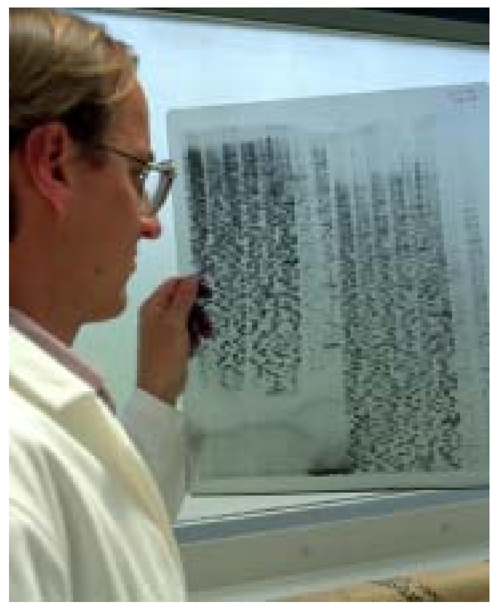
A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae







Close-Out Report

A Look Back at the U.S. Department of Energy's Aquatic Species Program—Biodiesel from Algae

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Background

Origins of the Program

This year marks the 20th anniversary of the National Renewable Energy Laboratory (NREL). In 1978, the Carter Administration established what was then called the Solar Energy Research Institute (SERI) in Golden, CO. This was a first-of-its kind federal laboratory dedicated to the development of solar energy. The formation of this lab came in response to the energy crises of the early and mid 1970s. At the same time, the Carter Administration consolidated all federal energy activities under the auspices of the newly established U.S. Department of Energy (DOE).

Among its various programs established to develop all forms of solar energy, DOE initiated research on the use of plant life as a source of transportation fuels. Today, this program—known as the Biofuels Program—is funded and managed by the Office of Fuels Development (OFD) within the Office of Transportation Technologies under the Assistant Secretary for Energy Efficiency and Renewable Energy at DOE. The program has, over the years, focused on a broad range of alternative fuels, including ethanol and methanol (alcohol fuel substitutes for gasoline), biogas (methane derived from plant materials) and biodiesel (a natural oil-derived diesel fuel substitute). The Aquatic Species Program (ASP) was just one component of research within the Biofuels Program aimed at developing alternative sources of natural oil for biodiesel production.

Close-out of the Program

The Aquatic Species Program (ASP) was a relatively small research effort intended to look at the use of aquatic plants as sources of energy. While its history dates back to 1978, much of the research from 1978 to 1982 was focused on using algae to produce hydrogen. The program switched emphasis to other transportation fuels, in particular biodiesel, beginning in the early 1980s. This report provides a summary of the research activities carried out from 1980 to 1996, with an emphasis on algae for biodiesel production.

In 1995, DOE made the difficult decision to eliminate funding for algae research within the Biofuels Program. Under pressure to reduce budgets, the Department chose a strategy of more narrowly focusing its limited resources in one or two key areas, the largest of these being the development of bioethanol. The purpose of this report is to bring closure to the Biofuels Program's algae research. This report is a summary and compilation of all the work done over the last 16 years of the program. It includes work carried out by NREL researchers at our labs in Golden, as well as subcontracted research and development activities conducted by private companies and universities around the country. More importantly, this report should be seen not as an ending, but as a beginning. When the time is right, we fully expect to see renewed interest in algae as a source of fuels and other chemicals. The highlights presented here should serve as a foundation for these future efforts.

What is the technology?

Biological Concepts

Photosynthetic organisms include plants, algae and some photosynthetic bacteria. Photosynthesis is the key to making solar energy available in useable forms for all organic life in our environment. These organisms use energy from the sun to combine water with carbon dioxide (CO_2) to create biomass. While other elements of the Biofuels Program have focused on terrestrial plants as sources of fuels, ASP was concerned with photosynthetic organisms that grew in aquatic environments. These include macroalgae, microalgae and emergents. Macroalgae, more commonly known as “seaweed,” are fast growing marine and freshwater plants that can grow to considerable size (up to 60m in length). Emergents are plants that grow partially submerged in bogs and marshes. Microalgae are, as the name suggests, microscopic photosynthetic organisms. Like macroalgae, these organisms are found in both marine and freshwater environments. In the early days of the program, research was done on all three types of aquatic species. As emphasis switched to production of natural oils for biodiesel, microalgae became the exclusive focus of the research. This is because microalgae generally produce more of the right kinds of natural oils needed for biodiesel (see the discussion of fuel concepts presented later in this overview).

In many ways, the study of microalgae is a relatively limited field of study. Algae are not nearly as well understood as other organisms that have found a role in today’s biotechnology industry. This is part of what makes our program so valuable. Much of the work done over the past two decades represents genuine additions to the scientific literature. The limited size of the scientific community involved in this work also makes it more difficult, and sometimes slower, compared to the progress seen with more conventional organisms. The study of microalgae represents an area of high risk and high gains.

These photosynthetic organisms are far from monolithic. Biologists have categorized microalgae in a variety of classes, mainly distinguished by their pigmentation, life cycle and basic cellular structure. The four most important (at least in terms of abundance) are:

- The diatoms (Bacillariophyceae). These algae dominate the phytoplankton of the oceans, but are also found in fresh and brackish water. Approximately 100,000 species are known to exist. Diatoms contain polymerized silica (Si) in their cell walls. All cells store carbon in a variety of forms. Diatoms store carbon in the form of natural oils or as a polymer of carbohydrates known as chyrsolaminarin.

- The green algae (Chlorophyceae). These are also quite abundant, especially in freshwater. (Anyone who owns a swimming pool is more than familiar with this class of algae). They can occur as single cells or as colonies. Green algae are the evolutionary progenitors of modern plants. The main storage compound for green algae is starch, though oils can be produced under certain conditions.

- The blue-green algae (Cyanophyceae). Much closer to bacteria in structure and organization, these algae play an important role in fixing nitrogen from the atmosphere. There are approximately 2,000 known species found in a variety of habitats.

- The golden algae (Chrysophyceae). This group of algae is similar to the diatoms. They have more complex pigment systems, and can appear yellow, brown or orange in color. Approximately 1,000 species are known to exist, primarily in freshwater systems. They are similar to diatoms in pigmentation and biochemical composition. The golden algae produce natural oils and carbohydrates as storage compounds.

The bulk of the organisms collected and studied in this program fall in the first two classes—the diatoms and the green algae.

Microalgae are the most primitive form of plants. While the mechanism of photosynthesis in microalgae is similar to that of higher plants, they are generally more efficient converters of solar energy because of their simple cellular structure. In addition, because the cells grow in aqueous suspension, they have more efficient access to water, CO_2, and other nutrients. For these reasons, microalgae are capable of producing 30 times the amount oil per unit area of land, compared to terrestrial oilseed crops.

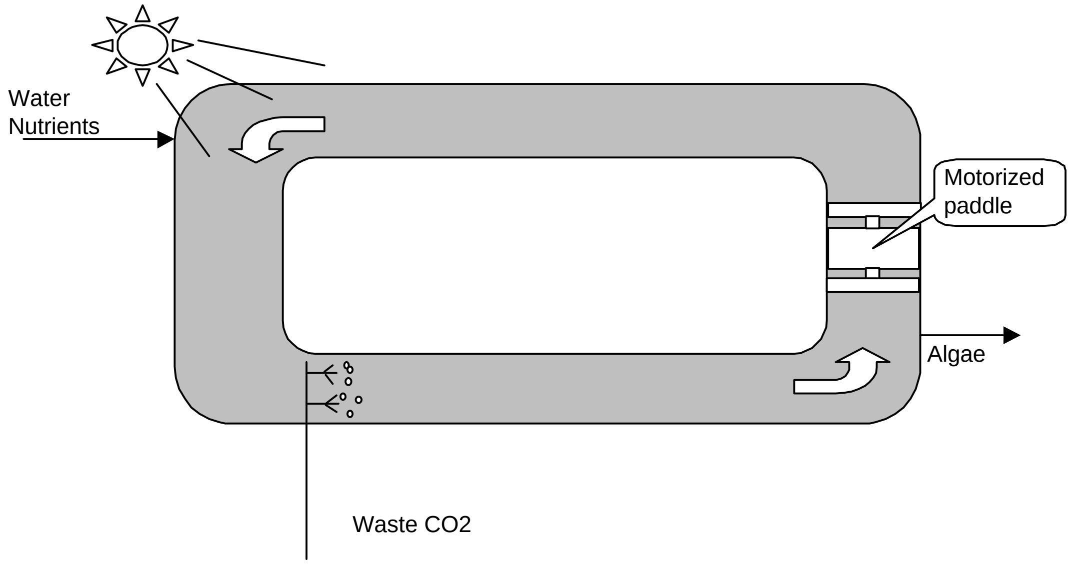
Put quite simply, microalgae are remarkable and efficient biological factories capable of taking a waste (zero-energy) form of carbon (CO_2) and converting it into a high density liquid form of energy (natural oil). This ability has been the foundation of the research program funded by the Office Fuels Development.

Algae Production Concepts

Like many good ideas (and certainly many of the concepts that are now the basis for renewable energy technology), the concept of using microalgae as a source of fuel is older than most people realize. The idea of producing methane gas from algae was proposed in the early 1950s[1]. These early researchers visualized a process in which wastewater could be used as a medium and source of nutrients for algae production. The concept found a new life with the energy crisis of the 1970s. DOE and its predecessors funded work on this combined process for wastewater treatment and energy production during the 1970s. This approach had the benefit of serving multiple needs—both environmental and energy-related. It was seen as a way of introducing this alternative energy source in a near-term timeframe.

In the 1980s, DOE's program gradually shifted its focus to technologies that could have large-scale impacts on national consumption of fossil energy. Much of DOE's publications from this period reflect a philosophy of energy research that might, somewhat pejoratively, be called "the quads mentality." A quad is a short-hand name for the unit of energy often used by DOE to describe the amounts of energy that a given technology might be able to displace. Quad is short for "quadrillion Btus"—a unit of energy representing 10^{15} (1,000,000,000,000,000) Btus of energy. This perspective led DOE to focus on the concept of immense algae farms.

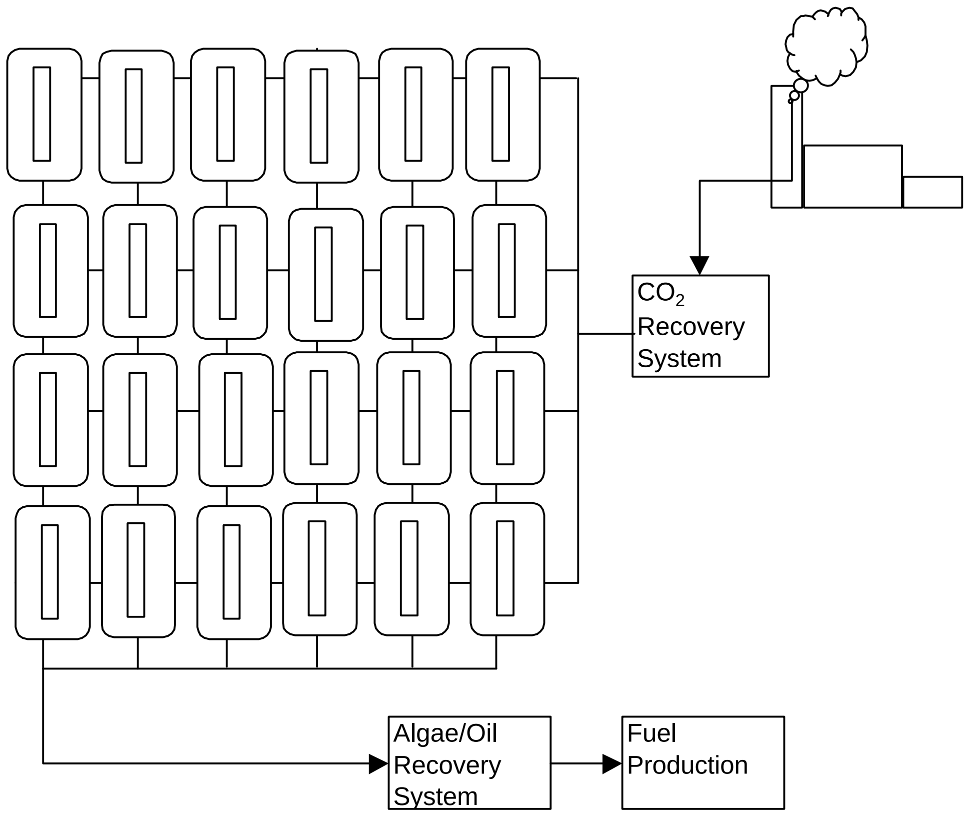
Such algae farms would be based on the use of open, shallow ponds in which some source of waste CO_2 could be efficiently bubbled into the ponds and captured by the algae (see the figure below).



The ponds are "raceway" designs, in which the algae, water and nutrients circulate around a racetrack. Paddlewheels provide the flow. The algae are thus kept suspended in water. Algae are circulated back up to the surface on a regular frequency. The ponds are kept shallow because of the need to keep the algae exposed to sunlight and the limited depth to which sunlight can penetrate the pond water. The ponds are operated continuously; that is, water and nutrients are constantly fed to the pond, while algae-containing water is removed at the other end. Some kind of harvesting system is required to recover the algae, which contains substantial amounts of natural oil.

The concept of an "algae farm" is illustrated on the next page. The size of these ponds is measured in terms of surface area (as opposed to volume), since surface area is so critical to capturing sunlight. Their productivity is measured in terms of biomass produced per day per unit of available surface area. Even at levels of productivity that would stretch the limits of an aggressive research and development program, such systems will require acres of land. At such large sizes, it is more appropriate to think of these operations on the scale of a farm.

There are quite a number of sources of waste CO_2. Every operation that involves combustion of fuel for energy is a potential source. The program targeted coal and other fossil fuel-fired power plants as the main sources of CO_2. Typical coal-fired power plants emit flue gas from their stacks containing up to 13% CO_2. This high concentration of CO_2 enhances transfer and uptake of CO_2 in the ponds. The concept of coupling a coal-fired power plant with an algae farm provides an elegant approach to recycle of the CO_2 from coal combustion into a useable liquid fuel.



Other system designs are possible. The Japanese, French and German governments have invested significant R&D dollars on novel closed bioreactor designs for algae production. The main advantage of such closed systems is that they are not as subject to contamination with whatever organism happens to be carried in the wind. The Japanese have, for example, developed optical fiber-based reactor systems that could dramatically reduce the amount of surface area required for algae production. While breakthroughs in these types of systems may well occur, their costs are, for now, prohibitive—especially for production of fuels. DOE's program focused primarily on open pond raceway systems because of their relative low cost.

The Aquatic Species Program envisioned vast arrays of algae ponds covering acres of land analogous to traditional farming. Such large farms would be located adjacent to power plants. The bubbling of flue gas from a power plant into these ponds provides a system for recycling of waste CO_2 from the burning of fossil fuels.

Fuel Production Concepts

The previous sections have alluded to a number of potential fuel products from algae. The ASP considered three main options for fuel production:

- Production of methane gas via biological or thermal gasification.
- Production of ethanol via fermentation

- Production of biodiesel

A fourth option is the direct combustion of the algal biomass for production of steam or electricity. Because the Office of Fuels Development has a mandate to work on transportation fuels, the ASP did not focus much attention on direct combustion. The concept of algal biomass as a fuel extender in coal-fired power plants was evaluated under a separate program funded by DOE's Office of Fossil Fuels. The Japanese have been the most aggressive in pursuing this application. They have sponsored demonstrations of algae production and use at a Japanese power plant.

Algal biomass contains three main components:

- Carbohydrates
- Protein
- Natural Oils

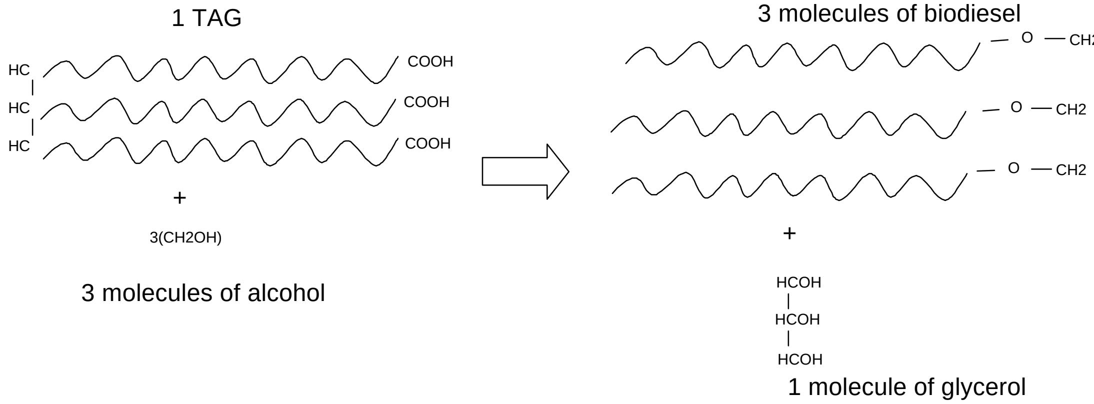
The economics of fuel production from algae (or from any biomass, for that matter) demands that we utilize all the biomass as efficiently as possible. To achieve this, the three fuel production options listed previously can be used in a number of combinations. The most simplistic approach is to produce methane gas, since the both the biological and thermal processes involved are not very sensitive to what form the biomass is in. Gasification is a somewhat brute force technology in the sense that it involves the breakdown of any form of organic carbon into methane. Ethanol production, by contrast, is most effective for conversion of the carbohydrate fraction. Biodiesel production applies exclusively to the natural oil fraction. Some combination of all three components can also be utilized as an animal feed. Process design models developed under the program considered a combination of animal feed production, biological gasification and biodiesel production.

The main product of interest in the ASP was biodiesel. In its most general sense, biodiesel is any biomass-derived diesel fuel substitute. Today, biodiesel has come to mean a very specific chemical modification of natural oils. Oilseed crops such as rapeseed (in Europe) and soybean oil (in the U.S.) have been extensively evaluated as sources of biodiesel. Biodiesel made from rapeseed oil is now a substantial commercial enterprise in Europe. Commercialization of biodiesel in the U.S. is still in its nascent stage.

The bulk of the natural oil made by oilseed crops is in the form of triacylglycerols (TAGs). TAGs consist of three long chains of fatty acids attached to a glycerol backbone. The algae species studied in this program can produce up to 60% of their body weight in the form of TAGs. Thus, algae represent an alternative source of biodiesel, one that does not compete with the existing oilseed market.

As a matter of historical interest, Rudolph Diesel first used peanut oil (which is mostly in the form of TAGs) at the turn of the century to demonstrate his patented diesel engine[2]. The rapid introduction of cheap petroleum quickly made petroleum the preferred source of diesel fuel, so much so that today's diesel engines do not operate well when operated on unmodified TAGs. Natural oils, it turns out, are too viscous to be used in modern diesel engines.

In the 1980s, a chemical modification of natural oils was introduced that helped to bring the viscosity of the oils within the range of current petroleum diesel[3]. By reacting these TAGs with simple alcohols (a chemical reaction known as "transesterification" already commonplace in the oleochemicals industry), we can create a chemical compound known as an alkyl ester[4], but which is known more generically as biodiesel (see the figure below). Its properties are very close to those of petroleum diesel fuel.



Commercial experience with biodiesel has been very promising[5]. Biodiesel performs as well as petroleum diesel, while reducing emissions of particulate matter, CO, hydrocarbons and SO_x. Emissions of NO_x are, however, higher for biodiesel in many engines. Biodiesel virtually eliminates the notorious black soot emissions associated with diesel engines. Total particulate matter emissions are also much lower[6,7,8]. Other environmental benefits of biodiesel include the fact that it is highly biodegradable[9] and that it appears to reduce emissions of air toxics and carcinogens (relative to petroleum diesel)[10]. A proper discussion of biodiesel would require much more space than can be accommodated here. Suffice it to say that, given many of its environmental benefits and the emerging success of the fuel in Europe, biodiesel is a very promising fuel product.

High oil-producing algae can be used to produce biodiesel, a chemically modified natural oil that is emerging as an exciting new option for diesel engines. At the same time, algae technology provides a means for recycling waste carbon from fossil fuel combustion. Algal biodiesel is one of the only avenues available for high-volume re-use of CO_2 generated in power plants. It is a technology that marries the potential need for carbon disposal in the electric utility industry with the need for clean-burning alternatives to petroleum in the transportation sector.

Why microalgae technology?

There are a number of benefits that serve as driving forces for developing and deploying algae technology. Some of these benefits have already been mentioned. Four key areas are outlined here. The first two address national and international issues that continue to grow in importance—energy security and climate change. The remaining areas address aspects of algae technology that differentiate it from other technology options being pursued by DOE.

Energy Security

Energy security is the number one driving force behind DOE's Biofuels Program. The U.S. transportation sector is at the heart of this security issue. Cheap oil prices during the 1980s and 1990s have driven foreign oil imports to all time highs. In 1996, imports reached an important milestone—imported oil consumption exceeded domestic oil consumption. DOE's Energy Information Administration paints a dismal picture of our growing dependence on foreign oil. Consider these basic points[11]:

- Petroleum demand is increasing, especially due to new demand from Asian markets.
- New demand for oil will come primarily from the Persian Gulf.
- As long as prices for petroleum remain low, we can expect our imports to exceed 60% of our total consumption ten years from now.
- U.S. domestic supplies will likewise remain low as long as prices for petroleum remain low.

Not everyone shares this view of the future, or sees it as a reason for concern. The American Petroleum Institute[12] does not see foreign imports as a matter of national security. Others have argued that the prediction of increasing Mideast oil dependence worldwide is wrong. But the concern about our foreign oil addiction is widely held by a broad range of political and commercial perspectives[13].

While there may be uncertainty and even contention over when and if there is a national security issue, there is one more piece to the puzzle that influences our perspective on this issue. This is the fact that, quite simply, 98% of the transportation sector in the U.S. relies on petroleum (mostly in the form of gasoline and diesel fuel). The implication of this indisputable observation is that even minor hiccups in the supply of oil could have crippling effects on our nation. This lends special significance to the Biofuels Program as a means of diversifying the fuel base in our transportation sector.

> *Our almost complete reliance on petroleum in transportation comes from the demand for gasoline in passenger vehicles and the demand for diesel fuel in commerce. Bioethanol made from terrestrial energy crops offers a future alternative to gasoline, biodiesel made from algal oils could do the same for diesel fuel.*

Climate Change

CO_2 is recognized as the most important (at least in quantity) of the atmospheric pollutants that contribute to the "greenhouse effect," a term coined by the French mathematician Fourier in the mid-1800s to describe the trapping of heat in the Earth's atmosphere by gases capable of absorbing radiation. By the end of the last century, scientists were already speculating on the potential impacts of anthropogenic

CO_2. The watershed event that brought the question of global warming to the forefront in the scientific community was the publication of Revelle's data in 1957, which quantified the geologically unprecedented build-up of atmospheric CO_2 that began with the advent of the industrial revolution. Revelle[14] characterized the potential risk of global climate change this way:

> *"Human beings are carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be produced in the future. Within a few centuries, we are returning to the atmosphere and the oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years."*

Despite 40 years of research since Revelle first identified the potential risk of global warming, the debate over the real impacts of the increased CO_2 levels still rages. We may never be able to scientifically predict the climatic effects of increasing carbon dioxide levels due to the complexity of atmospheric and meteorological modeling. Indeed, Revelle's concise statement of the risks at play in global climate change remains the best framing of the issue available for policy makers today. The question we face as a nation is how much risk we are willing to take on an issue like this. That debate has never properly taken place with the American public.

> *As Revelle's statement implies, the burning of fossil fuels is the major source of the current build up of atmospheric CO_2. Thus, identifying alternatives to fossil fuels must be a key strategy in reducing greenhouse gas emissions. While no one single fuel can substitute for fossil fuels in an all of the energy sectors, we believe that biodiesel made from algal oils is a fuel which can make a major contribution to the reduction of CO_2 generated by power plants and commercial diesel engines.*

The Synergy of Coal and Microalgae

Many of our fossil fuel reserves, but especially coal, are going to play significant roles for years to come. On a worldwide basis, coal is, by far, the largest fossil energy resource available. About one-fourth of the world's coal reserves reside in the United States. To put this in perspective, consider the fact that, at current rates of consumption, coal reserves could last for over 200 years.

Regardless of how much faith you put in future fossil energy projections, it is clear that coal will continue to play an important role in our energy future—especially given the relatively large amounts of coal that we control within our own borders. DOE's Energy Information Administration estimates that electricity will become an increasingly large contributor to future U.S. energy demand. How will this new demand be met? Initially, low cost natural gas will grow in use. Inevitably, the demand for electricity will have to be met by coal. Coal will remain the mainstay of U.S. baseline electricity generation, accounting for half of electricity generation by the year 2010.

The long term demand for coal brings with it a demand for technologies that can mitigate the environmental problems associated with coal. While control technologies will be used to reduce air pollutants associated with acid rain, no technologies exist today which address the problem of greenhouse gas emissions. Coal is the most carbon-intensive of the fossil fuels. In other words, for every Btu of energy liberated by combustion, coal emits more CO_2 than either petroleum or natural gas. As pressure to reduce carbon emissions grows, this will become an increasingly acute problem for the U.S.

One measure of how serious this problem could be is the absurdity of some of the proposals being developed for handling carbon emissions from power plants. The preferred option offered by researchers at MIT is ocean disposal, despite the expense and uncertainty of piping CO_2 from power plants and injecting the CO_2 in the ocean[15].

Commonsense suggests that recycling of carbon would be more efficacious than deep ocean disposal. No one clearly understands the long-term effects of injecting large amounts of CO_2 into our oceans. Beyond these environmental concerns, such large-scale disposal schemes represent an economic sinkhole. Huge amounts of capital and operating dollars would be spent simply to dispose of carbon. While such Draconian measures may ultimately be needed, it makes more sense to first re-use stationary sources of carbon as much as possible. Algae technology is unique in its ability to produce a useful, high-volume product from waste CO_2.

Consumption of coal, an abundant domestic fuel source for electricity generation, will continue to grow over the coming decades, both in the U.S. and abroad. Algae technology can extend the useful energy we get from coal combustion and reduce carbon emissions by recycling waste CO_2 from power plants into clean-burning biodiesel. When compared to the extreme measures proposed for disposing of power plant carbon emissions, algal recycling of carbon simply makes sense.

Terrestrial versus Aquatic Biomass

Algae grow in aquatic environments. In that sense, algae technology will not compete for the land already being eyed by proponents of other biomass-based fuel technologies. Biomass power and bioethanol both compete for the same land and for similar feedstocks—trees and grasses specifically grown for energy production. More importantly, many of the algal species studied in this program can grow in brackish water—that is, water that contains high levels of salt. This means that algae technology will not put additional demand on freshwater supplies needed for domestic, industrial and agricultural use.

The unique ability of algae to grow in saline water means that we can target areas of the country in which saline groundwater supplies prevent any other useful application of water or land resources. If we were to draw a map showing areas best suited for energy crop production (based on climate and resource needs), we would see that algae technology needs *complement* the needs of both agriculture and other biomass-based energy technologies.

In a world of ever more limited natural resources, algae technology offers the opportunity to utilize land and water resources that are, today, unsuited for any other use. Land use needs for microalgae complement, rather than compete, with other biomass-based fuel technologies.