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SYSTEMS AND ECONOMIC ANALYSIS OF MICROALGAE PONDS
FOR CONVERSION OF CO₂ TO BIOMASS

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SUMMARY

Microalgae cultivation in large open ponds is the only photosynthetic process likely to directly utilize power plant flue gas CO₂ for production of biomass. The algal biomass can be converted into substitutes for fossil fuels, in particular liquid fuels such as biodiesel (vegetable oil methyl or ethyl esters), thus reducing atmospheric CO₂ levels and the potential for global warming. This concept is being investigated, among others, at the National Renewable Energy Laboratory at Golden Colorado, with support from PETC.

Microalgae biomass is currently being produced for food supplements in the U.S. at three commercial facilities, each about 10 hectare in size and producing several hundred tons of algae at a cost of over \$10,000/ton. In scale, productivities and costs, microalgae biomass production technology must advance by an order of magnitude to be considered as an alternative fuel source and CO₂ mitigation technology.

Previous economic analyses of this concept, based on a number of favorable technical and site-specific assumptions, concluded that the large-scale (1,000 ha; 100,000 mt/y) production of microalgae could, in principle, be feasible technically. To be economically competitive with fossil fuels would require sites where low cost land and water are available and climatic conditions highly favorable. The prior studies had many limitations: mass balances and cost estimates were uncertain, designs not sufficiently detailed; the interface between the power plant stack gases and the microalgae production systems not addressed, and many of the scientific and engineering assumptions made were not sufficiently justified. For example, very high productivities were assumed, but how these were to be achieved was not detailed. Harvesting of the algae postulated a bioflocculation process, which remains to be demonstrated. Perhaps most important, the generic nature of those analysis did not consider constraints imposed by site specific factors.

Since these earlier feasibility studies, considerable experience has been gained in commercial microalgae production, and advances have been made in a number of fields related to this subject. An updated, more detailed and site specific, feasibility and economic analysis of microalgae systems for CO₂ capture from coal-fired power plants is being carried out under this project. A detailed review the prior work in this field has been completed, cost estimates for pond construction refined, and sites in California and Florida, are being selected for a site specific cost analysis. This project should allow an assessment of the potential of microalgae production as a process for CO₂ mitigation.

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INTRODUCTION

Microalgae comprise a vast assemblage of organisms characterized both by their microbial nature and their ability to produce oxygen through photosynthesis. They generally are single cell organisms or undifferentiated filaments or colonies. They grow suspended in water (planktonic forms) or attached to surfaces. The microalgae include procaryotes (cyanobacteria or blue-green algae) and eucaryotes (green algae, red algae, diatoms, etc.). Between and even within the thousands of known species there is great metabolic and physiological diversity.

Microalgae production combines characteristics of plant photosynthesis and microbial fermentations: high growth rates and hydraulic production systems using light, CO₂, and inorganic nutrients. Microalgae production R&D was initiated forty years ago in the U.S., with human food production as a major goal (Burlew, 1953). Over the past four decades microalgae production has been investigated in many countries for this and many other applications: human and animal waste treatment, fuels production, heavy metal sequestration, atmosphere regeneration in space vehicles, fertilizers, xanthophylls (pigments useful in animal feeds), omega-3 fatty acids, amino acids and vitamins, diagnostic reagents, surfactants, industrial polysaccharides and other specialty chemicals, and, of particular interest recently, CO₂ utilization from power plants for greenhouse gas mitigation (Benemann, 1992).

A major practical application of algal pond culture has been in the field of wastewater treatment. However, in such ponds algal species are not controlled and the biomass is seldom harvested. The first large-scale (> 1 ton/month) commercial microalgae production, of the single cell green alga Chlorella, was established in Japan during the early 1960's. Chlorella is sold as food supplements ("health foods"), and most production is currently located in Taiwan.

Production of the filamentous blue-green alga Spirulina, a traditional food in several countries, was initiated in Mexico about 1974. It is now also being produced in several other countries, including the U.S. where two large (> 200 tons/year) production plants are operating in California and Hawaii. Spirulina is sold mainly as a food supplement, but is also used to extract a blue pigment, phycocyanin, used as a food coloring agent in Japan, and in specialty animal and aquaculture feeds.

The third microalga already being produced commercially is the green alga Dunaliella, which grows in hypersaline environments and contains high amounts of beta-carotene, a pro-vitamin A, food coloring agent, and a reputed anticancer agent. These currently produced microalgae are sold at prices exceeding \$10,000/ton of organic dry weight. The production of microalgae for CO₂ utilization and fuels production requires production costs below \$500/ton. This project addresses the question of whether it could be feasible to reduce costs by such a large factor.

CURRENT COMMERCIAL MICROALGAE PRODUCTION

Current costs for commercial microalgae production are high for several reasons: small-scale of production, low productivities, high harvesting and processing costs and high capital costs. Chlorella cultivation systems become easily contaminated. Spirulina, a filamentous blue-green alga, requires a high (> 15 g/l) bicarbonate medium and Dunaliella requires high (> 100 g/l) NaCl concentrations, both of which add to production costs and reduce productivities, also provide a selective chemical environment that minimizes most contamination problems.

A fundamental issue is the design of the cultivation system, the "photobioreactor". Many designs have been proposed and tested, from small laboratory devices to open ponds many hectares in size. The design of such systems is constrained by the need to provide light (large surface to volume ratios), control environmental conditions (pH, temperature, dissolved oxygen, etc.), supply nutrients (mainly CO_2 ; also N, P, etc.), and control contamination (other algae, grazers, etc.). Of course, the ultimate constraint is economic, dictated by the value of the product.

The two main system designs are used in large-scale microalgae cultivation:

1. Shallow (< 30 cm), paddle wheel mixed, raceway pond design, which allows good control over conditions (such as CO_2 supply). Individual growth ponds are currently up to about 0.5 ha in size and are plastic lined, although much larger sizes and unlined ponds should be, at least theoretically, feasible.
2. Relatively deep (typically > 50 cm), large (> 1 ha, with some as large as 100 ha), unlined ponds, not mechanically mixed, relying mainly on wind mixing.

The latter design provides little possibility for process control, and is used in waste water treatment, by one plant in Mexico for Spirulina production, and by two plants for Dunaliella production systems in Australia. However, productivities are very low in such systems and they would not be practical for CO_2 utilization. Only the "raceway" design can achieve the high productivities required. Table 1 lists the three commercial raceway ponds production facilities in the U.S. Other commercial plants based on the same design are operating in Israel (for Dunaliella) and Thailand (for Spirulina).

Table 1. U.S. Commercial Microalgae Production Facilities

Alga	Location	Area (ha)	Production (t/y)
<u>Spirulina</u>	So. Calif.	8	200
<u>Spirulina</u>	Hawaii	6	200
<u>Dunaliella</u>	So. Calif.	5	< 50

MICROALGAE FUEL PRODUCTION AND CO₂ MITIGATION

The possibility of low-cost production of microalgae has attracted the attention of researchers for the past four decades starting with the work described in Burlew (1953). Oswald and Golueke (1960) first analyzed the possibility of growing microalgae on power plant flue gases (as a source of CO₂), and converting the biomass to methane gas, which could be used as a fuel to operate the power plant. This concept, of coupling algae production with power plant CO₂ utilization, and thus replacing fossil fuels, has received renewed attention with the concern about possible global warming due to CO₂ emissions.

The energy crisis of the 1970's had already spurred research on microalgae production for fuels. The U.S. Department of Energy, in large part through the Aquatic Species Program of the National Renewable Energy Laboratory (NREL, formerly SERI, the Solar Energy Research Institute), has sponsored almost \$20 million in basic and applied microalgae production research, with the objective of developing low cost technology for microalgae fuel production (Neenan et al., 1986). The emphasis of this program is on the production of liquid fuels, specifically vegetable oils that can be rather readily converted to "biodiesel". Microalgae, under certain conditions (such as N limitation) produce copious amounts of oils, a phenomenon studied for over 50 years. A pilot plant facility located in Roswell, New Mexico, demonstrated the feasibility of cultivating various species of microalgae on saline ground waters (Weissman and Tillett, 1989, 1992). The use of water resources unsuitable for agriculture is a requirement for such a process. An ambitious program on using microalgae for CO₂ mitigation was recently established in Japan.

The goal of producing fuels with microalgae may seem improbable considering the relatively high present costs of producing microalgae, well over one order of magnitude higher than those allowable for fuel production and CO₂ utilization. However, several factors could greatly reduce the cost of microalgae production:

1. Increases in scale of operation, from the less than 10 ha scale of current facilities to about 1,000 ha for a fuel production/CO₂ utilization system;
2. The use of unlined earthwork ponds, rather than plastic lined ponds;
3. The ability to maintain a stable culture, overcoming grazer invasions and other biological invasions at essentially no cost or loss of productivity.
3. The use of cheaper harvesting methods, such as bioflocculation (the spontaneous flocculation and settling of algal cells, Benemann et al., 1980);
4. The development of low cost processing of algal biomass to fuels; and
5. Increasing the productivity of algal cultures, from currently under 50 mt/ha-yr for commercial systems to near the theoretical maximum of 200 mt/ha-yr.

Indeed, previous economic analysis carried out by the author and colleagues (Benemann et al., 1982; Weissman and Goebel, 1987) suggest that, in principle, very low cost production systems are feasible, as reviewed next.

PROJECTED COSTS FOR LARGE-SCALE MICROALGAE PRODUCTION

The cost estimates, summarized in Table 2, reflect numerous favorable assumptions about both the engineering and biological aspects of such a process. The individual growth ponds would be earthwork construction, unlined, paddle wheel mixed raceway designs, with a single central baffle and about 10 ha in size. Contamination or grazing problems are ignored. Harvesting would be by bioflocculation. Available water would contain sufficient alkalinity to allow CO₂ storage. Very high productivities are assumed, up to the theoretical limit. Although design of some of the subsystems are based on significant detail (e.g. paddle wheels), others (such as the interface of the power plant, the flue gas distribution system and the processing of the algal biomass to oil) are based on very superficial estimates. Very favorable site characteristics are assumed, in terms of climate, land slope, soil properties, and availability of land and water at essentially zero costs.

Table 2. Capital and Operating Costs for Microalgae Fuels
(Based on a 1,000 Ha algae production facility)

Productivity Assumed: (ash-free dry weight)	Current	Maximum
Average Daily:	30 g/m ² -d	60 g/m ² /d
Annual:	<u>109 mt/ha-yr</u>	<u>219 mt/ha/yr</u>
Capital Costs (\$/ha):		
Ponds (earthworks, CO ₂ sumps, mixing)	27,500	33,000
Harvesting (settling ponds, centrifuges)	12,500	17,000
System-wide Costs (water, CO ₂ supply, etc.)	30,000	40,000
Processing (oil extraction, digestion)	10,000	20,000
Engineering, Contingencies (25% of above)	20,000	27,500
Total Capital Costs (\$/ha)	100,000	137,500
Capital Costs \$/t-yr	920	630
Barrels of Oil/ha-yr (@ 3.5 bar./t)	380	760
Capital Costs \$/Barrel-yr	260	180
Operating Costs (\$/ha-yr):		
Power, nutrients, labor, overheads, etc.	10,000	15,500
Credit for methane produced	- 3,000	- 6,000
Net Operating Costs \$/ha-yr	7,000	9,500
Net Operating Costs \$/barrel oil	18	13
CO ₂ Mitigation Credits (\$60/tC)	-10	-10
Annualized Capital Costs (0.2 x Capital)	52	36
Total Costs \$/Barrel	60	39
Land Area Required ha/MW:	12	6

Assumptions: Algae organic composition: 50% lipid, 25% carbohydrate, 25% protein,
60% C, 5% N, heat of Combustion: 7.5 Kcal/g.
Avg. Annual Solar Insolation: 500 Langleys, 45% visible.

LARGE-SCALE MICROALGAE PRODUCTION FOR FLUE-GAS CO₂ UTILIZATION

As already indicated above, many aspects of the proposed large-scale microalgae production process require R&D. For example, the individual growth ponds are over ten times larger than present experience. The hydraulics and wind effects in such large ponds must be determined. Major design factors are the depth of the CO₂ supply sumps (which determines CO₂ transfer efficiency), the pond mixing velocities (typically 20 - 30 cm/sec), the number of carbonation stations (a function of CO₂ storage, pH range, outgassing rates), and depth of the pond culture (typically 20 to 30 cm). These factors are interactive and must be optimized. Bioflocculation, a well known natural process which has also been observed in waste grown algae (Benemann et al., 1980), needs to be demonstrated in actual microalgae production. The extraction and processing of the vegetable oils from the algal biomass was cost estimated based on soybean processing, as no relevant data for algal oil is available. Conversion to biodiesel was not included in the cost estimates. The algal oils would be produced by limiting the algal cultures for nitrogen, which has been demonstrated at the laboratory scale but not yet in large outdoor ponds. Also, the assumption is made that desirable algal species can be cultivated in open ponds, with minimal losses due to grazing, predation, diseases, contamination. The development of the techniques for maintaining healthy, productive cultures in large-scale systems requires considerable work. Most important, two productivities are assumed, corresponding to about 5 and 10% solar energy conversion efficiencies at favorable sites in the U.S. The lower productivity is based on what is believed to be achievable with present experience. Approaching the higher productivity, essentially the theoretical limit, will require the development of greatly improved algal strains that, among other attributes, have a lower pigment content, allowing better light utilization in dense cultures (Benemann, 1990).

If close to theoretical productivities are indeed achievable, and the other technical assumptions on which this cost estimates are based verified, then such a process could utilize flue gas CO₂ and produce fuels at about \$40/barrel of oil, if a CO₂ mitigation credit of about \$60/ton C were provided. This is within the range of CO₂ credits discussed for greenhouse gas mitigation (Lashoff and Tirpak, 1989) and projected future oil prices.

A major constraint on such systems, besides the R&D issues, is the availability of sufficient land and water near the power plant. Each megawatt of power plant capacity would require between 6 and 12 ha. Thus several thousand hectares would be required for a large conventional power plant. Also, only about 30% of the CO₂ emissions from the power plant could be captured, as the system would be sized to utilize most of the CO₂ produced during peak summer daytime algal productivity and CO₂ utilization, wasting night and much of the winter CO₂ outputs. However, even a 30% CO₂ capture would greatly reduce the potential for adverse effects of CO₂ released from such a power plant (Benemann, 1992). And the land area required is a small fraction, less than one tenth, that required for other biomass systems (e.g. tree farms). And such systems would provide over 3,000 barrels of liquid transportation fuels per year per megawatt of power. Thus, in principle, such a process could have merit in the mitigation of power plant CO₂.

FUTURE DEVELOPMENTS IN MICROALGAE CO₂ MITIGATION.

A precedent for microalgae derived fuels exists: small deposits of oil were recovered earlier this century in Australia from the shores of several lakes. The oil derived from hydrocarbons produced by the microalga Botryococcus, which can produce over 60% of its dry weight as pure hydrocarbons of near diesel quality, which washed ashore, leaving hydrocarbons as oily remains on the beaches (Wake and Hillen, 1980). Perhaps it would be possible to mimic such a process under more controlled conditions.

Strong support for the contention that it is possible to produce microalgae in large-scale outdoor systems with low cost processes comes from recent experience with commercial and pilot plants. At Earthrise Farms, Inc. (S. Calif.), a paddle wheel mixed, unlined earthen pond of about 5 hectares has been successfully operated for Spirulina production. In New Mexico, a comparison between plastic lined and unlined 0.1 ha ponds revealed no significant difference (Weissman and Tillett, 1992). Also at this site, several species of diatoms and green algae were maintained for several months as near unialgal cultures at relatively high productivities using brackish waters (Weissman and Tillett, 1989).

Over the past decade, microalgae culture has advanced from small-sale pilot plant operations to full-scale commercial enterprises (Table 1). The utilization of microalgae in wastewater treatment is also advancing, with some channelized, raceway type systems being found in California, where they were pioneered by Prof. W.J. Oswald, of the University of California at Berkeley (Oswald, 1988). Indeed, microalgae waste water treatment systems could be a potential sink for CO₂, including CO₂ from power plants, rather than a CO₂ source as are conventional wastewater treatment plants.

In conclusion, although much R&D is still needed, no insurmountable problems are apparent and no "breakthroughs" are required for the development of low cost microalgae production systems. Thus, microalgae may become an option for CO₂ removal from flue gases and conversion to fuels. Due to resource limitations (the requirement for low cost land and water near power plants), such systems are not likely to provide a major solutions to this problem. Indeed, when considering limitations due to climate, land and water availability, and other factors, such systems could only reduce overall U.S. fossil fuel derived CO₂ emissions by a small percentage, possibly 1 to 2%. However, even such at first glance negligible impacts, represent a significant contribution to the overall effort of containing CO₂ emissions. There are many different, small-scale, approaches to the reduction in CO₂ emissions, providing a continuum of options of increasing costs. Another factor are the powerful self-cleaning capabilities of the earth system (almost half of the total CO₂ emitted to the atmosphere by human activity disappears into poorly known sinks). Thus, the goal of CO₂ mitigation need not reach a 100% of fossil fuel emissions, and even modest reduction in CO₂ emissions can have large effects on prospective climate changes. Any technology that can reduce even a modest fraction of total CO₂ emissions could have disproportionate impact on future climatic trends.

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