A Proposal to Establish an International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae

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SUMMARY

Microalgae mass cultures can use solar energy for the biofixation of power plant flue gas and other concentrated CO_2 sources into biomass that can be used to produce renewable fuels such as methane, ethanol, biodiesel, oils and hydrogen and for other fossil-fuel sparing products and processes. They thus can mitigate emissions of fossil CO_2 and other greenhouse gases. Microalgae are currently used commercially in the production of high-value nutritional products, in wastewater treatment and in aquaculture. One commercial microalgae production plant, in Hawaii, is already using flue gas from a small power plant as an exogenous source of the CO_2 required to grow algal biomass. Although still a relatively small industry (total production is only a few thousand tons of algal biomass per year world-wide), microalgae technologies have been extensively studied over the past decade in the context of greenhouse gas mitigation, specifically in Japan and the U.S.

In January of this year, a Workshop attended by 38 participants from major energy companies, the microalgae industry, governmental organizations, universities and others, was held in Monterotondo, near Rome Italy, to discuss the prospects of microalgae technologies in abating

greenhouse gases. The Workshop was organized by EniTecnologie (the R&D arm of ENI, the Italian oil company), the U.S. Department of Energy, and the IEA Greenhouse Gas R&D Programme. The consensus of the Workshop participants was that microalgae offer a variety of approaches to this goal, including the production of energy saving products (such as fertilizers and bioplastics) and applications in wastewater treatment and aquaculture. In addition, microalgae processes have potential for development of larger-scale systems, specifically for power plant CO_2 capture and renewable fuels production. Significant research, development and demonstration (R,D&D) efforts will be required to achieve the scientific and technical advances required, including high productivities, culture stabilities, control of biosynthetic pathways, and biomass harvesting and processing. Integrated processes in wastewater treatment and aquaculture were indicated as near-term applications of this technology. In addition to producing renewable fuels, such processes would, when compared to conventional processes, mitigate greenhouse gases by reducing CH_4 and N_2O emissions and by reduced fossil fuel consumption.

A formal proposal for establishment of an International Network for research coordination and collaboration, operating under the IEA Greenhouse Gas R&D Programme, was presented to the Executive Committee of the Programme at its meeting in Regina, Canada, in March 2001. The proposal focuses on practical R,D&D of microalgae systems that utilize concentrated sources of CO_2, in particular flue gas from stationary fossil fuel-burning power plants, and convert the algal biomass to renewable fossil fuel substitutes. The membership of this Network will comprise energy companies, government agencies, and other organizations interested in supporting the development of microalgae GHG mitigation technologies. The Network would start operations in 2002.

1. INTRODUCTION

The IEA (International Energy Agency) Greenhouse Gas R&D Programme was established ten years ago to evaluate technologies for the abatement/mitigation of greenhouse gas emissions, to disseminate information, to promote research activities and to develop targets for appropriate R,D&D. Some 16 countries and the EU participate in this Programme, which is also sponsored by several major energy companies. At the meeting of the IEA Greenhouse Gas R&D Programme Executive Committee in August 2000, in Cairns, Australia, the U.S. Department of Energy and EniTecnologie proposed the establishment of a new activity within the Programme to help coordinate and advance practical R,D&D in the area of microalgae technology for GHG mitigation. This activity was proposed to be organized as a "Network" of interested members and supporters of the IEA Greenhouse Gas R&D Programme, as well as other organizations and companies interested in promoting applied R&D in this area, and in coordinating and collaborating in such efforts.

Following up on this proposal, a Workshop was held in January of 2001, at the EniTechnologie research facility in Monterotondo, near Rome, Italy, to review the technological basis of this field and to discuss the proposal for this new activity. The U.S. Department of Energy and EniTecnologie supported this Workshop organized by the IEA Greenhouse Gas R&D Programme. About half of the 38 participants came from major energy companies, with the remainder representing microalgae companies, universities, government agencies, and private organizations. Aims of the Workshop were to:

1. review the technological basis and prospects of microalgae technologies in abating GHGs; and

2. elicit interest in the proposed "Microalgae Biofixation Network".
Technical presentations were followed by plenary and breakout sessions to develop consensus recommendations for R&D in microalgae technologies for CO_2 biofixation and GHG mitigation. These are discussed below, followed by a brief description of the Network proposal. A Workshop report is available on request from the authors.

2. TECHNICAL BACKGROUND

In recent years, major organized R,D&D efforts related to microalgae biofixation of CO_2 and production of renewable fuels were carried out in Japan and the U.S. (Usui and Ikenouchi, 1996; Sheehan et al., 1998). Although these prior efforts supported the potential of microalgae technologies, they also suggested the need for a more critical analysis of the proposed processes and R&D approaches, and the need to focus on both near- and long-term R&D goals. The Monterotondo Workshop brought together experts in microalgae mass culture to review the technical issues and provide a diversity of visions for microalgae applications in GHG mitigation. The main technical presentations (Table 1) provided the technical background to this Workshop (See the Workshop Report for summaries of the individual presentations).

TABLE 1. Workshop Main Technical Presentations

- **Mario Tredici**, University of Florence, Italy Introduction to microalgae biotechnology
- **John Benemann**, Consultant, USA The US experience in microalgae biofixation
- **Yoshi Ikuta**, SeaAg Japan Inc., Japan The Japanese experience in microalgae biofixation"
- **Paul Roessler**, Dow Chemical, USA Microalgae genomics and molecular biology
- **Norihide Kurano**, Marine Biotechnology Institute, Japan Biological CO_2 fixation and utilization project
- **Avigad Vonshak**, Ben-Gurion University, Israel Stress physiology of dense outdoor algal cultures
- **Miguel Olaizola**, Aquasearch Inc., USA The issue of cost of biological sequestration of CO_2: closed systems offer a solution
- **Gerry Cysewski**, Cyanotech Corp., USA Carbon dioxide recovery in open pond culture of *Spirulina*
- **Bailey Green**, Oswald Green, LLC, and University of California Berkeley, USA "Avoidance and mitigation of greenhouse gas emissions and microalgal biofixation of CO2 using the AIWPS
- **David Brune**, Clemson University, USA Greenhouse gas mitigation with a sustainable aquaculture process
- **Joseph Weissman**, SeaAg, Inc., USA System and process design

A practical example of a current microalgae production process is the case of *Spirulina*, a microalga already produced commercially in open ponds in many countries around the world. In these production systems, the algae are cultivated in large (typically 0.2 0.4 hectares), raceway-type open ponds mixed by paddle wheels. Nutrients, most importantly CO_2, are added to the ponds and these filamentous algae are then harvested by fine mesh screens, spray dried and sold as specialty human foods and animal feeds. The CO_2 is typically purchased from commercial sources, although in some cases it is also derived from the flue gas emitted by the drying operation.

At the Cyanotech Corp. algal production facility in Kona, Hawaii, (Figure 1) a small power plant was build to produce both power and allow the capture of the CO_2 required for algal production ponds (Figure 2). Two 180 kW generators (with one spare) produce the electricity required to operate the paddle wheels on the 67 algal production ponds (avg. 0.3 ha in size) and other process power needs. The stack gas comes out at some 485^{o}C at 20 scm/min and contains 8% CO_2, or 188 kg/hr of CO_2. This is transferred to the bottom of a CO_2 absorption tower, 2.4 m diameter and with some 6.4 m high packing material. The spent culture medium (after harvesting the *Spirulina*) comes in at the top and is collected in the bottom. The countercurrent absorption system is 75% efficient and provides some 67 t CO_2/month, supporting 36 t/mo of *Spirulina* production, enough to provide CO_2 to 12 ha of ponds. The system generates an annual net income (credit) of almost $300,000 from power and CO_2 savings (Cysewski, Workshop Proceedings). This patented system provides a practical example of microalgae biofixation of CO_2. Biofixation of CO_2 into specialty foods, such as *Spirulina* does not, by itself, mitigate greenhouse gases. The most direct way for greenhouse gas mitigation is for the algal biomass to be converted to a renewable fuel, displacing fossil fuels.

It was pointed out by the Workshop participants that the current cost of commercial algal production in open ponds, such as for *Spirulina*, is some $5,000 per ton, but that the allowable cost for biofixation of CO_2 and renewable fuel production would be at most $250 per ton. This will require a large increase in the achievable productivities of microalgae systems as well as major cost reductions in the production process. These can be envisioned, in particular through an at least ten-fold increase in the scale of such ponds, as well as major cost reductions in essentially all aspects of the production systems. Asides from productivity, major technical and economic issues in large-scale algal mass culture include contamination and culture stability, algal biomass harvesting, and processing of the biomass to fuels. These will be the challenges faced in advancing this technology from its present status in specialty foods and feeds production to large-scale systems for fuels production and greenhouse gas mitigation.

A major theme of the technical presentations was the contrast between the production of microalgae in open (raceway, paddle wheel-mixed) ponds versus closed (typically tubular, optical fiber, flat plate) photobioreactors. Although closed photobioreactors have been used in some commercial microalgae production, they are too expensive for application to the low-cost production systems required for microalgae fuel production and greenhouse gas mitigation. A current commercial application of closed photobioreactors is in the cultivation of the unicellular alga *Haematococcus pluvialis*, a source of the very expensive pigment astaxanthin, used in salmon aquaculture and also as an antioxidant in food supplements (Olaizola, Workshop Report). Although this alga is difficult to maintain in mass cultures, it can be cultivated in open ponds (see Figure 1), with closed photobioreactors required in the start-up phase of the production process.

FIGURE 1. TYPICAL COMMERCIAL MICROALGAE PRODUCTION FACILITY

Cyanotech Corp., Kona, Hawaii. Note green ponds culturing *Spirulina* and red ponds with *Haematococcus pluvialis.* Note paddle wheels.

FIGURE 2.
POWER PLANT AND CO_2 SCRUBBER FOR MICROALGAE PRODUCTION
Cyanotech Corp., Kona, Hawaii. See Text.

A similar process could be envisioned for larger-scale microalgae production processes for greenhouse gas mitigation: the initial starter cultures are cultivated in small closed photobioreactors and then transferred through increasingly larger systems to the final open production ponds. One potential application of such a scheme would be with the alga *Botryococcus braunii*, which contains up to 50% pure hydrocarbons by weight. Indeed, this alga blooms naturally in some Australian lakes and the algal biomass blown on shore has been used as fuel in Australia in the past (Wake and Hillen, 1980).

The application of closed photobioreactors was a focus of the very large (> $100 million) Japanese R&D program carried out during the 1990's to develop microalgae greenhouse gas mitigation technologies (Kurano, Workshop Report). This program involved a large number of private companies, as well as collaborative work with several research institutes and universities. Over 10,000 strains of microalgae were isolated and screened for tolerance to high CO_2, temperature, salinity, high growth rates, maximum cell densities, O_2 evolution rates, etc. Selected algal strains were investigated for optimized growth and production in photobioreactors of up to 200 liters in volume. In particular, designs using optical fibers were developed, although these are problematic due to the large light losses aside from their clearly excessive costs. Contrasting with this approach, at Tohuku Electric Power Co., in Sendai, Japan, a 16 month test of algal cultivation using the actual flue gas from a large oil-fired power plant was carried out using two small open raceway ponds (about 5 m^2 total) (Ikuta, Workshop Report). The strain cultured was a green alga, a *Tetraselmis* species that appeared spontaneously and replaced the initially inoculated strains. Seasonal productivities (Spring to Autumn) averaged some 17 $g.m^{-2}.day^{-1}$ (all biomass units are ash-free dry weights). This project demonstrated that power plant flue gases can be used directly in a stable algal production in open raceway ponds. Presently, commercial diatom cultivation is being carried out in Japan in the context of commercial clam aquaculture, demonstrating that such systems can utilize flue gas CO_2 with 90% efficiency (Ikuta, Workshop Report).

A major focus of the technical presentations and discussions was how to achieve the very high productivities required for greenhouse gas mitigation. This issue has been studied since the initial development of this technology, starting with an international R&D effort some 50 years ago (Burlew, <u>Algal Culture from Laboratory to Pilot Plant</u>, 1953). The advantages of microalgae mass culture were already recognized at that time, including that algal densities can always be maintained near the optimum for light absorption and utilization, and that microalgae have the potential for very high productivities. However, solar conversion efficiency (productivity) is limited by the so-called "light saturation effect": microalgae cultures can utilize only a fraction of the sunlight to which algal cultures are exposed, typically one third or less. The reason for this is that the algal photosynthetic pigments (e.g. the chlorophylls, carotenoids, etc.) capture more photons under full sunlight conditions than can be processed by the biochemical machinery of photosynthesis. The four major approaches to overcoming this limitation were already recognized a half century ago (Burlew, 1953):

1. use short (microsecond) pulses of light ("flashing light");
2. expose the cells to high turbulence, achieving a similar effect;
3. dilution of sunlight (such as with the optical fiber photobioreactors or with vertical panels), and
4. improved strains of microalgae, "mutants that can utilize light of very much higher intensity".

Although much work has been carried out with the first three approaches, in particular R&D on optical fiber bioreactors in Japan and the U.S., only the last approach, mutants that are not light saturated at high light intensities, is potentially practical, at least in the context of low-cost microalgae production. Recently, research in Japan and the U.S. has demonstrated that algal cultures and mutants with reduced antenna sizes can exhibit increased photosynthetic rates under high light intensities (Melis et al., 1999, Nakajima and Ueda, 2000). Application of such strains in large-scale, paddle-wheel mixed, raceway-type open ponds could achieve the very high productivities as well as the very low costs required for biofixation of CO_2 from power plant flue gases and their conversion to renewable fuels (Benemann, 1993). The molecular tools of modern genetic biotechnology are being developed for several microalgae species and are becoming available to allow the practical development of the improved strains required for high mass culture productivities (Roessler, Workshop Report).

Although the light saturation effect is perhaps the major limitation on productivity, it is not the only one. During cultivation, either in ponds or in closed photobioreactors, microalgae are subjected to diurnal variations in not only light intensity but also temperature and O_2 (which can accumulate to several-fold above air saturation levels, particularly in closed photobioreactors). High light intensities can often be detrimental to algal cultures: efficiencies for *Spirulina* drop dramatically during the middle of the day, due to the inhibitory effects of high sunlight. Temperature is another factor: the alga *Monodus subterraneus* growing in a diurnal temperature regime (13.5 to 28^{o}C), exhibits a strong inhibition in photosynthetic parameters as well as biomass productivity compared to a constant temperature control (Vonshak, Workshop Report). Respiration, both during the night and also during day-time can, and often does, significantly reduce overall productivity.

Near-term applications of microalgae in greenhouse gas mitigation could come through the development of wastewater treatment and aquaculture processes that combine their waste treatment features with reduction in greenhouse gas emissions and biofuels production. Microalgae ponds have been used in wastewater treatment for over 50 years. A multipond "Advanced Integrated Wastewater Pond Systems Technology (AIWSPfi)" was developed at the University of California Berkeley by Professor W. J. Oswald and colleagues over the past half century (Green, Workshop Report). This multi-stage process combines primary treatment (settleable solids removal and anaerobic digestion) in initial deep unmixed ("facultative") ponds, with secondary treatment (reduction of biochemical oxygen demand) taking place in shallow, paddle wheel-mixed, raceway ponds ("high rate ponds"). These are rather similar to those used for *Spirulina* production. In the facultative ponds, deep fermentation cells act as in-pond digesters where organic solids settle and undergo methane fermentation. In the high rate ponds, the O_2 produced by the microalgae supports the bacterial oxidation of waste organics. These are then followed by algal settling basins for removal and concentration of the algal cells. Alternatively, the algal biomass can be harvested by dissolved air flotation. A number of multipond systems are operating in California and around the world, treating municipal, agricultural and industrial wastes.

These systems could be applied to reduce greenhouse gas emissions by three main mechanisms:
1. The methane rich (typically >85%) biogas produced in the initial facultative ponds can be collected using submerged gas collectors, thereby reducing the atmospheric emission of this greenhouse gas.

2. The gas can then be used to generate power to mix the ponds and run the operating equipment, thus avoiding the fossil CO_2 emissions from the power consumed in conventional waste treatment.
3. Harvesting the algal biomass and its conversion to biofuels would replace additional fossil fuels.

The algal cultures in the high rate ponds are generally CO_2-limited, and supplemental CO_2 would greatly enhance algal production and biomass and thus, biofuels production.

Similarly, it is possible to consider microalgae greenhouse gas mitigation being carried out in connection with aquaculture systems. For example, a "Partitioned Aquaculture System (PAS)", developed at Clemson University (Brune, Workshop Report, Figure 3) uses paddle wheel-mixed raceway ponds to separate the pond fish culture into a series of separate physical/chemical/biological processes linked together hydraulically. The paddle wheel mixing provides good hydraulic control and maximizes algal growth, outgasing and waste treatment functions, thus greatly reducing the environmental impacts of such systems. Algal photosynthesis increases from about 1-3g C $m^{-2}.d^{-1}$ in conventional catfish ponds to 10 12 g C $m^{-2}.d^{-1}$ in the PAS system. This leads to greatly increased levels of O_2 in the ponds, reducing the mechanical aeration required in catfish aquaculture by 75 to 90%, saving power in excess of that required for paddle wheel mixing. Most importantly, from an economic perspective, these systems greatly increase fish production. Calculations of their GHG emissions reductions potential show an overall reduction of over 50%, from 2.0 kg C-CO_2eq/kg of product (fish flesh) for conventional systems to some 0.8 kg C-CO_2eq/kg of product for current PAS systems. The major part of this difference is due to the much lower CH_4 emissions from the PAS compared to conventional aquaculture ponds. Over 60,000 hectares (150,000 acres) of catfish ponds are currently operating in the Southeastern U.S., providing an opportunity for significant impacts in greenhouse gas mitigation through application of this technology, particularly if the much lower greenhouse gas emissions of such fish production compared to meat production are considered (Brune, Workshop Report).

The development and application of advanced microalgal waste treatment and aquaculture technologies required supplying CO_2 to the algal cultures in order to maximize productivities and utilization of waste nutrients. This greatly increases algal biomass and thus, the amount of biofuels that, as a byproduct of this process, can function in greenhouse gas mitigation. The application of such processes to animal wastes, food processing and other industrial wastes would greatly increase the potential of such integrated microalgae systems in GHG abatement.

The ultimate objective of microalgae biofixation of CO_2 is to operate large-scale systems that are able to convert a significant fraction of the CO_2 outputs from a power plant into biofuels. This will require considerable scale-up of such systems, high CO_2 utilization efficiencies, very high algal productivities and very low costs. These requirements cannot be easily achieved with closed photobioreactors that have inherently small-scale units, and where temperature and O_2 control are major problems. Ponds, due to their large open surface area, are self-limiting in oxygen accumulation and temperature increases, and contamination problems are not greater than with closed photobioreactors (Weissman, Workshop Report). CO_2 can be transferred with high efficiency into ponds, using in-pond sumps operated either with, or in the case of flue gas, against the current. Outgasing of CO_2 from ponds can be limited to a small fraction by operating within a defined range of alkalinity, pH, and mixing velocities.

FIGURE 3.
AQUACULTURE MICROALGAE PONDS FOR FISH AQUACULTURE
(Clemson University, South Carolina)

Results from operation of a pilot plant (two ponds, 1,000 m^2 each) operated in Roswell, New Mexico (1988-1990), demonstrated high (90%) CO_2 transfer and overall utilization efficiencies, and little difference was noted between plastic lined and unlined ponds. This resolved a major uncertainty, as plastic liners would be too expensive for large-scale, low-cost applications. In small-scale ponds, productivities with several diatom species averaged over 30 $g.m^{-2}.d^{-1}$of ash-free dry weight in experiments of up to several months, with light conversion efficiencies averaging over 7% of PAR (photosynthetically active radiation, about 3.5% of total solar energy). The larger ponds had lower productivity, maximally about 20 $g.m^{-2}.d^{-1}$ in summer, probably due to the less optimal hydraulic and other conditions achieved in these large-scale experiments (Weissman, Workshop Report). Overall, this pilot plant work demonstrated that it is possible to stably mass culture green algae and diatoms in low-cost unlined, relatively large-scale open ponds.

Finally, several participants highlighted the potential of microalgae, specifically the nitrogen fixing cyanobacteria, in biofertilizer production. One concept is to grow such algae in rice field, where they could be relatively cheaply integrated into rice cultivation. Considerable R&D is still required for such applications, in particular the development of strains that can successfully colonize rice fields. However, because in such rice-field applications there would be no requirement for CO2 fertilization, these potential applications are not further considered in the context of the microalgae biofixation of CO_2 R&D needs.

3. R&D NEEDS FOR MICROALGAE BIOFIXATION

The major technical challenges for microalgae biofixation of CO_2 for greenhouse gas abatement are the very large cost reductions required in the overall process, compared to current commercial production technologies. Absent other economic considerations, such as in wastewater treatment, very high solar conversion efficiencies, approaching 10% of total solar energy into biomass, will be required for stand-alone algal processes, where biofuels are the main output. This corresponds to a productivity of some 60 g ash-free organic dry weight.m^{-2}.day^{-1}, depending on location and biomass C-content. The cost of producing the algal biomass could be at most about $250/ton. This suggest total system capital costs, depending on productivity, of not more than $100,000 to 150,000/ha, including harvesting, infrastructure, and the processing of the biomass to fuels. This would exclude all but the lowest cost designs, e.g. large-scale open pond systems without plastic liners. Operating costs would also have to be quite low, not higher than $100 to 150/ton of algal biomass.

Engineering and costs analyses of large-scale (several hundred hectare) pond systems have projected such low costs, sufficient to allow for their use in fuel production and greenhouse gas mitigation (Weissman and Goebel, 1987; Benemann and Oswald, 1996). These studies assumed favorable sites, optimized production systems and, most importantly, the ability to achieve very high productivities, approaching 10% of solar energy conversion. Processes integrated with waste treatment would be competitive at much smaller scales and lower productivities, as their environmental functions would cover many, if not all, of the process costs.

Productivities of algal mass cultures are dependent on many factors, from algal strains to weather and culture techniques. However, under optimal conditions of sunlight and temperature, average algal biomass productivities are projected to be as high as 30 g.m^{-2} .d^{-1} using current or near-term future technology. It should be noted that commercial production rates for *Spirulina* are given only as 10 g.m^{-2}.d^{-1}, even in the rather ideal climate of Hawaii. One reason for these low productivities is that, to lower cost of harvesting, these cultures are operated to maximize cell density rather than productivity. Also, *Spirulina*, as other cyanobacteria, are not as highly productive as green algae and diatoms, because they exhibit high respiration rates and are easily photoinhibited. Work with green algae and diatoms has demonstrated productivities that could be extrapolated to an annual average approaching 30 g.m^{-2}.day^{-1}, if operated in a similar climate as Hawaii. Pilot plant work at Roswell, New Mexico, mentioned above, also suggested that relatively high productivities of these organisms are achievable with low-cost unlined (e.g. dirt bottom) ponds and that CO_2 utilization can be very high (>90%) in open ponds.

The main obstacles to further increasing algal productivities are light saturation and respiration (both night-time dark respiration and day-time photorespiration). Light saturation is the largest single factor limiting the productivity of algal mass cultures, and genetic selection of algal strains with smaller antenna sizes (fewer chlorophylls per photosynthetic unit) is the most plausible approach to overcoming this limitation. Respiration is another area requiring applied R&D, if the goal of high productivities is to be achieved. Other issues, such as how to stably cultivate and maintain highly productive algal strains in mass cultures, must also be addressed in any applied microalgae biofixation R&D program.

One central issue is whether closed photobioreactors exhibit higher productivities than open ponds, and whether they can avoid, not just delay, contamination with competing microalgae or other invaders. The high costs of such systems would, in any event, make them unsuitable for applications in biofixation of CO_2. However, closed photobioreactors would be useful in the building up of inoculum cultures from the laboratory for applications in large-scale outdoor systems, and as R&D tools.

In addition to productivity, the major objective of future R&D must be to reduce the very high capital and operating cost of microalgae production in current commercial systems. As stated above, the current costs of microalgae biomass production (e.g. for *Spirulina*) is some $5,000/t of biomass, some twenty-fold higher than is currently allowable for greenhouse gas abatement and renewable fuels production. Indeed, compared to lignocellullosic biomass, which can be produced for some $50/t (all biomass weights are given on a dry ash-free basis), even $250/t is high, though allowable if the algal biomass can be more easily converted at higher yields to liquid and gaseous fuels (biodiesel, ethanol, hydrocarbons, methane or even hydrogen). In any event, such a large cost reduction from current technology would need to be accomplished through major increases in productivity, process improvements and economies of scale. Process improvements would include development of a lower cost algal harvesting process. Economies of scale suggest that algal systems of several hundred hectares, at a minimum, will be required in power plant fossil CO_2 biofixation. To accomplish this objective will require long-term R&D efforts and funding.

In the near-term, the most likely applications of microalgae technologies are wastewater treatment and aquaculture where the algae provide both dissolved O_2 (for bacterial breakdown of wastes and for fish production) and excess nutrient removal. Such wastewater treatment and aquaculture processes can also reduce anaerobically generated CH_4 and N_2O, which are more potent greenhouse gases than CO_2.

The relative potential of the various microalgae biomass production processes in reducing GHGs still needs to be determined. It must be emphasized that microalgae biomass used as human foods or animal feeds do not mitigate GHGs. Also, high value byproducts would have very small markets, leading to negligible GHG reductions. In wastewater treatment, as in some aquaculture processes, the use of CO_2 for increasing microalgae biomass production would greatly increase the amounts of algal biomass produced and biofuel generated from such processes. Through CO_2 fertilization, GHG reductions can be maximized in wastewater treatment processes along with other environmental benefits, such as nutrient reductions. Thus, such processes do not require the large scales, very high productivities, or low costs required for stand-alone power plant flue-gas CO_2 utilization and biofuel-producing processes. Wastewater treatment and aquaculture systems provide an opportunity for near-term practical demonstration projects for biofixation of CO2, which could serve to highlight both the potential of these processes and provide practical experience for future development of microalgae processes designed for power plant flue gas CO_2 utilization.

The overall consensus of the Workshop participants was that microalgae systems could indeed be developed to achieve the very high productivities and very low capital and operating costs required for production of renewable microalgae fuels and to abate fossil fuel CO_2 emissions from power plants. On the issue of productivity, the saturating light effect should be a central focus of future R&D. However, this is not the only factor limiting productivity, respiration and photoinhibition also being important. It must be recognized that actually achieving these goals will require relatively long-term R&D efforts. The greatest potential for microalgae biofixation processes is in developing countries, which should be included in any future development of this technology.

4. THE INTERNATIONAL NETWORK FOR BIOFIXATION OF CO_2

The advantage of microalgae systems lies in their potential for high productivity, giving them a small footprint compared to other biological systems, their ability to use otherwise unsuitable water and land resources, their integration with waste treatment and their production of liquid and gaseous fuels not readily obtained from other biomass sources. These potential advantages still must be realized and will require extensive R,D&D to be achieved in practice. A specific R&D plan will need to be developed by the proposed International Network. Early pilot plant work, preferably at already established microalgae facilities, such as at wastewater treatment plants or commercial aquaculture systems, would help to more rapidly achieve these long-term goals. From such practical work, larger-scale systems could be extrapolated and more fundamental research issues identified and addressed.

At present, the major limitations are technological and economic; however resources (e.g. climate, suitable land, available CO_2, water or waste flows, etc.) will limit the ultimate potential of this technology. Estimates of the potential for GHG reductions by microalgae processes must still be developed, both geographically and for various applications, such as power plant flue gas utilization and waste treatment. A resource and potential impacts assessment should be one of the early activities by the proposed Network. More detailed economic and systems analyses are also required. Some higher value, energy-saving products, such as bioplastics and fertilizers, can be considered in microalgae biofixation, but require further analysis. Engineering and economic studies would be another early goal for the proposed Network. The major recommendation arrived at during this Workshop was to proceed with the preparation of a formal proposal for establishing an International Network on Microalgae Biofixation of CO_2 for GHG Abatement.

The Network would serve as a vehicle to encourage the practical development of this technology through coordination and collaboration in approaches identified as most promising in both the short- and long-term. It will be organized under the auspices of the IEA GHG R&D Programme as a Project under the existing Annex 1. The Network will focus on practical R&D of microalgae processes that use concentrated CO_2 sources and produce renewable fuels. The Network will be led by stakeholders, namely private companies, government agencies and other organizations interested in funding and promoting, internally and/or through cooperative R&D activities, the development of microalgae biofixation technologies and the practical applications of the results.

The specific objectives of the proposed International Network would be to:

- Encourage practical development of this technology.
- Identify the most promising R&D objectives for both the short- and long-term.
- Develop an overall multi-year R&D plan with specific technical goals.
- Carry out supporting engineering, systems, technology, and resource analyses.
- Coordinate R&D activities and facilitate joint R&D projects, including pilot plant work.
- Pool and provide technical expertise and resources to Network participants.
- Promote worldwide collaboration in this field, including with Less Developed Countries.

The general R&D topics required for practical development and applications include:

- Selection and improvement of algal strains able to be mass cultured in open ponds.
- Maximization of algal productivity under sunlight conditions.
- Maximization of algal biomass C-storage products.
- Development of large-scale, low cost systems for algal cultivation.
- Development of low cost algal-harvesting technologies.
- Improvements in the processes for converting algal biomass into fuels.
- Practical demonstrations in wastewater treatment, aquaculture and other near-term applications.
- Ongoing engineering and economic feasibility analyses to help focus R&D priorities.

At the Meeting of the IEA Greenhouse Gas R&D Programme Executive Committee in Regina, Canada, at the end of March, 2001, EniTecnologie and the U.S. DOE National Energy Technology Laboratory formally presented a proposal to move forward with the establishment of this Network. The Network would be comprised some of the of member countries and supporting energy companies participating in the IEA Greenhouse Gas R&D Programme, as well as other companies and organizations wishing to carry out and support microalgae biofixation R&D. The formal establishment of the Network is anticipated at the next Executive Committee meeting in August 2001, with Network activities starting by 2002.

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