FINAL REPORT

BIOFIXATION OF CO_2 AND GREENHOUSE GAS ABATEMENT WITH MICROALGAE – TECHNOLOGY ROADMAP

prepared by

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and to the

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ABSTRACT

This Roadmap provides an expert consensus of the R&D that needs to be carried out to develop practical microalgae processes that could abate hundreds of millions of tons of fossil CO_2 and other greenhouse gases. Such microalgae processes would use CO_2 from power plant flue-gases or similar sources to cultivate specific microalgal species in large ponds at high solar conversion efficiencies, with the harvested biomass converted to renewable fuels to replace fossil fuels. The objective of this Roadmap is to identify R&D issues that could be resolved within five years and result in the development of practical applications within the decade.

Currently, microalgae mass cultures have some applications in the production of human food supplements and specialty animal feeds as well as in wastewater treatment. Most commercial microalgae production processes use shallow raceway ponds, mixed with paddle wheels, and such designs can be used in the large-scale production of algal biomass. Considerable R&D has been carried out in the past, mainly in the U.S., on microalgae production of renewable fuels using open ponds. However, dedicated microalgae biofuels production processes are presently not economically competitive with fossil fuels, even assuming very high productivities. Only by combining microalgae biomass production with wastewater treatment and co-production of fuels with higher-value products, can relatively low-cost greenhouse gas abatement be projected.

Four multipurpose processes are presented in this Roadmap that could meet these objectives:

- Use of flue gas CO_2 in municipal wastewater treatment ponds for co-production of methane.
- Agricultural waste treatment for fertilizers, biofuels and animal feeds co-products.
- N_2-fixation and nutrient recycling processes with co-production of biofuels and biofertilizers.
- Co-production of biofuels with large volume/higher value biopolymers and other chemicals.

All these processes use the same raceway open pond production systems, would harvest algae by low-cost processes and use CO_2 from fossil fuel-fired power plant flue gases or similar sources.

The major R&D needs identified to develop these processes to a practical level include, in brief:

- Develop techniques to select and maintain specific algal strains in open pond mass cultures.
- Overcome limiting factors to achieve productivities of 100 ton/hectare/year in the mid-term.
- Develop low-cost harvesting processes, such as bioflocculation-sedimentation or screening.
- Integrate the co-production of higher value products or processes (e.g. wastewater treatment).
- Advance the engineering art of large-scale production systems based on open earthen ponds.
- Assess the potential of such technologies for GHG abatement, both regionally and globally.

Keeping specific, selected algal strain dominant in open ponds remains a major challenge and will require multi-stage inoculum production systems and development of superior algal strains. Achieving high productivities and higher-value co-products will require genetic improvement of such strains. Low-cost harvesting processes will also require cultivation of specific algal strains.

This Roadmap is intended to help guide the R&D efforts of the organizations participating in the International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae. Such R&D projects could include process development at the field scale as well as laboratory studies. The Network will help coordinate such R&D programs, foster collaborations, facilitate information exchanges, provide technical expertise through its Technical Advisers and carry out technology and resource assessments. The objective is to develop and initiate deployment of low-cost microalgae-based greenhouse gas abatement processes within the decade.

BIOFIXATION OF CO_2 AND GREENHOUSE GAS ABATEMENT WITH MICROALGAE - TECHNOLOGY ROADMAP

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Foreword

This Roadmap Report was prepared under a subcontract with the U.S. Department of Energy - National Energy Technology Laboratory. Its objective is to provide plausible R&D pathways for microalgae-based technologies that could be developed and start to be implemented in the short- to mid-term (five to ten years) and which could contribute significantly to the goal of greenhouse gas abatement. This Roadmap Report is also addressed to the Steering Committee of the recently formed "International Network for Biofixation of CO2 and Greenhouse Gas Abatement with Microalgae" organized under the IEA Greenhouse R&D Programme, Cheltenham, England.

This Roadmap Report was developed with the inputs and assistance of the many persons who participated in the development of the International Network, including the attendees at the initial Workshop in Monterotondo, near Rome, Italy (January, 2001), the Organizational Meeting in Reston, Virginia, USA (January 2002), and the two Technical Meetings held by the Network, in Almeria, Spain (May, 2002) and Kyoto, Japan (October, 2002). In particular the author wishes to thank Dr. Paola Pedroni, EniTecnologie, Chair of the Network Steering Committee, and all other members and alternates, the Technical Advisers, and Dr. John Davison, IEA Greenhouse Gas R&D Programme, for their help, feedback and support during the preparation of this document. The author also wishes to express his gratitude to Drs. Heino Beckert and Perry Bergman, U.S. Dept. of Energy – National Energy Technology Laboratory, for their advice and inputs during the development of the International Network and this Roadmap Report.

The views expressed herein are those of the author and not necessarily those of the Network Steering Committee, Participating Organization, U.S. Department of Energy - National Energy Technology Laboratory, Technical Advisers, or the IEA Greenhouse Gas R&D Programme.

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Executive Summary

Microalgae Biofixation of CO_2.

Microalgae are microscopic plants that grow in water and are typically cultivated in suspended cultures. Currently commercial production of microalgae biomass is limited to a few species, such as *Spirulina, Chlorella* and *Dunaliella*, cultivated in open, CO_2 fertilized, ponds for high-value nutritional products and specialty animal feeds. Microalgae ponds are also used in the treatment of municipal and other wastewaters. The appeal of microalgae cultures in greenhouse gas abatement is their ability to utilize concentrated forms of CO_2, as provided by power plant flue gases, as well as their potential for achieving higher productivities than conventional crops.

Prior R&D.

R&D on microalgae cultivation for renewable energy production and CO_2 utilization has been carried out in the U.S. and other countries for several decades. During the 1970's, R&D in the U.S., supported by the Department of Energy (DOE), emphasized processes combining wastewater treatment with the conversion of the harvested algal biomass to methane (biogas) by anaerobic digestion, processes already used to some extent in wastewater treatment. From 1980 to 1994 the U.S. DOE "Aquatic Species Program" (ASP) emphasized dedicated microalgae biomass systems for production of renewable fuels, specifically biodiesel, using open pond production systems. Engineering-cost studies concluded that with biofuels as the only products, economic viability required achieving productivities near the theoretical limits of photosynthesis in addition to higher than current fossil fuel prices and greenhouse gas abatement credits. In Japan a very large (>$250 million) government-corporate R&D program during the 1990's emphasized closed photobioreactors, in particularly optical fiber devices, for CO_2 capture and high value co-products. That approach was abandoned due to the high costs of such reactors.

International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae.

Research of microalgae processes for greenhouse gas abatement is currently supported by the U.S. DOE - National Energy Technology Laboratory (NETL) as well as other agencies, R&D organizations and private companies, in the U.S. and abroad. Recognizing that development of this technology could best be achieved through cooperation among such interested organizations, a proposal was developed for an "International R&D Network" on microalgae biofixation. The proposal was presented by the U.S. DOE-NETL and Enitecnologie to the Executive Committee of the IEA Greenhouse Gas R&D Programme in Cairns, Australia, in August 2000. In January 2001 a workshop was held near Rome, Italy, at the Monterotondo R&D laboratory of EniTecnologie (the R&D arm of Eni, the large Italian oil company). Over thirty representatives of interested organizations and technical experts discussed microalgae systems for greenhouse gas abatement and concurred that continuing R&D was warranted. An organizational meeting was held in Reston, Virginia, in January 2002, with representatives from ten potential participating organizations, agreeing to the goals and objectives of the Network, its duration (5 years with a possible 5 year extension), membership fees and governance through a Steering Committee of representatives from the members. The Network is to assist the participating organizations in developing their own projects and foster R&D cooperation and collaborations.

The Network was formally approved by the IEA Greenhouse Gas R&D Programme Executive Committee in April 2002 and officially started operations in June 2002, with the 1st Technical Meeting held in Almeria, Spain at the end of May. The Network currently has eight Participating Organizations: Arizona Public Services, ENEL Produzione Ricerca (the R&D arm of the major Italian electric utility), EniTecnologie, Electric Power Research Institute, ExxonMobil, Gas Technology Institute, Rio Tinto and the U.S. DOE-NETL. Six technical advisers, experts in practical algal mass culture, advise the Network. (See Foreword for listings).

The development of this Roadmap was supported by U.S. DOE-NETL and was discussed during the Almeria meeting and the 2nd Technical Meeting in Kyoto, Japan, October 5, 2002. This Roadmap Report represents a general consensus view of the Network Technical Advisers.

Processes for Microalgae Biofixation of CO_2

The potential of microalgae technologies for greenhouse gas abatement is limited by economics, climate and resources, such as suitable land, CO_2 and water. Capital costs of even simple algal culture ponds, including CO_2 supply, harvesting, processing and infrastructure, are high compared to other agricultural systems. This requires maximizing productivity by such processes, as measured by CO_2 capture, biofuels outputs and co-products and co-processes that could help defray part of the costs while also providing additional greenhouse gas credits.

Greenhouse gas abatement is achieved from the use of biofuels replacing fossil fuels, from reductions in energy use compared to current waste treatment technologies, and from the co-production of energy-sparing co-products, such as biopolymers, fertilizers, and animal feeds. Such multifunctional processes would greatly improve the overall economics of microalgae processes, allowing for smaller scales, lower productivities and nearer-term applications.

The most plausible applied R&D approaches combine elements of the prior microalgae R&D programs: use of low cost open ponds, as demonstrated by the ASP; integration with wastewater treatment, as in earlier U.S. DOE projects; co-production of higher value products, a focus of the recent Japanese program; and use of closed photobioreactors as adjuncts in inoculum production.

Four general processes are described in this Roadmap, involving municipal, agricultural and industrial wastewater treatment, production of biofuels (methane, ethanol, hydrocarbons, H_2, biodiesel) and large volume / higher value co-products. In brief, these processes include:

- Municipal wastewater treatment with CO_2 utilization and biogas (methane) production.
- Agricultural waste treatment for fertilizers, animal feeds and biofuels co-production.
- Nitrogen fixation and nutrient reclamation for biofertilizers and biofuels co-production.
- Production of biofuels with high volume/higher value co-products (e.g., biopolymers)

These general processes are all based on the cultivation of selected, specific microalgal strains inoculated into open raceway-type ponds, supplied with CO_2 (preferably from power plant flue gases) and harvested by flocculation-sedimentation or fine screens. These processes could be developed and start to be implemented in the planned 5 to 10 years timeframe of the Network. Dedicated, biofuels-only, microalgae processes could evolve at favorable sites from future developments based on such nearer-term applications of greenhouse gas abatement technologies.

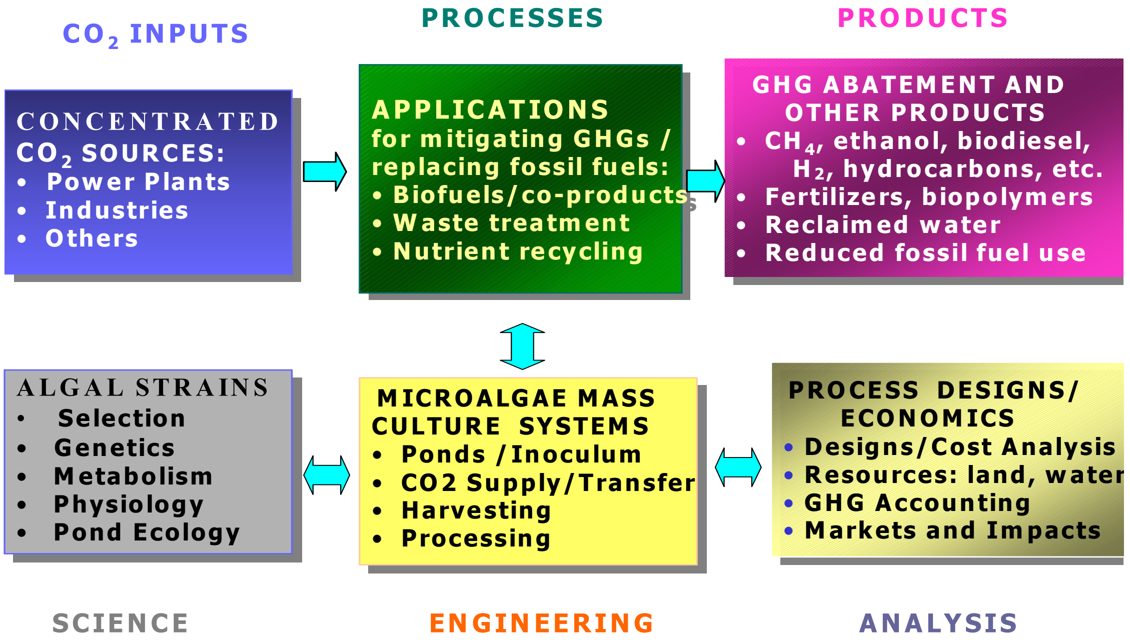
R&D Needs in Microalgae Biofixation.

The processes described above have similar R&D needs. One central R&D issue is the selection of the algal strains that can be stably maintained in large-scale open pond mass cultures. This requires screening for competitive algal strains as well as development of inoculum production systems that allow rapid re-start of cultures in case of contamination. Inoculum production would be based on a succession of closed and open photobioreactor stages. The selected strains could be genetically improved to maximize productivity. Harvesting the algal biomass requires low-cost processes such as spontaneous flocculation- settling ("bioflocculation"). Co-products and waste treatment functions also need to be addressed in the development of these processes. The utilization of CO_2 from flue-gases and other sources is reasonably well understood and is not considered a major R&D issue. Processing of the harvested algal biomass to generate biofuels, fertilizers, feeds, biopolymers, etc., requires R&D, but is also not considered a major barrier to the development of these processes. Economic and resource analyses are required to help guide applied R&D in this field. Although microalgae are not likely to become dominant greenhouse gas abatement technologies, their potential for high productivities and multipurpose processes suggest significant regional and global applications and economic benefits. The practical realization of this vision is the purpose of this Roadmap and of the International Network.

Development of the International Microalgae Biofixation Network.

The schematic in Figure 1 provides an overview of microalgae biofixation of CO_2 for greenhouse gas abatement discussed in this Roadmap, including the science and engineering R&D issues. This Report is intended to provide the Participating Organizations guidance in developing R&D projects and programs in this area, and how these would contribute to the goals of greenhouse gas abatement. The Network will provide technical assistance to the Participating Organizations, to help coordinate R&D activities and foster collaborative efforts within the Network.

FIGURE 1. Schematic of Microalgae Biofixation of CO_2



1. INTRODUCTION TO MICROALGAE CO_2 BIOFIXATION

Microalgae cultures have been proposed for almost fifty years as a source of renewable fuels to reduce global warming (Oswald and Golueke, 1960). A major appeal of microalgae cultures in greenhouse gas mitigation is that they can, indeed must, use concentrated forms of CO_2, such as provided by power plant flue gases, as well as their potential to achieve high productivities.

The U.S. Department of Energy (DOE) has supported microalgae-to-fuels R&D since the mid 1970's, starting with R&D at the University of California Berkeley on microalgae wastewater treatment, with the harvested algal biomass to be converted to methane gas through anaerobic digestion (Benemann et al., 1977). A major technical problem was the high cost of harvesting the algal biomass, and a low-cost spontaneous flocculation-settling process ("bioflocculation") was demonstrated at the pilot-scale (Benemann et al., 1980). Subsequently, the R&D focus shifted to the development of dedicated biomass production processes, with the "Aquatic Species Program" (ASP) supported from 1980 to 1994 by the U.S. DOE through the National Renewable Energy Laboratory (NREL), with a total budget of about $50 million (see Sheehan et al., 1998). The ASP aimed to develop microalgae biodiesel production processes, and supported many laboratory and outdoor culture projects, including a pilot plant project, with two 0.1 hectare raceway-type ponds, at Roswell, New Mexico. Resource analyses by the ASP suggested that sufficient land, water, CO_2 and other resources would be available in the U.S. Southwest alone for large-scale microalgae processes to capture several hundred million tons of CO_2 annually. Engineering and economic analyses (see Benemann and Oswald, 1996), concluded that for such processes to be economically feasible required very favorable sites and high productivities, near the theoretical maximum, along with high energy prices and greenhouse gas abatement credits.

In Japan, a major R&D program (over $250 million total funding) for microalgae biofixation of CO_2 and greenhouse gas abatement was carried out during the 1990's. Over a dozen major companies participated in this government-supported program, organized by RITE (Research for Innovative Technologies of the Earth) (Usui and Ikenouchi, 1996). The RITE program focused on closed photobioreactors, in particular systems based on concentrating mirrors and optical fibers. The Japanese electric utility industry independently sponsored microalgae R&D projects during this period (Ikuta et al., 2000). The Japanese R&D effort was not continued due to the high cost of closed photobioreactor, which also have other limitations (Weissman et al., 1987).

Presently, R&D in Japan is limited to a few projects, for example at Mitsubishi Heavy Industries (Nakajima and Ueda, 2000). In the U.S., DOE-NETL is supporting microalgae R&D using closed photobioreactors (Nakamura, et al., 2001), including optical fiber systems (Bayless et al., 2001). A project on algal growth and productivity is being carried out at the Pacific Northwest National Laboratory with U.S. DOE-NETL funding. Other participants in the International Network also are supporting R&D on microalgae greenhouse gas abatement, including Arizona Public Services, ENEL Produzione Ricerca, EniTecnologie, ExxonMobil, and Rio Tinto.

These governmental and private industry interests and activities in microalgae R&D suggested the need for such an "international R&D network", to help bring together the limited technical expertise in this field, provide for information exchange and coordination, and help these organizations to more effectively deploy limited R&D resources.

2. DEVELOPMENT OF THE MICROALGAE CO_2 BIOFIXATION NETWORK.

The "International Network on Microalgae Biofixation of CO_2 and Greenhouse Gas Abatement" was formed at the initiative of the U.S. Department of Energy and Enitecnologie, who jointly proposed such a Network to the Executive Committee meeting of the IEA Greenhouse Gas R&D Programme, in Cairns, Australia, August 2000. This was followed by a Workshop at the Enitecnologie R&D laboratories at Monterotondo (near Rome), Italy, in January 2001, bringing together over thirty experts and representatives of organizations interested in this subject. The participants supported the potential and goals of microalgae R&D for greenhouse gas abatement and the establishment of the present Network (Monterotondo Workshop Minutes, 2001). The proposed Network was presented at the DOE/NETL 1st National Conference on Carbon Sequestration in Washington D.C., in May of 2001 (Pedroni et al., 2001).

Development of the Network was discussed during subsequent meetings of the IEA Greenhouse Gas R&D Programme Executive Committee in 2001, in Regina, Canada, and London, England. An organizational meeting of ten potential Participating Organizations was held January 29, 2002, in Reston, Virginia, where a draft Agreement was developed and later finalized. Under the Agreement, the Network was to be established for a five-year period, with provision for a possible five-year renewal. Also under the Agreement, the Participating Organizations are to develop and carry out or support relevant R&D in this field. A "Steering Committee" of representatives from the participating organizations will manage the Network. John Benemann was nominated "Network Manager" and he recommended six technical advisers to assist the Network and its members in this effort (Reston Meeting Minutes, 2002).

In April 2002, the IEA GhG R&D Programme Executive Committee approved the creation of the Network which started operating officially on June 1, 2002, following the 1st Technical Meeting of the Network at the end of May, 2002, in Almeria Spain. A 2nd Technical Meeting was held in Kyoto, Japan in October 2002. The Network currently has eight members: Arizona Public Services, EniTecnologie, ExxonMobil, ENEL Produzione Ricerca, EPRI, Institute of Gas Technology Institute, Rio Tinto and U.S. DOE-NETL. Other organizations may join later.

In support of the International Network and its own R&D efforts, U.S. DOE–NETL supported the present "Roadmap", to provide an overview of the current state-of-the-art in this field and of the plausible R&D pathways that can be considered in the development of microalgae-based greenhouse gas abatement technologies. The U.S. DOE-NETL Carbon Sequestration Technology Roadmap (2002) provides an introduction to the roadmapping process and its applications to greenhouse gas abatement technologies. A Roadmap describes R&D pathways required to achieve practical applications within a given time frame, 5 to 10 years in case of the Network. An R&D Roadmap involves consensus development among experts of the most appropriate processes and R&D approaches to achieve stated programmatic goals. It provides opportunities for public-private partnerships and international cooperation. The schematic in Figure 1 (see the Executive Summary) outlines the various inputs and elements to be considered in this Roadmap.

This Roadmap was discussed during the 1st and 2nd Technical Meetings of the Network (see Minutes of Almeria and Kyoto Meetings, 2002) with inputs from the Network Technical Advisers, Steering Committee members and others. It focuses on relatively near-term R&D goals to allow achievement of some practical applications within the timeframe of the Network.

3. MICROALGAE CO_2 BIOFIXATION ROADMAP – GENERAL CONSIDERATIONS.

Microalgae are able to beneficially utilize concentrated CO_2 from power plant flue gases and other sources and produce renewable fuels and/or other higher value co-products. Microalgae processes are "novel sequestrations technologies" as described in the Carbon Sequestration Technology Roadmap (U.S. DOE-NETL, 2002), which lists as primary goals for their R&D to:

- ***increase the speed and energy efficiency of CO_2 conversion processes, and***
- ***identify conversion processes that produce high-value by-products to improve economics***.

These goals are specifically applicable to microalgae processes, attractive in greenhouse gas abatement because they can beneficially utilize flue-gas concentrations of CO_2 from power plants, avoiding the need and cost for CO_2 capture and disposal. Microalgae cultivation systems already produce high value human foods and animal feeds in open raceway-type ponds mixed with paddle wheels. Two >20 ha (hectares) production facilities are located in the U.S., in Hawaii and California (Figures 2 and 4). The paddle wheels used for mixing these ponds (Figure 3) are very energy efficient. In Hawaii, a small, dedicated power plant supplies the CO_2 required by the microalgae ponds (Figure 5). Microalgae ponds are also used in wastewater treatment (Figure 6). A large (1,000 ha) wastewater treatment utilizing microalgae plant operates near Melbourne, Australia. At Sunnyvale, California, electricity is generated from methane (biogas) produced from the microalgae biomass harvested from waste treatment ponds. Thus, there are already incipient practical applications of microalgae that reuse CO_2 and abate greenhouse gases.

Prior R&D by the Aquatic Species Program (ASP) for renewable fuels production by microalgae achieved a number of advances, including the development of a culture collection, culminating in a pilot plant project in Roswell, New Mexico, involving operation of two 0.1 hectare (0.25 acre) paddle wheel mixed raceway ponds that demonstrated (Weissman et al., 1989, 1992):

- the ability to cultivate algal monocultures with inoculated strains for extended periods;
- productivities projected at 50 dry tons biomass/hectare over a seven month growing season;
- the capture in the algal biomass of a large fraction (90%) of CO_2 injected into the ponds; and
- that low-cost unlined ponds give similar results as more costly plastic-lined ponds.

Despites such advances, practical CO_2 utilization and greenhouse gas abatement with microalgae still requires considerable scientific and technological development. R&D needs include achievement of higher productivities, longer-term culture stability, lower-cost harvesting and improved biomass-to-fuels conversion technologies. Closed photobioreactors, investigated in Japan and by some current DOE/NETL projects (see above) are too expensive for greenhouse gas abatement applications, but could be considered for inoculum production (see 5.4 below).

This Roadmap therefore considers only processes based on raceway, paddle wheel mixed, open ponds (Figures 2, 4), as these are the only sufficiently low cost designs. A fundamental issue is what co-products or co-processes could be integrated with microalgae CO_2 utilization and biofuels production to improve the economics of such processes while still providing significant greenhouse gas abatement. Possible co-products/co-processes are treatment/reclamation of wastewaters, in particular processes resulting in plant nutrients (fertilizer) reuse, co-production of biopolymers and animal feeds, and the production of nitrogen-fixing algae for biofertilizers. This Roadmap does not specifically address dedicated biofuels-only processes, as these require long-term R&D and also much higher fossil fuel prices and greenhouse gas abatement credits than are currently foreseen. In the future such dedicated microalgae biofuels production technologies for greenhouse gas abatement could evolve from the processes described herein.

FIGURE 2.
***Spirulina* Production Facility of Earthrise Farms, Inc., in California**
Note large (>2 ha), unlined growth ponds, mixed with single paddlewheels, on top left of picture.

FIGURE 3.
Paddle Wheel Mixing of Raceway Ponds at Earthrise Farms, Inc.
(Buildings in back are for spray-drying operation; white tank, back right, is for CO_2 storage).

FIGURE 4.
***Spirulina* and *Haematococcus* Cultivation at Cyanotech Corp., Hawaii.**
Spirulina: blue-green ponds; *Haematococcus*: orange-red ponds)

FIGURE 5.
Power Plant to Produce Power and CO2 at Cyanotech Facility in Hawaii
Power plant (right) produces power and CO_2 (captured in tower on left)
for the microalgae production facility shown in Figure 4 (Kona, Hawaii).
Note: the power plant uses biodiesel and thus generates no net greenhouse gases.

FIGURE 6.
Microalgae Wastewater Treatment Ponds at Hollister, California.
The raceway high rate pond, appx. 5 hectares, is bottom middle. Top right are the raw sewage receiving facultative ponds.

4. MICROALGAE BIOFIXATION R&D ISSUES AND PROPOSED PROCESSES

To allow for economics of scale and achieve significant impacts in greenhouse gas abatement, relatively large-scale algal cultivation systems would be required, individually from a few tens to several hundred hectares in size. The general design of the culture ponds used in commercial systems is rather well established: "raceway-type", shallow (20 - 40 cm deep) earthen ponds mixed with paddle wheels. CO_2 supply and transfer ("carbonation") stations intersect the channels, their spacing and design based on variables including pond size, productivity, alkalinity, mixing velocity, etc. For CO_2 utilization and greenhouse gas abatement applications, individual pond would several hectares in size, much larger than those presently used in commercial plants (< 0.5 hectare) and, perhaps most important, would not be plastic lined, to save costs. Some large unlined raceway ponds are used in wastewater treatment and at least one at a commercial operation (Figure 2). Although still requiring some R&D, the basic engineering designs and economics of large paddle wheel mixed ponds are relatively well established.

The design of this "hardware" is more advanced than that of the "software", the algal strains and cultivation processes. The major technological challenges in microalgae mass culture are:

- Selection, improvement and maintenance (long-term cultivation) of specific algal strains.
- Achieving high productivities, tons CO_2/ha/yr fixed into biomass and greenhouse gas abated.
- Harvesting of the microscopic algal cells to yield a concentrate of several percent solids.
- Processing this algal biomass to recover biofuels, biofertilizers and higher value co-products.

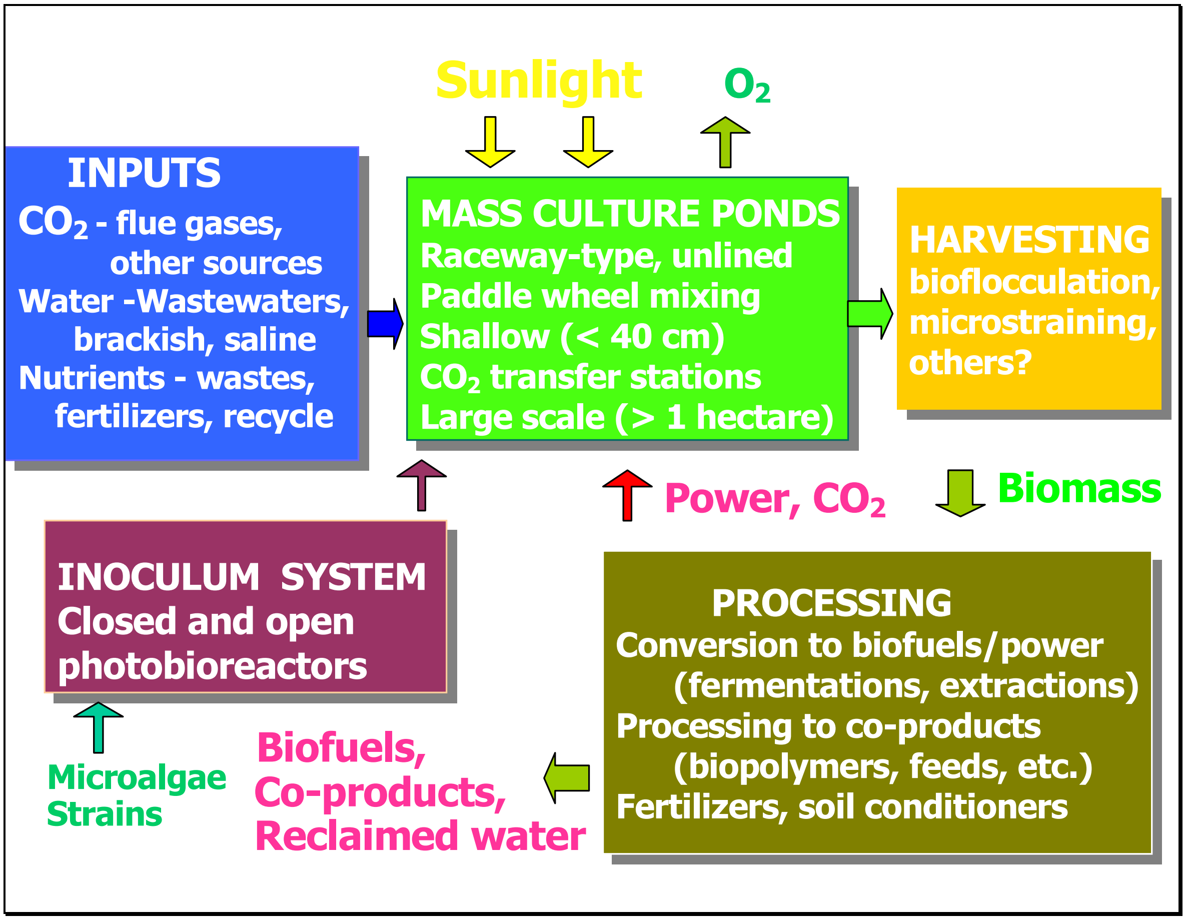
These issues must be resolved within the economic constraints of current or near-term fossil fuel prices and greenhouse gas abatement economics. The goal of the U.S. DOE-NETL Carbon Sequestration Program is \$10/ton of C-equivalent, or some \$2.7/ton CO_2 abated. For the present, greenhouse gas abatement through production of biofuels by microalgae systems cannot be credibly project such economic without benefits from co-products and/or co-processes.

Four general microalgae processes that could plausibly be developed in the 5 - 10 year timeframe planned for the Network are presented here. They encompass the main attributes of practical R&D pathways in terms of both economics and greenhouse gas abatement potential:

- Municipal wastewater treatment with CO_2 utilization, reduced energy use and biogas outputs.
- Agricultural and industrial wastewater treatment for biofuels and animal feed co-products.
- Fertilizer recycling and nitrogen-fixing processes for biofertilizer and biofuels co-production.
- Co-production of biofuels with fossil fuel sparing products such as biopolymers.

There is a large overlap between these four general processes in their overall designs and R&D needs (for a schematic see Figure 7). They are all based on raceway, paddle wheel mixed, ponds with CO_2 supply, similar to the ones already used in commercial microalgae production (Figures 2, 4). To reduce costs, the individual growth ponds would be much larger (over 2 hectares) and not lined with plastics. These processes also are based on co-products and/or co-processes that have large markets and higher values than biofuels. The economics of these processes must still be established for specific cases, but are more favorable than dedicated biofuels-only systems. Of course, microalgae processes are restricted to regions with favorable climates. Their potential for greenhouse gas abatement would also be constrained by the availability of suitable land and water or wastewater resources, in juxtaposition with CO_2 supplies. The latter makes the co-location of microalgae systems with distributed power generation particularly attractive. The economics and resource potential of the proposed multi-purpose processes require further study.

FIGURE 7.
Process Schematic for Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae.



5. DESCRIPTIONS OF THE MICROALGAE BIOFIXATION PROCESSES

5.1. Municipal Wastewater Treatment with CO_2 Conversion to Biofuels.

Municipal wastewaters are often treated in the U.S. and many other countries with so-called "oxidation ponds". These are relatively deep (> 60 cm) and not mechanically mixed. In such ponds a "secondary" treatment is achieved, i.e. the reduction of biological O_2 demand (BOD). The main function of the microalgae is to produce dissolved O_2, required by the bacteria that break down the organic wastes. More advanced microalgae wastewater treatment processes use raceway ponds, called "high rate ponds", that produce much more algal biomass per unit area, and thus also more O_2, thereby allowing higher loadings (volume of wastewater applied per hectare per day). However, in either case (oxidation or high rate ponds), a fundamental problem is the high cost of algae harvesting using chemical flocculants, the currently best technology. Harvesting using "bioflocculation" processes, in which algal cells settle spontaneously, have been demonstrated with pilot-scale high rate wastewater ponds, but must be made more reliable (Benemann et al., 1980). The removal of nutrients (mainly N and P) from wastewaters to achieve so-called "tertiary" treatment levels has the greatest potential for applications of microalgae in wastewater treatment. This is because nutrient removal with conventional technologies is expensive, while microalgae can remove nutrients at little additional costs above secondary treatment. This does, however, require fertilization of such waste treatment ponds with CO_2, the limiting nutrient in such processes and the main advance suggested herein.

CO_2 additions would dramatically improve the algal cultivation process in high rate wastewater treatment ponds by greatly increasing productivities and process reliability, including harvesting through bioflocculation. The harvested algal biomass would be most plausibly subjected to anaerobic digestion (methane fermentations) and the biogas used to produce electricity. CO_2 fertilization also allows somewhat better adaptation to seasonal variability in productivity, because N and P levels in algal biomass can be varied significantly. Most fundamentally, CO_2 fertilization results in a more stable pond environment, allowing cultivation of specific algal cultures, a major R&D objective of this Roadmap. A CO_2 fertilized wastewater treatment high rate pond system would have a much smaller "footprint" (land area requirements) than present facultative pond technologies that achieve only secondary treatment levels.

In the proposed CO_2-supplemented wastewater treatment process, the outputs are reclaimed water, biogas fuels and anaerobic digester residues. The latter can be applied on agricultural soils, although it would be classified as biosolids and does not qualify as an organic biofertilizer. Municipal wastewaters do not favor the production of additional co-products. However, economics for municipal wastewater treatment using high rate pond processes are expected to be favorable, in comparison to conventional secondary processes (e.g. activated sludge) and would be even more favorable for tertiary treatment (nutrient removal) (Eisenberg et al., 1980; Green et al., 1996). However, detailed engineering-cost studies must be carried out for specific sites.

The greenhouse gas abatement from such processes would be several-fold (Benemann, 2002):

- Reduction in fossil energy use compared to conventional wastewater treatment technologies.
- Reduction in the emission of CH_4 and N_2O gases, again compared to conventional processes.
- Production of renewable fuels and electricity from the algal biomass and other waste sludges.

In brief, supplying CO_2 to wastewater treatment ponds promises multiple benefits, including advanced treatment (nutrient removal), smaller footprint, and greater greenhouse gas abatement.

5.2. Agricultural /Industrial Wastewater Treatment with Biofuels Production

These processes are similar to those described above: the cultivation of microalgae on some industrial (mainly food processing) and agricultural wastewaters for both secondary (BOD removal) and tertiary (nutrient removal) treatment. The main difference is the nature of these wastes, which are more defined and less subject to contaminants and variability than municipal wastewaters. Agricultural wastewaters are also more seasonal, often smaller in scale and more dispersed than municipal wastes. However, with the intensification of agriculture, in particular large-scale swine and dairy operations that generate large volumes of liquid wastes, wastewater treatment has become a major issue and an opportunity for applying microalgae technologies.

One specific example is the several tens of thousands of hectares of catfish ponds in the U.S. South. These generate large quantities of wastes, which are treated *in situ* by energy intensive mechanical aeration. The Partitioned Aquaculture System (PAS), incorporating raceway paddle wheel mixed ponds, was developed at Clemson University, South Carolina, for the treatment and re-circulation of water from such aquaculture fish ponds (Brune et al., 1998; also Monterotondo Workshop Minutes, 2001). In this process the dense algal culture in the raceway ponds is directed through the fish-holding pens to flush out wastes while also providing O_2 for the fish, which in turn aid in the bioflocculation of the algae. Greenhouse gas mitigation accrues to the algal process from the avoidance of the power consumed by the surface aerators currently used in this industry, as well as to the biogas to be derived from the harvested algal biomass. The algal biomass can also be used to reduce feed inputs required by the fish, which further improves the economics of the process and even the greenhouse gas balances, as conventional animal feed production results in much higher greenhouse gas emissions than aquacultural systems. A PAS-type process is being tested for nutrient removal at the Salton Sea in California (see below).

Of even greater potential for microalgae applications are animal wastes, in particular from swine operations and flush dairies, some of which produce waste flows equivalent to those of small towns in terms of BOD and nutrient contents. The lagooning and land application of such wastes is increasingly unacceptable, and this provides an opportunity for microalgae systems, which can also serve in energy recovery and greenhouse gas abatement. The effluents from anaerobic waste lagoons need to be treated to reduce their BOD and nutrient levels to allow for water reuse and avoid eutrophication of receiving waters. High rate microalgae ponds could be used for such purposes, with the harvested biomass converted to biofuels and animal feed co-products.

Aquacultural and husbandry wastewater treatment processes, similar to municipal wastewaters, are generally limited by the availability of CO_2. Supplying CO_2 to such treatment ponds would both increase algal productivity and treatment effectiveness, in particular nutrient removal. As discussed previously, CO_2 fertilization would also help control the pond environment, aiding in algal species control and harvesting. Control over the algal species would allow utilization of the algal biomass for animal feeds. As the economics of agricultural wastewater treatment processes would be less favorable than municipal wastewater treatment, an animal feed co-product would be of great interest. Dried algae have been used as high value chicken feeds, wet algae for feeding swine, and pelletized algae in ruminant and aquaculture feeds. Animal feed-co-products, could greatly improve overall economics and also contribute to greenhouse gas abatement, due to less fossil fuel used in their production. The potential for microalgae greenhouse gas abatement in recycling agricultural wastes will likely ultimately be greater than for municipal wastewaters.

5.3. Nutrient Recycling and Nitrogen Fixation for Biofertilizers.

A major source of U.S. and global greenhouse gases is from the fossil fuel-based production of nitrogen fertilizers. As already discussed above, microalgae provide an opportunity to recover fertilizer values, both nitrogen and phosphorus, from wastewaters. In the U.S. natural gas used for synthetic N fertilizer production is equivalent to 3.15 kg CO_2 emitted/kg N (West and Marland, 2001). P fertilizers require little fossil fuel for mining and processing, though with transportation the total is some 1.2 kg of CO_2/kg of P delivered to the farm. Assuming N and P contents of 10 and 1%, respectively, in algal biomass, this is equivalent to some 0.33 kg CO_2/kg of algal biomass. Microalgae biomass contains some 45% C, equivalent to 1.64 kg of CO_2/kg biomass. However, only about 40% of the C, would be converted to methane fuel. Thus 1 kg of algal biomass could abate about 1 kg of CO_2 emissions, compared to natural gas with the nutrients recovered in digester effluents being equal to about half of the CO_2 abated from the biofuel (methane) derived from the biomass. The value of these nutrients would actually be larger than that of the biofuels. One issue is the delivery of such nutrients to crops, as the residue after methane recovery is some 95% water and the N content is 1% by weight and high in ammonia. This limits transportation distances and requires integrating wastewater treatment with agricultural operations. Irrigation systems afford a ready method for such fertilizer deliveries.

An example of a potentially very large-scale application of microalgae ponds in the reclamation of nutrients is the over 1 billion m^3 of agricultural drainage waters flowing annually into Salton Sea in Southern California. These wastewaters contain about 1,000 tons of P (as phosphates) and ten-times this amount of N (mostly nitrate). Nutrient removal from these drainage waters by microalgae cultures would avoid eutrophication of the Salton Sea while producing some 100,000 tons of microalgae biomass. Assuming an annual productivity of some 100 tons of dry algal biomass/hectare, the goal of this Roadmap, this would require some 1,000 hectares of ponds. Such a process appears economically promising, as the water, nutrients and land are essentially free and the climatic conditions favorable (Benemann et al., 2002). Indeed, the world's largest microalgae production facility, Earthrise Farms, Inc. (Figure 2), is located near the Salton Sea. Even larger-scale nutrient reclamation systems could be considered in Southern Florida.

In many wastewaters phosphates are typically present in excess compared to nitrogen, based on a typical composition microalgae biomass (1% P and 10% N, organic dry weight basis). However, the composition of microalgae biomass can be relatively plastic, ranging about four-fold for P (from 0.3 to 1.2%), and up to three-fold for N (4 to 12%), with N:P ratios ranging from about 5 to almost 30. Still, P removal is often limited by the amount of N present, in particular in municipal wastewaters. This led to a study of N_2-fixing cyanobacteria (a type of microalgae) in a final "polishing" stage to remove P (Weissman et al., 1978). N_2-fixing cyanobacteria have also been proposed for fertilizer production in their own right (Benemann et al., 1980), in particular for rice field biofertilizers. N_2-fixing cyanobacteria exhibit about a one-third lower productivity than non-N_2 fixing cultures, due to the high metabolic energy requirement for this reaction. From the above discussed CO_2 emissions in synthetic N fertilizer production, this makes algal N_2 and CO_2 fixation equivalent from a greenhouse gas abatement perspective. The economics of such N_2-fixation processes still need to be developed, whether part of a wastewater treatment or as stand-alone systems. The premium prices paid for organic fertilizers by organic agriculture could justify microalgae-based N_2 fixation processes for some applications even in the near-term.

5.4. Production of Microalgae Biofuels With Large Volume Co-products.

In the above-described processes, biofuels, wastewater treatment, reclaimed water, biofertilizers and animal feeds were the products and co-products resulting in greenhouse gas abatement. Another alternative, not involving waste treatment, is to combine biofuels production with large volume/higher value (higher than biofuels) co-products. The challenge is to identify co-products with sufficiently large markets to allow for significant greenhouse gas abatement and of high enough value to result in economically viable processes.

One often mentioned possibility is bioplastics, such as the PHA (polyhydroxyalcanoate)-based polymers, already produced commercially and found as storage compounds in many bacteria, including cyanobacteria (Asada et al., 1998). Cyanobacteria can contain over 10% of PHB (polyhydroxybutyrate) and it should be possible to produce altered forms more suitable for bioplastics. Other biopolymers of commercial interest are polysaccharides used as flocculating, dispersing and gelling agents in food and industrial applications. For example, carrageenans, obtained from seaweeds, are also produced by red microalgae and their production was patented in the 1960's for tertiary oil recovery. Where biopolymers replace synthetic products derived from fossil fuels, some greenhouse gas abatement can be imputed. However, the main benefit of such co-products would be to improve the overall economics of such processes. Bioplastics and functional polysaccharides would be valued at over $1,000/ton, compared to less than $100 /ton for biofuels obtained from algal biomass. The R&D need is to identify specific co-products, develop algal strains with high co-product yields and demonstrate their mass culture. This approach, and challenge, is similar to the "biorefinery" concepts for the conversion of starch and sugars from conventional crops into fuels (e.g. ethanol), feeds and higher value co-products.

The mass culture of selected strains is still a major challenge for all the processes described herein. One favored approach is the cultivation of so-called "extremophiles", species that thrive in extreme environments. Indeed, current commercial microalgae technology is mainly based on such species, with both *Spirulina* and *Dunaliella* being extremophiles. However, these require special media and cultivation conditions and also have relatively low productivities (see below). Another approach to this problem is the production of large amounts of inoculum. A conceptual low-cost inoculum production process was proposed by Benemann and Oswald (1996, Figure 8) for the case of *Botryococcus braunii,* a slow growing species that contains up to 50% by weight hydrocarbons, a potential source of fuels and specialty lubricants. The metabolic energy devoted to produce such large amounts of hydrocarbons makes this species noncompetitive in open mass cultures, since strains not so burdened can grow much faster and soon dominate an outdoor pond culture. This also applies to algal strains selected for increased content of other valuable co-products and, counter intuitively, even to strains selected for high productivity. Figure 8 provides a conceptual approach to the production of inoculum with a series of successively larger, lower cost, and less controlled photobioreactors. This proposed inoculum system builds up the culture biomass by a factor of ten-fold in each of ten stages, one billion-fold overall, a total of about 20 generations, starting with a laboratory stock and ending with the 400 hectare production plant. The key issue is the relative growth rate of the selected strain *vs*. that of potential contaminants. It should be noted that the inoculum system produces some 5% of the total biomass on 10% of the pond area, due to the expected tradeoff between fast growth and maximum productivity. The cost of the inoculum production would increase overall production costs by about 10 to 15%. Inoculum production is a requirement for large-scale mass cultures of selected microalgal strains.

FIGURE 8.
PROPOSED *BOTRYOCOCCUS BRAUNII* INOCULATION PROCESS

(From Benemann and Oswald, 1996)

Growth Stage	Area	Unit Cost $/m^2$	Total Cost $/stage
1. Initial inoculation Flask	40 cm^2	Laboratory	not included
2. Roux Bottles Culture	400 cm^2	>5,000	5,000
3. Laboratory Cultivation	0.4 m^2	5,000	2,000
4. Closed sterilizable reactors	4 m^2	2,000	8,000
5. Tubular Cultures	40 m^2	300	12,000
6. Tubular Reactors	0.04 ha	200	80,000
7. Plastic Sleeve Reactors	0.4 ha	50	200,000
8. Covered Ponds	4 ha	20	800,000
9. Open Lined Ponds	40 ha	6.5	2,600,000
10. Open Unlined Growth Ponds	400 ha	2.5	10,000,000
TOTAL SYSTEM	445 ha	3.4*	13,700,000

* Cost per m^2 of final 400 ha of growth ponds, not including harvesting, infrastructure, etc.

NOTES: The designs and capital cost estimates of each photobioreactor stage are meant to be illustrative, based on judgment and experience, rather than on specific engineering designs and cost analyses. This schematic is generic, the use of *Botryococcus braunii* in this meant to be only an example. Note that the inoculum system land produces some 5% of the total biomass on 10% of the land area as the inoculum processes would be operated at faster growth rates, to minimize contamination, assumed to result in reduced productivities. The inoculum system represents a 37% increase in capital costs for the ponds, with a total increase in overall process costs of some 15%, or less.

6. MICROALGAE BIOFIXATION R&D NEEDS AND ISSUES

6.1. Introduction.

The Roadmap methodology involves categorizing R&D needs in the various issues and areas of uncertainty: ***"Identify how and what R&D efforts will advance the various pathways."*** (DOE/NETL, Carbon Sequestration Technology Roadmap Report, 2002). A Roadmap provides a consensus by technical experts of the critical R&D needs to achieve specified technological goals. In this case the goals are the development, within the 10-year horizon of the Network, of microalgae processes that could result in significant greenhouse gas abatement, regionally and globally. The prior section briefly described four general microalgae production processes that could plausibly accomplish this goal. The R&D issues that must be addressed to develop and demonstrate such processes, within likely economic constraints, are discussed in this section.

Essentially the same R&D issues are common to all four general processes described above, which are, in any event, not distinct but blend into each other. All face similar fundamental and applied R&D issues: strain selection and maintenance, productivity, harvesting, processing to biofuels, and co-products and co-processes. Ultimately, these issues must be related to process economics and greenhouse gas abatement potential. A present limitation includes a paucity of engineering designs and cost analyses of such multifunctional processes and the quantification of their greenhouse gas abatement potential. That potential will be limited by the availability of land, water, infrastructure and other factors. These resource issues require further study.

The four general processes discussed above are based on the same fundamental production system (Figure 6): microalgae grown in paddle wheel-mixed raceway ponds with CO_2 supply stations and harvested by simple settling or other low cost methods. The main differences between the processes are in the sources of water and nutrients, and the output biofuels and other co-products. The co-products - fertilizers, animal feeds, reclaimed water, biopolymers, etc.- were discussed above, with water reclamation deserving additional emphasis as a valuable output of such systems. For biofuels, only methane (biogas) was discussed above. Although a likely first choice for municipal and most agricultural wastewater treatment processes, other biofuels can be derived from microalgae biomass and may be preferable in some cases, as they often have higher value than biogas. For examples, ethanol and H_2 fermentations could be possible for high starch microalgal biomass. Biodiesel was the focus of the ASP Program (Sheehan et al., 1998) and hydrocarbon production by *Botryococcus* has attracted some attention. In brief, biofuels production requires R&D, but is not the main limiting factor. Stable cultivation of selected algal strains in large ponds at high productivities with low-cost harvesting are the overall R&D issue.

Algal species control would plausibly allow control over algal harvesting and productivity. In the case of *Spirulina,* the filamentous nature of this most widely cultured algal species allows it to be easily harvested with screens. *Spirulina* is an "extremophile", it grows better than other algae in highly alkaline waters and thus dominates such ponds without need for frequent, or even any, inoculation. However, commercial productivities of *Spirulina* are only about 50 tons/ha/yr, possibly because it is an extremophile. R&D projects cultivating green algae and diatoms have projected productivities of 100 tons/ha/yr, deemed in this Roadmap to be achievable for large-scale systems in the mid-term (5–10 years) through focused R&D. The challenge is to select and cultivate specific strains in simple open ponds allowing for low cost application of multipurpose processes, such as described above, and resulting in significant greenhouse gas abatement.

6.2. Strain Selection and Genetics.

The initial R&D issue is the acquisition, selection, and maintenance of suitable algal strains. Suitable in this case being defined as the ability to be mass-cultured in open ponds as well as exhibiting high productivities, ready harvestability and desirable co-products. Such a long list of requirements makes it unlikely that candidate strains will be found in nature and, indeed, there would be some antagonism between these desired attributes. For example, highly productive strains would also be poor competitors in dense mass cultures (see next section). The standard paradigm in this field is to isolate strains from suitable natural environments, study their attributes in the laboratory, and then attempt to scale-up a process. The herein preferred option is to isolate competitive strains in scaled-down mass culture ponds and then study physiological manipulations and genetic improvements that would increase the productivity and harvestability of such strains, while maintaining their competitiveness in the open pond culture environment.

The complementary approach to achieving dominance of selected algal strains in open ponds is to produce large amounts of inoculum (Figure 8). Occasional re-inoculation should allow cultivation of strains that do not readily dominate open ponds on their own. The combination of relatively low-cost inoculum production with isolation of competitive strains provides a clear R&D pathway to solving a central problem in algal mass cultures - the ability to maintain selected algal strains in large-scale open ponds. Of course, each process, application even site will require its own suite of algal strains. The methodologies for isolating and improving algal strains for such applications is a central R&D need in this field. Techniques for isolating and selecting competitive algal strains must still be developed. The ASP did show that it is possible to isolate and maintain algal strains in laboratory cultures and still have them do reasonably well in open ponds. However, in general, culture collections are unlikely to contain strains useful in algal mass cultures. Many factors must be considered in algal species dominance, from invasion by "weed" algal strains, to grazing by zooplankton, to other, often unknown, factors resulting in pond "crashes". Mass culture stability is identified in this Roadmap as a central R&D need.

The powerful molecular genetic technologies now available can be applied to microalgae strain improvements. This is already being done to develop strains with increased productivity (see below). Genetic approaches can also be used to increase co-products yields, such as PHB in cyanobacteria or other biopolymers in green algae. However, practical applications of such biotechnologies would likely come only after superior algal strains, adapted to the open pond environment and meeting other process requirements, have been developed. Factoring in the social controversies and regulatory issues of releasing genetically modified organisms, practical applications of such biotechnologies are not projected within the time-frame of this Roadmap. Conventional strain selection techniques could be a more immediate starting point for practical process development. Still, molecular techniques are powerful tools for accelerating bioprocess development and are an essential component in the proposed R&D pathways in this Roadmap.

Waste treatment, nutrient recycling, or biofuels production do not greatly depend on algal species or strain. Thus R&D and even pilot-scale testing of the proposed wastewater treatment processes can be initiated without specific algal strains in hand. Promising algal strains would be isolated from species invading and dominating such ponds. This would constitute an early goal of this R&D. Pilot-scale and scale-down systems can be used for self-selection ("enrichment") of such strains, followed by the screening of the most promising isolates. The development of suitable algal strains is a central, immediate and ongoing R&D need in microalgae biofixation.

6.3. Microalgae Physiology and Productivity.

Responses by algal cells to nutrients and cultivation environment can be used to manipulate the processes to favor the production of algal biomass with high contents of starches or oils, and even to achieve increased productivity (Benemann and Weissman, 2002). R&D of physiological responses to nutrient limitations could achieve accumulation of large amounts of storage polymers, such as PHBs, or of extracellular polysaccharides, such as carrageenans, without compromising the objective of high productivity. Extracellular polysaccharides are also the determinant in bioflocculation, the harvesting method of choice in these processes (see below).

Certain physiological responses are detrimental to productivity or even survival in algal ponds. For example, O_2, which unavoidably accumulates to high concentrations in culture ponds, is an inhibitor of algae growth, with some strains highly susceptible and others not. Other examples are responses to diurnal and seasonal temperature cycles, CO_2 and pH fluctuations, or high light intensities, all factors that cannot be fully controlled in algal culture ponds. One required R&D tool, remaining to be developed and validated, is a "scale-down" bioreactor that can mimic the outdoor pond environment and would allow study of physiological responses to mass culture conditions. Such scale-down bioreactors do not obviate the need for outdoor pond operations. Both laboratory and field-scale R&D projects are required to advance this technology.

A primary focus of any R&D program in microalgae for greenhouse gas abatement and biofuels production must be the achievement of very high productivities, in terms of biomass production and CO_2 utilization. As stated above, current commercial systems for *Spirulina* production achieve productivities of only about 50 t/ha/yr, plausibly because this alga is an "extremophile" growing under highly alkaline conditions. *Dunaliella*, another commercially cultivated algal species, is grown selectively at high salinities and also exhibits low productivities. Pilot plant studies, such as those carried out by the ASP, among others, suggest that seawater and freshwater microalgae cultures could achieve some 100 t/ha/yr in the near- to mid-term, with some R&D effort. This is proposed as a key R&D objective for practical microalgae process development. Such a productivity goal will apply to good climates, require development of appropriate strains and some cultivation process improvements, but is considered an achievable R&D objective.

The maximum potential productivity of microalgae processes is some two to three-fold higher than the 100 tons/ha/yr goal, suggesting that technological advances in the future may allow further increases in productivity. One fundamental factor limiting microalgae productivity is the so-called light saturation problem. Briefly stated, the large amounts of chlorophyll and other pigments in algal cells result in cells near the surface of the ponds capturing more photons than their photosynthetic apparatus can actually use. The excess is wasted and not available to algal cells deeper in the ponds. The approach to this problem has been to reduce the light harvesting pigments in algal cells, using both physiological and genetic approaches (Polle et al., 2000; Nakajima and Ueda, 2000). In these studies, algal cultures with reduced pigment contents exhibited higher photosynthetic rates and productivities at high light intensities and in dense cultures than normal cells. Other factors, such as respiration, also reduce productivity and considerable R&D will be required to overcome the various limitations to productivity. The processes presented in this Roadmap do not depend on achieving the very high productivities required for dedicated microalgae biofuels-only systems (Benemann and Oswald, 1996). Still, productivity maximization is a major goal of this Roadmap and of microalgae R&D in general.

6.4. Harvesting and Processing.

Harvesting has been a major limiting factor in the use of microalgae systems for wastewater treatment and other applications. The uncontrolled nature of microalgae cultures in present-day wastewater treatment ponds requires universal harvesting processes, such as centrifugation or chemical flocculation. Both are expensive, at well over $500/ton biomass, and energy intensive, making such processes problematic from a greenhouse gas abatement perspective. As already discussed, spontaneous flocculation of algal cells after being removed from the mixed pond environment ("bioflocculation"), followed by settling of the flocs is often observed in algal cultures and is likely the lowest-cost harvesting process (Benemann et al., 1980; Benemann and Oswald, 1996). Costs depend on the time required for flocculation and floc settling velocities, but even unfavorable assumptions allow for low-cost projections. The challenge is to control the bioflocculation process to be both reliable and effective, with over 95% recovery of biomass. The physiological and genetic determinants that induce the spontaneous aggregation of algal cells, i.e. bioflocculation, have been little studied. The use of CO_2 fertilization and nitrogen limitations (as would be applied in tertiary treatment), as well as the selection of flocculating algal strains, all would allow much greater control of the process. Alternative low-cost harvesting methods, such as harvesting filamentous algae with screens ("microstrainers"), can also be considered. Reliable, low-cost harvesting has been the single most limiting factor in expanding microalgae applications in wastewater treatment and is an R&D priority.

Harvesting, by bioflocculation or microstraining, results in a biomass slurry containing some 5% (typically 3 to 7%) solids, which needs to be processed to biofuels and higher-value co-products. One processing option that is not plausible is drying of the algal sludge: even solar drying is an expense and use of algal biomass as solid fuels competes with low cost coal or wood. Further, burning algae biomass results in loss of fertilizer values. Thus, the use of microalgae as solid fuels for thermochemical processing (combustion, pyrolysis, gasification) is not recommended.

For microalgae wastewater treatment processes where biofuels and biofertilizers, along with reclaimed water, are the main outputs, fermentation of the algal biomass, in particular anaerobic digestion to produce biogas (a methane/CO_2 mixture) is the most readily applicable process. However, some algae (in particular green algae) are somewhat refractory to fermentations, and may require some pre-treatment, possibly by heat or mechanical cell disruption. Alternatively, algal strains more easily digested (fermented) can be cultivated. Cultivation under nutrient limitations would yield a biomass high in starches or vegetable oils that could be fermented to ethanol or H_2 or converted to biodiesel. Such cultivation conditions could also make the algal biomass more susceptible to bacterial attack, and, thus anaerobic digestion. R&D is needed to address process development and biofuels production issues in an integrated manner, combining laboratory R&D with outdoor pond operations.

The production of biogas or other biofuels results in effluents containing a significant amount of organic material as well as essentially all the N, P and other plant nutrients originally in the algal biomass. The main problem with the utilization of such fertilizers is their dilute nature, limiting their use to the near vicinity of the algal ponds. Higher value co-products, such as animal feeds or biopolymers, present additional R&D needs in biomass processing. However, the greater R&D challenges are in microalgae cultivation, productivity and harvesting, as discussed above.

6.5. Engineering Designs, Economic Analyses and Resource Potentials.

Engineering designs for large-scale ponds do not, in large part, present major uncertainties or R&D issues. For example, use of flue gas CO_2 for microalgae cultivation has been amply demonstrated and presents no major impediments. The transfer, storage, outgasing, pH effects and periodicity of CO_2 supplied to the algal ponds are well enough known to allow projection of an overall CO_2 utilization efficiencies of up to 90%. There is only limited experience with the operation of large (>1 ha) unlined raceway ponds, and their hydraulic behavior is not predictable from smaller-scale ponds. Thus, the design and operation of large unlined ponds needs study.

Engineering designs are useful for initial estimates of the relative costs of various options. For example, in the case of pure vs. flue gas CO_2, pure CO_2 would have to cost not much more than about $20/ton for these options to have similar overall costs. Assuming flat land and clay soils (no percolation), raceway-mixed ponds cost about $60,000 per hectare, including, earthworks, paddle wheels, carbonation stations, harvesting (bioflocculation-sedimentation), inoculum system and infrastructure (utilities, roads, drainage, etc.). This assumes relatively large systems (>100 hectares) and growth ponds of several hectares (Benemann and Oswald, 1996). For a productivity of 100/t/ha/y, an annual capital charge of 25% (including maintenance, depreciation, return on investment, etc.) and operating costs of $50/ton, this projects to $200/ton of algal biomass. This is over twice the value of fuel value of the algal biomass, even before processing to biofuels, and is a major reason that microalgae systems require higher value co-products and/or co-processes, such as biofertilizers and wastewater treatment, for economic viability.

There is a need for engineering designs and cost analyses of site-specific, multipurpose algal production processes, in particular of wastewater treatment systems with biofuels and fertilizer recovery and water reclamation. Another need is to address the utilization of the biofuels, such as electricity production from biogas, and the interfacing of power generation with CO_2 capture (e.g. Figure 4). These are required to compare the economics of the algal and conventional waste treatment systems, and the potential economic contribution of greenhouse gas abatement functions. It must be recognized that the present U.S. DOE goal for greenhouse gas abatement (about $2.7/ton CO_2) would make only a small contribution to the economics of such processes.

Perhaps the greatest need is to translate such preliminary engineering designs and cost estimates into resource potentials for greenhouse gas abatement by microalgae. Such resource estimates must integrate many factors, including land availability and suitability, climate, wastewater or other water resources, infrastructure, economics and many others. For example, climate and land availability near cities will limit the potential for microalgae in municipal wastewater treatment, to the equivalent of a few million tons (megatons) of CO_2 annually in the U.S. or Europe. This even assumes tertiary treatment (nutrient recovery) and reduced energy consumption compared to conventional, energy intensive, wastewater treatment processes (Benemann, 2002). However, by including animal wastes and other wastewater resources as well as biofertilizer production, the potential resource by an order of magnitude, and globally an even larger potential can be projected for such technologies. The land area, the "footprint", for microalgae biofuels production and greenhouse gas abatement would be a small fraction of that required by other biofuels systems, a major consideration. An important future objective of the Network will be to develop regional and global estimates for greenhouse gas abatement by microalgae processes. However, the key objective will be the achievement the projected productivities and economics.

7. ROADMAP DEVELOPMENT

The main objective of this Roadmap is to help direct the R&D efforts of the participants in the International Network into promising approaches and to foster collaborative and cooperative R&D projects. "***Areas of disagreement may exist over what paths to follow, or how to follow them***" (U.S. DOE-NETL Carbon Sequestration Technology Roadmap, 2002). This is as true for microalgae biofixation R&D as in other fields. However, a general consensus developed among the Network technical advisers and members regarding key issues, such as use of open ponds. Indeed, a design competition in the mid-1980's had already chosen such systems over closed photobioreactors, which were found to be much too expensive for low-cost microalgae processes (Sheehan et al., 1996), a conclusion also reached by the recent Japanese Program. Thus closed photobioreactors are not considered in this Roadmap, except for inoculum production. In a similar vein, high value products have very small markets and, thus, insignificant potential for greenhouse gas abatement. An ongoing project in The Netherlands came the same conclusions as this Roadmap: dual objectives of high value co-products and high volume greenhouse gas abatement are contradictory (see Almeria Minutes, 2002). Thus, microalgae greenhouse gas abatement processes must be integrated with high volume co-products and co-processes, that is waste treatment. Some other proposed uses of microalgae in greenhouse gas abatement, such as the promotion of calcium carbonate precipitation by microalgae cultures, can also be rejected. A major impetus for initiating the Network was to help direct R&D efforts into the more promising R&D approaches that can plausibly lead to practical and significant applications.

The R&D needs for the various processes described in this Roadmap greatly overlap. Thus, work on strain selection, productivity or harvesting, for examples, for any process would contribute to all others. The emphasis is on the near- to mid-term: "***…there are near- and midterm actions to be taken as we work to gain better understanding of the long-term opportunities.***" (U.S. DOE-NETL Carbon Sequestration Technology Roadmap, January 2002). Thus, the present Roadmap is designed to achieve practical applications in the near- to midterm to demonstrate the potential of this technology as well as determine whether microalgae systems could, in the longer-term, be developed as platforms for the production of biofuels in competition with other biomass sources.

In addition to a more in-depth discussion of R&D needs, other issues must also be addressed to develop this Roadmap and to broaden the consensus for the R&D approaches proposed herein:
1. Sources of CO_2. Flue gases from power plants vs. other sources – issues and constraints.
2. Scale of processes required for significant greenhouse gas abatement, in aggregate.
3. Accounting for additional greenhouse gas abatement benefits of co-products/co-processes.
4. Engineering-economics of microalgae processes, specifically for multifunctional processes.
5. Site-specific studies for processes to be developed in the 5-10 year Network time frame.
6. Selection among alternative projects to guide and focus process development programs.
8. Coordination and integration of approaches to microalgae greenhouse gas abatement.
7. Development of pilot-scale R&D activities and interests among Network participants.
9. Support ("buy-in") from experts in greenhouse gas abatement outside the microalgae field.
10. Overall potential for greenhouse gas abatement, in the U.S., Europe and globally.

However, most important is the initiation of R&D projects directed at the goals of this Roadmap. A number of such projects are already underway by Participating Organizations in the Network and additional ones will be developed in the future.

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