Technology Roadmap for Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae

John Benemann[1], Paola Maria Pedroni[2], John Davison[3], Heino Beckert[4], and Perry Bergman[4]

[1]Consultant, Walnut Creek, California, USA
[2]EniTecnologie S.p.A., San Donato Milanese, Milan, Italy
[3]IEA Greenhouse Gas R&D Programme, Cheltenham, Great Britain
[4]National Energy Technology Laboratory, U.S. Dept. of Energy, Morgantown, West Virginia, and Pittsburgh, Pennsylvania, USA

SUMMARY

Microalgae mass cultures can use CO_2 from power plants flue gases for the production of biomass suitable for conversion to renewable biofuels - methane, ethanol, biodiesel and hydrogen. Microalgae cultures can also be sources of fossil fuel-sparing products (fertilizers, biopolymers and lubricants) as well as of environmental services, specifically wastewater treatment and nutrient recyling. Currently microalgae are cultivated commercially in raceway-type, paddle wheel mixed, open ponds to produce food- and feed-grade algal biomass and are also used in wastewater treatment. However these systems are presently too expensive for applications in greenhouse gas (GHG) abatement. Engineering cost analyses project sufficiently low operating costs if large (> 100 hectare) open-pond cultivation systems were deployed, high algal biomass productivities achieved (100 metric tons/ hectare/year, or more) and large-volume co-products and co-processes reduce the costs of biofuels and GHG abatement from such systems. Achieving these goals will require both applied and fundamental R&D into algal physiology, genetics and photosynthesis, as well as improved biomass harvesting and processing.

To advance the development and applications of microalgae biofixation processes for GHG abatement, the U.S. Department of Energy–National Energy Technology Laboratory (DOE-NETL) and EniTecnologie, the R&D arm of the Italian oil company Eni, organized the "International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae". The Network, managed by the IEA Greenhouse Gas R&D Programme, also includes as members major energy companies, government agencies and other organizations with an interest in supporting R&D in this field: Arizona Public Services (a U.S. electric utility), the Electric Power Research Institute (EPRI), ENEL Produzione Ricerca (the R&D arm of a major Italian electric utility), ExxonMobil, Gas Technology Institute, and Rio Tinto, the international mining company. The Network provides to its member organizations research coordination, project development and review, other technical assistance and techno-economic analyses and resource assessments. The strategic goal of the Network is to demonstrate within five years the technical and economic feasibility of microalgae CO_2 biofixation technologies for GHG abatement and to achieve practical applications within the decade.

To help guide future R&D activities, an "R&D Roadmap" was developed, based on a consensus of technical advisers to the Network, which identifies key scientific and technological developments needed to achieve the Network goals. Four general microalgae processes were identified that combine CO_2 utilization from power plant flue gases with biofuels production and additional co-products and co-processes, specifically wastewater treatment, nutrient recycling, biofertilizers, biopolymers, animal fees or other large-volume co-products. The R&D needs of these processes and the potential of microalgae biofixation in greenhouse gas abatement, in the U.S. and globally, are discussed.

INTRODUCTION AND BACKGROUND.

Microalgae are microscopic plants that convert solar energy and CO_2 into O_2 and carbohydrates, then used to synthesize all other biomass constituents. Microalgae are typically grown suspended in a liquid nutrient media, with an enriched source of CO_2, such as power plant flue gas, required for cultivation. The biofixation of CO_2 from fossil fuel combustion flue gases is one of the attractions of microalgae in GHG abatement, although the biofixation of CO_2 is only a first step in such a process.

Microalgae cultures have been investigated as a source of commodities, including foods, feeds, fuels, and fertilizers, starting five decades ago, with the pioneering research carried out by the first international R&D collaboration in this field (Burlew, 1953), as well as by Oswald and Golueke (1960) at the University of California Berkeley. Even at this early stage two distinct concepts of algal mass culture emerged:

1. The use of closed "photobioreactors", such as the long transparent plastic bags, containing the liquid culture and an air/CO2 phase, described by Burlew et al. (1953), for production of high cost foods; and
2. Large, channelized, mixed open ponds ("high rate ponds") for wastewater treatment with possible animal feed co-production, as pioneered by Oswald and colleagues.

The first practical applications of high rate ponds were in municipal wastewaters, where the algal cultures produce dissolved O_2, required for bacterial oxidation of the wastes. The harvested algal biomass would be best convert it to methane fuel by the process of anaerobic digestion, a process already used extensive in conventional wastewater treatment. In the original concept of Oswald and Golueke (1960) the methane was to be used to generate electricity and the CO_2 from the power plant flue gas, along with the recovered nutrients, were to be used to grow additional algal biomass, expanding the potential scale of this process beyond the minimal needs of wastewater treatment alone. The initial feasibility analysis appeared favorable, but was rather sketchy. By contrast the techno-economic analysis of the closed photobioreactor concept demonstrated by Burlew and colleagues was less promising, due to need for cooling due to overheating in the plastic bags, as well as the overall capital and operating costs of such closed photobioreactor designs. Despite the enormous advances in technology over the past half century, such a comparison between open ponds and closed photobioreactors is still generally valid today.

Harvesting was recognized as a major issue since the first design of high rate ponds for wastewater treatment, which produce much more biomass than conventional, unmixed, so-called "oxidation" or "facultative" ponds. Although algal harvesting with chemical flocculants and dissolved air floatation is a well established and reliable process, its high costs (capital, chemicals, operating, and sludge disposal) have limited its applications to relatively few examples, and also limited the utilization of high rate ponds in wastewater treatment. The energy crisis of the 1970's gave renewed impetus to R&D of the concept of combined wastewater treatment-energy production with microalgae, with research emphasizing the harvesting of the algal biomass from raceway-type wastewater treatment ponds through "bioflocculation", the spontaneous flocculation and settling of algal cells (Benemann et al., 1980). During the 1980's the R&D support in the U.S. shifted from methane production in conjunction with wastewater treatment to dedicated, large-scale processes, where biofuels would the only outputs. This research effort, carried out from about 1980 to 1994 as the “Aquatic Species Program” (ASP), was sponsored by the U.S. Department of Energy through the National Renewable Energy Laboratory, and involved the participation of many university groups and several private companies (Sheehan et al., 1996). Significant technical advances were made by the ASP, culminating in the operation of a 0.2 hectare pilot plant in Roswell, New Mexico, which demonstrated the ability to grow selected algal strains in large, potentially low cost, raceway, paddle wheel mixed, unlined open ponds (Weissman and Tillett, 1992). However, the engineering analyses of such processes (reviewed in Benemann and Oswald, 1996) required very high biomass productivities, that is solar conversion efficiencies, among many other favorable assumptions, for the economic feasibility of producing microalgae biomass for fuels alone (biodiesel in the case of the ASP). This relatively negative outlook led, among other factors, to the cessation of the U.S. ASP by the mid 1990's, after an investment of about $40 million.

RECENT DEVELOPMENTS.

Prior to 1990 other countries had carried out relatively little work in this area, but this changed dramatically with the Japanese RITE (Research Innovative Technologies of the Earth) Program for microalgae biofixation of CO_2, supported by MITI (Ministry of International Trade and Industry) from 1990 to 2000. This ten year, approximately $250 million, effort included the participation of over twenty private companies and several government research institutions, in parallel efforts to develop closed photobioreactor technologies for the production of high value products using power plant flue gas for CO_2. A major focus of attention was the development of so-called optical fiber photobioreactors, which use concentrating mirrors to collect light that is injected into a bioreactor by means of light guides of various designs, although other close photobioreactors were also investigated (Usui and Ikenuchi, 1996). However, these R&D efforts were not continued, in part because of the very unfavorable economic projections for such approaches. R&D along similar lines continues presently in the U.S. (Bayless et al., 2001; Nakamura et al., 2001).

In the mean-time, a commercial microalgae production industry developed in several countries. This industry started in Japan during the 1960's with the commercial production of *Chlorella* for food supplements. In Mexico and Thailand during the 1970's, and in the U.S. and other countries starting int the 1980's in the U.S., the production of *Spirulina* was commercialized, for a similar market. *Chlorella* was the same alga initially studied by Burlew and colleagues, whereas Spirulina was a relatively newly discovered microalga, used as a traditional human food by people in Chad and others countries. During the 1980's, commercial production systems for *Dunaliella salina*, used as a source of beta-carotene, were developed in the U.S. and Australia. Recent commercial developments in microalgae biotechnology have been the mass cultivation of several novel algal species, in particular *Haematococcus pluvialis*, a source of the carotenoid astaxanthin, used in salmon aquaculture and also in food supplements. (See Figure 1 for a view of the Cyanotech, Inc., plant in Kona, Hawaii). Although all large-scale algal production systems use open ponds, a number of small-scale commercial production systems using closed photobioreactors have been established, although these are of much higher costs and their commercial success remains to be demonstrated. A large number of relatively small-scale both open pond (or tank) and closed photobioreactor systems produce live microalgae for aquaculture feeds, typically from a few kg to tons per year.

At present, about four to five thousand tons of microalgae biomass are produced annually at facilities around the world, mainly for the human food supplements market. Production costs are generally much higher than agricultural crops, limiting current applications to specialty food and feed products. Production costs for *Spirulina*, the largest volume microalgae product at present, with some 1500 tons produced world-wide, can be estimated to be approximately U.S. $ 5,000 per ton, plant gate. This is over an order of magnitude higher than what could be considered in any renewable fuel and GHG abatement process. In addition, microalgae ponds are extensively used for wastewater treatment, although these are generally rather small systems (< 10 hectares) and the algal biomass is seldom harvested or beneficially used.

Exceptions can be found at a number of larger wastewater treatment plants, including one, in Sunnyvale, California, that not only harvests the algae biomass produced from some 180 hectares (440 acres) of algal oxidation ponds but also converts this to methane fuel by anaerobic digestion and then generates electricity from the gas. In Kona, Hawaii, a commercial microalgae company, Cyanotech, Inc., operates a small power plant on biodiesel, producing renewable electricity and CO_2 for the algal cultures (Figure 2). These are the first, but still very initial steps in the commercial development of the processes first envisioned by Oswald and colleagues several decades ago.

THE INTERNATIONAL NETWORK FOR MICROALGAE BIOFIXATION

Despite several decades of R&D, significant applications of microalgae in fuels production and GHG abatement are yet to be realized and require considerable further basic research and applied development work. To advance both the near- and long-term development and applications of microalgae for biofixation of CO_2 and GHG mitigation, the U.S. Department of Energy (DOE) and EniTecnologie, the R&D arm of the Italian oil company Eni, with the assistance of the IEA Greenhouse Gas R&D Programme, in Cheltenham, Great Britain, organized the "International Network for Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae". The Network is an outgrowth of a Workshop, held in Monterotondo near Rome, Italy, in January 2001. This workshop, attended by over thirty technical experts and representatives of interested organizations, discussed the merits and limitations of microalgae mass cultures for GHG abatement. The consensus was that microalgae systems merited further R&D and the attendees supported the creation of such an "International Network" (Benemann, 2001; Pedroni et al., 2001).

Figure 1. Spirulina (blue-green ponds) and Haematococcus (red ponds) production plant of Cyanotech, Corp., Kona, Hawaii. Larger ponds, paddle wheel mixed and plastic lined, are about 0.3 hectares in size. Total area under cultivation about 20 hectares of a total of 36 hectares land (Courtesy of Cyanotech, Inc.).

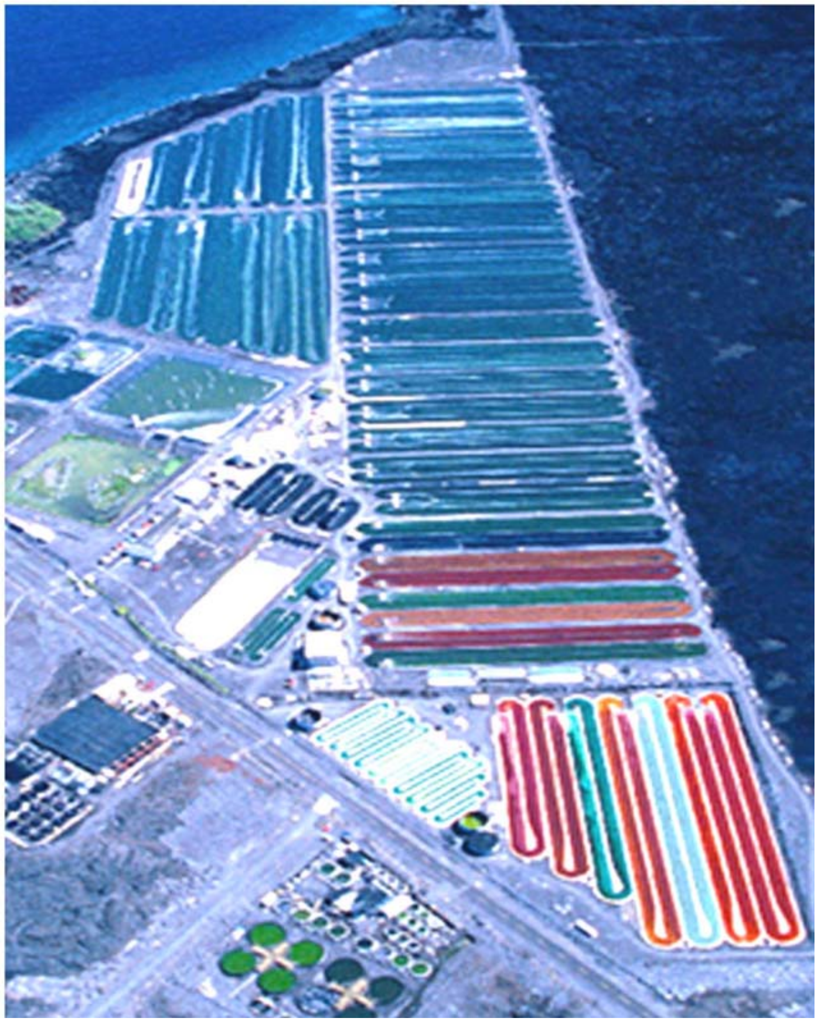


FIGURE 2. Small (0.36 MWe) power plant operated on biodiesel with flue gas CO2 absorption tower. (Cyanotech, Inc., Kona, Hawaii, photograph by the author).

The International Network became operative June 1, 2002, and presently includes as a members, in addition to the U.S. DOE and EniTecnologie: Arizona Public Services (a U.S. electric utility), Rio Tinto (an international mining company with major coal operations in the U.S.), ENEL Produzione Ricerca (the R&D arm of the Italian electric utility), EPRI (a U.S. R&D organization serving electric utilities), ExxonMobil, and the Gas Technology Institute (carrying out R&D in support of the natural gas industry). These companies and organizations with interest in promoting R&D and practical applications in this field have joined together to more effectively use limited resources in a coordinated and cooperative R&D effort. The Network is not a funding mechanism, it works with Member Organizations and others to assist in the selection and development of suitable R&D projects. The objectives of the Network are for such projects by member organizations to demonstrate the technical and economic feasibility of these technologies within five years and initiate practical demonstrations within this decade.

The International Network counts on the advice and inputs from several "Technical Advisers" with practical experience in algal mass culture, including commercial operations and larger R&D projects. The technical advisers have included Drs. Amha Belay (Earthrise Farms, California), David Brune (Clemson University, South Carolina); Gerald Cysewski (Cyanotech Corp., Hawaii), Mario Tredici (University of Florence, Italy) and Joseph Weissman (SeaAg, Inc., Florida).

Three technical meetings were held during the past year, in Almeria Spain (May 2002), in Kyoto, Japan (October 2003), and in Berkeley, California (April 2003), attended by representatives of the Member Organizations, Technical Advisers, and invited participants. The first meeting discussed the development of a "Technology Roadmap", outlining the most important R&D targets for the Network. The second meeting reviewed the draft Roadmap, described in some detail below. The most recent meeting focused on ongoing, planned and proposed R&D projects by the Network Member Organizations and Technical Advisers.

Among ongoing projects are three being carried out in the U.S. and represented in these Proceedings:
1. A study of the correlation between maximal growth rates and productivity among algal strains (are fast growing strains also highly productive?) (Huesemann et al., 2003, These Proceedings).
2. A comparative study of the productivity of microalgae growing in closed photobioreactors and open ponds under different light regimes (Weissman and Benemann, 2003, These Proceedings).
3. The development of a "Controlled Eutrophication Process" for the removal of P and N from agricultural drainage waters at the Salton Sea, California (Brune et al., 2003, These Proceedings).

Several other R&D projects are ongoing, under development or proposed by Network participants, additional studies of open ponds and closed photobioreactors, of oil producing algae, of biofertilizer production with nitrogen-fixing cyanobacteria, of genetic modifications to increase microalgae productivities, and of microalgae for GHG abatement in wastewater treatment. The International Network is open to participation by organizations interested in the development of the microalgae and related technologies for GHG abatement, as outlined in the Technology Roadmap

THE MICROALGAE BIOFIXATION TECHNOLOGY ROADMAP

A Roadmap provides a structured R&D planning process by identifying the scientific and technological developments needed to achieve a specific strategic goal. The key tool is to characterize those processes that could be practically developed within a given time-frame and from these derive the specific R&D needs that have to be addressed to achieve these objectives. Most importantly, the roadmapping effort involves consensus building among technical experts of the most plausible processes and the critical R&D needs that can meet the technical goals. This time-frame for the Network outlined above, five years to technology demonstration and ten years to practical applications, constrains the possible processes and approaches which can be projected, to those that need not invoke R&D "breakthroughs", but, rather, are based on a sound theoretical basis and reasonably established knowledge. However, the magnitude of the challenges faced in the development of this technology does require major advances in a number of different areas, from maximizing productivity to management and control of species and strains in open pond cultures, to harvesting and processing the algal biomass.

The R&D approaches and processes for the development of microalgae processes for GHG abatement ranges, as discussed earlier, from wastewater treatment to commercial algae production, from closed photobioreactors to large-scale open ponds, from algal genetics and physiology to conceptual processes for large-scale dedicated microalgae systems for energy production. During the development of the International Network a strong consensus developed that that dedicated, stand-alone microalgae systems to utilize flue gases CO_2 and produce renewable fuels as their sole outputs were not feasible, at least not within the R&D time-horizon of the Network. To allow projection of economic viability, such biofuels-only processes would require achievement of productivities near the theoretical maximum of solar energy conversion of photosynthesis, as well as very large-scale cultivation systems, ideal climates and locations and many other favorable assumptions (Benemann and Oswald, 1996). Similarly, a consensus developed during these discussions that only open pond systems could be applied to GHG abatement processes, due to the extremely high cost of closed photobioreactors. Closed photobioreactors were considered to be useful in the production of required algal inoculum, but only large open pond cultures could be of low enough cost to be potentially applicable in microalgae GHG mitigation. Indeed such ponds would not even be lined with plastics, as such liners almost double capital investments. The preferred alternatives were for multipurpose processes, which provide additional services, such as wastewater treatment or higher value, but large volume co-products, in addition to GHG mitigation functions (Benemann, 2003).

The three major R&D issues identified were the need to develop techniques allowing the mass culture of selected microalgae species in large open, unlined ponds, the low-cost harvesting of the algal biomass and the achievement of high productivities, of at least 100 tons/hectare/year, even in multipurpose processes. The consensus developed was that in the near- to mid-term GHG mitigation could only be achieved by microalgae systems through the development of such multipurpose processes, which not only fix CO_2 into renewable fuels but also avoid fossil energy inputs presently required by conventional processes, such as in the production of synthetic fertilizers or wastewater treatment.

The Roadmap outlines four general microalgae biofixation/GHG abatement processes, encompassing the near- to mid-term opportunities in this field:
1. Municipal wastewater treatment using flue gas CO_2 and CH_4 production and lower energy use.
2. Recovery of nutrients from agricultural wastes with co-production of biofuels and fertilizers.
3. Use of nitrogen fixing microalgae and nutrient recycling for agricultural biofertilizers.
4. Co-production of biofuels with large volume/high value biopolymers, animal feeds, etc.

These processes and the required R&D efforts are discussed in the following.

R&D ISSUES IN MICROALGE BIOFIXATON

There is a considerable overlap among the four general conceptual processes listed above. All require essentially similar production systems, i.e., open, paddle wheel-mixed, raceway ponds; all are based on using CO_2 from power plant flue gases or similar concentrated sources; all would produce renewable fuels (methane, ethanol, H2, etc.) and thus reduce GHG emissions by substituting for fossil fuels; all would have additional GHG abatement functions, such as reduced fossil energy consumption compared to traditional processes; all are plausibly economically feasible making reasonably favorable projections of productivities; and all would be of sufficient scale, both as individual processes and in aggregate, in order to achieve significant GHG mitigation on both national and global scales. These processes have to address essentially similar basic and applied research issues briefly summarized below (see Benemann, 2003):

Algal Strains. Mass culture of defined microalgal strains has been demonstrated in only a few cases (*Spirulina, Dunaliella*), with other algae (e.g. *Chlorella, Haematococcus)*, mass cultured with considerable difficulty and most algal species not yet able to be mass cultured in open ponds. R&D is required on how to select and maintain algal strains that are competitive in outdoor pond cultures.

Genetics and Molecular Biology. After selection of strains suitable for mass cultured in open ponds, these will need to be further improved. Application of modern biotechnology tools is only in its infancy for use in microalgae. Approaches include, for example, the selection of strains that have reduced chlorophyll contents and exhibit higher rates of photosynthesis and productivity in dense cultures (Nakajima and Ueda, 2000; Polle et al., 2000, 2001).

Physiology. In outdoor cultures algae are exposed to highly variable, often extreme, environments, in particular for light. How algal strains respond to these stresses requires a fundamental understanding of their physiology to allow modeling such processes (e.g. Rubio et al., 2002).

Culture stability. Algal cultures often succumb to invasions by competing algae, predation by zooplankton grazers, and crashes of unknown causes. Improving culture stability requires R&D.

Inoculum production. To start-up or replace failed cultures of selected microalgae strains requires a multistage inoculum production process, using closed photobioreactors and lined open ponds.

Productivity. Maximizing productivity, that is solar conversion efficiencies, is perhaps the most important R&D objective in this field. A central goal of the Technology Roadmap is to demonstrate 100 metric tons of biomass (organic dry weight) produce in one hectare of ponds in one year. This requires application of the physiological (Neidhardt et al., 1988) and genetic studies (above) with open pond cultivation studies.

Harvesting. Concentration of dilute suspensions of microscopic algae has been a major RF&D challenge in this field. Settling by spontaneous bioflocculation is one potential low-cost process but the mechanism for this process is obscure and its understanding and control necessary to reach the present objectives.

Biomass conversion. Biofuels production is a main mechanism for GHG abatement and CH_4, H_2, biodiesel, ethanol and hydrocarbons can all be derived from microalgae biomass, once the algal biomass has been produced with high yield and harvested with great efficiency, that is at low overall cost.

Co-Products and Co-Processes. Biofuels alone cannot economically justify microalgae processes. Waste treatment and large volume co-products must be integrated with biofuels production.

Engineering Designs. Although open ponds can be of low cost, these, and the supporting systems (e.g. CO_2 injection) have yet to be demonstrated at the large scales required.

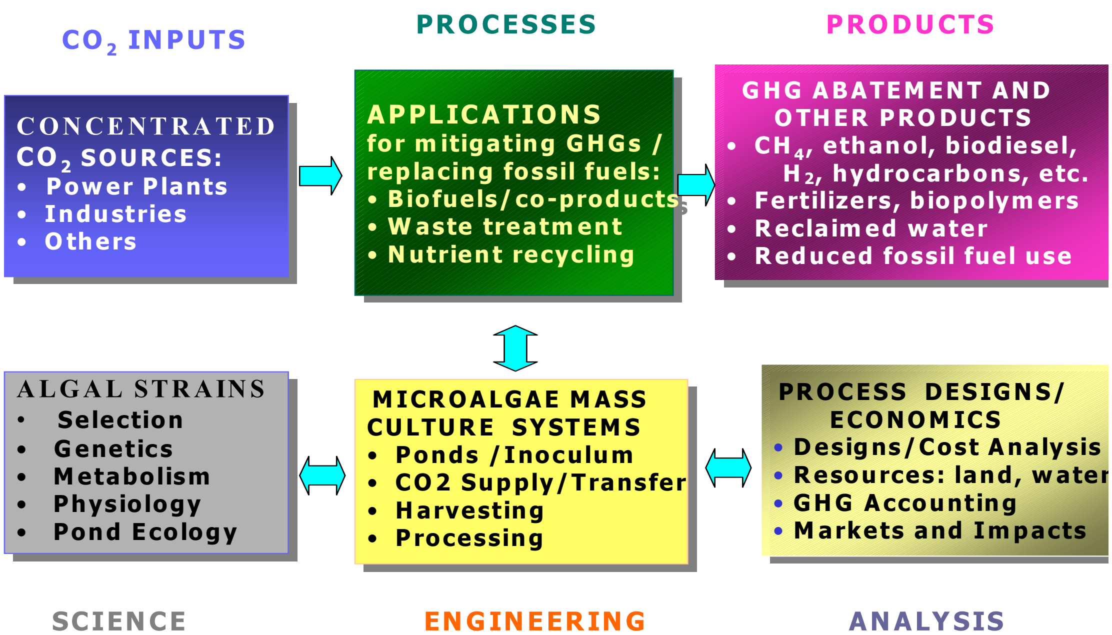
In this brief summary of R&D needs, the use of flue gas CO_2 was not highlighted as a major R&D issue because CO2 transfer into ponds and utilization by the algal is sufficiently well understood to provide no major impediment to such processes. Of course, flue gas transport becomes impractical beyond very short distances, and transfer into the ponds requires some energy, although this is a relatively small fraction of the outputs of such processes.

CONCLUSIONS

R&D challenges in microalgae biofixation of CO_2 and GHG abatement require multidisciplinary skills and a critical mass to allow a broad coverage among the many R&D topics outlined above. The major topics, disciplines and processes involved are summarized in Figure 3, and their interrelationships. This broad breath of disciplines and subjects cannot be easily encompassed by any single organization. The International Network provides a structure and mechanism by which the required expertise can be available and the research projects coordinated to help focus R&D efforts on most promising approaches for practical applications. The Technology Roadmap provides some guidance for such R&D activities by integrating in its broad vision the common and individual R&D needs and processes that must be developed to achieve the goal of significant GHG abatement by these technologies.

The application of microalgae technologies for GHG abatement will be decided not only by economics but also by their potential impacts: how many megatons, indeed gigatons, of CO_2-equivalent abatement microalgae processes could provide, both regionally and globally. As this is a solar conversion technology, the fundamental parameter will be the solar conversion efficiency, which translates into biomass productivity. Of course, additional factors must be considered, including the efficiencies of converting microalgae biomass to fuels (CH_4, ethanol, H_2, etc.), the parasitic energy requirements for the processes (e.g. net, rather than gross, outputs), any potential energy savings compared to conventional technologies (e.g. in wastewater treatment, or for other co-products) and similarly for abatement (or production) of secondary GHGs, such as methane and nitrous oxides. In general, biomass-to-fuel conversion efficiencies are relatively high and parasitic energy consumption low (Benemann and Oswald, 1996), and energy savings and other greenhouse gas considerations are secondary to the primary issue of biomass, and thus biofuels, productivity.

FIGURE 3. Schematic of Microalgae Biofixation of CO_2 Technology Roadmap



One central R&D goal of the International Network is to develop technology to double current productivities in microalgae mass cultures from about 50 today to at least 100 metric tons of dry biomass per hectare per year, in reasonably favorable (but not optimal) climatic conditions. Even higher productivities, could be projected for the longer-term. It can be estimated, for a first level of analysis, that one ton of algal biomass would produce net renewable fuel sufficient to abate a similar amount of fossil CO_2, based on a reasonable mix of natural gas, oil and coal. Therefore the potential of microalgae for GHG abatement is the product of productivity times the total aggregate scale of such processes, that is hectares of ponds. Thus, a global deployment of 10 million hectares of algal ponds would abate 1 gigaton of fossil CO_2 emissions. Adjustments would be required for other GHG credits (e.g. for energy savings in wastewater treatment), or if the fossil energy source being abated were an advanced natural gas power plant vs. a current coal power plants, for examples. However, overall, an estimate of 100 tons fossil CO_2 abatement per hectare of algal ponds appears to be a reasonable initial global estimate.

Although 10 million hectares of algal ponds would be an ambitious long-term goal, this scale is similar to that of ponds used globally in shrimp or fish aquaculture, and but a small fraction of the several hundred million hectares of rice paddies used for rice cultivation. Most importantly, microalgae production systems could use land and water resources not suitable for agriculture or aquaculture (e.g. saline, brackish, waste waters), and, in any event, their water use efficiency (tons of water per ton output) would be much higher than any terrestrial crop. The co-location of algal ponds with distributed power plants would be a major requirement, to provide the CO_2 required by such processes. The major limitations of this technology are not land, water or CO_2 resources, but the technical feasibility and economic competitiveness of microalgae processes compared to other alternatives, including crop production and forestry, for examples. Integrating algal GHG abatement with other large-volume co-processes and co-products, assures that microalgae will make a significant contribution to the global goal of GHG abatement.

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