IEA Bioenergy

Algal Biomass
Does it save the world?

Short reflections

Arthur Wellinger, Task 37 **April 2009**

Introduction

The technical potential of macro- and micro-algae for biomass production and greenhouse gas abatement has been recognised for many years, given their ability to use carbon dioxide and the possibility of their achieving higher productivities than land-based crops. Biofuel production from these marine resources, whether use of biomass or the potential of some species to produce high levels of oil, is now an increasing discussion topic. There are multiple claims in this sector but the use of algae as an energy production system is likely to have to be combined with waste water treatment or uptake of nutrients and minerals from polluted natural resources and co-production of high value products for an economic process to be achieved. These current biofuel discussions illustrate two issues. First, the potential broad utility of these organisms, that are capable of multiple products, ranging from energy, chemicals and materials to applications in carbon sequestration and waste water remediation. Second, the need for a robust evidence base of factual information to validate decisions for the strategic development of algae and to counter those claims made on a solely speculative basis to support commercial investment.

Photosynthetic macro-algae or micro-algae can grow both in salt or fresh water . Macro-algae or "seaweeds" are multicellular plants. They are often fast growing and can reach sizes of up to 60 m in length. They are classified into three broad groups based on their pigmentation: i) brown seaweed (Phaeophyceae); ii) red seaweed (*Rhodophyceae*) and iii) green seaweed (*Chlorophyceae*). Seaweeds are mainly utilised for the production of food and the extraction of hydrocolloids.

Microalgae are microscopic organisms. The three most important classes of micro-algae in terms of abundance are the diatoms (*Bacillariophyceae*), the green algae (*Chlorophyceae*), and the golden algae (*Chrysophyceae*). Diatoms are the dominant life form in phytoplankton and probably represent the largest group of biomass producers on earth. Green algae are especially abundant in fresh water. The main storage compound of these algae is starch, although oils can also be produced. The golden algae are similar to the diatoms and produce oils and carbohydrates.

Background

Seaweeds from natural populations have been used since the beginning of civilization for food, feed, and fertilizers. This has led to cultivation of this resource and extension of its use for industrial chemicals such as agar, alginate, carrageenans, and fucerellans.

Seaweeds are mainly produced for these end uses in Asian countries such as China, the Philippines, North and South Korea, Japan and Indonesia. As of the early 1980s, the Chinese and Japanese planted, cultivated, and harvested macroalgal crops valued at $1 billion annually from over 60,000 ha of sea surface. The world production of seaweeds was some 8 Mio t in 2003. The Kelp *Laminaria japonica* is the most important with 4.2 Mio t cultivated mainly in China.

Energy from algae became a topic only much later. In the 70ies The US Marine together with US DOE launched a large project to determine the technical and economic feasibility of production of substitute natural gas from marine biomass, i.e. macro algae (Chynoweth, 2002). It consisted of large, open ocean macroalgal farms as alternate sources of food, feed, fertilizer, other chemicals, and energy (Figure 1). In 1972, the U.S. Navy initiated a project on this concept with focus on *Macrocystis pyrifera*, because of its high growth rates in natural beds and its potential for repeated harvest.

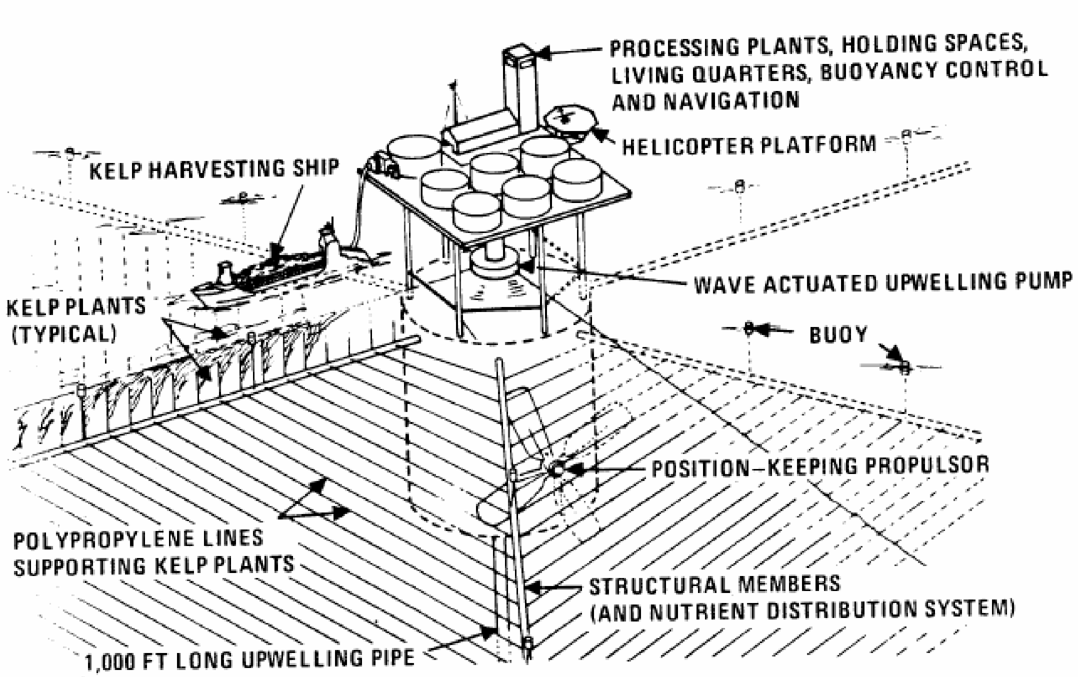


Figure 1. Conceptual design of 405 ha (1,000 acre) ocean food and energy farm unit. (Leese 1976) Source: David Chynoweth.

During the oil crisis in the early 70ies the focus shifted to the optimization of kelp growth biology, engineering design of an offshore kelp growth facility, evaluation and optimization of conversion by anaerobic digestion, and systems analysis. Up to the late 1970's, conversion of kelp to methane was successfully demonstrated, but several attempts to sustain kelp growth on artificial farms were unsuccessful; i.e., high growth rates observed in natural beds could not be demonstrated on artificial structures.

New species were added like *Laminaria*, *Gracillaria*, and *Sargassum* and nearshore aquaculture of *Macrocyctis. A*pproaches with these species brought numerous breakthroughs and successes including improvement of seaweed yields, maintenance of cultivars, successful artificial growth of plants on a sustained basis and improvements in bioconversion yields, kinetics and stability.

Combined algal growth and waste water treatment followed by digestion was tested on a pilot plant to treat the waste water at the EPCOT center. Despite this record, the program was cancelled in 1986 because of a decreased emphasis for renewable energy by the U.S. gas industry.

In the 80ies water treatment systems have been developed including mechanical separation, anaerobic treatment, algal ponds and fish ponds. The cleaned water was used for irrigation. Pilot plants cleaning slaughterhouse waste water and waste water from rubber factories were built in Morocco and PCR, respectively (Wellinger, personal communication).

Habitats

It is generally accepted that there are about 100'000 algal species growing. Thereof about 35'000 to 40'000 species are scientifically described but only about 10 or 20 are economically used.

Macro-Algae

The big advantage of macro-algae is their huge mass production. Typical yields are in the range of 7 to 30 t per ha and year. The major problems of off-shore macro algae growth are fixation and harvesting on engineered growth islands as experienced by the early US experiments. In newer approaches by German searchers (Buck and Buchholz, 2004) the earlier technical problems of support devices were confirmed.

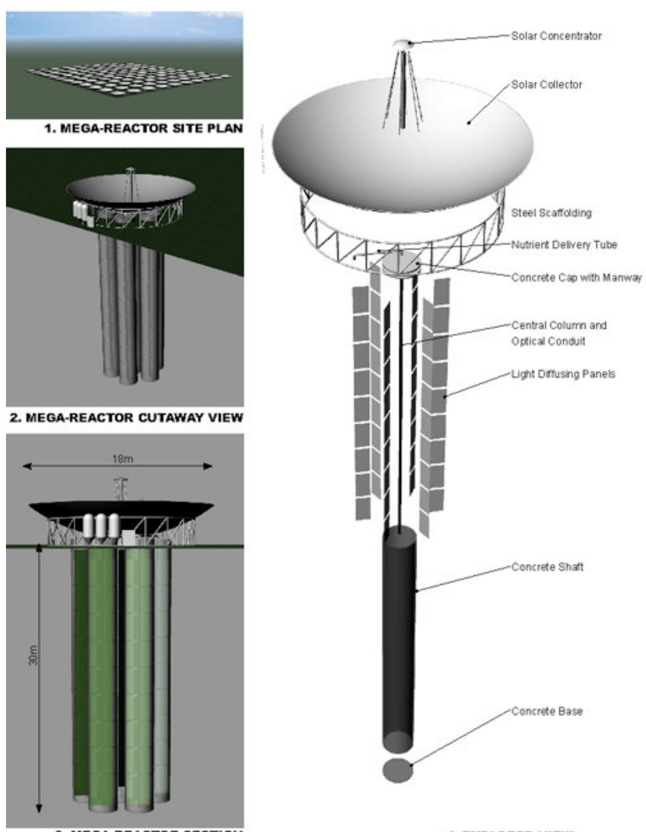


Fig. 2 New floating designs to grow and harvest macro-algae.

Only if floating algae could be used like *Sargassum* (Fig.3) efficient and cost-saving systems could be introduced.

Figure 3: Sargassum floating in the Venice bay (Picture: www.algaebase.org)

Micro-Algae
Micro-algae are microscopic photosynthetic organisms that are found in both marine and freshwater environments. Their photosynthetic mechanism is similar to land based plants, but due to a simple cellular structure, and submerged in an aqueous environment where they have efficient access to water, CO2 and other nutrients, they are generally more efficient in converting solar energy into biomass.

The most frequently used micro-algae are *Cyanophyceae* (blue-green algae), *Chlorophyceae* (green algae), *Bacillariophyceae* (including the diatoms) and *Chrysophyceae* (including golden algae). Many microalgae species are able to switch from phototrophic to heterotrophic growth. Micro-algae find uses as food and as live feed in aquaculture for production of bivalve molluscs, for juvenile stages of abalone, crustaceans and some fish species and for zooplankton used in aquaculture food chains. Therapeutic supplements from micro-algae comprise an important market in which compounds such as β-carotene, astaxanthin, polyunsaturated fatty acid (PUFA) such as DHA and EPA and polysaccharides such as β-glucan dominate (Pulz and Gross, 2004).

Today, biodiesel production by algae is of major interest. Many species of algae accumulate large amounts of oils. The algal oil is converted into biodiesel through a trans-esterification process. In a NREL sponsored project (Sheehan et al. 1998) roughly 3000 strains of algae were collected and screened for their oil-producing capacity.

Most of the work focuses on *Botryococcus braunii* because they have the highest potential of oil production. Cells (dry weight) might contain up to 75% of oil. Other candidates are *Nannochloropsis sp.* and *Nitzschia sp.* with oil contents of 68% and 47% respectively.

Production systems

Off-shore production systems of macro-algae have not much developed over the recent years. They are faced with tidal and wave problems requiring rather expensive support systems. But also feeding with nutrients is a challenge as long as the systems are not placed in polluted water. There is still a considerable research potential. The emphasis of off-shore research promotion should be directed from the start to a sustainable environment where marine species and habitats are protected and biological components function in balance.

For microalgae two basic approaches are applied: The open pond system and the enclosed photobioreactor. Open pond systems are shallow ponds in which algae are cultivated. Nutrients can be provided through runoff water from nearby living areas or by channelling the water from waste water treatment plants. The water is typically kept in motion by paddle wheels or rotating structures (raceway systems), and some mixing can be accomplished by appropriately designed guides. Most often mixed algal cultures are used.

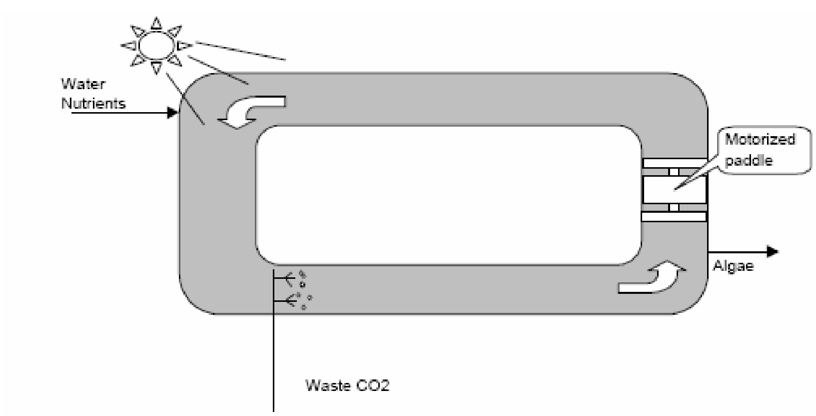


Fig.4 Raceway system. Source: Lookback Biodiesel from Algae (Sheenhan et al., 1998)

Photobioreactors are different types of tanks or closed horizontal or vertical pipes in which algae are cultivated (Richmond 2004). Algal cultures consist of a single or several specific strains optimised for producing the desired product. Water, necessary nutrients and CO2 are provided in a controlled way, while oxygen produced during the photovoltaic process has to be removed to avoid product inhibition. Algae receive sunlight either directly through the transparent container walls or via light fibres or tubes that channel the light from sunlight collectors.
Heterotropic algae grown in conventional digesters and fed with carbohydrates instead of using sun light, have also been discussed.

Over the past few years considerable progress has been made in the design of photobioreactors. A number of systems with horizontal and vertical tubes or plates made of either glass or transparent plastic and so called fence systems made of flexible plastic membranes exposed to the sun either in the free air or in green houses (Fig. 5 a, C and d) . Some of the plastic hoses or films are also imbedded in pools filled with water (Fig. 5b): water supported flexible films).

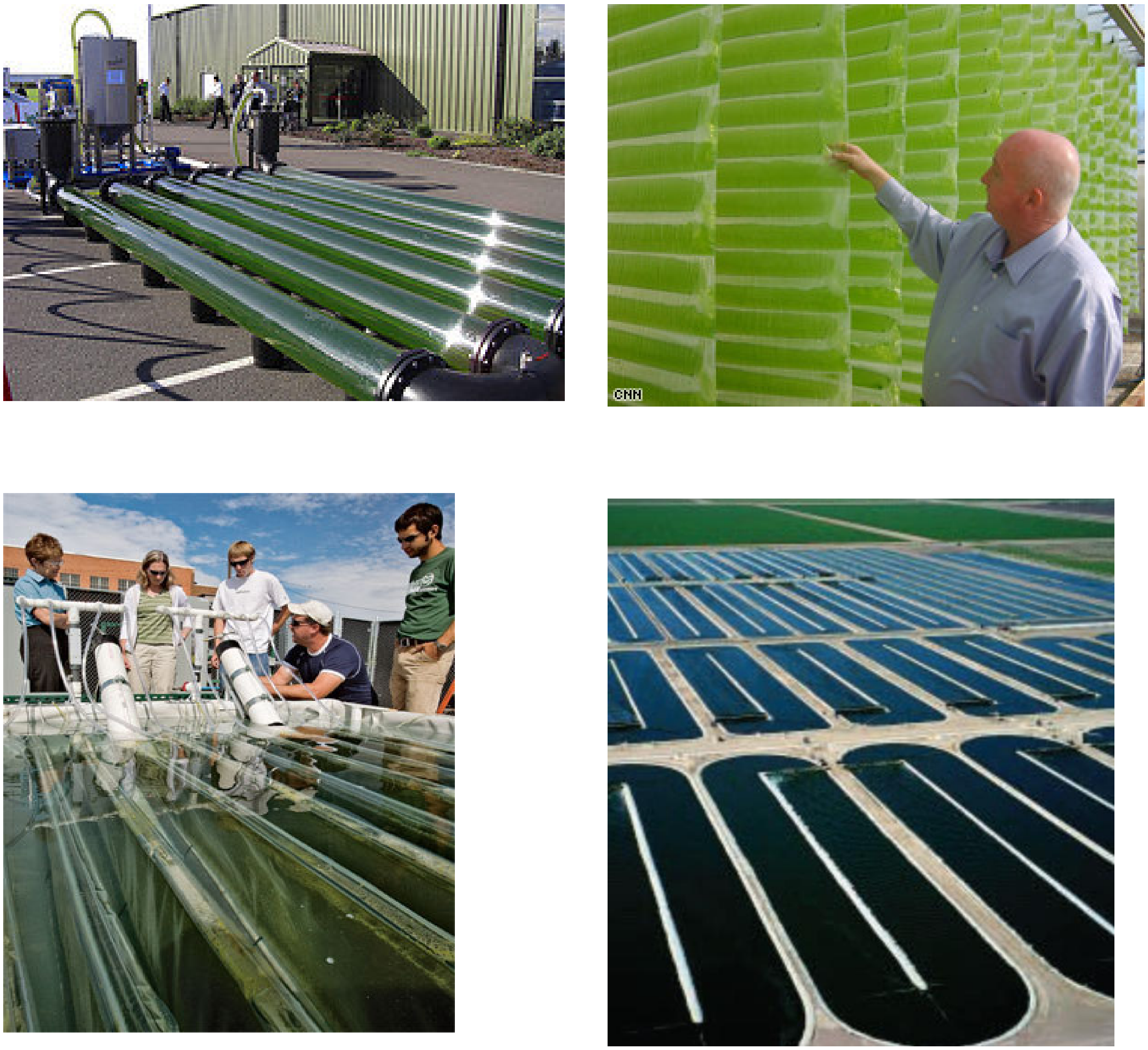


Fig. 5. Top: a) Horizontal glass tubes; b) Horizontal plastic films
Bottom: c) Water supported flexible films; d) raceway systems

Most often a continuous flow system is applied. The nutrient broth together with the microalgae are recycled through a tank were oxygen is removed and minerals and sometimes CO_2 (bubbling reactor) are added. In other systems nutrients and CO_2 are directly added to the photobioreactors (Fig.6).

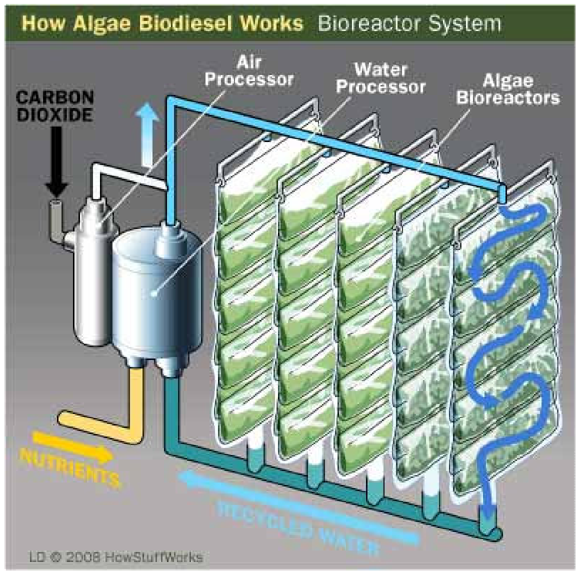


Fig. 6 Scheme of a horizontal plastic film system

John Benemann, the grandfather of microalgae research, recently (Algae World 2008) stated that "The cultivation of microalgae for biofuels in general and oil production in particular is not yet a commercial reality and, outside some niche, but significant, applications in wastewater treatment, still requires relatively long-term R&D, with emphasis currently more on the R rather than the D".

Most of the R&D efforts over the last years have been given to the production of microalgae biomass with focus on oil production. Little work however, is done on harvesting and drying. Alfa Laval is doing some research mainly with their classical equipment of centrifuges, etc.. If we can trust in a first announcement on the internet, there seems to be a big progress being made in a US-DOE sponsored project on suction drying. They claim that drying energy could be reduced by a factor of 100 as compared to classical methods.

There is still some macro-algae research going on, focusing on the engineering part of production islands.

Although biogas production from algae seemed to be the most advanced technology some 20 years ago, no new research efforts have been reported over the last few years. Only together with hydrogen production it might be considered.

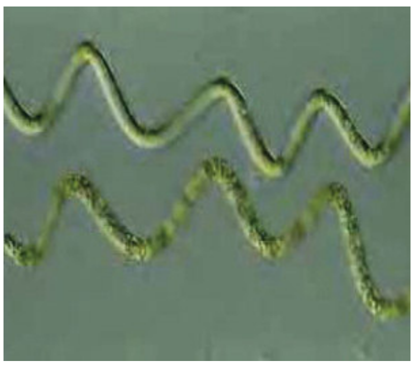
Surprisingly enough, only vague indications can be found on the internet for utilisation of algae in fluidized bed systems or gasification.

Industrial application

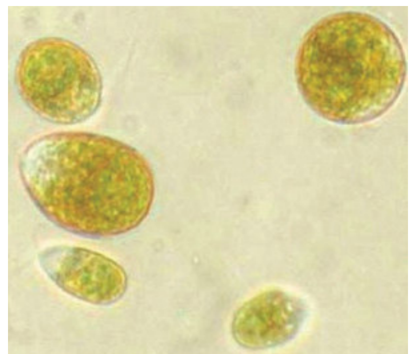
Alongside academic research, an important amount of money is invested into development of algal growth systems by the large energy producers and the oil industry. The latter had, in the seventies and eighties, invested huge capitals to develop algae for food out of oil very successfully because they were convinced that mankind would run short on nutrition but not on oil. Still now a number of products can be found in grocery stores. Much more successful is the production of pharmaceutical and chemical products (Fig. 7). Reason why Akzo Nobel is investing.

Fig. 7 Various beauty products, fish feed and nutrition for men (commercials from the internet).

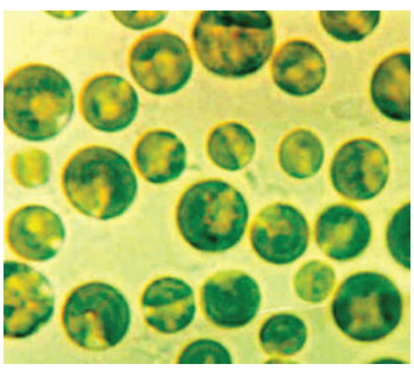
Microalgae are currently cultivated commercially for human nutritional products around the world in several dozen small- to medium-scale production systems, producing a few tens to a several hundreds of tons of biomass annually. The main algae genera currently cultivated photosynthetically (e.g. with light energy) for various nutritional products are *Spirulina*, *Chlorella*, *Dunaliella* and *Haematococcus* (Figure 8). Total world production of dry algal biomass for these algae is estimated at about 10,000 tons per year. About half of this produced takes place in mainland China, with most of the rest in Japan, Taiwan, U.S.A., Australia and India, and a few small producers in some other countries.



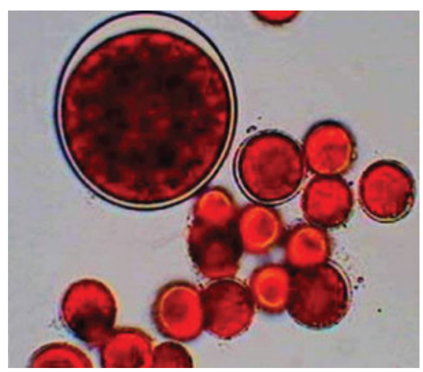
1. Spirulina (Arthrospira platensis)



2. Dunaliella salina



3. Chlorella vulgaris



4. Haematococcus pluvialis

Figure 8: Algal strains currently mass cultured (Benemann, 2008)

The major driver today for algal development is GHG reduction, i.e. CO_2 reduction and production of mineral oil substitutes. Even the oil companies have accepted that the oil will be depleted at some stage. Shell, Neste Oil, Petrotech or Biodiesel International (BDI) are therefore investing into algal R&D and application. The power companies are more interested in CO_2 depletion like E.ON, RWE, EnBW, formerly Preussag and Essent.

Their dream is to maintain the coal (or oil) to electricity power plants while fully recycling the CO_2 (Fig.9). However, according to Benemann (2008), algae as such can not sequestrate CO_2 unless they are harvested and used to replace fossil fuels.

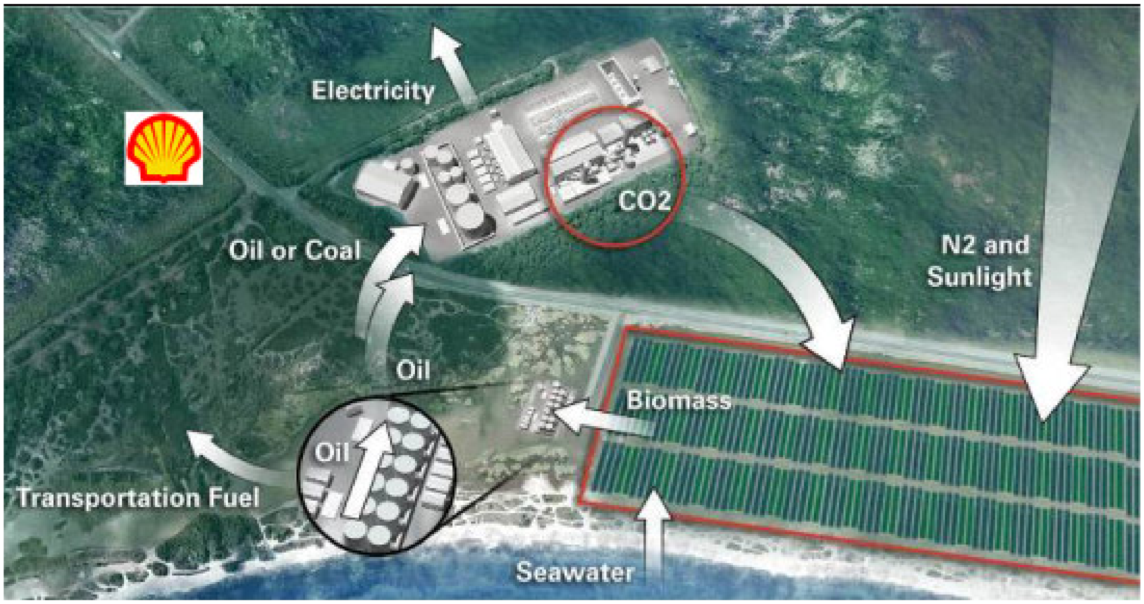


Fig. 9 CO_2-fixation in algal cultures from a coal or oil fired power plant (Source Internet: K. Spilling (SYKE 2008)).

In spite of all the hype about yields of 200,000 Litre of oil per ha and year or even up to 1 Mio Litre per ha, biodiesel from algae is still something for the future.

As of end of 2008, there is no such thing as biodiesel from algae apart from a few laboratory samples. The probably most advanced project of CO_2-fixation in photobioreactors is the one at a cement plant near Jerez in Spain.

On October 21, 2008 GreenFuel Technologies Corporation, one of the leading developer of algae farming technologies that recycle greenhouse gas emissions, and Aurantia, SA announced the second phase of their joint project to develop and scale algae farming technologies. Initiated in December 2007 at the Holcim cement plant the project's goal is to demonstrate that industrial CO_2 emissions can be economically recycled to grow algae for use in high-value feeds, foods and fuels. The project began with a Field Assessment Unit, which has successfully grown a variety of naturally occurring algae strains using Holcim flue gases. The second phase of the project commenced with the successful inoculation and subsequent harvests of a $100m^2$ prototype vertical thin-film algae-solar bioreactor. The final scale anticipated is 100 hectares of algae greenhouses producing 25,000 tons of algae biomass per year.

Conclusions and potential involvement of IEA Bioenergy

The interest in algae research has been increasing significantly over the last few years. A Google search on algae shows about 12 mio. hits, algae and energy shows about 4 mio., algae and feed about 3 mio. hits.

So far, no significant progress has been made going beyond the research work back in the 70ies and 80ies. However, there are distinct differences to earlier approaches. Today, industry is deeply interested in CO_2 reduction and alternative energy production and is therefore investing in R&D work. In earlier times, only a very limited number of academic searchers were involved in algae research where as today there are countless research labs all over the world in industry and universities involved, thus increasing the chance of a major break through. For example, the "Oil from Algae Online Group" has been working for the last four years exclusively on biofuel from algae production and now has more than 2,000 members.

All but three member countries of IEA Bioenergy are involved in algal research. Hence, there are good reasons that ExCo should start to take up the topic. Even more though as there is a tremendous gap between (too) high expectation on the success of algae research that is "just around the corner" on the one hand, and a frustration of those involved in the algae business for a number of years, who lost confidence in significant short term success. The situation reminds the fuel cell R&D situation a few years ago.

There is no doubt that there is a desperate need to screen the status of development by an independent body, trying to identify repetitive, overlapping research activities and in particular to identify research gaps in all fields covering algal strains, cultivation systems, engineering work, harvesting and utilisation.

A number of excellent overview papers have been written over the last two years (Benemann, 2008; Abayom et al. 2009; however, they are highly academic. At the same time industry has produced research reports that are easy to understand however, often read more like promotion brochures with wishful thinking.

IEA Bioenergy could fill that gap with a colourful, easy to understand but yet, carefully evaluated report on the state of the development and in particular clearly highlight research gaps. The network of the member countries (including Korea) could be activated to report on the respective national research efforts. A core group of two or three people at the most (preferentially made up of experts from Tasks 37, 39 and eventually Task 30) could establish the respective questionnaires and compile and evaluate the results. The outcome of the questionnaires could be enriched by a scrutinised analysis of the recently written overview papers and the newest publications. I would be happy to act as a coordinator of this core group. As a result, a publication (status report) could be published by the ExCo.

Within Task 39 a group from Canada and the USA has already started to review literature with the intention, to publish a report on oil from micro-algae. This work could be integrated into the suggested common project.

Literature

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