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Algae-based Biofuels

Applications and Co-products



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Review paper

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www.fao.org/bioenergy/aquaticbiofuels

GBEP Global Bioenergy Partnership

Executive summary

Although the need for dense energy carriers for the aviation industry and other uses is assured in the foreseeable future, there is currently lack of viable renewable alternatives to biofuels for that component of the transport sector. Algal biofuels have many advantageous characteristics that would lower impacts on environmental degradation in comparison to biofuel feedstock and in some cases improve the well-being of developing and developed communities.

Within the international debate surrounding algal biofuels, there are both endorsement and scepticism coming from scientists with different views on the ability of this source of biofuels to meet a significant portion of fuel demand. The private sector has invested in the technology to grow algae and convert it to liquid biofuels over the last few years. Technical scientists and business people tend to focus on their specific perspective rather than on a global perspective that clearly analyses the benefits (or drawbacks) of a technology for sustainable development. Sustainability experts need to liaise with different stakeholders to assess the practical applicability of algal biofuels and their suitability for developing regions in order to provide governments and policy-makers with the appropriate information to formulate optimal solutions.

Algae have a number of characteristics that allow for production concepts which are significantly more sustainable than their alternatives. These include high biomass productivity; an almost 100% fertilizers use efficiency, the possibility of utilizing marginal, infertile land, salt water, waste streams as nutrient supply and combustion gas as CO_2 source to generate a wide range of fuel and non-fuel products. Furthermore, another competitive advantage of algal biofuels is that their development can make use of current fossil fuel infrastructures. As more expensive sources of fossil fuels are starting to be exploited at the expense of the environment, the more rapidly algal biofuels can provide a viable alternative, the more rapidly fossil fuel consumption will be reduced.

Possible algal biofuels include biodiesel, bioethanol, bio-oils, biogas, biohydrogen and bioelectricity, while important non-fuel options include the protein part of algae as staple food, certain algal oils, pigments and other bioactive compounds as health foods, neutraceuticals or pharmaceuticals, or other renewable inputs for the food industry, including as feed for livestock and aquaculture. In addition, non-food compounds can be extracted for use by the chemical industry, in cosmetics and skin care products, as organic fertilizers and as an alternative fiber source for the paper industry.

Algae advantages and drawbacks should be considered without excessive enthusiasm of prejudices but exclusively with a scientific approach.

At the time of this publication, large scale production of algae-based biofuel is not yet economically viable enough to displace petroleum-based fuels or compete with other renewable energy technologies such as wind, thermal solar, geothermal and other forms of bioenergy. Current production efficiencies for algal biomass production result in a cost range of USD 0.60/kg to USD 7/kg. As shown in the report, the approximate cost of algal biodiesel is even higher (usually more than USD 6/liter) primarily dependent on the quality of the final product and the external conditions.

However, with policy support and incentives, the algal biofuel industry will continue to develop and, assuming that this technology will follow cost trends of other renewable energies, costs will decrease to eventually compete economically with fossil fuels. It is clear that the technology embodies some desirable characteristics for the environment and society, yet one of the principal challenges is the economic viability of this technology. Supportive policy conducive to advancement in research, development and deployment of algal biofuels could eventually contribute to the alleviation of a number of energy, hence environmental, problems.

Despite their high potential, both in terms of productivity[1] and sustainability, most algae-based biofuel (ABB) concepts still require significant investments to become commercially viable. One technical solution that would speed viability and sustainability, hence the competitiveness of ABB, is the co-production of multiple products to generate additional revenue.

The non-fuel co-product options investigated in this review can technically be co-produced with at least some of the ABB options (usually in the form of health food), except if complete algal biomass is the end product. From an economics perspective, there are many algal products with high market value, but their market volume is incompatible with the market volume of biofuels, preventing large scale use of the same co-production concept. More market compatible products are fertilizers, inputs for the chemical industry and alternative paper fiber sources. However, these have a market value that is similar or a slightly higher than biofuels. While a continued rise in fossil oil price can be expected, the production costs of algae are projected to drop as the technology develops and experience increases.

[1] Microalgae biomass productivities of 80 tons per hectare per year, which are in the range of high yields attained with C4 crops (e.g. sugarcane) in the tropics, must be considered as the maximum achievable at large scale (Tredici 2010).

Commercial production and harvesting of natural populations of both microalgae and seaweed predominantly take place in developing countries, indicating available experience, good environmental and economical conditions like sunshine and low labour costs. Large-scale industrial applications require a large amount of marginal, cheap but often ecologically valuable land and water sources. For poor rural communities, well designed small-scale Integrated Food and Energy System (IFES) approaches are most suitable, potentially reducing ecological impact while providing fuel, animal feed, human protein supplements, wastewater treatment, fertilizer and possibly more products that generate additional income. Capital inputs have to be minimized for this group, which means that the cultivation system would most likely be the open raceway pond, constructed in an area with an easily accessible, sustainable water supply, or *in situ* collection of macroalgae.

Novel technologies are contributing to develop a whole range of novel foodstuffs and renewable non-food commodities from algae in a sustainable way.

Capital input, immature technology, knowledge required for construction, operation and maintenance and the need for quality control are significant barriers to algae-based systems (and IFES concepts in particular). Although productivity and sustainability are potentially much higher for integrated systems, the time and effort needed to create a viable algae-based IFES concept seems to be significantly higher than for IFES concepts based on agriculture.

The report shows that, while the technology for large scale algal biofuel production is not yet commercially viable, algal production systems may eventually contribute to rural development, not only through their multiple environmental benefits but also through their contribution of diversification to integrated systems by efficiently co-producing energy with valuable nutrients, animal feed, fertilizers, biofuels and other products that can be customized on the basis of the local needs.

Algae-based biofuels: applications and co-products
by Sjors van Iersel and Alessandro Flammini

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1 Introduction

The FAO Inter-Departmental Working Group (IDWG) on Bioenergy established the Aquatic Biofuels Working Group (ABWG) in 2008 as an exploratory initiative with the aim of assisting interested stakeholders to understand the potential and sustainability of biofuel production from algae and fish waste in order to exchange knowledge and experiences with the objective of promoting R&D in this field. The focus of the ABWG activity is on the developing country context and the feasibility of pursuing biofuel production from algae and fish waste. As a first step, the report "Algae-Based Biofuels - A Review of Challenges and Opportunities for Developing Countries" has been published in 2009; which allowed FAO and interested stakeholders to better understand the potential and impacts of different technology options for algae-based biofuels production in developing countries[2].

The importance of investigating new options offered by algae cultivation is motivated by the fact that algae are very efficient at converting light, water and carbon dioxide (CO_2) into biomass in a system that does not necessarily require agricultural land. Depending on the concept, the water can be salty and the nutrients can come from waste streams. Depending on the species and cultivation conditions, algae can contain extremely high percentages of lipids or carbohydrates that are easily converted into a whole range of biofuels including biodiesel or bioethanol. Furthermore, the remaining biomass, mostly protein and carbohydrate, may be processed into many other products such as: foods, chemicals, medicines, vaccines, minerals, animal feed, fertilizers, pigments, salad dressings, ice cream, puddings, laxatives and skin creams (Edwards 2008). Algae- based products can serve as an alternative to a wide range of products that are currently produced from fossil resources or land-based agriculture, but without requiring high quality land and in some cases without requiring fresh water[3], with CO_2 as the only carbon input.

Some key conclusions of the first review paper are that the most significant obstacles are the high production costs and the fact that algae-based biofuels initiatives (typically R&D) are still predominantly based in developed countries. Both these conclusions justify a broadening of the scope to include the co-production of fuel, food and other valuable co-products. This co-production is seen as an important option to break though

[2] This review paper can be found online at http://www.fao.org/bioenergy/aquaticbiofuels/abwg-activities

[3] The fresh water need could become consistent for open ponds applications due to water evaporation

the barrier of economic viability, while at the same time producing a new protein source for human, livestock and fish consumption; the high nutritional value of algal protein has actually been known for decades, while malnutrition is one of the most serious problems in developing countries.

As a follow-up to the work previously undertaken by the ABWG and the consequent publication of the review paper, this document provides an overview of practical options available for co-production from algae and their viability and suitability for developing countries.

In the last few years, hundreds of scientific papers have been published on the use of algae in producing a wide variety of products and, at the same time, several companies have been set up in this field with the aim of entering the market. Therefore the focus of this review is on using light and CO_2 as the main energy and carbon sources for the biomass production of non-plant organisms (i.e. algae) for multiple purposes through integrated systems. In particular *integrated food and energy systems* (IFES) that rely on algae will be discussed and the wide range of algae-derived products will be briefly overviewed. These systems aim at the simultaneous production of food and energy through sustainable land use management, contributing to meet higher living standards, through the production of energy, food, feed, bio-chemicals and fertilizers. Integrated systems ensure a more sustainable management of land and natural resources by combining the production of bioenergy and other valuable co-products by transforming the by-products of one production system into the feedstock for another, hence intensifying the overall production on the same land and contributing to alleviate pressure on natural resources. Given the nature of algal application and their reduced need for land, algae can potentially optimize land use to meet multiple human needs.

Algae are defined as eukaryotic macroalgae and microalgae, but also prokaryotic autotrophic species such as cyanobacteria. These groups contain species that can make use of organic carbon, e.g., glucose, as a carbon source (often yielding higher productivities and biomass concentrations), but as this would require separate feedstock production (instead of CO_2 utilisation) there is a subsequent loss of many sustainability benefits. This option, known as heterotrophic cultivation, will not be considered in this report. While macroalgae are usually cultivated in their natural habitat, microalgae can be cultivated in dedicated cultivation systems, allowing for better manipulation of the growth conditions and subsequent quality control. The latter is a requirement for most algal product applications; therefore this report focuses primarily on microalgae.

2 Algae-based bioenergy options

2.1 Background

In recent years, biofuel production from algae has attracted the most attention among other possible products. This can be explained by the global concerns over depleting fossil fuel reserves and climate change. Furthermore, increasing energy access and energy security are seen as key actions for reducing poverty thus contributing to the Millennium Development Goals. Access to modern energy services such as electricity or liquid fuels is a basic requirement to improve living standards.

One of the steps taken to increase access and reduce fossil fuel dependency is the production of biofuels, especially because they are currently the only short-term alternative to fossil fuels for transportation, and so until the advent of electromobility. The so-called first generation biofuels are produced from agricultural feedstocks that can also be used as food or feed purposes. The possible competition between food and fuel makes it impossible to produce enough first generation biofuel to offset a large percentage of the total fuel consumption for transportation. As opposed to land-based biofuels produced from agricultural feedstocks, cultivation of algae for biofuel does not necessarily use agricultural land and requires only negligible amounts of freshwater (if any), and therefore competes less with agriculture than first generation biofuels. Combined with the promise of high productivity, direct combustion gas utilization, potential wastewater treatment, year-round production, biochemical content of algae and chemical conditions of their oil content can be influenced by changing cultivation conditions. Since they do not need herbicides and pesticides (Brennan and Owende 2010), algae appear to be a high potential feedstock for biofuel production that could potentially avoid the aforementioned problems. On the other hand, microalgae, as opposed to most plants, lack heavy supporting structures and anchorage organs which pose some technical limitations to their harvesting. The real advantage of microalgae over plants lies in their metabolic flexibility, which offers the possibility of modification of their biochemical pathways (e.g. towards protein, carbohydrate or oil synthesis) and cellular composition (Tredici 2010). Algae-based biofuels have an enormous market potential, can displace imports of fossil fuels from other countries (hence reduce a country's dependence), and is one of the new, sustainable technologies which can count on ever-increasing political and consumer support.

The reasons for investigating algae as a biofuel feedstock are strong but these reasons also apply to other products that can be produced from algae. There are many products in the agricultural, chemical or food industry that could be produced using more sustainable inputs and which can be produced locally with a lower impact on natural resources. Co-producing some of these products together with biofuels, can make the process economically viable, less dependent from imports and fossil fuels, locally self sufficient and expected to generate new jobs, with a positive effect on the overall sustainability (Mata, Martins et al. 2010).

A wave of renewed interest in algae cultivation has developed over the last few years. Scientific research, commercialization initiatives and media coverage have exploded since 2007. In most cases, the main driver of the interest in algae is its high potential as a renewable energy source, mainly algae-based biofuels (ABB) for the transport sector. In 2009 FAO published a report detailing various options for algae cultivation, multiple biofuels that can be produced and the environmental benefits and potential threats associated with ABB production. One of the main conclusions of this report is that the economic feasibility of producing a (single) low-price commodity like biofuels from algae is not realistic, at least in the short term.

This chapter summarizes some of the technology key findings of the aforementioned report and gives a brief overview of how algae can be cultivated and which biofuels can be produced. The following chapter investigates which other products can be produced from algae, and tries to asses the viability of co-production with bioenergy.

2.2 Cultivation systems for algae

Although not specific to biofuel production from algae, it is important to understand the basics of algae cultivation systems. Systems which use artificial light demand, per definition, more energy in lighting than what is gained as algal energy feedstock, hence only systems using natural light are considered in this document.

Seaweed has historically been harvested from natural populations or collected after washing up on shore. To a much lesser extent, a few microalgae have also been harvested from natural lakes by indigenous populations. Given that these practices are unlikely to sustain strong growth, only the cultivation of algae in man-made systems will be considered in this report. The main cultivation options are described in detail in

(FAO 2009a) and the main types are briefly presented below, since these have a significant different impact on the economics associated, the selection of the species, the technology requirements, etc.

A production system is geared towards a high yield per hectare because it reduces the relative costs for land, construction materials and some operation costs. It is not uncommon for published yield estimates to be too high, sometimes higher than theoretically possible[4]. These overestimations lead to unrealistic expectations. Realistic estimates for productivity are in the order of magnitude of 40-80 tons of dry matter per year per hectare, depending on the technology used and the location of production (Wijffels, Barbosa et al. 2010). This is still substantially higher than almost all agricultural crops. Surpassing yields of 80 tons per year per hectare will likely require genetically improved strains or other technologies able to counteract photosaturation and photoinibition (Tredici 2010).

2.2.1 Open cultivation systems

The main large-scale algae cultivation system is the so-called raceway pond. These are simple closed-loop channels in which the water is kept in motion by a paddle wheel. The channel is usually 20-30 cm deep and made of concrete or compacted earth, often lined with white plastic. It is designed for optimal light capture and low construction costs. The main land requirement is that of flat land.

Process control in such an open system is difficult since these are unstable ecosystems, temperature is dependent on the weather and, depending on climatic conditions, large amounts of water cyclically evaporate or are added by rainfall. Furthermore, the open character of the system makes it possible for naturally occurring algae or algae predators to infiltrate the system and compete with the algae species intended to be cultivated. Therefore a monoculture can only be maintained under extreme conditions, like high salinity (e.g. *Dunaliella)*, high pH (e.g. *Spirulina*) or high nitrogen (e.g. *Chlorella*) water. These conditions generally limit optimal growth and operate at a low algae concentration, making harvesting more difficult.

In conclusion, there is an important trade-off between a low price for the cultivation system and its production potential.

[4] It is important to point out that, conversely to what is sometimes stated, microalgal cultures are not superior to higher plants in terms of photosynthetic efficiency and productivity, as explained in Tredici (2010).

2.2.2 Closed cultivation systems

Many of the problems of open systems can be mitigated by building a closed system which is less influenced by the environment. Many configurations exist but all of them rely on the use of transparent plastic containers (usually tubes) through which the culture medium flows and in which the algae are exposed to light[5]. Such a system is clearly more expensive[6] and therefore capital intensive if produced on a large scale, but allows a wider number of species to be cultivated under ad-hoc conditions, normally with a higher concentration and productivity. On the other hand, these systems suffer from high energy expenditures for mixing and cooling than open ponds and are also technically more difficult to build and maintain.

Closed systems allow for the cultivation of algal species that cannot be grown in open ponds.

2.2.3 Sea-based cultivation systems

Whereas the previously described cultivation systems are almost exclusively used for microalgae, algae cultivation in the sea is the domain of seaweed. Seaweed cultivation, although very labour intensive near shore in shallow water and often at small-scale, is common practice in parts of Asia. To make an impact as bioenergy feedstock, seaweed should be produced in floating cultivation systems spanning hundreds of hectares. Most seaweeds require a substrate to hook to; which in practice means that the cultivation system must contain a network of ropes. The amount of construction material could be drastically reduced when free-floating seaweed (like some *Sargassum* species) is cultivated as just a structure to contain the colony would then be needed. Sea-based systems are less well developed than land based systems, although some R&D initiatives have been undertaken and are still ongoing. The system for seaweed cultivation in China has not changed much since it was invented in the 1950s, although options for modernization have been identified (Tseng 2004). Some countries, such as

[5] They can also be oriented to maximize light capture hence productivity per square meter of reactor, or to dilute light to maximize algae photosynthetic efficiency.

[6] In general, PBRs are much more expensive to build than ponds, but simple low-cost systems can also be designed. Tredici et al. have recently patented a panel reactor made of a disposable polyethylene film that costs approximately €5 per square meter (Tredici 2010).

Chile, are important seaweed producers, but rely completely on the harvesting of natural populations (Vásquez 2008).

2.3 Algae-based bioenergy products

There are a variety of ways to produce biofuel with algae. Figure 1 provides an overview of the options, which are explained in detail in FAO (2009a). In this section only the requirements of the algal biomass needed to produce various biofuels are briefly discussed in order to facilitate the selection of co-production options further in the report.

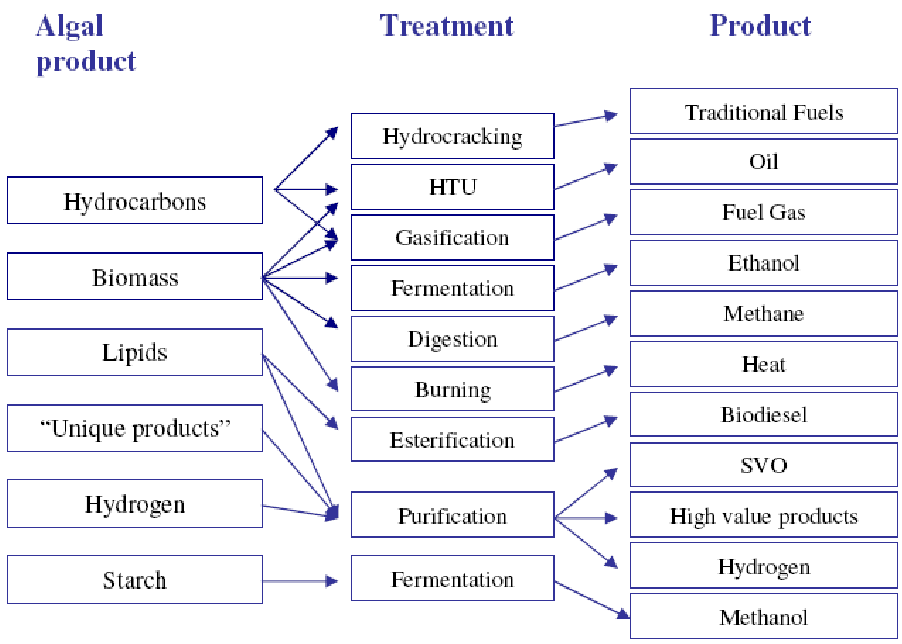


Figure 1: Overview of algae-to-energy options

2.3.1 Biodiesel

Biodiesel production from algal oils has received most attention since algae can contain potentially over 80% total lipids, (while rapeseed plants, for instance, contain about 6% lipids). Under normal growth conditions the lipid concentration is lower (<40%) and high oil content is always associated with very low yields. The various lipids production can be stimulated under stress conditions, e.g. insufficient nitrogen availability. Under such conditions, biomass production is not optimal though, reducing the non-lipid part of the biomass that can be further used as a source for co-products.

2.3.2 Hydrocarbons

One genus of algae, *Botryococcus*, does not produce the above-mentioned lipids, but longer chain hydrocarbons, which are not suitable for biodiesel production. Instead, they can be converted in a process similar to the production of conventional fuels from fossil oil. *Botryococcus* is a freshwater species but can also grow in saline water and it can produce certain carotenoids (Banerjee, Sharma et al. 2002). Its drawback is the relatively slow growth speed.

2.3.3 Ethanol

Ethanol is commonly produced from starch-containing feedstocks; some algae have been reported to contain over 50% of starch. Algal cell walls consist of polysaccharides which can be used as a feedstock in a process similar to cellulosic ethanol production, with the added advantage that algae rarely contain lignin and their polysaccharides, are generally more easily broken down than woody biomass. Co-products can potentially be derived from the non-carbohydrate part of the algal biomass.

2.3.4 Biogas

Anaerobic digestion converts organic material into biogas that contains about 60%-70% biomethane, while the rest is mainly CO_2, which can be fed back to the algae. A main advantage is that this process can use wet biomass, reducing the need for drying. Another advantage is that the nutrients contained in the digested biomass can be recovered from the liquid and solid phase.

Biogas as the main product is not economically viable[7], but this process can be applied to any left-over biomass after extraction of a co-product.

[7] Biogas production, as well as other conversion processes, is not viable to date because of the current high cost of the feedstock, although it is currently one of the cheapest biofuel that can be produced from biomass

2.3.5 Thermochemical treatment

The biological treatment of algal organic material has a non-biological counterpart, with the advantage that no live organisms are involved and therefore more varied and extreme process conditions can be used. The biomass undergoes a chemical conversion under high temperature and pressure conditions. Depending on the water content and how extreme these conditions are, the biomass carbon ends up in a raw gaseous, liquid or solid phase which can be upgraded for usage as a biofuel.

The energy input of this type of treatment is clearly higher compared to biogas production.

2.3.6 Hydrogen

Some algae can be manipulated into producing hydrogen gas. Currently the yield of this process is low and since energy is lost by the cells to form hydrogen, not much biomass is produced and therefore there is little potential for co-production.

2.3.7 Bioelectricity

Algal biomass can also be co-combusted in a power plant. For this, the biomass needs to be dried, which implies a significant amount of energy. This process is thus only interesting if the biomass is required to be dried in order to extract a certain co-product as a first step before being used as a biofuel.

3 Algae-based non-energy options

The number of products that can be made from algae is virtually unlimited, due to the large variety of species (possibly in the millions) whose composition can be influenced by changing the cultivation conditions. With only a few commercial algae-based products available, this resource is largely untapped. This is due to a range of reasons: poor marketing (Edwards 2008), the economic and bureaucratic barrier of getting new products approved by regulating authorities (especially for food) (Reith 2004), insufficient experience with algae production, and the commercial barrier due to lack of investments in large-scale production facilities.

The bulk of commercial products from algae are derived from seaweed, produced for food and alginates and partially harvested from natural populations, rather than cultivated. Commercial products from microalgae are largely limited to a few easily cultured species with proven market demand and market value, often as health food or feed in aquaculture. Table 1 shows the 7000 tons dry weight of total commercial microalgae production in 2004, adapted from Pulz and Gross (2004) in Brennan and Owende (2010). The total seaweed production in 2007 was 16 million tons fresh weight (FAO 2009b). The amount of commercially produced algae products is small if compared to the amount of known algal products, and more products are being discovered every day. A good example of this is shown in the annual reviews entitled “Marine natural products” by *Faulkner* and later by *Blunt et al.* Between (2000 and 2008): 7218 new marine products were reported, described in 6208 scientific articles. Note that not all these products come from algae (sponges are a very rich source as well). Well-known products and products from freshwater and brackish water algae are not included either.

Both commercial and yet-to-be-commercialized algal products can be interesting to co-produce with bioenergy.

Microalga	Annual production	Producer country	Application and product	Price
Spirulina	3000 tons dry weight	China, India, USA, Myianmar, Japan	Human nutrition	36 €/kg
			Animal nutrition	
			Cosmetics	
			Phycobiliproteins	11 €/mg
Chlorella	2000 tons dry weight	Taiwan, Germany, Japan	Human nutrition	36 €/kg
			Cosmetics	
			Aquaculture	50 €/L
Dunaliella salina	1200 tons dry weight	Australia, Israel, USA, Japan	Human nutrition	
			Cosmetics	
			β-carotene	215-2150 €/kg
Aphanizomenon flos-aquae	500 tons dry weight	USA	Human nutrition	
Haematococcus pluvialis	300 tons dry weight	USA, India, Israel	Aquaculture	50 €/L
			Astaxanthin	7150 €/kg
Crypthecodinium cohnii	240 tons DHA oil	USA	DHA oil	43 €/g
Shizochytrium	10 tons DHA oil	USA	DHA oil	43 €/g

Table 1: Commercially produced microalgae; amounts, locations, applications and market value (2004) (Brennan and Owende 2010)

Depending on the microalgae species, other compounds can also be extracted with several applications for many industrial sectors (biofuels, cosmetics, pharmaceuticals, nutrition and food additives, aquaculture, and pollution prevention): oil, fats, polyunsaturated fatty acids, natural dyes, pigments, antioxidants, sugar, high-value bioactive compounds, and other fine chemicals and biomass. (Mata, Martins et al. 2010).

3.1 Algae-based products for human consumption

Algae use as food has been cited in Chinese literature as early as 2500 years ago (Tseng 2004). Several parts of Asia are well known for consuming algae (mostly seaweed) directly and some indigenous people in Africa, South America and Mexico consume small quantities of naturally occurring algae mostly because of the vitamins and nutrients they provide (Edwards 2008).

Much less known to the general public is the variety of algae-derived ingredients that is used in food processing. Mostly as subordinate ingredients such as emulsifiers, thickeners, emollients (Edwards 2008), fats, polyunsaturated fatty acids, oil, natural dyes, sugars, pigments, antioxidants, bioactive compounds (Mata, Martins et al. 2010).

Microalgae for human nutrition are nowadays marketed in different forms such as tablets, capsules and liquids. They can also be incorporated into pastas, snack foods, candy bars or gums, and beverages, noodles, wine, beverages, breakfast cereals, nutrition bars, cookies (Lee 1997; Spolaore, Joannis-Cassan et al. 2006).

3.1.1 Staple food

Most algae cannot be used directly as a human food because the cell walls are not digestible. However, mechanical solutions, strain selection or bioengineering could overcome this problem. Digestible cell walls would potentially create the tipping point that enables algae to serve the world as food (Edwards 2008). Best known for large-scale consumption are the selected species of seaweed that are eaten in Asia (Moore 2001).

The cultivation and harvesting of this seaweed is a labor intensive process. The seaweed is dried and consumed completely, leaving no option for co-production.

Proteins are of major importance in human nutrition and the lack of them is one of the biggest factors in malnutrition. Some algae contain up to 60% protein. A well-known alga that is currently cultivated for its protein content is the cyanobacterium species *Athrospira*, better known as *Spirulina*. Consumption of *Spirulina* by the Aztecs during the sixteenth century in Mexico and by the Kanembo tribe at Lake Chad has been reported (Vonshak 1990).

Table 2 gives a comparison of nutritional values of some food products compared to *Spirulina* (dry matter) two decades ago in South India.

Food item	Protein content per 100 g (g)	Cost per 100 g of protein (Rs)	Comparative ratio of cost of protein with Spirulina	Comparative ratio of cost of lysine with Spirulina	Comparative ratio cost of cystine with Spirulina	Comparative ratio cost of tryptophan with Spirulina
Spirulina	66	1.38	1	1	1	1
Egg	13.2	11.20	8.23	5.10	5.11	3.82
Milk (100 ml)	3.3	15.15	10.97	6.19	11.98	6.62
Cluster beans	3.2	31.25	22.64	14.67	26.13	15.09
Eggplant	1.4	57.14	41.41	44.45	78.52	19.48
Carrot	0.9	88.88	64.41	10.10	28.90	14.13
Potato	1.6	62.50	45.28	26.56	95.97	7.55
Onion	1.20	66.66	48.30	46.30	96.66	13.88
Mutton	18.50	16.21	11.75	6.31	26.45	1.68

Notes: Only the cost of protein from consumed foods other than staple food is compared here. The costs per unit of vitamin A, nicotinic acid, riboflawin, thiamin, vitamin B12 and iron are cheaper in Spirulina than from other sources. The protein content of Spirulina is based on a dry weight whereas the protein content of other food sources is reported on a wet weight basis.

Table 2: *Spirulina* protein content compared with other staple foods in (vegetarian) South India, 1991 (Babu and Rajasekaran 1991)

The reason why *Spirulina* is the most cultivated microalga (see Table 1), besides its protein content, is that it is easy to cultivate as a monoculture. This is because it is one of the few species that grows at a high pH and is bigger than single cell algae[8] and easier to harvest. Following a resolution entitled "*Use of Spirulina to combat hunger and malnutrition and help achieve sustainable development*" by five developing countries at the UN General Assembly, the FAO published a comprehensive report on this microalga (Habib 2008). With reference to human consumption, it reports

[8] Spirulina is a prokaryote which can form multicellular groups.

numerous cases of beneficial health effects, although it also warns that some species may produce toxins of the microcystin group.

Spirulina is reported to contain not only around 60% raw protein, but also vitamins, minerals and many biologically active substances. Its cell wall consists of polysaccharides, has a digestibility of 86 percent, and can be easily absorbed by the human body (Becker 1994). In general, amounts for *Spirulina* consumption are around 15 grams per day, which is only a small part of the daily protein intake for adults.

As mentioned above, co-production for bioenergy purposes is not an option if the complete *Spirulina* cell mass is used as food. There are two main extracts from *Spirulina*: phycobiliproteins (a blue food dye) and a tasteless, odourless yellow-white protein extract that can have several food applications. The biomass remaining after extraction could be used for bioenergy or other products.

Spirulina is the main example of small-scale microalgae cultivation in various parts of the developing world. It also has applications in feed for livestock and aquaculture and as fertilizer, which will be reported on in the relevant sections of this chapter.

Other algae species are known to have high protein content as well (see Table 3), of a quality comparable with conventional protein sources. Despite its high protein content algae have not gained significant importance as food or food substitute yet. Strict approval regulations for new foodstuffs are a barrier, but also the lack of texture and consistency of the dried biomass, its dark green colour and its slight fishy smell are undesirable characteristics for the food industry (Becker 2007).

Alga	Protein	Carbohydrates	Lipids
Anabaena cylindrical	43-56	25-30	4-7
Aphanizomenon flos-aquae	62	23	3
Chlamydomonas rheinhardii	48	17	21
Chlorella pyrenoidosa	57	26	2
Chlorella vulgaris	51-58	12-17	14-22
Dunaliella salina	57	32	6
Euglena gracilis	39-61	14-18	14-20
Porphyridium cruentum	28-39	40-57	9-14
Scenedesmus obliquus	50-56	10-17	12-14
Spirogyra sp.	6-20	33-64	11-21
Arthrospira maxima	60-71	13-16	6-7
Spirulina platensis	46-63	8-14	4-9
Synechococcus sp.	63	15	11

Table 3: General composition of different algae (% of dry matter) (Becker 2007)

3.1.2 Health foods and pharmaceuticals

In addition to food, algae provide a wide variety of medicines, vitamins, vaccines, nutraceuticals and other nutrients that may be unavailable or too expensive to produce using plants or animals. Health food products currently dominate the microalgae market (Pulz and Gross 2004). A wide variety of algae and algal products have shown medical or nutritional applications. In Japan alone the 1996 consumption of health food from microalgae amounted to 2400 tons (Lee 1997).

Many of the algal applications in this section are highly technical or scientific. Since detailed analyses of all medical or biological effects are outside of the scope of this review, they are only given to illustrate the large variety of options and to refer the interested reader to more specialized literature.

Pigments

Microalgae contain a multitude of pigments associated with light incidence. Besides chlorophyll (the primary photosynthetic compound) the most relevant are phycobiliproteins (they improve the efficiency of light energy utilization) and carotenoids (they protect them against solar radiation and related effects). Carotenoids from microalgae have already many applications in the market: β-Carotene from *Dunaliella* in health food as a vitamin A precursor; Lutein, zeaxantin and canthaxantin for chicken skin coloration, or for pharmaceutical purposes and Astaxanthin from Haematococcus in aquaculture for providing the natural red colour of certain fish like salmon. Also the phycobiliproteins phycocyanin and phycoerythrin (that are unique to algae) are already being used for food and cosmetics applications (Pulz and Gross 2004).

The antioxidant functionality of carotenoids is of major importance for human consumption. Anti-oxidants function as free radical scavengers, which gives them an anti-cancer effect. Astaxanthin is known to be the most potent natural anti-oxidant. β-carotene is currently used in health foods as a vitamin A precursor and because of its anti-oxidant effect.

Many pigments from algae can also be used as natural food colorants, for instance in orange juice, chewing gum, ice sorbets, candies, soft drinks, dairy products and wasabi (Spolaore, Joannis-Cassan et al. 2006).

Polyunsaturated fatty acids (PUFAs)

PUFAs are important nutrients that must be supplied by external sources as they cannot be produced by the organism itself. Well-known PUFAs include n−3 fatty acids (commonly known as ω−3 fatty acids or omega-3 fatty acids) the most well-known source of PUFAs is fish oil. However, fish do not produce PUFAs but accumulate them by eating algae (or other algae-eating organisms). Algae are the true source of these essential nutrients. PUFA production from algae has been developed only in the last decade and has the advantages of lacking unpleasant fish odor, reduced risk of chemical contamination and better purification potential (Pulz and Gross 2004). PUFAs are known to play an important role in reducing cardiovascular diseases, obesity, in cellular and tissue metabolism, including the regulation of membrane’s fluidity, electron and oxygen transport, as well as thermal adaptation ability (Cardozo, Guaratini et al. 2007).

PUFA	Structure	Potential application	Microorganism producer
γ-Linolenic acid (GLA)	18:3 ω6, 9, 12	Infant formulas for full-term infants Nutritional supplements	Arthrospira
Arachidonic acid (AA)	20:4 ω6, 9, 12, 15	Infant formulas for full-term/preterm infants Nutritional supplements	Porphyridium
Eicosapentaenoic acid (EPA)	20:5 ω3, 6, 9, 12, 15	Nutritional supplements Aquaculture	Nannochloropsis, Phaeodactylum, Nitzchia
Docosahexaenoic acid (DHA)	20:6 ω3, 6, 9, 12, 15, 18	Infant formulas for full-term/preterm infants Nutritional supplements Aquaculture	Crypthecodinium, Schizochytrium

Table 4: The four most important PUFAs sourced from algae (Spolaore, Joannis-Cassan et al. 2006)

Some of the PUFAs are worth a particular attention:

- DHA is an omega-3 fatty acid present e.g. in the grey matter of the brain and in the retina, and is a major component of heart tissue. It has been shown to be important for cardiovascular health in adults and for brain and eye development in infants. DHA is found in a limited selection of foods such as fatty fish and organic meat and naturally present in breast milk, although absent in cow's milk. Since 1990, its inclusion in infant formula for pre-term and full term infants has been recommended by a number of health and nutrition organizations (Spolaore, Joannis-Cassan et al. 2006).
- EPA is normally esterified (by cyclo-oxygenase and lipo-oxygenase activities) to form complex lipid molecules and plays an important role in higher animals and humans as the precursor of a group of eicosanoids, hormone-like substances such as prostaglandins, thromboxanes and leukotrienes that are crucial in regulating developmental and regulatory physiology (Cardozo, Guaratini et al. 2007)

Other bioactive algal products

In *Chlorella* species, the most important compound from a medical point of view is β-1,3-glucan, an active immunostimulator, a free radical scavenger and a blood lipid reducer. Efficacy of this compound against gastric ulcers, wounds and constipation, preventive action against atherosclerosis and hypercholesterolemia, and antitumor action have also been reported (Spolaore, Joannis-Cassan et al. 2006).

Microalgae also represent a valuable source of almost all essential vitamins (e.g., A, B1, B2, B6, B12, C, E, nicotinate, biotin, folic acid and pantothenic acid) (Richmond 2004).

Furthermore, sulfated polysaccharides of microalgae can be used in anti-adhesive therapies against bacterial infections both in cold- and warm-blooded animals (Banerjee, Sharma et al. 2002).

The development of the cultivation of the alga *Caloglossa leprieurii* (Mont.) J. Ag., to produce an antihelmintic (a drug that expels parasitic worms) is needed (Tseng 2004).

3.1.3 Ingredients for processed foods

The most economically-valuable algae products are the macroalgal polysaccharides, like agar, alginates and carrageenans, especially due to their rheological gelling or thickening properties. An increase in research and development activities on microalgae, transgenic microalgae, protoplast fusion, or macroalgal cell cultures as biotechnological sources has been observed in the last years (Pulz and Gross 2004).

As previously mentioned, many pigments from algae can also be used as natural food colorants (Spolaore, Joannis-Cassan et al. 2006).

Agar

Agar is made from seaweed and is used in a wide range of applications: in food products (such as frozen foods, bakery icings, meringues, dessert gels, candies and fruit juices), industry uses (like paper sizing/coating, adhesives, textile printing/dyeing, castings, impressions), in biological culture media, in molecular biology (more specifically agarose, used for separation methods) and in the medical/pharmaceutical field (to produce bulking agents, laxatives, suppositories, capsules, tablets and anticoagulants) (Cardozo, Guaratini et al. 2007). When used in the EU, it is listed in the ingredients as E406.

Carrageenan

Carrageenan is a water soluble group of polysaccharides that are more widely used than agar as emulsifiers and stabilizers in numerous (especially milk-based) foods. κ- and ι-carrageenans are especially used in chocolate milk, ice cream, evaporated milk, puddings, jellies, jams, salad dressings, dessert gels, meat products and pet foods, due to their thickening and suspension properties. Several potential pharmaceutical uses of carragenans (like antitumor, antiviral, anticoagulant and immunomodulation activities) (Cardozo, Guaratini et al. 2007) have also been explored. When used in the EU, it is listed in the ingredients as E407.

Alginate

Alginate (or alginic acid) is produced by brown seaweed and is used in the textile industry for sizing cotton yarn. Its gelling capabilities make it of considerable technological importance. It is widely used in the food and pharmaceutical industries due to its chelating ability and its capability to form a highly viscous solution (Cardozo, Guaratini et al. 2007) When used in the EU, it is listed in the ingredients as E400 to E405, depending on the form of alginate.

3.2 Algae for livestock consumption

A biodiesel anecdote tells that, in the past, soy was cultivated for animal feed purposes due to its rich protein content. The oil was considered a waste product and discarded. Nowadays, the use of oil as a biodiesel feedstock is the main soybean product in many countries, while animal feed has become the by-product. Potentially, the opposite may occur for algae: biodiesel is currently the main focus for ABB, but the use of biomass as feedstock for animals after oil extraction also has an enormous market potential[9]. Most algae have a natural high protein content while a high oil content is mostly achieved

[9] To have an idea of the scale: all livestock in US consume about 300 million tons of protein/year Mayfield, S. (2008). Micro-algae as a platform for the production of therapeutic proteins and biofuels (presentation). Bundes-Algen-Stammtisch, 9-10 Oct 2008, Hamburg, Germany, Department of Cell Biology and The Skaggs Institute for Chemical Biology, The Scripps Research Institute.

though manipulation of cultivation conditions. If recent soy meal prices are taken as a reference, the value of algae after oil extraction would be at least €230/t (Steiner 2008).

The use of micro-algae as animal feed is relatively recent and predominantly aimed at poultry, mainly because it improves the color of the skin, shanks and egg yolks. Multiple nutritional and toxicological evaluations demonstrated the suitability of algae biomass as a valuable feed supplement or substitute for conventional protein sources (soybean meal, fish meal, rice bran, etc.) (Becker 2007).

Besides the use of algae as a protein source for livestock, many of the health benefits mentioned in section 3.1 also apply to animals (i.e. improved immune response, improved fertility, better weight control, healthier skin and a lustrous coat (Pulz and Gross 2004)) thus improving the product for subsequent human consumption of meat and milk. Adding algae to the diet of cows resulted in a lower natural breakdown of unsaturated fatty acids and a higher concentration of these beneficial compounds in meat and milk. Another important example is the feeding of poultry with algae rich in omega-3 fatty acids, which flows through the food chain, placing this cholesterol-lowering compound in eggs.

The use of algae in food for cats, dogs, aquarium fish, ornamental birds, horses, cows and breeding bulls has also been reported (Spolaore, Joannis-Cassan et al. 2006).

3.3 Algae for fish and shellfish consumption

Microalgae are essential during the processes of hatchery and nursery of bivalves, shrimp, and some finfish cultures. Microalgae are also used to produce zooplankton, typically rotifers, which are fed to the freshly hatched carnivorous fish (Benemann and Oswald 1996).

In 1999, the use of microalgae in aquaculture was reported to be divided as 62% for mollusks, 21% for shrimps, and 16% for fish. Like for humans and livestock, protein and PUFAs are of main importance. Algae are used fresh in fish cultivation, which is a big difference compared with other uses of microalgae. As production techniques advance, the trend is to avoid using live algae. The small scale of fish-feed algae cultivation is difficult, expensive and problematic to store. Alternatives have been developed, like preserved, microencapsulated and frozen algae, as well as a concentrated algae paste (Spolaore, Joannis-Cassan et al. 2006).

Wild salmon and trout acquire their characteristic red (muscle) color by eating algae with red pigments. Cultured species lack this color, resulting in a lower market value. This can be corrected by adding astaxanthin to fish feed. Astaxanthin is mostly produced synthetically, but there is a growing market for algae-based astaxanthin from *Haematococcos pluvialis.*

Abalone cultivation is a booming industry in Chile, requiring an estimated 100 tons of fresh seaweed for the production of each ton of abalone. The current harvesting of natural populations cannot support this, so the switch to cultivation has to be made. (Vásquez 2008)

Smith et al (2010) looked at ABB production from an ecologist point of view and mentioned herbivorous zooplankton (tiny microalgae-eating animals) as a major threat of invasion of the cultivation system, especially for open systems, which can have a strong negative effect on productivity. An example of a natural system is given: the introduction of zooplankton caused a more than 100 times decrease in algae concentration. The main option for controlling zooplankton is co-cultivating their predator: zooplankton-eating fish. This approach offers co-production during the cultivation phase rather than the processing phase.

3.4 Algae based non-food options

3.4.1 Chemical industry

The chemical industry is currently highly dependant on fossil oil, from which chemicals and transportation fuels are commonly co-produced. The chemical industry shows some important similarities to the combustion fuel industry, such as the low price of the fossil based feedstock and the primary interest into hydrocarbon parts of primary feedstock. Due to the specific processes in the chemical industry, it is currently generally not possible to use bio-based feedstocks in existing processes because of their higher cost. Novel bio-based processes require significant R&D and will initially focus on cheaper feedstocks than algae[10].

[10] Many developments exist yet, including large quantities of bio-based chemical already produced (capacity for 2009 is estimated to be over 5 Million tons). In some cases algae may already be competitive in specific applications like polyols and, possibly, 3GT, lactate acid, succinic acid and ascorbic acid (vitamin C)

Co-production of chemical products with bioenergy does not seem to have much potential yet at this stage. A more expectable pathway is the initial establishment of a biofuels' market, after which some of the algal bio-oil will be diverted into the chemical industry (Jensen 1993)

There are a few exceptions, mainly where big chemical companies like DuPont and DOW consider algae to produce some of the important small platform chemicals for their industry, like ethanol and butanol. Other projects, such as producing bio-plastics from algae (Cereplast) and paints (Algicoat), are in a very preliminary R&D stage.

3.4.2 Cosmetics

The use of some microalgal species, especially *Arthrospira* and *Chlorella,* is well established in the skin care market and some cosmeticians have even invested in their own microalgal production system (LVMH, Paris, France and Daniel Jouvance, Carnac, France). Their extracts are found in e.g. anti-aging cream, refreshing or regenerating care products, emollient and as an anti-irritant in peelers and also in sun protection and hair care products. Some of these products' properties based on algal extracts include: repairing the signs of early skin aging, exerting a skin tightening effect, preventing stria formation and stimulation of collagen synthesis in skin (Spolaore, Joannis-Cassan et al. 2006). In what lipid-based cosmetics (like creams or lotions) are concerned, ethanol or supercritical CO_2-extracts are gaining commercial importance and other lipid classes from microalgae, like glyco- and phospholipids, should not be neglected in future developments (Muller-Feuga, Le Guédes et al. 2003; Pulz and Gross 2004).

Due to the awareness that sun exposure is the main cause for of skin cancer and photoaging process, the consumption of sunscreen products has increased significantly in the last decades. The use of mycosporine-like amino acids as a highly efficient natural UV blocker in sunscreen is becoming commercially attractive (Cardozo, Guaratini et al. 2007)

3.4.3 Fertilizer

Historically, seaweed has been used as a fertilizer worldwide in coastal regions, mainly for its mineral content and to increase the water-binding capacity of the soil. Microalgal species that fix nitrogen are important, especially in rice cultivation. Both macro- and microalgae can contain compounds that promote germination, leaf or stem growth, flowering or can be used as a biological protection agent against plant diseases (Pulz and Gross 2004).

After the extraction of oil or carbohydrates from both seaweed and microalgae, most of the nutrients are still present in the left-over biomass. One potential market for this nutrient-rich biomass is as biofertilizer. Market volume is large while the market value is low. In many cases it might be more economic to extract these nutrients for reuse in algae cultivation.

Whether left-over biomass is used as fertilizer or algaculture nutrient source, anaerobic digestion is a valuable option. With this technology, the biomass doesn't need to be dried, but can be directly fed into the anaerobic digester where a large part of the remaining organic carbon is converted into biogas, while the nutrients are further concentrated in the liquid and solid output, so separated from the cell biomass, and easily concentrated.

Another option with significant sustainability benefits is the production of organic fertilizer. When applied in agriculture, the nutrients are released slowly which both benefits plant growth and reduces the microbial production of GHG emissions (Mulbry, Kondrad et al. 2008). More importantly, the production of chemical fertilizer is energy intensive with relative high greenhouse gases emissions. Given the expected increasing demand in fertilizers in the coming decades, the production of algae-based fertilizer shows potential to reduce the use of chemical fertilizer and hence alleviate their associated negative environmental impacts.

3.4.4 Fibres for paper

Most plant cell walls consist of cellulose, but in algae cell coverings are very diverse. Some algae species have intracellular walls, or scaly cell walls made of deposits of calcium carbonate or silica, but most algae derive structural strength from continuous sulphated polysaccharides in marine algae; other possibilities being cellulose, carrageenan, alginate and chitin (Okuda 2002).

Cellulose-containing algae can potentially be used as a renewable feedstock for paper production as the strong green colour of algae is more difficult to bleach than wood fibres but, although algae are generally known for their low cellulose and hemicellulose content, there are a few examples of research into the use of algae as a non-wood fibre source. Ververis *et al.* (2007) used a mix of algae taken from a municipal waste water treatment as 10% of the pulp mix, resulting in a significant increase in the mechanical paper strength and a decrease in paper brightness were reported, as well as a 45% lower material cost, which resulted in a 0.9-4.5% reduction in the final paper price. Hon-Nami *et al.* (1997) used a *Tetraselmis* strain as a 5-15% pulp additive, and found anti-print through, smoothness and tolerance for deterioration.

Using *Rhizoclonium* from brackish water in Taiwan containing 38-44% holocellulose, high pulp yields were found at short cooking times with a low chemical charge. The best result of pure algae-paper approached standard paper quality, showing lower bursting, tearing and folding strengths. Mixing with softwood pulp improved the paper to Kraft quality (Chao, Su et al. 1999; Chao, Su et al. 2000; 2005). This alga is filamentous (forms long threads) and is therefore much easier and cheaper to harvest than unicellular algae. Another benefit is the salt tolerance of *Rhizoclonium*, ranging from 1.0 to 3.3 % salt, with an optimum at 2.0% salt (seawater averages 3.4% salt). At this optimum, most naturally occurring freshwater algae will not be able to grow. *Chaetomorpha linum* and *C. melagonium* have similar cellulose contents (Chao, Su et al. 1999), while *Vaucheria* species can contain about 90% cellulose in their cell wall (Parker, Fogg et al. 1963) in (Okuda 2002).

Biologically different from algae and seaweed, but similar in cultivation and processing are certain aquatic plants. These may also have high productivities and may be grown on waste streams, and since they are closer to land plants, have high fibre contents.

Joedodibroto (1983) has investigated several aquatic plants (as shown in

Table 5) and concluded that all three weeds produced moderate quality paper pulp. Water hyacinth gave good folding and tearing resistance, but the processing of material from this plant was rather difficult. Other investigators reported that paper from 75% water hyacinth pulp and 25% bamboo pulp gave a high strength and also good greaseproof properties to the paper (Goswami and Saikia 1994).

	Cellulose	Lignin	Ash
Stem water hyacinth	58%	9%	22%
Leaf water hyacinth	49%	24%	15%
Torpedo grass	62%	21%	7%
Giant bulrush	62%	26	11%

Table 5: Cellulose content of aquatic plants (Joedodibroto, Widyanto et al. 1983)

There is some promising research on the utilisation of aquatic biomass for paper pulp, a development that deserves future attention, from economical, renewable and quality points of view. However this concept has not moved beyond the research stage yet and it is unclear when it will be commercialised.

4 Designing viable algal bioenergy co-production concepts

The previous chapters have shown the wide range of products that can be produced from algae despite the lack of experience and information on generating several products from one value chain.

Integrated food and energy systems are designed to integrate, intensify, and thus increase the simultaneous production of food and energy through sustainable land management[11]. The intensification of specific productions of energy and other co-products such as food, feed and biochemicals is achieved in two ways (Bogdanski and Dubois, 2010):

- *Multiple resource use through the diversification of land use and production*, i.e. by combining the production of food and fuel feedstock on the same land, through mixed cropping and/or agro-silvo-pastoral systems, or
- *Multiple resource use through the full utilization of products and by-products/residues,* i.e. multiple products (main products and by-products) are derived from a crop or from livestock. By feeding the by-products of one production stream into the next line of production, waste is eliminated. This leads to low- or zero-waste systems.

In the coming decades, the world population is expected to increase, resulting subsequently in a rising food demand on a planet of limited natural resources. In addition, energy demand is increasing and there is a challenge of climate change. Solving this problem cannot rely on just one solution and determination to tackle the problem with a mix of sustainable energy alternatives should persist. Solutions for alternative energy sources are required to enabling all humans to live sustainably. Theoretically, there is sufficient arable land to grow enough food for the increasing

[11] According to FAO, Sustainable Land Management is a combination of technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to manage land in a way that will simultaneously:

- maintain or enhance production/services
- reduce the level of production risk
- protect the potential of natural resources
- prevent the degradation of soils
- be economically viable, and socially acceptable.

population but it would be quite an achievement and a change from current circumstances if most agricultural land would be e would be used in a sustainable way. Moreover, there is increasing competition of land for other uses such as energy crop production, feed, fibre, fuel and urban infrastructure. Food should have the priority to uphold the human right to life.

The production cost of algal biomass, and consequently of algae-based biofuel or any other product, can only be determined by running a commercial scale production facility. Extrapolation from test scale or current operations is inaccurate and risky[12]. Furthermore, it is highly dependent on the technologies for cultivation, harvesting and processing, type and productivity of algal strain, prices of inputs like nutrients, CO_2, energy etc. While Pulz and Gross (2004) give an average market price of €250/kg algal biomass, other well-informed estimates range from €0.50/kg to €6/kg for large scale applications (Chynoweth 2002; Reith 2004; Barbosa 2007).

Identifying bioenergy co-production concepts is very challenging. However, an attempt to do so will be made in this section, first by determining which technical options exist, followed by a look at the economics of co-production of an algal product and bioenergy, and integrated multi-product and bio-refining concepts.

4.1 Technically feasible algal bioenergy co-production concepts

Among the algal products described in this review, several options for microalgae and seaweed make use of the entire biomass, for instance in sushi, health-food, cattle feed and feed for aquaculture. Clearly, if the entire biomass is consumed, there is no left-over for bioenergy production.

There is however the option to design cultivation systems that co-produce algae, seaweed, fish or shellfish, thereby providing possible feedstock for bioenergy.

Many of the algal products, especially those used for food, such as proteins, omega-3-fatty acids and some carbohydrates cannot be subjected to high temperatures, high or

[12] For instance, long-term photosynthetic efficiencies of 4-5 %, usually reported from test scale operations, are never reached with algal cultures under natural conditions (Tredici 2010). One of the most common errors is to use the same efficiencies registered in pilot plants for large scale productivity estimates.

low pH, toxic chemicals and/or high oxygen concentrations, as this would decrease their functionality. Usually these extreme conditions are used to speed up or improve the processing of algal biomass. If only mild conditions can be used, the preparation processes will be more difficult on a large scale, because they are slower and more expensive.

The use of different waste streams acting as a nutrient source for algae cultivation is clearly preferential over the use of expensive artificial fertilizers which require a lot of energy to produce. However, these waste streams most likely contain more contaminants than nutrients, which, can be reabsorbed by the algae, and in some cases reduce their growth. Most of the algal products are food or food-related, therefore cannot be contaminated by toxic compounds, while for biofuels this problem is less severe. Only certain wastewaters can be used and depending on the type of wastewater used, the algae product may require further purification in order to remove contaminants. This is the case for several algal products, independently of the nutrient source.

Another nutrient-related technical issue is the fact that optimizing the production of the desired compound(s) in algae is often dictated by available nutrients. Controlling nutrient concentrations is more difficult with waste streams than with artificial fertilizers.

If (part of) the nutrients in the harvested algae are recycled for reuse in algae cultivation, the risk exists that certain waste compounds are recycled too, leading to a toxic build-up in the cultivation system.

In recent years, several initiatives have been developed to guarantee the sustainability of bioenergy – and in particular that of liquid biofuels. For a biofuel to be accepted by the international sustainability criteria such as the UK Renewable Transport Fuel Obligation (RTFO), EU Renewable Energy Directive (RED), Roundtable of Sustainable Biofuels (RSB) and the USA Renewable Fuel Standard (RFS), it must be shown – amongst other criteria - that the biofuel requires less energy to be produced and/or its use releases less GHGs than conventional fuels.

When co-producing biofuel and other products, the energy and GHG balances have to be calculated including the co-products and subsequently spread over these, on the basis of the energy content of the final products. In general, co-production of biofuels would need little energy increase, since the algae need to be cultivated, harvested and processed in any case for other purposes.

However, this is not how GHG and energy emissions of biofuels are normally calculated. The total energy used in the process and therefore the associated GHGs are usually divided over the co-products based on their energy content (EC 2009). Calculated this way, the biofuel would account for the vast majority of the total GHG emissions in the chain. Since the total GHG emissions of a co-production system would be higher than a system only producing biofuel, this calculation method could penalize co-produced algae-based biofuel.

Life-cycle emissions of algae processing

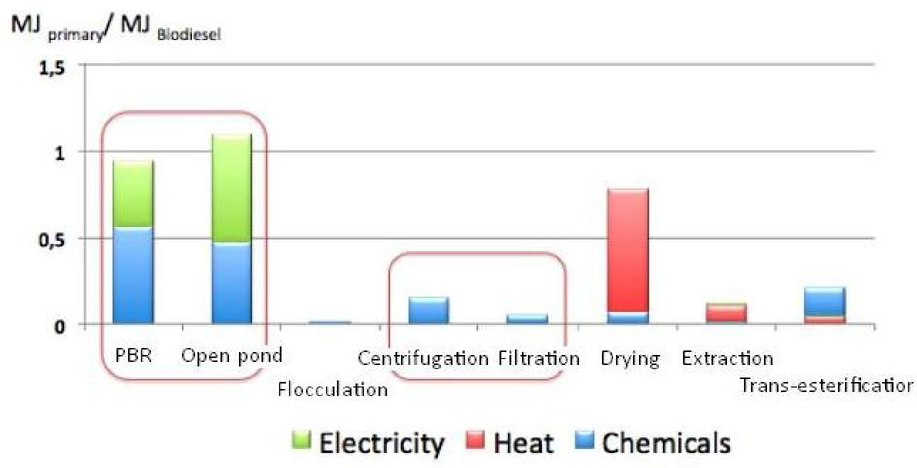
According to the IEA, the cultivation and the drying phase are extremely relevant when the production of algal biodiesel production is analyzed with respect to life-cycle emissions.

The cultivation is affected by the need to provide nutrients (chemicals) to the microalgae, and by the energy requirements and emissions related to their manufacturing.

Drying is characterized by high energy requirements. Specific GHG and pollutant emissions depend on the type of fuel used for the provision of the heat needed in the drying process.

The graph below shows the energy ratio (MJ of primary energy needed per MJ of biodiesel produced) for each step of the production chain of biodiesel from algae.

The first two bars show the energy ratio of growing microalgae in photobiorector (PBR) and in open ponds.



Source: Cazzolla (2009)

The problem arises when a producer of non-energy products from algae (e.g. nutraceuticals, pigments) decides to co-produce bioenergy (e.g. biogas from fermentation of processing residues). The co-production of biogas would require a minor increase of the total energy requirement. If the producer wants to use this biogas in the transport sector he has to comply with the minimum GHG reduction. In this case, since the co-products have a lower energy content than the biofuel produced, the application of the allocation method would show that the biofuel product is responsible for the vast majority of GHG emissions, whereas the additional biogas production actually only causes a minor increase in the overall energy consumption of the system. If the producer is not going to be able to use the biofuel for transportation he won't be motivated to shift towards integrated bioenergy production.

Therefore GHG emission allocation methods should be designed in a way that does discourage integrated bioenergy production.

4.2 Economic viability of bioenergy co-production from algae

Whether algae production is commercially viable or not depends on different factors. Because there are so many product options and production systems, the most interesting ones being just ideas that are still being developed, it is not possible to clearly determine the production cost of algae. However an attempt will be made to assess what the opportunities are.

4.2.1 Basic economic considerations of algae production

Algal productivity[13] has a strong influence on the economics of the process, as it determines how much product the cultivation system produces. If the market price of the product is known, the money available for producing the algae and extracting the products can be calculated.

Realistic estimates for dry microalgal biomass yield vary from 40 to 80 tons per year per hectare depending on the technology used and the location of production, despite common claims of higher yields (Wijffels, Barbosa et al. 2010).

The location of the production system is also of importance for the economics, as it determines the costs of land, labour, CO_2, nutrients supply and other factors that have a major influence on the process. For example there is a big seaweed industry in Chile

[13] It is important to point out that high grow rates are not necessarily associated with high productivity, which is what really matters (see Tredici 2010).

where the ocean borders the Atacama Desert, which allows for rapid solar drying and consequently a reduction in processing costs (Vásquez 2008).

Current microalgae production is based on relatively small systems, producing high-value products for special niche markets. Because of these high value products, the market price of microalgae is on the average €250/kg dry biomass (Pulz and Gross 2004), which is 1000 times too high for producing biofuel, if the algae have a 50% oil content[14]. Biomass prices between €0.5 and €5 /kg are regularly calculated for large systems. For biofuel, the technology needs to develop from a small scale activity to an industrial scale technology. During this development, production costs will decrease and, with every step in reduction, new markets will open. Most likely, initially the production of edible oils for food and fish feed will become economically viable and only later the production of bulk chemicals, biomaterials and biofuels can become feasible (Wijffels, Barbosa et al. 2010).

By assessing the viability of algae projects from a market perspective, it is clear that total installation, operation and maintenance costs will be a major barrier to future commercialization but technologies are being developed to further reduce costs and increase yields.

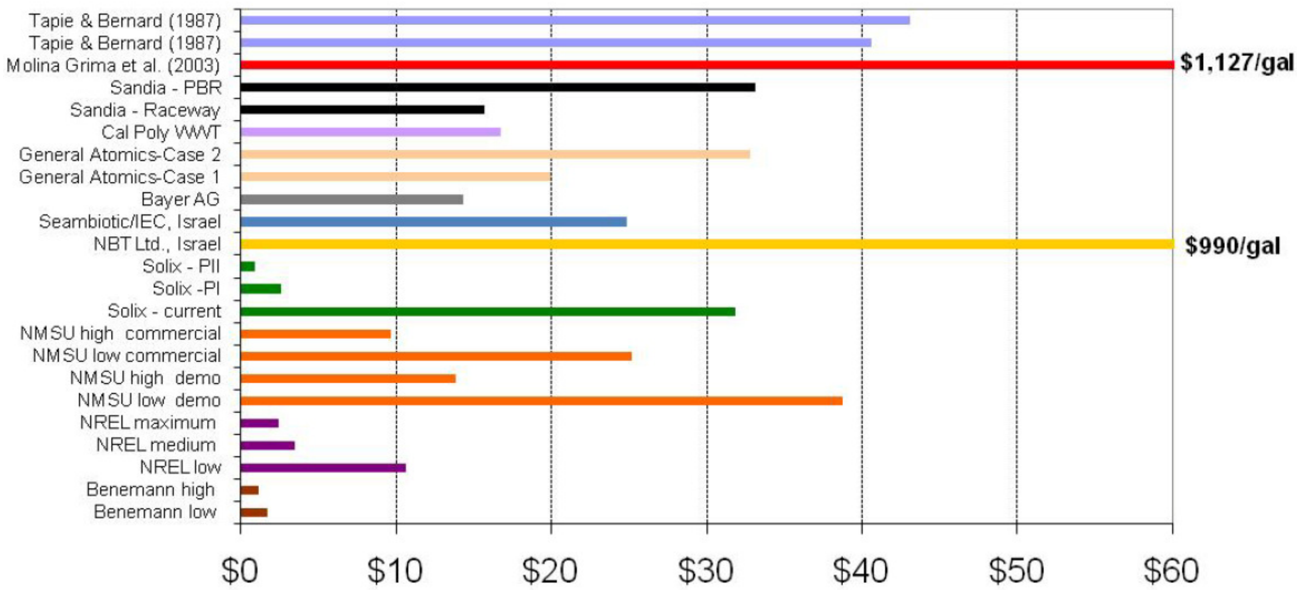


Figure 2: Production costs estimates for algal oil: trygliceride production costs in USD/gallon from different private companies and research centers (source: Philip T. Pienkos (NREL) – Algal biofuels: ponds and promises – presentation at the 13th Annual Symposium on Industrial and Fermentation Microbiology, 1 May 2009)

[14] Some algae have shown lipid contents of up to 85% of dry weight.

Today, after many years of R&D, there is not yet an algal strain or reactor or combination of both able to achieve large scale (hundreds of hectares) yields comparable to C4 plants (e.g. sugarcane) and no company has, at present, a mature technology to be on the market and compete with fossil fuels (Tredici 2010).

However, high yields and large scale production can only be successfully achieved through a comprehensive and well-funded RD&D programme which promotes business models that look not only at the potential of algae for energy production to displace the transportation fuels market, but also consider the cascading of algae chains with other higher-value products in order to make the economic viability achievable[15].

4.2.2 Product-specific co-production options and economics

As mentioned above, if the entire algal biomass is consumed as food or feed, no co-production options are available. Co-cultivation with different animals might be possible, but a large algae culture system can be expected to occasionally produce batches that are inferior to the quality standards, surpass the processing capacity or have other operational problems. This surplus biomass can be used for energy production using one of the technologies that can be applied to wet biomass. Anaerobic digestion appears to be a good candidate, as it is one of the cheapest bioenergy technologies, which can handle surplus algae and a variety of other organic wastes and can be kept dormant for extended periods of time. Depending on the type of algal product, other bioenergy options may apply as well, which will be discussed below.

Co-production with health foods and pharmaceuticals

Dry algal biomass contains only a few per cent of bioactive compounds, pigments, PUFAs etc. Their extraction typically requires drying and the breaking of cell walls. Subsequent use of this dry, disrupted biomass for bioenergy production appears relatively cheap and easy. The choice of the technology depends on the composition of the remaining biomass. High algal oil content is normally only achieved under very specific growth conditions, which are likely to differ from the optimal conditions for the primary high-value product. Furthermore, if the primary product is a lipid like PUFA, it will be removed from the oil content, leaving few opportunities for co-

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[15] See also: Dornburg et al., Cost and CO2-emission reduction of biomass cascading: methodological aspects and case study of SRF poplar, available at http://www.springerlink.com/content/r0661665336hq117/

producing biodiesel. Remaining polysaccharides and carbohydrates can be good feedstock for bioethanol production. An extra pre-treatment step will be needed for some, but not all algal compounds. Anaerobic digestion and thermochemical treatment can be applied even if the surplus biomass is not dry, although anaerobic digestion may be susceptible to toxicity of chemicals used in the extraction of the primary compound. If the surplus biomass is dry enough, it might be directly co-combusted in e.g. a power plant, but there is little or no experience with this process.

Products synthesized from microalgae

Product	Microalgae	Price (USD)	Producer
β-Carotene	Dunaliella	300-3000 /kg	AquaCarotene (Washington, USA)
			Cognis Nutrition & Health (Australia)
			Cyanotech (Hawaii, USA)
			Nikken Sohonsha Corporation (Japan)
			Tianjin Lantai Biotechnology (China)
			Parry Pharmaceuticals (India)
Astaxanthin	Haematococcus	10000 /kg	AlgaTechnologies (Israel)
			Bioreal (Hawaii, USA)
			Cyanotech (Hawaii, USA)
			Mera Pharmaceuticals (Hawaii, USA)
			Parry Pharmaceuticals (India)
Whole-cell dietary supplements	Spirulina	50 /kg	BlueBiotech International GmbH (Germany)
	Chlorella		Cyanotech (Hawaii, USA)
	Chlamydomonas		Earthrise Nutritionals (California, USA)
			Phycotransgenics (Ohio, USA)
Whole-cell aquaculture feed	Tetraselmis	70 /L	Aquatic Eco-Systems (Florida, USA)
	Nannochloropsis		BlueBiotech International GmbH (Germany)
	Isochrysis		Coastal BioMarine (Connecticut, USA)
	Nitzschia		Reed Mariculture (California, USA)
Polyunsaturated fatty acids	Crypthecodinium	60 /g	BlueBiotech International GmbH (Germany)
	Schizochytrium		Spectra Stable Isotopes (Maryland, USA)
			Martek Biosciences (Maryland, USA)

Product	Microalgae	Price (USD)	Producer
Heavy isotope labelled metabolites	N/A	1000-20000 /g	Spectra Stable Isotopes (Maryland, USA)
Phycoerythrin (fluorescent label)	Red Algae	15 /mg	BlueBiotech International GmbH (Germany)
	Cyanobacteria		Cyanotech (Hawaii, USA)
Anticancer drugs	N/A	N/A	PharmaMar (Spain)
Pharmaceutical proteins	Chlamydomonas	N/A	Rincon Pharmaceuticals (California, USA)
Biofuels	Botryococcus	N/A	Cellana (Hawaii, USA)
	Chlamydomonas		GreenFuel Technologies (Massachusetts, USA)
	Chlorella		LiveFuels, Inc. (California, USA)
	Dunaliella		PetroAlgae (Florida, USA)
	Neochloris		Sapphire Energy (California, USA)
			Solazyme, Inc. (California, USA)
			Solix Biofuels (Colorado, USA)

Table 6: Marktet values of some of the main algae based products (Rosenberg, Oyler et al. 2008)

The market value of different algal products differs greatly, as shown in Table 6 and Table 7. However the products with the highest value typically have the lowest market size. Therefore production of high-value products in niche markets is incompatible with that of biofuels, because the latter have a potentially much larger market (Wijffels, Barbosa et al. 2010). For example omega-3-fatty acids and other PUFAs have roughly a 10 times lower concentration in algae than lipids for biodiesel. Co-producing these two products at a scale to replace a few percent of the total diesel consumption would produce much more PUFAs than needed. This would make their price drop under economically feasible levels.

Microalgae potential markets

Applications	Price / Kg biomass	Market volume
Nutraceuticals (human consumption)	€ 100	€ 60 million
Nutraceuticals (animal and fish feed)	€ 5-20	€ 3-4 billion
Bulk chemicals	€ 1-5	> € 50 billion
Biofuels	< € 0.40	> € 1 trillion

Present market volume: € 1 billion

Segment: biomass process > € 50 / kg biomass

Objective: market segment < € 0.40 / kg biomass

Table 7: Prices and volumes of markets where algae can play a role (Wijffels 2008)

As mentioned earlier, if the whole-cell algal biomass is used as food or food ingredient, deriving another algal co-product is not possible. In the case of bioactive ingredients for health foods, pharmaceuticals etc, the interesting compound normally makes up a maximum of a few percent of the biomass, providing a variety of options for the co-production of bioenergy. This category contains many different compounds, some unique to algae, others currently artificially synthesised by chemical companies, or extracted from plant (products), and many more have been discovered but still need to be commercialised. In depth analysis of each individual compound is outside of the scope of this review. As an important example, the organic pigment group of carotenoids is used to demonstrate the relevant economic dynamics.

The potential use of algal pigments as natural food grade colorant in foods and cosmetics offers an interesting perspective of the reasonable color intensity and extensive practical applicability and the relatively high market price of relevant natural dyes for use in foods (€ 50 to € 1000 per kg pure material) (Reith 2004).

To be able to use extracted fatty acids and water-soluble pigments from algae biomass in food, mild ways of breaking the cell wall and extraction techniques based on the "food-grade" solvents ethanol and water are required. Subsequently the extracted products need to be stabilized for storage by concentrating them, using a carrier material and/or removing proteases and microbial contamination. Development on optimizing the separation and solvent recycling and fractionation of other complex materials at industrial scale is needed (Reith 2004).

Compound	Total market size (USD x 10^6 $year^{-1}$)	Volume of product (tons $year^{-1}$)	Microalgal part of volume (%)	Volume of microalgal product (tons $year^{-1}$)	Product prize Non-algal (USD/kg)	Product prize (algal product) (USD/kg)
Astaxanthin	250	100	~1	0.3 – 0.5	2000	> 6000
ß-Carotene	200	300	25[a]	60	600	>1200
lutein	25				30 - 800	
Lycopene	35				40- 400	
Notes:	a: based on an average ß-carotene content of 5 % dw.					

Table 8: Market sizes and prices of caotenoids and their algal share, kindly provided by Dr Niels-Henrik Norsker

Table 8 shows the current market data for several important carotenoids, two of which are currently partially produced from algae. Both these pigments have substantial existing markets. Note that the price of the algae-based product is several times higher than the non-algal product. The main reason is the general preference for natural products over the synthetic version.

The market for cartenoids is growing, but is not expected to increase dramatically (see Figure 2). If production costs can be reduced significantly, algae-based carotenoid production can be almost completely take over this market, but cost reduction will also be attempted for the current sources and potential new sources. If algae or any other source can significantly lower the current sales price, the consumption can be expected to strongly increase, because the lower price will allow its use in more products.

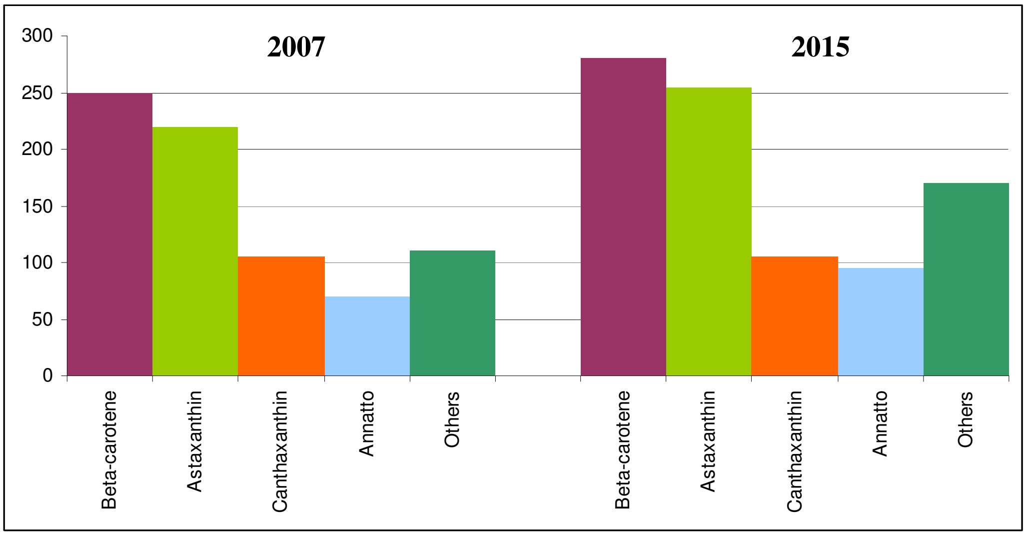


Figure 2: Global Carotenoid market and future outlook in millions of USD (BBC Research)

According to Brennan and Owende, (2010) the 2004 microalgae industry produced 7000 tons of dry matter per year, a significant part of which is used for complete-cell consumption (see Table 1). As an example, co-production of algae-based biodiesel, assuming this global microalgae production and containing a relatively high 40% oil content would yield 2.5 million liters of biodiesel, which is only about the amount of diesel consumed in one month in Spain[16]. To have a significant impact on the global fuel consumption, a production of three (or four) orders of magnitude is needed.

Therefore co-production, even if viable at the current scale, can not reach adequate scale of production. This means that algae-based biorefinery models could provide just a marginal amount of biofuel and, unless important cost reductions are achieved, the algal feedstock would not be economically viable without the revenues provided by the sale of the proteins and other co-products.

Algae-based non-food bulk products

According to the previous section, there is a strong potential for economically viable co-production of energy and high-value compounds, but the market size of the latter is much too low to achieve a substantial volume of biofuel co-production. Therefore, algal products in bulk-volume are needed for a large-scale co-production concept.

[16] Consumos de productos petrolíferos 2010, www.cores.es

If the algal biomass is used for the nutrition of humans or animals, its proteins will be of main interest, which, in most cultivated algae, commonly represent more than half of the dry biomass (see Table 3) The remaining biomass will consist of carbohydrates, (mainly cell walls and other membranes) and possibly lipids or carbohydrates for energy storage. Generally the lipid content will be too low for viable extraction for biodiesel production, as explained earlier. The carbohydrates may be a good source for bioethanol production, or else thermochemical treatment or anaerobic digestion can be used, depending on the toxicity and biodegradability of the remaining biomass. If recent soy meal prices are taken as a reference, the value of algae after oil extraction would be at least €230 /ton (Steiner 2008). The market size is very large, with US cattle alone consuming US about 300 million tons of protein/year (Mayfield 2008)

In the case of feedstock for the chemical industry, the production concept is still unclear, but most likely will be based mainly on the same carbon molecules the biofuel industry needs, therefore not open on the short term to combination with bioenergy production.

The option of algae-based paper production is still in the conceptual stage. The content of the waste stream after fiber extraction has not been reported, so energy co-production options are unclear. For the inverse process, after the extraction of valuable compounds and/or biofuel feedstock, the remaining biomass will most likely still contain the fibers, which could be channeled into paper production. The market value for these fibers is expected to be much lower than wood-based and wastepaper-based fibers, because of the strong coloration of algae fibers.

Algae cultivation requires nutrients. Supplying these (partially) from a waste stream (which can vary from a highly concentrated stream like manure or industrial waste to very dilute streams like effluent of a wastewater treatment plant that still contains some nutrients, of eutrophicated surface water) is not only cheaper than using artificial fertilizer, but it may be possible to generate additional income for the service of water purification and can significantly improve the economic viability of the algae feedstock production. However, chemicals and organisms present in this waste stream may be difficult to manage. Nutrients going into the system have to be separated. Unless the complete algal biomass is used as food or feed, these nutrients need to be disposed of properly. Waste treatment may be possible, recycling might be economically feasible in some cases, but as most algal applications extract the lipids and/or carbohydrates, the leftover biomass contains most of the nutrients, and can be applied as an organic fertilizer. This is not an energy co-product, but may displace the energy for production (and transport) of artificial fertilizer, while adding a revenue source.

Co-production from seaweed products

The production of seaweed and other aquatic plants reached to 16.0 million tons in 2007, of which aquaculture produced 14.9 million tons with a value of USD 7.5 billion. Another 1.1 million tons was harvested from wild populations. Apart from providing raw materials for industry, aquatic plants are an important food item, especially in Asia. (FAO 2009b)

Currently, seaweed that is commercially cultivated for food consumption doesn't allow co-production because the whole biomass is used for food and dietary supplements production, unless a cultivation system that co-cultivates seaweed with fish or shellfish can be devised. The same holds for the use of seaweed for abalone production.

The vast majority of seaweed production is directed to phycocolloid[17] production. Phycocolloids are extracted during a process that makes them soluble in water. The remaining biomass still contains significant amounts of carbon. One straightforward way to co-produce bioenergy is the anaerobic digestion of this left-over biomass. Kerner, Hanssen et al. (1991) have done this with the waste of alginate-extracted seaweed, and concluded that relatively high amounts of biogas containing around 60% methane can be obtained. Moreover, the waste was more easily separated from the water after this digestion step. They conclude that economic viability is likely (Kerner, Hanssen et al. 1991).

Bioenergy co-production options from seaweed appear limited, as the products available from seaweed are far less versatile and controllable than in microalgae.

Some bacteria have been reported to be able to produce alginate (Muller and Alegre 2007), but no microalgae have been found to produce significant amounts of this type of medium-value bulk product.

[17] These are also known as algal colloids. The three major phycocolloids are alginates, agars, and carrageenans.

4.3 Integrated and "biorefinery" concepts

Chapters 4.1 and 4.2 have focussed on co-producing one algal product and bioenergy, but concepts with a higher level of integration which make optimal use of multiple benefits that algae can provide can be envisaged. First, the example of a system is given that centres on bioenergy production from algae. A second concept includes livestock rearing. Lastly a true biorefinery concept in which the algal biomass is separated in multiple feedstocks for different industries is presented.

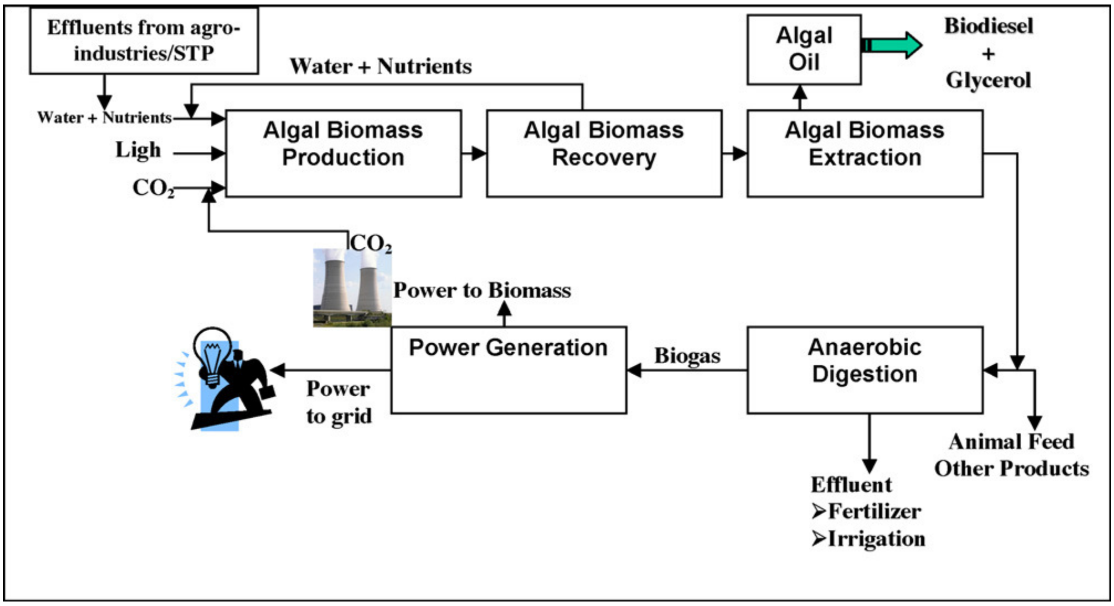


Figure 3: Integrated algal production concept with various co-products (Khan, Rashmi et al. 2009)

Figure 3 shows a concept with algae cultivation for biodiesel production if the left-over biomass after oil extraction can not be sold for high enough price (e.g. as animal feed) it is anaerobically digested to produce biogas. Combusting this biogas yields electricity and CO_2, which is again used for algae cultivation.

The "biorefinery concept" is a closed-loop system or zero-waste system transforming the by-products of one system into the feedstock of the other with the core set of characteristics common to other integrates food and energy systems (IFES). These are (Bogdanski and Dubois 2010):

(i) High productivity. The cultivation of biomass feedstock should be the first step of establishing IFES, which means basing the production on plants with high photosynthetic efficiencies.

(ii) Optimal use of biomass feedstock, based on the idea that nothing is considered 'waste.' By-products or leftovers from one process become the starting point for another in cycles that mimic natural ecosystems. This has some practical requirements, i.e. the cultivation of crops that are easily fractionated into food/feed components and fuel energy components; and the means for converting the fibrous elements into usable or saleable energy.

(iii) When possible, biomass and livestock integration. Bioenergy production from algae can reduce the environmental footprint of livestock through the multiple uses of animal feed.

(iv) Maximizing co-production by means of anaerobic digestion or gasification techniques, whose additional energy produced, will meet the energy demand of the production plant itself.

In order to assess the economic viability of the co-production of bioenergy and other products, Wijffels, Barbosa et al. (2010) have chosen a random combination of microalgal products that have a bulk-scale market, through biorefinery. Assuming 40% lipids, 50% proteins and 10% carbohydrates, a quarter op the lipids is sold to the food and chemical industry for €2/kg, the rest for biodiesel at €0.50/kg, soluble proteins (20%) for food at €5/kgm the rest (80%) for feed at €0.75/kg. The carbohydrates (sugars), used as chemical building blocks, at €1/kg. Furthermore, nitrogen removal is assumed, which conventionally costs €2/kg removed, and the oxygen that is produced during cultivation is captured and sold (to fish culture) at €0.16/kg oxygen. This biorefinery (see Figure 3) yields €1.65/kg algal biomass (not including costs for biorefinery), relying solely on products with a low market value but a very large market size. They conclude that this type of biorefinery is required to make algae-based biofuel economically viable, although the development of such an integrated concept will take many years (Wijffels, Barbosa et al. 2010).

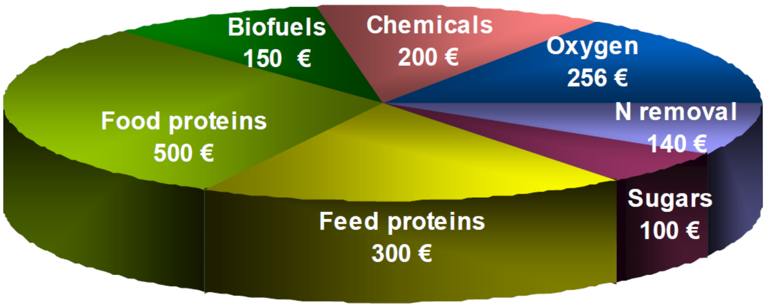


Figure 4: Market value distribution of 1000kg algae after biorefinery (Wijffels, Barbosa et al. 2010)

The Powerfarm! concept

Algae co-production can also be an integral part of a larger concept, such as the Powerfarm! concept (see Figure 5), in which animals are fed with conventional feed and the protein fraction of algae. The wastewater, CO_2 and heat from the stables are directed towards algae production. The manure is anaerobically digested to produce biogas, while the water fraction and minerals are recovered for use in algae cultivation. The biogas is combusted in a CHP plant, which delivers electricity, heat for algae processing and CO_2 and NOx for algae cultivation. The algae produce, besides the already mentioned animal feed, oil for biofuel and clean water (InnovatieNetwerk 2008).

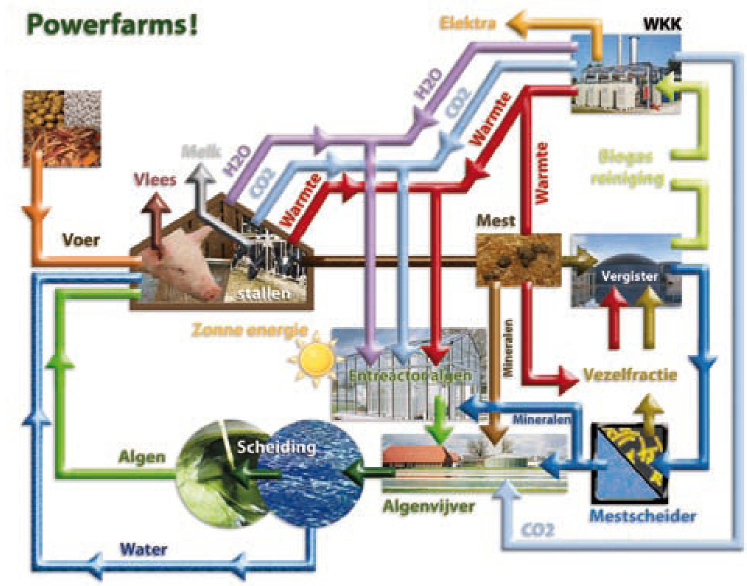


Figure 5: Schematic overview of the Powerfarm! concept (InnovatieNetwerk 2008)

5 Applicability of algae concepts in developing countries

Many countries – including a growing number of developing countries – are promoting biofuels for three main reasons: strategic concerns for energy security and energy prices, concerns for climate change, and agricultural support considerations (FAO 2008). These benefits are clear for developed countries, but are likely to have an even stronger impact if used in developing countries, especially among the rural poor. Algae (co-)production for bioenergy seems to have various benefits compared to the production of first generation biofuels from traditional food crops as soy or palm oil. The possibility of co-producing food and fuel from algae, self-sufficiency, combating hunger and malnutrition, reducing the negative health effects of using traditional biomass sources for cooking and heating can be added to the other advantages.

This chapter investigates to what extent these algae based concepts for bioenergy are applicable in developing countries. Due to the lack of practical experience with algae concepts, parallels are sought between ABB concepts and other biofuels or agricultural developments in general.

5.1 Technological feasibility of algae-based concepts in developing countries

The major challenge for solving world hunger is not production but fair distribution. If algae culture systems can be designed for small, medium and large scale production, many communities and villages throughout the world could produce their food and fuel locally on non-cropland (Edwards 2008). The potential for algae-based technology is clear, but their developing status also presents a number of barriers to be overcome.

Except for some existing commercial applications (most of which have been in existence for decades), algae technology is immature and, at least on the short term, will require investment and research and development. Developing countries are less likely to lead this research but may contribute to it. With the exception of countries like China and Brazil, the top ten largest economies are also the leaders of technology intensity;

economy, industrialisation and technological advance are interrelated. Partnerships between developed and developing countries could play an important role.

5.1.1 Commercial algae cultivation in developing countries

Besides the development of new algae concepts, making additions and innovations to existing algae production systems can be a viable pathway to co-producing energy. Therefore it is relevant to get an idea of existing algae operations in developing countries, and if any bioenergy research is done.

For microalgae, most commercial operations are located in China, Taiwan and India (Bunnag 2009). In 1997 there were around 110 commercial producers of microalgae in the Asia Pacific region, with capacities ranging from 3 to 500 tons /year (Lee 1997).

- In 1997, China counted 80 *Spirulina* producers, mostly for export, mainly located in the South, taking advantage of the long summer and warmer climate. A semi-closed culture system, where raceway culture ponds are covered by glass houses or transparent plastic sheets that allow year round production is most commonly used (Lee 1997). In 2004 about 50 producers were counted, producing about 1000 tons annually (Tseng 2004). China produces 8.000 – 10.000 tons of the seaweed based alginate annually, mainly for the textile industry. The industry started from natural resource but now relies completely on cultivation. Currently 11 seaweed species are cultivated in China (Tseng 2004).
- Taiwan produced over 50% of the world *Chlorella* production in the 1990s, mainly for export (Lee 1997).
- In Thailand, the KMUTT has been researching algae-based products for decades, with a focus on *Spirulina*. Recently research on algal oils has commenced at multiple universities, funded by the Petroleum Authority of Thailand (PTT). Thailand also has projects on wastewater treatment with algae, for instance wastewater from pig farming, tapioca, palm oil and tuna canning (Bunnag 2009). Thailand has significant *Spirulina* production for food and feed for decades (Lee 1997).
- In the Philippines, production of microalgal oil is being investigated at the University of the Philippines at Los Banos, funded by the Department of Science and Technology and the Philippine Council for Aquatic and Marine Resources (Bunnag 2009). Similar research investigations are also being

conducted by select private universities, notably by the Innovation Center of the Ateneo de Manila University. Microalgae are commonly produced in the Philippines as live food for shrimp larvae (Samonte, et al. 1993).

- Microalgal oil is researched at the Bogor Institute of Technology in Indonesia (Bunnag 2009). Indonesia developed significant *Chlorella* production in the middle of the1990s (Lee 1997).
- During the 1990s, 30 tons/year of *Spirulina* was harvested from volcanic lakes in Myanmar (Lee 1997).
- In Vietnam, 8 tons of *Spirulina* was produced during per eight month season in 1996 (Lee 1997).
- During the 1990s, most of the algae producers in Korea produced live algae for its aquaculture industry (Lee 1997). Renewable (including waste) energy, which constituted 2.3% of South Korea's total energy resources in 2006, will be required to reach 5% in 2011 and 9% in 2030. Biodiesel, which is currently only 1% of diesel oil consumed in South Korea, will be required to be 3% in 2012. Geographically, Korea, being surrounded by ocean waters on three sides, has a natural advantage for algae culture. There is a chance for Korea to advance algae-based biofuel technology. Specifically, industrialized Ulsan and Pusan, with their close proximity to the ocean, have the potential to be algal fuel hubs in Northeast Asia (Um and Kim 2009).
- For Central and South America, a big *Spirulina* facility closed in the early 1990s on Mexico. The product was reported to have worked with insect fragments, bird matter and rodent hair. *Spirulina* production in Chile and Cuba has been reported (Lee 1997). Chile is also an important seaweed producer harvesting of natural growth, but has no cultivation operations.
- South Africa also produces seaweed (Vásquez 2008).
- A USD1.7 million cultivation project is currently ongoing in Chad, funded by the European Union (EU), to produce high nutrition green cakes from *Spirulina*. The project is managed by the UN Food and Agriculture Organization (FAO). *In situ* production of Spirulina is seen as a possible cheap solution to malnutrition.

This list is by no means complete[18], but illustrates some important points: Firstly that algae cultivation is widespread, though with an apparent concentration in Asia. Furthermore, it demonstrates that the industry is mature. Also important to note is that, within the developing world, there appears to be more activity in countries that have a more developed economy. Finally, the potential for ABB has also been recognized in many developing countries.

Whether new concepts are initiated or existing production is elaborated with bioenergy co-production, the fact that experience with algae cultivation exists will benefit implementation.

5.1.2 Technological opportunities and threats for developing countries

Since most algae concepts are immature, most of the technological barriers are fundamental and of global relevance. However some of the socio-economic and geographical aspects present in developing countries lead to both opportunities and barriers.

Firstly, food security is of importance in developing countries, and algae concepts (co)producing food or feed provide the opportunities to tackle this. Furthermore, almost all developing countries are found at latitudes with high annual solar radiation, a key to a high productivity, and may also attract investments from richer foreign regions with less sunshine. Another attraction for investment is the lower wages in developing countries (this may also mean a lower average education level of the workforce) and lower costs for land and some required inputs and construction materials. However, some parts or materials may not be available locally and therefore require expensive imports.

Especially among the poor, the local market for (algae) products is based on the lowest possible price, whereas in developed countries a healthy or “green” product may be sold at a higher price. Also introducing and publicizing a new product is more difficult in developing countries. Independence of foreign oil/energy and energy access for the poor will greatly help both the economy and raising living standards. Furthermore,

[18] Further information about algal fuel producers are available at http://en.wikipedia.org/wiki/List_of_algal_fuel_producers

some of the negative impacts associated with plant-based biofuels in developing countries (e.g. sustainable land management) are avoided by using algae (FAO 2009a).

Scale of operations

The economics of algae-based biofuel production are often heavily dependant on the scale of operations. Through economies of scale, large-scale facilities can achieve a lower production price/kilogram biomass. In fact, Um and Kim (2009) state that the smallest practical size for an algal biodiesel plant is 1000 ha, which pumps about 1 billion litres of salt water a day.

For developing countries, two scenarios are foreseeable, one where these kinds of scales are achieved, and one where the concepts are reduced to the community level of the rural poor.

The large scale scenario requires large investment and market for inputs and outputs, as well as sufficient skilled personnel for construction, operation and management. This means such a concept will be more viable in an urban setting with substantial industrial development. Current commercial examples of algae cultivation in developing countries fit in this category.

Algae farming on a very large scale may result in alienation and lack of integration between the environment and people. These projects should be analyzed thoroughly for their possible environmental and social impacts. They risk forcing human populations into migration, and undervalue cultural and religious attachment to the land that contributes to well-being, destroys or disrupts entire ecosystems and their inhabitants and animals. If such large projects are envisioned, a strong effort needs to be made to integrate them into the existing ecosystem and social system (UNESCO 2009). The larger the system, the higher the risk if the technology doesn’t perform as expected. Obviously, these risks are common to large-scale land-based biofuel production as well. Note that positive impacts can be expected as well (e.g. employment creation), if projects are well designed.

For the one billion rural poor, small scale, community operated systems are much more appropriate. One consequence is that the initial investment costs will generally be a more significant barrier than in large industrial projects, where long-term profitability is pursued. Subsequently, the open pond systems are a more likely choice, as they are much cheaper to construct. Open systems limit the species available for cultivation. To obtain sufficient productivity, both nutrients and CO_2 are essential. Low cost nutrients will generally be available from waste streams, CO_2 supply may require nearby continuous (bio or fossil) fuel combustion, for instance, for energy generation. Furthermore, harvesting requires significant investment in technology, which can therefore be another crucial barrier. Two options to avoid the need for expensive harvesting technologies are (1) cultivating filamentous (thread-forming) species of algae like *Spirulina* or (2) feeding live algae to fish (or algae-eating organisms that serve as fish feed). Both concepts primarily provide a protein-rich food source. The most likely option for co-producing bioenergy in such a system is anaerobic digestion, which allows co-digestion of other organic waste streams, recycling of nutrients into the algae cultivation system and provides biogas, which can be used for cooking, heating and lighting or on a larger scale for electricity generation which feeds its CO_2 emissions into algaculture.

For small systems, it is possible to dry harvested algae naturally in the sun, while large operations will focus on using all available land to capture sunlight for algae cultivation. If oil-rich algae can be cultivated, the oil can be relatively easily extracted from the dry biomass using an oil press similar to the ones used in manual soybean oil extraction. The left-over biomass would make good animal feed.

The economics of small scale systems also benefit from reduced logistics cost. As an example, it was determined that for South African biodiesel plants, the increased cost of production due to higher capital cost per unit should be more than offset by savings in transportation cost (Amigun, Müller-Langer et al. 2008).

Potentials for algae production: limitations from water requirements

Water is a limited resource and a shortage of it can lead to heavy impact on well-being, possible forced migration and episodes of famine. Furthermore, climate change is likely to exacerbate existing issues.

As small scale systems will likely be open, shallow and located in sunny regions, a large amount of water will be lost through evaporation. This severely restricts the possibilities in arid regions, unless an alternative water source is available, but also regions with high annual rainfall may experience dry and wet seasons. Alternative water sources may be found, like wastewater streams from urban areas, or in some cases seawater or (saline) groundwater is available, but the cost of pumping the water to the cultivation system may be too high.

Due to the scarcity of freshwater reserves worldwide, and unsustainable use of freshwater aquifers, large operations should only consider the use of brackish water or seawater.

An illustrative example from the US Department of Energy calculates 60 – 454 trillion litres of saline water use per year to displace diesel use in the United States with algae diesel, depending on achievable productivity. Current saline aquifer extraction in the United States is approximately 83 trillion litres (for cooling power plants), while fresh water use for US corn cultivation is upwards of 15141 trillion litres per year (UNESCO 2009). So although water consumption for algal growth is substantial, it is still favourable compared with agricultural crop production.

Innovation and concept adaptation for developing countries

Many of the concepts for producing novel products from algae are not new. In fact, Bennemann et al (1987) presented Table 9, detailing the main microalgal products and their commercialization status. This status, over two decades later, has not changed substantially. Although every algal strain and every algal product has its own optimal cultivation conditions and cultivation system, a high degree of "spill-over" from one new commercial application to another is expected; if a low-cost working system for one product is developed, the adaptation for other algae-based products will be much easier than starting over from test-tube scale for each product. Additionally, such a system may produce the high-value compound as its main product, and co-produce bioenergy to reduce the GHG footprint of the main product or securing sufficient and low priced energy supply for internal use, instead of selling the bioenergy product to the market and operating the algae facility on fossil-based energy.

However, in recent years substantial private and public investments have been made and public money has been committed for algae R&D. The limited financial and technical resources in developing countries will prevent them from spearheading new developments. Intellectual property rights may inhibit technology transfer that would provide energy to the most vulnerable people.

Products	Uses	Approx. value	Approx. market[19]	Algal genus or type	Current product content	Reactor system or concept	Current status
Isotopic compounds	Medicine	>USD1000 /kg	Small	Many	>5%	Tubular, Indoors	Commercial
	Research						
Phycobili-proteins	Research	>$10000/kg	Small	Red	1-5%	Tubular, Indoors	Commercial
	Food color	>$100/kg	Small				Commercial
Pharmaceuticals	Anticancer	Unknown	Unknown	Blue-greens	0.1-1%	Tubolar, Fermentor	Research
	Antibiotics	(very high)	Unknown	Other			
β-Carotene	Food suppl.	>$500/kg	Small	Dunaliella	5%	Lined pond	Commercial
	Food color	$300/kg	Medium	Dunaliella			
Xanthophylls	Chicken feed	$200-500/kg	Medium	Greens, Diatoms, etc.	0.5%	Unlined pond	Research
Vitamins C&E	Vitamins	C: >$10/kg	Medium	Greens	<1%	Fermentor	Research
		E: >$50/kg	Medium	Greens		Fermentor	Research
Health foods	Supplements	$10-20/kg	Medium to large	Chlorella, Spirulina	100%	Lined pond	Commercial
Polysaccharides	Viscosifiers gums	$5-10/kg	Medium to large	Porphyridium, others	50%	Lined pond	Research
Bivalves feeds	Seed raising	$20-100/kg	Small	Diatoms	100%	Lined pond	Commercial
	aquaculture	$1-10/kg	Large	Chrysophytes			Research
Soil inoculum	Conditioner	>$100/kg	Unknown	Chlamydomona	100%	Indoor	Commercial
	Fertilisers		Unknown	N-fixing species		Lined pond	Research
Amino acids	Proline	$5-50/kg	Small	Chlorella	10%	Lined pond	Research
	Arginine	$50-100/kg	Small	Blue-greens	10%	Lined pond	Conceptual
	Aspartic acid	$2-5/kg	Large	Blue-greens	10%		
Single cell protein	Animal feeds	$0.3-0.5/kg	Very large	Green algae, others	100%	Unlined pond	Research
Veg and marine oils	Food, feed supplements	$0.4-0.6/kg	Very large	Greens	30%	Unlined	Research
		$3-30/kg	Small	Diatoms		Lined pond	

Table 9: Product market from microalgae in 1987

Small scale bioenergy co-production from algae has its unique benefits. For example, commercial algae-based biodiesel production requires degumming of the extracted oils, treatment of the unsaturated lipids and conversion into biodiesel, which is subject to multiple quality standard properties as shown in Table 10. All these requirements cause

[19] Market sizes: small, USD 1-10 million; medium, USD 10-100 million; large, more than USD 100 million

extra production and energy costs, as opposed to, small scale algal oil production which will be aimed at self-sufficiency or local use. The extracted oil can be used directly as fuel. Most systems for cooking, lighting and heating can be used; using this oil in engines requires adaptation and/or increased maintenance and cleaning.

Properties	Biodiesel from microalgae oil	Diesel oil	ASTM biodiesel standard
Density (kg/L)	0.864	0.838	0.84-0.90
Viscosity (mm^2/s, cSt at 40°C)	5.2	1.9-4.1	3.5-5.0
Flash point (°C)	115	75	min 100
Solidifying point (°C)	-12	-50 to 10	-
Cold filter plugging point (°C)	-11	-3.0 (max -6.7)	summer max 0 winter max -15
Acid value (mg KOH /g)	0.374	max 0.5	max 0.5
Heating value (MJ/kg)	41	40-45	-
H/C value	1.81	1.81	-

Table 10: Comparison of properties of microalgal oil, conventional diesel fuel, and ASTM[20] biodiesel standard (Bunnag 2009)

5.2 Economic aspects for developing countries

The economic viability of a system relying on algae as a feedstock is undoubtedly one of the most important criteria for successful deployment. Whereas in richer countries there may be financial support systems in place for more sustainable energy production,

[20] ASTM International is one of the largest voluntary standards development organizations in the world-a trusted source for technical standards for materials, products, systems, and services. Known for their high technical quality and market relevancy, ASTM International standards have an important role in the information infrastructure that guides design, manufacturing and trade in the global economy. For more information visit http://www.astm.org/

or a willingness to pay for "greener" products by end-users, in developing countries the concept should be able to compete with the prices of its conventional alternatives (which are sometime subsidised). Given that the exact configuration of algae concepts is unknown, a financial analysis is difficult to be made. However, the limitations set by economic viability should be further investigated.

5.2.1 Socio-economic aspects of ABB development

Looking only at biofuels from algae, it is commonly accepted that commercially viable production is still several years away, and including subsequent scale-up to the production of a significant part of the total fuel consumption will take at least ten years. As both public and private funds are limited, the choice will have to be made between investing in the development of ABB or other energy technologies. In general, a higher availability of funding increases the rate of development.

The availability of energy is of crucial importance to economic growth. In the coming decades, fossil fuel prices will most likely continue to increase, which impacts the rural poor through their use of fossil fuels for cooking, transportation, electricity, lighting, heating, petroleum-based fertilizers, and some agricultural products. A 74% increase in price overall household energy needs between 2002-2005 was reported (UNESCO 2009). Accessibility of energy is reduced at higher fuel prices. Forced decrease in energy use can result in cutbacks on many basic living comforts such as lighting and transportation, direct and indirect effects to health and education, population malnutrition and famine.

The private sector will only make big investments in ABB development if there is a good chance to profit from the investment. The profitability of investments will also partly depend on expected fossil fuel and carbon prices (which are expected to increase in the coming decades).

It is certainly plausible that ABB will become a successful technology, but of course there is no guarantee. Government funding is driven by the quest for the well-being of current and future generations. The spending of these funds needs to be balanced between energy supply and other social services, and also between the medium or long-term development of a more sustainable energy source like ABB or more short-term energy needs.

Over-investing and over-developing of new renewable energy source is likely to lead to inefficiencies due to poorly planned development, repetition of the same errors and future supply disruptions. Until now, investments in ABB research have been ad-hoc. Lack of communication, collaboration and information-sharing has lead to the inefficient use of capital due to overlap and duplication of research by independently funded working groups.

As for other renewable energy alternatives, under-investment leads to slower development which prolongs the dependence on fossil fuels, together with its multiple environmental and economical risks, that are costly to prevent or mitigate (UNESCO 2009).

These observations hold for both developed and developing nations, although the budget for public funding in developing countries is significantly lower. On a macro-scale, it is clear that significant investments are justified, but within certain economical limits. The main benefits of co-producing energy and other products from algae are improved economic feasibility and short-term gain in practical experience with algae cultivation and processing. Both of these will accelerate the development of the bioenergy from algae concept and attract more private funding.

5.2.2 Capital requirements of ABB co-production systems

Due to the absence of commercial (co-)production of biofuel from algae, we can draw upon analogous examples in developing countries. Amigun et al (2008) state that in developed countries, the feedstock for biodiesel consists of up to 85% of the production costs and the remaining 15% are due to "fixed" operating and capital costs. Therefore in order to be competitive, without governmental financial support or obligations, the cost of algal oil should not be higher than that of other vegetable raw oils, i.e. about 15% under the fossil fuel price. Government incentives are common practice in developed countries, aiming at energy security, environmental benefits and climate change mitigation and stimulation of the agricultural sector. Although more and more developing countries are announcing biofuel activities, many lack comprehensive policy that closes the price gap between fossil fuels and biofuel (Amigun, Müller-Langer et al. 2008).

In the future, higher production prices for fossil fuel are expected, but according to Duer (2010), this will not close the price gap between fossil and biofuel, because higher fossil fuel prices will most likely lead to higher biofuel feedstock production prices. Inclusion of the external costs of GHG emissions through a carbon credits system will help to decrease the price gap between fossil and biofuels, while at the same time stimulate biofuel with the highest GHG savings (Duer and Christensen 2010).

Algal oil will often require a more complex treatment than vegetable oils, causing slightly higher operating costs. Amigun et al (2008) state that the general consensus is that investment costs for a biodiesel plant will be higher in Africa than in Europe due to the additional cost of importation and other logistics such as market demands associated with it. They proceed by mentioning that capital expenses can be 15% lower in South Africa than in Germany because South Africa is technologically advanced and has a well-established infrastructure of engineering, industry, energy and R&D. These requirements are lacking in many other developing countries. Other factors impacting the economics are transport distances of feedstock and product, local utility prices (and if electricity supply is not very secure and consistent, auto-generation capacity needs to be installed), existing facilities for storage and distribution and access to ports for marine transport.

As previously stated, because algae use sunlight as their energy source, the potential yield is highest in warm countries close to the equator[21] as shown in Figure 6. Typically these high yield areas have also lower costs for land and labor. These factors dominate the cost of production and are commonly found in developing countries. They provide an economic advantage that is hard to match for countries in temperate regions[22] to match (Amigun, Müller-Langer et al. 2008). While this applies to fertile, tropical zones for plants, algae can be cultivated on even cheaper unfertile land in dry climate zones.

[21] It is interesting to note that, with few exceptions, the measured productivities of microalgal cultures are not higher than the short-term yields reported for C3 and C4 plants (Tredici 2010).

[22] As a comparison, *Nannochloropsis* sp. F&M-M24 has the potential for an annual oil production of 20 tons per hectare in the Mediterranean climate and of more than 30 tons per hectare in sunny tropical areas (Rodolfi et al. 2009). This is four-six times the productivity achievable by oil-palm in the tropics. However, this algae species is difficult to harvest and to extract oil from.

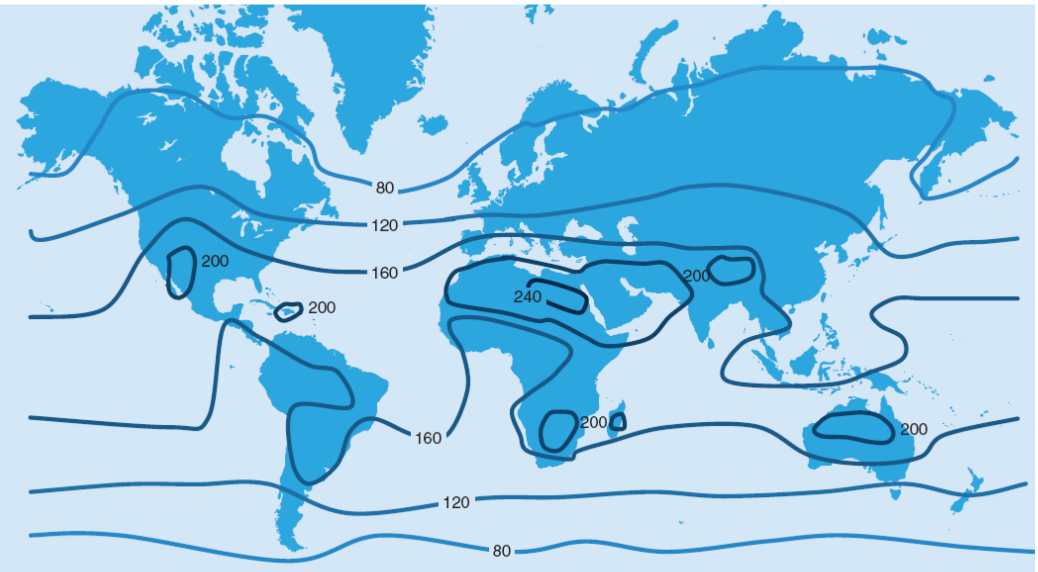


Figure 6: World map of algae biomass productivity (tons/ha/year) at 5% photosynthetic efficiency considering an energy content of 20 MJ/kg dry biomass (Tredici 2010)

5.2.3 Financial opportunities and threats for developing countries

Algae concepts are still under development in an attempt to reach commercial feasibility. Through innovation, technological improvements such as increased automation, genetically superior algae, higher oil yields, recycling of nutrients and water, and minimized light losses are to be expected, and co-production will improve the economics. However, main construction materials such as concrete, transparent plastic or glass and processing equipment are not expected to drop in price (UNESCO 2009).

A wide range of food and feed products can be co-produced from algae. Even though the urgency for these products is higher in developing countries, the market in developed countries for organic active ingredients from algae for food and clinical nutrition is undergoing strong growth. Introducing new products to the market is difficult because of costly, lengthy and complex approval procedures for new biologically active components (Reith 2004). On the one hand, this administrative barrier is expected to be more easily overcome in developing countries, on the other the absence of sufficient quality control can involve certain health hazards.

Under the Kyoto Protocol, projects which reduce greenhouse gas emissions, but are not economically viable, can break the economic barrier by qualifying as Clean Development Mechanism (CDM) projects. Each ton of emission savings by an algae concept generates additional income through the sale of Certified Emission Reductions (CER) (Khan, Rashmi et al. 2009). However the calculation method for algal CDM projects has not been developed yet. Since there are many different concepts possible and there is no international agreement yet if the CDM system will be extended beyond 2012, it is not sure that this will ever happen.

5.3 Environmental considerations for developing countries

For an algae concept to be successful, it has to be sustainable in addition to economically viable, or at least (significantly) more sustainable than its alternatives. While for developing countries the focus will lie on developing a concept that contributes to food and energy availability, environmental considerations should be kept in mind since the earliest development phases of a concept.

The high potential of algae to avoid some of the most pressing sustainability issues of biofuels derived from first generation agricultural crops is actually one of the key characteristics of algae concepts. Many of these benefits are mentioned earlier in this review, and all are thoroughly described in the previous FAO papers (FAO 2009a).

5.3.1 Sustainability requirements

Firstly, the deployment of algae co-production projects should consider and comply with the basic safeguards of biodiversity such as described in the international, legally binding Convention on Biological Diversity (CBD). It addresses strategies for sustainable use of biodiversity, meaning that human kind can use land (or water) and the ecosystems, flora and fauna it harbors, but in a way that prevents long-term damage. It is recognized that humans need to make use of ecosystems to provide in their wellbeing, but this is dependent on the availability and prosperity of natural resources. The CBD also included conservation biodiversity and fair use of its resources. It also contains a Biosafety Protocol, which has the objective to prevent that living microorganisms (like microalgae) modified though modern biotechnological methods become a threat to biodiversity.

More recently, sustainability in agriculture and aquaculture has been gaining importance, and, fueled by reports of negative side-effects of using food-crops for bioenergy production, sustainability criteria have been developed for biomass and bioenergy production. Almost all of these use (or consist entirely of) a certification system designed to guarantee that the product was produced in a sustainable way. Van Dam (2010) reports no less than 70 of such certification systems, all applying to biomass (including systems for agriculture and forestry)that can be used as a bioenergy source. All these certification systems have a different scope, e.g. internationally, nationally or state level, or address only certain feedstocks (like palm oil), only certain biofuels or only limited criteria (like only social, environmental), in various stages of implementation and some are voluntary, some binding. Although it is important to prepare these certification systems for the inclusion of (co-produced) algae based bioenergy, this is beyond the scope of the current review.

Below, some of the main documents prescribing sustainability criteria are introduced.

The Renewable Energy Directive (RED) sets targets for all European member states of the European Union on biofuels. It sets as mandatory target that 20% of the European energy consumption should come from renewable sources by 2020. For biofuels it includes the consideration of various social and environmental criteria. This includes a required GHG saving, excluding areas with high levels of carbon stocks or with a high level of biodiversity and good environmental management. A methodology to calculate GHG savings compared to fossil fuel is developed as well. Biofuels can only count for the national renewable energy target if a GHG saving of at least 35% needs is reached, which increases to 50% in 2017. This methodology is not sufficiently developed yet for algae and other next-generation biofuel sources.

The Renewable Fuel Standard version 2 (RFS2) is a USA-wide standard and part of the Energy Independence and Security Act of 2007. It sets both production targets and minimum GHG savings (including GHG emissions from indirect land use change) for different types of conventional and advanced biofuels, totaling 136 billion litres by 2022 and 17% reduction in total fuel emissions by 2020, 83% by 2050. As an advanced biofuel, algae based fuels could be part of this largo market.

Although these biofuel standards and legislations are mostly in place in developed countries as the EU and the US, biofuels imported from developing nations need to comply with them as well.

The Roundtable on Sustainable Biofuel (RSB) has developed global voluntary standards which cover all biofuels and a wide range of sustainability criteria, and are currently in a testing phase. It aims to facilitate the comprehensive, consistent, credible, transparent, effective and efficient implementation of RSB's principles and criteria, and RSB standards for production, processing, conversion, trade and use of biofuels (RSB 2010). As all biofuel sources are included, so are algae.

On the algae-specific level, the USA-based Algal Biomass Organization (ABO), the largest industry trade group, is developing the ABO Technical Standards, which will contain Standardized Descriptive language and Measurement Methods for algae producing operations (see Figure 7), later to be integrated with other existing standards. Life Cycle Analysis and GHG balance methods are part of the scope.

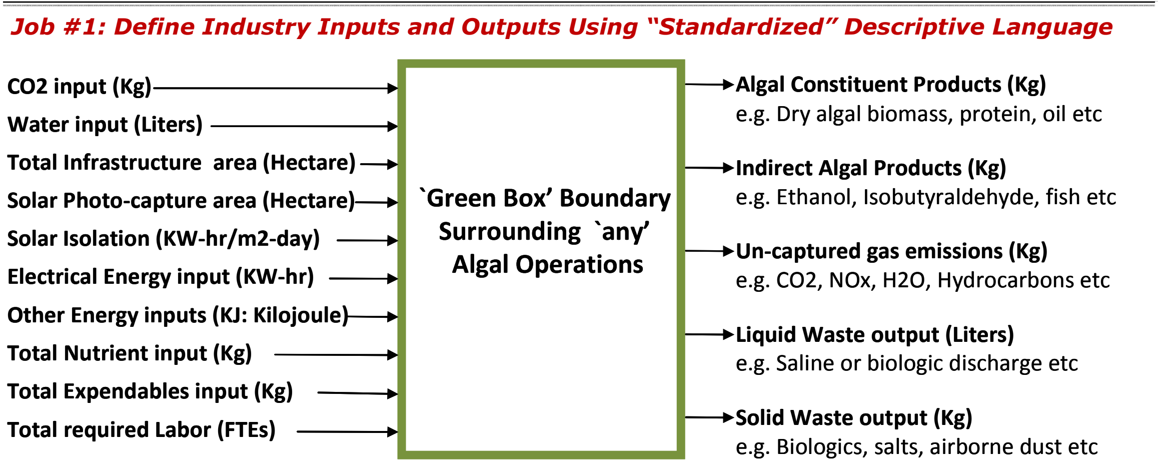


Figure 7: ABO Technical Standards Committee objective

It is worth noting that the majority of these initiatives, as also mentioned by Van Dam (van Dam 2010), are based on recognized international conventions. In all cases, these international conventions should be considered when developing algae based concepts for bioenergy production. Key international conventions are e.g. the Kyoto Protocol and the basic safeguards of biodiversity such as described in the international, legally binding Convention on Biological Diversity (CBD). It addresses strategies for sustainable use of biodiversity, meaning that human kind can use land (or water) and the ecosystems, flora and fauna it harbors, but in a way that prevents long-term damage. It is recognized that humans need to make use ecosystems to provide in their wellbeing, but this wellbeing is dependent on the availability and prosperity of natural resources. The CBD also included conservation biodiversity and fair use of its resources. It also contains a Biosafety Protocol, which has the objective to prevent that living microorganisms (like microalgae) that have been modified though modern biotechnological methods become a threat to biodiversity.

Note that impact studies on the sustainability performance of algae based bioenergy chains are still limited and more information is needed to gain more insight about the key sustainability concerns for algae based bioenergy chains, as developed in different geographical regions (dry or tropical areas, saline or fresh water) and under different management systems (large scale vs. small scale).

5.3.2 Relevance for climate change

Developing countries, and especially their poorest habitants, are the most vulnerable to the impacts of climate change. While they are not the decision-makers with power and impact to combat climate change, their health, food security, environmental security, provision of water resources, employment and incomes is at stake. If done correctly, algae co-production concepts can contribute to combating climate change, while mitigating part of its effects.

One of the most common criticisms on biofuels is that they do not necessarily reduce greenhouse gas emissions. It is true that the combustion of biofuels does not add any fossil carbon to the atmosphere, but greenhouse gasses are emitted during the production of biofuels. To assess the reduction of emissions compared to fossil fuels, a complete Life Cycle Analysis of the concept is necessary. This is widely available for first generation biofuels, and the biofuel standards mentioned above contain methodologies on how to perform LCAs on individual batches of biofuel. However, none of them include specific methodologies for algae concepts. Only a handful of algae scientific LCAs have been performed (Kadam 2002; Lardon, Helias et al. 2009; Sialve, Bernet et al. 2009; Clarens, Resurreccion et al. 2010).

Because there is a large variation in algae concepts, LCA methods and results will also vary widely. Co-production of biofuel and other products reduces the relative share of emissions that are attributive to the biofuel.

During the entire process of designing an algae concept, LCA can be an important tool to choose between different pathways, as each choice has a different impact on the total life cycle.

LCA is not restricted to comparing bioenergy with fossil energy, but should be applied to compare an algal product with its conventional counterpart(s), it they exist.

Algal biodiesel production integrated with heat and combined heat and power (CHP) production

The International Energy Agency (IEA) has identified a number of different pathways for biodiesel production and has estimated, for each of these, the energy balance (MJ of primary energy needed per MJ of biodiesel produced) and greenhouse gas (GHG) balance (CO_2 of GHG equivalent per MJ of biodiesel produced) that demonstrate how these improve if combined with heat generation or combined heat and power systems[23].

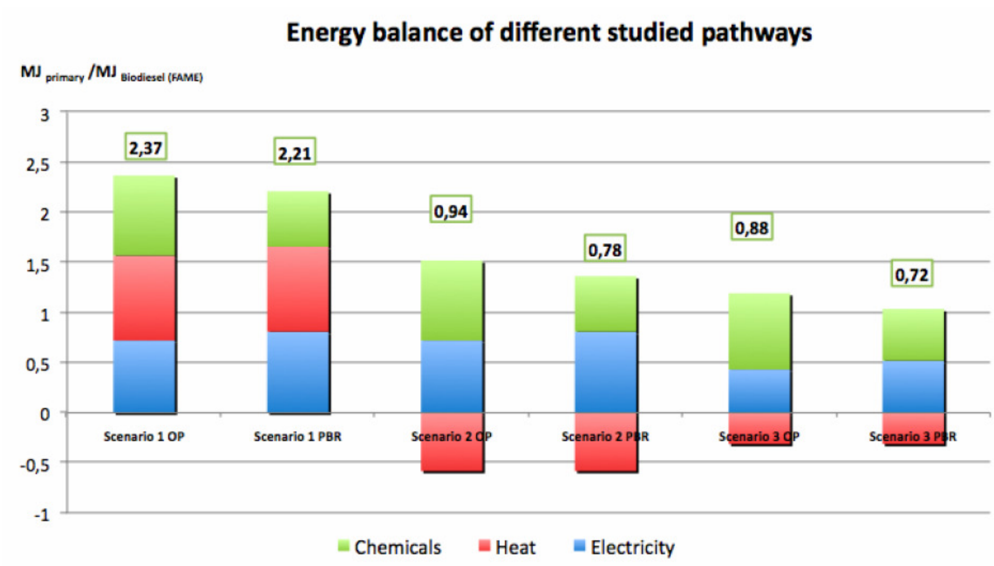
1. The "Base scenario" assumes the production of algal biodiesel with drying before extraction of oil. There is no use for residues of extraction and transesterification.

2. The "Dry Path" scenario assumes the production of algal biodiesel with drying before extraction of oil. There is burning of residues of extraction and the heat generated completely recovered.

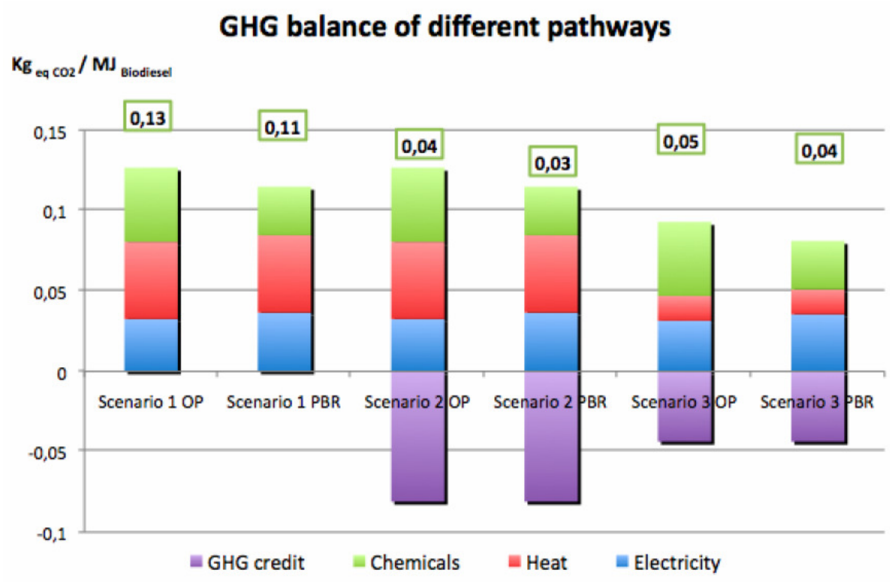
3. The "Wet Path" scenario assumes the production of algal biodiesel without drying before extraction of oil. Extraction residues are used for biogas generation via anaerobic digestion followed by heat and power generation via biogas-fuelled CHP, some nitrogen is recovered after anaerobic digestion and re-used for the cultivation phase, and burn of transesterification residues (i.e. glycerol) and the resulting heat recovered.

The assumptions in this study were:

- Algae biomass yield of 20 $g/m^2/day$
- Oil lipid content of 20 percent
- Lower heating value of algal biomass after extraction of 11,25 MJ/kg dry biomass
- The results are shown in the graphs below.



23 These are preliminary estimates and, given the uncertainties in the process, these values may change significantly.



Source: Cazzolla 2009

As a comparative value, a well-to wheel analysis of gasoline reports an energy balance in the range of 0.15-0.2 ($MJ_{required}$ / $MJ_{biofuel}$) and a GHG balance in the range of 0.08-0.084 ($kgCO_{2eq}$ / $MJ_{biofuel}$)

5.3.3 Making optimal use of unique algae characteristics

Algae have several characteristics that offer improvements in sustainability that are unique to this species in relation to other bio-based production systems, and should be used to their fullest potential

- Algae are grown in water containing systems, do not require fertile agricultural land thus cultivation systems can be located on marginal land. Protection of the ecosystem, soil integrity and alternative uses of these lands has to be balanced against the alternatives of algae-based production, which often will require existing agricultural land or the conversion of productive ecosystems. Furthermore, seaweed can be cultivated without the use of land, but also here the ecological impact should not be neglected.
- Algae can capture CO_2 from combustion gas; in fact CO_2 supply is essential for high productivity. Algae can even capture other pollutants from combustion gas, so whenever possible, algae cultivation should be co-located with CO_2 emitting industries.

- Many algae can be cultivated in saline water. Fresh water is the natural resource with the highest consumption, and increasingly scarce. Large scale concepts should only focus on salt water use, keeping in mind the disposal issues of wastewater and salts. Small scale concepts should only use fresh water on locations where availability and quality are not expected to be problematic in the foreseeable future.
- While dilute nutrient sources like wastewater or eutrophic surface water are not suitable for agriculture, algae can make efficient use of these sources, while providing the service of pollutant removal and/or nutrient recycling. Waste streams should be used as a nutrient source, without compromising the quality of the algae-based products, especially if they are used as food or feed.

6 Concluding remarks

While the technology for large scale algal biofuel production is not yet commercially viable, algal production systems may contribute to rural development, not only through their multiple environmental benefits but also through their contribution of diversification to integrated systems by efficiently co-producing energy with valuable nutrients, animal feed, fertilizers, biofuels and other products that can be customized on the basis of the local needs.

The non-fuel co-product options investigated in this review can technically be co-produced with some of the ABB options (usually in the form of health food).

From an economics perspective, there are many algal products with high market value, but their market volume is incompatible with the market volume of biofuels, preventing large scale use of the same co-production concept. More market compatible products are fertilizers, inputs for the chemical industry and alternative paper fiber sources. Current commercial production and harvesting of natural populations of both microalgae and seaweed predominantly take place in developing countries, indicating available experience, good environmental and economical conditions like sunshine and low labour costs. For poor rural communities, well designed small-scale IFES approaches are most suitable, potentially reducing ecological impact while providing fuel, animal feed, human protein supplements, wastewater treatment, fertilizer and possibly more products that generate additional income. Capital inputs have to be minimized for this group, which means that the cultivation system would most likely be the open raceway pond, constructed in an area with an easily accessible, sustainable water supply, or *in situ* collection of macroalgae. Large-scale industrial applications require a large amount of marginal, cheap but often ecologically valuable land and water sources. Further, capital input, immature technology, knowledge required for construction, operation and maintenance and the need for quality control are still barriers to integrated algae-based systems.

In developed countries, novel technologies are being developed to produce a wide range of novel foodstuffs and renewable non-food commodities from algae in a sustainable way.

Despite their high potential, both in terms of productivity and sustainability, most algae-based biofuel (ABB) concepts still require significant investments in R&D to become commercially viable.

7 References

Amigun, B., F. Müller-Langer, et al. (2008). "Predicting the costs of biodiesel production in Africa: learning from Germany." Energy for Sustainable Development **12**(1): 5-21.

Babu, S. C. and B. Rajasekaran (1991). "Biotechnology for Rural Nutrition - an Economic-Evaluation of Algal Protein Supplements in South-India." Food Policy **16**(5): 405-414.

Banerjee, A., R. Sharma, et al. (2002). "Botryococcus braunii: A renewable source of hydrocarbons and other chemicals." Critical Reviews in Biotechnology **22**(3): 245-279.

Barbosa, M. J. (2007). Personal communication on construction costs of a 100 ha tubular reactor plant.

Becker (1994). Microalgae: Biotechnology and Microbiology, Cambridge universitypress.

Becker, E. W. (2007). "Micro-algae as a source of protein." Biotechnology Advances **25**(2): 207-210.

Benemann, J. R. and W. J. Oswald (1996). Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass. Final report**:** Size: 214 p.

Benemann, J. R., D. M. Tillett, et al. (1987). "Microalgae Biotechnology." Trends in Biotechnology **5**(2): 47-53.

Blunt, J. W., B. R. Copp, et al. (2007). "Marine natural products." Natural Product Reports.

Bogdanski, A. and Dubois, O., (2010). Integrated food energy systems for climate-friendly sustainable agriculture – Overview and challenges. Paper at the European Biomass Conference, Lyon, April 2010.

Brennan, L. and P. Owende (2010). "Biofuels from microalgae-A review of technologies for production, processing, and extractions of biofuels and co-products." Renewable & Sustainable Energy Reviews **14**(2): 557-577.

Bunnag, B. (2009). Microalgae Research in Thailand and Southeast Asia. International Workshop Aquatic Biomass Sustainable Bioenergy from Algae November 2nd , 2009, Berlin.

Cardozo, K. H. M., T. Guaratini, et al. (2007). "Metabolites from algae with economical impact." Comparative Biochemistry and Physiology C-Toxicology & Pharmacology **146**(1-2): 60-78.

Cazzolla, P. 2009. Algae for biofuels production. Process description, life cycle assessment and some information on cost. Presentation at the IEA Bioenergy Executive Committee 64 on 1 October 2009, Liège, Belgium. IEA Secretariat

Chao, K. P., C. S. Chen, et al. (2005). "Aquacultural characteristics of Rhizoclonium riparium and an evaluation of its biomass growth potential." Journal of Applied Phycology **17**(1): 67-73.

Chao, K. P., Y. C. Su, et al. (1999). "Chemical composition and potential for utilization of the marine alga Rhizoclonium sp." Journal of Applied Phycology **11**(6): 525-533.

Chao, K. P., Y. C. Su, et al. (2000). "Feasibility of utilizing Rhizoclonium in pulping and papermaking." Journal of Applied Phycology **12**(1): 53-62.

Chynoweth, D. P. (2002). REVIEW OF BIOMETHANE FROM MARINE BIOMASS. Gainesville, Florida, USA, Department of Agricultural and Biological Engineering, University of Florida.

Clarens, A. F., E. P. Resurreccion, et al. (2010). "Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks." Environmental Science & Technology **44**(5): 1813-1819.

Duer, H. and P. O. Christensen (2010). "Socio-economic aspects of different biofuel development pathways." Biomass and Bioenergy **34**(2): 237-243.
Edwards, M. (2008). Green Algae Strategy - End Biowar I and Engineer Sustainable Food and Biofuels. Tempe, Arizona, USA, LuLu Press.
EC (2009). European Directive on the promotion of the use of energy from renewable sources. Brussels.
FAO (2009a). Algae-Based Biofuels - A Review of Challenges and Opportunities for Developing Countries. Roma, Italy.
FAO (2009b). Fishery and Aquaculture Statistics Yearbook 2007. Rome, Italy.
FAO (2008). The State of Food and Agriculture 2008 - Biofuels: prospects, risks and opportunities. Roma, Italy.
Faulkner, D. J. (2002). "Marine natural products." Natural Product Reports **19**(1): 1-48.
Goswami, T. and C. N. Saikia (1994). "Water Hyacinth - a Potential Source of Raw-Material for Greaseproof Paper." Bioresource Technology **50**(3): 235-238.
Habib, M. A. B. P., M.; Huntington, T.C.; Hasan, M.R. (2008). A review on culture, production and use of spirulina as food for humans and feeds for domestic animals and fish. FAO Fisheries and Aquaculture Circular. Rome, Italy, FAO**:** 33.
HonNami, K., A. Hirano, et al. (1997). "A new marine microalga cultivation in a tubular bioreactor and its utilization as an additive for paper surface improvements." Energy Conversion and Management **38**: S481-S486.
InnovatieNetwerk (2008). Powerfarms! Op weg naar een duurzame veehouderij, www.innovatienetwerk.org.
Jensen, A. (1993). "Present and Future-Needs for Algae and Algal Products." Hydrobiologia **261**: 15-23.
Joedodibroto, R., L. S. Widyanto, et al. (1983). "Potential Uses of Some Aquatic Weeds as Paper Pulp." Journal of Aquatic Plant Management **21**(JAN): 29-32.
Kadam, K. L. (2002). "Environmental implications of power generation via coal-microalgae cofiring." Energy **27**(10): 905-922.
Kerner, K. N., J. F. Hanssen, et al. (1991). "Anaerobic-Digestion of Waste Sludges from the Alginate Extraction Process." Bioresource Technology **37**(1): 17-24.
Khan, S. A., Rashmi, et al. (2009). "Prospects of biodiesel production from microalgae in India." Renewable & Sustainable Energy Reviews **13**(9): 2361-2372.
Lardon, L., A. Helias, et al. (2009). "Life-Cycle Assessment of Biodiesel Production from Microalgae." Environmental Science & Technology **43**(17): 6475-6481.
Lee, Y. K. (1997). "Commercial production of microalgae in the Asia-Pacific rim." Journal of Applied Phycology **9**(5): 403-411.
Mata, T. M., A. A. Martins, et al. (2010). "Microalgae for biodiesel production and other applications: A review." Renewable & Sustainable Energy Reviews **14**(1): 217-232.
Mayfield, S. (2008). Micro-algae as a platform for the production of therapeutic proteins and biofuels (presentation). Bundes-Algen-Stammtisch, 9-10 Oct 2008, Hamburg, Germany, Department of Cell Biology and The Skaggs Institute for Chemical Biology, The Scripps Research Institute.
Moore, A. (2001). "Blooming prospects? Humans have eaten seaweed for millennia; now microalgae are to be served up in a variety of novel health supplements, medicaments and preparations." Embo Reports **2**(6): 462-464.
Mulbry, W., S. Kondrad, et al. (2008). "Treatment of dairy and swine manure effluents using freshwater algae: fatty acid content and composition of algal biomass at different manure loading rates." Journal of Applied Phycology **20**(6): 1079-1085.
Muller-Feuga, A., R. Le Guédes, et al. (2003). "Benefits and limitations of modeling for optimization of Porphyridium cruentum cultures in an annular photobioreactor." Journal of Biotechnology **103**(2): 153-163.

Muller, J. M. and R. M. Alegre (2007). "Alginate production by Pseudomonas mendocina in a stirred draft fermenter." World Journal of Microbiology & Biotechnology **23**(5): 691-695.

Okuda, K. (2002). "Structure and phylogeny of cell coverings." Journal of Plant Research **115**(1120): 283-288.

Parker, B. C., G. E. Fogg, et al. (1963). "Studies of Structure and Chemical Composition of Cell Walls of Vaucheriaceae and Saprolegniaceae." Proceedings of the Royal Society of London Series B-Biological Sciences **158**(973): 435-&.

Pulz, O. and W. Gross (2004). "Valuable products from biotechnology of microalgae." Applied Microbiology and Biotechnology **65**(6): 635-648.

Reith, J. H. (2004). Duurzame co-productie van fijnchemicaliën en energie uit micro-algen : openbaar eindrapport E.E.T. project K99005/398510-1010. Petten, Energieonderzoek Centrum Nederland.

Richmond, A. (2004). Handbook of microalgal culture : biotechnology and applied phycology. Oxford [etc.], Blackwell science.

Rodolfi, L., Chini Zittelli, G., Bassi, N., Padovani, G., Biondi, N., Bonini, G., Tredici, M. R. (2009). "Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor". Biotechnology and Bioengineering.

Rosenberg, J. N., G. A. Oyler, et al. (2008). "A green light for engineered algae: redirecting metabolism to fuel a biotechnology revolution." Current Opinion in Biotechnology **19**(5): 430-436.

RSB (2010). Introduction to the RSB Certification Systems. Roundtable on Sustainable Biofuels. Lausanne.

Samonte, G. P. B., C. C. Espegadera, et al. (1993). "Economics of Microalgae (Chaetoceros-Calcitrans) Production Using the Multistep Method in the Philippines." Aquaculture **112**(1): 39-45.

Sialve, B., N. Bernet, et al. (2009). "Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable." Biotechnology Advances **27**(4): 409-416.

Smith, V. H., B. S. M. Sturm, et al. (2010). "The ecology of algal biodiesel production." Trends in Ecology & Evolution **25**(5): 301-309.

Spolaore, P., C. Joannis-Cassan, et al. (2006). "Commercial applications of microalgae." Journal of Bioscience and Bioengineering **101**(2): 87-96.

Steiner, U. (2008). Will Algae Biomass Production Ever be Commercially Viable? Bundes-Algen-Stammtisch, 9-10 Oct 2008, Hamburg, Germany.

Tredici, M. R. (2010). "Photobiology of microalgae mass cultures: understanding the tools for the next green revolution". Future Science.

Tseng, C. K. (2004). "The past, present and future of phycology in China." Hydrobiologia **512**(1-3): 11-20.

Um, B. H. and Y. S. Kim (2009). "Review: A chance for Korea to advance algal-biodiesel technology." Journal of Industrial and Engineering Chemistry **15**(1): 1-7.

UNESCO (2009). The Ethics of Adoption and Development of Algae-based Biofuels. L. McGraw. Bangkok, UNESCO**:** 83.

van Dam, J. (2010). Background document from: Dam et al (2010), from the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning, Journal of Renewable and Sustainable Energy Reviews (submitted). I. T. 40. http://www.bioenergytrade.org/downloads/overviewcertificationsystemsfinalapril2010.pdf

Vásquez, J. (2008). "Production, use and fate of Chilean brown seaweeds: re-sources for a sustainable fishery." Journal of Applied Phycology **20**(5): 457-467.

Ververis, C., K. Georghiou, et al. (2007). "Cellulose, hemicelluloses, lignin and ash content of some organic materials and their suitability for use as paper pulp supplements." Bioresource Technology **98**(2): 296-301.

Vonshak, A. (1990). "Recent advances in microalgal biotechnology." Biotechnology Advances **8**(4): 709-727.

Wijffels, R. H. (2008). "Potential of sponges and microalgae for marine biotechnology." Trends in Biotechnology **26**(1): 26-31.

Wijffels, R., H. , M. Barbosa, J. , et al. (2010). "Microalgae for the production of bulk chemicals and biofuels." Biofuels, Bioproducts and Biorefining **4**(3): 287-295

ANNEX: Algae concepts in practice

In recent years, many ideas for the deployment of algae-based technologies have evolved into practical projects. This chapter provides a collation of relevant case studies that illustrates the multiple applications and status of development of different concepts which make use of algae as a feedstock. Also some specific and simple technologies more suitable for the developing world are presented.

These are just a few examples of the many projects and ideas currently under development worldwide.

The information contained in this chapter has been provided by the project developers themselves and hasn't been proved by the FAO.

Algae Food & Fuel, The Netherlands

The project aims to grow algae on the waste streams of a biogas installation which powers a combined heat and power generator. The biogas system provides green electricity for LED illumination, heat, nutrients from digestate and CO_2 from the flue gas for algae cultivation. The algal biomass is primarily used for the extraction of algal oils for food and fuel applications, and utilisation of the non-oil biomass is anticipated.

Algae Food & Fuel is an initiative from BioSoil, Tendris and Solarix. These companies have a background in biological soil remediation, lighting innovations and biodiesel production. Combined, they provide a wide scope and diverse solutions. The first project is an algae production plant in Hallum, Fryslân, The Netherlands. Kelstein, a dairy farm and biogas company, owns the biogas installation which powers a combined heat and power generator that supplies. The results so far are successfully growing algae on the excess heat and flue gas. Current experiments use the digestate (after it passes a reverse osmosis step) as a nutrient source.

The 3 year, 3 million euro project is financed privately by the four partners above, except for 20% public funding by the Dutch Ministries of economic affairs and of agriculture.

The algal biomass contains approximately:

- 30 % raw Fat's (expected; 20 % PPO)

- 20 % proteins

- 30 % cell wall materials (sugar, cellulose based)

- 20 % ash, vitamins and minerals

Besides algal oil production, co-production of (refined) algae materials as feed for animal and fish industries, fine chemicals for chemical industry are considered. Some components can be interesting for health, cosmetic's or pharmaceutical purposes. A preliminary estimation of the income of the algal products is 60% derived from algal oil, 40% from other products.

The pilot facility at the dairy farm in Hallum Friesland consists of four 20 m3 photobioreactors. The unique combination of submerged LED illumination in conventional horticultural water basins creates a very efficient algae production system with low areal footprint in relation to productivity.

The pilot plant runs currently four reactors in chemostat or turbidostat mode for continuous production and to fullfill some criteria for convenience of research. The reactors have a volume of 20 m^3, and a depth of 2 m, and are connected to spargers with gas supply and horticultural pumps for dosing nutrients and trace elements, compressors for CO_2, pumps to mix and transport, centrifuges for harvesting biomass and a drying system for harvested biomass. In the pilot project an anaerobic digester with biogas driven combined heat/power generator supplies the CO_2, 2nd best would be a (municipal) water treatment system with anaerobic digester to treat sludge and get energy from the sludge. The goal is a closed carbon cycle for a dairy farm with an acceptable energy balance and economical viability. The system can be adapted to sweet water, brackish water or seawater, depending on the algae species, wild algae can be selected for any type of water. The nutrient source will be digestate treated to retain high nutrient concentration and transparent for light all optimised to sustain fast growth of algae. Future goals are to set up a productive algae biomass production system that can be run at farmsites, find and commit the market partners for algae biomass. Planned expansion of operation to four 200 m^3 scale systems on the drawing board for 2010. Currently several other algae based projects are in development but operational status is lower compared to the pilot plant.

The level of technological skills required to operate algae farms of significant scale could be a barrier to implementation of the concept in developing countries. Other, internationally present, barriers are that the rules considering the production of raw material, downstream processing and application field are a complication to market penetration.

Algae to Biofuel, United States

The Center of Excellence for Hazardous Materials Management (CEHMM)[24] has been cultivating and harvesting a (proprietary) marine alga from outdoor raceway ponds in south-eastern New Mexico in the United States. The minimum annual operating budget is approximately two million dollars.

Experimentation with a variety of algae species has been underway since June 2006 with construction of the first one-eighth acre outdoor raceway pond in 2007. Currently CEHMM has three outdoor raceways with approximately 416,395 litres maximum capacity. The New Mexico Environment Department has granted permission to construct additional twenty one-quarter acre ponds proximal to the current three. They collaborate with U.S. national laboratories and a variety of universities both within and outside New Mexico. The experimental extraction unit is provided by Solution Recovery Services (SRS, Inc.) out of Dexter, Michigan. They affirm to have the first vertically integrated pilot plant to grow and harvest algae and extract oil all in one location, with the aim of using this paradigm to build a commercial facility.

A suite of nutrients are provided at propitious times. The timing of nutrient delivery has been honed over the course of nearly three years of experimentation. The carbon dioxide source is atmospheric and any required supplemental carbon comes through other (proprietary) sources.

Several harvesting techniques have been attempted with effluent water recycled to source ponds. Currently centrifugation is the technique of choice, but additional experimentation continues with flocculants. During the summer, CEHMM harvests every day from nearly all the ponds. During the winter months, the rate of harvest decreases due to inclement weather and cold temperatures. CEHMM algae has been successfully grown and harvested year-round.

The intended co-products include human and livestock food products, neutraceuticals, and an array of chemical compounds used in such industries as cosmetics. Our extraction process is wet so there is no energy expended to dry algal biomass. De-lipified biomass is solar dried for use as food products, such as animal (livestock) feed. The estimated market value for chemical co-products include USD8.87 for 25,000 international units or 1500 micrograms for beta carotene, USD40.00/pound for essential amino acids (EAA), USD367/pound for eicosapentaenoic acid (EPA), which is part of omega 3, USD45,450/pound of decosahexaenoic acid (DHA), also a part of omega 3 and omega 3 itself for an estimated USD3,272/pound.

Currently CEHMM's focus is on conversion of algae oil to transportation fuel but plans exist to examine other fuel profiles and co-products (e.g., bioplastics) as well.

An environment with ample sunshine, generally warm temperatures, an area of little topographic relief and access to both fresh and saline waters is ideal. The desert southwest, including all of southern New Mexico and West Texas in particular, is a particularly hot, dry region with large tracts of land that are non- arable. The fact that algae do not compete with commercial agriculture and produce high quantities of lipid which in turn can be extracted and converted into transportation fuels and high value products makes this renewable energy source ideal. The application of the CEHMM model can be translated to alternate sites such as tropical climates.

To date, a significant part of private, state and federal investments has focused on companies that experiment predominantly in research laboratories working to develop genetically modified organisms (GMOs). There is considerable controversy about the use of GMOs in an open environment. CEHMM has chosen to use a wild strain which is safe to grow in open ponds and poses no threat to the peripheral environment.

CEHMM is planning to build a large facility. Much of the electricity requirements for a commercial facility will be provided through either solar or wind energy. A techno-economic model has been developed that suggests the approach could be successful at a commercial scale.

First oil from algae at the CEHMM Artesia algae plant and a quarter-acre pond with extraction facilities in the background

AlgaFuel, Portugal

AlgaFuel´s Secil project is an advanced prototype study which uses microalgae to capture the combustion gases from a Cement Plant. The project consists of the development and implementation of a Prototype Unit for CO_2 mitigation.

Tubular photobioreactors (left) and green wall panels (right)

The main differentiation and innovation of the AlgaFuel Prototype Unit consists of the development and selection of a technology for CO_2 fixation adapted to the specific conditions of the cement plant. The implementation of the Prototype Unit in a Cement Plant was preceded by a period of 12 months to develop several studies, fieldwork and laboratory activities, aiming to characterize the local conditions, namely a phycological study for characterization of the local microalgae, physico-chemical evaluation of the plant's water supply and flue gas analysis, and preliminary testing for flue gas use as microalgae carbon source. The results were crucial for the selection of the appropriate species to produce at this particular site.

The cultivation system implemented in the Prototype Unit operates in a semi-continuous and semi-automatic way and uses two distinct technologies: Tubular photobioreactors and Green Wall panels. The Prototype Unit established at the Secil cement company occupies an area of 1500 m^2.

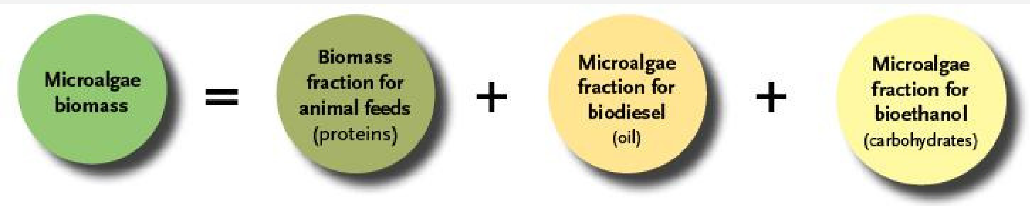
The cost of a Microalgae Production Unit Prototype can change significantly depending on the local conditions and the amount and type of experimental assays to be conducted in a Prototype Unit. As an estimate the investment required for such a Unit is approximately 0.7 M€. The annual operating and maintenance costs are around 0.5 M€.

The cement industry is currently responsible for 7% of global CO_2 emissions. The establishment of Microalgae Production Units in high-emitting industries could be an efficient alternative for the reduction of greenhouse gases emissions to the atmosphere. Several companies are emerging with the objective of large-scale production of microalgae as an energy source, AlgaFuel´s Prototype being the largest in operation with flue gas from a cement company.

A4F - AlgaFuel, S.A. is a bioengineering company aiming the development of projects for the industrial production of microalgae. It is a spin-out from Necton S.A., with an extensive R&D curriculum and the experience of large-scale production of microalgae using raceways and photobioreactors continuously in the last 12 years for the aquaculture and cosmetic markets. The Prototype Unit technology is in the market since March 2009 and is already operational at the Secil Cement Company's plant in Pataias, Portugal. The present results are very promising and the next scale-up for a pilot plant is already being considered.

The technology applied in the Microalgae Production Unit allows the fixation of greenhouse gases, namely CO_2. Furthermore, this process allows the continuous and reliable production of high amounts of biomass with a potential use as sustainable biofuels. The fixed CO_2 can be commercialized in the CO_2 license exchange market.

The microalgae biomass may be marketed for several purposes in a biorefinery-type approach: from the direct use of whole cells as sustainable biofuel raw material, to the applications of each biomass component: protein for feed, lipids for biodiesel, pigments and polysaccharides for pharmaceutical applications.



The break-through of this project is the combination of scale and the use of CO_2 flue gas from a Cement company as nutrient for microalgae. The AlgaFuel prototype is the world's first assemblage of systems using tubular photobioreactors, integrated in an emitting industry. This prototype combines all the steps from inoculum production in laboratory scale to the final biomass achievement.This technology can be used for other industries with CO_2 emission.

There aren't specific barriers in the developing countries where the climatic conditions are more often closer to optimum. Constrains in developing countries are the same as elsewhere: water and CO_2 availability for almost free, solar radiation, and knowledge.

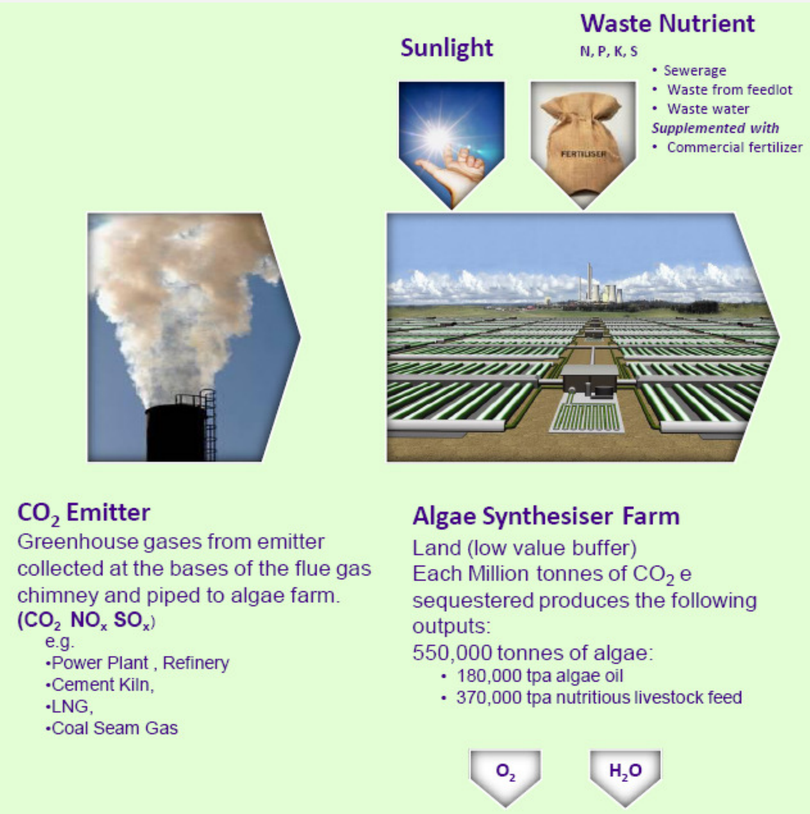
Bio CCS Algal Synthesiser Project, Australia

Established in 1997 and owned by the Queensland Government, Tarong Energy Corporation Limited (Tarong Energy) has the capacity to produce one quarter of Queensland's electricity needs. The Corporation owns a mix of generating and mining assets and employs more than 450 people in electrical and mechanical trades, engineering, and a wide variety of professional and support roles at its generating sites and in its Brisbane corporate office.

Tarong Energy reached a joint development agreement with MBD Energy in 2009 to develop a Bio CCS Algal Synthesiser plant at Tarong Power Station. The project is managed by a joint steering committee comprising representatives of both parties with MBD Energy responsible for personnel to design, construct, operate and maintain the display plant beginning in 2010; and Tarong Energy responsible for the supply and preparation of the trial site and the supply and maintenance of flue-gas, water and electricity to the Bio CCS Algal Synthesiser.

The initial facility will occupy a one hectare site adjacent to Tarong Power Station and, depending on the success of the trial and pending all appropriate approvals, Tarong Energy and MBD Energy may decide to design and construct a larger (nominally 80 hectares) Bio CCS Algal Synthesiser at Tarong Power Station.

MBD Energy and its partner team at JCU have developed a technology that allows this natural carbon cycle to be replicated under process controlled conditions for the bio-sequestration of industrial greenhouse gases over as short a timeframe as a single day.



Called Algal Synthesis, the process involves the injection of captured flue-gases into a waste water growth medium contained in large, elongated plastic membranes to produce rapid expansion approximating up to a doubling of oil-rich algal biomass every 24 hours. This algal biomass, grown from locally selected strains of microalgae in order to protect local biodiversity, may be harvested daily to produce algal meal suitable for nutritious, lower-methane animal feed, human nutritional supplements, and oils suited to the production of plastics and transport fuels including large quantities of bio-diesel.

Current production forecasts indicate that the sale of these commodities can be expected to readily offset the expenditure of building and operating such a greenhouse gas emissions reduction technology, thus progressively helping deliver cleaner electricity production at the lowest possible cost to consumers, whilst significantly reducing net CO2 emissions.

The Bio CCS Algal Synthesiser project at Tarong Power Station aims to determine whether Algal Synthesis can be scaled to achieve the desired CO2 emissions reductions. The project will also determine if the captured waste can be converted into supply chain input commodities for food production, plastics production and transport energy.

Planning and design of the display plant began in January 2010. The plant is anticipated to capture 800 tons per annum of greenhouse gases, produce over 400 tons per annum of algal biomass, 120 tons per annum of algal oil and 280 tons per annum of algal meal in 2011. Once proven and optimised at 1ha the project will then be scaled up in 2012/13 to 80ha, abating 70,000 tons of CO_2 producing 11.8 million litres algae oil and 25,000 tons of stock feed.

Cape Carotene, South Africa

Cape Carotene is a South African start-up biotechnology company that is developing a production process for the manufacture and marketing of natural products derived from micro-algae. The objective of its current project is to produce natural astaxanthin from microalgae for the local and international markets using closed system cultivation technology for better process control.

Astaxanthin is a valuable carotenoid pigment used in the aquaculture and animal feed industry and is gaining increasing status a human nutritional supplement because of its antioxidant properties. The major market for astaxanthin is the aquaculture industry which formulates feed for salmon (80%), trout (15%) and shrimp (3%). Other markets include the food and nutraceutical/ over the counter (OTC) market segments. Together these markets constitute about 2% of the global market value. Astaxanthin for the feed industry sales for between $2000-$3000 per kg, but is considerably more for the OTC markets as this requires further processing of the crude product. Worldwide consumption of astaxanthin is about 170 tons per annum in 2008. Major consumers of astaxanthin include Europe (65%), Latin America (25%) and Asia (10). Natural astaxanthin for the OTC or nutraceutical market is sold at a premium due to its associated health benefits. Ongoing research has proved that natural astaxanthin is effective against a number of health problems including cancer and blindness.

The main current focus is aquaculture; pen-reared salmonid fish cannot synthesise the carotenoids that cause their characteristic pinkish colour. Hence salmonid fish require feed where astaxanthin is added as a supplement.

Astaxanthin accounts for a large percentage of production cost (about 20%) of aquaculture feeds. Carotenoids, including astaxanthin, are largely produced synthetically via chemical processes; however, there is a trend towards deriving carotenoids naturally.

Cape Carotene currently uses facilities in Upington in the Northern Cape region of South Africa for its manufacturing and piloting studies where the climatic conditions are favourable to algal growth. The facility uses both municipal and fresh river water in ponds cultivation system where nitrogen and carbon nutrients are added. The carbon source is carbon dioxide and nitrogen source are nitrates. The waste water is recycled to recover nutrients and for reuse.

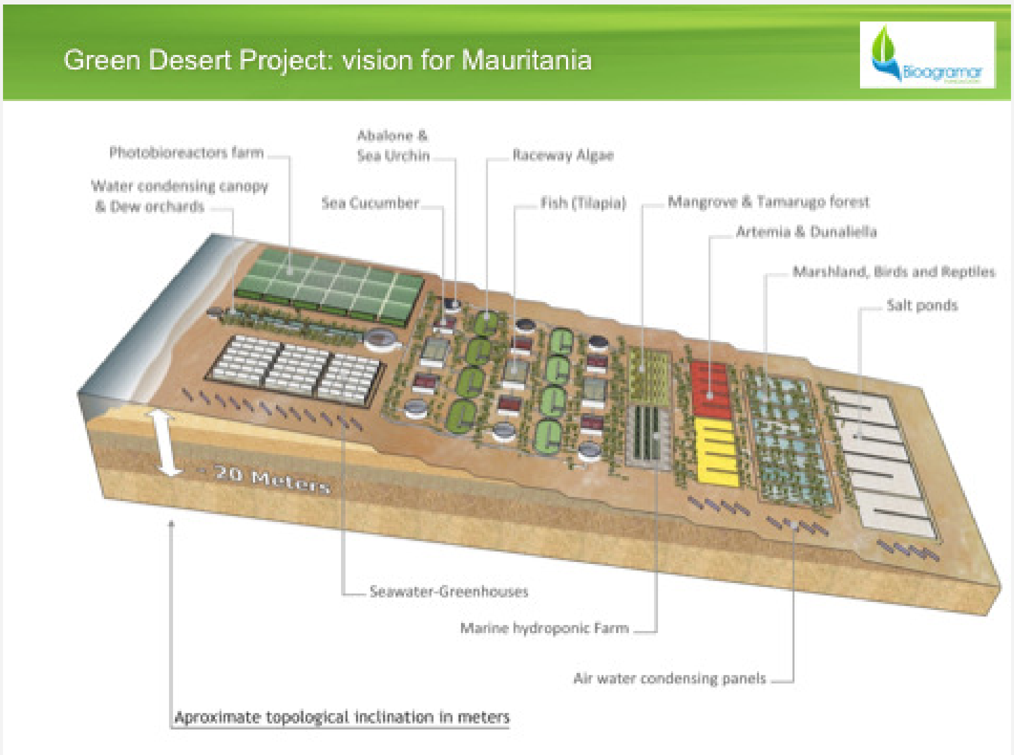
There is a plan for setting up an algal technologies platform at the pilot plant facilities in Upington where nascent algal companies can be accommodated. In this way commercialisation can be centrally stimulated and coordinated, benefitting companies such as Cape Carotene. The market depends very much on the type of product e.g. astaxanthin market in South Africa is miniscule, hence most of the product will be for export. In this regard companies such as Cape Carotene will act as primary algal products producers with onward distribution to established formulation global companies such as Nutreco in Europe, Fuji Chemicals in Asia or to the established players in the global carotenoids market, i.e DSM and BASF.

Cape Carotene was incorporated in March 2006 after receiving funding (~USD600,000) from Cape Biotech Trust, an independent trust under the auspices of the South African Department of Science and Technology. The astaxanthin project uses technology developed at the University of Cape Town. The company also has access to beta-carotene technology.

Cape Carotene is in a three year development phase from 2006 to 2009. After this phase a full scale plant capable of producing up to 2 tons of 100% astaxanthin will be established. Cape Carotene is now seeking a second round of funding to progress to full scale production.The natural astaxanthin is produced using the green micro-alga Haematococcus pluvialis. The final biomass yield on the test plant is between 0.5 to 1.0 g/l. Each test pond is has an area of 100 m^2 and volume of 10 m^3. The content of astaxanthin in the biomass is 2% of the dry weight.

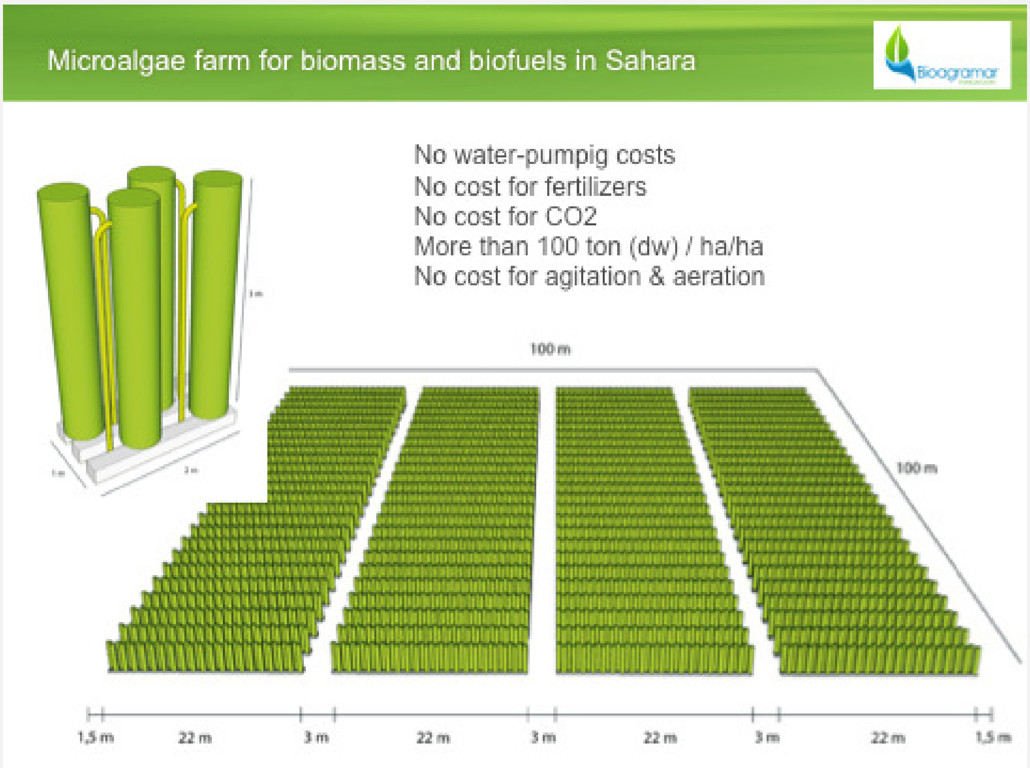
Green Desert Project (GDP)

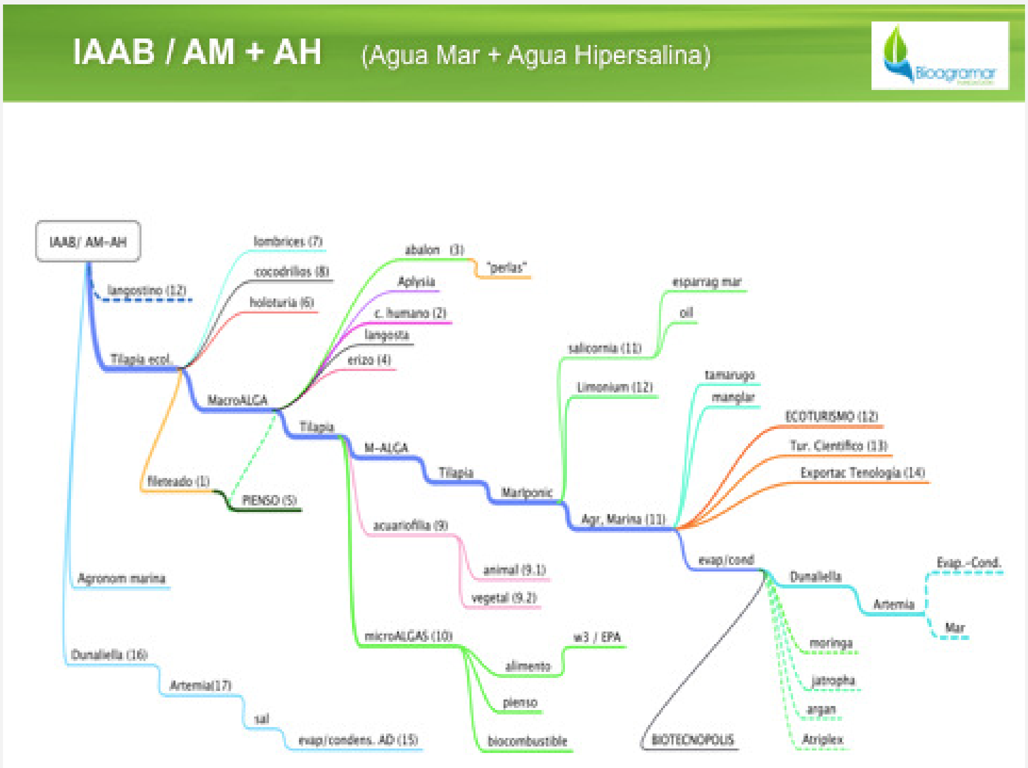
The Green Desert Project (GDP) is a concept for re-greening the Sahara through integrated marine polycultures, including microalgae, macroalgae and halophytes (plants grown with salt water). These are key links in the multitrophic biomass chain of on-land cultures. The concept has been developed by the Bioagramar Foundation, a private non-profit R&D foundation, based in Spain but with a global scope, who aims to realize this concept under a frame of joint-ventures with companies and international institutions.



Biomass (even for biofuels) from the IAAB-microalgae farms are planned in a new, simple, cheap and recyclable semi-closed photobiorector design, that might allow production costs lower than 765 €/ton (dw).

The first steps to develop a Technological Center at Gran Canaria (Canary Islands, Spain) as the 10 hectare pilot-plant polyculture farm have been made. The next step is to export the system to the Sahara, to the coasts of Mauritania (3.800 km^2, below sea level, but without hydroelectric seawater power). Eventually desert area of 20.000 km^2, below sea level, bordering the coast of Mauritania, Western Sahara, Morocco, Algeria, Tunisia and Libya might be put in production for marine and algae biomass for food, feed and biofuels.





The "basic GDP" contains 17 subsystems that co-produce fish, seaweed, molluscs, algae, crustaceans, salt, biofuels, quality food, feed, water, mangroves, trees, and amphibians. At the same time the concept brings quality of life and sustainable wealth in the Sahara desert. This new bio-industrial ecosystem polyculture co-production concept is called Integrated Aqua Agro-Biotechologies (IAAB). 90% of the technologies needed to form the IAAB are already applied at a commercial scale, but not integrated.

Other opportunities and benefits include as a side effect, the concept will reduce the rise in sea level through the hydration of the desert, an impact on food markets and global climate (not just Africa) and with potential to generate third-generation biofuels (energy balance positive), reuse of effluents from fish farming and shellfish production for cultivation of algae and halophytes, strategic location at the Scientific-Technological Park of the University of Las Palmas, Gran Canaria, off the coast of north-west Africa, with access to knowledge, experience and scientific and technological infrastructure in biotechnology of microalgae, seaweeds farming, cultivation of plants with sea water, one of the best collections of marine microalgae and extremophiles (many are native of NW Africa).

Stepwise development of the Green Desert Project for the implementation of Saharan Biotecnopolis

Improving Algal Oil Synthesis for Biodiesel, South Africa

The main aim of this project, implemented by the University of the Witwatersrand, is to produce lipids which are chemically suitable for the production of biodiesel.

The percentage of lipid composition on a dry mass basis in the microalgae species used in this research laboratory ranges from 20 to 65% depending on species and culture conditions. Co-products would be lipid or oils not suitable for biodiesel production. Some of the co-productions in the form of heavy oils could be used as fuels for steam generation for electricity generation. Other possible lipid co-products are certain essential oils. A major key co-product in algal biodiesel production would be glycerol. Glycerol could be used as feedstock in dark fermentation for the production of ethanol and methane. It could also be used as a carbon feedstock for heterotrophic algae production.

At this stage the market value or size for the possible products and co-products is not clear. However, a number of mining companies have already expressed an interest in algal biodiesel or algal heavy oils for electricity generation. This would reduce their dependency of state utilities for electricity supply and may reduce the cost of mining operations.

While biodiesel production being the main goal, heavy oils, waxes and essential oils would be an additional consideration for co-production. In addition algae biomass as a by-product of biodiesel can be used as a feedstock for anaerobic fermentation for methane production. This project is currently still at the R&D phase and therefore unable supply any reliable information on income flows from algal products at this stage.

The project work is based on a surface of 0.5 m^2 and uses the *Isochrysis galbana* alga.

The patented projected algal lipid production facility will have a volumetric capacity of 8000 m^3/ha in the form of plastic airlift tubular photobioreactors. In lab scale photobioreactors the lipid production ranges from 20 to 60 mg/L/d with an average of 38 mg/L/d. If this value is scaled up for the production facility above, an annual dry biomass production of up 110 tons per ha can be calculated.

The project is based at the University of the Witwatersrand and has a budget of over € 150.000.

The South Africa Government's Department of Science and Technology through its company South Africa National Research Institute (Saneri) (Pty) Ltd has provided the funding. The runtime is 3 years starting from October 2008. The Project is now in its second year. Saneri and The University of the Witwatersrand are the major partners. Sufficient Intellectual Property has been generated to provide a satisfactory foundation for commercialization.

Low cost raceway ponds and tubular photobioreactors can be constructed from plastic materials. Only brackish or seawater would be required. Nitrate and phosphate would be main nutrients. CO_2 is the main carbon source. However algal production system could be operated as a mixotrophic system using fermentation products such as volatile fatty acids. An algal oil refinery would generate waste algal biomass and glycerol which could be used as a feedstock for methane production via dark anaerobic fermentation or even as a feedstock for mixotrophic algal production. A combination of agricultural fertilizer and biomass recycling would be the source of N and P.

Oil and biomass production from microalgae could be one of the most appropriate means for energy farming in developing countries. Algal energy farming can be carried out on extremely marginal agricultural land resources and could contribute to the energy self-sufficiency of developing countries. In order to avoid possible barriers, to algae-based energy farming, socioeconomic stability is needed in areas such as the enforcing of national laws, protection of property rights, robust public institutions and civil society organizations, political and economic freedom. The investment would not be less than € 10.000/ha and the production process would be labour intensive as there would 100.000 photobioreactors per ha that would have be maintained. It would be a form of farming – roughly similar to green house crop production.

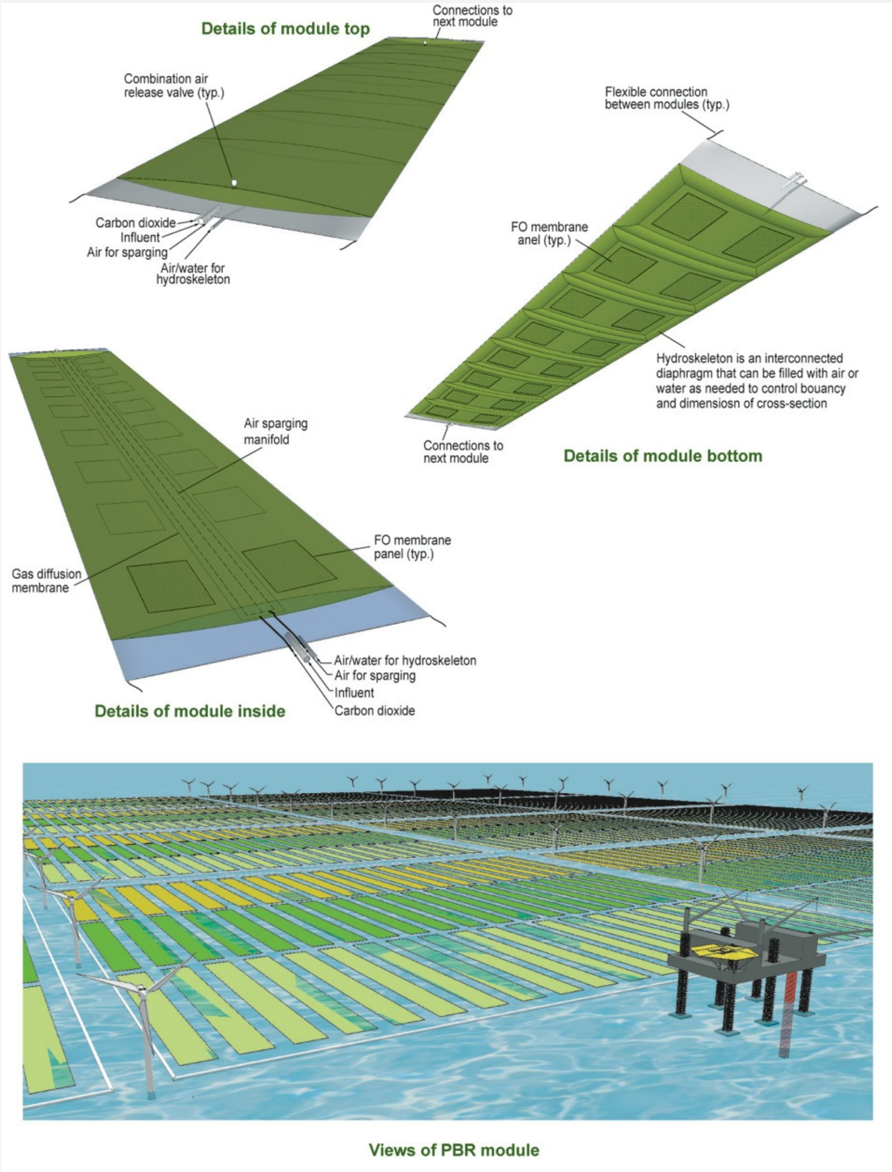
Offshore Membrane Enclosures for Growing Algae (OMEGA)

The Offshore Membrane Enclosures for Growing Algae (OMEGA) is a proposed system of floating photobioreactors for growing freshwater algae on municipal wastewater in marine environments. The algae grow within the enclosures and the surrounding seawater provides physical support, temperature regulation, wave energy for mixing, and a salt gradient for containment (freshwater algae die in saltwater) as well as forward osmosis (the flow of water molecules across a semi-permeable membrane in the direction of the highest salt concentration. Algae, nutrients and pollutants cannot pass the membrane. Forward osmosis membranes concentrate nutrients in the wastewater, dewater the algae in preparation for harvesting, and clean the water released into the surrounding seawater. OMEGA generates products from algae including sustainable carbon-neutral biofuels, as well as food, fertilizer, and nutraceuticals. OMEGA also provides services, including advanced wastewater treatment, environmental remediation, and carbon sequestration. It provides these products and services without competing with agriculture for land (it is offshore), or for fertilizer or freshwater (it uses nutrient-rich municipal wastewater currently discharged into the ocean).

The goal of the NASA OMEGA project is to demonstrate the feasibility and scalability of the OMEGA system with respect to the associated biology, engineering, economics, and environmental impact. The system represents an "ecology of technologies" in which "wastes" become resources, local energy sources are utilized, and compatibility with the environment is an essential part of the system.

On the one hand, the NASA OMEGA project is focused on the challenge of growing sufficient quantities of algae to substitute for fossil fuels and on the other, it is an ecology of technology that seeks to eliminate waste. As a biofuels system, OMEGA focuses on growing algae species with high lipid content for making jet fuels, and rapid growth rates for producing biomass. As a demonstration of technology ecology, OMEGA focuses on using all aspects of its products and processes; the non-oil biomass can be used for fertilizer, animal feed, and specialty algal products. The OMEGA system can grow any desired strain, species, or community of freshwater algae that can utilize wastewater, cope with local ocean temperatures, but that cannot thrive in saltwater. Hence, within these constraints, the OMEGA system can be used for any product or co-product associated with algae farming, in addition to the environmental services mentioned above. The value of OMEGA products and services will depend on local conditions and needs, and a host of down-stream considerations, such as processing requirements, transportation, market considerations and what can be considered secondary consequences: for example, the impact of wastewater treatment on fisheries or health or tourism.

There are no general barriers to installing OMEGA systems in developing countries, provided there is access to saltwater, wastewater, sunshine, and the large quantities of relatively inexpensive materials needed for OMEGA construction (such as plastic, pipes, valves, and moorings). The relevant engineering and fabrication skills are borrowed from the fields of marine engineering, plastics, aquaculture, wastewater treatment, and oil refining. The OMEGA system uses wastewater effluent for the nutrients required for algal growth, which is enhanced by the addition of CO_2. Therefore, if a country has a wastewater discharge into the ocean and a neighboring CO_2 source, such as a near-shore power plant, the OMEGA system can provide advanced wastewater treatment and quantitative capture of $CO_{2,}$ in addition to the algae products described above. Barriers to OMEGA in developed countries include restricted access to coastal zones and long permitting processes, which may not be problems in developing countries. Furthermore, the wastewater effluent may be higher in nutrients in some developing countries, which increases algal growth rates.



One of many hypothetical offshore photobioreactor designs being evaluated by the NASA OMEGA team

The OMEGA system consists of flexible plastic enclosures with reinforced plastic on the underside and clear plastic on the upper sunny-side. An internal gas-permeable membrane provides a constant supply of CO_2 and regions of forward osmosis membranes concentrate nutrients to stimulate growth and dewater the algae to facilitate harvesting. The OMEGA modules are floating photobioreactors (PBRs), used in either batch or continuous flow modes with inputs of non-saline wastewater and CO_2 along with an inoculum of oleaginous algae. The mature, concentrated algae suspension is pumped back to shore, thickened, dewatered, while the lipids are extracted and converted to fuels. The OMEGA system is focused on wastewater treatment, which includes removing nutrients that contribute to the creation and growth of dead zones as well as heavy metals and other potential toxins adsorbed or degraded by microbes included in the OMEGA biological consortium.

• *Project location:* OMEGA research on the laboratory scale is conducted at NASA Ames Research Center, Moffett Field, CA and at the California Department of Fish and Game in Santa Cruz, CA. The pilot scale testing will be conducted in the San Francisco Bay area, with plans for a site north of Treasure Island, CA.

• *Project budget:* USD10 million from NASA ARMD and USD800,000 from the California Energy Commission

• *Project funding source:* Two separate aspects of OMEGA are funded, one by NASA ARMD (Federal) and the other by the California Energy Commission (State).

• *Runtime/age*: The OMEGA concept originated in 2008, but the currently funded projects began in January 2010 and will be completed by December 2011.

•*Commercialization status:* A "business plan" was developed for Phase I and a "technology transfer strategy" with a commercialization objective is a component of Phase II.

• *Annual biomass yield per hectare:* Estimated 50 to 120 Mg/ha/yr (14 to 33 dry $g/m^2/d$, 365 d/yr).

• *Current/projected surface size:* Experiments with OMEGA modules range from laboratory sizes to a pilot deployment of 1000 m^2. The full-scale system will cover several km^2.

• *Species used:* Initially, *Chlorella vulgaris,* along with the natural community of microbes in wastewater, will be the basis for algae cultivation studies. The OMEGA system has the potential to use any other strains, species, and freshwater algal communities that are appropriate for a given location.

The OMEGA team consists of scientists and engineers from a variety of public and private organization. The team is using an "open source" model to meet their goals and welcomes contributions from colleagues and collaborators with interests in marine biology, ecology, engineering, environmental studies, economics, and public policy. The current project partners are: NASA Ames Research Center, URS Corp, SETI, USRA, Dynamac, the University Affiliated Research Center (UARC), Jacobs Technology, Inc. University of California (UC) Santa Cruz, California Polytechnic San Luis Obispo, Drexel University, California Department of Fish and Game, Hydration Technology Innovations, with consultants and advisors from Scripps Institution of Oceanography and the National Renewable Energy Lab.

ProviAPT: a scalable, light-efficient and robust photobioreactor

The ProviAPT is a flat panel photobioreactor with an efficient use of solar light. The panels are enclosed in a water-filled, outer bag that levels out the daily temperature cycles, thus being suitable for use in a wide range of climatic situations. It is produced from recyclable thin-layer polypropylene and does not require additional support structures. Scaling-up within the capacity limits of the service module is therefore straight-forward, and a production site can be built up very fast and requires little engineering or site preparation. It can be used for cultivating multiple algal species and multiple products. The polypropylene film is the only material in contact with the culture and the reactor can therefore be used with sea water as well as fresh water

The ProviAPT photobioreactor system is being developed by a Belgian chemical company, Proviron in collaboration with Wageningen University, the Netherlands and the Belgian custom-made machinery maker, Matthys nv. The project group is currently being extended with additional industrial and academic partners. The project development privately funded by the industrial partners and supported by the Belgian government through a research and development grant from IWT (*Agentschap voor Innovatie door Wetenschap en Technologie* of Flanders).

The project started in January 2008. Proof of concept has been completed. Proof of principle, including validation from a 500 m^2 pilot reactor plant, operated Belgium, is ongoing and will be completed in 2011. At present, there are no specific plans about the localization of future production sites.

Intended products are both unrefined algal biomass for aquaculture and feed purposes and refined products, such as specialty oils. Proviron is an established supplier of chemicals for the feed market. Oils and delipidized biomass for feed use are main anticipated products from algal biomass.

A number of food, feed and energy applications have been considered with the system. Multiple future products are anticipated, both by production of several species and by developing several refined products from the same biomass (biorefinery).

Laboratory trials have suggested that a photosynthetic efficiency of 5% (sunlight) is achievable with the system, which, at Belgian light conditions, is equivalent to an annual production of 125 ton dry weight/ha.

The water in the surrounding bag is not renewed. Water for the algal cultivation depends on species, currently sea water is used. Membrane technology based water recirculation is being investigated in a new research project.

Nutrients used are currently chemical fertilizers and compressed CO_2, but the use of flue gas carbon dioxide and waste ammonium is being investigated in a new research project.

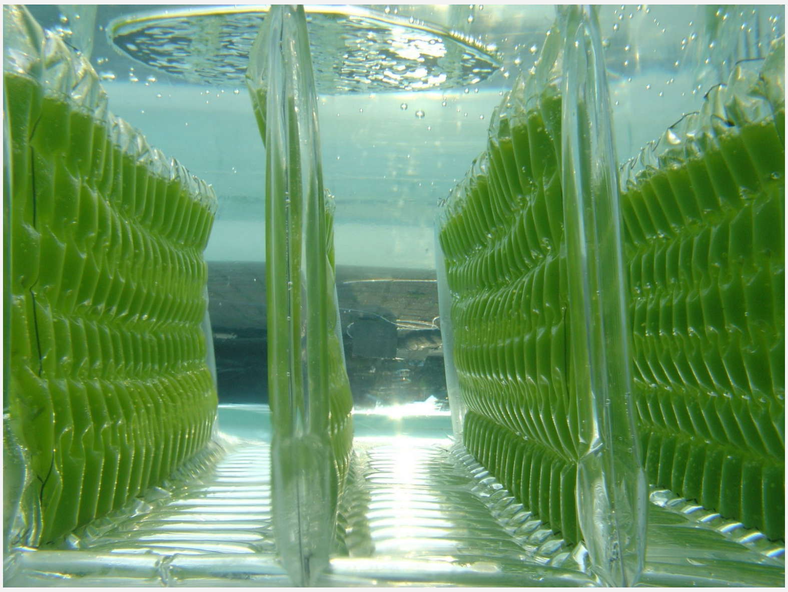
A custom designed polypropylene based film that can be recycled is currently used for the construction of panels and bags. A life time of 3-5 years is expected.

The system is a closely-spaced, flat panel system, keeping light intensities at the surface of the panels at low levels through mutual shading and reflection between the panels which is the basis for obtaining high photosynthetic efficiency values (5% solar). The panels are enclosed in a water filled outer bag, which serves as a heat reservoir, leveling the daily temperature cycles in the reactor (see photos below). The bags are currently being produced on a semi-automated machine in panel widths of 1.5 m. Feeding and harvesting channels are integrated in the bottom of the bag. Feeding and harvesting is carried out by a support unit in a semi-continuous way. One support unit (built in a container) currently serves 500 m^2 of reactor surface. This ratio may be increased 2-10 times. Keeping the aeration costs low is achieved by recirculating the maximum possible air because a lower pressure drop for recirculating air as opposed to freshly aspired air is required. Also, the height of the panels is kept low (< 0.5 m) to obtain low pressure drop on the aeration air. System oxygen and carbon dioxide is measured by the support unit, but no additional data collection is required from the reactors.

The system has been tested with the strains *Nannochloropsis oculata, CCAP 849/1* and *Phaeodactylum tricornutum, Utex 640* and un-interrupted production cycles of 6+ months have been experienced with these strains. Winter production with both species was tested. *Phaeodactylum* thrives at temperatures about 0 °C, whereas *Nannochloropsis* requires heating when ambient temperatures are below 15 °C.

It is the experience so-far that the algal production in the ProviAPT module has been robust once the culture has been established in the reactor and in principle the system would be well suited for implementation in developing countries where high solar irradiation is found alongside with scarcity of water.

The system is at present time not ready for routine production and a period of 3-4 years before it is sufficiently well tested for implementation elsewhere, including remote developing countries, is expected. The system requires a relatively flat surface area. For establishing the system in developing countries, a special concern is the recycling of the plastic material.



Experimental module of ProviAPT reactor, Algal species: Nannochloropsis

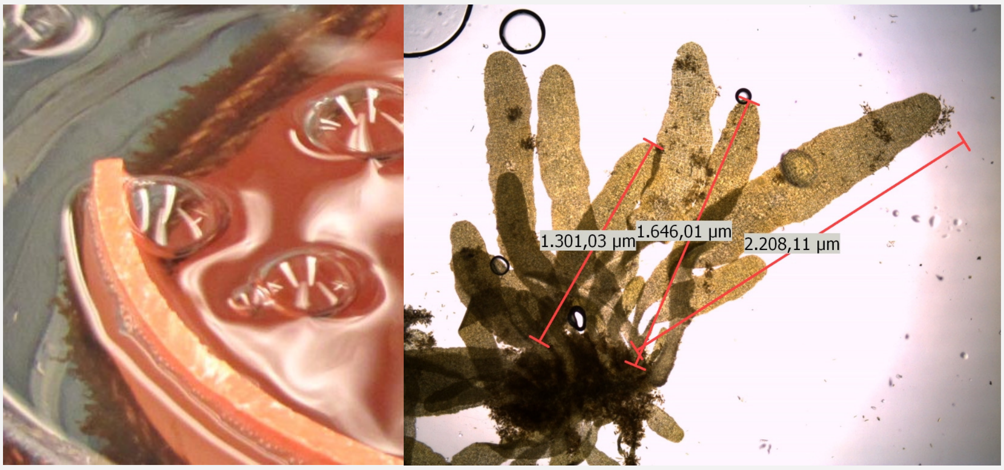
Seaweed cultivation, Peru

Brown seaweed (also known as kelp) has a long history of use in Peru, but only based harvesting natural sources. Over-exploitation of natural beds in recent years has led to a reduced seaweed population. This project is the first to cultivate brown seaweeds cultivation project in Peru. The project is coordinated and executed by Peruvian Seaweeds SRL, a company specialized in biotechnology, added value generation and commercialization of seaweeds products in Peru. The main goal of the project is to implement the culture technology for brown seaweeds considering the specific local natural conditions and to contribute to the sustainability of Macrocystis spp supply as raw material, mainly for the production of an organic agglutinate, attractant and bio-stimulant used by aquaculture feed industry.

The main motivation for developing this project was to assure in the mid long term the availability of raw material from this species without depending on the natural biomass offer. Starting in 2006, a massive overexploitation of natural beds occurred, due to the lack of control, management, regulations and ecological knowledge on seaweeds exploitation. As a consequence, a massive arrival of foreign companies in the alginate industry generated important social, environmental and ecosystem damages.

The primary target products with the cultured biomass obtained are nutritional supplements for the aquaculture feed industry, secondary options are the production of different seaweeds extracts, biogas or bioethanol. Besides, the culture itself could be used as a biofilter in coastal marine areas contaminated by mining or wastewater effluents.

The Macrocystis spp. or giant kelp culture is developed in two main stages. The first stage is carried out under controlled conditions (see figure below), where rope-attached zoospores grow until the sporophyte stage.



Hatchery under controlled conditions

Subsequently the ropes with the juvenile sporophytes are transferred to natural conditions.

Once the ropes are attached in a suspended long line system, they stay at this pre-stage nursery for 1 or 2 months depending on the season, until they reach an average of 10 cm size. For the second stage, the seaweed is transferred to the final culture ropes until harvest (Fig. 2).

Growing Macrocystis on a long line system

The expected production is 300 - 400 wet tons/ha/year. The project is funded by the Science and Technology Program of the Presidency of Ministries Cabinet, the Inter-American Development Bank (IADB) and Peruvian Seaweeds SRL. The total budget is USD 150.000.00. This funding covers the experimental and pilot culture (1 Ha). Kelp culture project is developed by Peruvian Seaweeds SRL with the collaboration of the Agronomic University La Molina. The runtime of the project is two years started in October 2008.

The only barrier for the kelp culture would be the resource geographical distribution and appropriate natural conditions for the species. To develop this project in a different region, coastal zones research with specific characteristics should de carried out first.

SunCHem: hydrothermal biomethane production, Switzerland

The SunCHem project aims at developing an innovative process for the production of bio-synthetic natural gas (BIO-SNG) via hydrothermal processing of algal biomass. As depicted in the simplified scheme below, the SunCHem process consists of two parts. The first part is concerned with the production of biomass using microalgae. Microalgae growing in photobioreactors or raceway ponds fix CO_2 and transform it into biomass through photosynthesis. Next, the biomass slurry is dewatered to about 20% dry matter and the nutrient-rich water is recycled back into the process. The biomass is then fed into the second stage of the process where it is gasified to methane (BIO-SNG) through hydrothermal treatment. Other types of biomass, such as manure, sewage sludge, seaweeds can also be process as long as they are pumpable. Hydrothermal treatment is performed at temperatures between 300 and 450°C and pressures between 20 and 30 MPa using water as the reaction medium. The nutrients contained in the biomass are separated and recovered in the hydrothermal step. Together with the CO_2 produced, they are recycled back into the algal production process. Alternatively, the CO_2 can relatively easily be sequestered to underground storage as the CO_2 stream after the hydrothermal treatment is at a pressure of 30 MPa and pure. 55-70 % of the energy content of the feedstock is recovered in the final product gas (based on the lower heating value of the biomass and the product gas). This value takes in account the energy required to provide the process heat as well as the energy to pump the biomass slurry up to 300 bars. Gas composition depends on the biomass composition but is usually in between 50-60% CH_4 and 40-50% CO_2 in the raw product gas. The coupled co-production of fine chemicals can be a value-adding option.

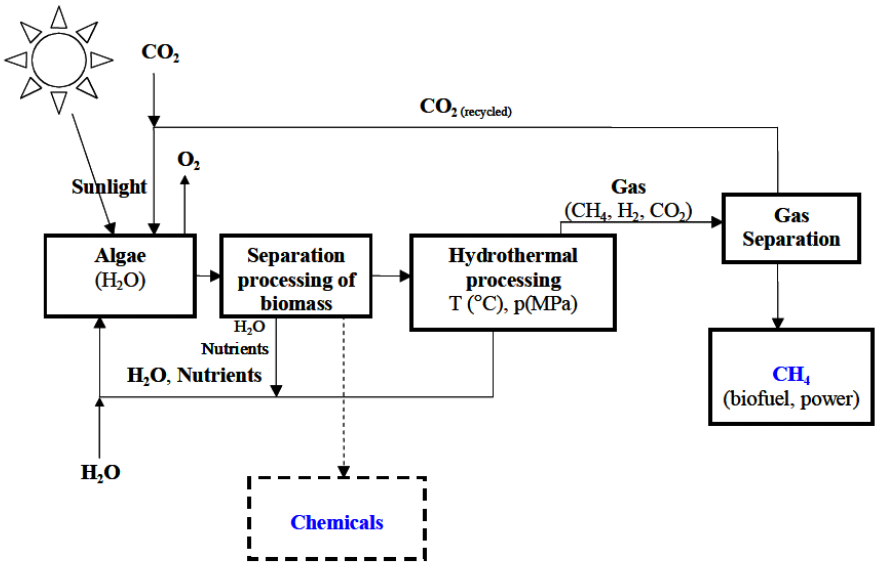


Figure 1. Simplified scheme of the SUNCHEM process for the production of methane (and fine chemicals) using microalgae.

The main advantages of the SunCHem process are:

- No drying of algal biomass is required. Dewatering up to 20 wt. % TS is sufficient. The dewatering technology is not yet fixed, but a combination of filtration with centrifugation is expected (depends on the algal species used in the process).

- Full conversion of algal biomass during the hydrothermal gasification process.

- Residence times during algal biomass conversion in the order of minutes.

- No use of solvents or other chemicals in the downstream processing (biofuel production).

- Clean energy carrier: Nitrogen and sulphur in the biomass stays in the water phase. There is no production of NO_x and SO_x during the fuel burning process.

- Limited resources such as phosphor and water are recovered and reused in the microalgae production process and not lost or evaporated during the production process of the fuel. SunCHem is a closed loop process.

Bio-synthetic natural gas (BIO-SNG) can be used for transport, heating and power production. The widely available natural gas grid infrastructure can be used for BIO-SNG distribution and storage. Possible co-products are high-value algae-based chemicals and a concentrated CO_2 stream. The focus lies on BIO-SNG production. The current calculated cost is anticipated to be around 0.66 €/kWhBIO-SNG. Presently natural gas is sold at around 0.06 €/kWhTH in Switzerland. In the future an SNG price of 0.14 €/kWhBIO-SNG may be achieved with open/raceway ponds if algal productivity and harvesting increases very significantly. In countries with lower labour costs than Western Europe, lower production prices may be achieved. The price to process one energy unit of microalgae through hydrothermal gasification amounts to around 0.0225 €(kWhTH) The remaining costs are due to biomass production, dewatering, labour, overheads…etc.

An inherent feature of gaseous fuels is that the distribution systems and technology with high efficiency and low impact on the environment are available, or in development: Gas combined cycle power stations approaching 60 % of electric efficiency, gas engines, fuel cell systems for decentralized combined heat and power production with electric efficiency well above 40 %, advanced concepts for gas engines for CNG (compressed natural gas) vehicles all share high efficiency coupled with very low emissions of atmospheric pollutants.

As an example, current results show that using the SunCHem process, a land area of 1 m^2 in Jerez (Spain) could produce an average of 1.89 kg SNG per year. This represents a potential range of 35.5 km with an average CNG (compressed natural gas) car. To meet the mobility requirements for the entire car fleet in Switzerland, assuming that it is only composed of average SNG (synthetic natural gas) cars and the climatic conditions are constant, a plant with a surface of 2080 km^2 with 1540 km^2 covered by ponds would be required. Compared to the size of Spain, i.e. 505.000 km^2, this would represent 0.41% of its total surface.

In developing countries, the substitution of wood by algae derived BIO-SNG as a cooking fuel, avoids deforestation and reduces significantly the emission of fine particle and other cancer-causing products during the cooking process in rural areas, but skilled engineers and operators are necessary to run the installation.

The intended water sources for the SunChem process are ideally brackish water and “the possible” make up nutrients should come from nutrient rich flows (such as wastewater).

Hydrothermal gasification is not dependent on the microalgae species. The requirements are solely focused on the areal productivity and carbon fixing efficiency of the organisms. High carbohydrate fraction may be an advantage.

The 2-part SunCHem project is located in Switzerland, 1st part running from 2007-2010 and with a budget of 500.000€, the 2nd part running between 2010 and 2013 on 3.000.000€, funded from both private and public sources. The project partners involved are: Paul Scherrer Insitute (PSI), Swiss Federal Institute of Technology at Lausanne (EPFL), Zürich School of Applied Sciences (ZHAW), Swiss Institute for Materials Science and Technology (EMPA), Subitec (GmbH).

Sustainable Fuels from Marine Biomass (BIOMARA), UK and Ireland

Co-ordinated at SAMS, Scotland, the Sustainable Fuels from Marine Biomass project, BIOMARA, is a 6 million Euro UK and Irish joint project aiming to demonstrate the feasibility and viability of producing third generation biofuels from marine biomass. This case study outlines the macroalgae and anaerobic digestion part of the BIOMARA project only. BIOMARA also has a microalgae and biodiesel research strand. Large brown macroalgae (kelps) can be cultured and naturally grow very fast in easily accessible coastal locations. They can potentially be used as biofuel. The most obvious route for the conversion of macroalgae to fuel is via anaerobic digestion (AD) to produce methane. They can also be fermented to produce ethanol. With no lignin and little cellulose, they provide better material than land plants for complete biological degradation via AD to methane, figures from the literature indicate methane yields of $0.27 m^3 kg^{-1}$ of volatile solids. AD systems are now in place at SAMS and the methane yield from seaweeds grown locally is being quantified. Seaweed cultivation is well established at SAMS in Scotland. Spores are germinated in laboratory conditions to form tiny plants, which are transferred to sea and then harvested 6-8 months later, thus generating the biomass for anaerobic digestion or fermentation to produce ethanol.

The primary aim of this part of the BIOMARA project is to further develop our knowledge and understanding of how the selected species of macroalgae perform in modern AD systems. The primary product is therefore biomass for AD to methane or biogas. However, other research projects are planned to run in tandem with the culture effort and examine high-value end products from the seaweeds including fucans, fatty acids and vitamin E. Methane yield from the residual biomass pre- and post extraction of these more valuable products will be compared. The resulting digestate will be used as organic fertiliser, an increasingly valuable commodity given the high price of chemical fertilisers. There are no specific barriers for developing countries other than the availability of suitable macroalgal species that can be grown in bulk; i.e. the species they are concentrating on are the temperate-water large brown kelps.

The cultivation system used to grow the seaweeds is similar to that for commercial mussel culture in Scotland: a horizontal long-line system from which strings bearing the culture plants are vertically suspended. This is similar to the system used in China for the culture of *Laminaria japonica*, the world's largest aquaculture crop by volume. Presently our seeded ropes are suspended vertically from depths of 2–8 m in inshore waters to allow easy access. In future, if cultured kelps is to make a significant contribution to energy then large farms further offshore are envisaged. The cultures require fully salinity and high water exchange (a tidal stream as opposed to breaking waves). The nutrients come from the surrounding seawater; they have cultured seaweeds alongside salmon cages to examine the bioremediation potential and to examine whether the seaweeds benefit from the extra available nutrients. The answer is yes, if / when background nutrients are limiting. As the cultures are small scale at present, they are harvested by hand. In the larger scale cultures (1 ha) planned, harvesting will be mechanised using a mussel farm harvest barge.

Germinating macroalgae (approx 2mm) on the strings ready for outplanting

The previous culture data suggests that production from research scale can be scaled up (1 ton max) to 200 tons wet weight per ha. The species in use are *Saccharina latissima*, *Sacchoriza polyschides* and *Alaria esculenta*. SAMS are developing a proposal for a pilot scale (1-5 ha) macroalgal farm near Oban.

Cultures of Saccharina latissima, Scotland

The project is co-ordinated by SAMS, Argyll Scotland, with partners in the Republic of Ireland and Northern Ireland; The Centre for Renewable Energy at Dundalk Institute of Technology (CREDIT), Ireland; University of Strathclyde, Glasgow, Scotland; Centre for Sustainable Technologies, University of Ulster, N. Ireland; Institute of Technology, Sligo, N. Ireland; The Questor Centre, The Queen's University Belfast, Northern Ireland.

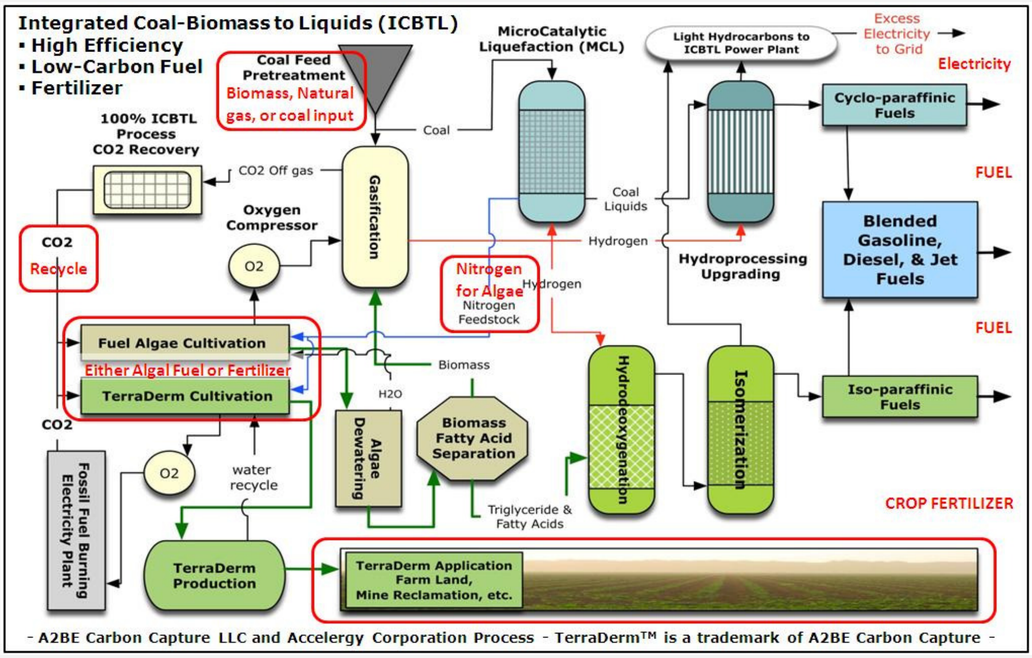
The total project budget for all partners and both research strands (macro- and micro- is 6 million Euro), the funding comes from the European ERDF fund Interreg programme, with additional funding from Scottish Government, Highlands and Islands Enterprise and The Crown Estate. This four year project started in 2009.

TerraDerm: algae based CO_2 recycle for fuel and fertilizers

A2BE Carbon Capture LLC of Boulder, Colorado and its partners are developing a sustainable low-carbon transportation fuel process that can further offset the fuel's CO_2 emissions via co-production of a unique living fertilizer. This algae-based fertilizer "TerraDerm" is produced using the CO_2 emissions of the biofuel production process. When applied, TerraDerm draws CO_2 directly from the atmosphere while improving soils. This technology is scalable and will allow countries with native access to biomass, coal or natural gas feedstock to become independent producers of transportation fuels and natural agricultural fertilizers while dramatically limiting their total CO_2 emissions and potentially earning significant CO_2 credits.

The process converts almost any carbon containing material to high quality fuel including Jet-Fuel using an ultra-high efficiency, Exxon developed, non-Fischer-Tropsch process that is exclusively licensed to Accelergy Corporation. Accelergy thereon has an exclusive relationship with A2BE Carbon Capture to recycle the remaining CO_2 process emissions using A2BE's algal cultivation technology that features scalable, low-water consumption, passively cooled, high productivity closed photobioreactors.

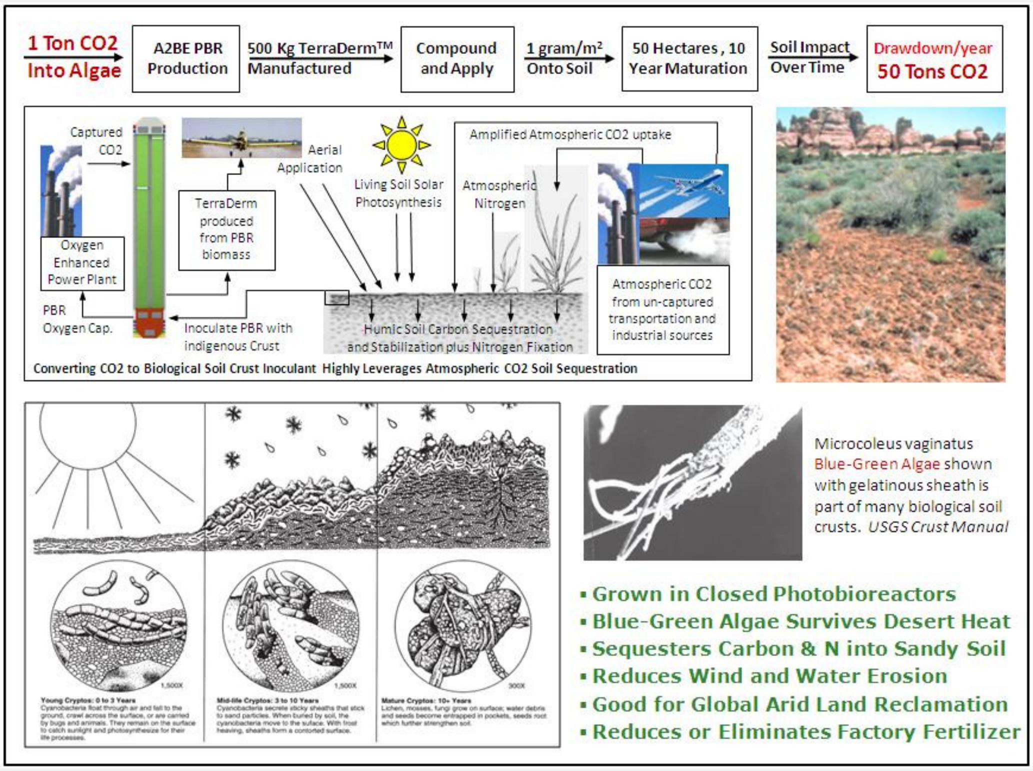
The combined process has not yet been installed at an operational site nor has all the technology been completely proven. However, significant US public and private funding is being focused on completing development of this specific combination of technology. The State of Pennsylvania is currently commissioning a study of the application of this technology in their state.



This diagram illustrates the combination of the best-in-class carbon-to-liquids technology with what is expected to be the best-in-class industrial algal cultivation technology being developed by A2BE. The resulting fuel will have a 20% lower carbon lifecycle emission that fossil oil based fuels allowing large scale ICBTL production globally. Even greater lifecycle CO_2 emission reductions result from TerraDerm.

Process CO_2 can be used to produce TerraDerm, a living soil fertilizer that not only sequesters CO_2 into the soil as in bio-char but that goes vastly beyond biochar as TerraDerm restores natural photosynthetic soil crust colonies that draw CO_2 and nitrogen directly from the atmosphere via photosynthesis. When tilled or damaged arid soils are treated with photobioreactor grown TerraDerm, then soil fertility and erosion stability are improved and the requirement for factory fertilizers can be eliminated or reduced.

The process shown below is in the development phase but significant partners such as Battelle Labs, Raytheon Corporation, and the Colorado School of Mines are joining A2BE in moving to demonstrate the fundamental technology. As shown in the diagram below, converting 1 ton of CO_2 into TerraDerm and applying it to damaged land is expected to induce a resurgence of restored natural biotic soil health over a period of years that can result in 50 tons of CO_2 being naturally drawn into the soil each year via restored natural process alone.



While biochar involves tilling approximately 1 kg of biologically inactive carbon into each square meter of soil, TerraDerm is a living indigenous-sourced cyanobacterial based re-inoculant sprinkled onto the soil surface by aircraft at the rate of only 1 gram per square meter. Even infrequent desert rains should be sufficient to re-propagate these naturally adapted soil microorganism consortia that use photosynthesis to continuously feed nitrogen and carbon based nutrition to the subsurface soil biota. The photosynthetic cyanobacteria surface layer feeding of these crypto-biotic sub-surface microorganisms is essential for overall soil health and the eventual establishment of vascular plants like grasses and shrubs that can then take over the sub-surface feeding by nourishing nitrogen fixing diazotroph species of soil bacteria. The results of this experimental soil crust re-inoculation approach may vary in different soils and climatic conditions. However, the CO_2 and nitrogen drawdown from the atmosphere is expected to be a continuous process over many decades leading to permanent improvement of the "soil net primary productivity" as long as the soil is not re-damaged by subsequent unsustainable land use such as overgrazing. Roughly 1 billion hectares or 1/7th of global landmass may be a candidate for this type of soil restoration. TerraDerm application as a replacement for factory fertilizer is being aggressively studied as well as how to qualify its carbon drawdown capability for carbon credits.

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ENVIRONMENT – CLIMATE CHANGE – BIOENERGY – MONITORING AND ASSESSMENT

FAO - ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER

The possible competition for land makes it impossible to produce enough first generation biofuel to offset a large percentage of the total fuel consumption for transportation. As opposed to land-based biofuels produced from agricultural feedstocks, cultivation of algae for biofuel does not necessarily use agricultural land and requires only negligible amounts of freshwater, and therefore competes less with agriculture than first generation biofuels. Combined with the promise of high productivity, direct combustion gas utilization, potential wastewater treatment, year-round production, the biochemical pathways and cellular composition of algae can be influenced by changing cultivation conditions and therefore tailored on local needs. On the other hand, microalgae, as opposed to most plants, lack heavy supporting structures and anchorage organs which pose some technical limitations to their harvesting.

The reasons for investigating algae as a biofuel feedstock are strong but these reasons also apply to other products that can be produced from algae. There are many products in the agricultural, chemical or food industry that could be produced using more sustainable inputs and which can be produced locally with a lower impact on natural resources. Co-producing some of these products together with biofuels, can make the process economically viable, less dependent from imports and fossil fuels, locally self sufficient and expected to generate new jobs, with a positive effect on the overall sustainability.

This document provides an overview of practical options available for co-production from algae and their viability and suitability for developing countries.

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