

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 management¹¹. 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 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 risky¹². Furthermore, it is highly dependent on the technologies for cultivation, harvesting and processing, type and productivity of algal strain, prices of inputs like nutrients, CO₂, 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

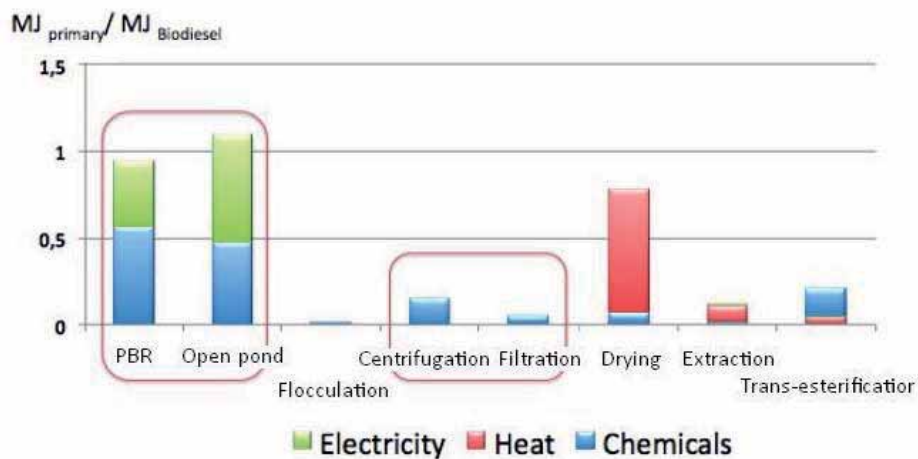
According to the IEA, the cultivation and the drying phase are extremely relevant when the production of algal biodiesel production is analyzed with respect to life-cycle emissions.

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 photobioreactor (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 productivity¹³ 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, CO₂, 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 content¹⁴. 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.

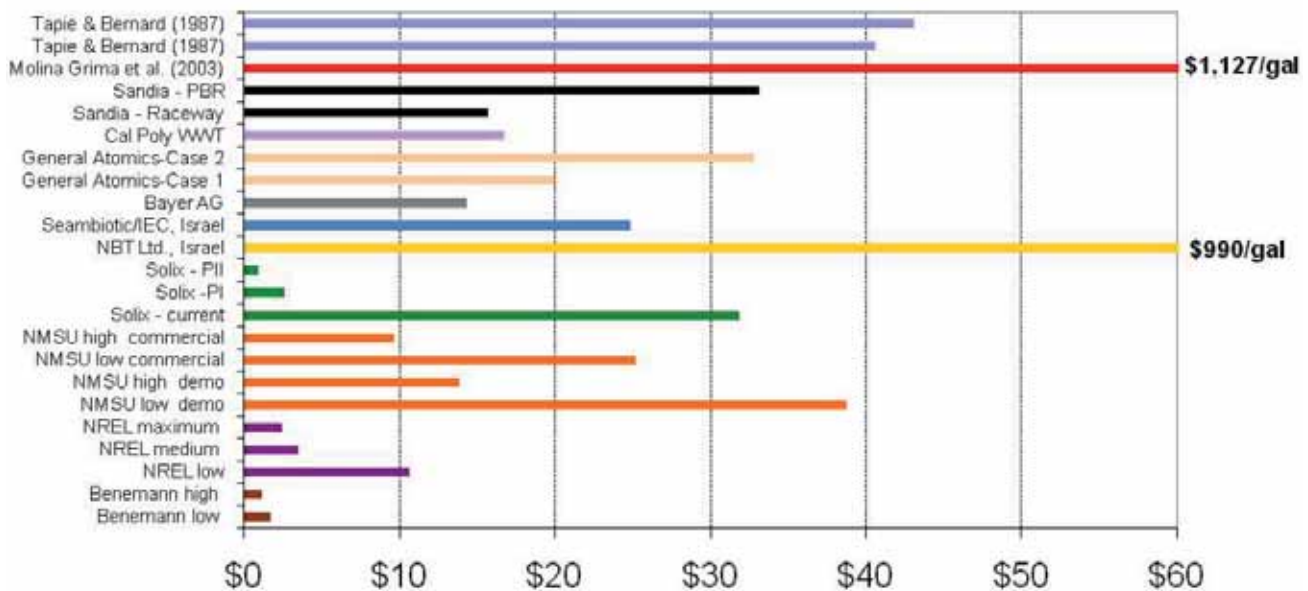


Figure 2: Production costs estimates for algal oil: trygliceride production costs in USD/gallon from different private companies and research centers (source: Philip T. Pienkos (NREL) – Algal biofuels: ponds and promises – presentation at the 13th Annual Symposium on Industrial and Fermentation Microbiology, 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 achievable¹⁵.

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-

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 Sohonsa Corporation (Japan)
			Tianjin Lantai Biotechnology (China)
Astaxanthin	Haematococcus	10000 /kg	Parry Pharmaceuticals (India)
			AlgaTechnologies (Israel)
			Bioreal (Hawaii, USA)
			Cyanotech (Hawaii, USA)
			Mera Pharmaceuticals (Hawaii, USA)
Whole-cell dietary supplements	Spirulina	50 /kg	Parry Pharmaceuticals (India)
	Chlorella		BlueBiotech International GmbH (Germany)
	Chlamydomonas		Cyanotech (Hawaii, USA)
Whole-cell aquaculture feed	Tetraselmis	70 /L	Earthrise Nutritionals (California, USA)
	Nannochloropsis		Phycotransgenics (Ohio, USA)
	Isochrysis		Aquatic Eco-Systems (Florida, USA)
Polyunsaturated fatty acids	Nitzschia	60 /g	BlueBiotech International GmbH (Germany)
	Cryptocodinium		Reed Mariculture (California, USA)
	Schizochytrium		BlueBiotech International GmbH (Germany)
			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)
Anticancer drugs	Cyanobacteria		Cyanotech (Hawaii, USA)
Pharmaceutical proteins	N/A	N/A	PharmaMar (Spain)
Biofuels	Chlamydomonas	N/A	Rincon Pharmaceuticals (California, USA)
	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: Market values of some of the main algae based products (Rosenberg, Oylar 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 10⁶ 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
β-Carotene	200	300	25 ^a	60	600	>1200
lutein	25				30 - 800	
Lycopene	35				40- 400	
Notes:	a: based on an average β-carotene content of 5 % dw.					

Table 8: Market sizes and prices of carotenoids 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 carotenoids 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.

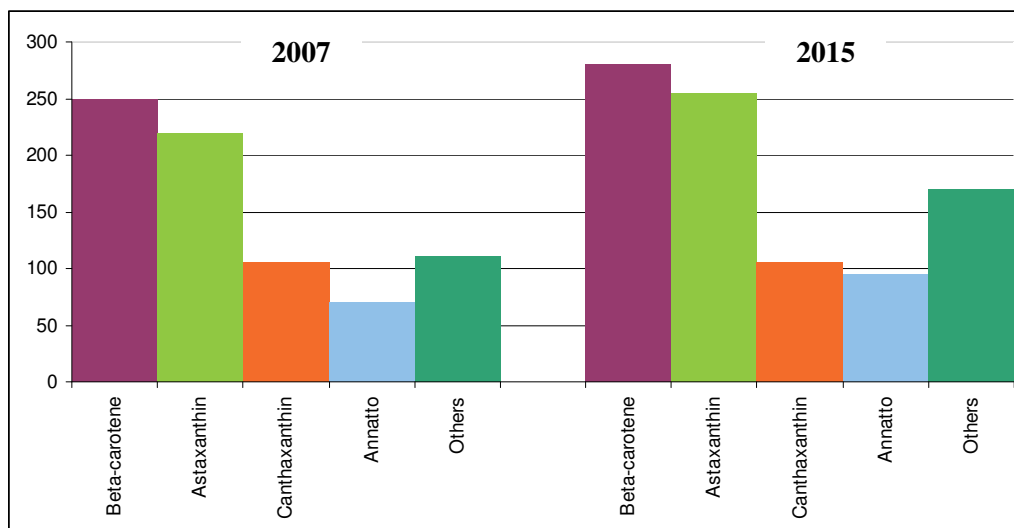


Figure 2: Global Carotenoid market and future outlook in millions of USD (BBC Research)

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 Spain¹⁶. 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, or 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 phycocolloid¹⁷ 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.

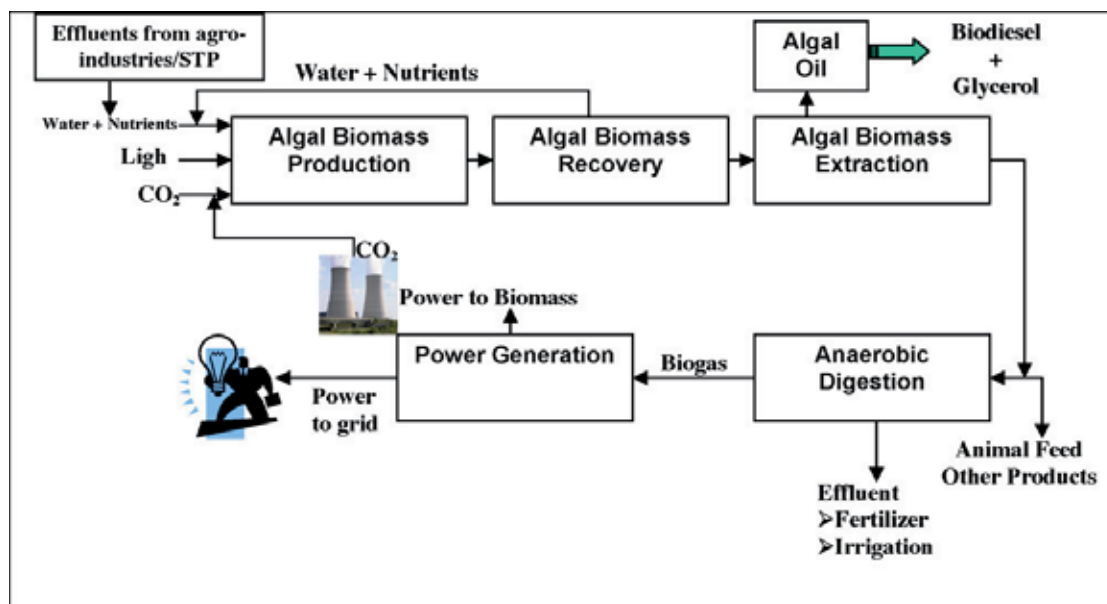


Figure 3: Integrated algal production concept with various co-products (Khan, Rashmi et al. 2009)

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 CO₂, 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):

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- (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 of 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).

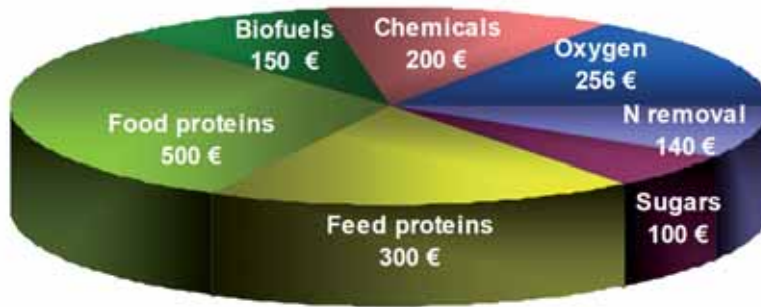


Figure 4: Market value distribution of 1000kg algae after biorefinery (Wijffels, Barbosa et al. 2010)

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, CO₂ 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 CO₂ and NO_x for algae cultivation. The algae produce, besides the already mentioned animal feed, oil for biofuel and clean water (InnovatieNetwerk 2008).

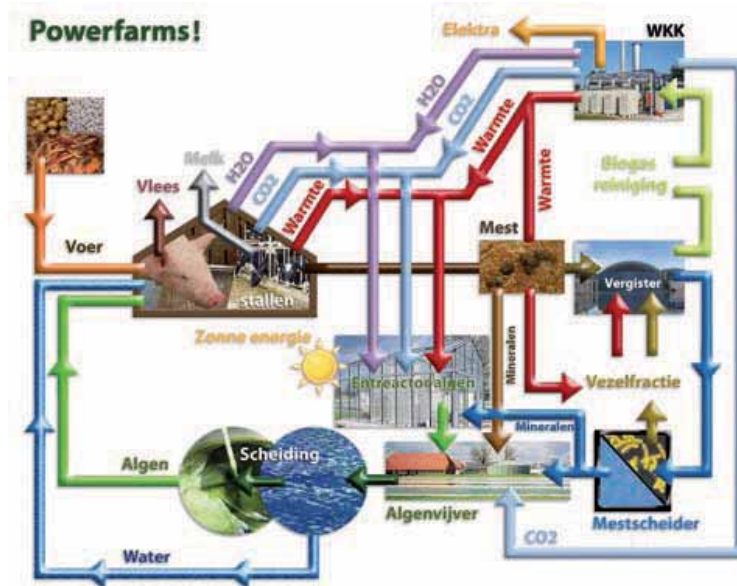


Figure 5: Schematic overview of the Powerfarm! concept (InnovatieNetwerk 2008)

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 the 1990s (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 complete¹⁸, 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 CO₂ are essential. Low cost nutrients

will generally be available from waste streams, CO₂ 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 CO₂ 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 Research	>USD1000 /kg	Small	Many	>5%	Tubular, Indoors	Commercial
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%	Tubular, 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 feeds	\$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 ASTM²⁰ 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 led 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 equator²¹ 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 regions²² 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.

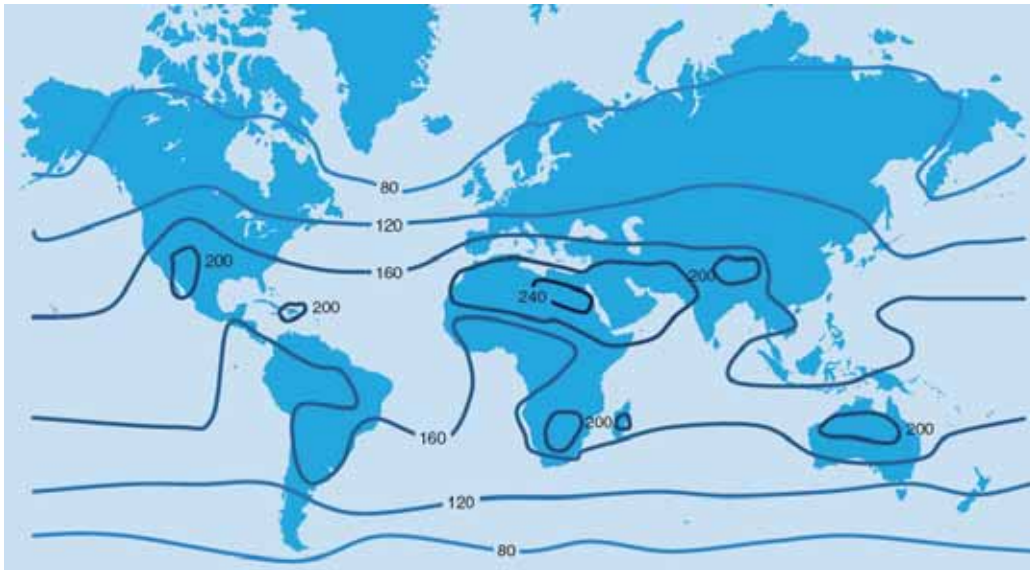


Figure 6: World map of algae biomass productivity (tons/ha/year) at 5% photosynthetic efficiency considering an energy content of 20 MJ/kg dry biomass (Tredici 2010)

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 micro-

organisms (like microalgae) modified through 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 large 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.

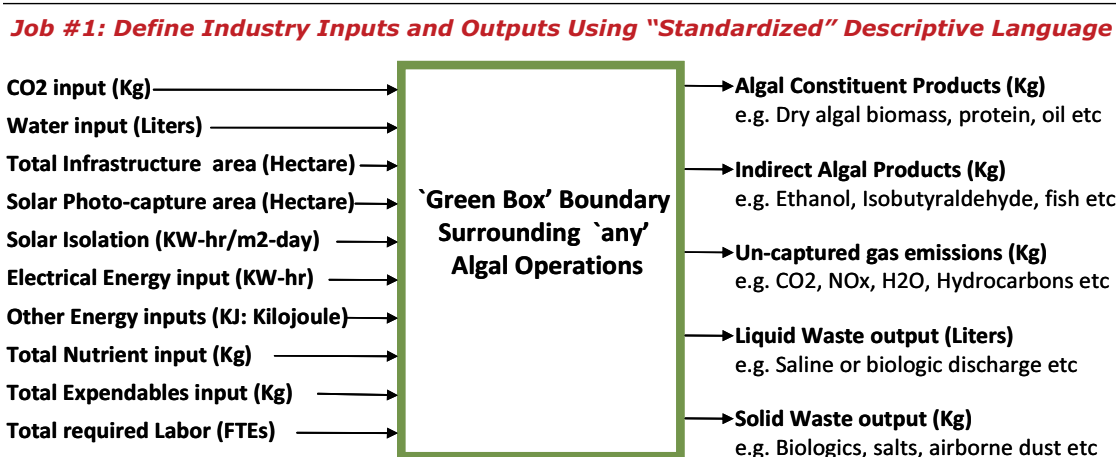


Figure 7: ABO Technical Standards Committee objective

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 micro-

organisms (like microalgae) that have been modified through 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), if they exist.

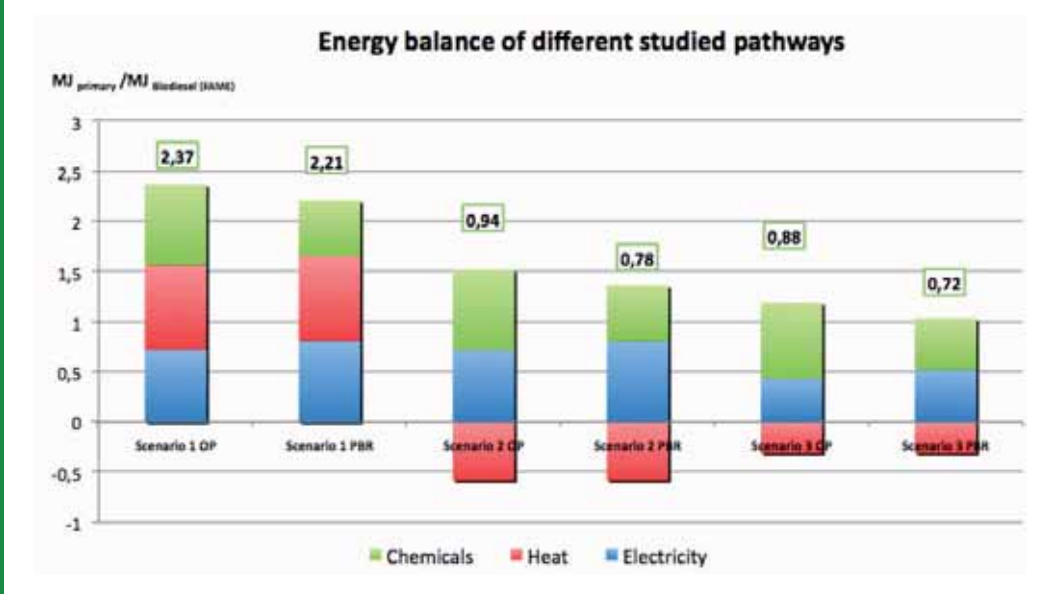
Algal biodiesel production integrated with heat and combined heat and power (CHP) production

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 (CO₂ of GHG equivalent per MJ of biodiesel produced) that demonstrate how these improve if combined with heat generation or combined heat and power systems²³.

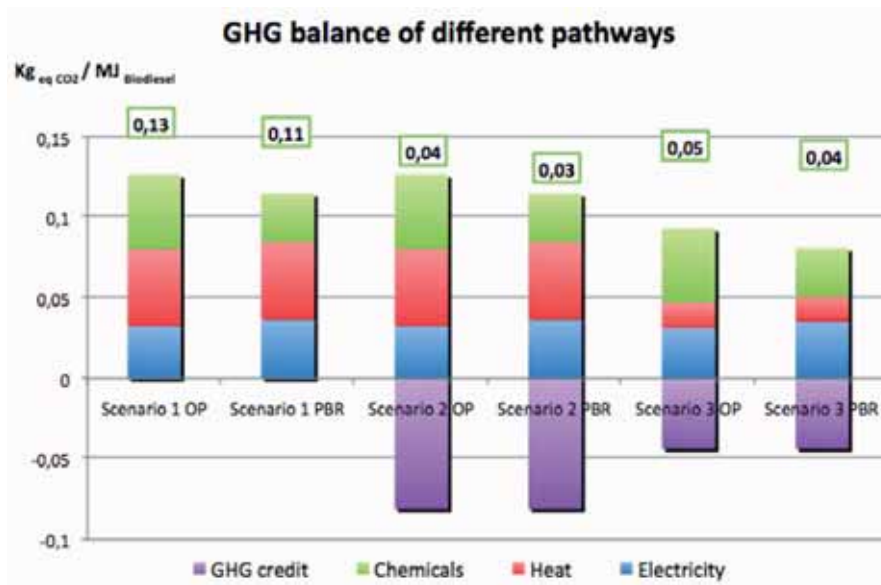
1. The “Base scenario” assumes the production of algal biodiesel with drying before extraction of oil. There is no use for residues of extraction and transesterification.
2. The “Dry Path” scenario assumes the production of algal biodiesel with drying before extraction of oil. There is burning of residues 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/m²/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 ($\text{MJ}_{\text{required}} / \text{MJ}_{\text{biofuel}}$) and a GHG balance in the range of 0.08-0.084 ($\text{kgCO}_{2\text{eq}} / \text{MJ}_{\text{biofuel}}$)

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 CO₂ from combustion gas; in fact CO₂ 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 CO₂ emitting industries.

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- 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.