ALGAE-BASED BIOFUELS:

A Review of Challenges and Opportunities for Developing Countries

May 2009

ECOFYS

GBEP Global Bioenergy Partnership

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Acknowledgements

In October 2008, the FAO Interdepartmental Working Group on Bioenergy recommended the preparation of this review paper on algae-based biofuels as a reference platform for possible future work of the Organization. Development of the review paper was coordinated by Alessandro Flammini (GBEP Secretariat) under the overall guidance of Mr Jeff Tschirley (Chair, FAO Bioenergy Working Group).

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We would like to acknowledge the valuable contributions of Prof. Mario Tredici (University of Florence), Lew Fulton (IEA), Soufien Taamallah (IEA), Joel Cuello (University of Arizona), Jim Sears (Algal Biomass Organization), Mohammad Hasan (FAO, Fisheries Department) and other FAO colleagues, who provided inputs and support in the preparation of this paper. The information contained does not necessarily reflect the official views of the Organization.

This review paper provides a joint contribution to the programme of work of the FAO Interdepartmental Working Group on Bioenergy and the Global Bioenergy Partnership (GBEP).

Summary

General conclusions

- A multitude of algae-based biofuel (ABB) pathways are possible and need to be determined on a case- by-case basis.
    - There is a variety of land based cultivation systems, and several different ABBs and other bioenergy carriers can be produced.
    - Land based systems are more developed then sea based systems.
    - Many input sources can be used, like combustion gas, salt water and wastewater. The availability of these influences the exact ABB concept.
    - Climatic conditions, such as annual solar irradiation and temperature, strongly influence ABB design.
    - ABB systems are suitable for many land and water types, with widely varying opportunities and restrictions.
- ABB's economic viability is still in its nascent phase.
    - There are no commercial scale examples producing only bioenergy.
    - Energy and biofuels tend to have a low value.
    - Algae cultivation and processing systems require a high capital input (higher than agriculture).
    - Biomass output is potentially high, but still under development.
    - At least in the short term, and probably in the medium term, higher value co-products are needed for economic viability.
- As with plant based biofuels, ABBs have important sustainability issues, but also several significant sustainability opportunities, often unique to algae.
    - Large amounts of land with a low economic and ecological value can be used.
    - Fresh water usage can be avoided.
    - Even more space in seas and oceans is available for ABB production.
    - Several GHGs can be captured and their emissions reduced.
    - Several waste streams can be treated, while at the same time being used as carbon and/or nutrient and/or water source.

Conclusions specific to developing countries

- ABB production holds future promise for developing countries.

- A new industry, generating jobs, GDP and energy independence.
- Developing countries are often situated in regions which are geographically interesting for algae cultivation (favourable climatic conditions, cheap labour and underdeveloped land).

- All ABB concepts require significant capital investment.
    - Access to this technology by the poor may be difficult.
    - Foreign investment could lead to revenues leaving the country.
    - Large-scale facilities are more economically viable, but are also more likely to have higher social and ecological impacts.
- Various knowledge levels required:
    - Developing and engineering ABB technology requires a high level of expertise until construction is finished.
    - Innovation for higher productivity also requires some knowledge and/or experience.
    - Operation and maintenance, as well as processing, can be mostly done without specific educational requirements. This group will be the majority of the workforce.
- Knowledge gaps exist for several critical factors:
    - Due to a lack of industrial scale experiments, there is insufficient knowledge to adequately judge the economic viability.
    - Productivity data is often extrapolated from small experiments, and not always presented clearly and consistently.
    - Overall analysis of energy balances, GHG balances and CO_2 abatement potential are lacking.

ABB technical concept considerations

- **Land based systems**
    - Closed systems have a higher capital, technology, technical skill, research and maintenance requirement than open systems, and therefore the latter are generally preferable.
    - Open systems have a high water loss due to evaporation, so a renewable water source that can be replenished is required.
    - Locally occurring algae species should be cultivated.
    - A renewable nutrient source is needed.
    - Co-production of food or feed strongly increases economic viability, allows small scale, near-term implementation, food supply and

experience, and therefore has to be considered a strict requirement in the short term.

- **Sea based systems**
  - Large potential in territorial waters of developing countries.
  - Can be labour intensive. This benefits developing countries in that more jobs are created, while this has a small economic impact due to lower wages.
  - Co-production of food or feed has the potential to increase economic viability and can build on existing experience.
  - Synergy with fish cultivation has high potential.

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1 Introduction

Algae have recently received a lot of attention as a new biomass source for the production of renewable energy. Some of the main characteristics which set algae apart from other biomass sources are that algae (can) have a high biomass yield per unit of light and area, can have a high oil or starch content, do not require agricultural land, fresh water is not essential and nutrients can be supplied by wastewater and CO_2 by combustion gas.

The first distinction that needs to be made is between macroalgae (or seaweed) versus microalgae. Microalgae have many different species with widely varying compositions and live as single cells or colonies without any specialization. Although this makes their cultivation easier and more controllable, their small size makes subsequent harvesting more complicated. Macroalgae are less versatile, there are far fewer options of species to cultivate and there is only one main viable technology for producing renewable energy: anaerobic digestion to produce biogas. Both groups will be considered in this report, but as there is more research, practical experience, culture and there are more fuel options from microalgae, these will have a bigger share in the report.

In chapter 2, the different technological components that make up Algae Based Biofuels (ABB) are discussed: algae cultivation technology; processing to biofuel options; locations and carbon; light and nutrient inputs. Both land based and sea based applications are discussed.

In chapter 3, ABB sustainability is investigated in depth. First, existing biofuel sustainability standards are analysed for applicability, followed by a thorough analysis of the opportunities and risks of ABB sustainability. Secondly, sustainability is discussed in the context of potential and threats for developing countries.

2 Concepts for bioenergy from algae

Algae have a clear potential to be used as a source for the production of renewable energy. In order to utilize algae for this purpose, the most common systems for cultivating them are investigated. Since there are many species of algae with varying characteristics, a diversity of options for the production of algae-based energy have been analysed. Subsequently, the inputs and conditions needed for growing algae are examined. The chapter is concludes with a formulation of complete concepts for producing a renewable energy carrier from algae, which will be used for in-depth analysis later in the report.

2.1 Algae culture systems

Culture systems are very different between macroalgae (seaweed) and microalgae. Because of their small (μm) size, microalgae have to be cultivated in a system designed for that purpose (placed on land or floating on water), while seaweed can be grown directly in the open sea. The first mention of seaweed culture dates back to 1690, in Japan (Tamura in Buck and Buchholz, 2004). Japan and China are still the main producers of cultured seaweed. Seaweed is mainly used as a food product, either eaten directly, or used in many processed foods as stabilizers or emulsifiers. Besides culturing seaweed, part of the current seaweed production comes from harvesting natural populations or collecting beach-cast seaweed. Besides the disturbance of the ecosystem by these practices, they are clearly unsustainable for application on a very large scale. Therefore growing macroalgae in a dedicated cultivation system is worth considering.

For microalgae, the development of dedicated culture systems only started in the 1950s when algae were investigated as an alternative protein source for the increasing world population. Later, algae were researched for the interesting compounds they produce, to convert CO_2 to O_2 during space travel and for remediation of wastewater. The energy crisis in the 1970s initiated the research on algae as a source of renewable energy.

For algae to grow, a few relatively simple conditions have to be met: light, carbon source, water, nutrients and a suitably controlled temperature. Many different culture systems that meet these requirements have been developed over the years, however, meeting these conditions for scaled systems is difficult. One important prerequisite to grow algae commercially for energy production is the need for large-scale systems which can range from very simple open air systems on- or offshore which expose the algae to the environment, to highly controllable, optimized but more expensive closed systems. The necessary technology for developing profitable algae-based fuel generation is still in various states of development and the final configuration is yet to be determined and demonstrated at the industrial scale.

2.1.1 Land based open culture systems

The simplest open air algae cultivation systems are shallow, unstirred ponds. The sizes range from a few m^2 to 250 ha (Figure 1a and b). CO_2 is the carbon source for algae. Its dissolution from air into water limits the growth rate, making the yield per hectare relatively low. Other negative influences are the slow diffusion of nutrients and flotation and sedimentation of dead and living algae, limiting the usage of available sunlight. This can be prevented by some form of agitation, which in practice is done in circular ponds with a mechanical arm stirring in a circular motion (Centre-Pivot ponds, Figure 1c), or more commonly in so-called raceway ponds (Figure 1d), in which a paddle wheel (Figure 1e) forces a circulating water flow through a long narrow pond. Blowing gas bubbles through the medium provides both agitation and (part of the required) CO_2. Air, compressed CO_2 or CO_2-containing combustion gases can be applied. The major bottlenecks of these open systems are that there is almost no possibility for temperature control (unless a source of cheap surplus heat is available) and that they are very susceptible to invasion of algal predators, parasitic algae or other algal strains that grow better at the applied conditions and therefore out-compete the desired species. Only a limited amount of species is dominant enough to maintain itself in an open system (Carlsson *et al.*, 2007; Chisti, 2007; Pulz, 2001; Rodolfi *et al.*, 2009).

Figure 1: Examples of open cultivation systems

a. Small pond for *Spirulina* culture, Asia (Wikipedia, 2007)
b. *Dunaliella salina* ponds of Cognis, Western Australia (BEAM)
c. Centre-Pivot ponds for the culture of *Chlorella* in Taiwan (BEAM)
d. Open raceway-type culture ponds of Earthrise in California, US(Spirulina.org.uk)
e. Paddle wheel of a raceway pond (NMSU)

2.1.2 Land based closed cultivation systems

Temperature, gas exchange and competition problems can be alleviated through closing an open system by covering it with transparent material or a greenhouse, but this is expensive for large surfaces. Another simple, but inexpensive example is using polyethylene bags or sleeves (Figure 2a) for batch culture. Sizes go up to 1 000 litres, but sensitivity to environmental conditions and short life expectancy make this system inappropriate for outside use. Several more advanced systems have been developed based on more durable transparent materials: glass, polyethylene and polycarbonate. These reactors offer continuous operation, a high level of controllability and elevated biomass concentrations, which results in lower space requirements and lower harvesting costs per tonne of algae. One example is the bubble column (Figure 2b), a vertical tubular reactor. Scalability of this system is limited since, when putting several systems close to each other, they will cast a shadow on each other (Figure 2c). Using a reactor consisting of long horizontal tubes eliminates this problem[1] (tubular reactor, Figure 2d-f). However, this has its own scaling problem: algae will consume nutrients and CO_2 while producing O_2 (which could inhibit[2] algal growth at elevated concentrations), so growth conditions deteriorate further along the tube. Up-scaling can be achieved by installing individual modules with optimized size vs. tube length ratios. To make optimal use of surface area receiving solar irradiation, a flat photobioreactor can be applied (Figure 2g). This system can potentially yield a much higher biomass concentration, but is still under development[3]. Difficulties are the complicated flow regime inside the reactor and scalability, although the latter has been greatly improved by a design called the green wall panel (Rodolfi *et al.*, 2009). Figure 2h shows flat photobioreactors in a solar panel-like set-up. There are many variations and innovations on the previously described closed systems.

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[1] It should not be easily concluded that simply replacing vertical tubes with horizontal tubes eliminates the problem of shadowing. Overcoming the problem in both instances is a function of their spacing.

[2] This will depend on the residence time of the algae in the tube.

[3] Like vertical or horizontal tubes, flat-pane reactors are not exempt from the problem of shadowing when arranged in arrays.

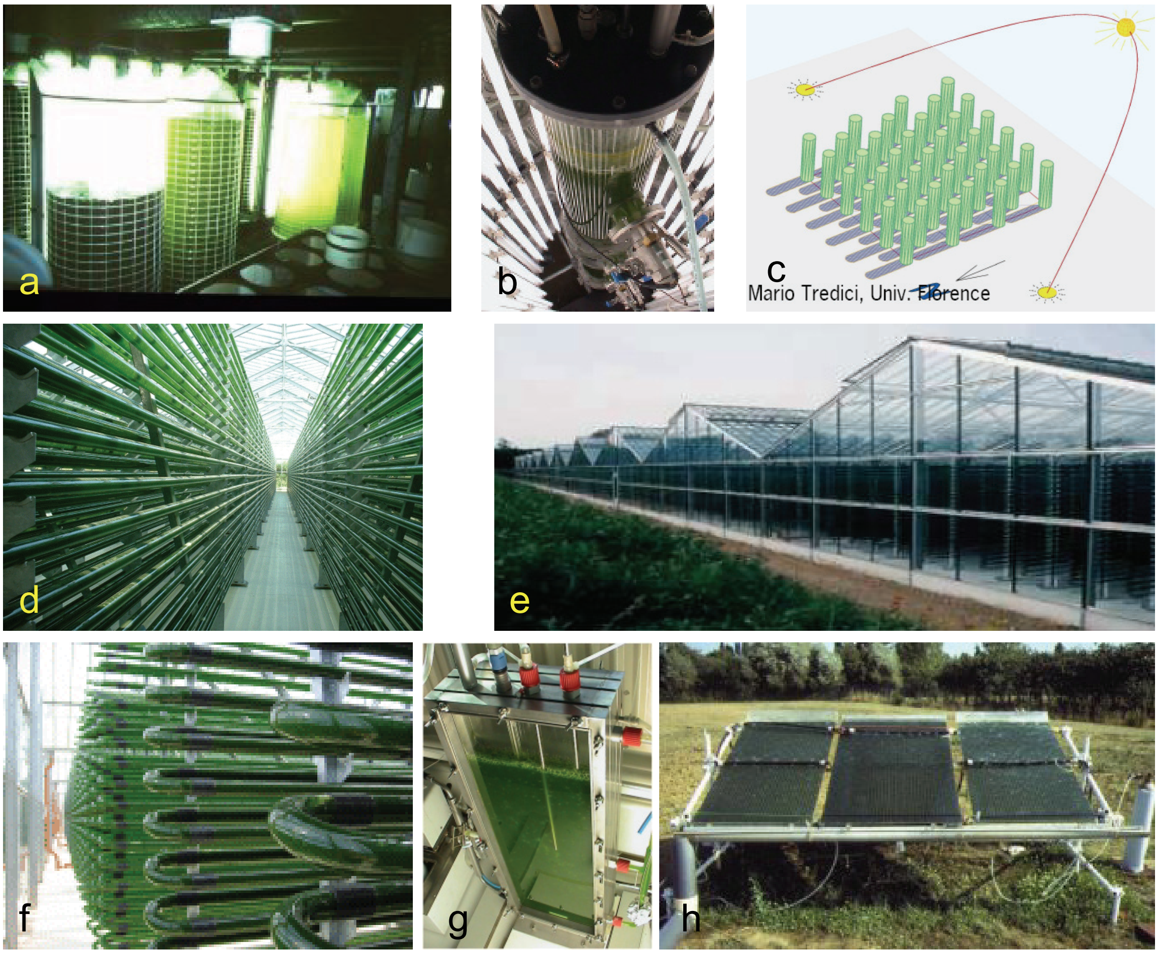


Figure 2: Examples of closed cultivation systems

a. 'Big Bag' culture of microalgae (BEAM)
b. Bubble column reactor (Tredici in Wijffels, 2007)
c. Field of bubble columns induce shading (Wijffels, 2007)
d-f. Tubular reactor system (Bioprodukte-steinberg.de)
g. Experimental flat photobioreactor (Wijffels, 2007)
h. Experimental alveolar-panel photobioreactor (Tredici and Materassi, 1992)

2.1.3 Offshore cultivation systems

Historically, seaweed cultivation techniques have been developed based on the local circumstances, often using shallow, protected coastal areas that are safe, easily accessible and allow for easy immobilization of the culture system to the seabed. Generally the techniques used are labour intensive and therefore are restricted to regions with the lowest incomes. Harvesting natural macroalgae populations is also common practice in selected areas. For renewable energy production, macroalgae production is not based on harvesting natural populations and therefore focuses on growing seaweed species that can attach to underwater ropes or similar support structures. Furthermore, available locations not intensively used for other purposes such as shipping routes, port areas, recreation, etc. will often be in deeper seas with rougher conditions. Important examples of cultivation systems adaptable to these conditions are those based on vertical ropes, which allow the cultivated seaweed to catch all available light until the maximum light penetration depth; systems based on horizontal lines, which minimizes the amount of rope material needed per unit of area, or hybrid systems combining horizontal and vertical lines. In all cases the systems can be floating, anchored to the sea or both. Problems of damage to rope structures and washed off biomass have been reported (Chynoweth, 2002), so a cultivation system that prevents these problems needs to be designed. During experiments at sea (Buck and Buchholz, 2004), using rings (diameter of 5m, surface of 19.6m^2 and 80-100 m substrate rope) with ropes as a base for seaweed to attach to, gave the best results, especially under high flow or heavy weather conditions. These rings can be attached to each other and/or the seabed and can include a slow-release fertilizer. The main problem of this system is that the rings need to be harvested individually, making cost-price reduction through economy of scale more difficult. For seaweed cultivation on a large scale (1 000s ha), a cultivation system that is simple, low-cost, low maintenance, and has a high light capture, productivity, resilience to climatic conditions, durability and life expectancy, while allowing easy harvesting and replantation is a great challenge and will require a lot of research and development.

When selecting a location for seaweed cultivation, several considerations have to be made. Besides temperature, nutrient and light consideration (which will be mentioned later) and previously mentioned competition with other functions of the sea, distance from shore (or distance from a suitable harbour) are some of the important criteria, as they imply energy and time spent on transportation. Fresh seaweed contains around 90 percent water and thus a high amount of mass with a relatively low energy content. The water content can be reduced at the harvest location, pressure filtration will remove around 20 percent of the water, alternative options need to be investigated and energy spent on dewatering versus transport have to be optimized. Furthermore, the (necessity of) treatment of the released press water needs to be investigated (Reith *et al.*, 2005). Another criterion is the availability of existing offshore infrastructure. Offshore oil or gas platforms provide an anchoring point, boat and helicopter landing, personnel accommodation and in some cases pipes to shore that could be converted to pump seaweed or biogas to shore, or even CO_2 or nutrient rich waste water to the cultivation location. Also, offshore wind turbine parks contain a considerable amount of unused space between the turbines (distance between turbines is seven times the rotor blade length) which is restricted to maintenance vessels. Turbines provide anchoring points and have and individual boat landing, and in case seaweed is (partially) converted into electricity on-site, or if electricity is needed for a first processing step, a grid connection is available. Most considerations also apply to installations that capture wave energy, with the added benefit of milder sea conditions "behind" the wave energy devices.

2.1.4 Culture systems appropriate for energy production through algae

Energy is a low-value product. ("High" oil prices are tens of €cents per litre, algal biomass for health-foods and cosmetics can cost €1 000s per kilo.) This means that algaculture should be as cheap as possible in order to make conversion into energy carriers economically feasible. Current production systems of micro- and macroalgae supply knowledge and experience on cultivation, but do not supply biomass for a production price that can compete with other sources of (renewable and non-renewable) energy. Systems have to be optimized for a minimal financial and energy input, economy of scale has to be utilized to reduce production prices and additional revenue from other sources than purely energy from algae have to be obtained, through co-production or treatment of waste streams (see sections 2.2 and 2.3).

Within the open systems, raceway ponds provide a much better yield than more extensive systems, while keeping capital investment generally low. In scientific literature, this system is sometimes mentioned as the only open system practicable for large-scale production (Carvalho *et al.*, 2006; Chisti, 2007). An important condition however, is the availability of a microalga that can remain dominant yearround and has good energy-yielding properties. In case this proves difficult or required land is costly, a horizontal tubular system has the best characteristics. Although much more expensive, it offers a much higher yield per hectare and controllability, while up-scaling is easier than with other closed systems. While a few large-scale commercial raceway examples exist, the biggest closed systems cover a few hectares. For either option, no commercial example of energy production from algae exists. In recent years, many claims have been made on possible productivities (and often oil contents) that approach or even cross the theoretical maximum. Often these are the result of extrapolating preliminary laboratory test and experiments of hours or days to dry weight or oil per hectare per year claims, often suspected to have been made to achieve financial gain. This has given rise to both euphoria over the potential of algae for renewable energy on the one hand and disappointment and distrust by the well informed on the other. This has resulted in an exponential growth of interest in the topic but also at times a negative perception surrounding commercial efforts. The fact is that no commercial algal energy producer yet exists, that high-yielding terrestrial crops will not easily be surpassed by algae in terms of energy content (but the area available for algaculture surpasses that of terrestrial crops by far), that a positive energy balance of energy output versus energy input for operation and the production of the cultivation system, and the subsequent financial returns to cover the process costs and the initial investment for the cultivation system are very challenging.

Table 1: Comparison of open versus closed land based systems

Parameter or issue	Open ponds and raceways	Photobioreactors (PBR)
Required space	High	For PBR itself low
Water loss	Very high, may also cause salt precipitation	Low
CO_2-loss	High, depending on pond depth	Low
Oxygen concentration	Usually low enough because of continuous spontaneous outgassing	Build-up in closed system requires gas exchange devices (O_2 must be removed to prevent inhibition of photosynthesis and photo oxidative damage)
Temperature	Highly variable, some control possible by pond depth	Cooling often required (by spraying water on PBR or immersing tubes in cooling baths)
Shear	Usually low (gentle mixing)	Usually high (fast and turbulent flows required for good mixing, pumping through gas exchange devices)
Cleaning	No issue	Required (wall-growth and dirt reduce light intensity), but causes abrasion, limiting PBR life-time
Contamination risk	High (limiting the number of species that can be grown)	Low (Medium to Low)
Biomass quality	Variable	Reproducible
Biomass concentration	Low, between 0.1 and 0.5 g/l	High, generally between 0.5 and 8 g/l
Production flexibility	Only few species possible, difficult to switch	High, switching possible
Process control and reproducibility	Limited (flow speed, mixing, temperature only by pond depth)	Possible within certain tolerances
Weather dependence	High (light intensity, temperature, rainfall)	Medium (light intensity, cooling required)
Start-up	6 – 8 weeks	2 – 4 weeks

Capital costs	High ~ US$100 000 per hectare	Very high ~ US$250 000 to 1 000 000 per hectare (PBR plus supporting systems)
Operating costs	Low (paddle wheel, CO_2 addition)	Higher (CO_2 addition, oxygen removal, cooling, cleaning, maintenance)
Harvesting cost	High, species dependent	Lower due to high biomass concentration and better control over species and conditions
Current commercial applications	5 000 (8 to 10 000) t of algal biomass per year	Limited to processes for high added value compounds or algae used in food and cosmetics

Source: (Pulz, 2001 adapted in Carlsson 2007)

2.2 Algal products

Since there are so many different algal species, algae as a group can produce a wide variety of products. This section investigates the algal energy products which are relevant from a renewable energy perspective; these will be treated in the paragraphs below.

2.2.1 Complete cell biomass

It is possible to dry algal biomass and combust it directly to produce heat and electricity, or use high-temperature high-pressure processes like pyrolysis, gasification and hydro-thermal upgrading (HTU) to produce fuel gas or fuel oil respectively. These technologies require dry biomass. Drying requires a great deal of energy, which has a strong negative effect on the energy balance and capital costs of required equipment (Wijffels, 2007) (drying with solar heat would compete for solar light with algae production). Thermochemical liquefaction is a high-temperature, high-pressure treatment in which a wet biomass stream can be applied (Banerjee *et al.*, 2002; Dote *et al.*, 1994; Tsukahara and Sawayama, 2005), but this technology is still under development and is likely to require at least five years before it can be commercially applied (Meuleman, 2007). A biochemical way to process the whole biomass is anaerobic digestion. This produces biogas from the wet stream and requires much less energy input than the thermochemical options. There is 55-75 percent methane in biogas (Mes *et al.*, 2003), which can be combusted to produce heat and/or electricity, or upgraded to replace natural gas. Some experiments showed that microalgae with an intact cell wall are quite resilient against fermentation, causing the valuable energy to remain locked inside the cells. In many cases a pre-treatment step to break these cell walls will be necessary. Anaerobic digestion is a well developed, robust technology with many commercial examples This technology is applied to waste streams containing organic compounds, with a very low feedstock price (Reith, 2004). Considering the constraints of the other whole-cell treatment technologies, anaerobic digestion appears the most favourable. With this option it is relatively easy to recover the nutrients as the nutrient-free energy carrier is in the gas phase. Also, this technology can be utilized as a second step after extracting compounds with a higher value or to treat substandard batches of algae grown for other uses.

2.2.2 Unique products

There are many initiatives on energy generation from algae, some ideas have been around for many decades, some are currently at the pilot-stage, but so far there is no commercial implementation. Algaculture however, is performed worldwide to produce products with a higher economical value than energy. Sometimes the entire alga is the product, but often compounds are extracted which are very difficult or impossible to produce in other ways. Some examples of these so-called "unique products" include food, food-additives and health-food, feed for fish, shrimp and shellfish, colorants and omega-3-fatty acids (Molina Grima *et al.*, 2003; Reith, 2004). The prices of these unique products range considerably: cheapest is healthfood Spirulina from Myanmar for 8€/kg, food for aquatic organisms Nannochloropsis costs 500€/kg, Vitamin A precursor ß-carotene costs 1 000 €/kg and the strongest known anti-oxidant astaxanthin costs up to 10 000 €/kg (Wijffels, 2007), at the extreme end are 13C labelled fatty acids, its price per kg is

US$38 000 000 (the company Spectra Stable Isotopes produces this commercially, but only about 400 g per year) (Fernandez *et al.*, 2003).
Unique products are not treated further in this report, but the experience with culture systems for these algae is successfully used for modelling energy generation.

2.2.3 Lipids and biodiesel

Lipids are one of the main components of microalgae; depending on the species and growth conditions 2–60 percent of total cell dry matter (Wijffels, 2006), as membrane components, storage products, metabolites and storages of energy. These lipids can be used as a liquid fuel in adapted engines as Straight Vegetable Oil (SVO). Tri-glycerides and free fatty acids, a fraction of the total lipid content, can be converted into biodiesel. In comparison with SVO, algal oil is unsaturated to a larger degree making it less appropriate for direct combustion in sensitive engines.

In order to efficiently produce biodiesel from algae, strains have to be selected with a high growth rate and oil content. If an open culture system is used, the selected strain must have the ability to remain dominant under the applied conditions. Because of environmental conditions such as temperature, this means in practice that using a locally occurring strain is preferable in most cases (Sheehan *et al.*, 1998). In a closed photo-bioreactor, competition from other algae can be prevented to some extent and optimal growth conditions can be more easily maintained. Lipid accumulation in algae usually occurs during periods of environmental stress, culture under nutrient-deficient conditions is most often referred to. This implies a trade-off; rapid growth but low lipid content under nutrient sufficient conditions, decrease or near-zero growth but lipid increase under nutrient-deficient conditions. To the contrary, a fairly unique result by Rodolfi *et al.,* (2009) showed an almost consistent productivity and almost doubling of the lipid content to 60 percent after switching to nutrient-deficient conditions in a outdoor pilot reactor under natural light.

From all energy carriers produced from algae, biodiesel has received the most attention and is the only initiative which is on the border of pilot-scale and full-scale deployment.

2.2.4 Carbohydrates and ethanol

Bioethanol can be used as a biofuel which can replace part of the fossil-derived petrol. Currently bioethanol is produced by fermenting sugars, which in the case of corn are derived from hydrolyzing starch. Algae species starch contents over 50 percent have been reported. With new technologies, cellulose and hemicellulose can be hydrolysed to sugars (Hamelinck *et al.*, 2005), creating the possibility of converting an even larger part of algal dry matter to ethanol. Algae have some beneficial characteristics compared to woody biomass, the traditional target for this technology. Most notable is the absence of lignin in algae, making its removal needed for woody material redundant. Furthermore, algae composition is generally much more uniform and consistent than biomass from terrestrial plants, because algae lack specific functional parts such as roots and leaves. Algal cell walls are largely made up of polysaccharides, which can be hydrolyzed to sugar.
Another algae-specific technology for ethanol production is being developed, in which green algae are genetically modified to produce ethanol from sunlight and CO_2 (Deng and Coleman, 1999). Ethanol production from or by algae has very interesting prospects, but is currently only in the preliminary phase of research. More development is needed to analyse a full-scale production system.

2.2.5 Hydrocarbons

One species of algae, *Botryococcus braunii* is well known for its ability to produce hydrocarbons which have been loosely described as equivalent to the "gas-oil fraction of crude oil." (Hillen *et al.*, 1982). Like petroleum, these hydrocarbons can be turned into gasoline, kerosene and diesel. While other algal species usually contain less than 1 percent hydrocarbons, in *B. braunii* they typically occupy 20-60 percent of its dry matter, with a reported maximum of >80 percent (Wijffels, 2006). Depending on the strain, these hydrocarbons are either C30 to C37 alkenes or C23 to C33 odd numbered alkenes (Ranga Rao and Ravishankar, 2007). These hydrocarbons are mainly accumulated on the outside of the cell, making extraction easier than when the cell wall has to be passed to reach the organics inside the cell (Wijffels, 2006). *B. braunii* lives in freshwater, but can also adapt to large range of (sea)salt concentrations. At present, the highest known salt concentration that a *Botryococcus* species can survive is 3 M NaCl, the optimum salinity being around 0.2 M NaCl (Qin, 2005) (seawater contains about 0.6 M NaCl (Dickson and Goyet, 1994)). Salinity manipulation may be used as a tool to yield algal biomass containing the desired lipid composition. Other factors affecting *B. braunii* growth and hydrocarbon production include availability of nitrogen and phosphate, light intensity and pH (Qin, 2005). *B. braunii*'s main disadvantage is that it grows very slowly: it's doubling time is 72 hours (Sheehan *et al.*, 1998), and two days under laboratory conditions (Qin, 2005). This is >20 times slower than fast-growing algae, therefore only low-investment growth systems like raceway ponds are interesting (Banerjee *et al.*, 2002). In such a system *B. braunii* would have to compete with natural occurring algae. Using saline water could give *B. braunii* a strong competitive position. There are parts in the world with brackish water or salty groundwater, which makes the land unusable for agriculture. Specifically for these regions, further investigation on large-scale *B. braunii* culture is certainly warranted, but in the scope of this research not treated further.

2.2.6 Hydrogen

As an energy carrier, hydrogen offers great promise as a fuel of the future, since it can be applied in mobile applications with only water as exhaust product and no NOx emissions when used in a fuel cell. One major bottleneck for the full-scale implementation of hydrogen-based technology is the absence of a large-scale sustainable production method for hydrogen. Currently, hydrogen gas is produced by the process of steam reformation of fossil fuels. Large-scale electrolysis of water is also possible, but this production method costs more electricity than can be generated from the hydrogen it yields. Biological hydrogen production is possible; several bacteria can extract hydrogen from carbohydrates in the dark, a group called purple non-sulphur bacteria can use energy from light to extract more hydrogen gas (H_2) from a wider range of substrates, while green sulphur bacteria can make H_2 from H_2S or $S_2O_3^{2-}$. These options are only interesting if a wastewater with these compounds is available (Rupprecht *et al.*, 2006). Other algae can make hydrogen directly from sunlight and water, although only in the complete absence of oxygen. In practice, this means that hydrogen formation is only possible under conditions that either cost a great deal of energy, or prevent storing solar energy (Kapdan and Kargi, 2006), and a closed culture system is required. At the moment, it is only possible to produce a fraction of the theoretical maximum of 20 g H_2/m2/d, making bulk-scale hydrogen production by algae not yet viable. For this to change in the future, more knowledge of the organisms that can produce hydrogen (only a few have been investigated) and the required conditions is necessary, as well as optimization of the biological route of solar energy to hydrogen, through genetic modification. If these improvements prove to be possible, this would constitute a profitable and renewable hydrogen production (Melis and Happe, 2001).

2.2.7 Conclusion

The choice for the most suitable energy carrier to be produced from algae is most clear in the case of seaweed. As visualized in Figure 3, only the utilization of the entire biomass is an option, because conditions in the open sea cannot be controlled as they can on land, and therefore specifically stimulating the production of e.g. alkanes, lipids or hydrogen are not possible. In Reith *et al.*, (2005), an economic analyses of treating macroalgae with anaerobic digestion, ethanol fermentation, HTU and super critical gasification resulted in the conclusion that only anaerobic digestion allowed for a feedstock price to be paid, the other options were not economically viable even if the seaweed biomass was free. Therefore seaweed is assumed to be converted through anaerobic digestion, if possible after extraction of compounds with a higher market value.

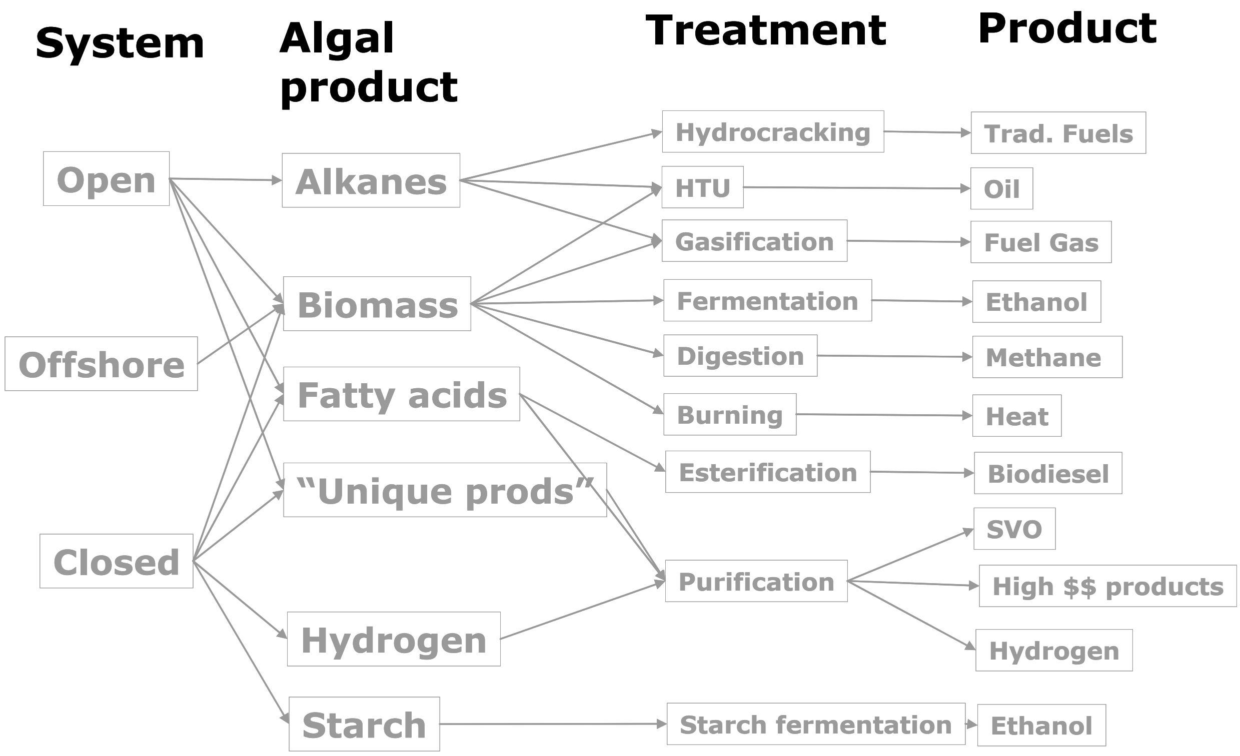
Of the algae-to-energy options reviewed in this paragraph, hydrogen production by algae is mostly far from commercial implementation. Although yield improvement options are being investigated, a breakthrough is not likely to occur in the next decade.

Using algae for ethanol production is in such an early stage that not much can be concluded yet about its strengths and weaknesses and is therefore not investigated further in this report. Nevertheless, its future development deserves attention.

The main product of *Botryococcus braunii* resembles compounds from fossil fuel, which offers exciting possibilities. A culture system used to produce *B. braunii* would cost the same to build and operate as with a fast-growing alga, but the yield would be 20 times less. There are possible scenarios where this would be acceptable, as this seems a relatively low-tech and robust option.

Algae for biodiesel is generally the favoured algae-for-energy option and has been researched the most. (Chisti, 2008a; Chiu *et al.*, 2009; Li *et al.*, 2008a; Li *et al.*, 2008b; Liu *et al.*, 2008; Meng *et al.*, 2009; Mulbry *et al.*, 2008; Rodolfi *et al.*, 2009; Sazdanoff, 2006; Sheehan *et al.*, 1998). Both open and closed land based cultivation systems appear suitable for this option. The conversion of the extracted lipids to biodiesel is relatively easy, and the product price can easily be compared with fossil fuel prices. Most commercially aimed pilot installations also chose this pathway. Since nutrient-limitation is often used as a lipid stimulation strategy, this technology requires strict nutrient input control, therefore using manure or wastewater as a nutrient source may be relatively complicated.

Figure 3: overview of algae to energy options



2.3 Algae cultivation inputs

Besides acquiring the product of interest, growing algae causes a flow of other inputs and outputs. Growing algae for the purpose of energy production requires analysis of these streams to be able to choose the most economical and environmentally friendly options.

2.3.1 CO_2 capture

As with all photosynthetic organisms, algae use CO_2 as a carbon source. No growth can occur in the absence of CO_2, and an insufficient supply of CO_2 is often the limiting factor in productivity. Based on the average chemical composition of algal biomass, approximately 1.8 tonnes of CO_2 are needed to grow 1 tonne of biomass. Natural dissolution of CO_2 from the air into the water is not enough. This could be improved by bubbling air through the water, but, since air contains about 0.0383 percent of CO_2, all of the CO_2 in about 37 000 m^3 air is needed for 1 tonne of dry algae.

Other options are using pure CO_2, which is rather expensive, or a waste source of CO_2 like flue gas from a boiler. Flue gas typically contains about 4 percent to 15 percent of CO_2 and is free or even produces revenue if a financial scheme for the prevention of greenhouse gas emissions is available. The only cost is the supply from the source to the cultivation system, which can be significant depending on the distance and water depth. CO_2 is only needed during daylight, at night it is actually produced, since algae also produce CO_2 for respiration, like all aerobic organisms. (A possible alternative is to dissolve CO_2 from flue gas to the maximum concentration at night, and add this water to the cultivation system during the day). In open systems not all of the supplied CO_2 will be absorbed, so flue gas is added in excess. In principle all available flue gas can be added to the algae pond. Part of the CO_2, NO_x and SO_x will dissolve, the rest will enter the atmosphere as happens conventionally.

After studying the culture of algae with flue gas, Negoro *et al.* reported that the SO_2 and NO_x in the flue gas inhibited algal growth, but a few years later they reported there was barely any difference with growth on pure CO_2 (Negoro *et al.*, 1991; Negoro *et al.*, 1993). More recently, others have also confirmed that flue gas can be used to grow algae without harmful effects (Brown 1996, Hauck *et al.* 1996 and Doucha *et al.* 2005) and at least one commercial algae cultivator on Hawaii is using CO_2 from a small power plant (Pedroni *et al.*, 2001). In addition, dissolved NO_x can be used by algae as a nitrogen source. The amount of flue gas needed per hectare will differ per species of algae, and will also vary throughout the day with light intensity and temperature, thus needs to be optimized for each specific application. High dissolved concentrations of CO_2 (and also SO_2) will affect the pH, thus need to be controlled or buffered. Solubility of CO_2 in a salt water system (higher pH) is higher than when sweet water is used. Also, extra CO_2 can be sequestered by growing algae that produce hard scales around theirs cells, made of calcium carbonate ($CaCO_3$) (Moheimani and Borowitzka, 2007).

2.3.2 Light

Algae rely on (sun)light for photosynthesis and thus growth. Light gets absorbed by the algae, so the higher the algae-concentration, the less deep light enters into the algae broth. Therefore, all algaculture systems are shallow and optimized to catch as much light as possible. Light is available in different quantities in different geological locations (see **Figure 4**). Only a part (about 45 percent) of the total light spectrum is photosynthetically active radiation (PAR, ~400-700 nm), thus can be used by algae to capture $CO_{2,}$ during photosynthesis, a process with a maximum efficiency of 27 percent multiplying these two factors gives the maximum theoretical conversion of light energy to chemical energy by photosynthesis: about 11 percent (Gao *et al.*, 2007). At night (or other dark conditions) photosynthesis cannot occur, so algae consume stored energy for respiration. Depending on the temperature and other conditions, up to 25 percent of the biomass produced during the day may be lost again at night (Chisti, 2007).

Algae have evolved under conditions where light is often limiting, therefore harvest as much of the available light as they can, but under good light conditions, this characteristic makes algae waste up to 60 percent of the absorbed irradiance as heat (Melis and Happe, 2001).

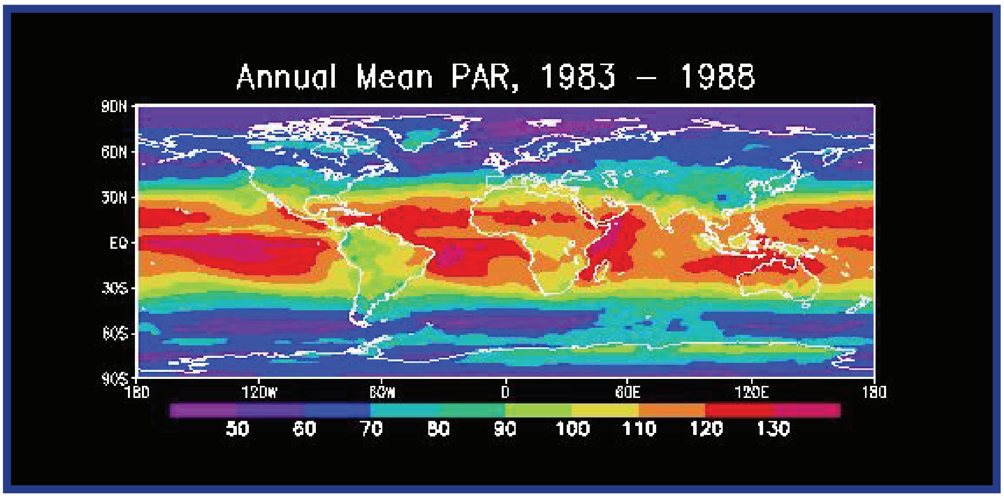


Figure 4: Annual Mean PAR levels (W/m2)(atmos.umd.edu)

2.3.3 Nutrient removal

Besides CO_2 and light, algae require nutrients to grow, nitrogen (N) and phosphorus (P) being the most important ones. These can be supplied in the form of agricultural fertilizer, which is simple, easily available but can be a significant cost factor (Braun and Reith, 1993; Chisti, 2008b). There are several options for cheaper sources of these nutrients. Aresta *et al.* (2005) mention wastewater effluent for example from a fishery, Olguín *et al.* (2003) describe a system where 84-96 percent of N and 72-87 percent of P was removed from the anaerobic effluent of piggery wastewater by growing algae, thereby reducing eutrophication in the environment. Another option is nutrient recycling within the process, depending on the treatment technology chosen. For example nutrient recycling after anaerobic digestion (Braun and Reith, 1993) or after gasification (Minowa and Sawayama, 1999).

The combination of nutrients and light will cause organisms capable of photosynthesis to produce chlorophyll in any part of the world. Because of it’s reflection of green light, chlorophyll concentrations can be measured by satellite, which is a good indication of the best geographic locations for (unfertilized) algae growth. Figure 5 shows a global map with chlorophyll distribution. With the help of GIS, Ecofys has plotted in white the coastal area between 0 and 25 kilometres from the coast, on locations with at least 5 mg/m^3 chlorophyll. Even this very narrow strip with a high natural nutrient level account for an impressive 370 million ha worldwide (Total European union 432 million ha).

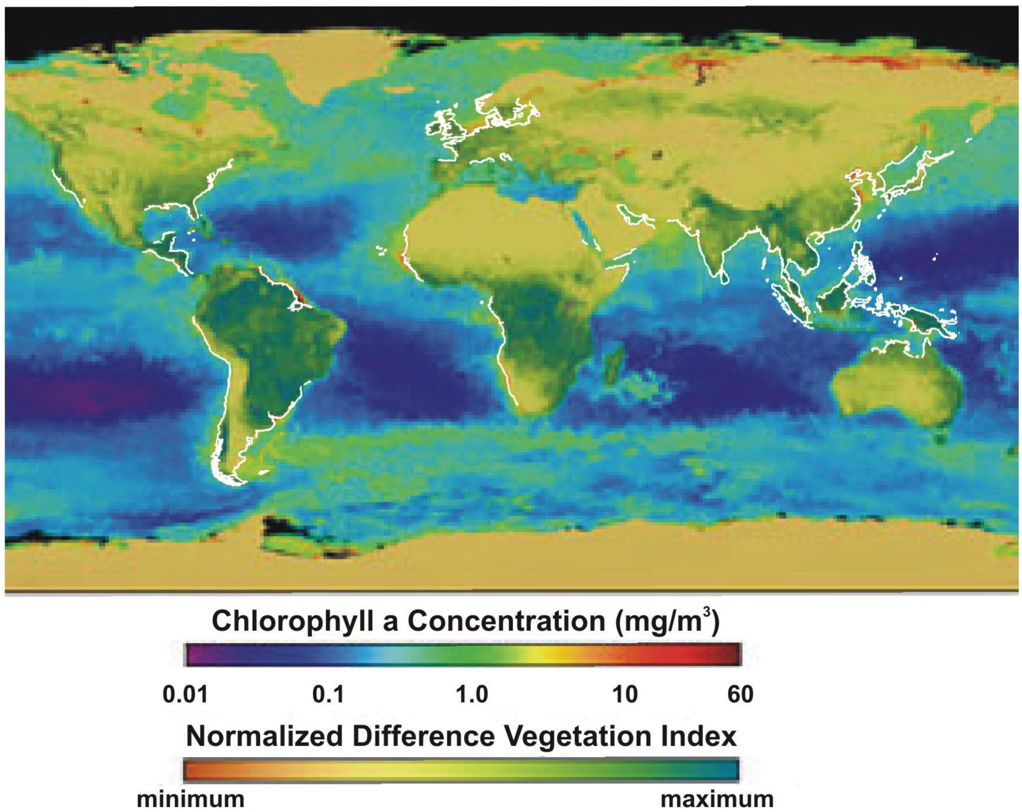


Figure 5: Satellite data, showing worldwide photosynthesis: an indicator for fertility. Area closer than 25 km to shore and at least 5 mg/m3 chlorophyll are marked in white (total 370 ha) (Florentinus *et al.*, 2008)

2.3.4 Temperature

In temperate and subtropical regions, algae have a growth season (for example, in the Netherlands from April to November); in the winter the outside temperature rops and algae only grow at a fraction of the summertime growth rate. In many industrial processes, heat is produced. Sometimes this heat is used somewhere else in the process, sold to neighbouring industries or used to heat neighbouring houses or other buildings. But often this surplus heat has no further use. This heat could be employed to optimize the temperature of the medium in which the algae grow.

Especially interesting is the combination with CO_2 of power plants, since power plants are important sources of this surplus heat.

On the other hand, closed systems can get too hot and require cooling, which can be done with heat exchangers (Chisti, 2007) or spraying water on the outside (Chini Zittelli *et al.*, 1999).

2.4 Biomass harvesting

When cultivating seaweed, every system requires a specific method of harvesting the biomass, but most commonly a specially developed harvesting vessel is used, which cuts the seaweed and hauls it inside (Reith *et al.*, 2005).

Microalgae concentrations always remain very low while growing, typically 0.02 percent to 0.05 percent dry matter in raceways and between 0.1 percent and 0.5 percent dry matter in tubular reactors (Tredici, 2009) (this means 1 tonne dry biomass has to be recovered from 200 m^3 to 5 000 m^3 water). The size of algae is only a few micrometers. These two aspects make the harvesting and further concentration of algae difficult and therefore expensive. Harvesting has been claimed to contribute 20–30 percent to the total cost of producing the biomass (Grima *et al.*, 2003). In order to produce energy from algae as economically as possible, the cheapest way of concentrating the algal biomass to a water content that is low enough for oil pressing is essential.

The technically simplest option is the use of settling ponds. Once a day the settling pond is filled with a fully grown algae culture and drained at the end of that day, leaving a concentrated biomass volume at the bottom, which is stored for further processing (Benemann and Oswald, 1996). This way generally 85 percent (and up to 95 percent) of the algal biomass was found to be concentrated in the bottom of the settler (Sheehan *et al.*, 1998) at 3 percent dry matter (Sazdanoff, 2006) although this will depend on the species used. Settling pond require significant additional space (see Figure 6).

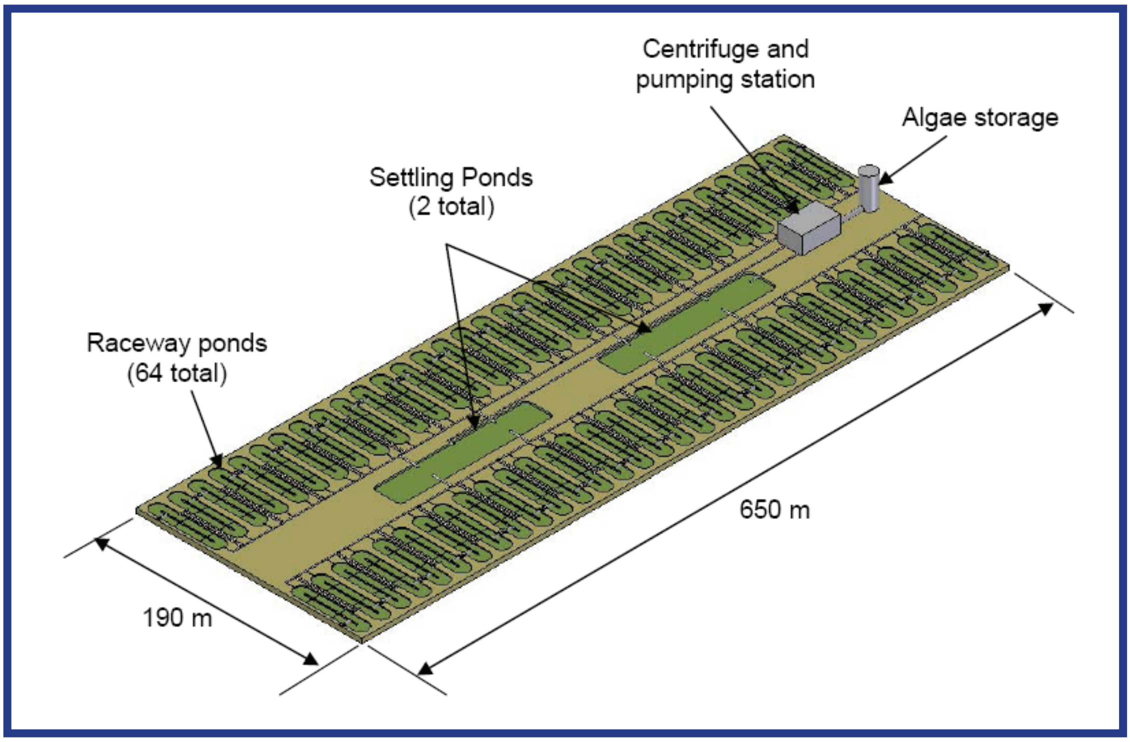


Figure 6: Scaled model of algae farm with raceways and settling ponds (Sazdanoff, 2006)

Another way of separating algae from the water they grown in, is filtration. Many options have been described, including different materials, vacuum, pressured and rotating filtering. Some acceptable results have been obtained for colonial microalgae, but not for unicellular species (Benemann and Oswald, 1996; Grima *et al.,* 2003). Furthermore, filtration is a slow process (Sazdanoff, 2006), so a very large total capacity system would be required to keep up with the production of a large algae farm. Filtration is not analysed further in this report.

Centrifugation is often used for the concentration of high-value algae, and generally considered expensive and electricity consuming. It is however the best known method of concentrating small unicellular algae (Grima *et al.*, 2003). Within the Aquatic Species Program the costs for centrifugation were estimated at 40 percent of production cost and 50 percent of investment cost. However, applying centrifugation as a secondary harvest method, to concentrate from 1-5 percent DM (dry matter) to 15-20 percent would reduce centrifugation costs at least 50 times (Benemann and Oswald, 1996). Benemann recommends in Sazdanoff's report (2006) to use centrifugation after pond settling, and a specific centrifuge (Figure 7) with an acceptable energy consumption is mentioned.

Figure 7: Alfa Laval CH-36B GOF Separator Centrifuge

Other options include flocculation and killing the cells with ultrasound, which are discarded off-hand because the huge consumption of chemicals and energy respectively is very undesirable. To acquire a dry matter content of above 30%, some form of thermal technology is needed (Braun and Reith, 1993).

Algae produce oils as a storage for energy. Thus, when removed from their reactor, may consume part of the stored energy for maintenance. According to Benemann and Oswald (1996) this does not cause a significant loss, as long as those conditions do not last longer than 24 hours.

3 Sustainability of energy from algae

In this chapter, the sustainability of ABB will be analysed, firstly by reviewing the three main documents describing biofuel sustainability criteria: Roundtable Sustainable Biofuels, Renewable Energy Directive and the UK's Renewable Transport Fuel Obligation. Secondly, other algae specific sustainability issues not yet identified in these documents will be described and the suitability and environmental, economic and social sustainability of this technology in developing countries will be analysed.

3.1 Existing biofuel sustainability standards

The discussion on the sustainability of biofuels has focused on terrestrial biomass based biofuels production, driven by the sustainability concerns arising from large-scale feedstock production. The increasing interest in algae based biofuel (ABB) production may lead to a similar development that biofuel from terrestrial biomass is currently undergoing. Existing sustainability standards may be extended to properly cover ABB related sustainability issues.

In reaction to the concerns on the sustainability of biofuels, governments and organizations around the world have initiated policy developments that aim to secure the sustainable production of biofuels – respecting both environmental and social sustainability criteria. Certification schemes are envisaged to play an important role in practically demonstrating compliance with such sustainability criteria.

The first country to have such a system operational is the UK, where the Renewable Transport Fuel Obligation (RTFO) requires suppliers of biofuel to report on the sustainability and greenhouse gas performance of their biofuels. Currently, only the UK has a full operating system in place by means of the RTFO. More recently, sustainability criteria for biofuels have been developed at the level of the EU in the Renewable Energy Directive (RED). The RED requires producers to comply with a set of sustainability criteria for the biofuel to count towards the EU biofuels target.

On the global level, the Roundtable on Sustainable Biofuels (RSB), a multi-stakeholders initiative of the UNEP in cooperation with the Ecole Polytechnique Federale de Lausanne, has developed a set of global sustainability standards for biofuels. The creation of a global certification scheme using a "meta-standard" approach is under discussion.

The Algal Biomass Organization for instance is developing standards across a wide variety of topics for the algal industry.

Table 2: Sustainability issues addressed by the RSB, RED and RTFO standards

Sustainability issues	RSB	RED	RTFO
GHG emissions	+	+	+
Carbon stock conservation		+	+
Biodiversity	+	+	+
Environmental protection (soil, water and air)	+	b	+
Land rights	+	d	+
Labour conditions	+	c	+
Community relations	+		+
Food security	+	d	
Competition with other non-food biomass applications			
Economic welfare	+		
Legal compliance	+	+	+
Indirect effects	+[a]		

Notes:

a) As a part of the GHG emissions reduction standard
b) Only for biomass grown in the EU. For third countries, no standards but report obligation for economic operators, EU Member States and the European Commission – no minimum compliance requirement. Scope of reporting obligation for economic operators to be defined.
c) Reporting obligation for the Commission and EU Member States on compliance with minimum requirement by countries – e.g. implementation of international conventions. Scope of reporting obligation for economic operators to be defined.
d) Reporting obligation for the Commission and EU Member States. Scope of reporting obligation for economic operators to be defined.

Based on Dehue et al., (2008a)

Table 2 presents an overview of the sustainability issues addressed by the RSB, the RED and the RTFO. Only the RED mentions algae, but only as part of a list of possible future second generation biofuel options (Dehue *et al.*, 2008b; EU, 2008; RSB, 2008). (Detailed analysis of the extent to which individual standards apply to ABB is outside of the scope of this report). In general, all of the issues addressed are to some degree relevant to algae based biofuels production. However, in the case of ABB not all issues are risks, in several points important opportunities are present, often unique to algae systems. The potential and likelihood of both risk and opportunities are often dependent on individual parts of an ABB concept, such as nutrient source, CO_2 source, location, conversion option etc. This chapter aims to give a broad overview of risks and opportunities of ABB from a sustainability point of view.

3.2 Algae Based Biofuel specific sustainability issues

ABB has some unique features that can greatly reduce some of the sustainability problems faced by many terrestrial biofuel crops, for example little or no competition for agricultural land, or even positive effects, such as fertilizer production instead of consumption. However, integrating the full potential of these benefits influences other choices within an ABB concept. Choosing the most environmentally, economically and socially sustainable concept is very complex. It is dependent on many factors and will need to be done on a case-by-case basis. Important risks and opportunities to be considered are discussed below.

3.2.1 Land use: risks and opportunities

Direct land use changes (LUC) are caused when new areas (e.g. forest areas or degraded land) are taken into production to directly cover the additional feedstock demand. An indirect land-use change (ILUC) is caused when existing agricultural land is used to cover the feedstock demand of additional biofuel production. This will indirectly cause an expansion of the land use for biomass production to new areas (e.g. forestland and degraded land) when the previous users of the feedstock (e.g. food markets) do not reduce their feedstock demand. LUC and ILUC can have both positive and negative consequences on aspects such as biodiversity, carbon stocks and livelihoods (Dehue, 2008; Dehue and Meyer, 2009).

- **Opportunities for land based ABB production**

Because algae are grown in water, the cultivation systems have much lower land quality requirements then agriculture. Soil fertility is not an issue at all. Land needs to be relatively level and sufficiently solid to build the cultivation systems on, which still allows a huge area of land to be used, such as deserts, infertile saline soils, polluted land and other land with low economic (and ecologic) value. As an example, Glenn *et al.* (1998) indicate that 43 percent of the earth's total land surface is arid or semi-arid and estimate that 15 percent of undeveloped land has sufficient access seawater (max 100 km), which amounts to 130 million ha. Furthermore, Bai *et al.* (2008) estimated that 24 percent of the earth's total land (about 3 500 million ha) has been degrading over the last 25 years. Part of the world's deserts further away from the sea may have saline ground water that could be used, or access to wastewater or sufficient fresh water. There is an enormous amount of land suitable for ABB production, that does not compete with agricultural land and avoids conversion of land with high carbon stocks. Much of the infertile land area overlaps receives high amounts of sunlight, compare the yellow land area in Figure 5 with sunlight levels in **Figure 4**.

- **Risks for land based ABB production**

One of the possible problems of production on land is the enormous size of envisaged ABB production systems, with facilities in the order of 1 000 ha having been proposed (Wijffels, 2008). Plots of this size with low current economic and ecologic value can be scarce. Investigation of the maximum facility size and location is outside the scope of this report. Large-scale open systems can cause fog blankets and other local climatic changes. During heavy rain, closed systems built on hard surface may result in water disposal problems (BCIC, 2009) and in open systems this may lead to high nutrient, high biomass excess water. Small-scale systems are possible in the future with suitable high technology controls when considering co-production of bioenergy and higher value products. Independent of facility size, site preparation for a facility and connected infrastructure could have varying ecological impacts.

- **Opportunities for sea based ABB production**

Considering cultivation at sea, it is well known that two thirds of the planet is covered by water. Clearly, not all this surface is equally suitable for seaweed culture.

Seaweed cultures will provide a safe place for young fish to grow up, which can contribute to the recovery of fish populations (Florentinus *et al.*, 2008; Reith *et al.*, 2005).

Synergy with offshore infrastructure

Ecofys work estimated the potential area for offshore wind turbines to be 550 million ha (considering water depths, shipping routes etc.) (Hoogwijk, 2004). The space between wind turbines could be used for seaweed culture, as it is off limits for shipping and supplies anchoring point and other possible advantages. Gas and oil platforms provide anchoring points, housing and existing fuel transport facilities. The area "behind" wave energy facilities will have milder sea conditions (Florentinus *et al.*, 2008).

Near shore high nutrient areas

Transportation costs will be of major influence in offshore concepts, but even only considering sea surface close to shore (which will contain a high nutrient concentration due to runoff of fertilizers and other anthropogenic and natural sources, as well as natural upwelling of nutrients from deeper sea layers) generates a potential cultivation area of about 370 million ha considering only 0–25 km distance to shore and at least 5 mg/m3 of chlorophyll a, an indicator of elavated nutrient - and other growth conditions. See Figure 5 on page 24. (For several reasons this amount of chlorophyll does not indicates that there is sufficient nutrients for the required productivity [Tredici, 2009]).

Open ocean biological deserts

The dark blue/purple areas in Figure 5 represent areas which are virtually devoid of nutrients, so called biological deserts. In these areas there is no competition with any economic activity and an ecosystem is practically non-existent. The potential area is over 5 billion ha (worldwide area of agricultural land 5.6 billion ha), but fertilization will need to be applied, however there is an option based on artificial upwelling (described in section 3.2.3) that has a high sustainability potential. Figure 5 also shows that a strip on the equator with a higher nutrient concentration is separating the biological deserts. This is caused by natural upwelling of nutrients due to the earth's rotation and the zone has a relatively constant gulf stream and no significant seasonal changes, all good characteristics for algae cultivation.

- **Risks for sea based ABB production**

Much of the spatial area at sea has existing uses, for example for nature, shipping, fishery, recreation, military training grounds and offshore infrastructure. (Florentinus *et al.*, 2008). Finding cultivation space that has not been claimed for other uses may prove difficult. Conflicts may arise from changing existing use to seaweed production. Another important aspect to be mentioned is the potential damage to ecological or species balance in the ocean, when algae is mass cultivated in parts of the ocean where they were previously not present in large populations, along with the potential decline in oxygen concentration in the water at night which might kill other species.

Further, the design of sea-based cultivation systems has to guarantee the prevention of sea mammals and other wildlife getting entangled in it (Florentinus *et al.*, 2008; Reith *et al.*, 2005).

3.2.2 Greenhouse gases: risks and opportunities

- **CO_2: opportunities**

CO_2 is the carbon source for photosynthesis, for algae and plants alike. The amount of CO_2 captured by algae varies per species, but in general about 1.8 tonne CO_2 is integrated in 1 tonne algal biomass (Chisti, 2007). This way, all carbon in ABB is directly sourced from Greenhouse Gas (GHG) CO_2 through algal biochemical conversion (other carbon sources are possible). The same is true for plant derived fuel. Algae have a few advantages over plant based CO_2 capture.

  - Algae can grow directly on combustion gas (typically containing 4-15 percent CO_2), whereas plants take up CO_2 from the atmosphere (open air concentration 0.036 percent)

- Algae can contain large concentrations of the desired product, whereas in plants this is often concentrated in the seeds, as in corn, soy and rapeseed.
- Algae are much more uniform than higher plants. Algae lack roots and leaves, microalgae are in many cases unicellular thus completely uniform, while seaweed may have very basic structural differentiation but all without hard, cellulosic material, therefore easily pumpable. This way the entire biomass can be processed, rather than just parts like seeds or roots.
- Algae growth is dependent on climatic conditions, and thus on the seasons, but does not have the annual growth cycle of sprouting in the spring and harvest in autumn.

- **CO_2: risks**

Overall algae have potentially higher annual yields and conversion to biofuels, thus more CO_2 capture per unit of area. CO_2 can originate directly from burning fossil fuel or ambient air, either way CO_2 captured in algal biomass is (temporarily) removed from the atmosphere. Ambient CO_2 is of such a low concentration that growth is limited. Extra CO_2 from combustion gas is cheap and desirable. However, gas cleaning is often necessary to remove components which are toxic to algae, the CO_2 (-containing gas) has to be transported and dissolved into the water phase, which will lower the pH, so energy input, chemicals, control equipment and gas cleaning facilities may be needed. Although the potential for CO_2 capture is huge, achieving an overall positive CO_2 balance is very challenging. Further decision criteria on whether or not to use combustion gas is outside the scope of this report.
At sea, introducing CO_2 would lower the pH, which is undesirable unless controlled. However, if algae use the CO2, pH rises again. The infrastructure needed for this would be very costly and energy intensive.
Further risks may arise if algae cultures establishment causes direct and indirect land use changes in high carbon stock areas.

- **Other greenhouse gases: opportunities**

Besides CO_2, combustion gas contains other gases like NOx and often SO_2. Both have indirect greenhouse effects. Algae cultivation using these pollutants as nutrients, with high removal efficiencies, has been reported in literature.

GHGs N_2O and CH_4 are emitted both naturally as well as induced by human activity. They are produced by micro-organisms and their formation requires an anaerobic or anoxic step. During daylight algae produce oxygen, preventing these steps from taking place, in effect reducing the emission of these gasses, both in natural systems, the sea as in manmade systems and wastewater treatment plants.

- **Other greenhouse gases: risks**

ABB has waste streams, GHG emission of these streams need to be prevented. At night algae consume oxygen, this may cause anaerobic conditions that can lead to the emission of N_2O and CH_4 gas, as explained in the previous section. Also, when cultivation conditions become toxic, mass algae death can occur, which in turn can result in GHG emissions.

3.2.3 Nutrients: risks and opportunities

- **Opportunities for land based ABB production**

The amount and kind of nutrients needed for algal growth depends very heavily on the species, but as an indication for the most important nutrients, about 5 percent (typically is 7-8 percent) of algal dry matter consists of nitrogen (N) and 1 percent of phosphorus (P).

The most convenient form to supply nutrients is through chemical fertilizer, but from sustainability point of view this is undesirable since nitrate production has a very high energy input and phosphorus is mined, thus a fossil resource that will be depleted.

A second option commonly used in agriculture is manure. This source is also applicable to algae. Wastewater is often too diluted and polluted with pathogens to be used in agriculture, but application in algaculture is certainly possible. Algae cultivation systems are watery systems that produce oxygen (O_2) during daylight, therefore there is a lower chance of ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4) emissions than with land application. Per tonne of manure, algae systems are likely to have lower over GHG emissions than agriculture. However, the fact that not all components in manure and wastewater are easily biodegradable, can contain heavy metals and other micropollutants such as

medicines and introduces a high concentration of bacteria and other organisms that may compete with target algae, using manure or wastewater as a nutrient source limits the type of cultivation system and algal species used significantly.
Another unique nutrient source is nitrogen oxides (NOx) and to a lesser extent sulphur dioxide (SO_2, has a large pH effect) from combustion gas. The gasses dissolve into the water phase (together with CO_2), where they are used for algae as a nutrient source.

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 GHG emissions (Mulbry *et al.*, 2008). Furthermore, it offsets fertilizer use.

- **Risks of land based ABB production**

When algae are grown for their oil or starch content, the leftover biomass will contain all the nutrients. It is very important that this is treated/disposed of in a sustainable way. If not, nutrients could cause eutrophication of surface water, change the local ecosystem, leach to the groundwater, or get converted into GHGs by micro-organisms.
Ideally, leftover biomass can be treated as a co-product rather then a waste product, for example as protein rich feed for cattle, fish or even humans. This would reduce feed production needs with a positive effect on feedstocks and/or land availability for food production. Common wastewater treatment techniques can be applied, but this results in extra costs, loss of nutrients and possible increased GHG emissions. One more viable option is nutrient recycling. A common option is anaerobic digestion of leftover biomass. Not only will the nutrients be mostly concentrated in the liquid phase of the digestate, biogas is produced as well.

- **Opportunities of sea based ABB production**

Seaweed cultivation relies on nutrients already present in the water, be it from natural sources or fertilizer runoff, wastewater outlets or other human activities. In fact, seaweed cultivation can be used to help remediate the anthropogenic flow of nutrients into the sea, which can cause serious eutrophication problems. Combining algaculture with fish cultivation allows for (partial) capture of the nutrients released to the environment though fish feed and faeces.

A more exotic algae concept has strong sustainability potential considering nutrients. When nutrients reach deeper sea layers, there is not much mixing and therefore these nutrients are basically removed from the nutrient cycle (unless brought to the surface again by natural upwelling). In the case of nitrogen, this loss is no significant problem because the atmosphere mainly consists of nitrogen gas. Phosphate however is produced in mines, which face depletion. As mentioned earlier, algae have the potential to capture nutrients and to be used as fertilizer. One concept involves artificially upwelling deep nutrient rich ocean water in biological desert areas, the nutrients are captured by seaweed, processed and serve as a new, renewable source of nutrients, of which phosphorus is the most interesting, since currently no large-scale alternatives are available.

- **Risks of sea based ABB production**

For seaweed cultivation, fertilization should generally be avoided, as the nutrients will not be taken up completely by the algae, but will diffuse and thus pollute outside the cultivation area.

If the distance to shore is too big, seaweed can be processed offshore. The nutrients contained in the seaweed need to be disposed of properly, which can be a significant problem or costly offshore. In some cases, nutrients can be released back to the sea, but doing this widely and in low concentrations is difficult.

Artificially upwelling deep nutrient rich ocean water in biological desert areas could again potentially damage the ecological or species equilibrium.

3.2.4 Water consumption: risks and opportunities

- **Opportunities**

One major advantage of algae cultivation over fuel crops and agriculture in general, is the ability of many algae to tolerate saline water. Fresh water is scarce in many parts of the world, and agriculture uses 70% of the total global fresh water consumption. This characteristic of algae allows a much greater area to be potentially utilized for algaculture. Besides seawater, other sources of salt water (usually with a lower salt concentration) are saline groundwater/aquifers and certain wastewaters.

- **Risks**

Since seaweed is cultivated directly in seawater, water consumption is not a concern. However, in land-based cultivation systems, algae are harvested and separated from the watery medium in which they grew. This rest water will contain some organic components due to imperfect separation and leaked algal cell content. Ideally, this water is (at least partially) recycled, which may require additional treatment and energy input. Possible problems are the accumulation of unwanted compounds and proliferation of micro-organisms feeding on the organics in the recycled water. Non-recycled water should be disposed of properly, which can be more difficult due to the high salt content.

Land based open cultivation systems will suffer from significant water loss due to evaporation. In this process, water is removed but the salts are left behind. Replenishing this water loss with saline water will lead to accumulation of salt in the cultivation system, which sooner or later will reduce algal growth. Evaporative losses therefore have to be replenished with low salt water, even in systems with a high salt concentration. Alternative options are batch culture without water recycling, or in case the saline water supply has a lower salt concentration then the cultivation system, replacing part of the cultivation medium to dilute the salt concentration (blowdown, (Neenan *et al.*, 1986)).

3.2.5 Genetically modified organisms (GMOs): opportunities and risks

- **Opportunities**

While many algal species show different interesting characteristics for biofuel production, there is still plenty of potential for modern biotechnology tools to increase their effectiveness. Two possible improvements have already received significant attention in research.

1. Reduction of antenna size. Under natural conditions, algae have to compete for light with surrounding photosynthetic organisms. Therefore the so-called

antenna part of chlorophyll which receive light has evolved to catch more light than can be photosynthetically processed under optimal lighting conditions, wasting up to 60 percent of the received light energy (Melis and Happe, 2001). Scientists have been able to reduce the chlorophyll antenna size, resulting in more efficient use of high intensity light (Mitra and Melis, 2008).

2 Triggering of lipid production. As mentioned before, certain algae species accumulate large amounts of intracellular lipids, usually after being exposed to some form of stress. The exact biochemical pathway has received significant attention, in order to find out what triggers this accumulation. Genetic tools could exploit this trigger to modify algal species to produce more lipids and throughout the whole growth cycle (Sheehan *et al.*, 1998). No significant progress has been reported.

- **Risks**

The application of genetically modified organisms (GMO) has received considerable protest and is subject to strict safety precautions. While there is in theory a large potential for advancement through genetic modification, large-scale application of genetically modified algae does not appear viable, because besides the general arguments against the use of GMOs, safety requirements will have a detrimental impact on both the economic and energetic output due to measures like sterilization of the entire cultivation system, and measures to prevent introduction of the modified species to the environment.

3.3 Sustainability standards specific to developing countries

Generally, few sustainability issues specific to developing countries are unique to ABB, most issues similar to terrestrial biofuel issues. As can be seen in **Figure 4**, many developing countries are in the zones with the highest annual solar irradiances, so with the highest biomass production potential.

- **Opportunities**

Development of ABB production can generate employment. A certain level of technical education is required during project deployment and, strategy and dealing with unforeseen circumstances, for operation and maintenance and biomass processing low-skilled workers can be employed. Independency of (foreign) energy can be achieved, as well as energy availability and access for the poor. This can be an important factor to allow economic development (FAO, 2008).

Both income and other products such as food, feed, fertilizer, and base chemicals, can be generated, first for self-sufficiency, on the longer term as new export products as well.

A few sustainability issues of plant based biofuels have a high impact in developing countries. Important examples are food security and loss of agrobiodiversity (Rossi and Lambrou, 2008). ABB can avoid these issues by using non-arable land or sea, and even add to food security through co-production of (often highly nutritional and essential nutrient containing) food.

During the preparation of this report, an elaborate scan was made, in order to identify and describe current ABB projects in developing countries. With a few exceptions, it proved very difficult to find examples, and the ones that were found were almost all in the idea or very early start-up phase. This in contrast to developed countries, that may have suboptimal conditions for ABB, but tens if not hundreds of initiatives. Algae technologies have the potential to supply fuel, food and feed in developing countries, but there appears a lack of stimulus for the development of these concepts.

- **Risks**

The biggest threat of the algae concept in developing countries stems from the fact that the scale envisaged for mass production is in the order of magnitude of 1 000 ha. There are obviously very few places on land suitable for algaculture at this scale, which are completely devoid of inhabitants and their economic activities, so great care has to be taken to prevent forced displacement of weaker social groups (small farmers and fishermen in particular).

Large-scale facilities require land, capital and technology, which small farmers traditionally have limited access to, making them less likely to adopt ABB technology. The risk of exclusion particularly high for women and female-headed households, due to persistent gender-based inequalities in most developing countries (Rossi and Lambrou, 2008). The high capital investments required and the high production potential in developing countries is likely to attract foreign investments, which provide economic stimulus, but will also lead to export of part of the revenues.

Developing countries typically cope with pressure of growing agriculture and urbanization, resulting in deforestation, land and water degradation and mechanisms preventing this are developing slowly. Care should be taken that ABB contributes to these issues as little as possible (FAO, 2008).

Labour rights and environmental protection policies are generally enforced less strict in developing countries, so as with any industry, care should be taken with regard to these issues. The same could be considered for quality control for fuel and food.

3.4 Knowledge gaps

Algae technology has enormous potential, not only for ABB, but also for food, feed, renewable chemicals and many other products that are critical for a more sustainable society. More research however, is relatively young and disperse and most importantly on a very small scale. To prove the viability of algae concepts, more information is needed on the economics of the process: optimized costs of the different inputs, but also the market value and market size of the outputs, not only fuels but also higher-value compounds. Especially in developing countries, if economical viability and robustness can be proven, many projects can be deployed rapidly, through microcredits or similar measures.

Not only economic sustainability is vital, but also environmental safety. Important tools to quantify this are energy and GHG balances. As there are many different concepts, generalized balances are difficult, but currently many factors required for a complete and consistent balance are unknown.

For both the economics and environmental balances, it is critical to have dependable and reproducible, long-term figures on productivity per unit area, as well as productivity of the desired compounds as a percentage of the total biomass. Much of the currently available data is from a very small scale, extrapolated from short-term experiments under optimal conditions, or even tainted by commercial and marketing benefits of high numbers. Also, it is often not clear if the total biomass is the measured unit, or only the organic fraction. This has a big effect, especially on algae and seaweed grown in seawater: some species contain over 40 percent of inorganic salts. In the case of biodiesel, the total lipid content is usually measured and reported, not the part that is extractable and usable for biodiesel.

Other environmental effects that need to be investigated: effects on the local ecosystem of mass cultivation of productive algal species. Especially at sea, but also on land it has to be shown that this is a controllable risk. Methane and nitrous oxide emissions from different systems may have significant environmental impact, but may also be easily avoided, to the extend of our knowledge, no research has been done on this.

Many descriptions of algae project, mention the generation of carbon credits. Although algae can be used to adsorb CO_2 from combustion gasses, this CO_2 is not sequestered, as it becomes available again during the use of the algal end-product. The GHG reduction of algae concepts is the displacement of less sustainable alternatives, such as fossil fuels, chemical fertilizers, but also any other end product that may be displace by an algae-based alternative. In order to generate carbon credits from this, a baseline methodology is required, to determine how to calculate the exact amount of GHG emission prevented. To the extent of our knowledge, no such baseline methodology exists, nor is under development, and furthermore it is not possible to accurately estimate the cost of CO_2 abatement through algae.

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