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).

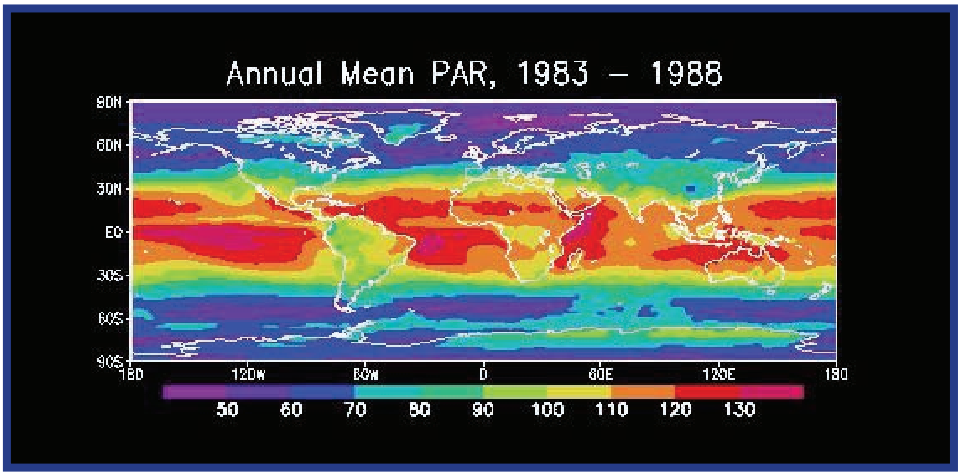

Figure 4: Annual Mean PAR levels (W/m2)(atmos.umd.edu)

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).

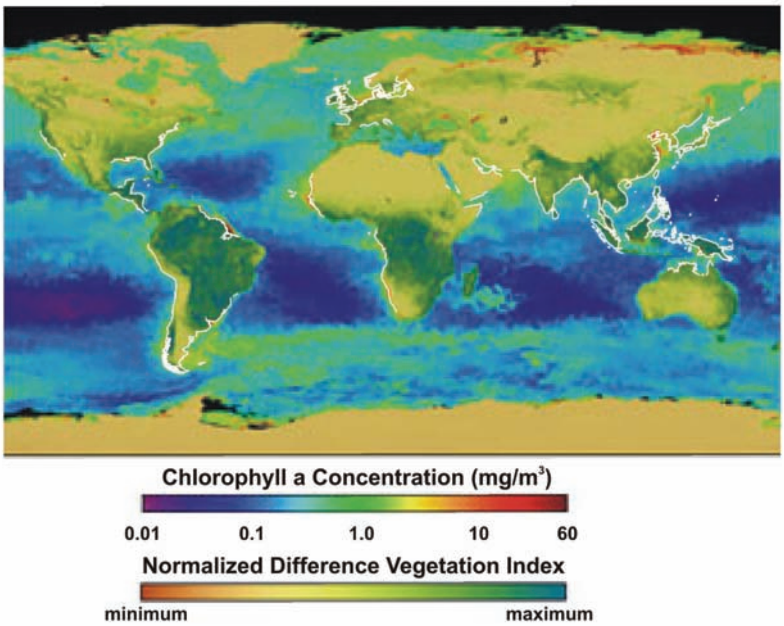

Figure 5: Satellite data, showing worldwide photosynthesis: an indicator for fertility. Area closer than 25 km to shore and at least 5 mg/m3 chlorophyll are marked in white (total 370 ha) (Florentinus *et al.*, 2008)

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).

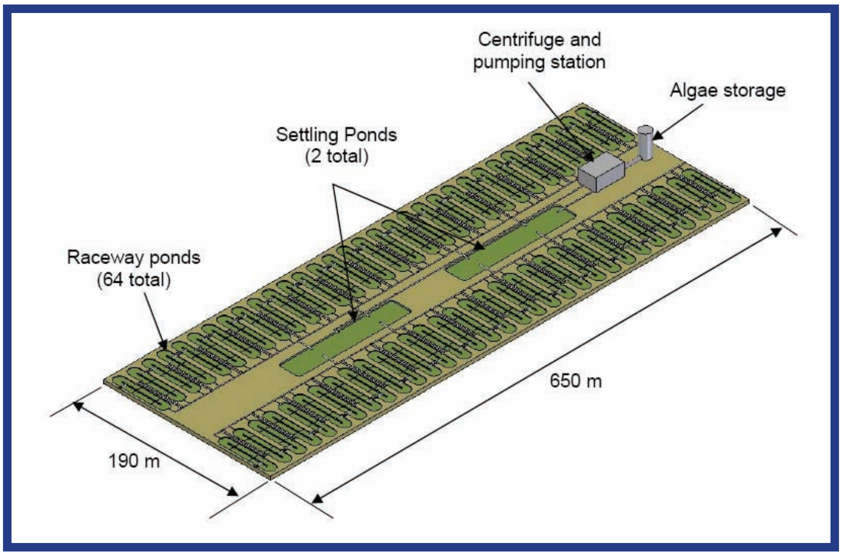

Figure 6: Scaled model of algae farm with raceways and settling ponds (Sazdanoff, 2006)

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 23. (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.