# 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.

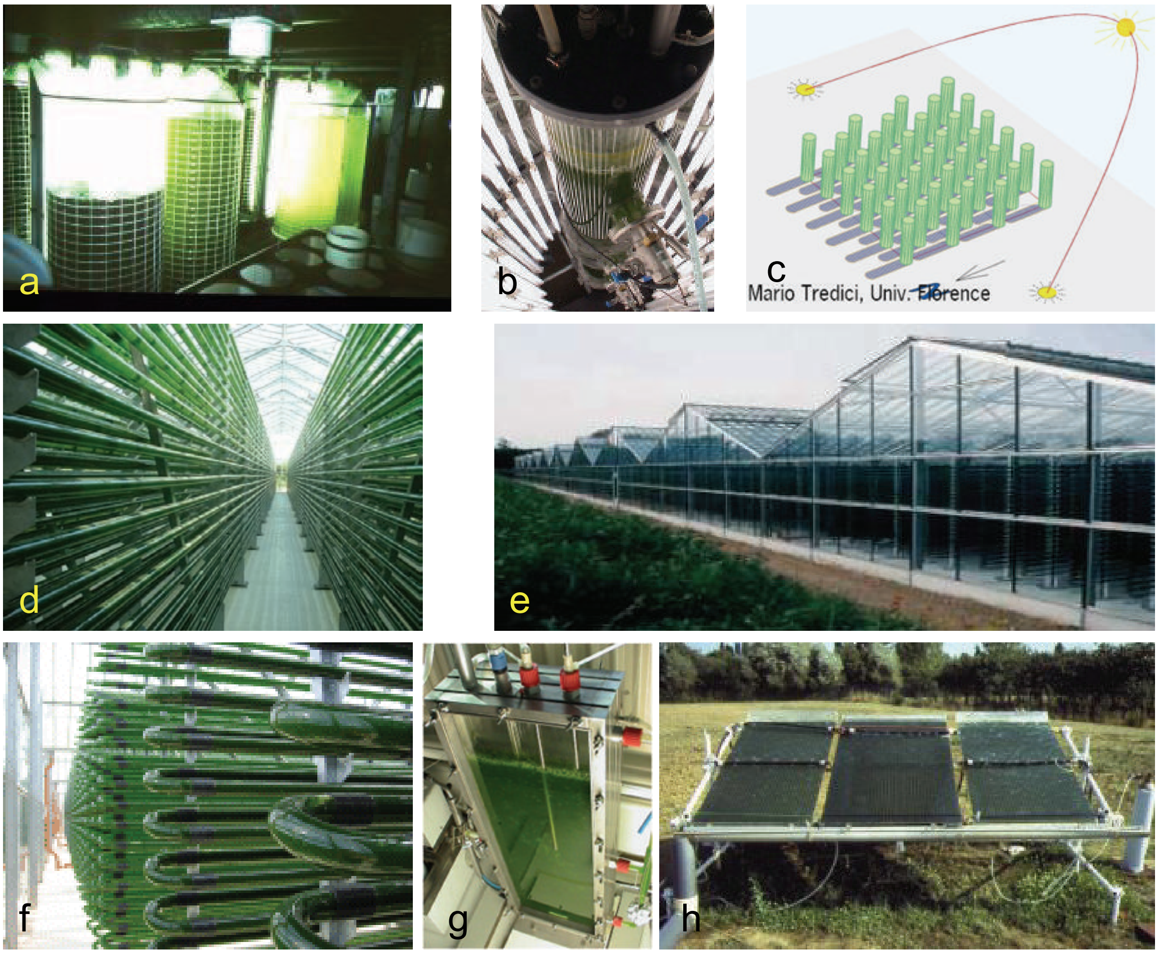

Figure 2: Examples of closed cultivation systems
a. 'Big Bag' culture of microalgae (BEAM)
b. Bubble column reactor (Tredici in Wijffels, 2007)
c. Field of bubble columns induce shading (Wijffels, 2007)
d-f. Tubular reactor system (Bioprodukte-steinberg.de)
g. Experimental flat photobioreactor (Wijffels, 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**