Ecofys the Netherlands BV
P.O. Box 8408
NL-3503 RK Utrecht
Kanaalweg 16-G
NL-3526 KL Utrecht
The Netherlands
www.ecofys.nl

T +31 (0)30 280 83 00
F +31 (0)30 280 83 01
E info@ecofys.nl

WORLDWIDE POTENTIAL OF AQUATIC BIOMASS

Drs. Anouk Florentinus
Dr. Carlo Hamelinck
Drs. Saskia de Lint
Sjors van Iersel, MSc.

January – May 2008
Ecofys Bio Energy group

By order of the Dutch ministry of the Environment (VROM)

Summary

Introduction

Ecofys was asked to investigate the potential of aquatic biomass for energy applications worldwide. Through a step-by-step approach a feasible potential for aquatic biomass has been determined based on literature, desk study and expert opinions. Since aquatic biomass production for energy applications is still very innovative and no commercial experiences are known today, results are considered to be only a rough indication of what this new biomass resource can mean for our transition towards a more sustainable economy.

From theoretical potential to technical potential

In the first stage of this study typical areas for production of marine biomass at sea or near sea were distinguished, the potential technical concepts for the application of aquatic biomass were investigated and the most promising combinations were determined to form six sets. Seagrass as aquatic biomass resource was considered not to lead to a large worldwide potential for energy applications, and therefore has been left out for further investigation. Two sets were determined for the production of microalgae, which can be converted to biodiesel. Four sets were determined for the production of macroalgae or seaweed to produce biogas through anaerobic digestion.

After the selection of most promising sets, these sets were investigated on their technical potentials. The technical concepts were determined in more detail and attainable yields were defined. This resulted in the following summary table.

Set	Distance to shore/ coast	Water depth	Continental shelf	Natural nutrient availability	Climate Zone	Average yield (tonne DM/ hectare/ year)	Energy yield (GJ/ hectare/ year)
1: Open pond on land	Max. 100 km from coast	n.a.	On shelf	Poor: fertilization	Sub-tropical to tropical	45	~ 720 (200 hecto litre/ha/yr oil)
2: Floating bags in inland seas and bays	Max. 100 km from shore	Min 8 meters; no high waves	Both on and outside shelf possible	Poor to medium: fertilization	Moderate to tropical	25	~ 400 (110 hecto litre/ha/yr)
3: Horizontal lines between offshore infrastructure	Max. 100 km from shore	Min 8 meters	On shelf	Poor to rich; fertilization possible	Moderate to tropical	30	~ 200 (6.000 m3/ha/yr)

Set	Distance to shore/ coast	Water depth	Continental shelf	Natural nutrient availability	Climate Zone	Average yield (tonne DM/ hectare/ year)	Energy yield (GJ/ hectare/ year)
4: Ring system in rougher near shore areas	Max 25 km from shore	Min 8 meters	On shelf	Medium to rich; slow fertilization possible	Moderate to tropical	30	~ 200 (6.000 m3/ha/yr)
5: Vertical lines nearshore in densely used areas	Max 25 km from shore	Min 20 meters	On shelf	Very rich	Moderate to tropical	35	~ 220 (7.000 m3/ha/yr)
6: Bounded floating structure in open sea	Open ocean	Min 100 meters	Outside shelf	Poor: fertilization	Moderate to tropical	30	~ 200 (6.000 m3/ha/yr)

Ecologic potential

The sets were also analyzed on their ecological impact.

Cultivation on land has the least risks on harmful ecological impact, because the cultivated organism and nutrients are bonded to the system, can be monitored and controlled. This will only be the case if open pond system is indeed realised on desert land, not suitable for agriculture and with use of seawater or waste water.

For cultivation at sea the main environmental impacts can be caused by introducing exotic species, with the risk of invasion of the area. Cultivation at biological deserts in deep oceans or degraded coastal areas can be used to enhance bioactivity from otherwise barren environments.

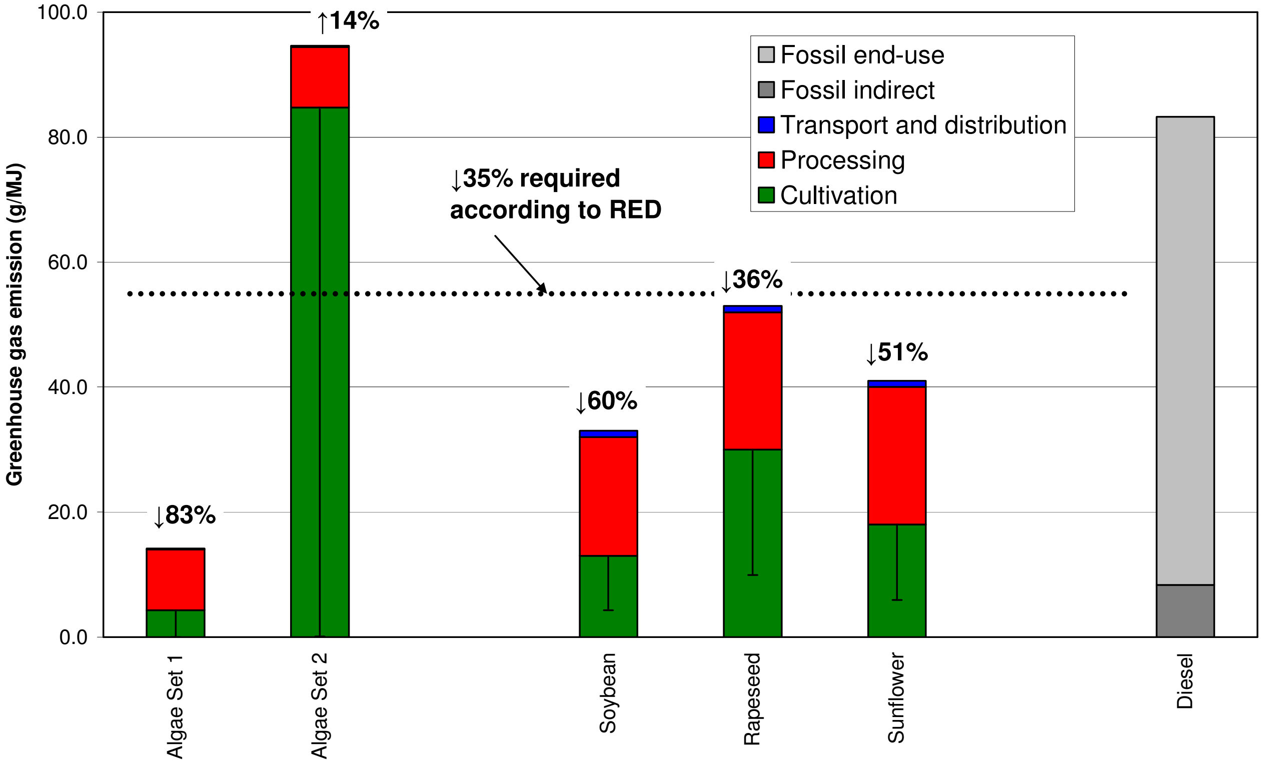
In any case, a new biological balance needs to be established when biomass is cultivated and regularly harvested. This remains an important research area to be investigated further.

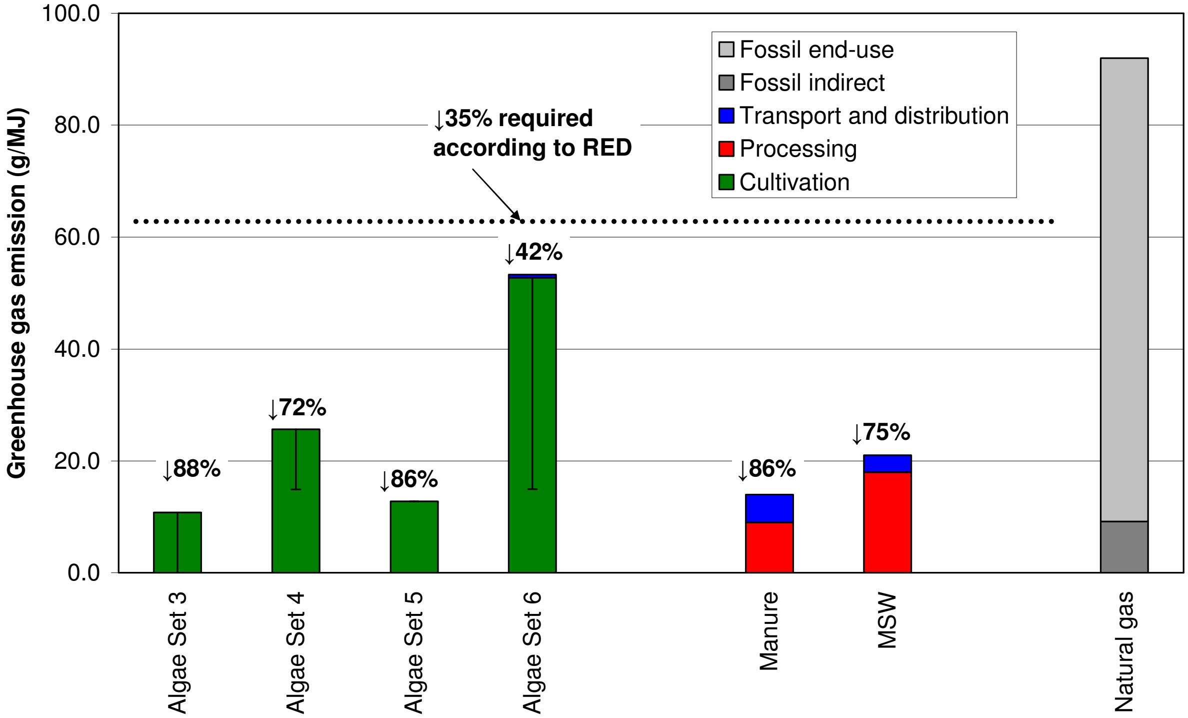
Fertilization in some sets could cause additional eutrophication. This can be minimized by setting the quantity of fertilizer to growth-limited and by choosing sea areas that have low water currents. The sets in coastal areas increase competition with space, lights and nutrients but integration with intensive mariculture can also be used to decrease eutrophication.

With the change of cultivation area from land to sea, a new topic of discussion appears on the change of sea use (instead of land use change). The spatial area used on sea for biomass cultivation can also be in competition with other applications.

The actual effect of large scale aquatic biomass farming in the ocean will depend strongly on the amount of fertilization and how it is used, sea conditions, total surface of covered area and the used species.

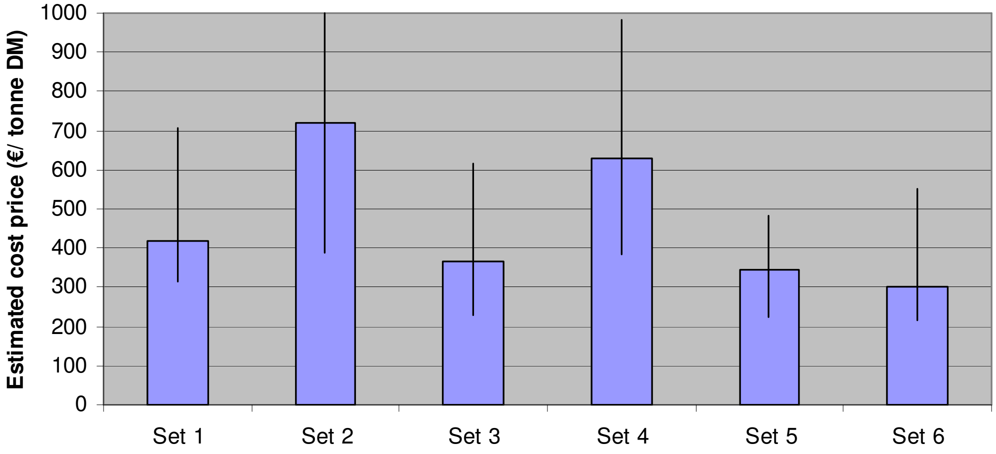
A greenhouse gas balance calculation is made for all sets. Results are presented in the graphs below. Aside from set 2, in which fertilization is considered to be applied in an inefficient way due to spills, all sets have a very positive GHG balance.





Socio-economic potential

Finally the socio-economic aspects of the sets were investigated. All sets are currently considered to be not economically feasible, since costs will be too high to compete with land-produced biomass conversion technologies and additional revenues from by-products are at this point unclear. The figure below shows the cost price estimation ranges for all sets in € per tonne DM. Insights into costs remain unsure, due to lack of practical experience for most of the sets. Only set 1, open pond raceways, are currently applied on commercial scale for the production of higher value products from microalgae.

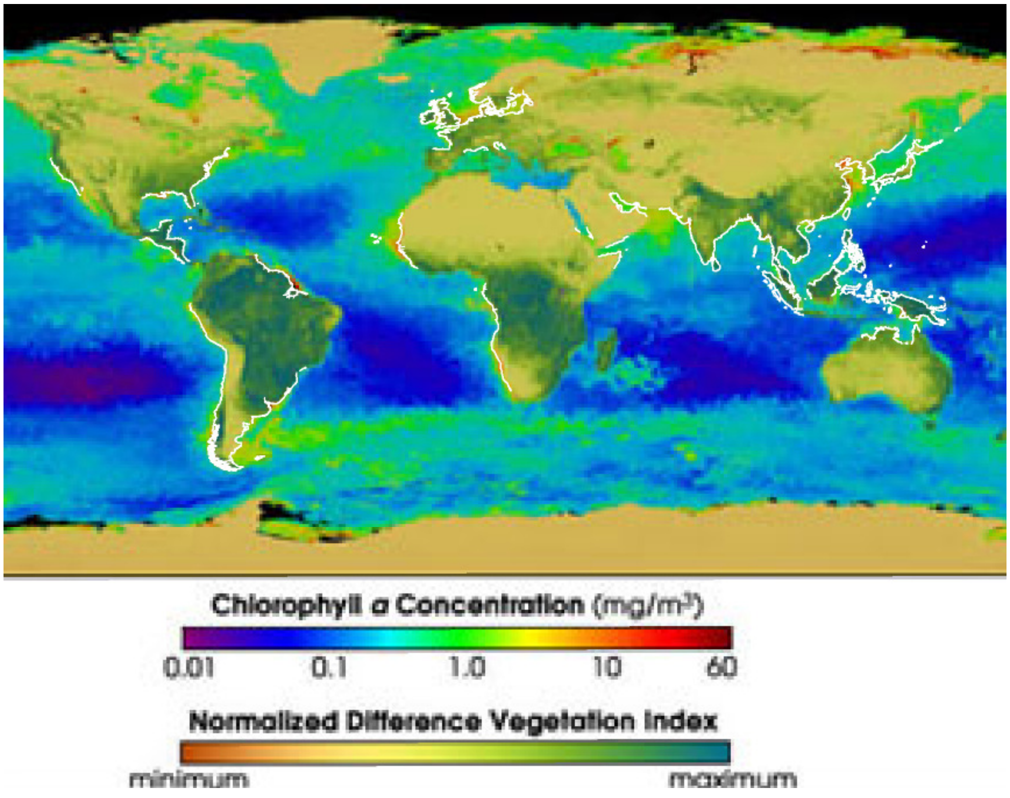


Based on the results above set 1, 3, 5 and 6 are considered to be most feasible sets on longer term, if cost reduction and/or revenues can be established.

Implementation of set 1 will be done in areas which do not have any other economic functions, specifically agriculture. The estimated surface of arid or semi-arid land lays around 130 million ha. This would imply that a potential is possible for only this set of around 90 EJ of biodiesel production. The potential of set 1 is considered to be disclosed most easily, being a land-based system, and based on the current development in the technical aspects of open pond raceway systems for microalgae.

The worldwide potential for set 3, horizontal lines, is comparable with the worldwide potential for offshore wind farms which is estimated around 550 million hectares. This would imply a worldwide potential for set 3 of around 110 EJ.

For set 5, vertical lines in densely used areas near shore (max 25 km) and in nutrient rich zones (chlorophyll level of higher than 5 mg/m^3), the potential worldwide surface is calculated to be around 370 million ha. Offshore wind parks can also be placed in this zone, so overlap with set 3 is possible. It is assumed that only half of nearshore available land for set 5 can be used, the potential still will be around 35 EJ. The figure below shows the potential area for set 5 with the white lines near the coasts.



If the open oceans and more specific the biological deserts can be used for set 6 a theoretical potential becomes available of over more than 5 billion hectares, mainly located on five prominent places (Caribbean Sea, South Atlantic Ocean, Indian Ocean, Mid Pacific and South Pacific Ocean) as is shown in deep blue areas on the figure above.

Disclosure of this complete area is considered to be unrealistic. However even if only one percent of this surface can be disclosed for algae cultivation with the average yield estimation of set 6, more than 50.000 million ha could imply an energy potential of more than 6.000 EJ. This leads to the following estimation of a feasible potential for aquatic biomass production for energy applications worldwide on longer term.

Most feasible technical concepts	**Area**	**Potential**
Set 1: Land based open ponds for microalgae	Arid land in (sub) tropical zones (deserts) and close to coast (max 100 km)	90 EJ
Set 3: Horizontal lines for macroalgae	At existing infrastructure – f.e. offshore wind farms (up to 100 km offshore)	110 EJ
Set 5: Vertical lines for macroalgae	Near coast (max 25 km) in nutrient rich water	35 EJ
Set 6: Macroalgae colony	At open sea (biological deserts), up to 2000 km offshore	~6000 EJ
TOTAL		**~ 6235 EJ**

Compared to the results of the GRAIN study which indicates an amount of 40 to 1100 EJ of biomass available on land, the potential of aquatic biomass can be a large additional resource for bio energy production.

Conclusions and recommendations

Final conclusions on the worldwide potential of aquatic biomass for energy applications are the following:

- The potential of aquatic biomass production for energy purposes is high.
- The energy products from aquatic biomass can be seen overall as more sustainable compared to bio-energy resources on land.
- The development of aquatic biomass production for energy purposes can be an impulse for new economic activities and interactive bridges between current industries.
- The estimated production costs for energy products from aquatic biomass are still high, higher than production costs for fossil fuels and even higher than most conventional bio-energy products from resources cultivated on land.
- Although most feasible technical combinations have been determined in this research project, no technological preferences can be defined at this point. More research and development, practical experience and growth towards commercial scale projects will need to point out the best technical solutions to cultivate, harvest and convert aquatic biomass to renewable energy products.
- With the lack of practical experiences with the investigated systems, the actual impact of large scale systems on the environment, economy and society are unknown.

Ecofys recommends the following steps to the ministry of Environment (VROM) to stimulate the development of this new biomass resource and towards the actual disclosure of the worldwide potential:

- Stimulate more dedicated and practical R&D projects on this topic to answer the current research questions
- Enhance knowledge exchange based on current experiences with offshore renewable energy and aquatic biomass cultivation for non-energy purposes
- Explore the legislative situation for aquatic biomass production, and determine possible market barriers of legislative nature and their solutions.

Table of contents

List of figures

List of tables

Abbreviations

CO_2	Carbon dioxide
N	Nitrogen
P	Phosphate
Fe	Iron
N_2O	Nitrous oxide or laughing gas
CH_4	Methane
GHG	Green House Gas
PAR	Photosynthetically Active Radiation
Tonne	1000 kilogram
Tonne D.M.	Tonne of dry matter
Ha	Hectare (100 ha = 1 km^2)
Km	Kilometre
Yr	Year
W	Watt (1 Watt = 1 Joule per second)
kW	Kilo Watt = 10^3 Watt
kWh	Kilo Watt hour
MJ	Mega Joule = 10^6 Joule
GJ	Giga Joule = 10^9 Joule
TJ	Tera Joule = 10^{12} Joule
PJ	Peta Joule = 10^{15} Joule
EJ	Exa Joule = 10^{18} Joule

1 Introduction

Biomass plays an important role in the transition towards a sustainable energy supply within our society. The use of biomass for electricity production and transport fuels has grown fast in recent years, based on ambitious targets set by national and European governments. With the increased demand for biomass resources new conflicts of interest have risen. The production of energy crops could compete with the cultivation of food crops or the use of land for vulnerable ecosystems like tropical rainforests. Additional sustainability criteria on the production and use of biomass for energy applications seem essential.

With this competition for use of land in the back of our minds, more frequently the sea is mentioned as an important potential area for renewable energy production. Aquatic biomass resources such as microalgae, macroalgae like seaweeds and seagrass, can be applied to multiple purposes. The technologies for cultivation, harvesting, transport and conversion are developing rapidly to commercial scales, especially for new food and pharmaceutical applications. But also for bio-energy applications aquatic biomass can be an interesting feedstock. While being at the frontline of a new development in the field of renewable energy, this study attempts to grasp a realistic potential this feedstock could have worldwide with the specific focus on energy applications. Also, not only the sea but also arid land, like deserts, unsuitable for agriculture are taken into account, to present a potential of aquatic biomass which can be complementary to the known potentials of biomass produced on land (like the GRAIN study; Lysen *et al*, 2001).

Through literature study, interviews with expert scientists and known producers of more commercial applications, along with the application of GIS (Geographical Information Systems), a realistic potential is determined. In the next chapter some boundaries have been determined by investigating the growth parameters that apply for aquatic biomass, which areas in the world would be interesting for production and which technical concepts can be applied to produce and convert the aquatic biomass to useful energy applications. This leads to the selection of sets; a combination between potential area and technical concept, which will be further analyzed in chapter 3 for its technical potential. In chapter 4 the ecological aspects of the sets are determined. In chapter 5 the socio-economic potential of the sets is analyzed, leading eventually to a most feasible potential worldwide for the production of aquatic biomass for energy applications. Conclusions and recommendations are given in chapter 6.

Because of the strong innovative nature of this development, and no commercial experiences of aquatic biomass production for energy applications are known today, results are considered to be only a rough indication of what this new biomass resource can mean for our transition towards a more sustainable economy.

2 Theoretic potential

To define the theoretic potential first a quick scan is made of which types of area in the world would be interesting for aquatic biomass production, based on an analysis of the most relevant parameters for cultivation. This is followed by a short review of most interesting and potential technical feasible concepts applicable for the production and use of aquatic biomass.

Together the combination of good cultivation locations and feasible technical concepts create most promising sets which will be further investigated in this report on their technical, ecological and socio-economic aspects.

2.1 Parameters for cultivation

For the use of marine biomass for energy production three groups of organisms are considered: microalgae, seaweed (macroalgae) and seagrass.

The growth of aquatic biomass is determined by several parameters. The most relevant parameters are discussed below. The parameters are divided into two groups:

1. Primary growth parameters influencing biomass growth of the selected species.
2. Cultivation parameters determining the technical feasibility of cultivation of aquatic biomass.

1. Primary Biomass growth parameters

a) Irradiation: photosynthetically active radiation determining the photosynthesis and therefore the growth of the biomass.
b) Temperature: optimum temperature between 15 and 30 degrees Celsius.
c) Nutrients: for the growth of biomass most important are Phosphate, Nitrogen and CO_2 and furthermore micro nutrients like Iron (Fe).
d) Limpidity: influencing the irradiation zone (how deep sun light penetrates the water).

2. Cultivation parameters

e) Sea conditions: currents, undulation (amount of waves), sea quakes, water depth, but also the general weather conditions are concerned in this parameter. Rough sea will hinder cultivation and harvesting. Depending on the chosen technology, it can cause severe damage to the cultivation system.
f) Presence/absence of substrate: to fix the cultivation systems and for anchorage of seaweeds.
g) Spatial planning: the sea harbours many functions: habitat of many species, nature, transport, fishery and recreation. The development of cultivation areas will have its influence on these pre-existing functions and will compete for space.

h) Control: Control is defined as the degree of being able to influence and monitor your biomass cultivation system, like the amount and composition of nutrients. A closed system has the highest control possibilities, whereas an open system has the lowest.

i) Logistics: areas near the coast generally have better accessibility to conversion units for the biomass and a lower transport requirement for operation and harvesting.

In the following paragraphs the most important parameters are clarified.

2.1.1 Irradiation

Aquatic biomass concerned in this study is autotrophic, which means that growth depends on photosynthesis. For this process light is essential (period of daylight, angle of sunlight on surface and intensity of the sunlight). Part of the light spectrum which is actually used for photosynthesis, is expressed in PAR (Photosynthetically Active Radiation = 400 – 700 nm).
However, irradiation can also be too intensive, causing DNA damage within the cells, which causes diminution of efficiency of the cells (Iersel van, 2007). Weather conditions will influence the irradiation, and coastal areas for example often are cloudier than open sea.

2.1.2 Temperature

The ideal temperature range for cultivation of marine biomass is between just above 0 to 30 ^{o}C and depends heavily on the exact species. For many algae the optimum is between 20 and 30 ^{o}C, but for example *Ulva* (zeesla in Dutch) the optimum lays between 10-20 ^{o}C. Temperature ranges under the optimum will cause a reduced growth speed, temperatures above a certain limit induce mortality, for example *Laminaria* (seaweed) dies at temperatures above 23^{o}C (Reith *et al.*, 2005).

2.1.3 Nutrients

Aquatic biomass will need several nutrients to sustain a sufficient growth. The main nutrients are CO_2, Phosphate (P) and Nitrogen (N). CO_2 is needed for photosynthesis. When light is abundant, N is often the limiting factor, to a lesser extent P and near the poles Fe can be limiting. The addition of nutrients can have a negative ecological impact and can result in additional investment and operational costs.

2.1.4 Sea conditions

Cultivating algae at sea will have a strong advantage that natural circulation in water is already present and no mechanical systems are needed for this. However, rough seas can damage the cultivation system and hinder operation and harvesting. Furthermore rough sea conditions make organisms be driven out of the nutrient rich and photovoltaic zone. Sea movement and currents affect the transportation of nutrients in and out of the cultivation zone.

2.1.5 Substrate

For the growth of aquatic biomass the presence of substrate (place for anchorage), whether natural or artificial, is highly important. Substrate is needed for anchored organisms like seagrass and most seaweed (macroalgae). Furthermore substrates can be used to fix the cultivation systems.
Microalgae do not need a substrate to attach to, but grow suspended in a liquid medium, within some form of containment structure. The nutrients required for efficient growth are added to this medium.

2.2 Interesting production locations

In this paragraph a long-list of the interesting areas for the production of marine biomass is generated. The relevant parameters for the growth of biomass, as described above, are specified for each area. The following main division in areas for the cultivation of marine biomass are considered:

1. Coastal areas
2. Inland seas and lagoons
3. Open oceans
4. Pole areas
5. Land based coastal areas
6. Areas containing existing offshore infrastructure

2.2.1 Coastal area

Within the coastal area we distinguish urban areas and areas without any urban settlements, since conditions in both situations differ significantly. Inhabited areas and estuaries have a continuous input of nutrients into the ecosystems, possibly causing eutrophication. The availability of nutrients is an advantage in terms of public acceptance for aquatic biomass production, while it will reduce the effects of the excess nutrients and will make the additional adding of nutrients into sea ecosystems, which can raise sustainability issues, unnecessary. A disadvantage is more competition with other functions like shipping and recreation. Than again, the presence of nearshore infrastructure could facilitate the logistics of the cultivation site.

Important for some cultivation systems will be the water depth to make anchor points. Also, nutrients often are bound to lower water depths. Therefore for coastal areas only those areas which are located on the continental shelves where water depth is limited up to 200-300 meter will be taken into account.

Coastal areas generally have a higher accessibility than open oceans, which improves operation and monitoring and reduces transport. Another advantage is that coastal areas are generally shallower, so more possibilities to anchor the culture systems, whereas open oceans lack these possibilities.

The following areas at the coast can be determined:

a) urban or estuary coastal areas – nutrient rich
b) less/ none urban coastal areas on the continental shelf
c) islands; these areas can be either urban or none urban

2.2.2 Inland seas

Inland seas, bays or lagoons generally have milder sea condition because of protection by the surrounding land, which may help retain the natural and anthropogenic influxes of nutrients. Furthermore the distance to shore will be relatively small. These areas may however have competing economic uses like shipping, specific ecology and a higher salt content if evaporation is high.

2.2.3 Open oceans

The main advantage of cultivation in open oceans is the availability of enormous amounts of space and very little competition with the present ecosystem and other functions. Open oceans have areas called biological deserts, where biomass density is very low because of lack of nutrients, whereas coastal areas in general have rich ecosystems. A prerequisite from a sustainability point of view is that cultivation should not significantly disturb the existing ecosystem.

Further conditions however in open oceans are very disadvantageous: control, operation, sea conditions, transport and logistics.

2.2.4 Pole areas

Pole areas on the continental shelf do contain rich algae communities and the potential available area is huge, however low temperature causes slow growth and very strong seasonal effects. In spring large amounts of nutrients are released from melting ice and in the summer season, irradiation happens 24 hours per day. Ice formation and drifting ice hinder logistics and can be very damaging to cultivation systems and their anchor points, which may lead to a huge increase in investment and maintenance costs. The pole areas are vulnerable ecosystems, which should be treated with extra care.

2.2.5 Land

Marine biomass can also be cultured in man-made systems build on land, by using seawater as the culture medium. Within the scope of this study, only areas which have hardly any possibilities for agriculture, like deserts and areas which suffer from soil salination are taken into account, to avoid competition between food and fuel. Cultivation on land has many advantages over cultivation on sea, concerning control, monitoring, operation and logistics. Most growth parameters can perfectly be monitored and managed.

2.2.6 Existing offshore infrastructure

Besides the areas described above another distinction can be made for locations which have existing offshore infrastructure already. Existing oil platforms for example often show a strong and diverse ecosystem around it, while anchor points are available and spatial planning prevents ships to come too close to the platform. To create a cultivation system at existing infrastructure will be easier.

2.2.7 Long-list

In the following Table 2-1 the selected areas are evaluated on their scores for the growth and cultivation conditions. However some parameters can be optimised in their score, for example for coastal areas, areas can be selected where irradiation and temperature are close to the growth optimum of the selected species. The conditions which can be optimised are indicated with the symbol “~”.

Table 2-1 Selected areas and growth conditions

Nr	Area	Specification	Irradiation	Temp.	Nutrients	Condition	Substrate	Spacial Planning	Control	Logistics
1	Coastal area	Urban/ Estuary	~	~	++	+	~	-	+	++
	Coast area	Unsettled	~	~	+	~	~	+	+	+
	Islands	Unsettled	~	~	+	+	+	+	~	+
2	Inland seas/ lagoons		~	~	+	+	+	-	+	+
3	Open ocean		~	~	-	-	-	+	-	-
4	Artic area		~	~	+	~	-	+	-	-
5	On land, near coast	Arid area (desert/ saline)	~	~	++	++	++	++	++	++
6	Offshore infrastructure		~	~	+	+	++	+	~	+

~	conditions to be optimalised; either by selection of location, cultivation system or biomass species
-, --	unfavourable conditions
+, ++	favourable conditions

2.3 Technical concepts

2.3.1 Cultivation and harvesting techniques

There are several options for the culture of marine biomass for renewable energy production. The first step is to select the best organism to grow:

1. High productivity
2. The larger the physical size, the easier and cheaper to harvest
3. Local species to minimize effect on the ecosystem
4. Suitable for a wide range in water temperature, light intensity, salinity
5. Not subject to major consumption by local fauna
6. Application of the biomass (oil production, digestion, extraction of other environmentally of economically interesting products)

Suitable species can be cultivated in different systems at sea and on land in marine water, which should be as cheap and simple as possible.

Microalgae

Microalgae are mainly cultivated in land-based systems, where cultivation conditions like depth, nutrient levels and mixing can be controlled to a greater extent. This allows the cultivation of more productive microalgae, which can contain high amounts of sugars or lipids for biofuel production. This is currently practiced commercially for other algal products and received much attention in recent years because of its potential to produce renewable energy. Since the applied organisms are much smaller, other harvesting techniques are needed. The technically most simple 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% (and up to 95%) of the algal biomass was found to be concentrated in the bottom of the settler (Sheehan *et al.*, 1998) at 3% dry matter (Sazdanoff, 2006) although this will depend on the species used.

As each of the over 100.000 species of microalgae has their own set of optimal conditions for growth, which may vary with climate, season and cultivation system, it is not possible to report the exact cultivation conditions of microalgae. Examples of commercial algae production in raceway ponds generally have facilities to prepare the growth medium and separate cultivators in which an amount of seed algae is grown, which is used to inoculate a raceway pond at the start-up. These inoculation producers are run aseptically (pure culture in sterilized medium), on a high nutrient medium with temperature control, often inside and under 24 hours artificial light. The amount of seed culture needed varies heavily with species, but especially on the capacity of the alga to remain the dominant species in the pond. After a pond is fully grown, it is drain and prepared for a new batch by cleaning and/or disinfecting, which reduces the amount of time per year that a pond is in operation.

This approach is clearly consuming from an energy- and monetary perspective, thus only feasible for algae with a higher value than energy products. This is one of the process steps requiring innovation, and seen as one of the bottlenecks to commercial implementation for biodiesel production. Current trends focus on finding algae whose dominance is strong enough that steps to keep the culture pure can be minimized, making the separate production of inoculate redundant. Whether this will work over long time periods still needs to be proven, but will be easier for biodiesel since the purity of the end product is a lot less strict than for food products (for example Spirulina health-food algae have a quality control level for rat droppings).

A more promising alternative is to adapt the harvesting system to make continuous harvesting possible, eliminating the need to restart a culture regularly, and keeping the algae concentration at the maximum growth rate continuously instead of a start-up phase and a reduced growth rate when the algae concentration becomes too thick to allow for sufficient light penetration.

A possible cultivation system in open water is a plastic transparent bag that needs to be semi permeable to let sea water through but not the biomass.

A way of separating algae from the water they grow 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; Molina 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. 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 (Molina Grima *et al.*, 2003). Other options include flocculation and killing the cells with ultrasound, which have a huge consumption of chemicals and energy respectively.

Seaweed (macroalgae)

Seaweeds are large algae clusters, macroalgae, and come in many types and colours. Cultivation of seaweed is commonly commercially performed on horizontal or vertical rope, which certain species of macroalgae can use to attach to with a specific organ called a hold-fast. These ropes can be suspended from structures which float or are attached to the seabed. Rough seas can however damage the structures or remove the seaweed from the lines. The best results have been attained using ring structures of 5-15m in diameter, but these rings are more difficult to harvest. If floating seaweed is cultured, the system only needs a structure to hold the biomass field together. There are no known working examples of such a system. Closer to land it is possible to grow seaweed on the seabed or harvest beached 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).

Seagrass

Seagrass are flowering plants, which grow in intertidal areas, anchored in mud or sand. In the Netherlands until 1932 natural populations of seagrass were harvested and used as fillings in mattresses and construction material. However, due to an epidemic in 1932 large populations of seagrass were destroyed. Nowadays some species of seagrass have a protected status (like Eelgrass, Groot zeegras in Dutch) (www.zeegras.nl). Sustainable exploitation of seagrass can provide a new boost for re-introduction. The growth of seagrass is very valuable for coastal areas, because they stabilize sea conditions, slow down currents and erosion and provide a safe habitat for many species. Seagrass can be grown in shallow, sheltered brackish and saline waters. Seagrass can be transplanted in the seafloor mechanically and manually, where they form large en dense beds of meadows. Harvesting is done by collecting individual plants or by underwater mowing. At the moment techniques are successfully developed for mechanical planting and harvesting, with minimal disturbance. These new machines are located semi-permanently on the sea floor (Paling *et al.*, 2001).

2.3.2 Conversion techniques for energy products

Depending on the organism used for cultivation several techniques can be considered to convert and use the energy content of the organism, leading to different energy products.

Complete biomass content

It is possible to dry algal biomass and combust it directly to produce heat and electricity, or use high-temperature high-pressure processes like gasification and hydro-thermal upgrading (HTU) to produce fuel gas or fuel oil respectively. These technologies require dry biomass. Drying of algae costs a lot of energy, which has a strong negative effect on the energy balance and capital costs of required equipment (Wijffels, 2007).

Thermo-chemical 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.

A biochemical way to process the whole biomass is anaerobic digestion. This produces biogas from the wet stream and requires much less energy input then the thermo chemical options. There is 55%-75% methane in biogas (Mes *et al.*, 2003), which can be combusted to produce heat and/or electricity, or upgraded to replace natural gas. From the waste-stream, N and P can be recovered and can be used as a nutrient input in alga culture or sold. If the organic waste stream doesn't contain too much heavy metals etc, it is normally processed and applied as compost. It is unclear whether this is possible for marine biomass due to its high salt content. Another option that has been suggested is the transfer of this organic waste stream to the ocean floor as a means of CO_2 storage (Chynoweth, 2002).

Anaerobic digestion is a proven technology and has been researched in depth in combination with marine macroalgae (Chynoweth, 2002).

Extraction of favourable compounds

Some species of macro- (Aresta *et al.*, 2005) and microalgae (Chisti, 2007) contain large amount of vegetable oils, which can be converted into biodiesel (Meiser and Riese, 2007). The percentage of oils depends heavily on the growth conditions (Chisti, 2007), which can be optimized. Also, oil extraction for the algae is a tested technology. However, this requires a large level of process control, which is almost impossible to realise in open sea.

Other organisms contain large amounts of starch, which can be converted into bioethanol. Furthermore, all species contain a large amount of polysaccharides and no lignin (Chisti, 2007). Currently advanced pre-treatment methods are under development, which enable ethanol formation from these algal polysaccharides. Waste streams left over after extraction can be subjected to anaerobic digestion.

Algae press cake as animal feed

Besides oil, algae can contain high percentages of protein and carbohydrates, and up to 10% of fibres. This could in potential lead to a nutritious cattle feed, even if the algal oil is not completely extracted while the oil is completely biodegradable and is a source of healthy poly-unsaturated fatty acids. In literature about energy production, utilising algal by-products as feed is often mentioned, for the improvement of the overall economics and added sustainability. However, specific research into this topic is rare, and no quality standards have been found. Recent presentation of the Feed Innovation Services (FIS, 2008) reports on the high amounts of vitamin C and beta carotene in algae which can be interesting for feed. Possible mixes for feed in which algae are used are good starting point. Algae can deliver the fatty acids EPA and DHA for cattle feed. Quality standards and use differ per type of cattle. Feed Innovation Systems expects the first application of algae for feed in the piglet industry, after that dairy cows.

In the context of this report, only marine algae are considered, which contain anywhere from 10% to 45% salt within their dry matter, a percentage which will increase after the oil is extracted. This could make the algal by-product too salty for cattle feed, unless it is used in marginal amounts or after salt removal. In a 1987 FAO report, the use of marine algae sum up to a maximum of 5%, and is referred to a dated article on the benefits of using the specific species: “The trace element and vitamin components of *Ascophyllum* meal are the active ingredients for growth of cattle, milk production, colour in eggs and improving wool colour in sheep (Neeb and Jensen 1965)”.

Other aquaculture products, like cultured fish, is often carnivorous while herbivorous species like Tilapia have very specific diets, preventing the use of algal press cake for aquaculture feed.

Based on the high salt content of the marine algae and the absence of research and standards for the use of algal by-products in animal feed, this option is assumed to have little or no relevance, at least in the near future.

Conclusion

Algae can be used for many purposes and applications, such as pharmaceutical, nutraceutical, cattle feed, and energy applications. In this study, only the latter are considered as main products.

From the energy products presented above, biodiesel is regarded here as the most interesting because of its technical development stage, which is more advanced than the experiences with ethanol production from algae. Also, the market perspectives of the conventional biodiesel sources are currently under attack regarding their sustainability. For the technical concept of aquatic biomass production, an energy product like biodiesel offers several advantages. Biodiesel is easier to transport than gas (and electricity), easily applicable in the current transportation fuel infrastructure and marine algal biodiesel can displace fossil fuel with a probably better greenhouse gas balance than the current criticised first generation biofuels. Hence, biodiesel from algae could be a nice market opportunity.

The potential of marine algae to produce the vegetable oil for biodiesel production will be investigated. It is already concluded based on information above that oil production is only feasible with microalgae, therefore biodiesel will only be the end product in sets with microalgae.

For macroalgae it has been shown that currently anaerobic digestion is the most interesting conversion option. Depending on the local circumstances, the produced biogas can be converted to bioelectricity or upgraded to displace natural gas. Biogas production

can take place on land or at sea, to be optimized depending on transportation distance and availability of off-shore gas/electricity grid connections from oil/gas platforms or wind turbines. Off-shore gas production, and subsequent shipping to land is also possible, but to reduce transportation costs, upgrading to pure methane and compression are required off-shore.
Dedicated harvesting and conversion ships can be designed, to optimize the process, like the Innofisk concept (InnovatieNetwerk, 2005) to directly process the captured fish in the ocean.

Furthermore, the use of by-products from energy conversion techniques is possible for other applications, such as the use of algae press cake or algae digestate as cattle feed. The quality standards for this application, as well as possible economic value are still unclear, therefore the use of by-products is not analysed further in this study.

2.3.3 Long-list of technical concepts

Below a summary long list is given of the selected technical concepts for the production and use of marine biomass.

1) Free-floating cultivation of floating seaweed, periodically harvested by dedicated harvesting vessel equipped with press to bring biomass to a dry matter content (DM) of 25% (Reith *et al.*, 2005) and transport it to an anaerobic digestion plant (Chynoweth, 2002; Gunaseelan, 1997)
    a) Digestion off-shore
    b) Digestion on-shore
2) Bounded cultivation of floating seaweed (Chynoweth, 2002), harvested by dedicated harvesting vessel (Chynoweth, 2002), which delivers the fresh biomass (DM 10%) (Reith *et al.*, 2005) to
    a) A pumping station at sea
    b) Shore

    For conversion to an energy carrier like biodiesel and biogas
3) A floating structure with horizontal lines with clonal (Santelices, 2001) macroalgae is positioned by a tug boat (Chynoweth, 2002)
    a) Which tows it to shore at the end of the growth season
    b) And harvested in situ by a custom designed vessel

    For conversion to energy carrier like biodiesel and biogas
4) Anchored (horizontal or vertical) line structures with attached seaweed (Chynoweth, 2002; Luning and Pang, 2003; Reith *et al.*, 2005) are harvested in-situ by dedicated harvesting vessel, which delivers the fresh biomass (DM 10%) to
    a) A pumping station at sea
    b) Shore

    For conversion to an energy carrier like biodiesel and biogas
5) Ring system culture (Buck and Buchholz, 2004) (best system for open sea from literature, (Reith *et al.*, 2005)) is used in large clusters
    a) Fully grown rings are transported to shore for harvesting

   b) A completely new in-situ harvesting method is developed
6) Land based open ponds are used for the production of biodiesel from algal oil, residues are digested (Chisti, 2007)
7) Collection of beached seaweed (Kirkman and Kendrick, 1997) and disturbing microalgae at urban areas near shore.
8) Floating transparent bags to cultivate microalgae that produce vegetable oils, harvest by collecting the bag on periodic moments, for further conversion: pressing the vegetable oil out of the algae and conversion in to biodiesel, residues for digestion
   a) Conversion on land (shipping the plastic bags)
   b) At infrastructure at sea (shipping the biodiesel)
9) Land based closed reactors are used for the production of biodiesel from algal oil, residues are digested (Chisti, 2007)

2.4 Creating sets

Now the long list of potential cultivation areas together with the described technical concepts above can be matched to make a selection of most interesting sets for aquatic biomass production worldwide. The following table shows an overview of these possible sets.

Table 2-2 Combination matrix for sets of interesting areas and technical concepts

Nr	Technical concept	On land	Near shore	Island	Inland sea	Offshore infrastructure	Open ocean	Pole area
Seaweed								
1	Free floating				X		X	X
2	Bounded floating			X	X	X	X	X
3	Horizontal lines		X		X	X		
4	Vertical lines		X	X	X	X		
5	Ring system		X	X	X	X	X	X
6	Beached seaweed		X	X				
Microalgae								
7	Floating bags				X			
8	Open ponds	X						
9	Closed reactors	X						
Seagrass								
10	Open fields		X	X	X	X		

2.4.1 Seaweed production

Coastal areas have many possibilities for cultivation of seaweed. Production is not based on harvesting natural populations and therefore focuses on growing seaweed species that can attach to underwater ropes. Problems of damage to rope structures and washed off biomass have been reported, so a cultivation system that prevents these problems needs to be designed. Each described system has its own advantages, depending on depth of water and use of coastal areas for other purposes (shipping routes, port areas, recreation, etc).

The vertical lines are suitable in densely used areas, while the irradiation per surface can be optimized, making cultivation possible in vertical structures in the sea. The seaweed can be applied as digester input, in digestion installations close by on the land. Electricity produced out of the biogas can instantly be fed to the grid.

Ring systems are strong cultivation systems, applicable for rougher seas, hence further away from shore. If a maximum distance is kept of 100 km to shore, energy conversion would still be possible on land.

Structures containing horizontal lines need to be anchored. A combination with existing infrastructure would be an interesting combination. Besides functioning as anchor point, the existing infrastructures could also be used to digest the biomass and transport on-site produced bio-electricity and/or biogas, while the zones they are built in are already a no-go area for ships and the seaweed colony would form a safe place for young fish to hatch and mature.

Offshore cultivation systems could be in any near shore area, near islands, in inland seas or even pole area. As long as the cultivation structure is not based on a floating construction, it can be assumed that existing offshore infrastructure will not be far from shore.

In the open ocean there are large parts that are extremely low in nutrients because of the big distance to land, which is by far the main source of nutrients. In these zones biological life is virtually absent. The available area is huge and does not have any economical value. If fertilized, these zones would have a huge potential for biomass production, due to the enormous amount of area available. The main disadvantage is the big distance between production and consumption. Therefore the system needs to be as cheap as possible. The most extensive growth system possible would be to fertilize (with a floating slow-release fertilizer) an area to grow a floating species of seaweed. This would prevent the costs of a cultivation system. To gain more control over its location, a floating seaweed colony could be surrounded by a floating barrier that prevents the colony from breaking apart. Besides these floating barriers a floating vessel equipped to digest the produced biomass and upgrade and compress the produced methane for shipping to shore is needed.

2.4.2 Microalgae production

Cultivation on land would be very suitable for the production of microalgae in either open or closed reactors. Land based systems focus on microalgae because these can have a higher production rate than macroalgae. Nutrient levels, cultivation time and mixing are easily controlled, allowing a far greater variety of species to choose from than when cultivating in open water. Open ponds seem more attractive based on lower cost price. The most interesting choice of species for an energy application are species with a high oil content, which can be converted into biodiesel. Biodiesel has a higher feedstock price and also higher social demand than to use the aquatic biomass only for dry matter content to produce for example biogas. Biogas can still be produced from the remaining biomass of the oil algae.

The only technical concept capable of producing microalgae at sea is a floating bags system. With floating transparent bags, which are permeable for water and light but not for algae and ideally nutrients the cultivated algae can be contained. Such a physical barrier from the bordering seawater would allow more intensive, controlled cultivation of algae rich in oils as a source for biodiesel. While the floating bags need to be open on top to receive as much light as possible, these systems are only suitable for calm seas like in inland seas or bays.

2.4.3 Seagrass production

Seagrass can grow in open fields, but needs a sandy bottom to grow in. Water depth therefore should not be deep so harvesting is made easier. In case of larger scale aquatic biomass production, it is likely that the production of seaweed or microalgae will be more interesting than seagrass because of these necessary growth conditions.

2.5 Selected sets

The following sets have been selected for further investigation in this report. The selected sets capture all the main options for location, culture systems and conversion product. The described cultivation systems are not confined to the accompanying location, but could also be applied at another location, or at a location several systems can be combined. The same way, other biomass conversion technologies can be chosen when they are more appropriate, or become so in the future. The following sets are a guideline of probable combinations, used for the estimation of the global potential. Specific combinations should be investigated case by case.

1. Open pond production of microalgae for biodiesel production on non-agricultural land areas near the coast (deserts in mid-Africa; on (sub) tropical islands like Hawaii).
2. Floating bags for microalgae production at inland seas for collection and vegetable oil production on land.
3. Floating structures with horizontal lines for seaweed production near existing offshore infrastructure with digestion and electricity production at sea.
4. Ring system for seaweed production in nutrient rich near-shore but rougher sea areas for digestion and electricity production at land.
5. Vertical lines for seaweeds in near shore densely used areas with a high nutrient availability (f.e. near shipping routes or port areas) with digestion on land.
6. Floating seaweed production in a surrounding structure in open ocean areas with digestion in designated ships.

Ad 1. While currently the cultivation of biomass for renewable energy purposes competes for agricultural land with food production, marine biomass can be grow on land which is unsuitable for agriculture, due to salination of the soil or the lack of a fresh water source. Land based cultivation systems containing seawater as a medium for the production of algae already exist, and can be adapted and scaled to grow algae for bio-energy production. Land based systems focus on microalgae because these have a higher production rate than macroalgae. Nutrient levels, cultivation time and mixing are easily controlled, allowing a far greater variety of species to choose from than when cultivating in open water. The most interesting choice is species with a high oil content, which can be converted into biodiesel. Biodiesel has a higher feedstock price and (social) demand than biogas, which can be produced from the remaining biomass. The highest production rates are achieved in complex transparent closed systems, but these are very expensive to build, and require a high level of knowledge and experience to maintain. Areas where agriculture is not possible will generally be underdeveloped countries, therefore a more simple and robust open pond cultivation system is most appropriate for land based cultivation.

Ad 2. As noted before, very little control on growth conditions like nutrients and mixing can be exercised in open waters. A possible solution to this problem is to construct floating transparent bags, which are permeable for water and light but not for algae and ideally nutrients. Such a physical barrier from the bordering seawater would allow more intensive, controlled cultivation of algae rich in oils as a source for biodiesel. To receive as much light as possible and avoid possible clogging of algae on the liners, these systems should be open at the top, which makes them vulnerable to rough seas. Therefore this system is best situated in calm areas like inland seas, lagoons and bays.

Ad 3. Biomass cultivation in open water is not very suitable for microalgae, so only seaweed is considered. This has been investigated for bio-energy purposes and is practiced commercially on a big scale for other products. Production is not based on harvesting natural populations, but focuses on growing seaweed species that can attach to underwater ropes. Problems of damage to rope structures and washed off biomass have been reported, so a cultivation system that prevents these problems needs to be designed. Such a system would benefit from good anchoring points to the seabed or to existing structures such as wind turbines or oil platforms. Existing infrastructures offshore could also be used to convert or pre-treat the biomass and transport on-site produced bio-electricity and/or biogas. The zones around existing infrastructure are already a no-go area for ships so the seaweed colony can grow uninterrupted, also making it a safe place for young fish. If attached to empty gas platforms other functions like CO_2 sequestration are possible, which can be combined with CO_2 fertilization of the algae.

Ad 4. During experiments at sea with line structures for cultivation, rings with a 5 meter diameter as a base for seaweed cultivation gave the best results, especially under high flow or heavy weather conditions. These rings can be attached to each other and/or the seabed or offshore infrastructure and can include a slow-release fertilizer from the ring centre. The main problem of this system is that the rings need to be harvested individually and completely lifted out of the water doing so, making cost-price reduction through economy of scale very difficult. For a large scale aquaculture, this system needs to be adapted to include easy harvesting. Existing infrastructures offer several benefits as described under set 3. This system is more robust and can therefore be applied in rough sea areas with the best sunlight/temperature conditions and/or high nutrient levels due to river outflow, natural upwelling of nutrients or nearby industrial activity. If no existing infrastructure is present, harvested biomass is most easily processed on land, therefore this system should be applied at a maximum of 25 km from the coast.

Ad 5. Vertical lines can be a space efficient system to grow possibly several types of aquatic biomass. This way, using for example green, brown and red algae, more elements of the light spectrum can be converted through photosynthesis making it more energy efficient. The lines can either be anchored to the sea bottom or be a floating construction. Several harvesting techniques are available and are considered more intensive than horizontal line systems. However per m^2 more aquatic biomass can be produced, with more efficient use of sun irradiation on the water surface. Also, the vertical system can be placed in densely used areas, for example near ports or river deltas, using the nutrient outflow of urban activities. Being close to the coast the biomass can quickly be transported to conversion units on land, like digesters. Pre-treatment of the seaweeds can be done there as well.

Ad 6. Large parts of the ocean are extremely low in nutrients because of the big distance to land, by far the main source of nutrients, and the larger water depth allowing nutrients to sink to the ocean ground. In these zones biological life is virtually absent at the water surface. The available area is huge and does not have any economical value. If fertilized, either from nutrient upwelling or from adding nutrients to surface, these zones would have a huge potential for biomass production, due to the enormous amount of area available. The main disadvantage is the large distance between to shore between production and consumption. Therefore the system needs to be as cheap as possible. The most extensive and cheapest growth system possible would be to fertilize (with a floating slow-release fertilizer) an area to grow a floating species of seaweed. This would prevent the costs of a cultivation system. To prevent diffusion of nutrients to larger depths or outside the cultivation area, the fertilization has to be growth-limiting, which will result in lower yields per hectare, but the huge amount of available hectares will make up for this. Another way to fertilize the cultivation is to dwell up the sunken nutrients from the ocean ground, but this will cost energy. Seasonally the seaweed is harvested while leaving enough material to re-grow. Harvested material needs to be upgraded to a high volumetric energy content on-site, before transport. For this system to become economically attractive, the size of a seaweed field should be at least 1000 km^2. Besides the risk of storms breaking up the colony, the whole seaweed field is subject to transport by ocean current. To gain more control over its location, a floating seaweed colony could be surrounded by a floating barrier that prevents the colony from breaking apart. These floating barriers are connected to a floating vessel equipped to pre-treat or even digest the produced biomass and upgrade and compress the produced methane for shipping to shore. The waste stream of the digester could be applied as fertilizer.

3 Technical potential

The selected sets now need to be investigated on their production per hectare or yield to determine the technical potential. Based on a more thorough analysis of the technical concept compared to chapter 2 and several assumptions concerning growth parameters an average estimate of the yield is given in tonnes dry matter biomass per hectare per year. Schematic overview of each set and picture material is attached in the annexes. Also the translation of these yields is converted to possible energy yield, depending on the technical concept within each set.

3.1 Set 1: Open pond microalgae for biodiesel

The proposed cultivation system is made up of a so-called raceway system, build as a shallow closed loop channel that allows the water to circulate. Raceway ponds are commonly build in concrete or compacted earth. Their shape may vary, but for a large area with multiple raceways, long stretched ponds with 180° curves on both ends are the most compact and efficient. Raceways may be lined with plastic. This plastic liner should be white in order to reflect light back to the algae and can be large part of the construction costs (Carlsson *et al.*, 2007), makes the system deployable on any soil type and with locally available construction materials and improves maintenance and life expectancy. For mixing and circulation a paddle wheel is used. This prevents sedimentation, eliminates the formation of a temperature gradient, helps the distribution of nutrients, the removal of produced oxygen and the transportation of algae from and to the surface, which improves the total light utilization efficiency (Terry and Raymond, 1985). Benemann and Oswald (Benemann and Oswald, 1996) have calculated a power requirement of 18 kWh/day/ha to achieve a flow speed of 0.15 m/s.

The temperature in an open raceway fluctuates within a diurnal cycle and seasonally. The optimum differs per algae species but is generally in the 20 – 30 °C range. Temperature is very difficult to control. Cooling can occur by means of evaporation, which requires either resupplying water of sufficiently low salt content or restarting a new batch when the salt content becomes too high. Other options for cooling or heating are using cool ocean water or natural or industrial sources of warm water, which all require a more advanced design of the ponds and an additional energy input.

Nutrients only need to be supplied during daylight hours, since the algae do not grow in the dark. Under these growth conditions, CO_2 is the first essential input to become limiting. Therefore, a supply of CO_2 is needed to achieve an optimal productivity. Industrial sources of waste CO_2 are abundant but may contain contaminants and gas transportation is expensive and should be minimized (Dimitrov, 2007). Examples of cheap sources of nutrients are digester effluent, manure, and sewage but may be unavailable in low inhabited areas without agriculture. For the system proposed here, 80%

of the nutrients are recovered by anaerobically digesting the algal rest stream (Sheehan *et al.*, 1998), adding the remaining 20% as agricultural fertilizer.

Algae concentrations will be less than 0.1% to 0.5% dry matter in raceways and the size of algae is only a few micrometers. These two aspects make the harvesting and further concentration of algae difficult and therefore expensive. The technical most simple 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% (and up to 95%) of the algal biomass was found to be concentrated in the bottom of the settler (Sheehan *et al.*, 1998) at 3% dry matter (Sheehan *et al.*, 1998) although this will depend on the species used. 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 (Molina Grima *et al.*, 2003) and proposed here as a second concentration step to reach a DM content of 20%.

In this case microalgae are used that have a high oil content (Chisti, 2007; Iersel van, 2007). Specific knowledge on removing the oil from algae is limited. It is generally assumed that 70% percent of the oil can be extracted with a mechanical press and applying an organic solvent increases the maximum extraction level 99%, but at a higher cost. Both methods can be used separately or in combination (Danielo, 2005). The oil content of algae can exceed 80% (Chisti, 2008), but only under specific circumstances, which are not optimal for the highest possible productivity in tonne dry matter per hectare. The algal biomass that remains after oil extraction is digested anaerobically, the resulting biogas is used to produce enough electricity to run the whole algae plant. In general a methane yield of around 200 m^3 per tonne DM can be assumed (which sums up to 6,5 GJ per tonne DM). The residue of digestion could be used as fertilizer for the raceway pond, enabling nutrient recycling up to 80%.

Productivity is influenced by many different factors, but current commercial practices show yields of up to 30 tonne DM/ha/yr with fertilization of 50 kg per tonne DM, while reproducible test results show up to 60 tonne DM/ha/yr (Carlsson *et al.*, 2007). Assuming that only areas in sub-tropical to tropical regions are taken into account, yields can be higher than commercial practices, and an average yield is considered in this report of 45 tonne DM/ha/year. The vegetable oil content of the algae is an important factor, but currently unclear for a large scale operation with the mentioned yields. Assuming an optimal strain and optimized conditions, an average oil content of 50% resulting in an oil yield of about 200 hectolitres/ha/year is considered feasible.

Schematic overview of set 1, together with some picture material is attached in Annex 2.

3.2 Set 2: Floating bags for microalgae production at inland seas

Some of the problems associated with the culture of marine biomass on land could be mediated by growing algae in contained systems in the sea, for example in bag shaped nets or plastic semi-permeable bags. The main advantages, besides to no use of land, are that (1) availability and transportation of (sea)water is not an issue, (2) there is no build-up of salts and other compounds because the growth medium is in direct contact with the surrounding water, (3) when removing the net from the sea water will be drained, which in practice is a built-in harvesting system and (4) the temperature will only change slightly throughout the year.

The nets or bags will have to be open on top to allow the content to be replaced and the maximum amount of light to reach the algae. If the bag is closed, the risk of clogging algae on the top is high. With an open top though, high waves may wash the biomass from the enclosure, so this system can only be applied in more calm inland seas and bays. The nets should be transparent too, to allow light arriving under an angle to reach the culture. The nets will have to be hoisted out of the water, so the pore size has to be large enough to allow all water to leave in a matter of minutes, but small enough to retain the biomass. In practice this means the cultured species must have a physical size of at least the millimetre scale. Seaweed meets that criterion, but the investment costs of these nets will be several orders of magnitude higher than the much simpler cultivation systems for floating and attaching seaweeds, as described in the other sets. The only remaining option is a filamentous (single cells that form long chains) microalga and should be occurring locally for ecological reasons. If the growth medium within the net is the same as outside the net, the same (low) productivity can be expected, so in order to reach a sufficiently high productivity an amount of seeding culture needs to be added, together with nutrients and possibly a source of CO_2, in a solid, slow release form. Due to the open nature of the system, part of all these inputs will leave the system, possibly leading to eutrophication or other environmental problems. It is assumed that 50 kg agricultural fertilizer/tonne DM is needed (Braun and Reith, 1993) and only 25% of the supplied nutrients remain in the system long enough to be taken up, so 75% of the added nutrients is lost to the environment through the holes of the net. To avoid this loss, the bag would have to be made of impermeable plastic, but then salt, O_2 and other waste would accumulate, while preventing CO_2 rich water to flow in from outside the bag and loosing the advantage that the biomass is separated from the water by hoisting the bag out of the sea. Using a net instead of a closed bag is therefore unavoidable. Such a net structure is most likely very susceptible to clogging with biomass and biofouling, as it will serve a good substrate for various marine life forms. Therefore recycling digester effluent as a nutrient source is not possible in this set. Severe changes in net mesh size, weight and buoyancy by biofouling have been reported for fish cages (Braithwaite *et al.*, 2007), giving the nets a relatively low life expectancy.

Since this culture system has never been used, estimating yields is difficult. Commercial productivity on land for the fresh water filamentous alga *Spirulina* is about 30 tonne DM/ha/yr. Without adding nutrients and CO_2, a minimum productivity of 20 tonne DM/ha/yr is assumed, while the maximum technical potential is assumed to be 50 tonne DM/ha/yr. Considering the risk of clogging spills and nutrient loss through the open top and the distance between individual bags, the default productivity is estimated at 25 tonne DM/ ha/ year , with algae with a 50% oil content, following set 1.

Additional picture material concerning this set can be found in Annex 3.

3.3 Set 3: Floating horizontal lines of seaweed production at existing infrastructure offshore

Commercial cultivation of macroalgae is commonly done using systems with horizontal ropes suspended under water, to which certain species of seaweed can attach to. Several reports have analysed such a system for the production of energy from aquatic biomass (Carlsson *et al.*, 2007; Chynoweth, 2002; Reith *et al.*, 2005). The large US bio methane from marine biomass program tested several concepts, but could not obtain sustained cultivation because either the structure broke in heavy weather and became entangled, or the biomass was washed from the lines (Chynoweth, 2002). A Dutch report on seaweed culture in off-shore wind parks assumes that improved design and using existing infrastructure as wind turbines and gas/oil platforms for anchoring can solve the aforementioned problems, but requires further investigation (Reith *et al.*, 2005).

One comprehensive study on yield assumes a baseline productivity of 11 tonne DM/ha/yr, based on commercial experience, and mentions that highly controlled tests yielded 45 tonne DM/ha/yr, but the costs of this optimized approach were too high for scale-up and commercialisation (Chynoweth, 2002). Higher expected yields of 28 – 46 tonne/ha/y are reported in (Carlsson *et al.*, 2007) based one an experiment that was lost during a storm. The Dutch ECN study (Reith *et al.*, 2005) assumes 20 tonne DM/ha/yr is possible for a one-layer system without fertilization. They propose a pilot with a surface layer and another layer 1,5 m below with another seaweed species which will use different spectrum of the light, enabling with fertilisation through hollow ropes for substrate attachment a high yield of 50 tonne DM/ha/y (Reith *et al.*, 2005). Here we assume 30 tonne DM/ha/yr as default yield while fertilization can take place (especially CO_2 fertilization in case of oil/ gas platforms where in future possibly also CO_2 storage could take place) and otherwise areas apply with favourable weather, temperature and nutrient conditions.

3.4 Set 4: Ring system for seaweed production in nutrient rich near shore but rougher sea areas

During experiments at sea (Buck, 2006), using rings 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 very difficult. For a large scale aquaculture, this system needs to be adapted to include easy harvesting. Existing infrastructures offer several benefits as described under set 3. This system is more robust and can therefore be applied in areas with the best sunlight/temperature conditions and/or high nutrient levels due to river outflow or nearby industrial activity. If no existing infrastructure is present, harvested biomass is most easily processed on land, therefore this system should be applied at a maximum of 25 km from the coast. The approach followed by Buck and Bucholz (Buck and Buchholz, 2004) encompassed the preparation of the ring on shore and the hoisting of the complete ring from the water to harvest it.

Several tests for growing seaweed on lines in the open sea have shown damage to the culture or culture system (Buck and Buchholz, 2004; Chynoweth, 2002). One experimental ring system stands out for not showing this problem. A ring has a diameter of 5 m, surface of 19,6 m^2 and 80-100 m substrate rope (Buck and Buchholz, 2004). Because of the robustness of this system sea conditions are less important, making the potential area to deploy this system large.

The annual biomass production in the North Sea has been extrapolated from field experiments to 20 tonne DM (Reith *et al.*, 2005). By deploying this system in more advantageous conditions, and possibly supplying a part of the nutrients by a slow release fertilizer at the centre of the circle, it is assumed the yield can be optimized to 50 tonne DM/ha/yr. The default yield is estimated at 30 tonne DM/ha/year.

Schematic overview of this set with additional pictures can be found in Annex 5.

3.5 Set 5: Vertical lines for seaweed in near shore densely used areas

At locations with a high light intensity and low turbidity, light energy can penetrate deep under the water surface. To optimally use this light, seaweed can be cultured on vertical ropes. The lines can either be anchored to the sea bottom or a floating construction. Harvesting is more labour intensive. However per m^2 more aquatic biomass can be produced, with more efficient use of sun irradiation on the water surface. It also makes the system suitable for locations that do not allow for much space for cultivation, but have relatively high nutrient concentrations due to eutrophication, river outflow, upwelling or other sources. These areas are often found close to land, which allows the harvested biomass to be converted on land. Maximum distance to shore is set on 25 km. It is assumed no nutrients need to be supplied artificially so the cultivation concept only applies for nutrient rich areas.

Layered cultivation systems are estimated to have a maximum productivity of 50 tonne DM per hectare per year (Reith *et al.*, 2005). For this layered cultivation different kinds of seaweed in vertical structure will optimize the use of sunlight even more (Reith *et al.*, 2005). Assuming a more efficient use of the available light, the minimum, maximum and default yields are estimated to be slightly higher than for sets 3 and 4. Minimum yield is around 25 tonne DM/ha/yr, maximum at 55 and default is set at 35 tonne DM/ha/yr.

In Annex 6 a schematic overview is presented of this set.

3.6 Set 6: Bounded floating structure for seaweed production in open seas areas

Mariculture of seaweed in the previously described sets is limited by the high costs of the production system. For naturally floating seaweed, the system only needs to fence off the circumference to prevent spreading. The larger the culture, the lower the relative amount of circumference needed, so ideally this system is deployed on a huge scale. The largest area available would be far from shore, in the open ocean. Large parts of the ocean receive a lot of light but support very low biological activity due to nutrient deficiency.

They are located far from land and at roughly the same latitudes as the world's deserts. The potential is enormous, but nutrients need to be supplied in order to make growth possible. In fact, nutrients are present in these biological deserts but in the large depths of the deep ocean (Brandenburg, 2008). Therefore *Sargassum* species seem ideal; besides floating, this seaweed has the ability to bind nitrogen from the air (Chynoweth, 2002). Distances from land will be large, up to 2000 km, requiring the production of an energy carrier from the biomass at sea, in the middle of the system. To reduce the costs of shipping the energy product to land, the upgrade and compression of biogas to Synthetic Natural Gas (SNG) for injection in the natural gas grid, after ocean transport is a possibility. A large part of the nutrients can be recycled from the digester, and N is partially supplied by nitrogen binding organisms growing on the seaweed surface. Which part is still unclear, but based on the findings by Philips *et al.* (Philips *et al.*, 1986) at open sea near Florida, is estimated to average 25 %. However, P and other nutrients are likely to leave the system by diffusion and will need to be brought in from land. To prevent excessive loss and eutrophication, the seaweed should be cultured under limiting nutrient conditions, which will result in loss of productivity, so an optimum needs to be found. Fluorescence measurement by satellite will pinpoint areas low in nutrients.

Currently the possibility is investigated to pump up the available nutrients in these deep oceans from the bottom of the sea (Ursem, 2008). These researchers analyse and develop a cultivation concept for open sea in which a special harvesting and conversion vessel is constantly gathering the grown algae and converting it to an engine fuel for airplanes.

Another option for adding nutrients is to position the system near the equator, which has relatively smooth climate conditions, and natural upwelling of nutrients from deeper water layers (Chynoweth, 2002). To prevent diffusion of nutrients to larger depths or outside the cultivation area, the fertilization has to be growth-limiting, which will result in lower yields per hectare, but the huge amount of available hectares will make up for this. Seasonally the seaweed is harvested while leaving enough material to regrow. Harvested material needs to be upgraded to a high volumetric energy content on-site, before transport.

For this system to become economically attractive, the size of a seaweed field should be at least 1000 km^2 (Ursem, 2008). Besides the risk of storms breaking up the colony, the whole seaweed field is subjected to transport by ocean current.

Although this approach seems to have a high potential, only a limited amount of small scale experiments has been performed at near shore locations. This resulted in a model assuming 32 to 66 tonne DM/ha/yr (Chynoweth, 2002), which seems rather high for a low maintenance, extensive, once per year harvest approach which is needed for commercial production far away from land.

The concept of TU Delft for open oceans (Ursem, 2008) works with an estimated yield of 30 ton DM/ha/year for a constantly harvested field of 1.000 km^2.

Although unclear, the unfertilized minimum and technical maximum yields are assumed to be 15 and 45 tonne DM/ha/yr respectively. The default yield therefore is estimated at 30 tonne DM/ ha/ year.

Annex 7 contains a schematic overview of this set.

3.7 Conclusions

Translating the technical potential in an estimated average yield, the crucial parameters and corresponding yield are presented in Table 3-1 below based on current state of the art techniques.

The energy yield is based on the final product of each set. In case of digestion of aquatic biomass per tonne dry matter around 200 m^3 methane can be produced which is around 6,5 GJ per tonne. The vegetable oil that is derived from microalgae in set 1 and 2 has an energy content of 36 MJ/ litre.

Table 3-1 Parameters per set leading to average estimation of the yield

Set	Distance to shore/ coast	Water depth	Continental shelf	Natural nutrient availability	Climate Zone	Yield (tonne DM/ hectare/ year)	Energy yield (GJ/ hectare/ year)
1: Open pond on land	Max. 100 km from coast	n.a.	On shelf	Poor: fertilization	Sub-tropical to tropical	45	~ 720 (200 hecto litre/ha/yr oil)
2: Floating bags in inland seas and bays	Max. 100 km from shore	Min 8 meters; no high waves	Both on and outside shelf possible	Poor to medium: fertilization	Moderate to tropical	25	~ 400 (110 hecto litre/ha/yr)
3: Horizontal lines between offshore infrastructure	Max. 100 km from shore	Min 8 meters	On shelf	Poor to rich; fertilization possible	Moderate to tropical	30	~ 200 (6.000 m3/ha/yr)
4: Ring system in rougher near shore areas	Max 25 km from shore	Min 8 meters	On shelf	Medium to rich; slow fertilization possible	Moderate to tropical	30	~ 200 (6.000 m3/ha/yr)
5: Vertical lines nearshore in densely used areas	Max 25 km from shore	Min 20 meters	On shelf	Very rich	Moderate to tropical	35	~ 220 (7.000 m3/ha/yr)
6: Bounded floating structure in open sea	Open ocean	Min 100 meters	Outside shelf	Poor: fertilization	Moderate to tropical	30	~ 200 (6.000 m3/ha/yr)

This technical potential is based on literature, desk research and practical research experiences. All discussed techniques are not yet available on a commercial scale for energy applications and are currently in a research and development phase. Innovation, technical optimalization within the selected sets, and interaction with other applications is possible to a large degree. This could influence the sets, parameters and displayed yields.

4 Ecologic potential

In this chapter the ecological aspects of the sets are discussed. Which ecological impact will the sets have and are there benefits of these systems that can improce the environment, aside to the assumed positive on climate change due to greenhouse gas emission reduction. And, what is the actual GHG emission reduction of energy products produced from aquatic biomass?

4.1 Ecological effects of aquatic biomass production

Since aquaculture has expanded over the years, the impact of aquaculture on the environment and effects of environment on aquaculture production have become important issues. Six different sets have been described in previous sections. Ecological effects of these sets differ from the cultivation and harvesting techniques, location and target species. There will be some overlap in the ecological effects of the different sets. The major differences depend on the location: cultivation at open sea, near shore, near existing infrastructure or land based systems. Below the ecological effects of the sets are described for each of these locations.

For all sets in sea counts the following. Cultivation should be avoided in vulnerable ecosystems and places where marine mammals can be entangled in the cultivation structure. Before wind parks or oil platform are realised, most likely an Environmental Impact Assessment have been executed, assuring that no conservation areas, migrating routes or vulnerable ecosystems are in the vicinity of the infrastructure.

4.1.1 Cultivation at open sea

Set 6: Bounded floating structure for seaweed

In this set large scale cultivation of naturally floating seaweed like *Sargassum* is proposed. No cultivation structure is needed except to fence off the system. So there is low risk of sea mammals getting entangled in the structure. The location will be at open sea where the available space is enormous and marine life is scarce, the so-called biological deserts.

Nutrients are limited in these areas at surface level and therefore fertilization is needed. By using *Sargussum* as a specie N_2 does not need to be fed to the system, while *Sargussum* can bind N_2 from the air (Chynoweth, 2002). To restrain the additional fertilization growth-limited quantity of fertilizer needs to be added and the cultivation area should have a lowest water current as possible, to prevent large spreading of the nutrients (InnovatieNetwerk, 2007). Better would be to use the nutrients that have dwelled to the bottom of these deep oceans, through pump system and recycle these lost nutrients this way.

The bounded structure and nutrients will give opportunities for other species to settle, leading to a higher biodiversity at the spot (an oasis). It is unclear what this attraction of marine herbivores will have for effect on the cultivation (InnovatieNetwerk, 2007). Maybe measures need to be taken to prevent the cultivation from being food for other marine life.

There might be some disturbance if digestion and electricity production is done at the spot, but the advantage of conversion at sea is that not as much transport for the biomass is needed, which will have a positive effect on the environmental performance (CO_2 balance, energy balance). After digestion of the seaweed, residue is left, which possibly can be used as fertilizer for the field keeping the nutrient cycle closed.

4.1.2 Near shore

Three of the selected sets are located near shore:

- Set 2: Floating bags for microalgae production
- Set 4: Ring system for seaweed production
- Set 5: Vertical lines for seaweeds

In general cultivation of aquatic biomass near shore has many logistic advantages, and the local ecosystems often support higher bioactivity and biodiversity. However, space is limited, which leads to more disturbance and competition with local species and more chance of invasion when exotic species are used.

In case fertilization is needed within the cultivation system, the water current determines the possible effect of eutrophication to the surrounding sea (InnovatieNetwerk, 2007).

Set 2: Floating bags for microalgae production

This set defines cultivating algae biomass on a large scale near shore in inland seas or bays in perforated polythene bags attached to long floating lines. The algae produce oils and conversion to vegetable oil will take place at land.

The floating bags need to be transparent to allow light to penetrate in order to grow microalgae. Also this way accurate fertilization can take place, allowing the cultivation system to be placed in nutrient poor areas.

The bags however will be very vulnerable for fouling and clogging and therefore need to be open at the top, so light can penetrate. This has the disadvantage that the cultivated species and nutrients can be washed out, which can lead to invasion of the cultivated algae and eutrophication. For the system there is a risk of unwanted algae or predators entering the system.

Harvesting of the algae will be done by pulling the bags up, letting water to leave the bag or by pulling the bags onshore. This will cause some disturbance and increase of turbidity. Harvesting will be done after 60 days. Because other species can enter the bags there is a high risk of by catch when harvesting.

The hanging bag structure it self has influence on the surrounded ecosystem. Positive ecological effect can be that the bags provide substrate and shelter for several species. Negative effects are caused by competition for light and nutrients. Also the described bag

structures appear to have a high risk for marine fauna to become entangled. Dead biomass may sink to the bottom of the net, possibly leading to the production of the greenhouse gas methane.
Ecological risks of this system are considered high, or will cause much effort to be controlled.

Set 4 and set 5: Seaweed cultivation ring system and vertical lines

In set 4 and 5 seaweed is cultivated in coastal water either through a ring system or vertical lines. Literature about the ecological effects of cultivation of seaweed in coastal areas is in general positive: no harmful effects and positive effect on already present eutrophication of human activities on land.
Coastal areas in general receive all the water runoff from land by groundwater or rivers with high amounts of organic waste, leading in many areas to eutrophication and deterioration of the water quality which can lead to toxic algae blooms. Another source of eutrophication is the growing aquaculture. Especially in China these business develops very fast. Very dense populations of fish and other aquatic animals are cultivated releasing large amounts of P en N. It is well known that seaweeds have a positive impact on moderately eutrophic water by absorbing nutrients from surrounding waters (Muraoka, 2004).
Seaweed resources are also an important source of carbon fixation (Muraoka, 2004). Experiments in China with cultivation with several weed species to diminish the eutrophication were promising (Fei, 2004). Xiungeng Fei states in his article that 47 years of *Laminaria* cultivation and no harmful ecological effects have been recorded (Fei, 2004)
A policy paper of NAAS in India promotes the cultivation of seaweed in the coastal zones in India and claims that seaweed cultivation of indigenous is ecologically safe (NAAS, 2003).

Some reports mention some negative influences, but not the size of the impact.
Seaweed cultivation can have an impact on sedimentation processes, increase of invertebrate assemblages and algal epiphytic abundances (Buschmann *et al.*, 1996).
Furthermore seaweed cultivation has influence on coastal water movement and can enhance sedimentation, but can also protect coastal areas from erosion. Enhanced sedimentation of organic matter coming from the weed and physical shading can result in changes in benthic communities (bottom life) and microalgae (Phillips, 1990).

In a few reports the use of fertilizer and the use of chemicals to prevent disease is mentioned. In euthropic coastal areas no fertilizer is needed, as is the case in set 5. The ring system allows very precise and measured fertilization, in the middle of the circle, minimizing the possible wash-off from added nutrients. Furthermore there is no evidence that seaweed diseases have been transferred as a result of seaweed cultivation (Phillips, 1990). Diseases do not seem a mayor problem (yet), but in combination with other sea farming activities such as production of clamps or fish this will be a point of attention. Also, attention should be given though when large scale monocultural systems are used or exotic species not familiar to that area.

Ecological impact of marine plant harvesting is related to the intensity of exploitation, the harvesting technique, and the vulnerability of the species or habitat to perturbation. Scientific work from Norway reports on a decrease in fish population possibly caused by intensive cultivation and extraction of seaweed from the ocean (Brandenburg, 2008).
Harvesting of seaweed is considered to be done one to four times a year by special ships which pull in the rings/lines or manually. This will cause disturbance and increase turbidity, but no severe impact is expected.

Seaweeds are also efficient in absorbing heavy metals. Accumulation in the weed is caused when cultivations is close to a nutrient rich stream including heavy metals (Phillips, 1990).

Positive effects are the provision of habitat and nursery areas during the growing season of the seaweed. However, the attraction of other marine life could result in less production because of feed. For the vertical structures, which will be placed closed to densely used areas, this is considered negligible. For the ring system this could be a problem.

4.1.3 Near existing offshore infrastructure

Set 3: Horizontal lines attached to existing infrastructure at sea

Existing infrastructure, like oil platforms and wind parks provides artificial substrate which attracts all kinds of marine species. However the abundance of marine life depends on the availability of nutrients. If nutrients are limiting, than fertilizer is needed for seaweed cultivation. This has shown to enhance local production of phytoplankton and invertebrates (Phillips, 1990). In this set we assume fertilizer will be added to some extent. Especially in case of offshore infrastructure like oil or gas platforms, CO_2 fertilization will be quite interesting combined with sequestration. Seaweed culture in general is an extensive culture system which relies mostly on a natural nutrient supply (Phillips, 1990). In high density culture areas however nutrient depletion can occur (Phillips, 1990), so to control the fertilization again growth-limited quantities will be added if necessary and water current will be optimized to lowest possible locations.

There can be already a wide variety of species present at the infrastructure. The cultivation of seaweed will influence this exciting ecosystem in several ways (InnovatieNetwerk, 2007).
In the first place the cultivated seaweed can be washed away from the lines spreading in the environment. At open sea far from coastal areas using seaweed species that need anchoring, there is less risk of causing extensive growth besides the cultivation area. To minimize the effects only indigenous species should be used and no exotic species should be introduced, which have the risk to invade the environment and suppress native species.

Other effects are that seaweed cultivation competes with nutrients and will cause shading, which can defeat other algae in their need for light.

A positive effect of seaweed cultivation is that seaweed will provide a shelter especially for young fish. However harvesting will create disturbance and takes away all the seaweed at once. Depending on the kind of seaweed harvesting will take place once up to three times a year. If the growing season of seaweed is matching the breeding season of local fish it can have a positive effect. Again, the cultivation system could also become a new feeding source, affecting the production especially near existing infrastructure where shipping routes and other activities are minimized by law.

4.1.4 On land

Set 1: Open pond system microalgae (raceway ponds)

Of the chosen sets there is one land based system. In set I a raceway open pond system is used for the cultivation of microalgae for biodiesel production on non-agricultural land areas near the coast (desserts in mid-Africa; on (sub) tropical islands like Hawaii).
The focus is a system applied on arid, set-aside land which is not suitable for agriculture due to high salinity or shortage of freshwater. Therefore seawater is suggested to be used as growth medium. A disadvantage of sea water is that evaporation causes the rising of the salinity and therefore continuous input of fresh seawater is needed or even waste water can be added, which dilutes the salt and at the same time is a valuable source of nutrients. A continuous flow of cold seawater is also required to control the water temperature. Therefore distance to coast is not larger than 100 km.

A land based system has the ecological advantage that the cultivated species are bonded to the system, and won't suppress native species or cause diseases in the surrounding ecosystem. Also nutrients and waste water are bonded to the system and can be controlled. For land based systems, the main ecological effects will come from the construction, operation of the plant (traffic, waste, infrastructure) and space used for ponds, which is unlikely to cause significant harm when unfertile land is used.

A Life Cycle Analysis showed that cultivation of algae in open pond systems in combination with water purification of waste water and energy production has the best environmental performance (NAAS, 2003). Cultivation can be done without pesticides. Fertiliser is used but can be controlled. When combined with waste water no fertilizer is needed or higher yields can be obtained. The waste water from the ponds should be recycled and be reused. After conversion to biogas, the residue of digestion remains and can be re-used as fertilizer, keeping the nutrient cycle closed.

4.2 Green House Gas (GHG) balance

All sets have been analysed on their GHG balance. Of each set the whole production chain is analysed on its energy use, use of fertilizers or other energy intensive products than can cause GHG emissions, and the amount of recycling or use of possible by-products.
The materials used for construction or buildings within the production chain and the GHG emissions of the production of these materials are not taken into account.

Figure 4-1 below shows a schematic overview of which steps are considered.

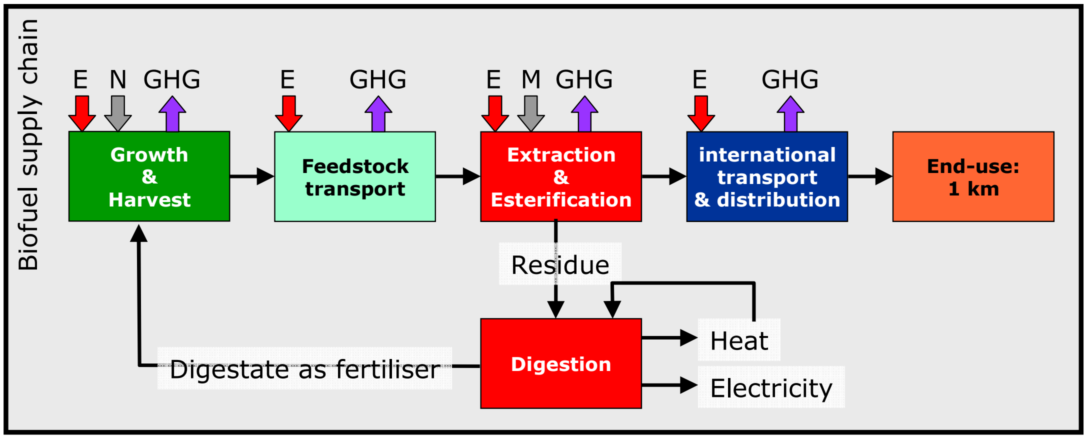


Figure 4-1 Schematic overview of analyzed steps in GHG balance calculation

N stands for nitrogen fertilization. N fertilization is also taken into account for biomass cultivation on land. Distinction is made between the direct and indirect GHG emissions (CO_2, N_2O and CH_4) of N fertilization. The indirect emissions are caused during the production of N fertilizer (consumption of electricity, consumption of methane, material use). The direct emissions are the emissions emitted during the application of fertilization on the algae system. These direct emissions are different if N fertilizer is used on land or in water. N fertilization in water will have little to no direct N_2O emissions, while on land 33 gram of N_2O emissions are produced for every kg of N fertilizer applied.

To compare the results of the sets on possible GHG emission reduction and energy efficiency with other products, differentiation is made between set 1 and 2 and the other sets 3 until 6, based on their end product (biodiesel and biogas).

Also, the possible reduction of indirect GHG emissions of N fertilizer is brought into perspective in a second calculation in which insight is given into the future GHG balance of all presented products. N_2O emissions caused during production of N fertilizer can for example easily be reduced (Hamelinck, 2005). The assumption is made that CO_2 emissions caused during production will be captured and stored in the future to reduce emissions and generate carbon credits.

4.2.1 Algae to biodiesel

For set 1 and 2 the whole production chain from algae cultivation to biodiesel is taken into account. The GHG balance and energy use is compared with biodiesel from other biomass resources and with fossil diesel as reference fuel. For the esterification process the same input values are used for the algae sets as for rapeseed.

Figure 4-2 shows the results. Fossil diesel is marked grey, indicating it as the reference fuel at a 100% score. Set 1 clearly comes out with a very positive GHG balance, reducing emissions more than 83% compared to fossil diesel, and even significantly cleaner than biodiesel from biomass resources from agricultural crops.

Set 2 on the other hand has a negative GHG balance, producing even more GHG emissions than fossil diesel. This is caused for larger part by the large amount of N-fertilization needed in the process. The uptake of nutrients is considered low because of open top or semi-permeable bag structure and therefore large chance for spill-outs.

Both sets however are more energy efficient though than fossil diesel. Energy use during production steps is considered to be delivered by own digestion process and therefore not taken into account within the calculations.

Within the most recent draft version of the new European Renewable Energy Directive (23rd of January 2008, version 15.4) at least 35% GHG emission reduction is needed to comply with the biofuels target of 10% in 2020[1]. Set 1 will than definitely be eligible within the biofuels obligation.

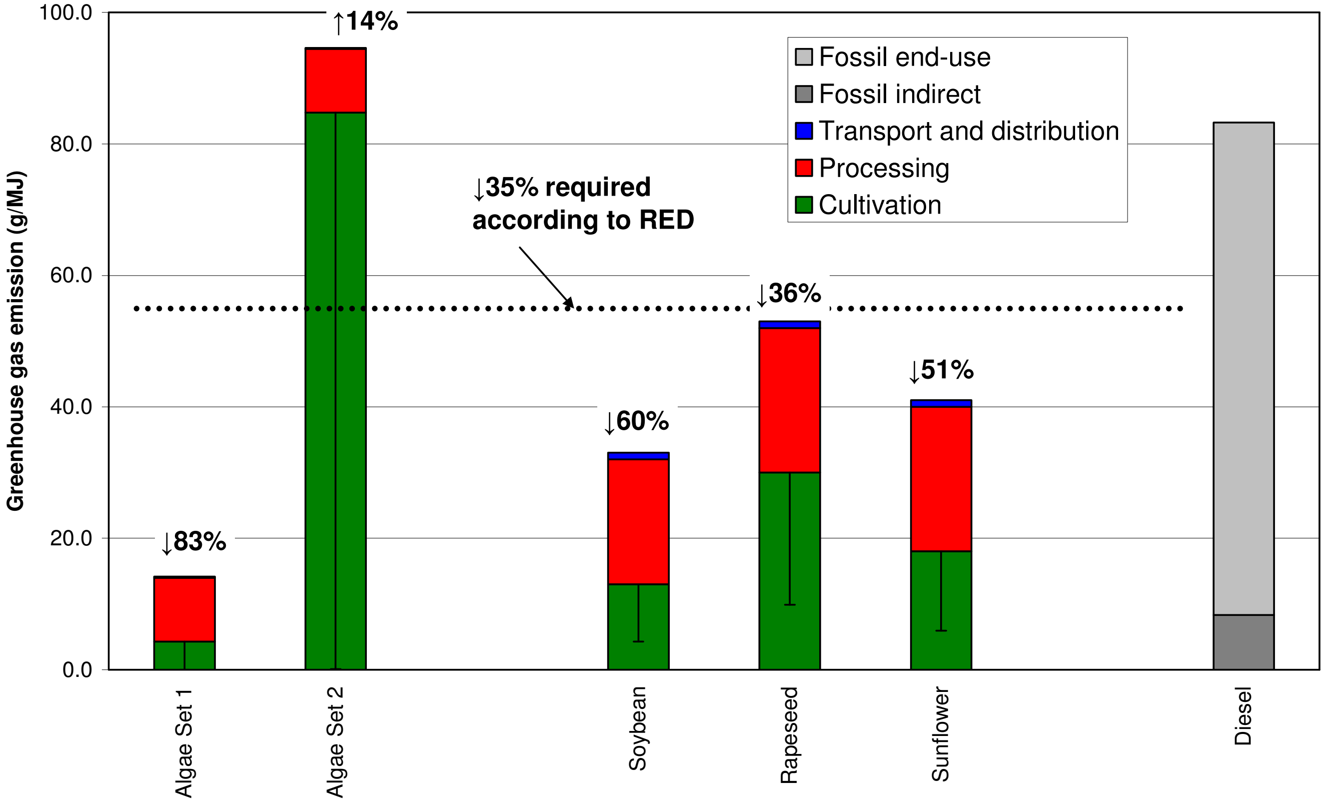


Figure 4-2 GHG balance for algae to biodiesel (set 1 and 2)

The black line within the cultivation step of each renewable source shows the possible reduction of GHG emissions if the indirect emissions of N fertilization (CO_2 and N_2O emissions that are caused during production) are avoided. Than the algae sets perform much better, while no N_2O emissions occur in direct use of N fertilizer and no transport fuels are needed during cultivation.

---

[1] Stated in draft version 15.4, dated 23th of January 2008, in article 15.2

4.2.2 Algae to biogas

For set 3, 4, 5 and 6 the whole production chain exists of algae cultivation to biogas production. For set 5 the amount of N fertilization is considered zero, while the cultivation takes place in nutrient-rich waters. Set 3 and 4 have the same amount of N fertilization of around 250 kg/ha/year to achieve the average yield. Set 6 will need even more fertilization, around 880 kg/ha/year, while less nutrient uptake on the large cultivation fields at open sea is possible.

For set 3 the possible GHG emissions from internal energy use is not taken into account, this energy is assumed to be produced by own renewable means on location. For set 4, 5 and 6 energy use for harvesting is taken into account. For all sets also transportation through ship vessel working on diesel is taken into account, as well as digestion.

The following graph presents the results of the calculations for the sets of algae to biogas in comparison with other biogas production means and referenced on the GHG balance of natural gas.

It becomes clear from this graph that set 3 and 5 also have a very positive GHG balance, even better than biogas produced from manure or land filling (Municipal Solid Waste). For set 4 this is somewhat higher caused by the energy use for extracting the whole ring system from water for harvesting. Set 6 performs less because of the use of more N fertilizer and partially because of the larger distance to shore (calculated with 2000 km distance to shore).

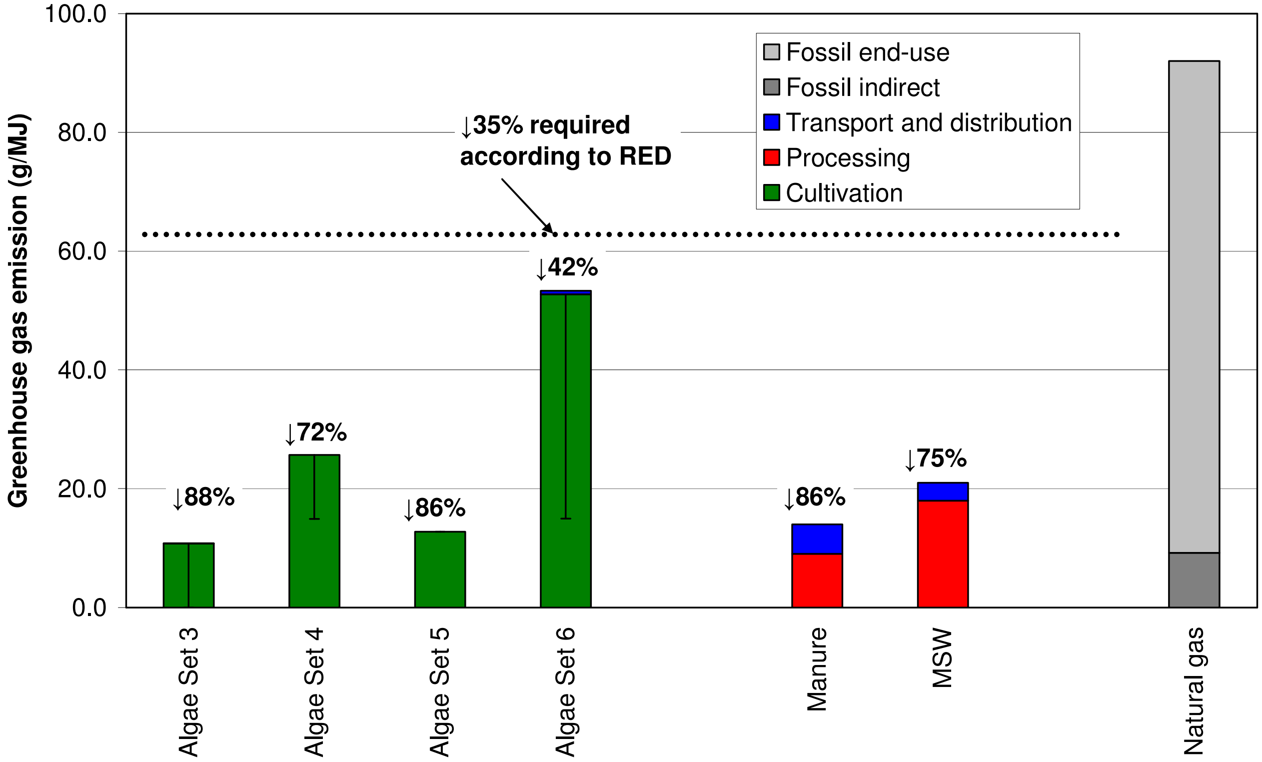


Figure 4-3 GHG balance for sets 3 to 6, algae to biogas

All compared renewable sources for biogas will lead to GHG emission reduction of more than 35% as is stated in the draft Renewable Energy Directive compared to the GHG balance of natural gas as fossil fuel.

If indirect GHG emissions of N fertilizer are avoided, the GHG balance can be reduced as is shown in the graphs with the vertical black line. For set 5, in which N fertilization was already not taken into account, this will have no effect. Emissions during cultivation here are caused by energy use for setting out the cultivation system and harvesting.

4.3 Conclusions

Cultivation on land has the least risks on harmful ecological impact, because the cultivated organism and nutrients are bonded to the system, can be monitored and controlled. This will only be the case if open pond system is indeed realised on desert land, not suitable for agriculture and with use of seawater or waste water. Also the GHG balance of set 1 is very positive, even better with currently assumed values than biodiesel production from rapeseed.

For cultivation at sea the main environmental impacts can be caused by introducing exotic species, with the risk of invasion of the area. Cultivation at biological deserts in deep oceans or degraded coastal areas can be used to enhance bioactivity from otherwise barren environments.

In any case, a new biological balance needs to be established when biomass is cultivated and regularly harvested. This remains an important research area to be investigated further.

Fertilization in some sets could cause additional eutrophication. This can be minimized by setting the quantity of fertilizer to growth-limited and by choosing sea areas that have low water currents. The sets in coastal areas increase competition with space, lights and nutrients but integration with intensive mariculture can also be used to decrease eutrophication.

With the change of cultivation area from land to sea, a new topic of discussion appears on the change of sea use (instead of land use change). The spatial area used on sea for biomass cultivation can also be in competition with other applications.

The floating bags of set 2 seem least attractive from ecological point of view while cultivation at will cause more competition for space and light with local species and could cause hinder to sea mammals but blocking out water surface completely. Also the clogging and eutrophication that can lead from spills can cause more harm than the open line systems. The GHG balance of set 2, while much N fertilization is needed because of the chance of spills, is negative causing even more GHG emissions than fossil diesel, making this line-up of set 2 not attractive.

Vertical lines (set 5) will have an additional advantage in environmental impact while they are to be placed very accurately in those areas where eutrophication and pollution in sea water from activities on land are high.

5 Socio-economic potential

Finally the social and economic aspets of the sets are determined. In first part of this chapter the social effects are investigated for the possible economic interactions that can occur if aquatic biomass production for energy applications would develop towards a commercial scale.
In the second part of this chapter a cost price calculation is made for all sets. The results of the socio-economic aspects are translated towards restrictions for the potential to come to a feasible worldwide potential.

5.1 Economic interactions

5.1.1 On land

If aquatic biomass is produced on land, the main restriction for the cultivation system is to use arid or desert land for this. In no aspect agricultural land should be used and use of scarce resources for other activities (for example use of fresh water) should be minimized. This way the direct competition with food production will be low, enhancing the overall sustainability of the cultivation system.
Fertilization will be needed, so interaction could be possible with CO_2-producers and anaerobic digestion plants to use their residues. The product, biodiesel from algae, can be used as transport fuel, but the algae oil or biodiesel is also very suitable for electricity production under higher efficiency (as is the expected application on the island of Bonaire, working towards a completely renewable energy infrastructure).

5.1.2 At sea

Creating new agricultural applications, not on land but disclosing the large potential of the sea seems very interesting as a new economic drive for current agricultural companies (NAAS, 2003). It could also be an incentive for the fishing industry. The technical aspects of the cultivation systems offshore will stimulate the already booming industry of offshore infrastructure companies. Side effects could be the construction of specialised harvest and energy carrier ships.
Negative interaction could be the competition of cultivation systems for energy with aquatic biomass production for food and pharmaceutical or cosmetic purposes. However, these different applications of aquatic biomass can also enhance each other and create learning effects that will reduce production costs. One can think of cascaded use of the aquatic biomass in the same way research is done now on the most efficient use of biomass on land (Grondstoffen, 2007), while for the higher value unique products from algae lesser quantities are needed. Larger volumes and residues than can be used for energy applications from algae.

5.2 Economical feasibility

In order to determine whether a set can be applied commercially, its economics need to be assessed. Since none of the sets is currently applied in practice on a commercial scale, there is no hard data available and estimates and assumptions are generally imprecise. Practical data only exists for cultivation systems of algae to energy applications for systems on land. To still perform a qualitative analysis of the systems at sea an intensive analysis is made on set 1, followed by a comparison of the other sets on where production costs could differ from this set. This is complemented with expert opinions and scarcely available and rather theoretical literature on the different sets.

5.2.1 *Set 1: Land-based open pond culture of marine microalgae with for biodiesel production*

The costs for this set can be generally divided into the following groups. A thorough description of the technical concept has been given in chapter 3.

- Purchase of land
- Plastic liner for pond
- Paddle wheel and pumps
- Harvesting equipment
- Pressing machine for oil extraction
- Esterification unit to convert oil into biodiesel
- Digestor for biomass waste (and fertilizer production)
- Use of electricity, sea water transport, algae, possible additional fertilizer

Whether atmosphere CO_2 or CO_2 from an industrial waste stream is used, each tonne DM of produced biomass captures 1.8 tonne CO_2 (Chisti, 2007). The capturing of CO_2 has economical value under the different emission trading schemes, but since extra expenses have to be made to provide CO_2 to the algae, here it is assumed that these costs and revenues cancel each other out.

Following graph shows the division in estimated investment costs of this system (Iersel van, 2007) in euro/ hectare.

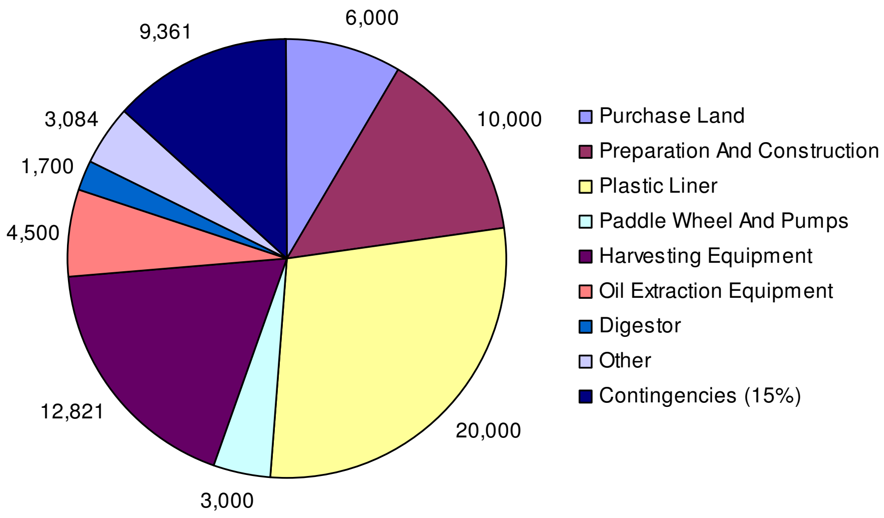


Figure 5-1 Investment cost breakdown for open pond system on land [€/ha]

The plastic liner contributes most to the investment costs.

The total investment costs have been calculated at about 73.000 €/ha by two independent sources (Carlsson *et al.*, 2007; Iersel van, 2007) or around 1600 €/tonne DM with a default yield of 45 tonne DM/ha/year.

Modelling of operation and maintenance cost and productivity of an open pond system resulted in an estimate cost price range of 0,80 to 1,80 €/l vegetable oil for a economic life span of 10 year (Iersel van, 2007).

5.2.2 Set 2: Floating bags for microalgae production at inland seas

Purchase of land will be not applicable for this set, if compared to set 1. The exact design needs to be further developed, it is clear that the investment costs for this system of bag shaped nets with a few meters in diameter and depth, made of strong, thin, fine mesh material with the right buoyancy, transparency and a positioning structure will be very high, certainly higher than plastic liner for set 1, since the bags have a much bigger surface than the almost flat raceway ponds. Costs for the plastic are estimated at € 35.000 per ha (Cohen, 2008). Costs for paddle wheel or around € 3000/ ha are not needed in this set.

Other costs determined in set 1 will be the same for set 2, with additional transport costs of the harvested bags to the conversion location on land. Transport costs are calculated as follows (Hamelinck *et al*, 2003). One medium sized vessel can carry up to 1000 ton DM of algae and ship this in one day up to 700 km. Costs for a vessel are € 6000 per day. Fuel costs are around € 18 per km. Costs for loading and unloading are considered around € 8 per tonne. With a maximum distance of 100 km offshore, transport costs are in this set around € 400 per ha/yr for default yield of 25 tonne DM/ha/yr.

5.2.3 Set 3: Electricity from biomass cultivated on horizontal ropes near offshore infrastructure

It is estimated that cultivation system for this set will be cheaper than for set 1, with no cost for land and only investment in horizontal rope structure itself. Per hectare 1 km of lines is necessary in a one-layered system, about 10 lines of 100 meter (Brandenburg, 2008).

Some anchor points are already there, namely the offshore infrastructure. It is assumed that the complete cultivation system of horizontal lines and construction will cost around 25.000 €/ha. Transport costs to land will be the largest difference from set 1.

Reith *et al.* (Reith *et al.*, 2005) have calculated transportation costs, assuming 200 km for transport to shore and harvesting movements at about 37 €/tonne DM, which could be reduced by a factor 3 if the harvested biomass is concentrated/dewatered offshore from 12% DM to 30% DM. Based on (Hamelinck *et al*, 2003), parameters as discussed above at paragraph 5.2.2, transport costs are assumed at around € 475 per ha per year in default situation.

Although large part of these transportation costs, more than half, are due to loading and unloading, a possible way to reduce the need for transportation is to digest the harvested biomass on an off-shore location in the middle of the production field. Current infrastructure, especially (unused) oil/gas platform will greatly reduce the construction costs of such an installation, but also allow easy transport of the energy carrier to shore, through the current power and gas lines. Using this approach, the system becomes more comparable to a near-shore operation. In elaborate economic analysis in Chynoweth (Chynoweth, 2002) shows a total capital cost of 87 M$, O&M 3,8 M$ and fuel 1,34 M$ for a 2671 ha system with 57 tonne DM/ha/y production, resulting in 7,83$/GJ gas or around 5,20 €/GJ gas (in 1987). Also an energy requirement of 10% of the total production is mentioned, or 5,7 tonne DM/ha/y equivalents as energy input for this system.

Assuming digestion can be done on existing infrastructure and electricity can be transported by existing power lines, costs could be significantly lower than for set 1, around 40.000 €/ha, or 1340 €/tonne DM with default yield. The additional costs for CO_2 fertilization will depend strongly on the chosen location and existing infrastructure (oil platform as CO_2 storage).

5.2.4 Set 4: Seaweed biomass production on ring structures in dynamic environments

The approach followed by Buck and Bucholz (Buck and Buchholz, 2004) encompassed the preparation of the ring on shore and the hoisting of the complete ring from the water to harvest it. This resulted in a labour-intensive process, which costs 2500 €/tonne DM. Costs for cultivation are higher than for set 1 and much higher than costs for the horizontal lines.

It seems unlikely that this set will be economically feasible and that other floating line structures will become interesting first because of cheaper production costs. Cost reduction for this concept therefore is essential. The system needs to be redesigned, keeping its beneficial characteristics but making a cheap, automated harvest possible.

5.2.5 Set 5: Marine biomass culture on vertical lines at space-limited locations

Costs for cultivation of vertical lines will probably be comparable with the horizontal lines. Construction will be easier, being closer to shore and only leaving a buoy with anchored or floating line behind. Lines will be little more expensive because of the buoys needed at top end. Harvesting will be more intensive because of vertical structure and more water, resulting to higher costs.

However, as the set is determined in areas of 25 km maximum offshore, transport costs will be lower than is mentioned in set 3. Based on transport parameters as discussed before, transport costs will be around € 400 per ha per year for default yield. Together with no use of fertilization, this set is assumed to be around the same investment costs as set 3, around 45.000 €/ha or 1270 €/tonne DM for default yield.

5.2.6 Set 6: Floating culture of Sargassum in biologically inactive open ocean zones

This system will have very low investment costs for the cultivation system itself. However, energy conversion and transportation costs will be higher here. If indeed a floating conversion unit has to be installed, this will lead to high costs. Biogas needs to be upgraded, compressed and shipped over a long distance to shore.

Another option is to use a special harvesting and conversion ship which will be constantly harvesting the large cultivation area in open ocean. Such a ship for an area of 100.000 ha (20 by 50 km) is expected to cost around 1 billion € (Ursem, 2008). Together with costs for contingencies and some small additional costs this would result to estimated investment costs of around € 21.000 per ha, or around € 720 per tonne DM with default yield.

Transportation costs are high, and although costs for vessel are not taken into account while this is included in the investment costs, the transport costs are calculated at around €1300 per tonne DM per year.

5.2.7 Conclusions

The cost information discussed can be summarized as follows, see Table 5-1.

Table 5-1 Investment costs per set

Set	**Yield (tonne DM/ ha/ yr)**	**Energy Yield (GJ/ ha/ yr)**	**Investment costs (euro/ ha)**
1: Open pond on land	45	~ 720 (200 hecto litre/ha/yr oil)	73.000
2: Floating bags in inland seas and bays	25	~ 400 (110 hecto litre/ha/yr oil)	69.000
3: Horizontal lines between offshore infrastructure	30	~ 200 (6.000 m3/ha/yr)	40.000

Set	Yield (tonne DM/ ha/ yr)	Energy Yield (GJ/ ha/ yr)	Investment costs (euro/ ha)
4: Ring system in rougher near shore areas	30	~ 200 (6.000 m3/ha/yr)	84.000
5: Vertical lines nearshore in densely used areas	35	~ 220 (7.000 m3/ha/yr)	44.000
6: Bounded floating structure in open sea	30	~ 200 (6.000 m3/ha/yr)	22.000

These investment costs per ha are calculated to annual capital costs in € per ha per year. Together with estimation of yearly O&M costs and transport costs, a cost price estimation can be made for default yield, maximum yield and minimum yield.
The following graph (Figure 5-2) shows the cost prices in €/ tonne DM for the default yield, with a cost price range based on costs for maximum and minimum yield.

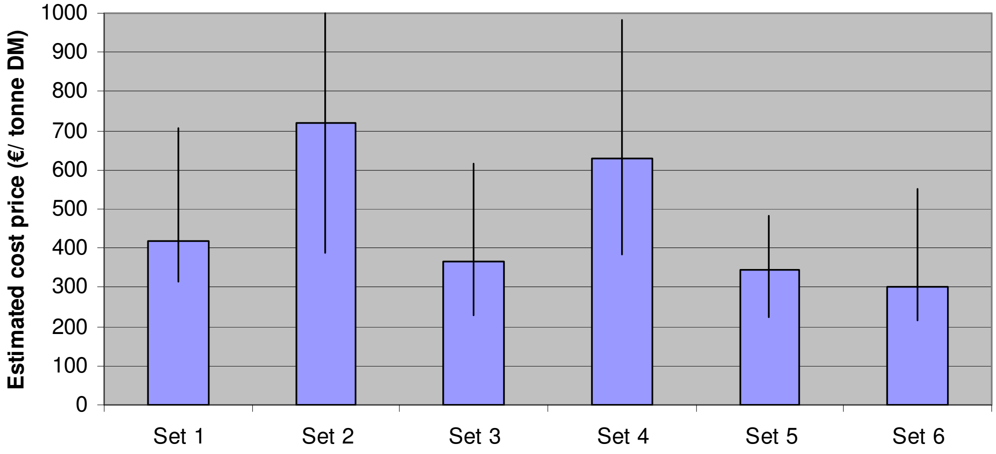


Figure 5-2 Cost price ranges for investigated sets

Set 3, 5 and 6 seem cheapest. A rope system shows significant potential for seaweed cultivation, but the relatively low price of energy prohibits commercial exploitation. While the horizontal cultivation system showed the highest production price of all systems tested in (Chynoweth, 2002), combining it with existing off-shore infrastructure potentially will bring down the costs for construction, anchoring and transport.

If these prices per tonne DM are compared to the price indication of some conventional agricultural products (see Table 5-2), it becomes clear that algae production are much higher than these well-developed products. However, labour costs are taken into account for the investigated algae production systems where in these agricultural costs and prices this is left out.

Table 5-2 Production costs and prices of agricultural products[1]

Crops on land	Yield (tonne/ha)	Production costs[2] (€/ha)	Price[3] (€/tonne)
Winter wheat	9	700	100
Rapeseed	4	850	230
Sugar beet	74	1400	35 [4]
Maize silage	13	1200	130

1) All data from KWIN (PAV 2006)

2) Costs of energy, materials, product related duties and hired contract work. The labour of the farmer is not included. Furthermore, the farmer may receive an EU subsidy (per hectare).

3) The current agricultural feedstock price is generally higher, however, Ecofys estimates that the KWIN presents a more sustainable price.

4) The price depends on the sugar content and the height of the quota per farm.

Based on a price per GJ set 1 and 2 are cheaper, while more GJ can be produced through biodiesel production from algae. Table 5-3 below shows the comparison of the algae energy products in the different sets (based on default yield), compared to its reference fuels.

Table 5-3 Cost price comparison on energy content

Fuel	Price (€/ GJ oil)	Fuel	Price (€/ GJ gas)
Fossil diesel	~ 22	Natural gas	~ 6
Vegetable oil from rapeseed	~ 22	Biogas from co-digestion	~ 12
Vegetable oil from algae (set 1)	26	Biogas from algae (set 3)	57
Vegetable oil from algae (set 2)	44	Biogas from algae (set 4)	97
		Biogas from algae (set 5)	53
		Biogas from algae (set 6)	46

Data: CBS Statline; Shell consumer price.

In a report on the Dutch situation, Reith *et al.* (Reith *et al.*, 2005), the four main conversion options have been analysed economically. The resulting production costs the break-even without additional government subsidies are summarised in table 2-2 (Reith *et al.*, 2005). Table 5-4 shows that biogas production and subsequent conversion to electricity is currently the only conversion technology that allows any price to be paid for the feedstock biomass and a chance on economical feasibility.

Table 5-4 Break-even costs for feedstock for energy production in €/tonne DM, source (Reith *et al.*, 2005)

Product	Scale: 100.000 tonne DM/y	Scale: 500.000 tonne DM/y
Electricity from biogas	7	10
Ethanol and electricity	-43	3
HTU biocrude and electricity	-55	-31
Electricity via super critical gasification	-112	-41

But algae energy products do have advantages that at this point are not yet translated into added market value. The GHG balance of most algae sets studied in this project is more positive than that of bio-energy products produced on land. The additional GHG emission reduction could generate on longer term additional value, if policy instruments and carbon trade systems are installed correctly.

Also optimalization is still very possible in the whole production chain, for example leading to revenues from by-products or cost reduction caused by system integration with other functions or technologies.

5.3 Restrictions for potential

All of the sets investigated will have higher costs than current established bio energy applications, based on biomass production on land. Differentiation can be made within the analyzed sets on their economical feasibility.

From this analysis it is concluded that such production according to set 2 does not outweigh the limited applicability, high investment, inherent nutrient requirement and loss, low life expectancy danger to animal entanglement and other environmental risks of the system. Therefore this proposed system is deemed inappropriate and not subjected further to economic analysis.

Also the ring system of set 4 is assumed to have very high costs. Although it will be applicable for rougher seas, it needs to be close to shore to reduce transportation costs. Set 3 and 5, horizontal and vertical lines, will become interesting much sooner from economic point of view.

Set 1 seems expensive still, but learning curves can make the system cheaper. Cultivating aquatic biomass in land-based system will be done in areas which do not have any other economic functions, specifically agriculture. Glenn et al. (Glenn *et al.*, 1998) mention that 43 percent of the earth's total land surface is arid or semi-arid and estimate that 15 percent of undeveloped land is has sufficient access seawater, which amounts to 130 million ha. This would imply that a potential is possible for only this set of around 90 EJ of biodiesel production. The potential of set 1 is considered to be disclosed most easily, being a land-based system, and based on the current development in the technical aspects of open pond raceway systems for microalgae.

The worldwide potential for set 3, horizontal lines, is comparable with the worldwide potential for offshore wind farms (taken into account water depths, shipping routes etc.) which is estimated around 550 million hectares (Hoogwijk, 2004). This would imply a worldwide potential for set 3 of around 110 EJ.

For set 5, vertical lines in densely used areas near shore (max 25 km) and in nutrient rich zones (chlorophyll level of higher than 5 mg/m^3), the potential worldwide surface is also large. Figure 5-3 shows this surface on the earth. The available area for placing set 5 is estimated to be around 370 million ha. Offshore wind parks can also be placed in this zone, so overlap with set 3 is possible. However, offshore wind parks can also be built beyond the continental shelf and 25 km offshore or in nearshore zones where less nutrients will be. It is assumed that only half of nearshore available land for set 5 can be used, the potential still will be around 35 EJ.

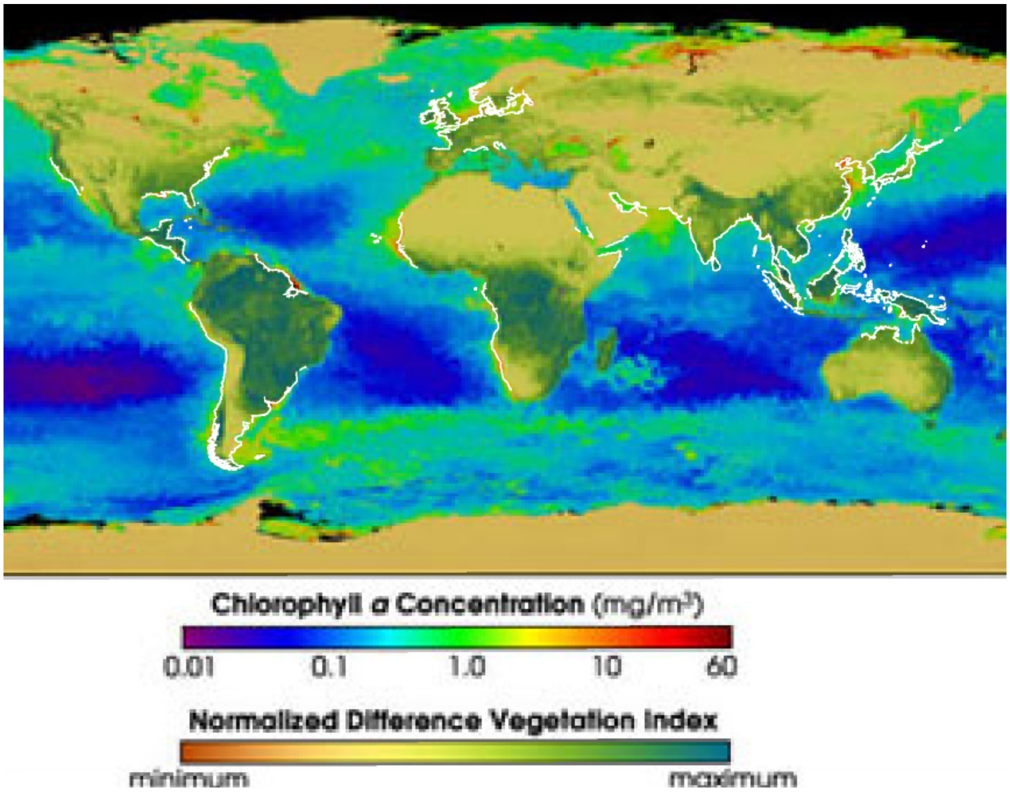


Figure 5-3 Worldwide potential for set 5 (white lines near coast)

The floating structures at open sea seem also interesting considering the low cultivation costs. Much will depend on the possibility to pump up the nutrients from the bottom of the ocean. If the open oceans and more specific the biological deserts can be used for algae cultivation a theoretical potential becomes available of over more than 5 billion hectares, mainly located on five prominent places (Caribbean Sea, South Atlantic Ocean, Indian Ocean, Mid Pacific and South Pacific Ocean) as is shown in deep blue areas on Figure 5-3.

Disclosure of this complete area is considered to be unrealistic. However even if only one percent of this surface can be disclosed for algae cultivation with the average yield estimation of set 6, more than 50.000 million ha could imply an energy potential of more than 6.000 EJ.

Table 5-5 sums up the potential on longer term, when economic feasibility is attained, of the most feasible sets.

Table 5-5 Total potential for aquatic biomass based on most feasible technical concepts

Most feasible technical concepts	**Area**	**Potential**
Set 1: Land based open ponds for microalgae	Arid land in (sub) tropical zones (deserts) and close to coast (max 100 km)	90 EJ
Set 3: Horizontal lines for macroalgae	At existing infrastructure – f.e. offshore wind farms (up to 100 km offshore)	110 EJ
Set 5: Vertical lines for macroalgae	Near coast (max 25 km) in nutrient rich water	35 EJ
Set 6: Macroalgae colony	At open sea (biological deserts), up to 2000 km offshore	~6000 EJ
TOTAL		**~ 6235 EJ**

6 Conclusions and recommendations

6.1 Conclusions

Potential is high

The potential of aquatic biomass worldwide is high, up to 6235 EJ. Compared to the potential for biomass on land, which can be between 40 to 1100 EJ (Lysen *et al*, 2001), aquatic biomass can make a strong contribution as a sustainable energy resource and towards a bio-based economy. With a global increasing energy consumption of currently more than 470 EJ (IEA, 2007), aquatic biomass for energy application can be the new solution for the depleting energy sources in the world.

A more sustainable resource

Biggest advantage of aquatic biomass as a source for renewable energy is the sustainability of the cultivation systems. No land use change will result from these analyzed sets, avoiding the so-called food versus fuel discussion which currently threatens the land-based biomass production for energy applications. Also, the greenhouse gas balance of the investigated sets are in 5 out of 6 cases more climate neutral than fossil fuels or land-based biomass resources. This GHG balance does depend on the amount and uptake of fertilization, as well as on the internal energy balance (whether internal energy use can be delivered from own energy production).

Other environmental advantages of aquatic biomass productions are the production of algae on nutrient losses of urban activities as a way to reduce eutrophication, and the possibility to use algae production as part of coastal defence areas. Aquatic biomass production in the biological deserts, the open oceans, can even recollect the lost nutrients over long time periods, by pumping the nutrients from the depth of the ocean.

Impulse for new economic activities

Another advantage or benefit of aquatic biomass production is the new impulse the farming of aquatic biomass can give to other industries in for example the Netherlands. Farming of aquatic biomass can be a new driver for the agricultural sector in the Netherlands, possibly combined with other aquaculture production like fish and clamps. It could also make an economic bridge with the fishery, a decreasing industry with a low sustainability image. And the already strong developed offshore industry in the Netherlands can learn and exchange knowledge for new specialised offshore applications for aquatic biomass farming. Combinations with other offshore infrastructure such as wind farms or oil/gas platforms and the possibility to consume additional CO_2 within the cultivation system make this new development a very interesting additional function for current relatively expensive activities.

Costs still high

However, based on available literature, desk study and expert opinions, the costs for aquatic biomass production for energy applications remains at this point too high to compete with bio energy applications from biomass produced on land.

There are points of improvement that could lead to higher revenues on one hand and cost reduction on the other hand. The possible revenues of by-products from aquatic biomass for energy production are at this point not defined and therefore taken into account. It could be possible to, for example, sell the algae press cake of pressed micro algae for biodiesel as a cattle feed or fish food product. Also, by integrating the cultivation of aquatic biomass for energy application with other functions, such as fish cultivation, offshore wind farms, carbon sequestration, or other algae applications like nutraceuticals and pharmaceutical applications, costs could be reduced. The additional sustainable value that aquatic biomass for energy would have, compared to biomass resources produced on land, could on longer term be translated into an additional market value, for example with creating additional carbon credits.

Costs and revenues all depend on the future technological development and types of aquatic biomass used.

No technological preference

In this stage of development, in which the production of aquatic biomass exists, no conclusions can be drawn on which technical combination or set ultimately will be the best technical option to produce energy from aquatic biomass. Many assumed components of the investigated sets remain unsure, while large-scale nearshore/ offshore farming of aquatic biomass for energy applications has not yet been realised in practice.

Actual impact of large scale systems unknown

While practical experience with large cultivation and conversion of aquatic biomass is missing, uncertainty remains on what the actual effects and impact will be if this source is used to fill the energy needs of modern society.

With the change of cultivation area from land to sea, a new topic of discussion appears on the change of sea use (instead of land use change). The spatial area used on sea for biomass cultivation can also be in competition with other applications or purposes.

Also the actual environmental impact on surrounding ecosystem needs to be discussed further. In any case, a new biological balance needs to be established when biomass is cultivated and regularly harvested. This remains an important research area to be investigated further.

6.2 Recommendations

Based on the conclusions described above Ecofys would like to propose the following recommendations towards the ministry of Environment (VROM).

Stimulate towards practical R&D projects and pilots to enhance innovation and commercialisation of aquatic biomass production for energy purposes

Although the determined sets of this research project already described a detailed picture of how aquatic biomass can be produced, harvested and converted to bio-energy products, many research questions remain while practical experience on commercial scale is lacking. The technological development of the investigated sets in this project is still in its infancy. Much space exists to innovate and develop these concepts further, towards commercial implementation. The main research questions at this point are:

- which species will be best to use and how should it be fertilized;
- which conversion technology will lead to most efficient use of the resource;
- what will be the actual costs of cultivation and conversion systems;
- which multifunctional combination would be most feasible, looking at costs and revenues;
- what will be the ecological effects of large scale production in the oceans;
- how can logistics be optimized;
- how can current economic feasibility be increased by cost reduction and additional or increased revenues;

The only way to answer these questions is to attain practical knowledge and experience on the production, harvesting and conversion of aquatic biomass for energy applications.

It is therefore recommended to stimulate more dedicated and practical R&D projects on this topic to answer the current research questions and achieve the first steps towards the disclosure of the wide potential for this renewable resource.

Stimulate knowledge exchange based on current (offshore) renewable energy experience and aquatic biomass production for non-energy applications

Also, knowledge exchange with other innovative sectors is recommended. In the current development of offshore wind farm implementation much is learned already on the impact of these activities on the marine environment for example.

In the Asian countries but also in countries like Norway much practical experience is available on the cultivation of aquatic biomass for mostly non-energy applications.

This knowledge should be shared with aquatic biomass experts and interested aquaculture producers. Here lays an ultimate role for national government to act as intermediate not only between market parties but also between the several ministries within the Netherlands and between research institutes, governments and market parties internationally. By enhancing and streamlining the exchange of knowledge the development of aquatic biomass production for energy applications can be accelerated.

Explore legislative situation for aquatic biomass production offshore, determine possible market barriers and their solutions

Amongst the involved experts within this project a current opinion exist that implementation of large scale production of aquatic biomass or even of test site projects will come upon many legislative hurdles, as was the case with offshore wind farms. Different ministry organisations with different legislative grounds have authorization when it comes to activities in the North Sea or even in interdepartmental sea waters. To stimulate the development and streamline the implementation of aquatic biomass for energy insights into these legislative issues can be investigated already at this point.

Also the embedding of the biofuels obligation target in the new European Renewable Energy Directive, differentiation amongst the different biofuels based on GHG reduction performance, a solid and uniform certification system for biofuels and the possible revenues the additional GHG emission reduction could generate are imperative for the feasibility of aquatic biomass production for energy applications in the future. The Dutch government can play an important role in this part, both on a European level and in national legislation.

Annex 1 References

Aresta, M., Dibenedetto, A. and Barberio, G. (2005). "Utilization of macro-algae for enhanced co2 fixation and biofuels production: Development of a computing software for an lca study." Fuel Process. Technol. 86(14-15): 1679-1693.

Banerjee, A., Sharma, R., Chisti, Y. and Banerjee, U. C. (2002). "Botryococcus braunii: A renewable source of hydrocarbons and other chemicals." Crit. Rev. Biotechnol. 22(3): 245-279.

Benemann, J. R. and Oswald, W. J. (1996). Systems and economic analysis of microalgae ponds for conversion of co2 to biomass. Final report**:** Size: 214 p.

Braithwaite, R. A., Carrascosa, M. C. C. and McEvoy, L. A. (2007). "Biofouling of salmon cage netting and the efficacy of a typical copper-based antifoulant." Aquaculture 262(2-4): 219-226.

Brandenburg, W. (2008). Personal communications with Ecofys. Wageningen University, Netherlands.

Braun, A. and Reith, J. (1993). Algen in de nederlandse energiehuishouding, in opdracht van het programma, energiewinning uit afval en biomassa (ewab) van novem. Utrecht, Braun Consultants.

Buck, B. H. and Buchholz, C. M. (2004). "The offshore-ring: A new system design for the open ocean aquaculture of macroalgae." Journal of Applied Phycology 16(5): 355-368.

Buck, B. H. and Smetacek, V. (2006). "Project: Rotor Sand." Summary of aquafarm pilot. Alfred Wegener Institut, Germany.

Buschmann, A. H., Lopez, D. A. and Medina, A. (1996). "A review of the environmental effects and alternative production strategies of marine aquaculture in chile." Aquac. Eng. 15(6): 397-421.

Carlsson, A., Beilen van, J., Möller, R., Clayton, D. and Bowles, D. e. (2007). Micro- and macroalgae - utility for industrial applications Bioproducts, E. R. t. E. P. o. S. R.-. and Crops, f. N.-f., CNAP, University of York**:** 86.

Chisti, Y. (2007). "Biodiesel from microalgae." Biotechnol. Adv. 25(3): 294-306.

Chisti, Y. (2008). "Biodiesel from microalgae beats bioethanol." Trends Biotechnol. 26(3): 126-131.

Chynoweth, D. P. (2002). Review of biomethane from marine biomass. Review of history, r. a. c. o. t. U. M. B. E. P.-. Gainesville, Florida, Department of Agricultural and Biological Engineering, University of Florida**:** 194.

Cohen, T. (2008) Personal communications. Ecofys, Netherlands.

Danielo, O. (2005). "A fuel based on algae oil." Biofutur(255): 33-36.

Dimitrov, K. (2007). Greenfuel technologies: A case study for industrial photosynthetic energy capture.

Dote, Y., Sawayama, S., Inoue, S., Minowa, T. and Yokoyama, S. (1994). "Recovery of liquid fuel from hydrocarbon-rich microalgae by thermochemical liquefaction." Fuel 73(12): 1855-1857.

Fei, X. G. (2004). "Solving the coastal eutrophication problem by large scale seaweed cultivation." Hydrobiologia 512(1-3): 145-151.

FIS (2008), "Presentation on use of algae for cattle feed production (in Dutch). First Dutch Algae congress 27 May 2008. Dronten, the Netherlands

Glenn, E. P., Brown, J. J. and O'Leary, J. W. (1998). "Irrigating crops with seawater." Scientific American 279(2): 76-81.

Grondstoffen, P. G. (2007). Groenboek energietransitie. Sittard, Platform Groene Grondstoffen.

Gunaseelan, V. N. (1997). "Anaerobic digestion of biomass for methane production: A review." Biomass Bioenergy. 13(1-2): 83-114.

Hamelinck, C.N., Suurs R.A.A., and Faaij, A.P.C.. (2003) "International bio energy transport costs and energy balance. Utrecht University, August 2003.

Hamelinck, C.N. (2005). "Participative LCA on biofuels, report 2GAVE-05.08 for SenterNovem. Utrecht, the Netherlands.

Hoogwijk, M. (2004). On the global and regional potential of renewable energy sources. Faculteit Scheikunde. Utrecht, Universiteit Utrecht. PhD Thesis.

IEA (2007). World energy outlook 2007, China and India Insights. OECD/IEA 2007. Paris, France.

Iersel van, S. (2007). Renewable energy from microalgae. Ecofys. Utrecht, Wageningen University. MSc.

InnovatieNetwerk (2005). De innofisk 1 - een haalbaarheidsstudie naar een nieuw concept voor duurzame visteelt aan boord van een schip. 04.2.086, R.

InnovatieNetwerk (2007). Mariene parken: Duurzame energiewinning en biomassaproductie op zee.

Kirkman, H. and Kendrick, G. A. (1997). "Ecological significance and commercial harvesting of drifting and beach-cast macro-algae and seagrasses in australia: A review." Journal of Applied Phycology 9(4): 311-326.

Luning, K. and Pang, S. J. (2003). "Mass cultivation of seaweeds: Current aspects and approaches." Journal of Applied Phycology 15(2-3): 115-119.

Lysen, E., Broek, R.C.A. van den., Faaij, A.P.C. Hoogwijk, M. (2001) "GRAIN; Global Restrictions on Biomass Availability for Import to the Netherlands." Novem Report 2EWAB01.18, Utrecht July 2001.

Meiser, A. and Riese, J. (2007). Marine biomass – a potential feedstock for biofuel? Presentation. Eilat, Israel.

Mes, T. Z. D. d., Stams, A. J. M., Reith, J. H. and Zeeman, G. (2003). Methane production by anaerobic digestion of wastewater and solid wastes. Bio-methane & bio-hydrogen : Status and perspectives of biological methane and hydrogen production. Reith, J. H., Wijffels, R. H. and Barten, H. Petten, Dutch Biological Hydrogen Foundation**:** 58 - 102.

Molina Grima, E. M., Belarbi, E. H., Fernandez, F. G. A., Medina, A. R. and Chisti, Y. (2003). "Recovery of microalgal biomass and metabolites: Process options and economics." Biotechnol. Adv. 20(7-8): 491-515.

Muraoka, D. (2004). "Seaweed resources as a source of carbon fixation." Bull. Fish. Res. Agen. Supplement No. 1,: 59-63.

NAAS (2003). Seaweed cultivation and utilization. National Academy of Agricultural Sciences, I. Policy paper 22.

Paling, E. I., van Keulen, M., Wheeler, K. D., Phillips, J., Dyhrberg, R. and Lord, D. A. (2001). "Improving mechanical seagrass transplantation." Ecol. Eng. 18(1): 107-113.

PAV (2006), Quantitative information "KWIN" 2006 - Agriculture and vegetable cultivation (in Dutch), Practice research for agriculture and vegetable cultivation PAV. Lelystad, the Netherlands.

Phillips, M. J. (1990). Environmental aspects of seaweed culture. Regional Workshop on the Culture and Utilization of Seaweeds 27-31 Aug 1990, Cebu City, Philippines.

Phlips, E. J., Willis, M. and Verchick, A. (1986). "Aspects of nitrogen-fixation in sargassum communities off the coast of florida." J. Exp. Mar. Biol. Ecol. 102(2-3): 99-119.

Ursum, W.N.J. (2008). Personal communications with Ecofys. TU Delft, Netherlands.

Reith, J. H., Deurwaarder, E. P., Hemmes, K., Curvers, A. P. W. M., Kamermans, P., Brandenburg, W. and Zeeman, G. (2005). Bio-offshore : Grootschalige teelt van zeewieren in combinatie met offshore windparken in de noordzee. Petten [etc.], Energieonderzoek Centrum Nederland [etc.].

Santelices, B. (2001). "Implications of clonal and chimeric-type thallus organization on seaweed farming and harvesting." Journal of Applied Phycology 13(2): 153-160.

Sazdanoff, N. (2006). Modeling and simulation of the algae to biodiesel fuel cycle, College of Engineering, Department of Mechanical Engineering, The Ohio State University.

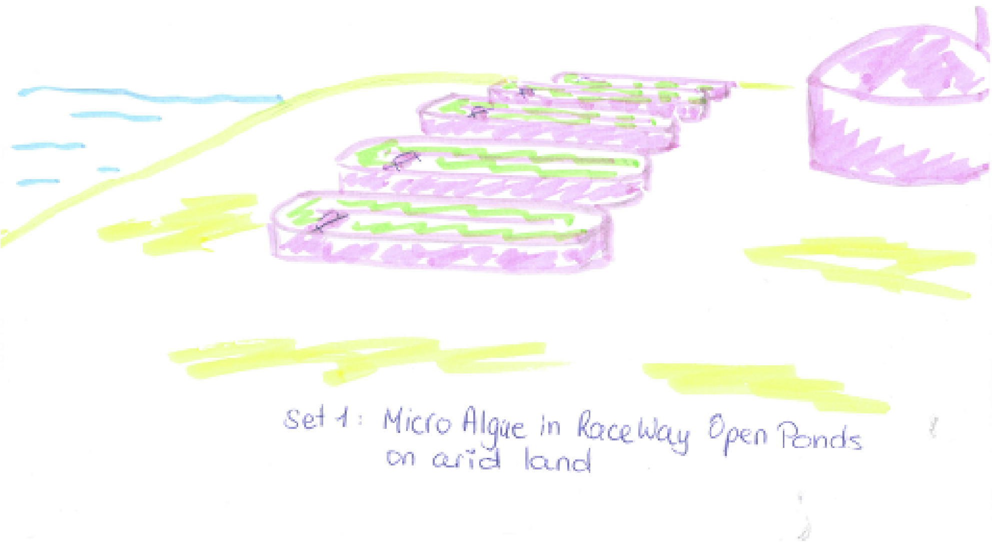
Sheehan, J., Dunahay, T., Benemann, J. and Roessler, P. (1998). Look back at the u.S. Department of energy's aquatic species program: Biodiesel from algae; close-out report**:** Size: 325 pages.

Terry, K. L. and Raymond, L. P. (1985). "System-design for the autotrophic production of microalgae." Enzyme Microb. Technol. 7(10): 474-487.

Tsukahara, K. and Sawayama, S. (2005). "Liquid fuel production using microalgae." J. Jpn. Pet. Inst 48(5): 251-259.

Wijffels, R. (2007). Presentation microalgae for production of energy. www.zeegras.nl. Retrieved 04-02-2008.

Annex 2 Set 1 - Microalgae in open pond systems on land

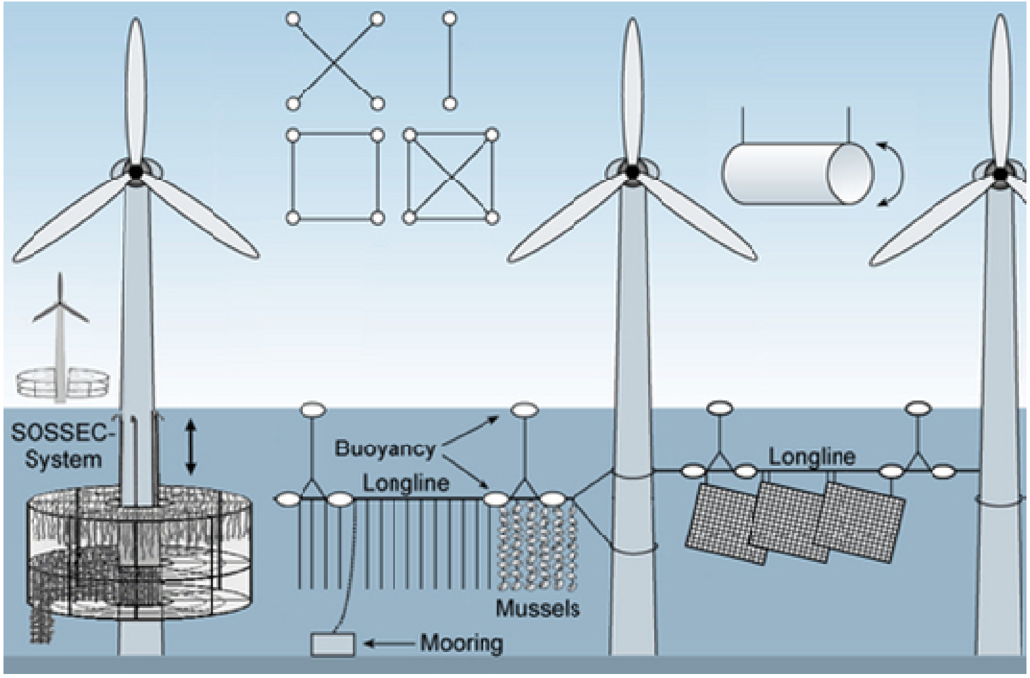


Open pond raceway system

Annex 3 Set 2 – Microalgae in plastic bags in inland seas

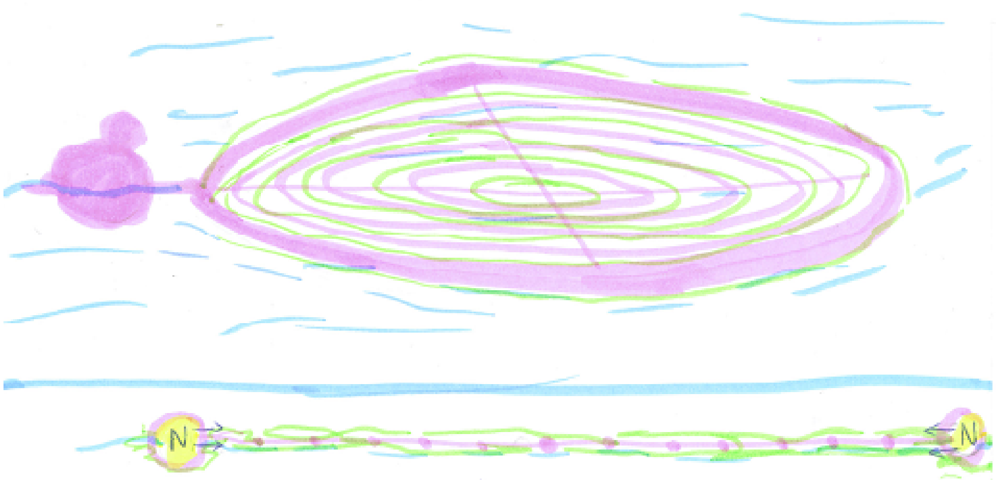
Microalgae in plastic bags – Valcent Products US

Annex 4 Set 3 – Horizontal lines for seaweed near offshore infrastructure



Long line system for aqua farming according to (Buck, 2004).

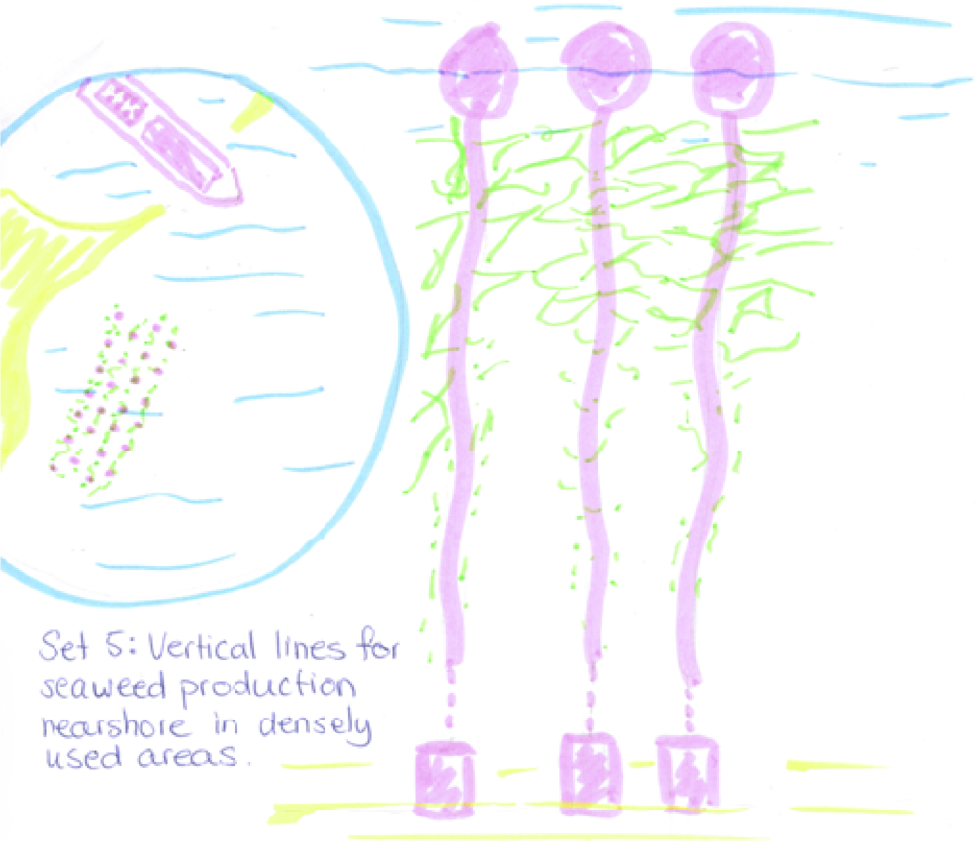
Annex 5 Set 4 – Floating ring system for seaweed production in rougher seas



Set 4: Ring system for seaweed production in rougher seas nearshore

Results of experiment Rotor farm by (Buck, 2006).

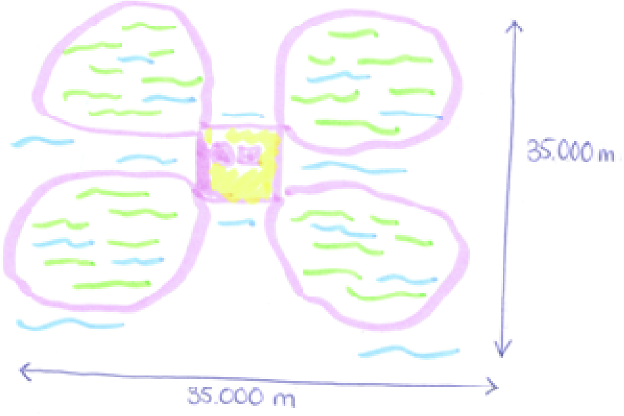
Annex 6 Set 5 – Vertical lines in nearshore, nutrient rich densely used waters

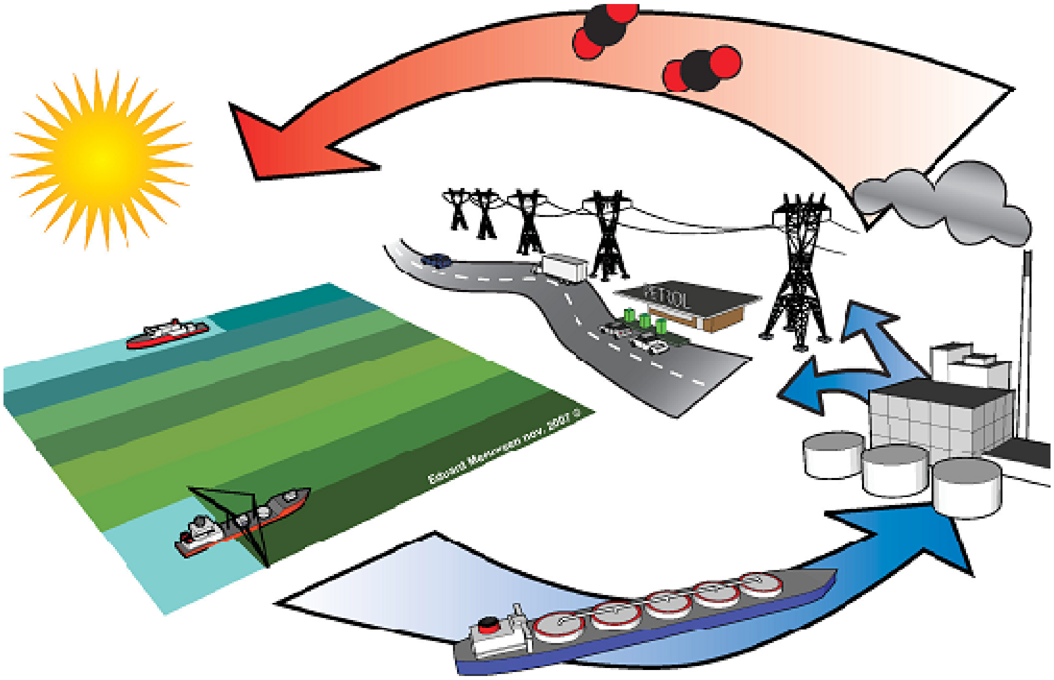


Large seaweed strings in ocean.

Annex 7 Set 6 – Floating seaweed colony in open ocean

Set 6: Bounded floating seaweed structures at open sea





Concept for offshore open ocean farming according to TU Delft (Solar power from the sea 2007).