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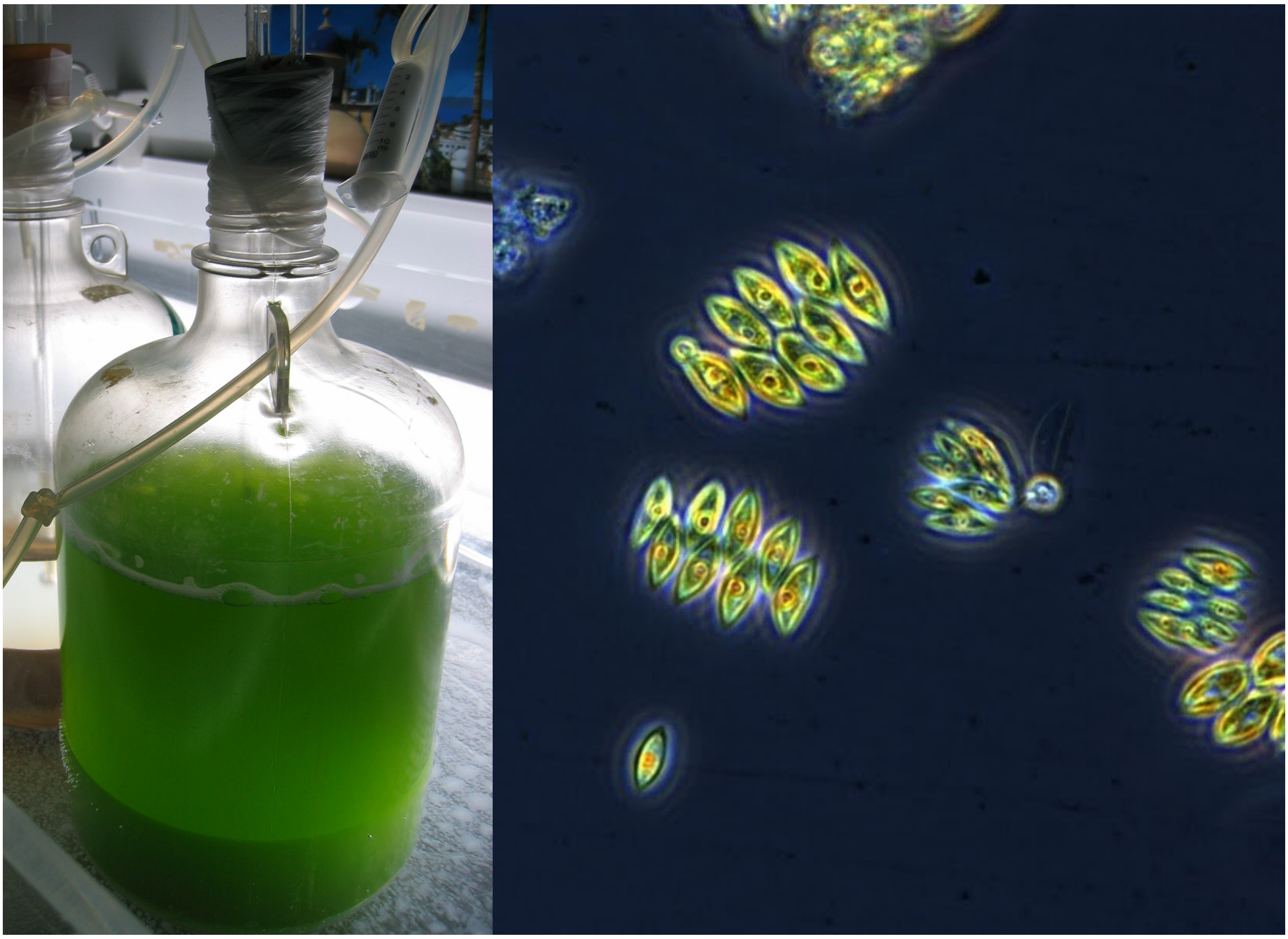

GROWING ALGAE FOR CARBON CAPTURE: A REVIEW OF AVAINALABLE TECHNOLOGIES AND LIFE CYCLE ANALYSES

CARBON CAPTURE AND STORAGE PROGRAM REPORT

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TABLE OF CONTENT

1. INTRODUCTION TO ALGAE 3
1.1. Microalgae 3
1.2. Macroalgae 3
1.3. Historical and present use of algae 3
2. BENEFITS OF GROWING ALGAE 3
2.1. Carbon capture 3
2.2. Bioenergy 4
3. THE CHALLENGE OF GROWING ALGAE 4
3.1. Main limitations 4
3.2. Optimizing growth 5
3.3. Temperature 5
3.4. Harvesting 5
4. PRODUCTION COST 5
4.1. Microalgae 5
4.2. Macroalgae 5
5. PREVIOUS RELATED RESEARCH 5
6. GROWTH AND HARVEST TECHNOLOGY 6
6.1. Cultivation systems 6
6.2. Harvesting or 'milking' 6
6.3. End product – solid, liquid or gas 6
7. LCA PRINCIPLES 7
8. LCA LITERATURE REVIEW 7
8.1. Main findings and results of the reviewd studies 8
8.2. General conclusions of the study 10
9. REFERENCES 11
10. APPENDIX I 12
11. APPENDIX II 17

Growing algae for carbon capture: a review of available technologies and life cycle analyses. A report for the Carbon Capture and Storage Program (CCSP) by Kaisa Manninen and Kristian Spilling

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1. INTRODUCTION TO ALGAE

Algae are a very heterogeneous group of photosynthesizing organisms, mostly living in aquatic environments. There are several ways to divide algae into different subgroups, e.g. based on taxonomic groups, but in this review we will divide algae up into microalgae (which can range 1-1000 µm) and macroalgae (>1 mm). Microalgae are often termed phytoplankton, whereas seaweed is the common term for macroalgae. Kelp is only a specific group of seaweed.

1.1. Microalgae

Planktonic algae are unicellular, microscopic organisms, which grow suspended in water and reproduce by cell division. They are characterized by high metabolic rates compared to higher plants, due to their efficient surface/volume ratios, as well as by their lack of supporting structures necessary for terrestrial primary producers, due to their floating life mode. While terrestrial plants require specialized structures for obtaining dissolved nutrients (roots) and running photosynthesis (leaves), each phytoplankton cell is a complete production unit living immediately in nutrient suspension. Consequently, while forest harvest cycle is measured in decades or at best in years, and agricultural harvest cycle in months, species of planktonic algae are able to double their biomass under optimal growth conditions even several times a day (e.g. Brennan and Owende 2010).

1.2. Macroalgae

Macroalgae, or seaweeds, can be viewed as simple aquatic plants, but are not normally included in the plant kingdom. They differ from microalgae both in size (but many species have microscopic life cycle forms) and by having different structural parts. Seaweeds lack a root system but have some form of holdfast, and many can be further divided into a stem (termed stipe) and blades (lamina). They typically also contain separate reproductive organs that take part in sexual reproduction. However, asexual reproduction is also common. Certain groups of seaweed have other specialized structures, for example air filled bladders that assist in floating of the blades.

1.3. Historical and present use of algae

Historically it has been the macroalgae that has been used by humans, as microscopic algae were not discovered until the development of microscopes. To some extent, seaweed have been used for human consumption or animal feed for a very long time. There are records of algal used for these purposes dating back 2000 years ago. During the medieval times there are also records of algae being used as fertilizer and to improve agricultural soil.

In the 18th century the first algal industry grew up, collecting and burning seaweed. The product was algal ash, which initially were added to quarts-sand and this mixture was used in glass production. It was also used in other products, for example in soap production. In the early 19th century the element iodine was discovered in seaweed ash, and iodine production based on algae was an industry for approximately 100 years before production shifter to other raw materials. During the early 20th century alginate was discovered and production from seaweed started. The alginate was used for production of different materials for example in packaging and in the textile industry.

Today the main products of seaweed are agar, alginate and carragenan, which are used in several different industries. The main application is as a thickener in foodstuffs (for example in added to margarine, ice cream, noodles, toothpaste etc) and in textile printing. Macroalgae is also used as feed in aquaculture, for example in shellfish production, and it is also used for direct animal or human consumption.

Cultivation of microalgae dates back to the 1950's and there is an industry producing microalgae both in indoor cultivation and in outdoor pond type of cultivation. The main product is neutraceuticals e.g. as dietary supplement in the form of a powder or as tablets. The most important commercial species are either blue green (e.g. Spriulina) or green algae (e.g. Chlorella sp, Hematococcus sp.). To some extent microalgae is also used as feed in the aquaculture industry.

2. BENEFITS OF GROWING ALGAE

2.1. Carbon capture

When CO_2 dissolves in water, the carbon either stays as carbon dioxide (CO_2) or forms biocarbonate (HCO_3^-) or carbonate (CO_3^{2-}). The relationships between these forms are dependant on the pH. At low pH most of the carbon is in the form of CO_2, at neutral pH mostly as bicarbonate and at high pH mostly as carbonate. Only CO_2 can be used as the input to photosynthesis, but many algae are also able to take up bicarbonate from water, which is then transformed to CO_2 intracellularly. During photosynthesis the uptake and removal of CO_2 will increase the pH, as the carbon balance is shifted towards the bicarbonate and carbonate forms. Water is to some extent buffered against pH changes. In particular salt water is well buffered, but even here dense algal cultures will quickly increase the pH, if an effective gas exchange is lacking.

The gas exchange can be done several different ways. The easiest and most straight forward way of increasing gas exchange is to bubble gas through the algal cultivation unit. The partial pressure of CO_2 in air is relatively low, and its CO_2 addition will be insufficient to stabilize the pH in dense algal cultures. Therefore gas with higher concentrations of CO_2 is needed in order to keep a dense algal culture from being limited by high pH, and in some cases also from becoming carbon limited. Simply bubbling flue gas from industrial plants such as power plants can be used as a boosting factor for growing algae. In principle the same would be possible for higher plants, but technically it is much simpler to bubble flue gas through the cultivation water then to concentrate the CO_2 in an air filled growth container.

The carbon captured by algae is converted into biomass that potentially can be used for several different purposes depending in the composition of the biomass.

Company	Power plant	Country	Duration	Use of biomass	Budget
Green Fuel	Natural gas	USA	bankrupt in 2009		--
Seambiotic	Coal	Israel		bioenergy	--
Vattenfall	Coal	Germany	2010-2011	bioenergy	2 mill €
E.ON Hanse	Coal	Germany		bioenergy	--
MBD energy	Coal	Australia	start 4Q 2011		--
RWE	Coal	Germany	2009-2011	bioerngy	--
AECI	Coal	USA		bioerngy	- -

Table 1. An overview over pilot plans utilizing flue gas from power plans as a CO_2 source for algae.

Traditionally algae have been used in human and animal consumption, but several commercial products are based partly on algae as the raw material. In the future algae may also be important as a source of bioenergy or other biobased products like bio-plastics. The CO_2 captured in the biomass will eventually be released again once the biomass is burned or decomposed, and will offer no permanent storage. However, the capture of carbon will increase the time the organic bound carbon, increasing its retention time. If the biomass produced is used as bioenergy or other products, more energy will be extracted per unit CO_2 emitted. This kind of CO2 capture and releasing represents carbon recycling, not mitigation. If fossil fuels are replaced by using algal bioenergy, new fossil carbon reserves are reduced, when carbon is recycled from the atmosphere during algae growing. However, the total impacts from algae cultivation to biofuel/biogas production and use should also yield negative CO2 emissions. (Soratana & Landis, 2011, Packer, 2009) Life cycle assessment is a useful tool to clarify the environmental effects, including CO2 emissions, from cradle to grave of algae based bioenergy and to assess its sustainability. Life cycle assessment is discussed more detailed in Chapter 7.

Table 1 gives an overview over pilot plants, that has been or are in operation, where algal have been grown in order to capture carbon flue gas. A more extensive list of companies having R&D programs on algal bioenergy can be found in Appendix I.

2.2. Bioenergy

Bioenergy from burning wood has been used for millennia, but the new focus on bioenergy has centered on biofuels and biogas. As a consequence of political incentives and legislation, industrial stakeholders have increased production of biofuel and biogas. Much of this increase in production capacity is based on a narrow selection of food and energy crops. There are many environmental and societal problems associated with the use of these bioenergy sources:

- Food price increases when farm land is used to growing energy crops instead of food, raising political and ethical concerns.
- Biodiversity suffers when pristine areas (such as rain forest) are cleared
- The carbon balance is in some cases minor or even negative when considering the whole life cycle (affected by e.g. fertilizer consumption).

There is a growing concern, in particular within the biofuel industry, that energy crops will not be sufficient to reach political targets for biofuel production. Thus, new sources of biomass for biofuel production have to be explored and put to use. The first criterion for such new biomass production must be environmental sustainability. In this respect, microalgae offer a feedstock that is environmentally friendly and has some obvious advantages compared to the current use of higher plants:

- Biomass production is rapid and the yield per area is higher, even by orders of magnitude (e.g. Sheehan et al. 1998).
- Algal production does not have to compete for fertile land with food production and may be placed in areas where farming or forestry is not at all possible.
- Algal biomass production can be upscaled and downscaled at will. This flexibility opens up a variety of economically and socially interesting implementation options, from localized units at the level of farms and greenhouses to large scale municipal or industrial plants.
- Harvested algal biomass offers promising sidestream and downstream utilization, in addition to energy, increasing economical benefits.
- Algal production facilities offer synergy effects. In addition to the potential for CO_2 capture it can be coupled with water treatment plants, as their refuse is a growth promoting substrate which can be effectively introduced into confined liquid growth media.

Macroalgae have many of the same benefits as microalgae in this respect, but are not able to reach as high productivity as microalgae. In addition, coupling macroalgal cultivation with wastewater treatment and CO_2 uptake from flue gas will be technically more difficult than with microalgae.

3. CHALLENGE OF GROWING ALGAE

Growing algae is not that difficult, provided a liquid media, nutrients and light. However, considering algae as raw material for bioenergy, or as used in carbon capture, the challenge lies in obtaining the high growth potential of algae while keeping production cost low.

3.1. Main limitations

One of the main differences between algae and higher plants is that algae lives submerged in water (with some exceptions) and consequently the amount of water is not as issue for the growth. In addition, all the nutrients that algae take up come directly from the surrounding water and not from the soil (macroalgae have a holdfast but there is not any root system as with higher plants).

Algae are, like higher plants, primary producers that use mineral nutrients, water and CO_2 as the main building blocks for growth. The main limiting mineral nutrients for algae are nitrogen (N) and phosphorus (P). The composition of water is very different from soil, and come of the nutrients that can be limiting higher plants, are not normally limiting algal growth. For example, sea water contains a lot of sulfur, which is a macronutrient sometimes limiting terrestrial plant growth.

Nitrogen can be taken up in a variety of forms by algae ranging from nitrate and ammonia and to some extent in organic forms like urea. Phosphorus uptake on the other hand is limited to orthophosphate and there is a range of phosphorus compounds that is not biologically available.

As for all photosynthetic plants, the carbon source is CO_2, which is taken up and transformed to sugars during photosynthesis. The energy needed for running the photosynthetic machinery comes from light, and light is the other main factor (in addition to N and P) that generally limits growth of algae. With all resources plentiful, algae can grow very rapidly, which leads to increasing absorbance of light. In a dense algal culture, all available light energy may be absorbed within a few mm from the surface in full sunlight. The algae closest to the light source absorb all the light and this 'self shading' is one of the main factors limiting the growth potential of dense algal cultures.

High light may also affect growth negatively as high light usually induces photoinhibition. This is caused by too much light energy absorbed compared with what the photosynthetic machinery can handle, resulting in damage of photosynthetic components. The severity of the damage depends on how much light energy the photosystem has received and for how long time. In order to prevent this from happening, algae have photoprotective pigments that functions as a sunscreen dissipating excess energy as heat. The light energy that is transformed to heat is lost, and consequently decreasing the efficiency in converting light energy into biomass.

Seaweeds occur naturally along the shoreline, and needs to be close to the surface in order to get sufficient light for running photosynthesis. Thus seaweeds have an additional limitation compared with microalgae, as suitable substrata they can attach to may be a factor limiting their growth.

3.2. Optimizing growth

Optimizing the utilization of the light is one of the main challenges for achieving the high growth potential of algae. In order to ease the harvesting step it is important to grow a dense algal culture, which in soon runs into self shading issues in stagnant water as described above. This can be counteracted by active mixing. Then the individual algal cell will be mixed between the full light at the surface to the virtually dark a few cm below. Several studies have shown that increasing the mixing, thus increasing the shift from high to low light, increases overall production.

The other main challenge is dissipation of light energy as heat. Algae will compensate for too high light levels, as full sunlight will be for most algae, by increasing photoprotective pigments that dissipate light energy as heat. This energy is lost, and reduces the overall efficiency.

Macroalgae will experience some of the same problems as microalgae in respect to light. Particles in the water will increase turbidity and absorb light energy, shading for the macroalgae. Some macroalgae are also affected by epiphytes that will attach and absorb the light.

3.3. Temperature

Much of the light energy ends up as heat when absorbed by in the algal culture, due to different loss processes (mainly through absorption by non photochemical pigments/particles), and in a closed system the temperature increase may be very rapid. Most algae will not grow in temperatures above 35°C, and to keep the algae growing the cultivation units must be cooled. Technically applying cooling to a closed system is easy, but it requires a lot of energy, which should be considered when estimating production costs.

In an open system, the temperature increase is dampened by the cooling effect of evaporation. This causes the cultivation volume to decrease, and in the case of saltwater become more salty. The evaporated water must therefore be replaced by freshwater. In many parts of the world, freshwater is a scares commodity and open cultivation will not be well suited for these types of areas.

Macroalgae is traditionally cultivated in a much larger pool of water, e.g. directly in the ocean, which means that the temperature does not play an important effect.

3.4. Harvesting

Even in a thick algal solution, the dry weight concentration is only a few grams per liter. One of the main challenges in developing microalgal cultivation is effective and low-cost dewatering and harvesting. Different methods exists, many like centrifugation is effective even at relatively large scale (m^3), but have a high energy requirement, not well suited for low cost production. Filtration may prove difficult as the algae tend to clog the filter. Other methods include flocculation or flotation after injecting different chemicals (e.g. a flocculation agent), but these comes also with additional cost and might have to be removed afterwards depending on what the algae will be used for.

One of the benefits of considering macroalgae for bioenergy or carbon capture is that harvesting is relatively easy compared with microalgae. Traditionally macroalgae have been harvested in many coastal regions of the world, and is still today an important regional industry, in particular in the Far East. Macroalgae can be harvested mechanically, much like harvesting of agricultural crops.

4. PRODUCTION COST

4.1. Microalgae

A relatively small scale algal industry already exists, with an annual production of approximately 5000 tons dry weight. The production cost is generally considered to be in the range 5-20 € kg^{-1} dried algae (The Israel based company Seambiotic publicly stated a production of \$17 kg^{-1}). Production cost should be lowered at least an order of magnitude before algal bioenergy can become economically viable. However, the many benefits of growing algae, as stated above, could add value through societal and environmental benefits. The most direct route to increase the gain from algal biomass production is to create cultivation systems that use industrial or municipal wastes, which currently only has negative economic value, to create a product e.g. bioenergy. The most obvious benefits would be from algal treatment of wastewater and through CO_2 removal from flue gases. Development of such an integrated algal biomass cultivation system should focus on the current largest producers: urban/industrial/agricultural waste water and CO_2 exhaust. The challenge to achieve this will be to demonstrate the economic viability of such a system at the site of the waste production.

4.2. Macroalgae

Production cost of macroalgae is very different as the production process is slower and less labor and energy intensive. On a global scale, approximately 1 million tons is harvested from naturally growing seaweed whereas ~15 million tons is cultivated annually. From cultivated macroalgae production, the lower end of production costs are in the range 0.02-0.03 € kg^{-1} dried algae.

5. PREVIOUS RELATED RESEARCH

The first major research effort into the potential of using microalgae for bioenergy was conducted in the Aquatic Species Program, USA (Sheehan et al. 1998). It was initiated as a result of the oil crisis in the 1970's, and the program addressed production of biodiesel from algae with high lipid content. The main focus was on low-cost, open pond units in the warm environments of New Mexico and Hawaii. An economical assessment during the 1980's indicated that the cost of algal biodiesel produced was at least twice the price of petroleum diesel at the time. This was seen as a major obstacle for large scale production of algal biodiesel, and the effort winded down. The price of crude oil has since quadrupled (from <20 \$ barrel in 1996 to >100 \$ barrel in February 2012).

Relatively few published studies of algae as a biodiesel source appeared in the years following the Aquatic Species Program. However, during the last decade, the increased focus on biofuels has lead to several new projects on algal biofuels (see e.g. reviews by Greenwell et al. 2010 and Brennan and Owende 2010). This has included both academic research projects and by industry R & D, ranging from start-ups to large energy companies (e.g. Shell and Chevron). A few pilot scale facilities have been built or are under construction, but no large scale production is yet operational, and the economical viability of algal biofuels has been questioned (e.g. Sheehan et al. 1998).

Using algae for bioremediation of wastewater is a classic idea, the first investigations stem from the 1950's (Oswald and Gotaas 1957), but the research effort into this area has been relatively modest. Most of the published literature are studies on algal species that has been tested growing in different wastewater streams ranging from municipal wastewater (e.g. García et al. 2000) to treatment of animal manure (e.g. Mulbry et al. 2008). Generally, algae are able to remove a high percentage of the bioavailable nutrients (e.g. Olguín 2003) at least at lower latitudes, and might also remove other environmental hazardous components such as heavy metals (e.g. Ahluwalia and Goyal 2007). Recent development has focused on high rate algal ponds (HARPs), which have achieved a high recover rate of nutrients, in particular when coupled with CO_2 addition (e.g. Park and Craggs 2010).

CO_2 uptake by algae is elementary to photosynthesis, and the share of algae in global CO_2 uptake is on the same scale as that of terrestrial plants (Falkowski and Raven 2007). The potential for CO_2 capture using algae has been getting some attention (e.g. Benemann 1997), and the biofixation of carbon could be coupled with Carbon Capture and Storage (CCS) technology to produce a carbon negative energy source, a unique selling point for this approach (IPCC 4th assessment report).

6. GROWTH & HARVEST TECHNOLOGY

There are several different technologies being developed, ranging from different cultivation systems, what and how the harvesting is done, to the downstream processing and end product.

6.1. Cultivation systems

The two main cultivation systems are open pond type cultivation and closed photobioreactors. In a closed photobioreactor every aspect of algal cultivation can be monitored and controlled to great extent. The drawback of this cultivation method is that it is expensive to build and run. Open pond type cultivation can in principle be as efficient as closed systems, but in most cases growth will be much slower in open systems. In addition, they are vulnerable to contamination both from undesired algae, other microbes and perhaps most critical, from zooplankton that starts to feed on the cultivated algae. Open systems are, however, much cheaper to build and run compared with closed systems. There are also hybrid systems where closed photobioreactors feed inot larger open systems, and this could draw benefits from both sides.

The main open systems in use are either stagnant ponds without any turbulence, or raceway ponds, which normally have a paddlewheel that circulates the water around the raceway. These are often termed High Rate Algal Ponds (HRAP).

A third alternative for cultivation technology is algal turf scrubbers, which has been used for cleaning waste waters. An algae turf scrubber typically creates a thin film of water flowing continuously over a suitable, flat substrate. A biofilm, consisting of algae and associated bacteria, quickly forms and can be very effective in removing both nutrients and contaminants. The biomass can be harvested by simply scraping it off at regular intervals. The biofilm that is formed is very effective in absorbing the light in the top layer, creating problems with high light intensities at the surface and self-shading for the cells further down.

6.2. Harvesting or 'milking'

In most operations, the biomass that is produced is at some point harvested. Several options exist for harvesting such as centrifugation, filtration, flocculation or flotation. However, many species of algae are known to excrete different compounds under specific conditions. This can be either lipids or even alcohols, which can be collected without harvesting the algae themselves. The prospect of 'milking' out the compounds of interest would be highly beneficial as it would reduce cost for harvesting and downstream processing. There are research efforts into development of genetically modified and metabolically engineered algae, which has the potential to enhance the production and induce excretion of desired compounds.

6.3. End product – solid, liquid or gas

There are several potential end products of algal cultivation. At present most algal production is producing dry mass in the form of powder that is further refined or used as such. In terms of bioenergy from microalgae, most efforts have focused on producing biofuels, which can either be biodiesel or bio-alcohols. For biodiesel production, it is the lipids in the algae that are used, for bio-alcohols it is the sugars that is fermented, producing alcohols. A third alternative is to use the biomass for biogas production either as pure algal biomass or mixed with other sources of biomass.

The target end product will affect both growth operation and harvesting. For biofuel production, lipids or carbohydrates have to be optimized for biodiesel or bio-alcohols respectively, and after harvesting a relatively dry paste is needed before these compounds can be extracted. For biogas production, on the other hand, both lipids and carbohydrates are good, and the harvested biomass can have higher water content without causing problems. Problems arise however, if the algae are grown in saltwater as the salt is not good for the biogas production, at least not using conventional methods.

Macroalgae has very low concentration of lipids and is primarily a source of sugars. Consequently most of the research into using macroalgae for bioenergy has focused on fermentation or on biogas production.

7. LCA PRINCIPLES

Life cycle assessment methodology is a useful tool to assess the environmental effects of a product. In our study, we try to clarify the sustainability of algae production and use and its potential as carbon capture. As it was discussed in Chapter 2.1, algae based bioenergy can be seen to have carbon mitigating potential, if it replaces fossil fuels and its emissions from cultivation to use are negative.

The LCA methodology is standardized according to SFS-EN ISO standards 14040 and 14044. According to SFS-EN ISO 14040 (2006), the aim of LCA is to address the environmental impact of a product during its life cycle, from cradle to grave, so that the LCA takes into account the impacts of manufacturing the raw material used, the disposal and recycling. The environmental aspects and impacts are taken into account, when economic and social aspects and impacts are typically excluded from the LCA (Koskela et al. 2010.) Also other instructions exist, which try to clarify with the examples the application of standards and to give general frames and demands of the inventory data reporting. One example is the ILCD (International Life Cycle Data System) Handbook by JRC (Joint Research Centre), which gives instructions for the life cycle assessment. The handbook does not have official status but all the information accepted into the book has to be in the accordance with its directions.

The LCA consists of four stages, which are defined in SFS-EN ISO 14040. These are:

1) Goal and scope definition, which defines the system under study, the functional unit, the product specifications of the systems and the system boundaries.

2) Life cycle inventory (LCI), which calculates all the inputs into the system and the outputs from the system. The LCI takes into account all the processes in the life cycle that produce inputs. The allocation of flows and releases are also included in the LCI.

3) Impact assessment (LCIA), in which the most significant environmental aspects are evaluated with the results of the LCI. The inventory results are associated with specific environmental impact categories and category indicators. The purpose is to understand these impacts.

4) Interpretation of the results. In this phase, the re-

sults of the LCI and LCIA are considered together. The results should be consistent with the defined goal and scope. Based on these results, conclusions can be reached, limitations explained and recommendations provided.

8. LCA LITERATURE REVIEW

The literature review was made to collect the recently published research related to the sustainability of the algae cultivation and the production and use of algal based bioenergy. The review gives us an overview of the environmental impacts of different life cycle phases related to algae cultivation and use. The aim is also to get the understanding, if the algae based bioenergy can be produced and used with the yield of negative carbon dioxide level, and thus regarded as carbon mitigation source. According the reviewed studies, the energy consumption is in a major role, when considering the environmental effects of algal bioenergy production. Thus, it is important to identify the main energy consumption phases in order to find the main bottlenecks. Life cycle assessment is a useful tool also for this purpose, because in the inventory phase, all the material and energy flows related to specific unit processes are collected.

In our literature study, we reviewed articles and papers which were mainly related to environmental life cycle assessment but also which only focused on the net energy analysis. We chose a set of questions, based on our aim to clarify what kind of type LCA studies related to algae applications exist and which are the most promising algae technologies in the field of CCS. The purpose of the review was also to present the main findings and results of the LCA studies. The questions that we went through with each study are listed below and a short clarification of is provided.

- Classification of the publication.
    - what kind of approach at stake, article or some other type of paper.
- The aim of the study.
- Technology studied:
    - short technology description,
    - what algae species studied,
    - main assumptions, which are essential when comparing the result with each other.
- Description of LCA details:
    - environmental impact categories/studied emissions,
    - functional unit,
    - used methods (impact assessment, specific software, etc.)
- Main results and conclusions.

The summary of the answers of the reviewed studies are presented in Appendix II. Short and more detailed descriptions of the conclusions and the findings of the studies are also presented in the following chapters. We focused on the studies related to biodiesel and biogas production. Both open ponds and PBRs (photo bioreactors) were included. The overall picture is that algae based biodiesel applications is the most researched technology, and the same conclusion was made by FAO (2009). The reviewed studies can be divided mainly in three different categories:

1) cultivation of algae and biofuel production,
2) algae based biofuel production (and use)
3) combination of 1 and 2.

It is difficult to compare the results from different studies, because the system boundaries, used methods and assumptions differ. We try, however to find, if there are similarity between the conclusions of reviewed study.

8.1. Main findings and results of the reviewed studies

Renewable fuels from algae: An answer to debatable land based fuels (Singh et al., 2011).

The study is not an independent LCA study, but presents the results from other research. According to Clarens et al. (2010) the conventional crops (switchgrass, canola and corn) have lower environmental impacts than algae in energy use, greenhouse gas emissions and water regardless of cultivation location. Only total land use and eutrophication potential were more favorable for algae. The harmful effects are mainly related to CO_2 demand and fertilizer use during the upstream processes, and thus these effects can be decreased by using flue gases and wastewater. Further research and development are needed to establish an economical industrial scale production of algal biofuels.

A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels (Singh & Olsen, 2011).

The study presents different algal biofuel production technologies. It is not an independent LCA study, but the sustainability and LCA of algal biofuels is discussed. The study brings out the CCS (carbon capture and storage) viewpoint of algae production, when the CO_2 for example from power industry is used as CO_2 source. However, the biggest difficulty with this approach is the added cost of separation of the CO_2 from the emission streams. The study concludes that comprehensive life cycle assessment can and should be a tool for guiding technology development as well as for policy decisions to illustrate environmental benefits and impacts of algal biofuels.

Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors (Jorquera et al., 2010).

The study compares the properties and net energy ratio of different microalgae production methods. It states that photobioreactors (PRB) have typically higher volumetric productivity than open ponds, and they are easier to control. The PRBs are however, more expensive from the cost point of view, but open need large areas. According to the results, the NER was for both, flat-plate photobioreactors and raceway ponds > 1, indicating favorable energy processes for mass cultivation of algae. The study did not take into account the concentrating the microalgae from culture medium and extracting oil, and it was mentioned, that it would turn the algae production unfavorable for PRBs.

Net energy analysis of the production of biodiesel and biogas from the microalgae: Haematococcus pluvialis *and* Nannochloropsis *(Razon & Tan, 2011).*

The study presents the results of net energy analysis for the system to produce biodiesel and biogas from two microalgae. A large energy deficit was found for both systems. Largest energy consumers are the culture phase and the oil recovery operations, such as drying and cell disrupting phases. The study suggests that the net energy deficit of the system might be reduced for example by using primary treated wastewater as the feed, thus reducing the fertilizer requirement. According to the study a financially process may be possible, if the energy products can be seen as mere by-products in a multifunctional biorefinery system. Thus these systems may be coupled with carbon capture and storage (CCS) to potentially achieve negative life cycle CO_2 emissions. The same can be said if the energy production from microalgae can be considered to be an incidental by-product of sewage treatment.

Life cycle energy and CO2 analysis of microalgae-to-biodiesel: Preliminary results and comparisons (Khoo et al., 2011).

The total life cycle energy requirements for microalgae and biodiesel production were calculated in the study. According to the results of the, the biggest energy consumer in the microalgae production phase is PRB and next the raceway pond. The lipid extraction is however, the biggest energy consumer of the total biodiesel production chain (85%) and thus the main bottleneck. In the study, a comparative analysis with other researches was made. According to the results, it is very important to take all the life cycle phases into account, because the results were varying quite much depending which life cycle stages were included

Life cycle assessment of biodiesel production from microalgae in ponds (Campbell et al., 2011)

Environmental impacts (primarily GHG emissions) and economic viability of biodiesel production from microalgae in ponds were studied. The study does not present the energy requirement of the process, but it is mentioned, that algal mass is fed into an anaerobic digester unit after lipid extraction and the produced biogas is used to produce electricity. Based on that, it can be assumed, that the negative effect of energy consumption in lipid extraction process can be decreased. From GHG perspective, the study showed that the production of biodiesel from algae is beneficial.

Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance (Yang et al., 2011)

The study presents the life-cycle water and nutrient usage of microalgae-based biodiesel production. Water usage can be decreased if all the harvest water is recycled. However, the water usage in culture, drying, extraction or esterification does not reduce with the change of harvest water recycling rate. Also the use of seawater or wastewater as the culture medium can reduce 90% water requirement and also eliminate the need of all the nutrients expect phosphate.

Evaluating industrial symbiosis and algae cultivation from a life cycle perspective (Soratana & Landis, 2011)

The study concentrates on the algae cultivation phase, excluding the biofuel production. Also the construction phase is included, while it is not taken into account in many life cycle assessment studies. According to the life cycle results, the selection of PBR construction material is important and they dominate the total impacts but of course decrease over longer PBR lifetime. According to the study, when the lowest PBR construction material (mainly affect acidification and smog formation results) is selected, the next step is to reduce the demand for CO_2 and nutrients. Using waste water as nutrient source, the eutrophication can be avoided and when flue gases are used as CO_2 source, the GWP decreases.

Life-cycle assessment of microalgae culture coupled to biogas production (Collet et al., 2011)

Because the life-cycle assessment and energy analyses have shown that the algal biodiesel production needs a lot of energy, which might jeopardize the overall interest

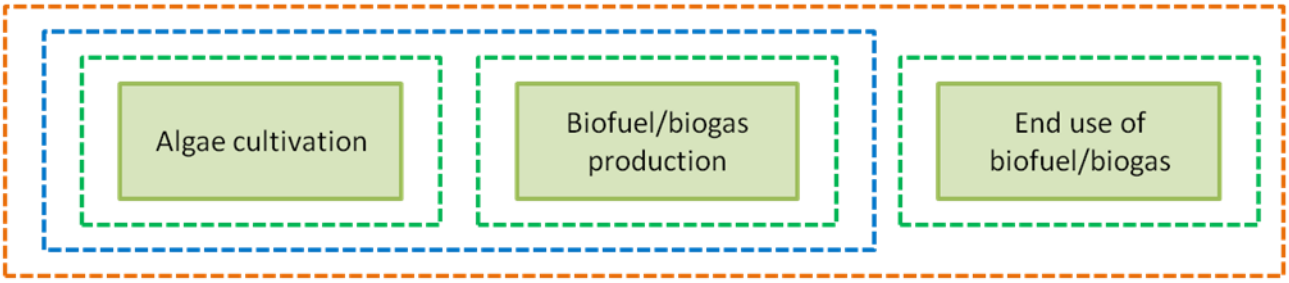

Fig. 1. Different life cycle system boundaries in algae production and use.

Bottleneck	Main problem	Suggestion for solution
Algae production		
Cultivation technology	Open pond - large area need Photobioreactor - high construction and operation costs, emissions from construction phase.	- material choices - combination of open pond and PRB
Ferilizer need	- energy consumption of mineral fertilizer production	- use of waste water - reject biomass use from anaerobic digestion
CO_2 need	- the emissions and costs of the use of pure CO_2	- CO_2 from flue gases
Harvesting and drying technologies	- energy usage	- biofuel production technology choice
Biofuel/biogas production		
- lipid extraction in biodiesel production	- energy consumption	- flue gas use as heating source - intensify biodiesel production with the use of crude glycerol (co-product during lipids to biodiesel conversion) through heterotrophic fermentation - combined biodiesel and biogas production > biogas as energy source, digested reject as fertilizer - biogas production alone > less energy needed for drying
- digester heating in biogas production	- energy consumption	

Table 2.Main findings of the reviewd studies

of algal biofuel. Therefore another transformation process by directly carrying out anaerobic digestion of raw algae is worth to investigate. Because concentration and oil extraction steps are not needed, a significant cost and energy are reduced. The liquid fraction from digester can be also used as fertilizer source in algal ponds. The highest energy demand of algal biogas production comes from heating the digesters. The study compares the results with algal biodiesel, but the boundaries and allocation methods differ and thus the results are difficult to compare.

Generation of algal biomass for biogas production: energetic and environmental from a Life Cycle Assessment (LCA) perspective (Romagnoli et al., 2011)

The environmental assessment of the use of biogas from algae as a biofuel for the heat and electricity production is compared with the case of natural gas/diesel supplies. According to the results the biogas combustion cause 95% of the total impact in the endpoint impact category related to human health. In the climate change impact category, the heating of digester is the main source, which is in the line of the study of Collet et al. (2011).

Environmental assessment of a biomethane production system from offshore-cultivated macroalgae (Langlois et al., 2011)

Macroalgae is used as biogas production source in the study. The results highlight the importance of the macroalgae cultivation techniques. It has to be also noticed that almost 27% of the produced biogas is used to heat the digester in the study. This scenario is not efficient enough to have less environmental impacts than natural gas (expect some impact categories). The alternative energy sources, as electricity from offshore wind farms, results in some impact categories were better.

Reduction of environmental and energy footprint of microalgal biodiesel production through material and energy integration (Chowdhury et al., 2011)

The study presents the results of three different scenarios of the life cycle impacts of an integrated microalgal biodiesel production system that facilitates energy- and nutrient- recovery through anaerobic digestion, and utilizes glycerol generated within the facility for additional heterotrophic biodiesel production. The study concentrated on to establish relationships of studied LCA parameters on process-relevant variables – lipid content and biomass productivity. It can be stated that when the lipid content of the cells increase, the waste biomass decrease and thus less biogas can be produced and nutrient recycled, but the total energy demand of the biodiesel process decrease because less algal biomass is needed to produce one ton of biodiesel. The study also brought up the possibility to utilize the flue gas energy as heating source.

Greenhouse gas sequestration by algae – Energy and greenhouse gas life cycle Studies (Campbell et al., 2009)

The study presents environmental, cost and social aspects of algae cultivation and biodiesel production. According to the results, algae based biofuel is very favorable compared with canola and ULS diesel. It is assumed that the biomethane based electricity replaces fossil fuel produced electricity and thus give emission credit to algae. System boundaries of canola and ULS diesel are not explained.

Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks (Clarens et al., 2010)

The study presents a first-generation approach of "algae farming" and it has been criticized among other of that (AquaFUELs, 2010). The study brings out, that significant improvements in algae cultivation could increase the favorability of energy production from algae over the next several decades. Only the cultivation part is taken into account, which has a major impact on the results. The eutrophication and land use are more favorable for algae than other crops. According to the study, the first-generation algae production systems release more CO2 to the atmosphere than is taken up during growth of the biomass, but it should be noted that only production and preliminary transportation of the biomass is included.

Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors (Stephenson et al., 2010)

The results of the study show that the cultivation of microalgae in raceways has the potential an environmentally sustainable feedstock for the production of biodiesel. Cultivation method is however in a big role for example from that point of view that electricity required during cultivation was found to contribute the most of the overall requirement for fossil energy and GWP.

According to the studies, the algal biomass is seen as a promising raw material alternative to first and second generation biofuels. There are however, many things to considerer to produce algae sustainable. Every study has its own system boundaries and assumptions, thus the comparison of the results is difficult. System boundaries are in an important role, when considering environmental impacts, because they define which life cycle phases stand out most. Different life cycle system boundaries, which emerged from the reviewed studies in algae production and use are presented in Figure 1. Some studies take only algae cultivation phase into account while other have examined also biofuel/biogas production phase and also their end use for example as transportation fuel or in energy production. In order to get the comprehensive understanding of the sustainability of algae use as bioenergy source, all the life cycle phases from algae cultivation to end use of algae based biofuel/biogas have to be included in the life cycle assessment.

8.2. General conclusions of the study

Algae biofuel production seems to be a promising technology. However, many things have to take into account. Compared with conventional energy crops, algae cultivation does not need to compete with food crops for land use because they can be produced areas unsuitable for crops. The grow rate is also much faster. The problem of algae based biofuels are mainly related to cost issues and energy consumption. With life cycle assessment main bottlenecks can be identified and thus affected.

When considering environmental effects, the system boundaries have to be defined carefully because, it might have significant effects on the results, as reviewed studies showed. When examining only the cultivation phase of algae, the construction materials and CO2 and fertilizer sources were mentioned in many studies to be the critical values of the environmental life cycle assessment. When also the biofuel production phase was taken into account, the energy consumption in extraction phase stood out most. Also the end use of produced biofuel is in a notable role when examining total effects of algal based biofuel. It has to be stated, that algae based biofuel cannot be considered as a carbon sink if the final combustion is not taken into account and if the fuel does not replace fossil fuels and the total impacts from algae cultivation to biofuel/biogas does not yield negative CO2 emissions. This situation is also perceived more likely as carbon recycling and not mitigation. (e.g. Soratana & Landis, 2011).

These barriers are discussed in the studies and suggestions to improve the efficiency and the sustainability of the process are presented. Flue gases form near power plant can be used as CO2 source in algal cultivation. More detailed information of CO2 use can be found for example from Kadam (2002) and Packer (2009). Algae growing in waste water stream were seemed to be promising way to avoid the negative environmental effects of mineral fertilizer production. But also the reject use from biogas production plant has been studied. The studies brought up many technologies/methods, how to avoid negative environmental effects, but quite many studied only one possible solution (for example algae cultivation in waste water stream but the use of chemical CO2, or CO2 from flue gases but mineral fertilizer use). The combination of these were only found from Soratana & Landis (2011).

There are also differences between biofuel production technologies. Algae based biodiesel requires much energy in lipid extraction and drying phase, as against in biogas production process, raw algae can be used without concentration and oil extraction steps. (Collet et al., 2011.) Attention must be paid, however the properties of the algae species. For biodiesel process, algae with high lipid rate is suitable, as against in biogas process, it does not matter that much. The combinations of biodiesel and biogas production were studied also and in that case the properties of algae species were relevant.

It would be interesting to examine also much wider combination (=industrial symbiosis) where algae is grown in waste water stream, CO2 is from flue gas and either biodiesel and biogas or only biogas is produced and reject from biogas plant is used to replace mineral fertilizer for example as soil amendment.

In some studies different environmental impact assessment categories were examined. However, different characterization and normalization factors were used, thus the comparison is difficult. However, the results showed, that in some impact category algae cultivation/ algae based biofuel was more favorable than conventional crops or biodiesel, but from other view they were worse. Energy use in algae cultivation and biofuel production was seen to affect most almost in every impact categories, thus much attention should be paid on that

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APPENDIX I

A list of companies that are or have been involved in algal bioenergy

A2BE Carbon Capture LLC
Algae Biofuels
Algae Floating Systems
Algae Fuel
Algae Fuel Systems
Algae Link
AlgalOilDiesel
Algenol
Algodynne
Algoil
Aquaflow Bionomic
Aquatic Energy
Aurora BioFuels Inc.
Bionavitas
BioFuel Systems
Blue Biofuels
Blue Marble Energy
Bodega Algae
Cellena
Cequesta
Chevron
Circle Biodiesel & Ethanol
Community Fuels
Diversified Energy
EnBW
E.ON Hanse
Energy Farms
Enhanced Biofuels & Techologies
Exxon Mobile
General Atomics
Global Green Solutions
Green Star
Greener BioEnergy
GreenFuel Technologies Corp
GreenShift
Growdiesel
GS Cleantech
HR Biopetrolium
IGV
Imperium Renewables
InfinfuelBiodiesel
Inventure Chemical
Joule Unlimited
Kai BioEnergy
KAS
Kent SeaTech Copr.
Kwikpower
LiveFuels Inc.
Mighty Algae Biofuels
NesteOil
Oilfox
Organic Fuels
OriginOil
PetroAlgae
PetroSun
Phycal
Revolution Biofuels
RWE AG
Sapphire Energy
Seambiotic
SeaAg Inc.
Shell
Solazyme
Solena
Solix Biofuels Inc.
Statoil
Sunx Energy
Susquehanna Biotech
Texas Clean Fuel
Trident Exploration/Menova
Valcent Products
Vattenfall
Vertigo
W2 Energy
XL Renewables

APPENDIX II

	Author	Title	Publication type	Objective of the study	Technology studied + algae species	LCA details	Main results and conlusions
Ireland, UK	Singh & al. 2011	Renewable fuels from algae: An answer to debatable land based fuels	Article in Bioresource Technology 102: 10-16.	The review the utilization of the first and second-generation biofuels as the suitable alternatives to depleting fossil fuels.	Microalgae	General information about algae utilization and properties. Not an LCA study, but presents some results of other studies.	> Third generation biofuels from algal cell grown on non-arable land is the answer to the food-fuel competition. > Wastewater and flue gases are the best option for reducing the environmental burden from the cultivation of algal biomass.
Denmark	Singh & Olsen. 2011	A critical review af biochemical conversion, sustainability and life cycle assessment of algal biofuels	Article in Applied Energy 88: 3548-3555	To present pros and cons of various algal biofuels production pathways, their sustainability and life cycle assessment. The state of the art for different types of en-product biofuels from algae will be revied.	Different biofuel production technologies: biodiesel, biogas, bioethanol, biohydrogen, microalgae gasification.	Not an LCA study, but presents some results of other studies.	> Algal biomass can be utilized for the production of various biofuels.
Br, USA	Jorquera, O. & al. 2010	Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors	Article in Bioresource Technology 101: 1406-1413.	Energy life-cycle analyses of the production of biomass from the oil-rich microalgae with different technologies and to calculate their corresponding NERs in order to evaluate ther feasibility.	Microalgae *Nannochlorophis* sp. Raceway ponds, tubular and flat-plate photobioreactors.	> Energy LCA. > GaBi software as a tool.	> Net energy ratio (NER) for each process was calculated. The energy consumption for pumping in the horizontal tubular-type photobioreactors is too high (2500 W/m3), which renders this system economically unfeasible at present. > NREs for flat plates = 4,33 and for open pond = 7,01. > The higher energy consumption in both cases is related mostly to pumping and not so much to materials costs, since the latter are offset by the long lifetime of the systems.
Phillipines	Razon, L. F. & Tan, R.R.	Net energy analysis of the production of biodiesel and biogas from the microalgae:*Haematococcus pluvialis and Nannochloropsis*	Article in Applied Energy 88: 3507-3514	The net energy analysis for two scenarios for obtaining biodiesel and biogas from microalgal biomass	Microalgae *Haematococcus pluvialis (fresh water) and Nannochloropsis (salt water).* > Flat-plate PRB -> slurry into raceway pond. > Algal slurry is concentrated by gravitational settling and microfilter -> distruption in a cracking bead mill -> decanter (separation of oil from the aqueous and other components) > transesterification (similar process as for soybean oil) > Thickener overflow and depleted algal slurry are used to produce biogas	> Energy LCA. > Functional unit: 1 kg methyl esters from algal oil. > The Cumulative Energy Demand method, part of the ecoinvent database in Simapro 7.2.2, was used to assess the energy requirements for each process. In addition, the data for key inputs like electricity and chemicals were obtained from the ecoinvent database. > Allocation are done on a dry basis, three displacement scenarios were analyzed.	> Large energy deficits were observed even with highly optimistic assumptions. > The largest energy burdens were from the oil-recovery operations such as drying and celldisruption - > a positive net energy balance could be obtained only if a ''wet extraction'' process were used. > The results do not preclude the possibility that either of these systems would be desirable from a greenhouse gas-reduction viewpoint. > A financially viable process may be possible if the energy products can be viewed as mere by-products. > The search for species to cultivate should thus be directed towards finding species that have thin cell walls and thus require minimal energy for disruption and oil extraction.
UK	Scott, S. & al. 2010	Biodiesel from algae: challenges and prospects	Article in Current Opinion in Biotechnology 21:277-286	The study presents an overview of a potential algal biofuel pipeline, and focus on recent work that tackles optimization of algal biomass production and the content of fuel molecules within the algal cell	> Factors to be considered and optimized during algal biofuel pipeline. > Include e.g. following stages: Choice of algal strain, Growth of algal biomass and production of fuel molecules, Harvesting and extraction, Final processing and use of co-products, Overall energy balance for algal biodiesel production, Optimization of algal growth – the importance of light, Maximizing the TAG content in algae	Not an LCA study, but see some data related to algae production	> According to the study, life-cycle analyses suggest that, using current methodologies, the algas biodiesel process is marginal in terms of positive energy balance and global warming potential.

	Author	Title	Publication type	Objective of the study	Technology studied + algae species	LCA details	Main results and conlusions
USA	Sander, K. & Murthy, G. S. 2010	Life cycle analysis of algae biodiesel	Article in Int J Life Cycle Assess 15:704-714	1. Perform well to pump LCA for the production of 1,000 MJ energy from algal biodiesel 2. Establish baseline information for algal biodiesel process3. Assess sustainability of algae biodiesel by characterizing energy use and emissions	> Culturing algae in PRB/indoor ponds -> seed culture for the open ponds. > Chamber filter press or centrifuge followed by drying in a natural gas fired dryier. > Hexane extraction step and transesterification (modeled based on a previous soybean biodiesel LCA) >Transportation and distribution of biodiesel .> Algae by-products used as feedstock for an ethanol conversion process.	> Functional unit: 1000 MJ algal biodiesel.> Studied emissions: CO2, CH4, N2O, VOC's, NOx, CO, particulate matter, andSOx. > System boundary with RMEE method (cutoff ratio of 5%) .> Co-product allocation with system expansion.	> As the lipid content of algae decreases, a larger amount of residual algae mass is processed into ethanol resulting in larger coproduct credits.Therefore, total energy increases due to increased processing energy, as algae lipid content decreases. However, net energy also increases due to higher coproduct credits as algae lipid content decreases. > NER=-6.7 for algal biodiesel using a filter press and -3.8 for centrifuge. > CO2-eq=-18.4 kg for a filter press process with coproduct allocation. > Net CO2= -20.9 kg for filter press and 135.7 kg for centrifuge. > Thermal algal dewatering requires high amounts of fossil fuel derived energy (3,556 kJ/kg (850 kcal/kg) of water removed) and consequently presents an opportunity for process improvements to reduce energy use.
ingapore	Khoo, H.H. & al. 2011	Life cycle energy and CO2 analysis of microalgae-to-biodiesel: Preliminary results and comparisons	Article in Bioresource Technology 102:5800-5807	To compare life cycle energy and life cycle CO2 of the following: (I). ICES (the Institute of Chemical and Engineering Sciences in Singapore). microalgae-to-biodiesel production: - from cultivation and harvesting (integrated lab-scale), - lipid extraction (lab scale with estimated energy requirements), - theoretical Conversion (from literature), - sensitivity analysis. (II). Comparison of ICES microalgae-to-biodiesel system with five other case studies.	Microalgae *Nannochlorophis sp* > Culture preparation and growth in PRB and raceway ponds > Harvesting by using ASACF (air sparging assisted coagulation flocculation) and dewatering (centrifugation). > Hexane extraction > Biodiesel production via chemical conversion of the oil by trans-esterification.	> Fnctional unit: 1 MJ biodiesel. > Studied emissions: CO_2 > Based on ISO 14000 standardization.	> Total energy consumption 4.44 MJ/MJ,biodiesel -> 13% biomass production, 85% lipid extraction, 2% biodiesel production. See CO2-emissions from Fig. 6 of the article. > Sensitivity analysis was performed by making adjustments to the energy requirements, percentages of lipid contents, and lower and higher heating product value. -> Energy demand of liquid extraction is critical value.
Australia	Cambell, P. K. & al. 2010.	Life cycle assessment of biodiesel production from microalgae in ponds	Article in Bioresource Technology 102:50-56	A notional production system designed for Australian conditions was conducted to compare biodiesel production from algae with three different scenarios for carbon dioxide supplementation and two different produciton rates.	> Flattened toroidal ('raceway design') ponds. > Concentration by a chemical (hydrophobic polymer) flocculant. > Dissolved air flotation (DAF) system. > Extraction of the the lipids. > Transesterification via the addition of methanol and a catalyst. > Algal mass remaining after lipid extraction is fed into an anaerobic digester unit -> methane compusted to produce energy.	> Functional unit: 1 tkm fuel use. > Studied emissions: CO2, CH4, N2O. > Calculation made by SimaPro 7 software tool. > Data from the relevant Australian authorities (e.g. the Energy Supply Association of Australia for electricity), and other relevant sources including AusLCI (the Australian Life Cycle Inventory). Where local data is not available the closest item or system in the EcoInvent database that comes with SimaPro is used.	> From a GHG mitigation perspective, the production of biodiesel (and electricity) from algae in this fashion is beneficial, with a reduction in greenhouse gas output of between 63.1 and 108.8 g/tkm. > Algae GHG emissions (27.6 to 18.2) compare very favourably with canola (35.9) and ULS diesel (81.2). > Costs are not so favourable,
US	Yang, J. & al. 2010.	Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance	Article in Bioresource Technology 102:159-165	To study the life-cycle water and nutrients usage of microalgae-based biodiesel production. The influence of water types, operation with and without recycling, algal species, geographic distributions are analyzed.	Microalgae *Chlorella vulgaris* > Comparison with eleven other species. >Biodiesel production system includes the processes of culture (open ponds), harvest, drying, extraction, and esterification (same process as for soybean biodiesel production (Dominguez-Faus et al., 2009).	> Functional unit: 1 kg of microalgae-based biodiesel. > Studied impact categories: water footprint and nutrient balance.	> 3726 kg water, 0.33 kg nitrogen, and 0.71 kg phosphate are required to generate 1 kg microalgae biodiesel if freshwater is used without recycling. > Recycling harvest water reduces the water and nutrients usage by 84% and 55%, respectively. > Using sea/wastewater as culture medium decreases 90% water requirement, and eliminates the need of all the nutrients except phosphate.

	Author	Title	Publication type	Objective of the study	Technology studied + algae species	LCA details	Main results and conlusions
USA	Soratana, K. & Landis, A. E.	Evaluating industrial symbiosis and algae cultivation from a life cycle perspective	Article in Bioresource Technology 102:5892-6901	To evaluate the potential utilization of both CO_2 and nutrients from industrial wastes during microalgal cultivation. A comparative LCA of different microalgal cultivation scenarios over three different assumed useful lifetimes of a PBR: 5, 10 and 20 years.	Microalgea *Chlorella vulgaris*cultivation in PRB. > Twenty different cultivation scenarios were evaluated for three main microalgal cultivation parameters: - PRB construciton materials, - source of nutrients (synthetic fertilizers and municipal wastewaters), - source of CO_2 (synthetic CO_2 and CO_2 from flue gas)	> Functional unit: the microalgal mass produced from one cultivation system operated for 20 years, which is 3650 kg of microalgae. > Nine of the TRACI impact categories were evaluated: global warming potential (GWP), acidification, carcinogenics, non-carcinogenics, respiratory effects, eutrophication, ozone depletion, ecotoxicity and smog. > The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) version 3.01 (Bare et al., 2003).	> The selection of PBR construction materials is important. > The utilization of wastes as resources of microalgae mass production has the potential to avoid negative impacts. >Even though not every scenario with nutrients and/or CO2 from waste streams resulted in impact avoidance, the total impacts were less than scenarios not utilizing waste streams as resources. > Because the scope of this paper is a cradle-to-gate LCA of microalgal cultivation for microalgal diesel production, impacts from the combustion of microalgal diesel were not included. Thus, microalgal diesel cannot be considered a carbon sink at this stage. > Further study on environmental impacts of harvesting, dewatering, drying, extraction, conversion and combustion of microalgal diesel should be conducted and combined with the results of this study (see Magill, 2010).
France	Collet, P. & al. 2010	Life-cycle assessment of microalgae culture coupled to biogas production	Article in Bioresource Technology 102:207-214	A life-cycle assessment (LCA) of biogas production from the microalgae *Chlorella vulgaris* is performed and the results are compared to algal biodiesel and to first generation biodiesels. To identify the main bottlenecks of a methane production process from algae, and to compare them with the advantages and the drawbacks of mature (first generation biodiesel and diesel) and immature technologies (algal biodiesel).	Microalgae *Chlorella vulgaris* >Cultivation in open raceways. > Harvesting in two steps: - natural settling and concentration of the algae by centrifugation. > Anaerobic digestion. > Biogas upgrading. > Liquid digestates recycling step	> Functional unit: the production of 1 MJ by burning algal-based methane, algal-based biodiesel (Lardon et al., 2009) and diesel (Frischknecht et al., 2007) in an internal combustion engine. > Impact assesment with CML (Centrum voor Milieukunde Leiden), described in Guinée (2002): abiotic depletion (Abd), potential acidification (Acid), eutrophication (Eutro), global warming potential (GWP), ozone layer depletion (Ozone), human toxicity (Hum Tox), land competition (Land), ionising radiation (Rad) and photochemical oxidation (Photo). > Methodologial framework of the LCA based on a "cradle to grave".	> Different bases in comparison: this study substitution, algal biodiesel is based on allocation. > Compared to algal biodiesel and diesel, the algal biomethane is the worst case for abiotic depletion, ionising radiation, human toxicity and global warming potential impacts, mainly because of the strong demand in electricity. For the land use category as well, diesel and algal biodiesel reveal less impacts than algal methane. > At the energy consumption level, energy need of paddlewheels as well as pumps make algal methane less competitive compared to algal biodiesel. > Regarding photochemical oxidation, algal methane and diesel are much lower (respectively 13.3% and 9.3%) than the algal biodiesel. > Algal methane is a much better option in terms of acidification and eutrophication (52.9% and 9.9%). > Any reduction of the electricity consumption will result in a major reduction of the total environmental impact.
	Romagnoli, F & al. 2011	Generation of algal biomass for biogas production: energetic and environmental from a Life Cycle Assessment (LCA) perspective	Article in International Congress, March 30 - April 01, 2011. Progress in Biogas II. Biogas production from agricultural biomass and organic residues	To carry out an environmental assessment of the use of biogas from algae as a biofuel for the heat and electricity production on a cogeneration (CHP) unit (40kW) and compares it in case of natural gas/diesel supplies	Macroalgae, *Ulva Prolifera,* production in PVC open ponds in the Augusta-Italy. > Acidification. > Effluent clarification: the solid part is recycled to complete the hydrolysis, the liquid part will pass through the second phase for methanization. > Outflow from digestion phase is separated: solid part is dryid to obtain pellets and fertilizers, the liquid fraction is reused in the open ponds. > Produced biogas is burnt on a cogeneration (CHP) unit (40 kW).	> Functional unit: the amount of TJ,th and TJ, el produced in a 40kW cogeneration unit in 1 year, this mean 1.28 TJ,el/year and 2.2 TJ,th/year. > Cradle-to-grave, LCA, ISO 14044, Impact 2002+. Midpoint and endpoint categories	> Endpoint category results: human healt (55%) of the total impacts (biogas combution), climate change (30%) (heating of digester, tranportation of manure, energy spend for building up for algal growth at the pond level). > Impact 60% now, when compared the situtation if CHP fuelled with general agricultural waste and 7 times lower than the use of natural gas.

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	Langlois, J. & al. 2011	Environmental assessment of a biomethane production system from offshore-cultivated macroalgae	Paper in LCM 2011 conference, August 28-31, 2011.	To make a comparative LCA to assess, if macroalgae is affectively an environmentally friendly feedstock for bioenergy production - > is macroalgae more environmentally friendly than natural gas.	The brown seaweed *Laminaria saccharina* cultivated in a coastal environment. > Plantlets production onshore - >Nursery in a closed building. > Open ocean cultivation and harvesting. > Anchored tying floating lines on a coastal environment. > Anaerobic digestion in stirred tank reactors.	> Functional unit: 1 MJ consumed in an internal combustion engine. > Studied impact categories: (CC=Climate Change, OZ=Ozone Depletion, HT=Human Toxicity, POF=Photochemical Oxidant Formation, PMF=Particulate Matter Formation, IR=Ionising radiation, TA=Terrestrial Acidification, FEU= Freshwater Eutrophication, M-EU=Marine Eutrophication, TE=Terrestrial Ecotoxicity, FE=Freshwater Ecotoxicity, ME=Marine Ecotoxicity, ALO=Agricultural Land Occupation, ULO=Urban Land Occupation, NLT=Natural Land Transformation, WD=Water Depletion, MD=Metal Depletion, FD=Fossil Depletion). > ReCiPe method with EcoInvent v2.2. database and SimaPro 7.3 software.	> The results highlight that one of the key improvements to focus on is electric consumption (coupling offshore wind turbines and seaweed). > The results highlight that the scenario of reference is not efficient enough to have less environmental impacts than natural gas, except for ozone depletion, marine and freshwater eutrophication. > With coupling, climate change and fossil depletaion decreases. In addition of coupling, remaining impacts where efforts have to be made are the offshore infrastructures.
	Chowdhury & al. 2011	Reduction of environmental and energy footprint of microalgal biodiesel production through material and energy integration	Accepted manuscript in Bioresource Technology (2011)	To minimize the environmental impact associated with algal biodiesel by maximizing resource utilization within an integrated system. The study seeks to understand the effects of algal lipid content on life-cycle GWP as well as energy and water demand	Some process steps (e.g. dewatering and dryoing of algae) are modeled using data for other similar processes being currently practiced. > Glycerol fermentation (glycerol is a co-product of biodiesel production). > An-aerobic digestion of biomass residues. > Lipid extraction and transesterification (hexane). > Three case studies: - a base case scenario: stand-alone biodiesel facility (external fossil energy, no integrate/reuse energy and nutrient), - a without-allocation scenario (biogas used as energy source, nutrient and water recycled), - a with-allocation scenario (in addition of biogas use and water recycling, substitutioin credit was allocated to the co-products).	> Functional unit: 1 ton biodiesel. > Studied impact categories: GWP, energy and water demand. > Used method: cradle-to-gate. See case descriptions	> Process integration can significantly decrease energy demand (12 GJ lower), GWP and water demand. > Lipid content of algal adn the chocen scenario has an effect on energy demand. Dewatering and drying was found to be the major energy consumer. > GWP for algal biodiesel could range between 2830-836 kg,CO2/ton biodiesel -> a maximun of 71% reduction is possible compared with chain for fossil fuel.
Australia	Campbell, P. K. 2009	Greenhouse gas sequestration by algae – Energy and greenhouse gas life cycle Studies	Report by CSIRO, http://www.csiro.au/en/Outcomes/Energy/Powering-Transport/Greenhouse-Sequestration-Algae.aspx	To examine the greenhouse gas, costs and energy balance on a life-cycle basis for algae grown in salt-water ponds and used to produce biodiesel and electricity. Comparing the results with biodiesel canola and ULS (Ultra Low Sulphur) diesel	> Algae farm (*Botryococcus braunii*) in Australian conditions next to sea (salt water use), cultivation in raceway ponds. > Harvesting: concentration with (hydrophobic polymer) flocculant and after that dissolved air flotation system and centrifuge. > Lipid transesterification by combining with alcohol and a catalyst such as potassium hydroxide to produce biodiesel. > Remaining algal mass is moved ino anaerobic digestion system to produce methane, which is used to produce electricity, which is used in the algae farm.	> Functional unit: 1 tkm. > Studied emissions: CO2, CH4, N2O.	> All three biodiesel scenarios (different CO2 sources) seems to bee more favorable than biodiesel from canola or ULS diesel. -> Less fossil fuel inputs is used and also electricity from biogas decrease fossil fuel usage. > In carbon sequestration issue: during night and in poor weather, algae slow down and take up less CO2. > In a larger scale, commercial algae industry, extra costs could make the biodiesel economically nonviable.