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STATE OF THE ART OF ALGAL BIOMASS AS RAW MATERIAL FOR BIOFUEL PRODUCTION

Report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

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SUMMARY

Algal biomass is a promising future source of sustainable fuel, and efforts are being taken all around the world to develop the opportunity. A variety of fuel types are considered, such as biodiesel, biogas, biohydrogen, bioethanol and biobutanol. The purpose of this study is to obtain knowledge of the worldwide competence within the area of using algal biomass as a source for biofuel, through a systemic structuring and mapping of the work which has been performed as well as ongoing initiatives. The scope of the study is limited to results of recent studies, current industrial activity and ongoing research initiatives.

This study focuses on four areas. The first is algal biofuel production research, containing an analysis of which cultivation processes that have been recently studied, and which results these studies have obtained. The second focus area is life cycle assessments (LCA), showing how environmental analyzes of algal biofuel production processes have been conducted, and presenting the conclusions from the studies. The third focus area is industrial activity, indicating where industry is located and what algal activities they are involved in. The fourth focus area is research activities, describing in which parts of the world such research is being conducted, focusing particularly in the Nordic countries.

Conclusions from the study are that there is a variety of research and industrial activities going on within the field of algal biofuel, but the Nordic countries are only to a certain extent involved. Research is focusing on different fuels, and biodiesel is by far the most investigated one. A variety of cultivation methods and algal species, both micro and macro, are being studied. LCA research on algal biofuels has increased significantly in the last years. The majority of the LCA studies focus on biodiesel. Researchers agree on that energy efficiency is crucial for a sustainable fuel production, but they point to different parts of the process (cultivation, extraction, transportation, combustion) as the energy bottleneck.

SAMMANFATTNING

Att använda alger som råmaterial för bränsleproduktion kan vara en av lösningarna till att öka mängden förnybara bränslen. Intresset och utvecklingen av alger som bränslekälla är stort och pågår över hela världen. Det är olika bränsletyper som är intressanta, såsom biodiesel, biogas, biovätgas, bioetanol och biobutanol.

Syftet med denna studie har varit att sammanställa kunskap och aktiviteter som utförts och pågår inom detområde som handlar om att använda algbiomassan till bränsle. Detta har utförts genom att systematiskt identifiera, strukturera och kartlägga utförda och pågående studier och aktiviteter. Projektet begränsades till resultat från nyligen publicerade studier, pågående industriella aktiviteter och pågående forskningsstudier.

Fyra områden har beaktats i studien. Först behandlades forskning om produktion av alger som biobränsle. Där ingick en analys av studier på odlingsmetoder och deras resultat. Andra området var genomförda livscykelanalyser (LCA). Där ingick en analys av hur studierna av miljökonsekvenserna var genomförda och resultatet av dem. Industriella aktiviteter var det tredje området. Där redogjordes för industrins aktiviter och hur de är geografiskt lokaliserade. Sista området behandlade forskningsaktiviteter över världen med fördjupning på de nordiska länderna.

Slutsatserna från studien är att det finns en mängd aktiviteter inom området att använda alger som biobränsle, både vad gäller forskning och industriella aktiviteter. Dock visade det sig att de nordiska länderna har begränsade aktiviteter. Flera olika odlingsmetoder har studerats för mikro- och makroalger. Det biobränsle som undersökts mest är biodiesel. Forskning om miljöpåverkan av att producera och tillverka algbiomassa och biobränsle med hjälp av LCA metodik har ökat dramatiskt de sista åren. De flesta LCA-studier har fokuserat på algbiomassa som används till biodieselproduktion. Forskarna är ense om att energieffektiviteten är viktig för en uthållig bränsleproduktion men har olika syn på vad som utgör flaskhalsen i livscykeln (odling, extrahering, transporter eller förbränning).

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1 INTRODUCTION

Algal biomass is a rather new resource with potential to be used as biofuel. Research is going on in Sweden, Europe and worldwide and there is a need for a systematic structuring and mapping of the work which has been performed as well as the ongoing initiatives. The purpose of this study is to cover the knowledge of the worldwide competence within the area of using algal biomass as a source for biofuel. By covering the state of the art for use of algal biomass, and structuring the references in several matrixes (biofuel produced, species of algae, techniques and processes used, geographic origin, and the outcome of the study), we will get the picture of the knowledge in the area. The study does not include economical aspects or future potentials for algal biofuel production.

1.1. BACKGROUND

Algae, both macro- and microalgae, are considered one of the most promising alternative feedstocks for sustainable production of commodities, *e.g.* food, fodder, chemicals and biofuels. Algae are found in many different types of habitats from the ice and snow of the Arctic to tropical rainforests and in marine waters as well as in fresh waters. Algal taxonomy is highly diverse and mainly based on cellular structures and content of pigments. The classification is still under debate; however, fourteen phyla of eukaryotic algae have been recognized[1]. Both macro- and microalgae can be found in all different phyla.

Cultivation of seaweeds (macroalgae) in aquaculture has many unique advantages over terrestrial crops; faster growth, efficient CO_2 capturing, no needs of pesticides or fertilizers, no consumption of fresh water, and the extensive areas in coastal regions of the oceans provide a limited conflict with food supply. Furthermore, seaweeds function as ocean biofilters, which can be used for nutrient stripping of eutrophicated coastal waters, *e.g.* by placing seaweed cultures in conjunction with fish farms to remove excess nutrients. Cultivation of macroalgae has so far developed on a massive scale only in Asian countries, mainly for food and chemical markets. It is, however, now being developed in Europe for the purpose of biofuel production.

The possibility of culturing microscopic algae for biofuels production was a focus of interest especially in the USA in the 1970s, when oil prices peaked during the oil crisis. The interest in algae has again reached high levels mainly due to the anticipated peak oil, the global need for replacement of fossil fuels, and the climate/global warming issue. The interest in microalgae is based on their high growth rate and higher oil production per cultivated land area, the fact that arable land is not needed, and a possibility for production of various biofuels, preferably in combination with other chemicals using biorefinery concepts in industrial clusters.

The basis for biofuel production is extraction of cellular components from harvested biomass, followed by conversion to the fuel intended. In this respect, lipids are converted to biodiesel, and carbohydrates can be converted to a range of biofuels in fermentative processes; bioethanol, biohydrogen and biobutanol. Several microorganisms are used in the fermentative steps for formation of biofuels. In addition, several components of the algal biomass (proteins, carbohydrates, lipids) are used in anaerobic digestion for biogas production. In contrast to these mentioned biofuels, biohydrogen can as well be produced through algal metabolism in itself. For efficient biofuel production three aspects need to be optimized; cultivation to yield composition and amount of algal biomass, extraction methods to obtain the component of interest, and conversion of the cellular component to the biofuel.

2 METHOD

To get an overview of the state of the art within algal biofuel production, we have gathered and compiled information within four areas:

1. Algal biofuel production research
2. Conducted life cycle assessments (LCA)
3. Industrial activity
4. Research initiatives

For the two first areas, peer reviewed articles found using the search engine Scopus were analyzed, and findings were sorted in matrixes with the following headlines: Biofuels produced, Species of algae, Techniques and processes used, Geographic origin, and the Outcome of the studies. The scope was limited to the last five years (2008-2013).

For “Algal biofuel production research” we collected the 24 most recent articles [2-25] for a thorough examination. The analyzis of the articles is presented in Appendix A-C.

For “Conducted life cycle assessments” we collected the 23 most recent LCA studies [26-48] for a thorough examination, one being a macroalgal study. The analyzis of the articles is presented in Appendix D-F.

General conclusions from central reports describing algal production systems and algal life cycle assessment were also included.

For the third area, industrial activity, an internet research was conducted to investigate the algal related companies listed on the Planktoleum website [49], much similar to a list compiled by Oilgae and regularly updated [50]. The companies involved with algal fuel production are listed in Appendix G and H. In addition, a special survey on the situation for the industrial acitivities in the Nordic countries was executed, using a recent market analysis on microalgal activities [51].

For the fourth area, the same market analysis on microalgae activities was used and complemented with websites of actors, who to our knowledge have macroalgal activities, in order to obtain knowledge of ongoing research initiatives in the Nordic countries.

3 RESULTS AND DISCUSSION

3.1 ALGAL BIOFUEL PRODUCTION RESEARCH

The numbers of Scopus search results provide an indication of research activity within different types of algal biofuels. Biodiesel is by far the most studied algal fuel.

- "Algae and biodiesel" 794 results
- "Algae and bioethanol" 112 results
- "Algae and biogas" 110 results
- "Algae and biohydrogen" 66 results
- "Algae and biobutanol" 9 results

In Table 1, the number of selected articles per fuel type is listed.

Table 1. Overview of selected scientific articles covering different types of biofuels from algae.

Fuel type	Articles
Biodiesel	11
Biogas	4
Biohydrogen	4
Bioethanol	4
Biobutanol	1

The use of microalgae has mainly been studied in 19 of the selected articles, whereas the use of macroalgae was studied in 6 articles only. Algal species from both fresh and saline water have been investigated, with a slight majority of the studies (60%) using fresh water algae. Most species under investigation have been part of the Chlorophyta phylum (green algae), but also species belonging to Heterokontophyta (including brown algae and diatoms), Rhodophyta (red algae) and Haptophyta phyla have been investigated. Some of the most studied macroalgae are part of the Heterokontophyta and Rhodophyta phyla. One of the most studied genus is *Chlorella* (Chlorophyta), which has been used for production of all the main biofuels (biodiesel, biogas, bioethanol and biohydrogen).

Some examples of microalgae used for biodiesel production are *Chlorella vulgaris* and *Nannochloropsis salina*. *Chlorella vulgaris* has also been used for biogas production and fermentative production of hydrogen as well as ethanol from algal biomass. An example of macroalgae used for biofuel is *Saccharina latissima*, which has been used for biogas production.

Microalgae for biofuels have been cultivated in both open, *i.e.* ponds, and closed systems, the latter using different types of photobioreactors and flasks. Macroalgae are mainly obtained by collection of biomass in nature but several initiatives are establishing cultivation techniques for macroalgae. Some examples of possible levels of biofuel production are presented in Table 2.

Table 2. Examples of biofuel production reported by selected articles

Type of biofuel	Biofuel production	Algae	Reference
Diesel	0.10 g/g algae*	*Ulva*	[5]
Hydrogen	53.5 ml/g algae	*Gelidium*	[18]
Hydrogen	92.7 ml/g algae*	*Chlorella*	[17]
Ethanol	0.26 g/g algae	*Chlorococcum*	[22]
Ethanol	0.4 g/g algae	*Chlorella*	[24]
Butanol	0.045 g/g algae	*Ulva*	[25]

*Calculated from data given in the article

3.2 CONDUCTED LIFE CYCLE ASSESSMENTS

According to the EU research programme AquaFUELs [52], only a limited number of algal biofuel production life cycle assessments (LCAs) have been conducted. AquaFUELs identified only 7 microalgal LCAs and no macroalgal LCA. This situation has certainly changed since 2009, as we identified far more LCA studies.

In Table 3, the fuel type investigated in the LCA selected studies are listed. Most LCA are of bio-diesel.

Table 3. Selected LCA studies on different types of biofuels from algae.

Fuel type	LCA studies
Biodiesel	19
Biogas	3
Biohydrogen	
Bioethanol	
Biobutanol	
Biogas + bioethanol	1

As AquaFUELs [52] points out, and as is shown in Table 4, there is a considerable variation in the choices of the functional unit for the LCA studies. Functional unit is a measure of the function of the studied system and all calculations is related to it. When comparing results from different studies using LCA as a tool it is important to take into consideration all dissimilarities between the studies, for example functional unit, system boundary and allocation methods used. Therefore, a difference in functional unit makes comparisons of results from LCA studies difficult.

Table 4. Overview of functional units used in LCA studies of algae biofuels

Author & year	Functional unit
Liang et al. 2013 [26]	0.2 million tons of biodiesel
Frank et al. 2013 [27]	Not mentioned
Rickman et al. 2012 [28]	Not mentioned
Alvarado-Morales et al. 2013 [48]	Cultivation and processing of one ton of dry seaweed biomass produced in Denmark for biofuels production
Wibul et al. 2012 [29]	1 MJ biodiesel
Borkowski et al. 2012 [30]	1 MJ of delivered fuel
Soratana et al. 2012 [31]	0.67 billion gallon of biodiesel/year
Yanfen et al. 2012 [32]	1 t of biodiesel
Chowdhury et al. 2012 [33]	Not mentioned
Langlois et al. 2012 [45]	1 km trip with a gas-powered car
Hou et al. 2011 [34]	1 MJ of energy from bio- and fossil diesel “well-to-wheel”
Khoo et al. 2011 [35]	1 MJ biofuel
Campbell et al. 2011 [36]	The combustion of enough fuel in an articulated truck (AT; the most common form of freight transport in Australia) diesel engine to transport one ton of freight one km
Yang et al. 2011 [37]	The production of 1 kg of microalgae-based biodiesel
Brentner et al. 2011 [38]	10 GJ Biodiesel
Collet et al. 2011 [46]	1 MJ produced by combustion in an internal combustion engine
Pardo et al. 2010 [39]	100.000 ton biodiesel /year
Sander et al. 2010 [40]	1,000 MJ of energy from algal biodiesel using existing technology
Batan et al. 2010 [41]	1 MJ of energy produced
Powers et al. 2010 [42]	Liters biodiesel produced
Stephenson et al. 2010 [43]	1 t of biodiesel
Lardon et al. 2009 [44]	1 MJ of fuel in a diesel engine
Liu et al. 2009 [47]	1000 kg of dry microalgae biomass

The system boundaries of the LCA studies also vary. Of the 19 studies in which the life cycle approach was easy to identify, twelve were well-to-tank studies and seven were well-to-wheel studies, including combustion of the fuel. The studies provide data for different kinds of emissions. Six of the studies only provide data for CO_2 or Global Warming Potential, while 17 provide data for more emissions and impact categories.

The conclusions of the LCA studies are presented in Table. Because of the different production systems, conditions and functional units applied, the results cannot be compared. While there is a uniform agreement that energy efficiency is crucial, the authors point to different parts of the process (cultivation, extraction, transportation, combustion) as the energy bottleneck. Two authors report that the process has a net energy loss, while one reports a net energy gain.

Table 5. Overview of results from LCA studies on algal biofuels.

Fuel	Author	Conclusions
Biodiesel	[26]	Net energy loss
	[27]	Not clear if hydrothermal liquefaction or lipid extraction is the best method
	[28]	CO_2 delivery energy requirements and growth reactor efficiency must be improved
	[29]	CO_2 uptake in cultivation results in lower global warming potential than rape seed and soybean, but higher abiotic depletion, human toxicity and acidification potential
	[30]	Production of renewable diesel (Also referred to as “green diesel” or “hydrotreated vegetable oil) and biodiesel have similar environmental qualities
	[31]	Energy demand must be reduced if the fuel is to be labeled as renewable
	[32]	Energy demand and CO_2 emissions are sensitive to oil content, drying rate and esterification rate
	[33]	Integrated systems require less energy
	[34]	Algae is better than soybean in all impacts (mainly result of lower level of agricultural inputs r unit of oil output)
	[35]	Lipid extraction is the most energy intensive process. Number 2 is biodiesel production
	[36]	GHG emissions compare favorably with canola and ultra-low sulphur diesel
	[37]	It is important for the environmental performance to recycle water and use sea or waste water
	[38]	Slightly net energy loss, but industry practice has improved
	[39]	Distribution and combustion of fuel have the greatest environmental impacts
	[40]	Energy efficiency is crucial
	[41]	Slightly net energy gain
	[42]	Climate differences (location of cultivation) have great influence on biomass productivity
	[43]	Raceway cultivation is significantly more sustainable than closed air-lift tubular bioreactors
	[44]	90 % of energy consumption is dedicated to lipid extraction
Biogas	[45]	Macroalgae biomethane from fresh algae is interesting from an environmental point of view
	[46]	Electricity consumption strongly correlates with environmental impact
	[47]	Biomass production is the most energy intensive process
Biogas + bio-ethanol	[48]	Producing biogas alone has a better environmental performance on all impact categories than biogas + bioethanol

AquaFUELS [52] gives an overview of the critique that has been expressed towards algal LCAs. The critique mostly focuses on the fact that the algal industry is a young industry and that LCAs cannot provide a holistic view of the environmental impact situation. In addition, the LCA studies refer to each other’s findings, lowering the credibility even further.

3.3 INDUSTRIAL ACTIVITY

The internet search for companies active in the algal business area was based on the lists of the algal industry information support resources Planktoleum [49] and Oilgae [50] and showed that the number of companies has increased since these lists were compiled. When searching for companies mentioning biofuel, it was difficult to judge from many of the company websites whether the companies are presently active, to what extent they are active, or if they have closed down. Some pages are several years old and all are naturally written to show the best side of each company. Many of them mention algal biofuels, but may not directly produce any themselves (such as airline companies). Instead they finance e.g. producing equipment for algal cultivation, or offer their support in other ways. These companies were, nevertheless, included in the matrix. It is also difficult to get an overall picture of the total amounts of biofuels actually produced. The algal species and specific source of nutrients used are also unclear in many cases. No company mentions the energy consumption in detail and few companies refer directly to scientifically published results.

A map of the algal industry in the US (Figure 1) was recently published by the Algae Biomass Organization (ABO). ABO, focusing on activities in the US, reports that out of 470 algal industry contacts, more than 67% plan to expand in 2013. The percentage of these contacts that are biofuel focused has not been investigated in our report based on this map, but ABO claims that 95% of the contacts believe that algae-based fuels may be able to compete with fossil fuels as soon as 2020.

Figure 1. ABO map of algae companies in the US [53].

A similar organization in Europe is the EAEA (European Algae Biomass Association), based in Italy. It has a number of industries, universities and research insitutes as members listed on their website [54]. Neste Oil is presently the only member company from the Nordic countries (see also section 3.3.1). Member companies not included in our matrix, but that mention biofuel activities in their homepage), include AER Bio (Ireland), AlgaEnergy (Spain), A4f Algafuel (Portugal), BDI-Bioenergy International AG (Austria), Bioalgostral (France), Bio-Oils Energy (Spain), Ecoduna (Austria), Elin Biofuels (Greece), Fermentalg (France), Oxem SPA (Italy), Phytolutions (Germany) and Repsol (Spain). Whether these companies actually produce biofuels is not clear. The countries and number of companies found that are possibly involved in biofuel production from algal activeties are summarized in Table 6. The dominance of companies developed in the US is very clear.

Table 6. Countries and number of companies found in these countries working with algae biofuels.

Country	No. of companies	Country	No. of companies
USA	28	Denmark	1
Spain	3	Great Britain	1
Australia	3	Finland	1
Austria	2	Israel	1
France	2	Portugal	1
Germany	2	Malaysia	1
Italy	2	Argentina	1
Canada	2	India	1
Ireland	1	Greece	1
Switzerland	1	New Zeeland	1
The Netherlands	1	Japan	1

3.3.1 Industrial algal activities in the Nordic countries

In the Nordic countries, there is so far little industrial activities regarding algae and most existing activities are not towards biofuel production at all. However, some large international companies have started biofuel activities. Neste Oil in Finland has efforts aiming at using algal oil as raw material for biodiesel production and is also currently doing this in a joint research program with the Finnish Environment Institute (SYKE) to evaluate lipid quality, production capacity and optimization. In Norway, several companies work with production of omega-3 fatty acids from microalgae for the aquaculture industry, and there are also some companies constructing algal cultivation systems. In addition, Statoil investigates the use of seaweed biomass for biofuel production. The industrial algal activities are still modest in Sweden. No company or institute is currently involved with R&D or production of biofuels, but a few existing businesses produce high value products from microalgae (AstaReal AB, Simris Alg AB), fodder (Ostrea AB), and use macroalgae for the baking of hard bread and for beauty treatments in spas.

3.4 RESEARCH INITIATIVES

During the last years, interest in algal research has increased dramatically because of the potential to achieve sustainable production processes when using algae. This is reflected in the on-going research activities. From the articles included in our description of the technical state of the art, it can be summarized that the authors are affiliated to Asia, North America, Europe, Africa and Oceania.

Table 7 provides an overview of the specific countries. In the cases where an article is written by authors from more than one country, all countries are counted for once.

Table 7. Overview of affiliated countries for authors of the technical algae biofuel articles.

Country	No. of articles	Country	No. of articles
South Korea	5	Germany	1
USA	4	Belgium	1
China	3	Algeria	1
France	3	Australia	1
Taiwan	2	Portugal	1
Spain	2	Malaysia	1
India	1	Germany	1

Regarding other research initiatives, we have, in this report, focused on describing research and development activities in the Nordic countries [51], even if there are large activities in Asia, the US, and other parts of Europe. Activities in respective countries are described below.

3.4.1 Sweden

There is a solid base of fundamental biological research on algae in Sweden, at several universities and research stations. This knowledge can now be used, when the biotechnology research is moving into the algal area. The main focus is on microalgae, even though there are some recently started initiatives for macroalgal biotechnology.

Algal biofuels research activities in Sweden include the following:

- The Industrial Biotechnology group at Chalmers University of Technology focus on bioethanol production with yeast, using sugars for the fermentation from lignocellulosic material and lately also from algal biomass. The algae used are both marine, freshwater algae consortia grown at SLU (see below) and seaweed.
- SP Technical Research Institute of Sweden studies algal biofuels within the competence platform SP Biofuels, focusing on all kinds of liquid and gaseous biofuels with a main focus on biodiesel, SP performs tests in lab and field scale and leads a test site project with algae culturing at a pulp- and paper industry in Bäckhammar for production of biooilthat might be suitable for biofuels.
- KTH Royal Institute of Technology studiesbiobuthanol production in the form of 1-buthanol from metabolically engineered cyanobacteria and system sustainability assessments of biofuel production systems. Their studies include biogas and biodiesel production potential from microalgae and cyanobacteria.
- Mälardalen University studies the potential for biogas production together with The Swedish Institute of Agricultural and Environmental Engineering (JTI) in Uppsala. They

are investigation the methane production potential from algae biomass alone or in combination with other digestion components like sludge.

- Uppsala University studies the conversion of solar energy into biofuels with a strong focus on biohydrogen production of cyanobacteria and green algae. The research involves molecular and genetic tools to find new production pathways within the cells.

- Linnaeus University studies algal productivity with seasonal variation in lipid profiles and potential use of algae for biogas and biodiesel together with the cement industry. They are working with the capture of CO_2 in flue gas from the cement industry to enhance microalgae growth.

- Swedish University of Agricultural Sciences (SLU) studies the use of municipal waste and flue gas from waste incineration for production of algal biomass possibly used for biofuel production together with Umeå Energi, Umeva and Ragnsells.A pilot plant at the Umeå Energi test site, owned by Processum, was started in 2012 and consists of 4 raceway ponds (2 inside a greenhouse and 2 outdoors) where microalgae production is now being tested.

- The municipality of Trelleborg has led the recently finished the *Wetlands, Algae, Biogas - a Southern Baltic Sea Eutrophication Counteract Project* (WAB), with participants from around the South of the Baltic Sea. Trelleborg has evaluated the production of biogas from beach-cast filamentous macroalgae in a small pilot plant and has tested suitability of different types of machines for collecting the algae.

3.4.2 Norway

Norway has a solid algae-based industry for production of hydrocolloids, but there are also vast research activities especially in basic algal research. A lot of activities are devoted to the use of algae in the fish aquaculture, and for bioprospecting of high-value compounds. At the Norwegian University of Science and Technology (NTNU), several activities are related to microalgae for biofuels, including growing diatoms to use the silica frustules as material in solar cells, and optimized lipid accumulation in microalgae for biodiesel production. At NTNU research is also performed on Seaweed Biorefinery Systems (SBS) for multiproduct strategies, e.g. combined production of ethanol and biogas.

The Norwegian University of Life Sciences (UMB) collaborates with Bioforsk, the Norwegian Institute for Agricultural and Environmental Research, (both in Ås) regarding hydrogen production by green microalgae grown on flue gas.

3.4.3 Denmark

In Denmark, the research is to a large extent focused on macroalgae with extensive collaborations between actors in *e.g.* AlgaeCenter Denmark and a Danish interest network for macroalgae.

On the Risø site of Technical University of Denmark (DTU), there are research activities on improving lipid content and growth in microalgae by mutagenesis and altering growth conditions for biodiesel production as well as on biogas production from biomass, including macroalgae.

Aarhus University is working on cultivation of brown macroalgae for remediation and biomass production, which will be evaluated for production of *e.g.* biogas, ethanol, and butanol. The Danish Technological Institute (DTI, Aarhus) is leading the MAB3 project [55], with Aarhus University as a partner, aiming at converting brown macroalgae to other biofuels (ethanol, biogas, butanol).

The main work is on cultivation facilities, harvesting, handling, and conditioning of the biomass. DTI and Aarshus University have also additional projects working on biogas from macroalgae and have worked on converting green macroalgae to ethanol, biogas and solid biofuel.

The Kattegat center (Grenaa) has a recirculation system to cultivate macroalgae in tanks to be used *e.g.* for sustainable energy production.

Lolland Energy Holding (LOKE), a Danish holding company managed by the local authority of Lolland Municipality, has many activities in the fields of renewable energy and sustainable development, including algae to biofuels research.

3.4.4 Finland

The Finnish activities are mainly on microalgae with a few actors. At the Finnish Environment Institute (SYKE) there are several projects examining the potential use of algal biomass for energy production. These projects evaluate the potential of macroalgal cultivation in the northern Baltic Sea for producing biomass for *e.g.* bioenergy (biodiesel, biogas) and removing excess nutrients. The projects provide information on lipid production of Baltic planktonic algal species, biological foundations of algal lipid production, microalgal biomass harvesting techniques and techno-economic modeling of biofuel production from microalgal biomass.

VTT Technical Research Center of Finland is looking into using fatty acids from algae as feedstock for biodiesel, *e.g.* by screening known and new species, and to produce volatile hydrocarbon fuels by engineered cyanobacteria.

In University of Turku, work is carried out on transforming algal oils to biodiesel and to better understand the photosynthesis, in order to be able to increase the photon conversion efficiency and thereby optimize hydrogen production in cyanobacteria.

4 CONCLUSIONS

Globally there are a lot of both industry and academic activities being performed on production of biofuels from algae, mainly with focus on biodiesel. However, looking at the Nordic arena there are a lot less activities regarding algae and most existing industry activities are not towards biofuel production at all. Nevertheless, an increase can be seen. In Sweden, recent studies suggest that farming and processing of both micro- and macro algae has a great potential to establish itself as a thriving new industry and innovative business.

Algal biofuel research focuses mainly on micro algae, with most species under investigation being part of the Chlorophyta phylum. Chlorella is the most studied genus, ans also the genus used for production of all main biofuels. A variety of cultivation systems have been studied. The number of life cycle assessment studies has increased significantly in the past years. The studies arrive at different conclusions, mostly because they study different functions and apply different system boundaries. Researchers agree that energy efficiency is crucial for a sustainable fuel production, but they point to different parts of the process (cultivation, extraction, transportation, combustion) as the energy bottleneck.

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APPENDIX A. OVERVIEW OF THE ALGAL STUDIES

No.[1]	Title	Authors	Country (authors)	Year	Purpose of the study	Fuel
[2]	A process for biodiesel production involving the heterotrophic fermentation of *Chlorella protothecoides* with glycerol as the carbon source	Cerón-García, M.C., et al.	Spain	2013	Evaluate the potential of the algae as producer of saponifiable oil using glycerol as the main carbon source in the culture medium.	Biodiesel
[3]	Cultivation of *Chlorella vulgaris* on wastewater containing high levels of ammonia for biodiesel production	He, P.J., et al.	China, Taiwan	2013	Examine the feasibility of cultivating *Chlorella vulgaris* with wastewater containing high ammonia nitrogen concentrations.	Biodiesel
[4]	Microwave-mediated non-catalytic transesterification of algal biomass under supercritical ethanol conditions	Patil, P.D., et al.	U.S.A.	2013	Explore the potential of the process microwave-mediated non-catalytic transesterification	Biodiesel
[5]	Production of algal biodiesel from marine macroalgae *Enteromorpha compressa* by two step process: Optimization and kinetic study	Suganya, T., et al.	India	2013	Produce biodiesel from *E. compressa* algal oil by conventional methods catalyzed by homogeneous catalyst.	Biodiesel
[6]	Culture aspects of *Isochrysis galbana* for biodiesel production	Sánchez, Á., et al.	Spain	2013	Explore the potential of biodiesel production from the microalgae *Isochrysis galbana*	Biodiesel
[7]	A new Arctic Chlorella species for biodiesel production	Ahn, J.-W., et al.	South Korea	2012	Evaluate the potential of ArM0029B as a source of biodiesel	Biodiesel
[8]	Enhanced mixotrophic growth of microalga *Chlorella* sp. on pretreated swine manure for simultaneous biofuel feedstock production and nutrient removal	Hu, B., et al.	U.S.A	2012	Assess the usage of fermented liquid swine manure as nutrient supplement for cultivation of Chlorella sp. UMN271, and evaluate the nutrient removal efficiencies by alga compared with those from the conventionally decomposed LSM–algae system	Biodiesel
[9]	Direct lipid extraction from wet Chlamydomonas reinhardtii biomass using osmotic shock	Yoo, G., et al.	South Korea	2012	Exploring a novel approach using osmotic shock for microalgal cell disruption aiming to wet lipid extraction	Biodiesel
[10]	Isolation of a novel strain of Monoraphidium sp. and characterization of its potential application as biodiesel feedstock	Yu, X., et al.	China	2012	Explore the biodiesel production potential of a novel algae strain	Biodiesel
[11]	Lipid accumulation and growth characteristics of Chlorella zofingiensis under different nitrate and phosphate concentrations	Feng, P., et al.	China, U.S.A	2012	Find the potential of C. zofingiensis in photoautrophic cultivation for producing biodiesel feedstock (indoors and outdoors)	Biodiesel
[12]	Growing wastewater-born microalga Auxenochlorella protothecoides UMN280 on concentrated municipal wastewater for simultaneous nutrient removal and energy feedstock production	Zhou, W., et al.	U.S.A	2012	Identify robust algal strains, the nutriend removal efficiency, and biomass productivity	Biodiesel
[13]	Batch and semi-continuous anaerobic digestion of *Palmaria palmata* : Comparison with *Saccharina latissima* and inhibition studies	Jard, G., et al.	France	2012	Investigate Palmaria palmata and compare it to Saccharina latissima for biogas production	Biogas
[14]	Methane production from glycolate excreting algae as a new concept in the production of biofuels	Günther, A., et al.	Germany	2012	Introduce concept for methane production by the interaction of a glycolate-excreting alga and methanogenic microbes operating in separate compartments within one photobioreactor	Biogas
[15]	Carbon conversion efficiency and population dynamics of a marine algae-bacteria consortium growing on simplified synthetic digestate: First step in a bioprocess coupling algal production and anaerobic digestion	Vasseur, C., et al.	France	2012	Explore the potential of natural assemblages of marine microbial consortia to produce high biomass when coupled with an anaerobic digester	Biogas
[16]	The techno-economic potential of renewable energy through the anaerobic digestion of microalgae	Zamalloa, C., et al.	Belgium	2011	Evaluate the potential of microalgae as feedstock for methane production from a process technical and economic point of view	Biogas

[1] Study No's refer to reference list.

[17]	Fermentative hydrogen production by *Clostridium butyricum* CGS5 using carbohydrate-rich microalgal biomass as feedstock	Liu, C.-H., et al.	Taiwan	2012	Explore the potential of the alga C. vulgaris for fermentative production of hydrogen	Biohydrogen
[18]	Feasibility of biohydrogen production from *Gelidium amansii*	Park, J.-H., et al.	South Korea	2011	Investigate the feasibility of hydrogen production from red algae	Biohydrogen
[19]	Biohydrogen production by immobilized *Chlorella* sp. using cycles of oxygenic photosynthesis and anaerobiosis	Song, W., et al.	South Korea	2011	Investigate the feasibility of electricity generation from green microalgae and assess the effectiveness of a photobioreactor coupling to a fuel cell	Biohydrogen
[20]	Biohydrogen production using green microalgae as an approach to operate a small proton exchange membrane fuel cell	Chader, S., et al.	Algeria, France	2011	Explore the use of an immobilized cell system for rendering condition changes more rapidly and convenient	Biohydrogen
[21]	Pretreatment of Laminaria japonica for bioethanol production with extremely low acid concentration	Lee, J.Y., et al.	South Korea	2012	Optimize the hydrothermal pretreatment conditions for L. japonica, using extremely low acid to significantly improve glucan content	Bioethanol
[22]	Exploring alkaline pre-treatment of microalgal biomass for bioethanol production	Harun, R., et al.	Australia, Malaysia	2011	Exploring alkaline pre-treatment of microalgal biomass for bioethanol production	Bioethanol
[23]	Nutrient limitation as a strategy for increasing starch accumulation in microalgae	Dragone, G., et al.	Portugal	2011	Evaluate starch accumulation in Chlorella vulgaris P12 under different initial concentrations of nitrogen and iron sources, using a central composite design (CCD) for two factors	Bioethanol
[24]	Converting Carbohydrates Extracted from Marine Algae into Ethanol Using Various Ethanolic Escherichia coli Strains	Lee, S., et al.	South Korea	2011	Explore the possibility of utilizing structural carbohydrates from marine algae for bioethanol production	Bioethanol
[25]	The Production of Butanol from Jamaica Bay Macro Algae	Potts, T., et al.	U.S.A.	2012	Ascertain the technical potential of producing biofuel from algae that naturally grows in nutrient contaminated rivers, lakes, and bays	Biobutanol

APPENDIX B. PRODUCTION METHODS OF THE ALGAL STUDIES

Year	Study No.[2]	Fuel	Cultivation										Harvesting method	Extraction	Further Processing
			Location (Collected)	Algae type			Cultivation size	System	Nutrition		Light	Temp. (°C)			
				Size	Water	Latin name		Type	Content	Source					
2013	**[2]**	Biodiesel		Micro		*Chlorella protothecoides*	2-L glass stirred-tank bioreactor		KH2PO4 (0.7 g L−1), K2HPO4 (0.3 g L−1), vitamin B1 (0.01 g L−1), MgSO4·7H2O (0.3 g L−1), FeSO4·7H2O (3 mg L−1), glycine (0.1 g L−1), yeast extract (4 g L−1), A5 trace mineral solution (1 mL L−1) and a carbon source (10 g L−1 of glycerol).		Philips TLD 36 W/54 fluorescent lamps	28			Direct transesteri-fication
2013	**[3]**	Biodiesel		Micro	Fresh	*Chlorella Vulgaris*		Tubular photobio-reactors	TN, NO3−-N, NO2−-N, NH4+-N, COD, BOD, TOC, TP	Waste water	8000– 10000 lux LED lights	27 ± 1	Centrifugation, washing with deionized water, drying	Pigment in the cell pellet extracted with methanol	
2013	**[4]**	Biodiesel		Micro		*Nannochlor-opsis salina*								Microwave-assisted super-critical transesteri-fication	
2013	**[5]**	Biodiesel	Gulf of Mannar, India	Macro	Saline	*Enteromorpha compressa*							Drying	Soxhlet extraction	Transesteri-fication
2013	**[6]**	Biodiesel		Micro	Saline	*Isochrysis galbana*	1.25 × 107 cells/mL conc.	Methacrylate pond (open)	Fe, Mn, Co, Zn, Cu, Mb, N, PO32-, Vitamin B1 and B12, Biotin	Purchased	Philips TLD 965 36 W daylight-type fluorescent lamps		Flocculation and coagulation with AlCl3, followed by vacuum filtration and drying	Hexane mixed with the dried ground algae. Accomplished using Soxhlet method	
2012	**[7]**	Biodiesel		Micro	Saline	*Chlorella sp.*			TAP Medium		White light (40 µmol m−2 s−1).	4, 15, and 25			
2012	**[8]**	Biodiesel		Micro		*Chlorella sp.*		Erlenmeyer flasks	pH, NH3-N, TN, phosphatPO4-P, COD	Fermented liquid swine manure	Cool-white fluorescent light illumina-tion at 100 µmol m−2	25 ± 2		Centrifugation	

[2] Study No's refer to reference list.

											s−1				
2012	**[9]**	Biodiesel		Micro		*Chlamydomo-nas reinhardtii*		Flasks	TAP Medium		Fluorescent tubes (500 µmol m−2 s−1)	25	Concentration through gravity	Osmotic shock	
2012	**[10]**	Biodiesel		Micro	Fresh	*Monoraphidium sp.*		Flasks			White fluores-cent lamps (70 µE m−2 s−1)	25	Centrifugation, freeze drying	Chloroform / methanol blending	Esterification
2012	**[11]**	Biodiesel		Micro		*Chlorella zofingiensis*		Plate photo-bioreactors indoors + bottles outdoors	BG-11 medium	C sources: Na_2CO_3 (20 mg L−1 in BG-11) + CO_2 presented in the air	Indoors: fluorescent light (100 ± 2 µmol m−2 s−1)	Indoors: 25	Filtering, drying		
2012	**[12]**	Biodiesel		Micro	Fresh	*Auxenochlorella protothecoides*	COD, TOC, TVSS, No3-N, Al, Fe, Mg, Na	BIOCOIL reactor		Waste water					
2012	**[13]**	Biogas	Lézardrieux, France	Macro	Saline	*Palmaria palmata* and *Saccharina latissima*			Urea, NPKS				Drying		Both batch and semi-continuous reactors
2012	**[14]**	Biogas		Micro		*Chlamydomo-nas reinhardtii*		Air-lift culture	Kuhl-medium			20	No production and harvesting of cellular bio-mass, but con-vertion of cells into glycolate producing units		Glycolate re-fined into methane by methanoge-nic bacteria under an-aerobic conditions
2012	**[15]**	Biogas		Micro	Saline	*Nannochloris spp*	7.3×10^6 cell mL−1	Photo-bioreactor	Modified Conway medium. PO_4^{3-}, NH_4^+, acetate		OSRAM L18W/954 daylight fluorescent tubes	19-35			
2011	**[16]**	Biogas		Micro			0.2–0.5 g DM L−1	Raceway pond (open)					Flocculation, dewatering		Upflow anae-robic sludge blanket reac-tors, anae-robic filter reactors, and anaerobic membrane bioreactors

2012	**[17]**	Bio-hydrogen		Micro	Fresh	*Chlorella vulgaris*			Bold's basal medium[1]		Fluorescent lamps (light intensity = 125 μmol/m2/s)	Room temp.	Centrifugation	Hydrolysis	C. butyricum CGS5 utilizes reducing sugars from *C. Vulgaris* ESP6 biomass to produce H2
2011	**[18]**	Bio-hydrogen	Littoral zone in Morocco	Macro	Saline	*Gelidium amansii*							Drying	Hydrolysis	Hydrogen fermentation conducted in a 7-L fermentor
2011	**[19]**	Bio-hydrogen		Micro	Fresh	*Chlorella sp.*	1 L.	Conicalended cylindrical glass reactor	MA medium		White fluorescent light at 120 μmol/m2/s	25	Centrifugation, washing, resuspended in medium, solidified		Photoauto-trophic incu-bation, medi-um replaced by sulfur-deprived MA medium (S-medium) for H2 produc-tion
2011	**[20]**	Bio-hydrogen		Micro		*Chlorella sorokiniana*			Tris-Acetate- Phosphate (TAP) solid medium		Cool white fluorescence lamps (∼100 photon m−2 s−1)		Centrifugation, washing, re-suspention in same medium		Photobioreac tor coupled with a small PEM Fuel Cell
2012	**[21]**	Bio-ethanol		Macro	Saline	*Laminaria japonica*							Drying	Hydrolysis	
2011	**[22]**	Bio-ethanol		Micro		*Chlorococcum infusionum*							Centrifugation, drying	NaOH for relea-sing and breaking down entrapped polysaccharides in algae cell walls into fermentable subunits	Fermentation in flasks
2011	**[23]**	Bio-ethanol		Micro	Fresh	*Chlorella vulgaris*	2 _ 107 cells mL 1	Glass bubble columns photo-bioreactors			Fluorescent lamps (Sylva-nia Std F18 W) (irradiant-ce level of 70 μmol m−2 s−1)	30	Centrifugation, drying		
2011	**[24]**	Bio-ethanol		Macro Micro	 Saline	*Undria* *Chlorella*									Fermentation

					Fresh	*vulgaris* *Chlamydomonas reinharditii*									
2012	**[25]**	Bio-butanol	Jamaica Bay, New York City	Macro	Saline	*Ulva lactura*							Manual and mechanical, drying	Hydrolysis with dilute acid	ABE fermentation, butanol removed by destillation

[1] Bold's basal medium: (g/L): NaHCO3, 6.72; NH4HCO3, 5.24; K2HPO4, 0.125; MgCl2・6H2O, 0.1; MnSO4・6H2O, 0.015; FeSO4・7H2O, 0.025; CuSO4・5H2O, 0.005; CoCl2・5H2O, 1.25 _ 10_4; thioglycolate, 0.5; Lcystein, 0.5; Resazurin-2127, 0.001.

APPENDIX C. RESULT OF THE ALGAL STUDIES

Year	Study No.[3]	Fuel	Results		
			Fuel production	**Energy yield**	**General findings**
2013	**[2]**	Biodiesel			Achieved very high biomass yields. Proposal of process for obtaining biodiesel by transesterification of wet biomass paste.
2013	**[3]**	Biodiesel			Product quality can be manipulated by NH4+-N concentrations of the initial feeds.
2013	**[4]**	Biodiesel			Extraction improved significantly (higher efficiency, reduced extractive-transesterification time, increased FAEE yield, extracts free of harmful solvent residues, may reduce energy consumption and cost of the process).
2013	**[5]**	Biodiesel	Maximum biodiesel yield 90.6%		*E. compressa* could be used to produce biodiesel. Maximum yield is achieved with optimum parameters of base transesterification using NaOH.
2013	**[6]**	Biodiesel			From an initial amount of 10 L of inoculum and 1.25 × 107 cells/mL, a culture of 115 L with 7 × 106 cells/mL was obtained after 23 days. The best harvest shows a biomass concentration of 0.305 g/L with a FAME content of 12.5%.
2012	**[7]**	Biodiesel			The algae can be cultured cost-effectively for biodiesel production without temperature control, especially in a cold climate.
2012	**[8]**	Biodiesel			*Chlorella sp*. grown on acidogenically digested manure could be used as a feedstock for high quality biodiesel production.
2012	**[9]**	Biodiesel			Osmotic shock could increase lipid recovery approximately 2 times.
2012	**[10]**	Biodiesel			The algae have potential as a biodiesel feedstock. Cellular lipid content was 56.8% growing under autotrophic condition. Lipid productivity of heterotrophic microalgae was higher than autotrophic.
2012	**[11]**	Biodiesel			*C. zofingiensis* is promising for feedstock production of biofuel and can be used in scaled up culture outdoors
2012	**[12]**	Biodiesel			Maximal removal efficiencies for total N, total P, COD and TOC were over 59%, 81%, 88% and 96%, respectively.
2012	**[13]**	Biogas			*P. palmata* is more suitable for anaerobic digestion than Laminaria saccharina due to its composition in cations
2012	**[14]**	Biogas		Maximum annual net energy gain of 240 GJ per hectare	Glycolate fermentation has several synergistic advantages: higher bio-methane production compared to biofermentation of biomass, decreased energetic costs for harvesting, extraction and refinement, limited need of nutrients, and no heavy hardware requirement
2012	**[15]**	Biogas			Maximal growth rate (0.72 days−1) and maximal cell abundance (70.2 × 106 Cell mL−1) observed in the study were greater than previously observed with marine microalgae. Carbon conversion efficiency was 4%, 6.3% when bacteria were included into the carbon budget (bacteria recycled the carbon lost during photosynthesis and originated from anaerobic digestion).
2011	**[16]**	Biogas		The best scenario utilizes 18% of the electric energy and 46% of the thermal energy produced	Use of high rate anaerobic digesters reaching 10–20 kg COD m−3 d−1, productivities of minimum 90 ton DM ha−1 a−1 and a percentage VS fermented of 75% is technically crucial. Economically, a feed-in tariff of €0.133 kWh−1, rewarding thermal and electrical energy on an equal basis, is crucial, in contrast to the carbon credit of €30 ton−1CO2(eq), (delivers only 4% of the revenues)
2012	**[17]**	Biohydrogen	Under optimal conditions, the cumulative hydrogen production, production rate, and yield are 1476 ml/L, 246 ml/L/h, and 1.15 mol/mol RS, respectively		The optimal conditions for hydrogen production are 37 °C, hydrolysate loading of 9 g RS/L and pHcontrol at 5.5.

[3] Study No's refer to reference list.

2011	**[18]**	Biohydrogen	When hydrolyzed and detoxified, 1 g of dry algae would be converted to 53.5 mL of hydrogen		Red algae can be a suitable substrate for dark hydrogen fermentation.
2011	**[19]**	Biohydrogen			Immobilized *Chlorella* cells can produce H2 by utilizing both endogenous carbohydrate storage and externally added glucose under anaerobic and sulfur-deprived condition. Addition of glucose enhances H2 production. Lag time shortens and rate of H2 production increases at temperature increase from 25 to 42 °C.
2011	**[20]**	Biohydrogen			*C. sorokiniana* strain Ce culture produces a high amount of biohydrogen under sulfur-deprived conditions. H2 content in the mixture gas injected in Proton Exchange Membrane Fuel Cell has been converted in electricity. This fuel cell is successfully operated using the produced biohydrogen with similar response as with pure H2 under standard conditions.
2012	**[21]**	Bioethanol			Maximum glucan content of 29.09%, (4* higher than that of the raw *L. japonica)* was obtained.
2011	**[22]**	Bioethanol	Maximum bioethanol yield obtained was 26.1% g ethanol/g algae for alkaline pre-treatment under 0.75% (w/v) NaOH and 120 °C for 30 min		
2011	**[23]**	Bioethanol			Starch content reached up to 41.0% of dry cell weight
2011	**[24]**	Bioethanol	The maximum yield of bioethanol, 0.4 g ethanol/g biomass, was achieved with pretreated *C. vulgaris* and *E. coli* SJL2526, derived from wild-type E. coli W3110 and which includes the adhB, pdc, galP, and glk genes		
2012	**[25]**	Biobutanol	Butanol concentration in the fermentation broth reaches about 4 g/L. Recovery of grams of butanol from grams of reducing sugars in the media was 29%		Butanol may be made on a pilot scale from algal sugars

APPENDIX D. OVERVIEW OF THE LIFE CYCLE ASSESSMENT STUDIES

Study No.[4]	Title	Authors	Country (authors)	Year	Purpose of the study	Fuel
[26]	Life cycle assessment of biodiesel production in China	Liang, S., et al.	U.S.A.	2013	Evaluate energy, economic, and environ-mental performances of 7 categories of biodiesel feedstocks by using mixed-unit input–output LCA	Biodiesel
[27]	Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae	Frank, E.D., et al.	U.S.A.	2013	Explore the tradeoffs between the benefits and challenges in the hydrothermal liquefaction pathway compared to a lipid extraction pathway	Biodiesel
[28]	Life-cycle and techno-economic analysis of utility-connected algae systems	Rickman, M., et al.	U.S.A.	2012	Assess the feasibility of different algae processing systems from lifecycle and technoeconomic standpoints, in order to guide future research and development	Biodiesel
[29]	Life Cycle Assessment of Biodiesel Production from Microalgae in Thailand: Energy Efficiency and Global Warming Impact Reduction	Wibul, P., et al.	Thailand	2012	Perform an LCA of biodiesel production from microalgae in Thailand based on ISO 14040 in order to evaluate the ener-gy efficiency and environmental impact of microalgae-based biodiesel	Biodiesel
[30]	Integrating LCA and Thermodynamic Analysis for Sustainability Assessment of Algal Bio-fuels: Comparison of Renewable Diesel vs. Biodiesel	Borkowski, M.G., et al.	U.S.A.	2012	Compare the life-cycle impacts of renewable diesel production to those for biodiesel production.	Renewable diesel II (RD2) or biodiesel
[31]	Microalgal biodiesel and the Renewable Fuel Standard's greenhouse gas requirement	Soratana, K., et al.	U.S.A.	2012	Conduct a comparative LCA on 4 condi-tions of microalgal biodiesel productions to evaluate their potential to meet the RFS2 and then to identify processes or inputs that could be targeted to minimize the overall environmental impact of microalgal biodiesel production	Biodiesel
[32]	Energy analysis and environmental impacts of microalgal biodiesel in China	Yanfen, L., et al.	China	2012	Identify the energy requirements and en-vironmental impact loading of microalgal biodiesel, and to seek ways to reduce energy consumption	Biodiesel
[33]	Reduction of environmental and energy footprint of microalgal biodiesel production through material and energy integration	Chowdhury, R., et al..	U.S.A.	2012	Seek to understand the effects of algal lipid content on life-cycle GWP as well as energy and water demand	Biodiesel
[34]	Life cycle assessment of biodiesel from soybean, jatropha and microalgae in China conditions	Hou, J., et al.	China	2011	Quantify and compare the environment-tal impacts by producing and driving with biodiesel derived from soybean oil, jatropha oil, and microalgal oil in China conditions	Biodiesel
[35]	Life cycle energy and CO2 analysis of microalgae-to-biodiesel: Preliminary results and comparisons	Khoo, H.H., et al.	Singapore	2011	Compare life cycle energy and life cycle CO2 of various biofuel production technologies from ‘cradle to gate’	Biodiesel
[36]	Life cycle assessment of biodiesel production from microalgae in ponds	Campbell, P.K., et al.	Australia	2011	Analyse the potential environmental im-pacts and economic viability of produ-cing biodiesel from microalgae grown in ponds	Biodiesel
[37]	Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance	Yang, J., et al.	U.S.A.	2011	Examine the water footprint of biodiesel production using microalgae as the feed-stock.	Biodiesel
[38]	Combinatorial Life Cycle Assessment to Inform Process Design of Industrial Production of Algal Biodiesel	Brentner, L. B., et al	U.S.A.	2011	Compare various methods, either proposed or under development, for algal biodiesel to inform the most promising pathways for sustainable full-scale production.	Biodiesel

[4] Study No’s refer to reference list.

[39]	Life Cycle Assessment of Third Generation Biofuels Production	Pardo, Y., et al.	Colombia	2010	Evaluate the environmental sustainability of the biodiesel production from microalgae oil.	Biodiesel
[40]	Life cycle analysis of algae biodiesel	Sander, K. & Murthy, G.S.	U.S.A.	2010	Establish baseline information for the pro-cess of making algal biodiesel, to which other transportation fuel LCA's can be compared.	Biodiesel
[41]	Net Energy and Green-house Gas Emission Eva-luation of Biodiesel Derived from Microalgae	Batan, L., et al.	U.S.A.	2010	Evaluate the net energy ratio (NER) and net greenhouse gas emissions (GHGs) of microalgae biodiesel in comparison to petroleum diesel and soybean-based biodiesel	Biodiesel
[42]	Sustainable Algae Biodiesel Production in Cold Climates	Powers, S.E. & Baliga, R.	U.S.A.	2010	Determine the most suitable operating conditions for algae biodiesel production in cold climates to minimize energy consumption and environmental impacts	Biodiesel
[43]	Life-Cycle Assessment of Potential Algal Biodiesel Pro-duction in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors	Stephenson, A.L., et al.	U.K.	2010	Compare hypothetical operations in either raceways or tubular photobioreactors.	Biodiesel
[44]	Life-Cycle Assessment of Bio-diesel Production from Micro-algae	Lardon, L., et al.	France	2009	Assess the environmental impacts of bio-diesel production from microalgae.	Biodiesel
[45]	Life cycle assessment of bio-methane from offshore-cultivated seaweed	Langlois, J., et al.	France	2012	Assess if aquacultured seaweed (macro-algae) could be considered an environment-ally friendly source of biomass for bioenergy.	Biomethane
[46]	Life-cycle assessment of microalgae culture coupled to biogas production	Collet, P., et al.	France	2011	Undertake an environmental assessment of the use of methane from algae as a biofuel.	Biogas
[47]	The analysis on energy and environmental impacts of microalgae-based fuel methanol in China	Liu, J. & Ma, X.	China	2009	Study the energy analysis and environ-mental impacts of the microalgae-based methanol in its whole life.	Biomethanol
[48]	Life cycle assessment of bio-fuel production from brown seaweed in Nordic conditions	Alvarado-Morales, M., et al.	Denmark	2013	Assess the potential environmental impacts and perform an energy analysis of sea-weedbased biofuels, as well as identify hotspots in the life cycle where the environ-mental performance of the system can be improved.	Biogas + Bioethanol

APPENDIX E. PRODUCTION METHOD IN THE LIFE CYCLE ASSESSMENT STUDIES

			Cultivation											
				Algae type			Culti-vation size	System	Nutrition					
Year	**Study No.**[5]	**Fuel**	Location (Collected)	Size	Water	Latin name		Type (O=Open, C=Closed)	Content	Source	Light	**Harvesting method**	**Extraction**	**Further Processing**
2013	**[26]**	Biodiesel												
2013	**[27]**	Biodiesel						Pond (O)	NH3, DAP, flue gas			Dewatering by settling, dissolved-air flotation (DAF), and centrifugation	Hydrothermal liquefaction or lipid extraction	
2012	**[28]**	Biodiesel						Raceway pond (O)	flue gas, CO_2, and fertilizers	Power plant		Dewatering via floccu-lation, centrifugation	Hexane extraction	Transesterification
2012	**[29]**	Biodiesel		Micro	Fresh	*Scenedesmus armatus*						Centrifugation, drying	Hexane extraction, evaporation	Transesterification
2012	**[30]**	Renew-able diesel II (RD2) or biodiesel						Pond (O)	Synthetic fertilizers and CO_2			Flocculation, drying	Hexane extraction	Hydrogenation and decarboxylation, or transesterification
2012	**[31]**	Biodiesel		Micro				Photobioreactor (C)	HDPE, freshwater, wastewater, urea, N in wastewater, P in wastewater, super-phosphate, potas-sium chloride, Syn-thetic CO_2, CO_2 in flue gas, NaOH	Power plant, municipal waste water	CFL, 15W	Flocculation, drying	Hexane extraction	Transesterification
2012	**[32]**	Biodiesel	Waterfront cities in South China	Micro		*Chlorella vulgaris*		Tubular photo-bioreactor	Exhaust CO_2, N, P, K	Gas fired power plant		Sedimentation and centrifugation, flocculation	Homogenization, hexane extraction	Anaerobic digestion, esterification
2012	**[33]**	Biodiesel		Micro		*Schizochy-trium limacinum*			NPK fertilizer			Dewatering, drying	Hexane extraction	Anaerobic digestion
2011	**[34]**	Biodiesel		Micro					N, P, K, CO_2					
2011	**[35]**	Biodiesel		Micro		*Nannochlo-ropsis sp*		Photobioreactor-raceway	N, P, Fe, Cu, Zn, Co, Mn, Mo			Dewatering	Recycable solvents (hexane and methanol)	Transesterification
2011	**[36]**	Biodiesel	Australia	Micro	Saline			Raceway pond				Flocculation		Transesterification

[5] Study No's refer to reference list.

2011	**[37]**	Biodiesel		Micro		*Chlorella vulgaris*		Pond (O)	N, P, K, Mg, S					Esterification
2011	**[38]**	Biodiesel	Phoenix, AZ	Micro	Fresh	*Scenedesmus dimorphus*		ORP, 3 PBRs (annular, inclined, tubular)	Ammonium nitrate, calcium phosphate	CO_2 sourced as a waste product from either a power or ammonia plant		Flocculation		3 different types of esterification, 1 supercritical methanol
2010	**[39]**	Biodiesel	Andina region, Columbia	Micro	Saline	*Chlorella vulgaris*								Trans-esterification
2010	**[40]**	Biodiesel						Photobioreactors/ indoor ponds, thereafter raceway pond				Centrifugation	Hexane extraction	
2010	**[41]**	Biodiesel	Temperate region of the U.S.A.	Micro	Saline	*Nannochloropsis salina*	91 000 kg ha-1	Photobioreactor	Fertilizer			Centrifugation, filtration	Heating, centrifugation	Methanol catalyst
2010	**[42]**	Biodiesel	Syracuse and Albany, NYC	Micro		*Phaeodactylum tricornutum*		Photobioreactor	N, P	CO_2 from fossil fuel or biomass power plant	High-efficiency fluorescent GRO lights (intensity : Lw=220 Lu/W)	Dewatering, drying	Hexane extraction	
2010	**[43]**	Biodiesel		Micro	Fresh	*Chlorella vulgaris*		Raceway, airlift tubular bioreactors	N, P	Flue gas from gas-fired power station		Flocculation	Hexane extraction	Anaerobic digestion
2009	**[44]**	Biodiesel		Micro		*Chlorella vulgaris*		Raceway pond				Flocculation	Either hexane extraction (after drying) or direct extraction from wet algal paste	Esterification
2012	**[45]**	Bio-methane		Macro	Saline	*Saccharina latisima*		Long-lines in costal environment, following plantlet production in a nursery (O)			Flourescent lamps	Drying		Anaerobic digestion
2011	**[46]**	Biogas	Southern Europe	Micro		*Chlorella vulgaris*	0.5 kg m^{-3}	Raceway pond (O)	C, N, P, K	Industry		Natural settling, spiral plate centrifugation		Anaerobic digestion
2009	**[47]**	Bio-methanol	Coastline in China	Micro								Sedimentation, centrifugation		Gasification
2013	**[48]**	Biogas + bio-methanol	Coastline in Denmark		Saline	*Laminaria digitata*		Long line (string) systems at open sea, preferably associated to a fish farm (O)						Anaerobic digestion and/or fermentation

APPENFIX F. RESULTS OF THE LIFE CYCLE ASSESSMENT STUDIES

			Results			LCA				
Year	**Study No.[6]**	**Fuel**	**Fuel production**	**Energy**	**General findings**	**Functional unit (FU)**	**System boundaries**	**Impact categories**	**GWP per FU**	**Energy per FU**
2013	**[26]**	Biodiesel		Less than life cycle energy demand	Algae is the preferred biodiesel feedstocks in the long term	0.2 million tons of biodiesel	The mixed-unit input–output LCA extends the sys-tem boundaries of traditional LCA	GWP, POCP, AP, EP, HTTP, FAETP, MAETP and TETP	2,756,614 ton CO_2-eq	40,276 Terajoule
2013	**[27]**	Biodiesel			The likely conclusion is that HTL will reduce biomass requirements, but it is possible that actual performance may give comparable requirements if the LE cellular disruption and extraction processes efficiencies were higher or if HTL yields were lower		Well to wheel	The GREET model		
2012	**[28]3**	Biodiesel			Localized strategies should be pursued to reduce the excessive energy requirements for longdistance CO_2 delivery. Furthermore, research should focus on improving the ability of growth reactors to efficiently utilize CO_2			GWP		
2012	**[29]**	Biodiesel		Net energy ratio: 0,34 and 0,19 for mass alloca-tion and energy allocation, respectively	CO_2 uptake in microalgae cultivation leads to better performance in GWP when compared to conventional diesel and biodiesel produced from rapeseed and soybean. On the other hand, algae biodiesel is the worst case for ADP, HTP and AP	1 MJ biodiesel	Well to pump	GWP, ADP, ODP, HTP, POD, AP, EP	0.012 and 0.021 kg CO2 eq. for mass allocation and energy allocation respectively	2.98 MJ for mass Allocation and 5.29 MJ for energy allocation
2012	**[30]**	Renewable diesel II (RD2) or biodiesel			While hydrotreating is less than half as energy in-tensive a fuel upgrade process as transesteri-fication, the overall life-cycle energy consumption and greenhouse gas emissions are found to be nearly equal for renewable diesel and biodiesel	1 MJ of delivered fuel	Well to pump	GWP, ADP	309 g CO_2-eq (both RD2 and diesel)	RD2: 5 MJ, diesel: 5,2 MJ
2012	**[31]**	Biodiesel			None of the assumed production conditions meet the Renewable Fuel Standard's GHG requirement. Decrease environmental impact: decrease energy consumption of the microstrainer and belt filter during the harvesting process, recycle hexane from the extraction process, and/or increasing of lipid content of microalgae	8.94×1010 MJ/ year of biodiesel or 0.67 billion gallon of biodiesel/year	Well to pump	GWP, EP, ODP, ETP, AP, CP, NCP, REP, Smog, NREU	kg CO_2 eq.: LS: $17.7x10^{10}$, HW: $6.9x10^{10}$, HS: $8.5x10^{10}$, LW: $1.2x10^{11}$	
2012	**[32]**	Biodiesel	3.1 t dry micro-algae needed to produce one unit of micro-algal biodiesel		1 MJ of biodiesel requires an input of 0.74 MJ of fossil energy and the GWP is 0.16 kg CO_2-eq. These are particularly sensitive to oil content, drying rate and esterification rate	1 t of microalgal biodiesel	Well to wheel	GW, AC, NE, PO, SA	0.16kgCO_2-eq/MJ	26000 MJ/ton

[6] Study No's refer to reference list.

2012	**[33]**	Biodiesel		NER: 0,41	Relative to stand-alone algal biofuel facilities, ener-gy demand can be lowered by 3–14 GJ per ton of biodiesel through process integration. GWP of bio-diesel from the integrated system can be lowered by up to 71% compared to petroleum fuel.		Well to pump	Energy demand, GWP, water demand		
2011	**[34]**	Biodiesel			Jatropha and microalgae are more competitive biodiesel feedstock compared to soybean in terms of all impacts (mainly a result of the lower level of agricultural inputs per unit of oil output)	1 MJ of energy from bio- and fossil diesel "well-towheel"	Well to wheel	ADP, GWP, ODP, POCP, AP, EP, HTP, FAETP, MAETP, TETP	1.6E-02 kg CO_2 eq.	
2011	**[35]**	Biodiesel			The main bottleneck for most systems lie in the energy intensive processes of lipid extraction, and next, biodiesel production	1 MJ biofuel	Cradle-to-gate	CO_2		4,44 MJ
2011	**[36]**	Biodiesel			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 (need of higher production rate)	The combustion of enough fuel in an articulated truck (AT; the most com-mon form of freight trans-port in Austra-lia) Diesel en-gine to trans-port one tonne of freight 1 km	Cradle-to-grave	GHG	18.2 to -27.6 g CO_2-e/t km	
2011	**[37]**	Biodiesel			Microalgae-based biofuels are competitive. But there is a necessity of recycling harvested water and using sea/wastewater as water source	The production of 1 kg of micro-algae-based biodiesel	Cradle to gate	Water and nutrients usage		
2011	**[38]**	Biodiesel		Slightly negative	The best case production system yields a cumul-ative energy demand savings of more than 65 GJ, and saves 86% GHG compared to early industrial practices	10 GJ Biodiesel	Cradle to gate	GHG) emissions, water use, eutrophication, direct land require-ments	805-5340 kg CO_2eq.	10800-78200 MJeq
2010	**[39]**	Biodiesel			The stage of distribution and use of the B10 blend (10% biodiesel) has the greatest influence in the impact categories studied	100.000 ton biodiesel /year		Climate change, AP, EP, POCP, respira-tory effects, non-renewable energy		
2010	**[40]**	Biogas		-6,7	Efficiency is crucial. Thermal algal dewatering requires high amounts of fossil fuel derived energy	1,000 MJ of energy from algal biodiesel using existing technology	Well to pump	CO2	135.7 and -20.9kg/ functional unit for a process utilizing a filter press and centrifuge, respectively	3,292 and 6,194 MJ for the pro-cess with filter press and centri-fuge as the initial filtering step, respectively
2010	**[41]**	Biodiesel		0.93 MJ of energy consumed per MJ of energy produced	Microalgae-based biofuels avoid 75 g of CO_2-equivalent emissions per MJ of energy produced. The scalability of the consumables and products of the proposed microalgae-to-biofuels processes are assessed in the context of 150 billion liters (40 billion gallons) of annual production	1 MJ of energy produced	Well to pump	GHG	(net) g CO2eq - 75,26	0.93 MJ
2010	**[42]**	Biodiesel			Difference in 12 % annual biomass productivity in the two cities because of climate differences	Liters BD produced	Well to pump	Fossil fuel use, GHG, VOC, C, NO, particu-lates, sulfur oxides	630-1350 g CO2eq	15-23 MJ
2010	**[43]**	Biodiesel			Cultivation in typical raceways would be significantly more environmentally sustainable than in closed air-lift tubular bioreactors	1 ton of biodiesel	Well to combustion, time horizon 100 years	GWP fossil energy requirement	11.9 x10^3 kg CO2eq	200 GJ

2009	**[44]**	Biodiesel			90% of the process energy consumption is dedicated to lipid extraction (energy consumption has much to say for environmental impacts)	1 MJ of fuel in a diesel engine	Cradle to combustion	AD, AP,EP, GWP100, ODP, Human + marine toxicity, land compe-tition, ionizing radiations, POCP		19,8-106,4 MJ/kg biodiesel
2012	**[45]**	Biomethane	241 L CH4 kg-1vm	Electricity consumption repre-sented 8% of the energy pro-duced within the plant	Macroalgal biomethane from fresh algae appears to be an interesting biofuel from an environmental point of view	1 km trip with a gas-powered car	Well to combustion	GW, OD, HT, POF, PMF, IR, TA, F-EU, M-EU, TE, FE, ME, ALO, ULO, NLT, WD, MD, FD		
2011	**[46]**	Biogas			The impacts generated by the production of methane from microalgae are strongly correlated with the electric consumption	1 MJ produced by combustion in an internal combustion engine		Abd, Acid, Eutro, GWP, Ozone, Hum Tox, Land, Rad, Photo		3.2 kWh by cubic meter of methane
2009	**[47]**	Biomethanol		The energy conversion effi-ciency of Fuel metha-nol is 1.24	The major part of the required energy, about 61.1%, was occupied in the process of microalgae biomass production. CO2 emission has the biggest variation	1000 kg of dry microalgae biomass	Well to combustion	GW, acidification, nutrient enrichment, photochemical ozone formation, solid waste, slag and ashes	302.1gCO2 eq/g	180.45 kg
2013	**[48]**	Biogas + bioethanol	Per one tonne of dry seaweed: Biogas: 1320 kW h en-ergy production with an elec-tricity produc-tion of 555 kW h. Giogas + Bio-ethanol: 855 kW h energy production with an electricity production of 359 kW h	Net energy consumption is 2.26 and 3.04 GJ per one tonne of dry seaweed for biogas and biogas + bioethanol respectively	Production of seaweed is the most energy intensive step. Only producing biogas has better environmental performance in all impact categories than biogas + bioethanol	Cultivation and processing of one tonne of dry sea-weed biomass (*Laminaria digitata*) produced in Denmark for biofuels production	Well to tank, 100 years time horizon	GWP, AP and TEP	176 kg of CO2	4.28 and 3.70 GJ

APPENDIX G. OVERVIEW OF THE ALGAL COMPANIES

Company	Location (Company)	Fuel
(Algenol Biofuels, Inc.) + Dow Chemical	Florida, USA, Switzerland, Germany	Ethanol, possibly also jetfuel, biodiesel
Airbus + European Aeronautic Defense and Space Company (EADS) + ENN Energy Service Co	Worldwide	Biodiesel, aviation fuel
Algaelink + KLM	Netherlands	Aviation
Algae.Tec Ltd + Lufthansa	Australia	Biodiesel, jet fuel, ethanol
AlgaeTech	Malaysia	Biodiesel
AlgoDyne Ethanol Energy Inc	Canada	Ethanol for energy
Aquaflow Bionomic/Air New Zealand	New Zeeland	Green crude for fuels
Aurora Algae	USA	Biodiesel
Blue Sun Biodiesel	USA	Biodiesel
British Petroleum	Great Britain	
Cauffiel Technologies	USA	Jet fuel + ethanol simultaneously
CEHHM	USA	Oil for biofuel
Cellana (from HR Petroleum and Shell)	USA?	Oil biorefinery, biofuels etc.
(Chevron/Texaco)	USA	?
(Cobalt Tecnologies)	USA	Biobutanol
Culturing Solutions, Inc.	USA	Biodiesel, ethanol
Eni Divison R&M	Italy	Biodiesel
ExxonMobil	USA	
General Atomics	USA	Biodiesel, biofuels
Green Gold Algae and Seaweed Sciences Inc.	USA	Ethanol
Green Star, Inc.	USA	Biodiesel
International Aero Engines	USA	Biodiesel
Japan Airlines	Japan	
Jetblue		
(Kent Seatech; Kent Bioenergy)	USA	Not yet?
MBD Energy Ltd/MBD Biodiesel Ltd	Australia	Biocrude, biodiesel?
Novozymes + Sea6Energy	Denmark/India	Ethanol
(Neste Oil)	Finland	Biofuels
Oilfox Argentina	Argentina	Biodiesel
(Origin Oil)	USA	Algae paste for biofuels etc
PetroSun Biofuels	USA	Jet fuel
Phycal	USA	Oil for biofuel
PrimaFuel	USA	For gasoline?
Sandia Labs (DOE)	USA	
Sapphire Energy, Inc	USA	Crude oil for refining into 91 octane gasoline, biodiesel, jet fuel
Scipio Biofuels	?	Biofuel algae oil factory
Seambiotic	Israel/USA	Biomass for bioethanol, biodiesel etc.
Solar Biofuels (consortium, incl Neste Oil etc)	Australia	Hydrogen, biomethane, biodiesel
Solazyme, Inc.	San Francisco, USA	Biodiesel (FAME), jet fuel
Solena Group	USA	Gas, biodiesel, jet fuel
Solix biofuels	USA	Crude oil for biodiesel, etc.
Synthetic Genomics (Craig Venter)/Exxon Mobil Research and Engineering Company	USA	R&D for fuels
Valcent	USA	Biodiesel

Virgin Airways	USA?	Jet fuel
W2 Energy	Canada	Biomass for biofuels including buthanol etc.
United Continental		Jet fuel
UOP LLC, Honeywell	USA	Jetfuel, biodiesel, green gasoline

APPENDIX H. PRODUCTION METHOD OF THE ALGAL COMPANIES

Company	Cultivation								Harvesting method	Extraction	Productivity
		Algae type				System					
	Location (Company)	Micro/ macro	Water	Latin name	Cultivation size	Type (O=Open, C=Closed)	Nutrition	Light			
(Algenol Biofuels, Inc.) + Dow Chemical	Freeport, Texas	Cyano-bacteria	Salt		Pilot	PBR (C)		Sun	None	Vapor Compression	100 000 gallons/year
Airbus + European Aeronautic Defense and Space Company (EADS) + ENN Energy Service Co	Mongolia	Micro			Demonstration, capacity 5000 tons/year		Flue gas				10 tons oil/year
AlgaeLink + KLM											
Algae.Tec Ltd + Lufthansa	Planned in Europe	Micro				Shipping containers (C)	Flue gas	Sun			
AlgaeTech					Lab scale						
AlgoDyne Ethanol Energy Inc		Micro	Marine		Development	Collect algal blooms					
Aquaflow Bionomic/Air New Zealand	New Zealand	Micro	Waste water / wild			Harvesting technique, settling pond			Aquaflow		
Aurora Algae	Australia (+ California, Mexico, Florida)	Micro	Marine		20 acres	Pond (O)					
Blue Sun Biodiesel	USA				R&D (earlier)						
British Petroleum											
Cauffiel Technologies											
CEHHM	New Mexico	Micro	Marine		5 ponds	Pond (O)					1000 gallons / day
Cellana (from HR Petroleum and Shell)	Hawaii	Micro	Marine	Local species?	Demonstration, 6 acres	Ponds + PBR (O+C)		Sun			
(Chevron/Texaco)					R&D						
(Cobalt Tecnologies)	California	? Variety of biomass, algae mentioned									
Culturing Solutions, Inc.	Florida + Rhode Island, Australia, Romania, Hungary, Russia	Micro			7 acres, demonstration	PBR + ponds (O+C)	Flue gas for CO_2			High pressure homgenizer cracks the algae	

Eni Divison R&M	Company: Gela refinery/ Texaco	Micro			1 hectar	PBR + ponds (O+C)	Flue gas, waste water				
ExxonMobil											
General Atomics	Hawaii	Micro			Demonstration, DARPA-funded	Pond (O)	Probably from waste sources				
Green Gold Algae and Seaweed Sciences, Inc.		Macro			Lab scale						
Green Star, Inc.		Micro?	Brackish, saline								Refinery capacity: 8 million gallons/year
International Aero Engines											
Japan Airlines											
Jetblue											
(Kent Seatech; Kent Bioenergy)		Micro	Waste water treatment		160 acres, now, 700-2000 acres planned (full scale commercial)	CEP controlled eutrophication pond system (O)	Waste water		Stepwise in ponds, physical separation		
MBD Energy Ltd/MBD Biodiesel Ltd	Australia, Canada, Thailand, Africa	Micro and macro	Waste water treatment			Pond (O)	Flue gas and waste water				
Novozymes +	India	Macro									
(Neste Oil)	Cooperates	Micro									
Oilfox Argentina	Buenos Aires	Micro	Fresh?		Green house scale		From an-aerobic digestion and flue gas	Sun + LED		Ion exchange	Capacity: 100 000 tonnes/year
(Origin Oil)		Micro							Own collection/ filter system	Own system, one step	Produces harvesting and extraction solution
PetroSun Biofuels	Arizona, USA	Micro			1100 acres						
Phycal	Hawaii	Micro			34 acres, pilot scale	Pond? (O)					150 000 gallons of oil/year
Primafuel	USA, Israel	Micro			In and outdoors	Pond (O)					
Sapphire Energy, Inc.	New Mexico	Micro, photo-trophic			Demonstration/ commercial, 300 acres, world´s largest	Pond (O)		Sun			
Scipio Biofuels						PBR, no pump (C)		Solar	Continuous		

								collector	flow harvester		
Seambiotic	Israel	Micro	Marine	*Phaedactylum tricornutum, Nannochloropsis salina*	1000 m2, 250 l/m2	Pond (O)	Flue gas				$25 g/m^2/day$
Solar Biofuels (consortium, incl. Neste Oil etc.)											
Solazyme, Inc.	USA, France, Brazil	Micro, heterotrophic			Pilot/ commercial	Fermentors (C)	Sugar from other plants	None			80 000 litres in 2010, increasing
Solena Group	Many	?								Plasma gasification	
Solix Biofuels	Colorado, USA	Micro			0,3 hectar, 150 000 l, demonstration	Floating PBR panels in ponds (O+C)	Industrial CO2, waste water				
Synthetic Genomics (Craig Venter)/Exxon Mobil Research and Engineering Company					?						
Valcent		?				PBR					
Virgin Airways											
W2 Energy										Syngas	
United Continental											
UOP LLC, Honeywell	Hawaii	Micro			Pilot			Sun			Refining, algae from Sapphire Energy