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REPORT

MARINE RESOURCES FOR BIOJETFUEL

AVINOR AS

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Marine resources for biojetfuel

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Summary:

Algae is seen as potential feedstock to bio jet fuel, as part of the strategy for reducing the carbon footprint of the aviation sector. Avinor AS has given DNV KEMA (DNV) the task of evaluating the potential for using algae and fish waste as a feedstock for producing Jet A1 fuel in a 10-15 years perspective in Norway. Microalgae production in reactors is feasible in Norway, but the cost of production and focus of the stakeholders in this value chain give little indication that microalgae will contribute to the supply of jet fuel in Norway by 2025-30. Macroalgae (seaweed) is already an important commercial feedstock for products in Norway (alginate).The stakeholders in this value chain are aiming for production for conversion to ethanol. Although there is potential for a thriving industry in the future, macroalgae are not likely to be a feedstock for commercial jet fuel production by 2025-30.

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Table of Contents *Page*

1 EXECUTIVE SUMMARY 4

2 INTRODUCTION 5
  2.1 Why the interest in algae? 5
  2.2 What are the production options? 5

3 METHODS 8

MICROALGAE 10
  3.1 Introduction 10
  3.2 Identifying suitable species of algae 11
  3.3 Biomass Production – Growing Technologies 12
  3.4 Requirements for microalgae production 15
  3.5 Biomass harvesting 17
  3.6 The Commercialization and Industrialisation of Algae Technology 19
  3.7 Summary: Microalgae based fuel internationally 23
  3.8 Biorefinery for microalgae 23
  3.9 Feasibility of microalgae as a source of jet fuel in Norway 24
  3.10 Modelling of Microalgae production in Norway 25
  3.11 Summary discussion 28

4 MACROALGAE = SEAWEED 30
  4.1 Introduction 30
  4.2 The macroalgae to biofuel production chain 31
  4.3 Feedstock production 32
  4.4 Commercial production and industrialisation 35
  4.5 Biorefinery for macroalgae 38
  4.6 Feasibility of macroalgae as a source of jet fuel in Norway 43

5 SUSTAINABILITY AND BIO JET FUELS 46
  5.1 Sustainability of microalgae 47
  5.2 Sustainability of macroalgae 50

6 OTHER MARINE RESOURCES 52

7 LOOK TO THE FUTURE 54

8 CONCLUSIONS 56

9 BACKGROUND LITERATURE 57

APPENDIX A INTERVIEWS 58

APPENDIX B ALGAEVALUE™ 72

1 EXECUTIVE SUMMARY

The aviation industry is searching for new ways of producing jet fuel in order to reduce its environmental footprint. Biofuel is one of the few realistic alternatives to achieve this. Test flights using biofuel based on algae have been conducted and algae are seen as a promising potential feedstock for producing bio jet fuel. Avinor AS has given DNV KEMA (DNV) the task of evaluating the potential for using algae and fish waste as a feedstock for producing Jet A1 fuel in a 10-15 years perspective in Norway.

The main methods used in the project are interviews with major stakeholders in Norway, document reviews and model evaluations. There are two major groups of commercially produced algae that have been considered as potential jet fuel feed stock.

Conclusion - microalgae

The species currently used in commercial production are optimised for growth in sun-intensive, warm climates. Studies have suggested that open pond systems are the only viable method for commercial algae production for fuel, and then first when systems are optimized and costs are minimised. Weather conditions and land availability in Norway are not suitable for commercial open pond systems. Therefore, microalgae production in Norway will most likely have to use photobioreactors. The cost intensity of this production method requires high value products for commercial viability. Current jet fuel prices are lower than the prices of alternative products. In DNV's opinion, there will be little biomass or oil produced from microalgae for the national fuel market in Norway by 2025-30.

Conclusion - macroalgae

Macroalgae (seaweed) is already an important commercial feedstock for products in Norway (alginate). The natural conditions in Norway are suitable for production of certain species of seaweed. As with microalgae, there are several issues along the entire production chain that need to be resolved before seaweed can be produced and processed on a commercial scale.
The commercial stakeholders in Norway are focusing on ethanol production from macroalgae. Ethanol is therefore the most likely fuel product from macroalgae production, so the most likely pathway for jet fuel production is the "ethanol to jet" conversion. According to the commercial stakeholders, the first biorefinery for ethanol from seaweed will not be in place before 2020, at the earliest. Although there is potential for a commercial industry in the future, DNV considers that macroalgae are not likely to be a feedstock for commercial jet fuel production by 2025-30.

Conclusion - fish waste

Considerable efforts have been made to ensure that the by-products from the fish industry are utilised in profitable ways. Currently much is used in the food and feed industry and biogas production. Given that fuel production generally needs to keep feedstock prices to a minimum, fish by-products are not a likely source of feedstock for bio jet fuel production at this point.

2 INTRODUCTION

The aviation industry is searching for new ways of producing jet fuel in order to reduce its environmental footprint, in particular its CO_2 emissions. Biofuel is one of the few realistic alternatives to achieve this. Test flights using biofuel based on algae have been conducted and algae are seen as a promising potential feedstock for producing bio jet fuels.

This report provides a general description of micro- and macro- algae and current production methods. Also, a description of fish waste as a potential feedstock is given. Based on this, the feasibility for algae and fish waste as feedstock for bio jet fuel production in Norway in a 10-15 years perspective will be evaluated. The evaluation is part of a larger project on sustainable aviation biofuels in Norway. Sustainability is an important issue when evaluating feedstock for biofuels, and this is covered in a separate chapter.

2.1 Why the interest in algae?

Biofuel production relies of feedstock that is based on biomass, i.e. plants. Production from agricultural plants has led to debates regarding sustainability issues including land use and food security issues. Algae have been seen as having a unique potential to provide a sustainable source of biomass for a number of reasons:

- Fuel production from algae will not compete with traditional food crops.
- Algae convert solar energy and carbon dioxide into biomass in an efficient and fast production cycle with a minimal need for fertilizers.
- Algae produce more per land mass than any known terrestrial crop.
- Algae can grow in salt, brackish or polluted water thereby avoiding strain on freshwater supplies.
- Algae can recycle CO_2, such as flue gas from industry, and can clean polluted water.
- By-products from algae production include sustainably produced proteins for feed and bio chemicals.

There are two main groups of algae, microalgae, which are small organisms, and macroalgae which is seaweed. The growth to fuel production chain of the two algae types are very different and will be looked at separately.

2.2 What are the production options?

The focus of this report is the production of algae as a feedstock to bio jet fuel production, as the conversion techniques are covered in detail in a another report by SINTEF in the project. The following section is to give an overview of the options for production pathways from algae as a feedstock.

2.2.1 Microalgae

Microalgae can contain oil, and many producers have focused on algae oil production that results in triglycerides that can be used directly in the current refining chain for fossil oil ("drop-in fuels"). The most common route to date has been for biodiesel and bio jet fuel production. Although there are attempts to develop methods to milk the algae [1] or develop algae and/ or cyanobacteria that release the oil during growth,[2] most oils produced by harvesting the whole algae and separating the oil from the rest of the biomass. The resulting biomass, proteins and carbohydrates are utilised in other value chains. The proteins are often used for feed, and the biomass for either biochemical or thermochemical conversion, as shown in Figure 1. Some producers do not separate the algae oil, and concentrate on processing the algae as it is. The production methods that are currently approved production methods for jet fuel is HEFA processing of triglycerides (lipids/oil) and Fisher-Tropsch synthesis from syngas and bio-oils.

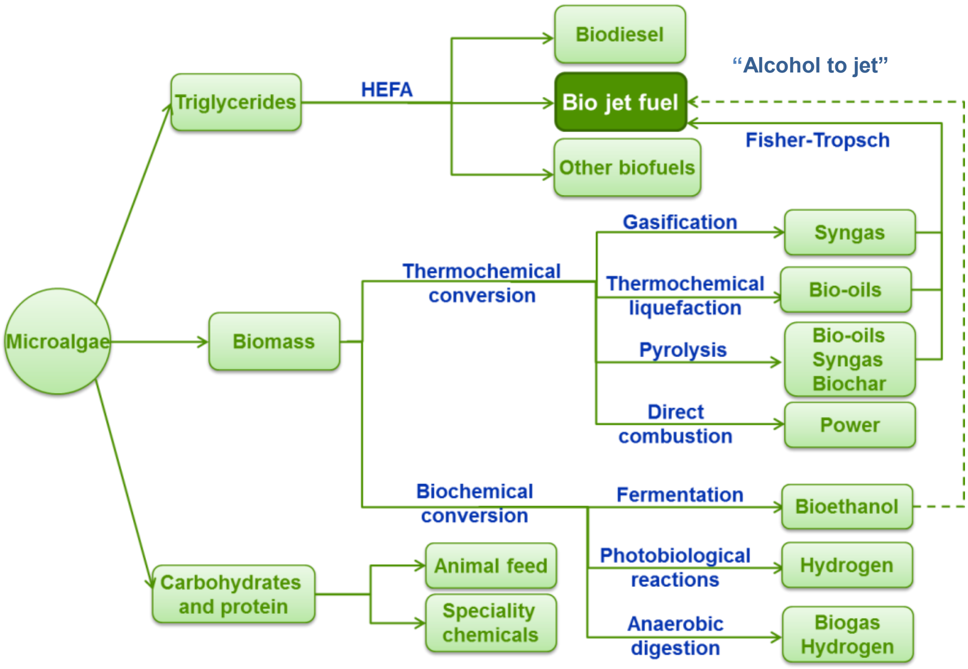

Figure 1 Microalgae are currently the major source of algae based bio jet fuel. The fuel can be made from triglycerides (lipid/oil) or biomass through various types of conversion. The routes for conversion will depend on the algae used and the focus of the production.

2.2.2 Macrolagae

Macroalgae, or seaweed, contains carbohydrates that can be fermented to ethanol, which can then potentially be converted to bio jet fuel in the "alcohol to jet process" (see SINTEF report). Macroalgae biomass that can be converted through various technologies to products (syngas/bio-oils) that can be used to produce bio jet fuels. The fermentation pathway is the main focus area for

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[1] http://www.originoil.com/technology/live-extraction.html

[2] Eukaryot Cell. 2010 April; 9(4): 486–501. Genetic engineering of algae for enhanced biofuel production http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2863401/

the stakeholders in this market with ethanol and feed as major products. The possible pathways for the use of macroalgae biomass as a fuel feedstock are shown in Figure 2.

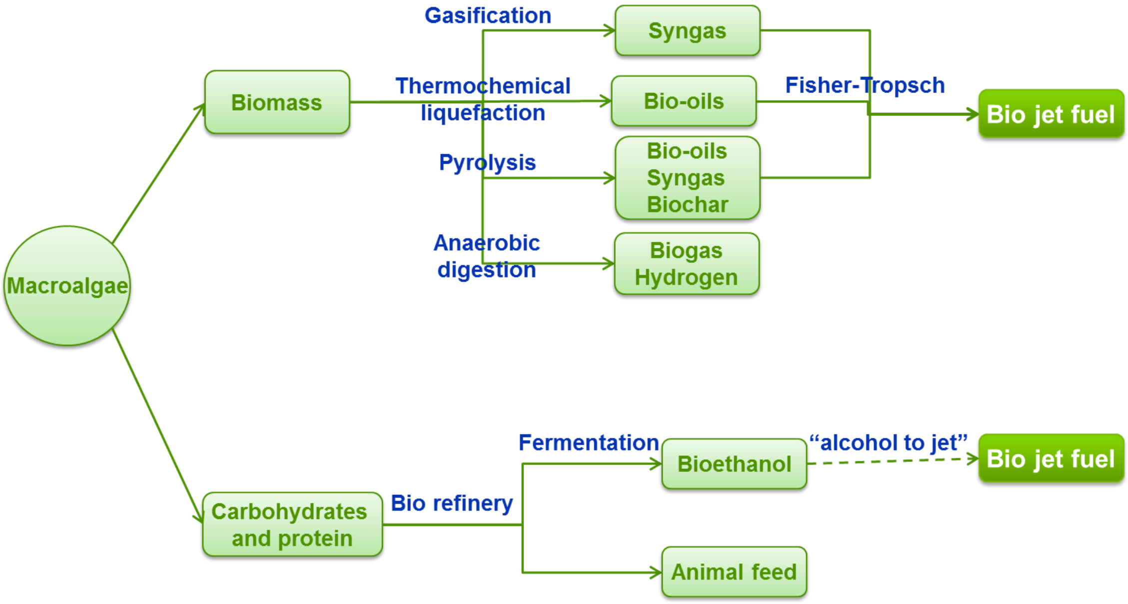

Figure 2 Macroalage pathways that provide fuel or fuel-precursors to bio jet fuel.

3 METHODS

The main methods used in the project are interviews, document reviews and model evaluation. In the following sections we describe how these methods were used to obtain information about the different feedstocks and value chains.

In general, the production of algae for fuel use is an immature industry that has potential, but is under development and is in search of capital. As the production is not developed, all production data on amounts, process and costs is somewhat speculative. Given the commercially sensitive nature of production data, the available data is, in general, somewhat dated and often based on research papers. As the industry matures and the technologies improve, the data will be less speculative. The development of the industry will depend on a large number of factors, and the conclusions are based on the current stakeholder's opinions, and the type of data that we have utilised in the AlgaeValue tool.

Microalgae

Microalgae technology is a relatively small industry in Norway, but is larger and rapidly growing internationally. We searched for current production systems in use for algae to biofuel production to examine whether these might be suitable for use in Norway. Sources of information included published papers, web sites, press releases, conference papers etc. The collected data were examined to identify companies who were in the "algae to jet fuel" business and how they operated. Microalgae production for use as biofuels is most common USA and Australia. Therefore information from these countries was targeted in particular.

We then conducted interviews with key people from the identified companies (see appendix for details). The interviews aimed to obtain information about algae production, including critical numbers for determining production potential and costs, which could be translated to a Norwegian context. Six interviews were conducted in this part of the study.

In addition, we interviewed representatives from different microalgae competence centres in Norway and Denmark. The competence centres in Norway are aiming to develop suitable species with a focus on high value products such as oils, bio-active ingredients and feed.

There are also commercial actors working with algae production in Norway. However, the information about the process was considered to be commercially sensitive and we were therefore unable to obtain much information about the current industrial trials in Norway. The focus of the activities in Norway is not on fuel production but high value products.

Macroalgae

The utilization of macroalgae is done mainly in three different industries; Cultivation in Asia, harvesting of natural crops and cultivation in Europe.

Cultivation of seaweed for food purposes have long traditions in Asia, especially China and Japan. This type of cultivation is very labour intensive, is minted to a high value food market and uses different types of algae than will be used for energy production. Some of the propagation techniques are of interest, but as an overall business model for algae production it was considered less relevant when evaluating the potential for macroalgae for fuel production in Norway.

Harvesting of natural macroalgae crops for hydrocolloid production is a thriving business. In Norway, FMC is the only major player. A representative from FMC was interviewed to obtain non-sensitive information regarding harvesting logistics, FMC's processing of macroalgae and the potential to produce jet fuel or ethanol as a co-product in FMC's process.

In Norway and Europe, cultivation of macroalgae is at the pilot stage. There are a few commercial stakeholders in addition to research institutions working with macroalgae. As with microalgae, public information from papers, web sites etc. were gathered and interviews with stakeholders and research institutions were held. Given that the results here are also commercially sensitive, there were details about the plans and potentials that were not disclosed, but general goals for the projects and time lines were shared. Information regarding the possible products and the processing of macroalgae were collected in the same way.

Cultivation of macroalgae will require the use of large areas along the coast, and possibly out at sea. The permits to use this area must be given by local authorities. The authorities will have to take into account several factors when considering giving permits. Interview with Nordland Fylkeskommune and information from Norwegian aquaculture that have some of the same issues were used to shed light on this aspect of macroalgae cultivation.

Fish by-products

Aquaculture is a more mature industry, and the utilization of by-products from fish has been in focus for many years. Since it is a developed industry, information regarding the utilization of fish by-products was available from organizations like the Norwegian Seafood Federation, the Norwegian Directorate of Fisheries and the RUBIN foundation.

AlgaeValue$^{\text{TM}}$ Tool

AlgaeValue™ developed by KEMA is a Excel/VBA model (Visual Basic) is used for calculating cultivation yields and costs/revenue indications for cultivation and conversion of algae for different product groups. Results are based on test- and literature data, with parameters on: climate, economy, scale, algae species, cultivation system, conversion system and product. Interdependencies are captured in logical and pragmatic functions, which facilitate quick and well-organised outlining of concepts.

MICROALGAE

3.1 Introduction

There are two main groups of microalgae,

- **Photoautotrophic** require only inorganic compounds such as CO2, salts and a light energy source for growth.
- **Heterotrophic** are non-photosynthetic and require an external source of organic compounds as well as nutrients as an energy source.
- Some photosynthetic algae are mixotrophic, and can perform photosynthesis and acquire exogenous organic nutrients.

Photoautotrophic algae cultivation is cultivating algae in the presence of light that can be either freely available sunlight or artificially provided light. Microalgae are known for their photosynthetic efficiency and are among the fastest growing orgnisms on earth. The need for light penetration limits the depth / breadth of the solution that algae are grown in.

Heterotrophic cultivation essentially means the algae are cultivated in the dark by providing it with some carbon sources such as sugar for its growth. One of the main arguments for using algae as a feedstock is to avoid the “fuel vs food” issue as they do not need agricultural land to produce biomass. If sugars are used as the major nutrient source for the algae then the land and water use of the production of sugars will need to be included in the algae equation. There may be advantages in converting sugar to oils for certain uses, but for biofuel production it would seem to make more sense to ferment the sugar directly to ethanol.

Microalgae contain lipids, some more than others, which can be extracted and refined into fuel oils. With lipid content as high as 70 percent in a few of the more than 30,000 strains of microalgae so far identified, estimates of algae fuel yields have consistently been projected in the 2,500-10,000 gallon per acre range (24,000-94,000 l/ha). This compares to 400 gallons per acre (3800 l/ha) for corn ethanol.

Around ten microalgae species are used for commercial applications.[3] The total production volume of microalgae for all application is in the tens of thousands of tons.[4] Currently the food supplement algae Spirulina and Crypthecodinium dominate the production and represent about 70% of the global production.

Most of the microalgae projects that have an intention of producing jet fuel are in the US as well as some activity in New Zealand and Australia. This section focuses on the state of the microalgae industry in the US as they are leading in this area. It covers the following:

- Some of the major species
- Growing methods
- Techniques for separating water and algae
- The process of technology commercialization

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[3] For complete list see http://www.aquafuels.eu/attachments/079_D%203.3-3.5%20Life-Cycle%20Assessment%20and%20Environmental%20Assessment.pdf

[4] www.agbioforum.org/v13n2/v13n2a04-richardson.htm

- Major companies in the arena and compare their relative position on the commercialization pathway.

There are very few companies that are currently producing just jet fuel from algae. Many of the companies described in this section are producing a crude oil equivalent that can then drop directly into the downstream (refining) infrastructure of the oil industry as it exists in the US today. Using this path these companies are able to focus on development of their specific species and leave the fractionation process to experts that already exist in this area, and the related distribution networks.

3.2 Identifying suitable species of algae

Algae production has to date been limited to a few species that have been developed over a number of years. There is work in a number of research labs, including in Norway, to screen naturally growing algae for useful attributes and develop a number of strains that would be suitable for large scale production. Algae have a rapid life cycle which helps in the screening process.

Many factors have to be considered when identifying the species that is to be grown.

Key factors include

1. Oil content: different species produce different mixtures of alkane and alkene chain lengths. A simplified example of the impact of this could be Botryacoccus braunii, which in ideal growing conditions reliably produces oils with 40 carbon atoms in the chain. Through reactions these are broken down into chains that are around 8 atoms long which are useful for gasoline. In non-optimal growing conditions, the quantity of oil is substantially reduced, and the content has a wider spread of chain lengths which break down into bi-products which can actually damage an engine.

2. Yield: Some species have maximum theoretical lipid yields of 40% of biomass grown. Others can produce as much as 70-80%.

3. Growing environment: different species require different growing temperatures, different micro-nutrient quantities, and inputs such as potassium, sodium, and magnesium can impact the products that are grown. Some strains, such as Botryacoccus braunii, requires low nitrogen levels to produce the best oil. Frequently the greatest quantity of lipids is produced when the species is subjected to extreme conditions, including temperature and air pressure. Lifecycle energy use considerations can come into play here as using large quantities of energy to raise or lower the temperature of growing environment is not sustainable.

4. Space: Some species grow best in open ponds that require large areas of flat land– others require the precisely controlled environment of a photobioreactor (PBR).

5. Sunlight requirements: Most species that are in commercial production today grow best in environments that receive 3-7 kwh/square meter/day. In the US, this is typical south of the Mason-Dixon line that runs west from the Pennsylvania Maryland border. The equivalent in Europe is the south of Spain, Italy, and Greece. Work is inderway to find species that can grow well with less sunlight. Artificial lighting can also be used.

3.3 Biomass Production – Growing Technologies

The three principal growing technologies that have received most attention are:

1. Open pond
2. Photobioreactors
3. Fermentation reactors

In recent years, R&D attention has been split evenly among these, with the leading companies each championing a specific technology. As the industry evolves, it is clear that old assumptions continue to be questioned by the incoming start-ups. These have lead to new versions of each technology with no clear winner emerging. Table 1 gives a summary of the advantage abd disadvantages of the open vs closed systems.

3.3.1 Open Ponds

Open ponds can be categorized into natural waters (lakes, lagoons, ponds) and artificial ponds or containers. The most commonly used systems include shallow big ponds, tanks, circular ponds and raceway ponds. One of the major advantages of open ponds is that they are easier to construct and operate than most closed systems.

However, major limitations in open ponds include poor light utilization by the cells, evaporative losses, diffusion of CO2 to the atmosphere, and requirement of large areas of land. Furthermore, contamination by predators and other fast growing heterotrophs have restricted the commercial production of algae in open culture systems to only those organisms that can grow under extreme conditions. Also, due to inefficient stirring mechanisms in open cultivation systems, their mass transfer rates are very poor resulting to low biomass productivity.

The ponds in which the algae are cultivated are usually what are called the “raceway ponds”. In these ponds, the algae, water & nutrients circulate around a racetrack. With paddlewheels providing the flow, algae are kept suspended in the water, and are circulated back to the surface on a regular frequency. The ponds are usually kept shallow because the algae need to be exposed to sunlight, and sunlight can only penetrate the pond water to a limited depth. The ponds are operated in a continuous manner, with CO_2 and nutrients being constantly fed to the ponds, while algae-containing water is removed at the other end.

Raceway Pond

Circular Pond

The biggest advantage of these open ponds is their simplicity, resulting in low production costs and low operating costs. While this is indeed the simplest of all the growing techniques, it has some drawbacks owing to the fact that the environment in and around the pond is not completely under control. Bad weather can stunt algae growth. Contamination from strains of bacteria or other outside organisms often results in undesirable species taking over the desired algae growing in the pond. The water in which the algae grow also has to be kept at a certain temperature, which can be difficult to maintain. Another drawback is the uneven light intensity and distribution within the pond.

Open ponds require realtively flat land and temperate weather in addition to a CO2 source and nutrients. Open ponds can also be in a combination solution with greenhouses.

Companies using open ponds include:

- Cellana
- Sapphire Energy
- Aurora Algae

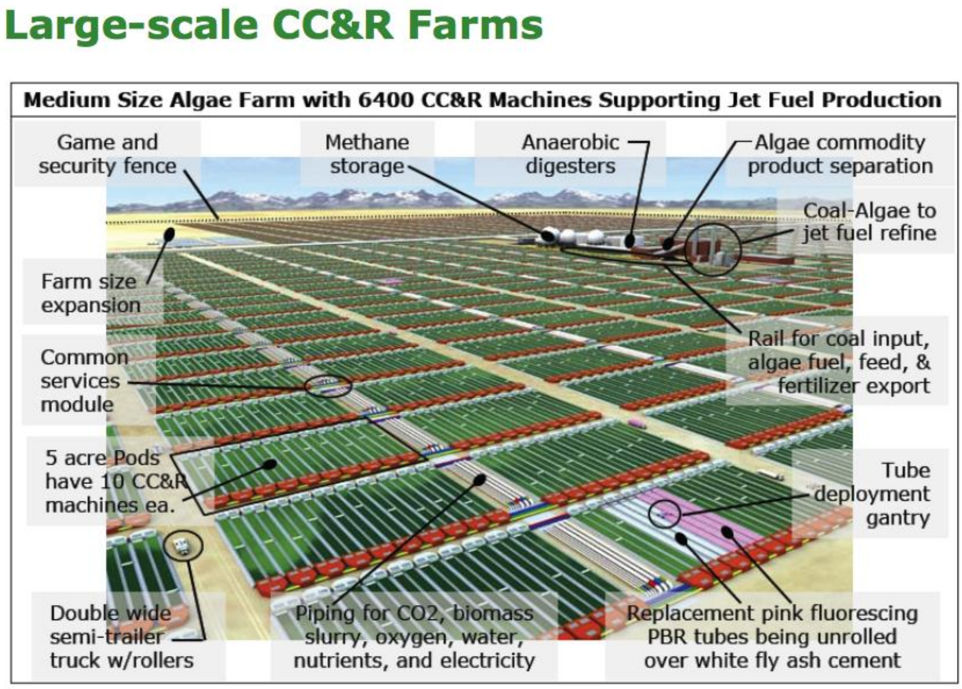
3.3.2 Photobioreactors

These systems enclose water in a plastic or glass, vertical or horizontal photobioreactor. Inoculums, nutrients, and carbon dioxide are injected into the photobioreactor, which also receives solar energy which passes through the plastic or glass walls, or light of a specific wavelength.

There are two reasons to use closed systems — control over contamination and higher productivity. Contamination can kill off algae or retard their development as competing organisms fight for carbon, sunlight, and nutrients. The challenge for bioreactors is that they are not yet economically feasible, nor are they expected to offer cost parity with fossil fuels for the foreseeable future. They appear to be better suited to the cultivation of algae for the high-price nutraceutical market, where purity is more of a concern and cost is more affordable given the high prices for Spirulina and other microalgae used for nutrition and health supplements.

Figure 3 is a visualization of a commercial-scale photobioreactor system that also features an integrated facility that burns coal for power and carbon dioxide

Figure 3 Large scale photobioreactor



Companies using this carbon-capture system model use a system of 10 ½ acre bioreactors per 5-acre pod, and the 128 pods roll up into a 640 acre system that could produce up to 4 Mgy of algae fuel, plus protein for animal feed and fertilizer.

Companies using photobioreactors include:

- Joule Unlimited – Although their feedstock remains secret, it may be a cyanobacteria rather than an algae
- Synthetic Genomics
- Chingoo Research Partners

3.3.3 Fermentation Reactor

Additional models of algae production are the fermentation system employed by Solazyme, in California and the algae-to-ethanol system employed by Algenol.
In the Solazyme model, algae is fed sugar in large tanks which ferment microalgae from the resulting brew. The sugar is made from solar energy, but is a food product that uses land, is a substitute to the solar radiation energy input, and algae is in fact cultivated in the dark. The fermented algae is burst and the oil floats to the surface where it is scooped off as a biodiesel feedstock.

In the Algenol model, a specific algae strain is employed that excretes ethanol as a by product of its own biocycle. The Algenol system is the only one announced to date in which the cells are not destroyed to capture the resulting stored energy. Open pond systems are employed and the ethanol is removed continuously.

The fact that sugar, which is easlty fermentable to fuel, is used as a major compenent in order to produce oil means that the oil should have major advantages over the sugar input.

Companies using fermentation reactors include:

- Solazyme
- Algenol
- Kiverdi

Table 1 Comparison of "open pond" and "closed reactor" as production systems for algal biomass

	Open pond	Closed reactor
Algae concentration	1 g/L	3-10 g/L
Biomass production	Doubles 1x day	Doubles 2x day
Water	Fresh or salt	Fresh
Initial flooding	38 L/L fuel	12 L/L fuel
Production consumption	7,5 L/ L fuel	7,5 L/ L fuel
Feasibility in Norway	Not suitable due to weather/ availability of affordable flat land areas	A possible production method in Norway

3.4 Requirements for microalgae production

The current metrics general requirements for production of algae and important requirements for a fuel production faciliy are given are given in Table 2, based on interviews with numerous algae ventures and a survey of algal-related publications (See table A.1 in appendix A for interview list).

Algae production needs to be optimised at all parts of the production system.

Table 2 General requirements for algae production

Requirement	Amount	In Norway?
Sunlight		
Energy requirement (ideal amount)	3-7 KWh/m^2	Artificial light is needed in combination with natural light and development of strains that grow well under these conditions.
Ideal location (for commercial algae used today)	Around the Mediterranean, near and south of 39° N	
CO_2		
Per kg algae	2.1 kg CO_2/kg algae	
For 40 M L fuel facility	74 000 ton CO_2/yr	33 industrial sites with these levels of CO_2 emissions in 2011
For a 200 M L fuel facility	370 000 ton CO_2/yr	8 industrial sites with these levels of CO_2 emissions in 2011
Nutrients		
Nitrate	> 1 mg/L	Internationally sewage water is used as a source for nutrients. Since industrial sites in Norway are often located in remote areas, sewage is not a practical source of nutrients in Norway.
Phosphate	> 0,05 mg/L	
Fe, Cu, Zn, Co	Trace amounts	
Temperature		
Average	> 10°C	Industrial sites that have enough CO_2 in many cases also have waste heat that can be used for algae production
Land		
For a 200 M L fuel facility	35-45K Ha	
People		
For a 200 M L fuel facility	450-550 jobs	People cost will be one of the major production cost for an algae fuel facility in Norway
Shift technicians	15-20 per shift	
Biologist for strain maintenance	5-6	
Central lab		
Engineering		
Infrastructure		
Proximity to CO_2 source	< 16 km	Locations near existing industry will fulfill these requirements
Proximity to a source of waste heat	< 16 km	
Proximity to logistics for distribution of products and raw materials	Preferably on site	
Revenue		
Fuel	$ 530-800 /ton	
Meal	$ 270 /ton	Important product for aquaculture and is a replacement for soybean meal

3.5 Biomass harvesting

Gathering algae consists of separating algae from the growing medium, drying, and processing it to obtain the desired product. Separating algae from its medium is known as harvesting. Harvesting methods depends primarily on the type of algae. The high water content of algae must be removed to enable harvesting. These must be energy-efficient and relatively inexpensive so selecting easy-to harvest strains is important.The most common harvesting processes are described below.

Flocculation
Flocculation is a method of separating algae from the medium by using chemicals to force the algae to form lumps. The main disadvantage of this separation method is the additional chemicals are difficult to remove from the separated algae, probably making it inefficient uneconomic for commercial use, though it may be practical for personal use. The cost to remove these chemicals may be too expensive to be commercially viable

Flocculants, or flocculating agents, are chemicals that promote flocculation by causing colloids and other suspended particles in liquids to aggregate, forming a floc. Alum and ferric chloride are chemical flocculants used to harvest algae. Chitosan, a product made from ground shells of crustaceans and commonly used for water purification, can also be used as a flocculant but is expensive. Water that is more brackish, or saline requires additional chemical flocculant to induce flocculation.

Flotation
Usually flotation is used in combination with flocculation for Algae Harvesting in waste water. It is a simple method by which algae can be made to float on the surface of the medium and removed as scum.

- *Dissolved Air Flotation*
  Dissolved Air Flotation (DAF) separates algae from its culture (Kenyan lakes and ponds) using features of both froth flotation and flocculation. It uses alum to flocculate an algae/air mixture, with fine bubbles supplied by an air compressor. Alum is a common name for several trivalent sulfates of metal such as aluminum, chromium, or iron and a univalent metal such as potassium or sodium, for example $AlK(SO_4)_2$.

- *Froth Flotation*
  Froth Flotation is a method of separating algae from the medium by adjusting pH and bubbling air through a column to create a froth of algae that accumulates above liquid level. The algae collect in a froth above the liquid level, and may be removed by suction. The pH required depends on algal species. Froth flotation and drying are currently considered too expensive for commercial use.

Micro-screening /straining

Filtration is carried out commonly on membranes of modified cellulose, with the aid of a suction pump. The greatest advantage of this method as a concentrating device is that it is able to collect microalgae or cells of very low density. However, concentration by filtration is limited to small volumes and leads to the eventual clogging of the filter by the packed cells when vacuum is applied.

Several methods have been devised which avoid these problems. One involves the use of a reverse-flow vacuum in which the pressure operates from above, making the process more gentle and avoiding the packing of cells. This method itself has been modified to allow a relatively large volume of water to be concentrated in a short period of time (20 liters to 300 ml in 3 hours). A second process uses a direct vacuum but involves a stirring blade in the flask above the filter which prevents the particles from settling at all during the concentration process.

Centrifugation

Centrifugation is used to separate algae from the medium by using a centrifuge to cause the algae to settle to the bottom of a flask or tank and has been used for biolipid extraction from algae and chemical separation in biodiesel. Coupled with a homogenizer, one may be able to separate biolipids and other useful materials from algae. Centrifugation and drying are currently considered too expensive for personal use, and are energy intensive which may limit usefulness on a commercial and industrial scale. There are also issues with cell integrity and the efficient speration of the products using this method.

3.6 The Commercialization and Industrialisation of Algae Technology

“The successful growth of algae is more or less an art and a daily tightrope act with the aim of keeping the necessary prerequisites and various unpredictable events involved in algal mass cultivation in a sort of balance” (Wolfgang Becker, posted at commercial production plant)

In algal fuel production, most systems produce fuel from algal oil, and there are several important co-products, primarily protein for animal feed which can be sold at $270 per ton and has an excellent comparative nutritional value to, for example, soybean meal.
The types of products that will be the focus of algae production are shown in Table 3.

Table 3 potential types of products from algae and value.

Product	Usage	Approx. Value ($/kg)
Phycobiliproteins	Medical diagnostics	> 10 000
Astaxanthin	Food supplement	> 2 500
Xanthophyll	Fish feed	~ 1 000
Betacarotene	Food supplement	> 500
Health supplements	Dietary supplement	~ 10
Biofuels	Energy	< 1

The commercial revenue model for algae fuel systems is relatively well understood, because algal fuel and its co-products are essentially substitutes for products such as biodiesel and animal protein the pricing for which is well established in the market.

Feasibility of algal fuel systems typically focuses at this time on cost reductions, as opposed to revenue enhancement, although revenue-side assumptions must be continuously re-evaluated because of the variations caused by working with different technologies or production scales. In addition, competing companies in the field have developed cost disruptive new production methods. The primary areas for disruptive process cost improvements at this time are oil extraction and dewatering/harvest.

The prices given by producers of oil/ biomass producers vary greatly (see Table 4 and Figure 4). Table 5 gives an overview of the current producers of algae to jet fuel.

Table 4 Cost estimates from various sources. As there are no commercial biofuel production facilities these figures are based on modelling or estimates of specific types of production

Source of estimate	$	Capital costs	Running costs
NREL[5]	$0.93 to $1.65 gallon		▨
John Benemann[6]	$9 to $16 gallon	$100,000 ha/ open $1,000,000 closed	▨
General Atomics	$20 to $33 gallon	▨	▨
Aurora Biofuels	$1.30 per gallon	▨	▨
Norsker et al [7]	4-6 EUR/kg dry weight	▨	▨
University of New Hampshire Biodiesel Group /Michael Briggs		$80,000 /Ha	$12,000 /ha
DOE open system	1,319 Biomass costs ($/t)	$101,256/ha	$14,417 /Ha
Scotia_Capital		$50,000-$250,000 /ha	$15,000-$20,000/ ha
Richardson et al(Texas A&M)[8]	$0.85 to 367/ lb of algae oil	$42,774 to 77,095/ acre	$0.27 to 4.44/ lb
Green Global Solutions Closed system	$150 – 200 per ton/ biomass	$1,000,000 /ha	▨
Grima report (bioreactor)[9]	Biomass costs ($/t)35,649	$3,014,803	$ 429,240/ha

In terms of the division of costs between the various aspects of labor, production of biomass, the most expensive aspects of larger scale systems are the power costs and labor. The power costs primarily stem from the dewatering process. Labor costs in some countries could be lower, for example in India, but the work requires competnce, and competent labor will always have some expense.

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[5] http://www.nrel.gov/biomass/proj_microalgal_biofuels.html Sheehan, J., Dunahay, T., Benemann, J., & Roessler, P. (1998). *A look back at the US Department of Energy's aquatic species program—Biodiesel from algae* (NREL/TP-580-24190). Golden, CO: National Renewable Energy Laboratory (NREL), US DOE.

[6] Benemann, J.R. and W.J., Oswald 1996, *Systems and economic analysis of microalgae ponds for conversion of CO2 to biomass*. Final report. US DOE-NETL

[7] http://algalbiofuels.pbworks.com/f/Norsker+et+al+2010+Biotech+Advances+economics+of+algal+production.pdf
N.-H. Norsker et al. / Biotechnology Advances 29 (2011) 24–27

[8] Richardson, J.W., Outlaw, J.L., & Allison, M. (2010). The economics of microalgae oil. *AgBioForum*, *13*(2), 119-130. http://www.agbioforum.org/v13n2/v13n2a04-richardson.htm#R24

[9] http://www.massey.ac.nz/~ychisti/EPA%20Review.pdf

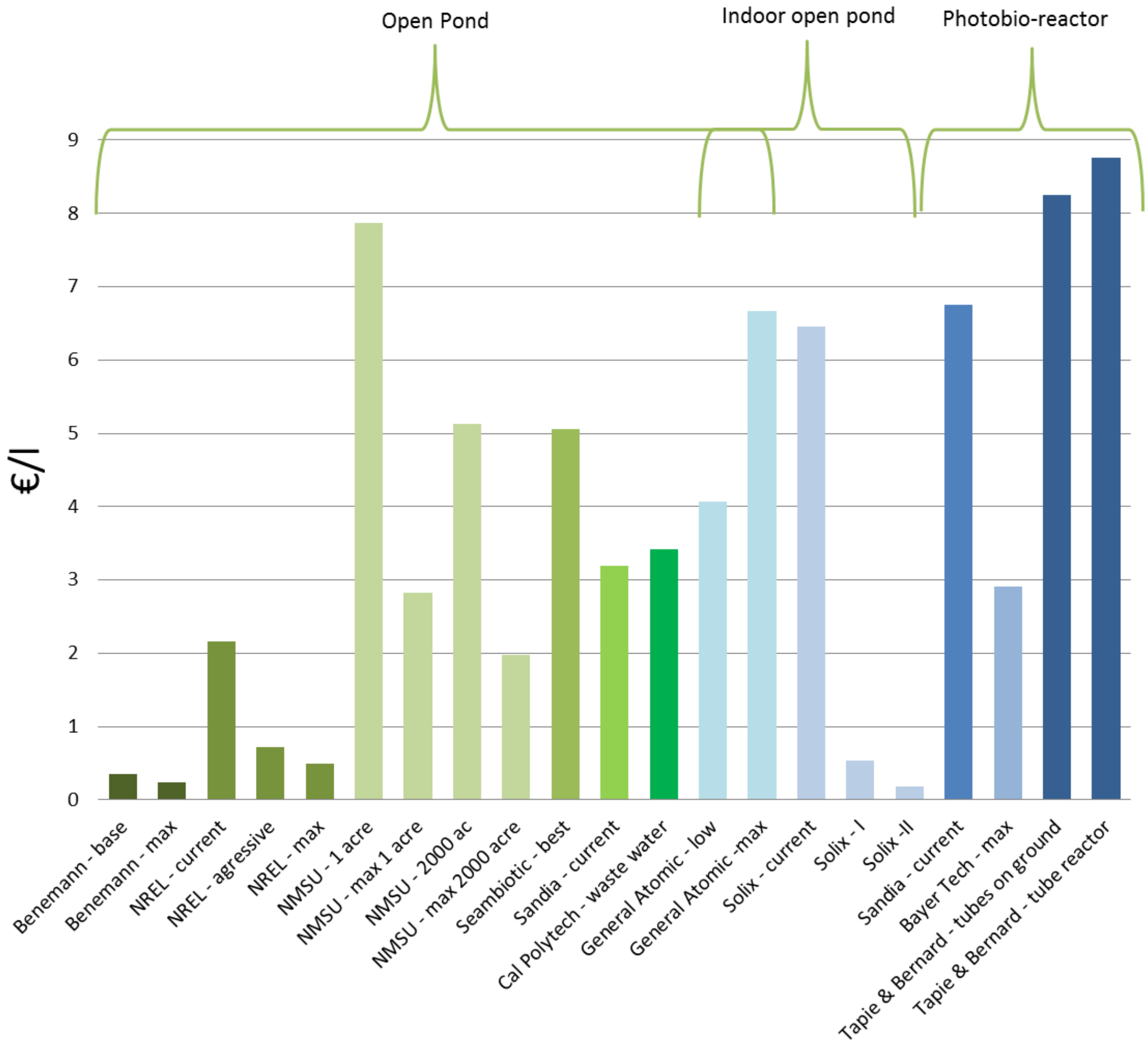

Figure 4: EURO / liter Triglyceride production cost from different publically available estimates adjusted to 2008 cost basis (adapted from [10]). Base and current cases are used to compare maximal (max) production inputs. Solix has a phased approach where large production gains and cost reductions are anticipated.

There is a gap between the actual production capacity and cost of production compared to the market expectation of biofuels. Production costs will only reach acceptable levels by getting the volumetric biomass productivity near the theoretical values and utilization of effluents (flue gases and wastewater) as raw materials. [11]

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[10] Modified from A. Sun et al. / Energy 36 (2011) 5169e5179

[11] http://www.aquafuels.eu/deliverables.html http://www.aquafuels.eu/attachments/066_Presentation%20-%20G.%20Acien%20(University%20of%20Almeria)%20-%20Microalgae%20production%20costs.pdf

Table 5 An overview of companies that are currently producing jet fuel from microalgae

Company	Country	Products	Feedstock	Scale/ Maturity	Production type	Funding to Date
AFS BioOil	USA	Biodiesel	Microalgae	Demonstration	PBR	Unknown
Algae.Tec	Australia	Renewable Crude	Microalgae	Demonstration	Modular PBR	>AUD 11 MM
Algenol	USA	Ethanol	cyanobacteria	Pilot	PBR	>USD 70 MM
Aquaflow	New Zealand	Renewable Crude	Microalgae in municipal waste	Pilot	No Algae Production	Unknown
Aurora Algae	USA	Biodiesel and non-oil products	"Enhanced" salt water microalgae	Demonstration	Open Pond	>USD 40 MM
Cellana	USA	Jet Fuel, Biodiesel & non-oil products	Non-GMO microalgae	Demonstration	Open Pond and PBR	>USD 100 MM
Chingoo Research Partners	USA	Renewable Crude	*Botryococcus braunii*	Lab	PBR	USD 300K
MBD	Australia	Renewable Crude and non-oil products	Microalgae	Lab	PBR	Unknown
Phycal	USA	Jet Fuel and other fuels and sugars	Microalgae and Cassava	Sub-pilot	Open Pond	Unknown
Sapphire Energy	USA	Renewable Crude	Portfolio of microalgae species	Demonstration	Open Pond	>USD 300 MM
Solazyme	USA	Jet Fuel and other fuels and non-oil products	Microalgae and vegetable waste	Demonstration	Fermenters	>USD 320 MM
Synthetic Genomics	USA	Next Generation Fuels & Chemicals	Various including microalgae	Pilot	Open Pond and PBR	>USD 600 MM in 2009; Total to date undisclosed
Univerve	Israel	Renewable Crude and non-oil products	Microalgae	Lab	Small Pond	Unknown

3.7 Summary: Microalgae based fuel internationally

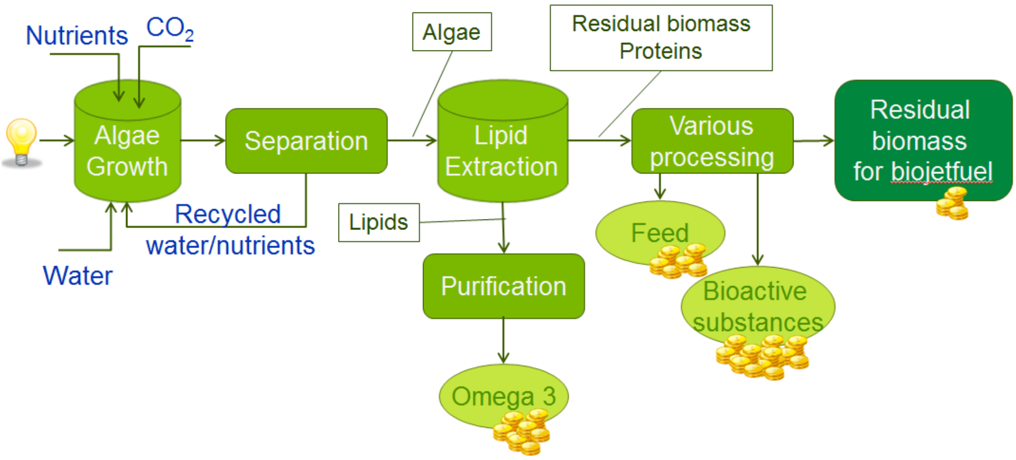
Many of the companies examined in this report are very optimistic about their abilities to produce price competitive and commercial qualities of microalgae based fuel products in the next decade. As is typical in new market and technology areas, few companies will achieve their targets and fewer still will make money doing it. One of the main challenges will be to produce a fuel that is comparable in price and quality to petroleum products, as this market is the refineries which will blend the microalgae products with everything else they produce.

The IEA Bioenergy (2011)[12], quoting various sources, puts the demonstrated productivity at 3,800 litres/ha/yr of algal oil and the future potential at 50,800 litres/ha/yr. The IEA states that it is too early yet for any realistic assessment of the potential for algae production and large scale commercial exploitation, it is probably not possible before 2020.[13]

3.8 Biorefinery for microalgae

Microalgae production will focus on producing a range of products from the biomass produced. There are companies that focus on making biocrude that is used in the current oil refining industry in the US. Technically there is nothing that will hinder the production of biocrude for fuel in the reactors in Norway, but the price for the fuel will be very high. A Norwegian biorefinery from microalgae will most likely produce omega3 for human and animal consumption, in addition to protein based feed and if possible a small amount of bioactive substances as shown in Figure 5. The potential for highly priced bioactive substances depends on the specie of algae, and major research efforts are needed to map the bioactive substances in algae species suitable for production in Norway. Any fuel production is likely to be based on the residual biomass and will not produce significant amounts of fuel in the next 15 years.

Figure 5: illustration of a microalgae biorefinery concept where high value products are the main focus and biomass for fuel is the residuals from the process



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[12] IEA Bioenergy (2011) Algal biofuels Status and Prospects, Annual Report 2010, International Air Transport Association. (2010) *IATA 2010 Report on Alternative Fuels.* 5th Edition. Motreal, IATA. Report number: 9709-03.

[13] **The Potential Role of Biofuels in Commercial Air Transport – BioJetFuel**
IEA Bioenergy Task 40, August, 2012 http://www.bioenergytrade.org/downloads/T40-Biojetfuel-Report-Sept2012.pdf

3.9 Feasibility of microalgae as a source of jet fuel in Norway

The evaluation of algae as a feedstock needs to be kept in context of the demands from the aviation industry. There must be a stable supply of certified product at an acceptable price. The question is not just if algae can be produced in Norway, but if it is feasible for use as part of the jet fuel value chain.

Table 6 Key factors and status for microalgae production in Norway

Key factor	Status and main challenge
Algae strains suitable for Norwegian conditions	Still need for identification of the most suitable species for scale-up. Artic species are in focus
Light requirements	Development of efficient artificial light systems is needed. With artificial lighting, locations are not limited by dark winters in the north, but the need for artificial light leads to higher production cost
Nutrients	“Fertilizing” of the algae production sight is needed. Availability of phosphates may be an issue
Locations near existing industry	Gives access to CO_2, waste heat and infrastructure. Several sites are possible in Norway, among other alongside aluminum and other metallurgic industry.
High value products	High production cost makes high value products like omega3 and feed the most likely products.
Cost	CAPEX is high, as cheaper completely open systems will not be viable in Norway.

Work done by Johannes Skarka,[14] (Figure 6) shows that there is a total microalgae production potential in Europe of 45 Mt/y, with production costs ranging from 629 – 2000 US$ ton. Norway is not included in this survey, but Sweden evaluated as having relatively high production capacity and high costs/ ton, and we can expect this would also be the case for Norway. They have also calculated that, assuming 50 % oil content, 22 % of the jet fuel demand in EU could be provided by microalgae, if all production was used for that purpose.

There are a number of EU projects on the production of algae for fuel. The European Biofuels Technology Platform webpage[15] provides an overview of the EU projects. The current 7th framework programme has an Algae cluster of 3 algae projects, BIOFAT, All-gas abd InteSusAl. [16]

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[14] Johannes Skarka , Karlsruhe Institute of Technology (KIT), Institute for Technology Assessment and Systems Analysis http://www.itas.fzk.de/tatup/121/skar12a.htm

[15] http://www.biofuelstp.eu/algae.html

There is currently a limited production of microalgae in Norway, and the production is geared towards producing high value products such as omega 3, feed, and bio-active chemicals. There are research projects and interest in developing photo-bioreactors that utilize algae that are adapted to Norwegian conditions. Use of excess heat and CO2 from industrial production seems to be a major consideration in the localization of the reactors. The major commercial actor is Biopharmia (http://www.biopharmia.no) who plan on producing Omega-3, EPA, DHA, ALA, beta-1,3/1,6-glucan, astaxanthin and biomass for aquaculture and agriculture uses. The market for higher value products than biofuels (food supplements, feed) will not be a limiting factor in the foreseeable future.

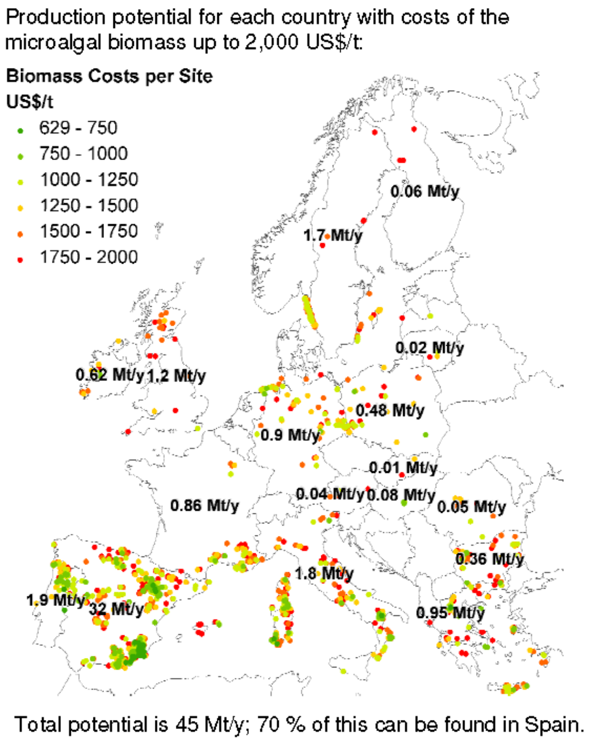

Figure 6. Potential production and costs of microalgae biomass in the EU. [17]

3.10 Modelling of Microalgae production in Norway

The KEMA AlgaeValue tool (see appendix for details) was used to model algae production in Norway compared to a comparable production in Spain. Two production techniques, open oval pound and the closed photo-bioreactor, and three different locations, North Norway, South Norway and for comparison Spain, were considered.

The amount of solar energy available and the different costs of both land and labour are included. The CO_2, heat and electricity cost were assumed to be equal. An algae species was selected with a

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[16] http://www.algaecluster.eu/

[17] Johannes Skarka , Karlsruhe Institute of Technology (KIT), Institute for Technology Assessment and Systems Analysis http://www.itas.fzk.de/tatup/121/skar12a.htm

relatively high lipids production, and different temperature optimal . The other possible products from production were not considered. It is clear that sale of protein and other products will change the overall costs. Since little detailed site and plant specific information was available for these scoping calculations, the main purpose of the modelling is to compare the different scenario outcomes instead of interpreting the absolute results.

Table 7 and Figure 7 show that the price of production in Norway will be over twice of comparable production in Spain. Production in Norway will need to have algae strains that are developed for use in colder (and darker) climates. The different algae types are represented by algae that have optimum growth at the temperatures indicate. The warmer weather/ high light algae are T= 23°C, colder weather algae are represented by T= 18°C, and artic algae (cold weather/ low light) by 6°C. The right type of algae will be essential in keeping the price of production down. Open pond solutions will be more expensive than reactors in Norway.

The breakdown of the costs in the scenarios Spain and Southern Norway are shown in Figure 8. As shown, personnel and consumption costs are the largest costs. Capital costs are between 20-25%. The capital costs can be reduced with technological advances, but personnel costs will only be reduced if the systems become more automated.

Table 7 Results of modelling on amounts of algae produced and costs in Spain and Norway. The numbers are not absolute, and must only be used for comparison of the production methods and geographies.

location	**Spain**				**South Norway**				**North Norway**			
	Open pond		**Reactor**		**Open pond**		**Reactor**		**Open pond**		**Reactor**	
	oil ton/ (yr/ha)	**price** €/ton	**oil** ton/ (yr/ha)	**price** €/ton	**oil** ton/ (yr/ha)	**price** €/ton	**oil** ton/ (yr/ha)	**price** €/ton	**oil** ton/ (yr/ha)	**price** €/ton	**oil** ton/ (yr/ha)	**price** €/ton
Algae (T=23 °C)	39	€ 265	54	€ 256	15	€ 741	21	€ 695	11,6	€ 938	16	€ 880
Algae (T=18 °C)	43	€ 248	59	€ 240	27	€ 673	23	€ 632	13	€ 843	18	€ 790
Algae (T= 6 °C)	34	€ 294	48	€ 285	21	€ 557	29	€ 523	17	€ 683	23	€ 641

Figure 7 Results of the AlgaeValue^{TM} modelling comparing production methods and costs in different geographies. The costs shown are based on all the algae used for oil (triglyceride) production.

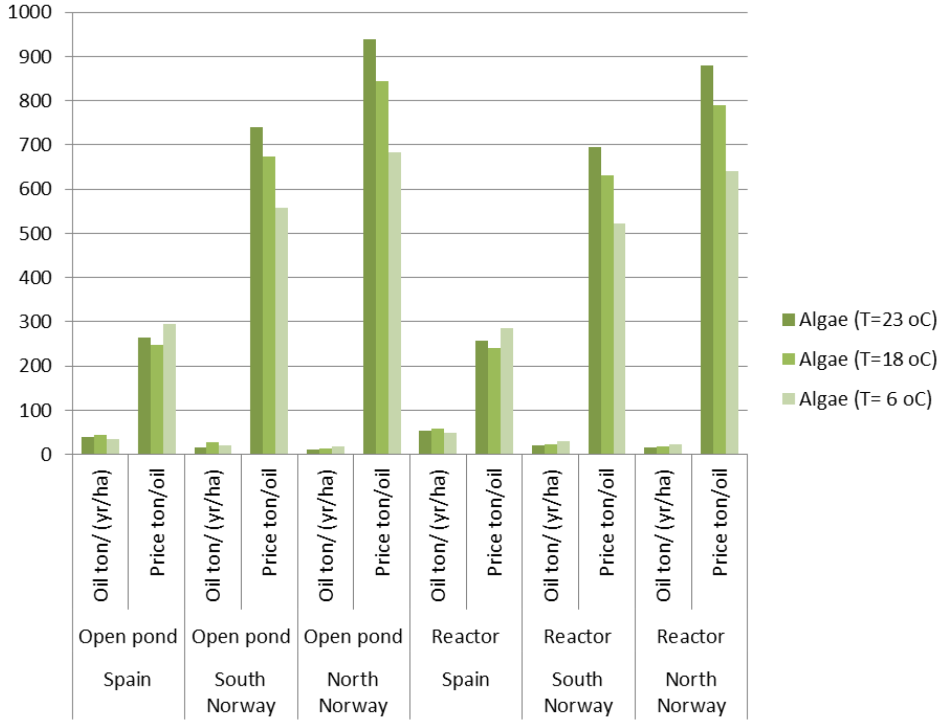
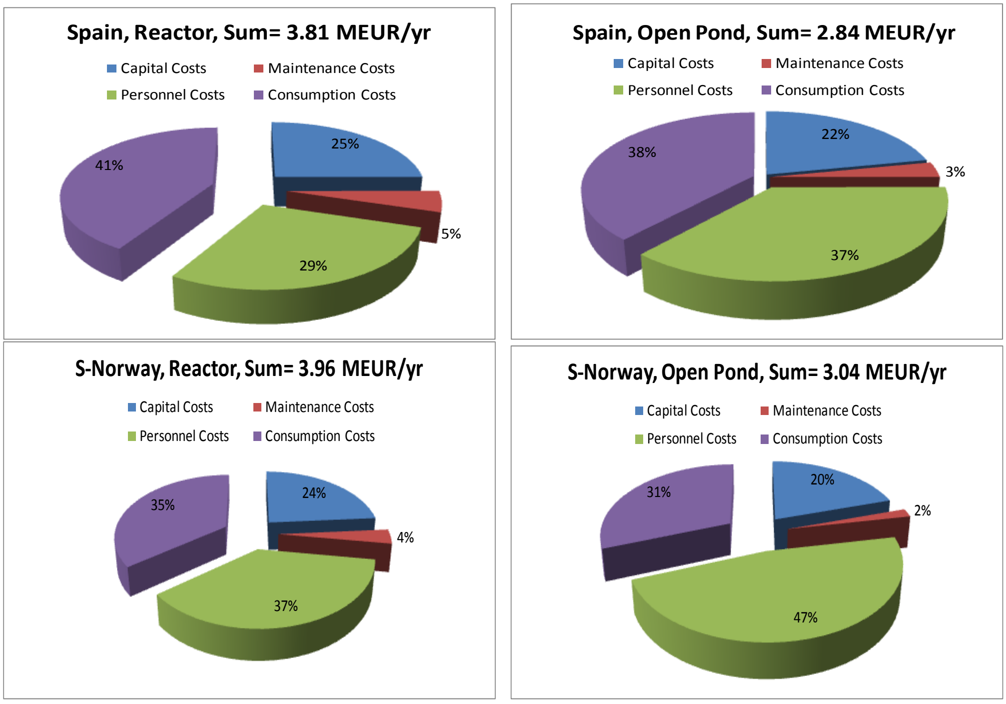


Figure 8 The breakdown of the costs in open pond and reactor simulations for Spain and Southern Norway.



3.11 Summary discussion

All parts of the microalgae production must be optimised in order to bring down the costs of the final product. The major areas are discussed in a Norwegian context below.

- **Algae** – fit for purpose strains that perform consistantly in the environment in question. Different producers will need different strains.
    - In Norway the focus is on algae species and strains that have one or several properties that can make the production of microalgae commercially viable. The focus is finding algae that have active bio-products or high yield of high value products, such as omega 3.
    - The time line from natural identification to a commercially viable strain can be illustrated by the Aquatic Species Program (ASP) funded by the Department of Energy (DOE) under the Office of Fuels Development from 1978 to 1998. This program collected over 3000 species of algae and had concurrent laboratory studies investigating algae's composition and oil yield and outdoor studies testing large-scale systems and analyzing the cost-efficiency. [18] None of the strains in the database were completely suitable for biofuel production, but are a valuable resource for further research.
    - Norwegian research institutions have algae collections and are actively working to identify suitable strains for production in Norway
    - The development of a suitable commercial strain is underway, but the time scale is unknown.

- **Control of the growth environment**
    - Correct light/ alterntative light sources
    - Norway has variable hours of daylight and low light intensities. Assuming that year round production is needed, artifical light will need to be used at least part of the year, giving an added expense.
    - CO_2 – a suitable source at a comptetitive price. CO_2 from industry often needs to be cleaned before use due to other imputrities. Production of biofuel will require a cheap source of CO_2. This limits the number of production locations in Norway.
    - Nutirients – a inexpensive source of nutrients is needed. Waste water is one alternative. This requires that there is a certain popluation of people and a source of waste water that is not used already. Many of the locations where there is CO_2 the population density will be small, and the available waste water limited.

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[18] Gao *et al. Chemistry Central Journal* 2012 **6**(Suppl 1):S1 doi:10.1186/1752-153X-6-S1-S1
http://journal.chemistrycentral.com/content/6/S1/S1

- **Volume** – upscaling is needed. The production needs to be large enough that the logistics of fuel production are profitable. It will take many years to move from pilot plants to many production units with a large volume.

- **Costs** – the CAPEX needs to be managed, and should come down when the volume of production allows efficient production of equipment. Labour costs will not go down, so the equipment needs to be as automated and easy to clean and maintatin as possible.

Microalgae production in Norway may be developed over time into a new and profitable business sector. However, given the price of production and the current focus on producing high value products, there will be little biomass or oil produced for the national fuel market in Norway. There may be microalgae based fuel available on the international market by 2030, but there are a large number of challenges to be overcome before the volumes will make an impact on the availability of microalgae based biofuel for use in aviation.

4 MACROALGAE = SEAWEED

4.1 Introduction

There are three types of macroalgae:

Green algae - Chlorophyta phylum, bottom dwelling, uni- and multicellular, no other pigments that mask chloropyll, includes Sea lettuces (also named *Ulva*)

Brown Algae -Phaeophyta phylum, multicellular bottom dwelling, chlorophyll, and yellow-brown pigments such as fucoxanthin, found on temperate and polar rocky coast, is the largest and most complex of the seaweed groups; includes Kelp

Red algae - Rhodophyta, the largest group of seaweeds (has the most species), contain red pigments phycobilins, includes Coralline algae

Macroalgae as a food source is a $7.5 billion business, while the international market for algal hydrocolloids is currently a $985 million. Around 1.1 million tons is yearly harvested from wild populations.[19] Cultivation of seaweed has a long tradition in East-Asia. The annual production of 14.9 million ton wet weight (FAO 2009) represents the largest aquaculture production on a global basis and is 93 % of the worldwide commercial harvest. Seaweed cultivation in Europe is still in its infancy with a few commercial attempts. Total production of these farms combined is less than 50 ton wet weight and all is used in the food industry.[20]

Fuel from macroalgae is currently not available on a commercial scale.

There are currently 180 people are working in the seaweed industry in Norway, around 45 of these harvest seaweed.[21] Norway currently harvests about 150,000 to 190,000 tons of “wild stock” *L. hyperborea* algae a year that is used for alginate, food and feed. This is under strict control to ensure sustainable harvesting. It may be possible to harvest larger areas, but the algae used for alginate is not the type that is suitable for commercially targeted ethanol fermentation. *A. nodosum* is harvested between Møre and Romsdal and Nordland. The annual landings are 10-20 000 tons are for seaweed meal for agricultural, nutraceutical and cosmetics use. *Ulva lactuca* is harvested by hand in Rogaland yearly and sold to restaurants.

Since there are no established methods of growing, harvesting and converting macroalgae suitable for culturing in Norwegian waters, new methods will be needed in order to produce feedstock that can meet the aviation industry needs. There are a number of research projects that are trying to develop this area, including Norwegian and European research projects.

There are two main routes to produce fuel from macroalgae, either using macroalgae as a generic biomass for a Fisher-Tropsch type process, or to ferment the sugars in macroalgae to ethanol. The

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[19] Fishery and Aquaculture Statistics Yearbook 2007. Rome, Italy.

[20] Macroalgae for second generation biofuels: myth or reality? A European perspective.
Dr Stefan Kraan, Scientific Director and Co-founder Ocean Harvest Technology, N17 Business Park, Milltown, Tuam, Co. Galway, Ireland , Stefan@oceanharvest.ie

[21] http://www.netalgae.eu/uploadedfiles/WP1-Norway-Bioforsk_FOKUS_7(2)_s275-277.pdf

ethanol may be used as a fuel directly (mixed with gasoline) for cars or converted to jet fuel by the developing “alcohol to jet” process. Most of the focus in Europe is on production of seaweed to ethanol.

For this project, major groups in Norway and the EU have been contacted regarding information about the current status of feedstock production and harvesting, logistics and production issues. As all studies have pointed to the considerable potential of seaweed as a biomass source for ethanol and feed most of the algae related research activities in Norway have been focused in this area. There are two major commercial partners in this area in Norway, SES and Statoil. There seems to be a general optimism that seaweed aquaculture will be a viable venture in the future, with a time line of 2020 for the earliest date for an establishment of a biorefinery, and then the establishment of a complete value chain for the various products produced.

4.2 The macroalgae to biofuel production chain

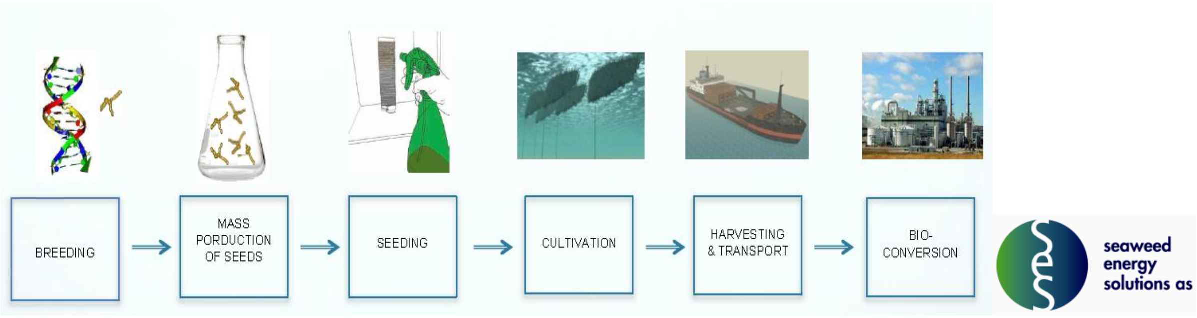

Figure 9: The algae to ethanol production chain. There are currently challenges at all stages of production. Illustration from SES presentation.

The current situation for macro algae production in Norway is, in many ways, similar to the fish aquaculture industry in its initial stages of development. There is a lot of knowledge at the research institutions and within individual companies, but efforts will have to be made at many levels to create a viable industry. There are bottlenecks that need to be overcome at all stages of the production chain. For the results to accelerate into a viable business government support will also be needed. Figure 9 shows the production chain and the main areas of production development.

4.3 Feedstock production

4.3.1 Which algae

L. hyperborea is harvested between Rogaland and Sør-Trønderlag for the production for alginate, the commercial production and propagation for macroalgae for energy purposes has just started. The algae grown for alginate are not suitable for energy production as the sugar level is too low. Given that the algae will be in open environmental systems, focus has been on algae species that are found naturally in environment in question. This means that the breeding, seeding developments and strain selection must be performed in the various geographical areas. As the production of ethanol is the focus of seaweed production in Norway, the species that has the most attention in Norwegian development is sugar kelp (*Saccharina latissima*) with some trials using *Alaria esculenta.* These types of macroalgae are native to Norwegian waters and have high sugar content. Breeding of algae to meet commercial production has started, but these processes will take time.

4.3.2 From breeding to seeding

The production chain for macroalgae starts with breeding, production of seeds and seeding. There are several research environments that have this as a part of their focus area. The production of seeds is understood, but there are challenges in the up-scaling of the process to the volumes needed for commercial production. The best method for seeding is also being developed. The seeding will depend on the methods and species developed for cultivation.

There will probably be a limited number of seeding laboratories will probably serve the industry. This will be a vital part of the commercial development of macroalgae production in Norway.

4.3.3 Cultivation and harvesting

Cultivation methods used in China/ Asia are productive. The production uses ropes and baskets, and the harvesting is manual. The market is food, feed and chemicals, for generally a high price market. Although there is a lot to be learned from cultivation in Asia, the industry will need to develop the cultivation and harvesting system to fit with the Norwegian environment and cost levels.

Manual harvesting will be too expensive in Norway and if fuel production is to be the primary market, costs of cultivation must be brought down.

The Figures (10-11) below show some of the concepts that have been developed for algae production. The commercial interests in Norway are initially concentrating on using shallow coastal waters where there are documented more than sufficient nutrients and minimise issues regarding extreme weather events. With regards to nutrients, it would be possible to cultivate macroalgae further from the coast[22], but growth can be slower and there are more issues regarding extreme weather and harvesting logistics at offshore locations.

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[22] SINTEF

Figure 10 Algae cultivation on rings and ropes (4)

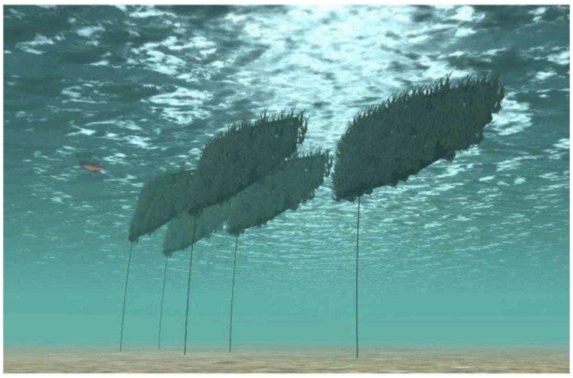

Figure 11 The Seaweed Carrier - SES cultivation concept is inspired by biomimicry is a sheet-like structure that basically copies a very large seaweed plant where seaweed can be seeded and grown on.[23]

A number of alternatives to “conventional” rope cultivation have been launched. There are challenges with all models that need to be addressed, with price and harvesting as central issues. There is a general opinion that harvesting solutions will be found as soon as there are systems that provide commercial levels of algae biomass.

4.3.4 Integrated growing systems

Integrated Multi-Trophic Aquaculture (IMTA) is the combined cultivation of multiple commercially farmed species that belong to different levels on the food chain. In an IMTA system, fish are farmed together with other species including shellfish (such as mussels) and algae or seaweed, creating a more efficient, cleaner and less wasteful production system. IMTA allows nutrients from fish farms that are otherwise lost to the environment to be turned into useful products as they are utilised by these additionally grown species. Two concepts are illustrated in Figure 12.

The development of the idea of integrated growing systems will now be funded by the EU with a €5.7 million project, called IDREEM (Increasing Industrial Resource Efficiency in European Mariculture) set to start in October 2012, coordinated by the Scottish Association for Marine Science (SAMS).

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[23] http://www.seaweedenergysolutions.com/seaweed/our_solution/

From the interviews with stakeholders in Norway there was an interest in integrated growing systems, (IMTA). The concept will need to more mature before the major fish aquaculture community in Norway looks to this type of production. Given that the nutrients from the fish farm are detected at considerable distances from the source, the algae production does not need to be in what could be physical conflict with the fish farms. There are estimates that the area of *S. latissima* needed for remediation of a 500 tonne salmon farm in Scotland, over the two year growth cycle, would be between 20 and 100 hectares.[24]

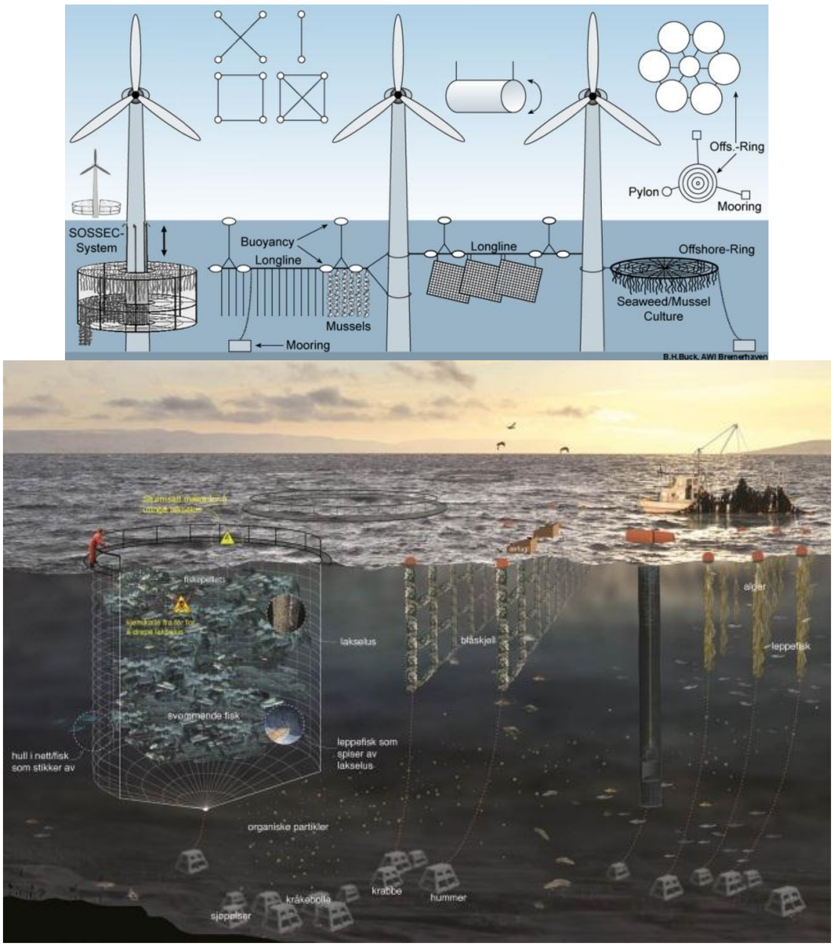

Figure 12 Two different views of integrated offshore marine products production concepts [25]

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[24] SANDERSON, J. (2006) *Reducing the environmental impact of seacage fish farming through cultivation of seaweed.* Scottish Association of Marine Science

[25] http://www.awi.de/en/research/new_technologies/marine_aquaculture_maritime_technologies_and_iczm/projects/marine_aquaculture_projects/roter_sand/
http://www.bellona.org/imagearchive/Ocean%20forest%20project.jpg

4.3.5 Nutrients

Macroalgae need CO_2, nutrients and light to grow. According SINTEF fisheries and aquaculture CO_2 is abundant and exposure to light can be regulated by regulating depth at which the algae are grown. The amount of nutrients is growth rate determining.

The FAO Culture of Kelp Manual states that the need for fertiliser depends on the minimum nitrogen growth requirements of kelp and the hydrodynamic regime of the farm area[26] The water needs to be able to distribute the nutrients, and there are many areas along the Norwegian coast where the water has a good nutrient flow through up-welling. Nitrogen uptake is important for heat tolerance and maximising the growth season, which can improve yields. According to simulations[23] several locations along the coast of Norway as well as off-shore locations have sufficient nutrients to be suitable for macroalgae cultivation.

The nutrient availability can also come from pollution sources, and algae production can remove some of the nutrients from the water around, for example, aquaculture production areas. Given that nitrogen has been detected 500 – 1350 m from a fish farm[27], there are benefits for growth of the algae and nitrogen removal from the water.

4.4 Commercial production and industrialisation

The main focus of the current activities in macroalgae production is to produce a feedstock that is suitable for ethanol fermentation for fuel, with the utilisation of by-products.

The commercial production of algae requires that there is feedstock, a refinery and logistics that can produce enough products such that investment and running costs are met and a profit is made. Estimates made to date indicate that an area of 10 000 ha needs to be available to deliver the 2000000 ton/ year needed to produce 200M l ethanol. This is the amount of ethanol that will need to be produced to have a viable biorefinery. The area required for production is illustrated in Figure 13.

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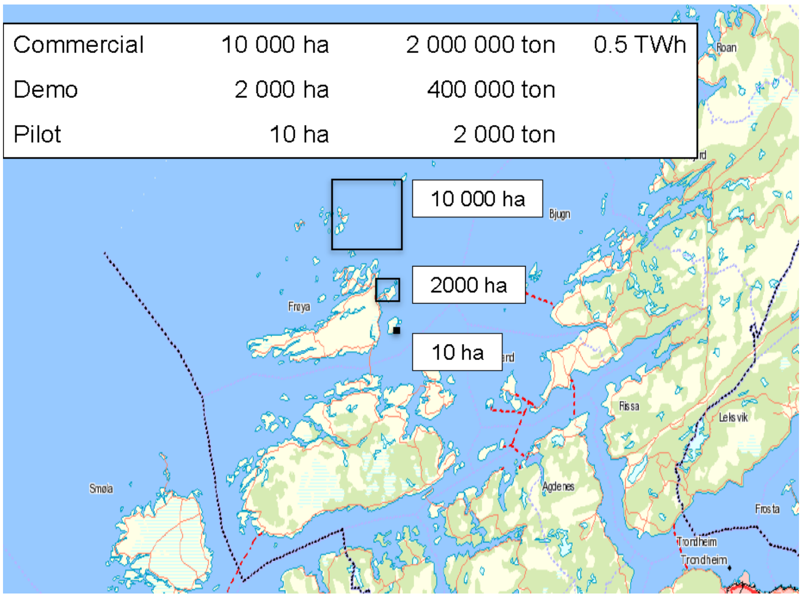
[26] FAO (1989) *Culture of kelp (Laminaria japonica) in China. Training manual 89/5.* Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/docrep/field/003/AB724E/AB724E00.htm

[22] SINTEF

[27] SANDERSON, J. (2006) *Reducing the environmental impact of seacage fish farming through cultivation of seaweed.* Scottish Association of Marine Science,



Commercial	10 000 ha	2 000 000 ton	0.5 TWh
Demo	2 000 ha	400 000 ton	
Pilot	10 ha	2 000 ton	

Figure 13 An illustration of the total area that will be required to meet the production of one biorefinery. [28]

4.4.1 The potential yield of biomass and ethanol

The amount of algae that can be produced per given area will depend on a large number of factors, such as light, temperature, water quality and nutrients. There will be differences in the natural growth density, and the range has been estimated by various stakeholders, as given in Table 8. Given the wet ton weight and assuming that 80% of the carbohydrates are converted to ethanol and the 10% of the wet weight is solids, the ethanol produced per/ hectare was calculated and given in Table 8.

Table 8 Estimates that give the potential ton/ algae/ Ha and the ethanol production expected. The estimated values are based on experience in other countries, the natural growth densities and from field trials in Norway. The ethanol production is based on 10% solids in wet weight and 80% conversion of carbohydrates to ethanol.

Estimates by[29]		ton wet algae /Ha	L Ethanol/ton wet algae
SINTEF	min	75	37
	max	140	78
SES	min	200	43
	max	250	50
Kraan	min	100	50
	max	133	50

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[28] http://greengrowthnordic.no/docs/foredrag//Day%202,%20Session%201%20-%20Green%20growth%20in%20marine%20food%20production/Andreas%20Putz%20-%20A%20seaweed%20cultivation%20business%20-%20dream%20or%20reality.pdf

[29] See interviews in appendix A

4.4.2 Estimates of feedstock cost

Feedstock costs are a significant part of the product cost, some estimate feedstock are around 37% of the product cost.[30] The successful commercialisation of algae to fuel will require that the feedstock prices can be drastically reduced compared to the current prices for macroalgae (see Table 9)

Table 9 Prices of seaweed/ ton[31]

Seaweed species	US $ /ton (2009)
Gracilaria	1300
Lessonia	950
Cottonii	1400
Spinosum	350
Chondrus	3400
G. skottsbergii	3000
S. crispata	2300

The current cost of sugar kelp is at least 30 €/ton wet weight, which gives a feedstock cost of 0.4 to 0.8 €/L ethanol (see Table 10). This cost estimate is feedstock alone. The processing cost is not estimated since the process is not established enough to give reliable estimates of cost at scale. The feedstock cost estimate for ethanol is based on the yields of ethanol/ton wet algae given earlier and assuming that ethanol is the only product. With a biorefinery concept, the cost of feedstock will be distributed between the various products, and the cost for ethanol will be lower. The estimate for bio jet fuel (also table 10) is based on the assumption that 2 litres of ethanol will give 1 litre of bio jet fuel in the "alcohol to jet" process[32] and a feedstock cost estimate for ethanol.

Table 10 The feedstock cost estimate for ethanol based on the yields of ethanol/ton wet algae and assuming that ethanol is the only product. Bio jet fuel estimate is based on 2 L of ethanol giving 1 L of bio jet fuel[25]

Feedstock cost €/L		30 €/ ton wet algae	20 €/ ton wet algae
Feedstock Ethanol	Min	0,4 €/L	0,3 €/L
	Max	0,8 €/L	0,5 €/L
Feedstock Bio jet fuel	Min	0,8 €/L	0,5 €/L
	Max	1,6 €/L	1,1 €/L

During the interviews the commercial algae production companies stated that they aimed to produce feedstock for 20 €/ton, which will give feedstock costs from 0.5 to 1.1 €/L bio jet fuel. Production and transport costs will come in addition to the feedstock cost.

Capex in bioenergy systems range from $4 to $9/ gal ethanol (0.82 to 1.85 €/L)[33].

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[30] http://www.winrockusprograms.org/public/pdfs/EDA-bioenergy-apr12-economics.pdf

[31] Harris J. Bixler & Hans Porse , 2010, A decade of change in the seaweed hydrocolloids industry, J Appl Phycol http://www.algaebase.org/pdf/AC100CF011cce16156PIqW9AFCE2/Bixler_Porse.pdf

[32] http://www.lanzatech.com/ This is a yield in the area of 80 % from ethanol to biojetfuel.

[33] http://www.cinram.umn.edu/srwc/docs/Powerpoints/M.Downing_Economic%20and%20Social%20Aspects%20of%20Bioenergy%20Systems.pdf

4.5 Biorefinery for macroalgae

4.5.1 A potential biorefinery process

Macroalgae consist of carbohydrates (alginate, laminaran, and mannitol), proteins and various minerals such as phosphorus. There will be a range of products that can be produced from these constituents (see Table 11).

Table 11 Possible products from macroalgae

Constituent	Product	Intended use	Source of biojetfuel	Comments
Laminaran	Ethanol (butanol)	Bioethanol	Yes	Fermentation of laminaran to ethanol, then potential conversion to jet A-1 through the “Alcohol to jet” process
Mannitol	Ethanol (butanol)	Bioethanol	Yes	Fermentation of mannitol to ethanol, then potential conversion to jet A-1 through the “Alcohol to jet” process
Alginate	Alginate	Cosmetics etc.	No	
	Ethanol (butanol)	Bioethanol	Yes	Fermentation of alginate to ethanol, then potential conversion to jet A-1 through the “Alcohol to jet” process
Proteins	Proteins	Animal feed	No	Proteins cannot be converted to alcohols.
Residual biomass	Ash containing various minerals	Fertilizer and soil conditioner	No	Ash is an inorganic material and cannot be converted to fuel
	Biomass for “wet combustion”	Fuel	No	The amounts of residual biomass are too small to be considered for biojetfuel

In Norway, most of the development in cultivation of macroalgae focuses on *Saccharina latissima* (Sugar kelp); the chemical composition is given in Table 12. A macroalgae biorefinery will therefore have sugar kelp as its main feedstock. Ethanol from the carbohydrates and animal feed from proteins are the likely major products from such a biorefinery, although this process is not yet operational. The residual biomass consists in large part of mineral residue that contains important minerals like phosphorous and can be used as soil conditioner or fertilizer.

Table 12 ***Chemical composition of Saccharina Latissima***[34]

	% of D.M.
Carbohydrates	50-65 %
Proteins	6-15 %
Mineral residue	15-40 %

The current main commercial use of algae in Norway is FMC production of alginate from *Laminaria hyperborean* (tagle), as it has a suitable carbohydrate composition for alginate production. The algae are preserved with formaldehyde during transportation and this excludes the possibility of ethanol production from the same feedstock as is used for alginate production. Sugar kelp is not suitable for commercial scale alginate production. Due to this, alginate is not a part of the product portfolio from a sugar kelp biorefinery. A schematic of a macroalgae biorefinery is given in Figure 14.

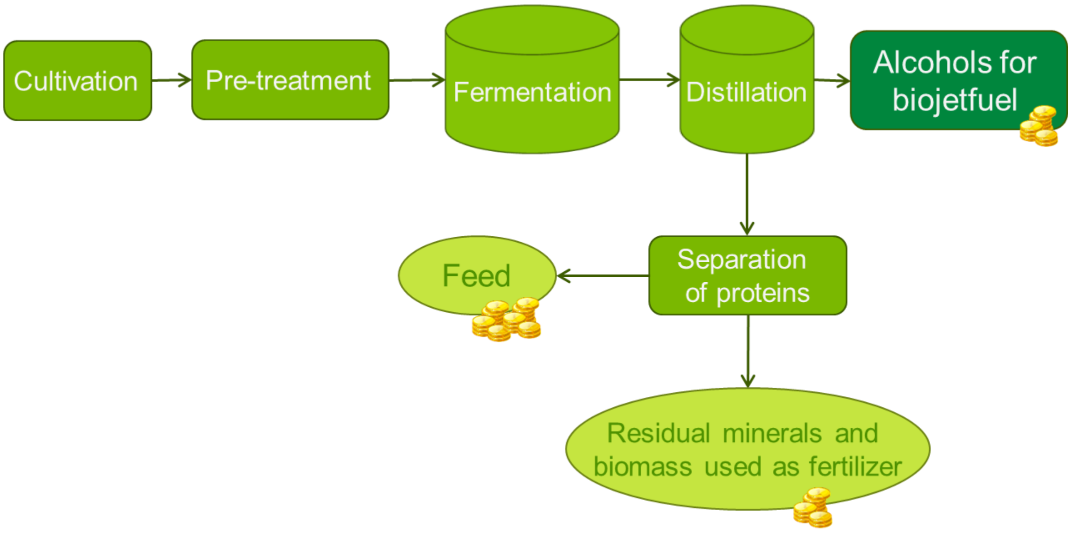

Figure 14 A schematic presentation of a possible macroalgae biorefinery.

4.5.2 Bioprocessing of macroalgae

Wet macroalgae can be fermented directly after a simple mechanical pre-treatment (cutting/grinding). The sugar concentration in the fermentable solution is about 100 g/L (carbohydrates content is ca. 60 % DM). This is a bit lower than the theoretical optimum (~150 g/L), but it is less costly to distil the resulting ethanol from a more diluted solution than to concentrate the starting material. Laminaran and to some degree mannitol can be fermented to ethanol with conventional microorganisms (non GMO). Modified microorganisms are needed to ferment alginate, and these are also better at fermenting mannitol. In lab scale experiments, 80 % of the

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[34] Agrimer – algues marines

carbohydrates (including alginate) have been fermented to ethanol[35]. And with process development and development of optimized microorganisms for this process, an 80-90 % yield should be obtainable for an industrial process.

The potential yield of feed and ethanol is limited by the protein and carbohydrate content of the seaweed. As the Figure 15 shows, the carbohydrate content is higher in the summer/fall, and therefore the potential ethanol yield is higher for seaweed harvested in the summer/fall. Proteins cannot be converted into ethanol, but has the potential use as animal feed. During the winter months the seaweed consumes its own carbohydrates, and therefore the relative protein content is higher in winter.

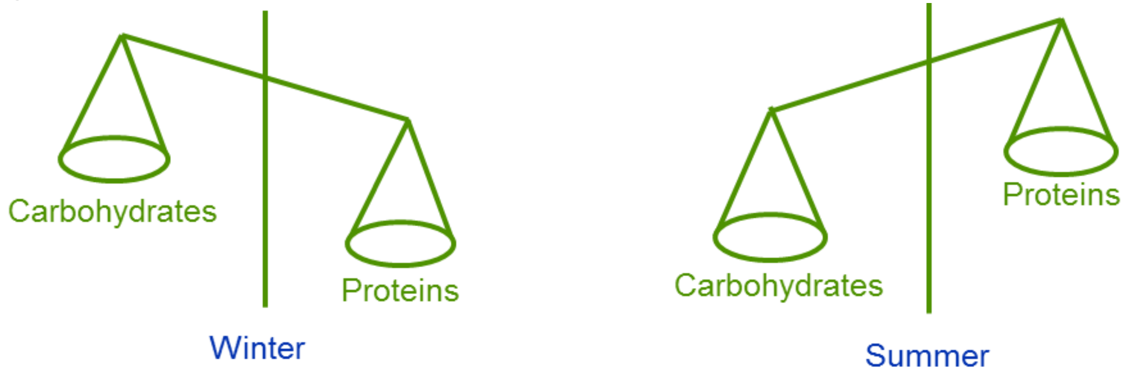

Figure 15 the carbohydrate content is higher in the Summer/Fall, and therefore the potential ethanol yield is higher for seaweed harvested in the Summer/Fall.

For a macroalgae harvested with a given carbohydrate and protein content, the production process can be optimised with regards to either ethanol or feed production. The product mixture can be adapted to changes in the marked and the feedstock (see Figure 16). Extraction of proteins for feed requires more water than producing ethanol. This will lead to an increased overall production cost. When the protein content is at its lowest in the summer/fall, it might be more profitable to use all the remaining biomass after ethanol distillation as fertilizer and soil conditioner instead of extracting proteins.

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[35] Wargacki et al., 2012

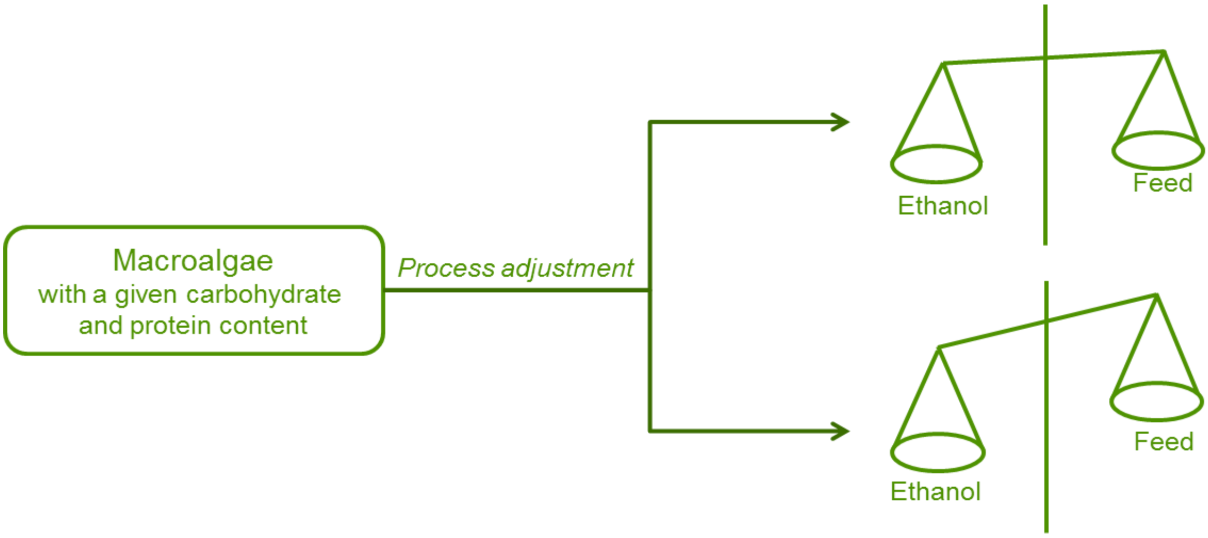

Figure 16 The product mixture can be slightly adapted to changes in the marked and the feedstock. Process adjustments can alter the ratio of ethanol and feed, but not tip the scale entirely. The chemical composition of the macroalgae feedstock is the main reason for the product mixture.

It is also possible to ferment sugars into butanol instead of ethanol. Butanol has a higher energy density than ethanol, and is also a better starting point for the “alcohol to jet” process. The fermentation from sugar to butanol has not been done on a commercial scale yet (either from macroalgae or other sources of sugar), and most of the efforts are still at the research stage. Some research institutes like “Danish Technological Institute” and Berkeley (BAL) are working on macroalgae to butanol, and as there is considerable interest in this conversion pathway. The main focus, however, is on producing ethanol where the technology is much more developed and makes ethanol production is more promising as a biofuel from macroalgae in the foreseeable future.

A biorefinery needs to produce the optimal combination of products based on the market prices and feedstock availability. If the market for proteins is very good, it could be that the process utilised is optimized for protein production, and this can possible reduce the amount of biomass that is available for fermentation.

4.5.3 Conversion of macroalgae to fuel

There are two main pathways for conversion for the algae biomass – thermal conversion and fermentation to alcohol. The industry in Norway is currently focused on conversion to ethanol, but the biomass produced can be used for fuel production by other technologies.

Thermal conversion of macroalgae is challenging as macroalgae have:

- High moisture content (up to 90wt %).
- High ash content (up to 50wt %).
- High alkali metal content (high K and Na)
- High nitrogen and sulphur content (up to 3.5wt % N)
- High halogen content (KCl, NaCl)
- Low heating value (10-15 MJ kg-1)

Hydrothermal processing – the reaction of biomass in water at high temperature and pressure (200-500 C, 100-200 Atm) is a developing technology that is a possible option:[36]

- Advantages
    - Tolerate high moisture content
    - Tolerate high ash content
    - Can produce biochar, biocrude or syngas depending on conditions
- Disadvantages
    - High pressure
    - Technological challenges (technology still in development stages)

4.5.4 A reliable, yearlong supply of biomass is needed

One requirement for an economically viable macroalgae biorefinery is a plant that can operate continuously throughout the year. To achieve this, a reliable source of biomass for the whole year is needed. There are three ways of obtaining this:

Alternative A – Harvest throughout the year
The carbohydrate and protein content of macroalgae varies through the year. Cultivation trials have shown that the optimum time for harvesting with regards to sugar content is in June[37]. The protein content is higher in the winter and spring. The variation in the feedstock quality will require adjustments to the processes in the biorefinery.

If one is to harvest at various times throughout the year the biorefinery process has to be able to cope with extensive variations in the feedstock quality, and cultivation and harvesting techniques may have to be adapted to the different seasons.

Alternative B- Preserving/ maintaining harvested macro algae
Trials for maintaining harvested algae have shown that considerable degradation takes place, including release of mannitol, when the algae are kept in sea water. Currently there are no viable techniques for preserving macro algae without the use chemicals that will hinder fermentation.

Alternative C –Multiple sources of biomass
If a biorefinery can process both macro algae and lignocellulose (either wood or other terrestrial plants) then it could be feasible to source raw material for continual production. Some of the same production units, like the fermenter and distillation unit, are used in the processing of both sources of biomass, but additional process steps for each biomass source are needed (separation of lignin and cellulose, processing of lignin after fermentation). There are also some challenges in the value chains of the various products which may be different depending on the feedstock. The robustness of the process towards variation in the raw material must be even greater than in alternative A, and two of the major challenges are:
The choice of microorganism/ enzymes for fermenting carbohydrates from macroalgae and lignocellulose, and handle the different fermentation conditions.

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[36] Thermal conversion of *macroalgae* *www.algecenterdanmark.dk/_root/media/46123_Andy%20Ross.pdf*

[37] Theoretically, the sugar content of *Laminaria saccharina* is highest in September, but in practice bio-fouling in the summer months leads to the best harvesting results in the spring/ early summer.

The process will have to be controlled so that down time and periods of low yield is reduced to a minimum when changing between biomass sources.
It is uncertain if a macroalgae /lignocellulose biorefinery in sum will have any advantages over a pure algae or a pure lignocellulose biorefinery.

From a process view, alternative A is the most viable for processing macro algae, but it is uncertain if it is possible and practical to harvest macroalgae throughout the year.

4.5.5 The price of a biorefinery demo plant

To estimate the investment cost of a biorefinery demo plant for macroalgae, or a combined macro algae and lignocellulose biomass demo plant will require more detailed information regarding the production process than is available at this point for this emerging industry. To have a ballpark estimate, one can look to similar demoplants. Borregaard is building a second generation bioethanol demo plant in Sarpsborg which is designed to process various types of lignocellulosic biomass to ethanol and other products. A macroalgae demo plant will have a complexity that is similar or higher than Borregaards demo plant. Borregaards has a price of around 130 million NOK[38], and it can be assumed that the price of a macroalgae demo plant will be in the same range.

4.6 Feasibility of macroalgae as a source of jet fuel in Norway

Macroalgae production as a feedstock to ethanol for bioenergy use seems to be a promising industry for development along the Norwegian coast. There are suitable native algae; there are locations to grow the algae and considerable competences in place, although this must be strengthened, and a market of the products if the price of production can be lowered. There will need to be focused efforts in all parts of the production chain. The timeline for this development, however, is uncertain, with the most optimistic prognosis being 2020 for the start of construction the first biorefinery. The status is illustrated in Figure 17 and in Table 13. There is little to suggest that there will be large volumes of ethanol (or jet fuel) available before 2030.

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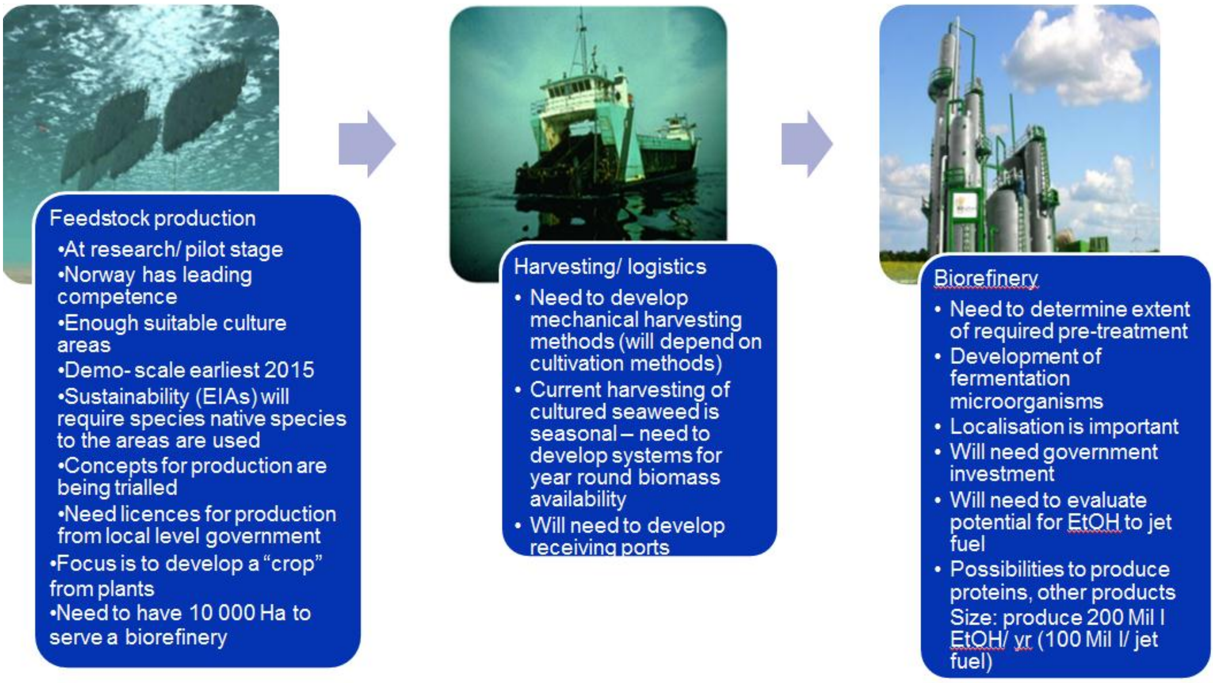
[38] http://www.borregaard.com/content/view/full/17331

Table 13: Factors and challenges for macroalgae production in Norway

Key factor	Status and main challenge
Seaweed species	Sugar kelp is the main species of interest Needs to be developed from a “wild strain” to a “crop strain”
Propagation methods	Lab scale needs to be scaled up to commercial production
Growing methods	Appropriate methods for growing – ropes, new scaffolding Investment costs for these Suitability for mechanized harvesting and Norwegian climate
Harvesting methods	Development will depend on the growing methods Mechanical harvesting will be required
Nutrients	Both locations near the shore and off-shore locations have sufficient nutrients for seaweed cultivation Nitrogen excess from aquaculture can be utilized
Localization and permitting	Laws will be similar to aquaculture laws Permitting for location. Conflicts with regard to local area use is to be expected
Sustainability	Will need to perform environmental impact assessments and have monitoring plans Ensure that production follows international biofuel standards
Processing of macroalgae	Biorefinery processes optimization based on feedstock and product portfolio Enzymes/ bacteria processes Stable feedstock supply is vital
Funding	Will need private investors and government support for biorefinery demo plant, research and incentives



Feedstock production

- At research/ pilot stage
- Norway has leading competence
- Enough suitable culture areas
- Demo-scale earliest 2015
- Sustainability (EIAs) will require species native species to the areas are used
- Concepts for production are being trialled
- Need licences for production from local level government
- Focus is to develop a "crop" from plants
- Need to have 10 000 Ha to serve a biorefinery

Harvesting/ logistics

- Need to develop mechanical harvesting methods (will depend on cultivation methods)
- Current harvesting of cultured seaweed is seasonal – need to develop systems for year round biomass availability
- Will need to develop receiving ports

Biorefinery

- Need to determine extent of required pre-treatment
- Development of fermentation microorganisms
- Localisation is important
- Will need government investment
- Will need to evaluate potential for EtOH to jet fuel
- Possibilities to produce proteins, other products Size: produce 200 Mil l EtOH/ yr (100 Mil l/ jet fuel)

Figure 17: An overview of the seaweed to jet fuel issues in Norway.

5 SUSTAINABILITY AND BIO JET FUELS

Sustainability is a broad term, and needs to be defined for the case at hand. Sustainability includes environmental, social and financial issues where all three aspects need to be considered to ensure sustainability. In the case of algae production, the production should be financial viable, the environment needs to be preserved, and the production should not lead to social injustice. All aspects need to be considered in relation to where production is taking place. Materiality of the issues needs to be assessed for each production site.

This report focuses on algae that will be the feedstock for biofuels. This means that the production must meet the sustainability requirements of the country for production of algae itself, and in addition the requirement specific to fuel where the fuel is sold and should meet the requirements that the airline industry sets. The specific issues for the different types of production are covered below.

The sustainability criteria for fuel are based on a sustainable production of the feedstock.

The EU Directive 2009/28/EC (Renewable energy directive: RED) requires:

- Proof of sustainability of biomass:
    - no production from no-go areas (high biodiversity or high carbon stocks),
    - sustainability of production and operations
    - monitor social sustainability and food security
- Raw material should not be obtained from :
    - wetlands
    - continuously forested areas
    - from areas with 10-30% canopy cover
    - from peatlands
    - if the status of the land has changed compared to its status in January 2008
- GHG savings:
    - biofuels and bio-liquids must yield a GHG emission savings of at least 35%
    - (50% from 2017, 60% from production started after 2017)
- Traceability and mass balance must be assured

Sustainable Aviation Fuel Users Group (SAFUG) has defined that bio jet fuel should:

- Perform as well as, or better than, traditional fossil fuel jet kerosene from a technical perspective but with a smaller carbon lifecycle;
- Use only biomass feedstock sources that minimise biodiversity impacts, require minimal land, water, and energy to produce;
- Not compromise food security;
- Not jeopardise drinking water supplies;
- Provide socioeconomic value to local communities where biomass is grown

The SAFUG has recommended The Round Table for Sustainable Biofuels (RSB) certification scheme, as it is currently the only EU approved certification scheme that includes social and biodiversity issues. The principals and how they relate to algae production in Norway is given in Table 14.

Table 14 Certification Principals that biofuels from algae will need to meet.

RSB Principles	Microalgae in Norway Assuming closed system	Macroalgae in Norway Assuming natural strains
Legality	No use of GMO, permits	Will need national and local permits
Planning, Monitoring & Continuous Improvement	A quality control system	Will need approved monitoring systems for ecosystems
Greenhouse Gases Emissions	Appropriate distribution of GHG between products	Need to have carbon uptake data in addition to energy use in the whole production chain
Human & Labour Rights	Norwegian laws	Norwegian laws
Rural & Social Development	Localisation of production	Ensure that local counties get a fair % for area usage
Food Security	Can add to food security	Show that there is no negative effect on fish
Conservation		Show that there is no negative effect on ecosystem
Soil		Should be positive with soil enhancement products
Water	Release of organisms in water, water use	Water quality can be improved
Air	Norwegian laws	Norwegian laws
Use of Technologies, Inputs & Management of Wastes	If GMO are used – need to have approvals and control	If GMO are used in processing– need to have approvals and control
Land Rights	Permits	For biorefinery and on land activities

5.1 Sustainability of microalgae

The sustainability of production for fuels from microalgae will depend on the location and the type of algae used. Water availability is often a major issue in algae production. As lack of available water does not tend to be a limiting factor in Norway, the main risks would be the potential for discharge of contaminated water from the algal ponds/ reactors, and a biosecurity risk if selected biofuel algal strains escaped into the environment.

Algae need CO_2 to grow, and the growth will give a positive benefit in CO_2 recycling. Given the price of CO_2 in larger amounts, the algae production will presumably be in the vicinity of a CO_2 release point. This use is a positive effect on the amount of CO_2 released into the environment. Based on the average chemical composition of algal biomass, approximately 1.8 tonnes of CO_2 are needed to grow

1 tonne of biomass. Flue gas typically contains about 4 % to 15 % CO_2. In open systems not all of the supplied CO_2 will be absorbed, so flue gas is added in excess. The CO_2 absorbed into the algae can replace the CO2 that would come from fossil fuel during combustion if the algae product is used in an combustion engine or to produce electricity. There is currently no approved methodology for getting carbon credits from algae as such, but there are fuel replacement methodologies that will allow for carbon credits once the technology is mature enough to produce the needed data on production so that the CO_2 savings compared to fossil fuels can be verified.[39]

Part of the CO_2, NOx and SO_2 will dissolve; the rest will enter the atmosphere.[40] In closed systems it will be easier to calculate the amount of CO_2 absorbed.

5.1.1 LCA of algae production

Performing LCAs of algae production is one way of determining the sustainability of the production pathway. Performing an LCA is beyond the scope of this work, but it worth mentioning in a sustainability perspective. Several LCA studies have been performed on algae production. The results have been variable, which is not surprising given that there is currently no established production methodology optimised for biofuel production.

Table 15 Overview of Global Warming Potential claims in microalgae biomass LCA[41], [42]. The LCAs performed on microalgae have used different reference systems. The results have shown that production can compare favourably compared to fossil fuels (diesel or gasoline) but production methods will determine if the amount of CO_2/ GHG released. The energy used in centrifugation can result in a "+ GHG" use compared to a "less GHG" result using filter press.

Author & Year	Reference System	CO_2 balance
Kadam 2002	Electricity from coal firing	- 36.72 % (direct injection of the flue gas) - 2.46 % (monoethanolamine (MEA) extraction of CO_2 from flue gas
Lardon *et.al.* 2009	Diesel	- 25 %
Clarens *et.al.* 2010	Corn /canola / switch grass	+244 % / +189 % / + 233 %
Sander & Murthy 2010	Gasoline	-117 % (dewatering using filter press)[a] +14 % (dewatering using centrifuge)
Stephenson *et.al.* 2010	Diesel	-78 % (Raceway ponds) +273 % (PBR)
Campbell *et.al.* 2010	Diesel per freight Km.tonne	-66 % -122 %

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[39] http://www.fao.org/uploads/media/0903_CSIRO_-_Greenhouse_gas_sequestration_by_algae.pdf
Peter K. Campbell, Tom Beer, David Batten **Greenhouse gas sequestration by algae – Energy and greenhouse gas life cycle studies**

[40] Sustainability of energy from *algae* - FAO, ftp://ftp.fao.org/docrep/fao/012/i1199e/i1199e03.pdf

[41] http://www.aquafuels.eu/attachments/079_D%203.3-3.5%20Life-Cycle%20Assessment%20and%20Environmental%20Assessment.pdf

[42] Sustainable Aviation Fuels Road Map: Data assumptions and modelling
CSIRO 2011,Paul Graham, Luke Reedman, Luis Rodriguez, John Raison, Andrew Braid, Victoria Haritos, Thomas Brinsmead, Jenny Hayward, Joely Taylor and Deb O'Connell

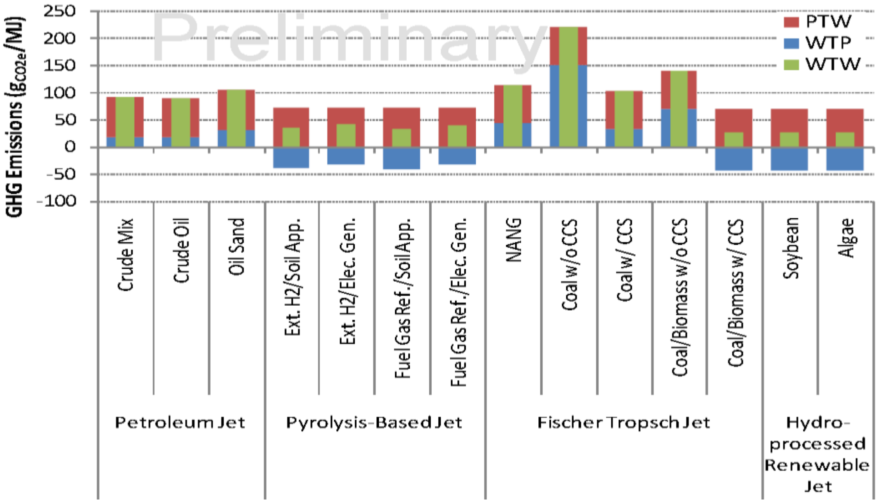
The GHG values of the LCA for microalgae production are shown in Table 14. It is clear that not all production methods will result in a "negative GHG value", meaning that the algae production produces less CO_2 / GHG than the fossil fuel baseline, and thereby not meet the sustainability criteria for biofuels set by the EU and the aviation industry.

The EPA in the US has developed a software tool, GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation), "a full life-cycle model, that allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle from wells to wheels/vehicle-cycle basis"[43] Using this software the EPA has determined that "Diesel produced from algal oils complies with the 50% GHG threshold for the biomass-based diesel category". [44]

A general conclusion from the various LCAs is that all parts of the production will have to be optimised in order to compare favourably to alternative production methods of jet fuels. As shown in Figure 18, algae are comparable to soy based jet fuel. Co-product handling is a key issue, [45] as is reducing the energy from thermal dewatering. The algae plants will need to be co-located with industry with CO2 flue gas and excess heat in colder climates. [46]

"The potential of green algae as a fuel source is not a new idea; however, this LCA and other sources clearly show a need for new technologies to make algae biofuels a sustainable, commercial reality." [47]

Figure 18 WTWa GHG Emissions of Alternative Jet Fuels - LCA Functional Unit: per MJ of Fuel Consumption [48] Algae biomass based jet fuel has a GHG similar to soybean and pyrolysis based jet.



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[43] ***greet****.es.anl.gov/*

[44] http://www.life-cycle.org/?tag=biodiesel

[45] greet.es.anl.gov/files/2012ws_**aviation**

[46] Rudras Baliga and Susan E. Powers , 2010 , Sustainable Algae Biodiesel Production in Cold Climates, International Journal of Chemical Engineering *www.hindawi.com/journals/ijce/2010/102179/*

[47] http://hero.epa.gov/index.cfm?action=reference.details&reference_id=1225651
Sander, K; Murthy, GS (2010) Life cycle analysis of algae biodiesel International Journal of Life Cycle Assessment 7 (Aug 2010) 704-714

[48] greet.es.anl.gov/files/2012ws_**aviation**

5.2 Sustainability of macroalgae

The main environmentally related sustainability issues of production of algae as a feedstock are the avoidance of disturbing the current ecosystems, no invasive species introduction, and good monitoring system in place to ensure that there is no negative effects including detrimental nutrient depletion and plant pathogens/ disease. Sustainability issues will need to be addressed through Environmental Impact Assessments (EIA). The first project will require considerable effort to ensure that the right indicators and issues are addressed, and although all locations will have to perform a separate EIA, important ground work will been undertaken and issues addressed.

Macroalgae also have the ability to have positive impacts on the environment. They can take up excess nutrients, provide shelter for other marine animals, and they take up carbon when they grow. The uptake of carbon is, of course, important in the GHG calculations of the products, ie the fuel. There is currently no standard method of calculating the CO_2 uptake and retention in seaweed. Methods for calculating CO_2 and the retention in the farmed seaweed can possibly make having “standing seaweed” a part of producing CO_2-nuetural algae based products. [49]

Seaweed aquaculture at commercial scale has been primarily in Asia. The expansion has brought benefits in terms of income, employment and foreign exchange, but has also been accompanied by some conflicts with other users of the coastal zone and concerns over potential environmental impacts.[50] The overview of these issues is given in Table 16.

Table 16 Potential physical and environmental issues associated with seaweed culture

OPERATION AND ISSUES	POSITIVE EFFECTS	NEGATIVE EFFECTS
Cleaning and preparation of culture areas **Routine management (weeding, harvesting)**	Improved production and management	Potential loss of native species and habitat diversity
Shading by growing seaweed	Reduced competition	Reduced water column and benthic production
Attenuation of waves and water currents	Shelter for sensitive species	Increased sedimentation
Aesthetic issues	Enhanced coastal productivity in degraded ecosystems	User conflicts Loss of resource value
Space	Enhanced productivity of barren or degraded ecosystems	User conflicts (e.g. with fishermen)
Substrate area and volume	Enhanced productivity of barren or degraded ecosystems	Ecosystem changes
Water quality	Enhanced oxygen, removal of nutrients, seaweed production	Reduced coastal phytoplankton
Fertilization and chemical treatments	Seaweed production, Enhanced polyculture production	Product quality, water quality changes, nutrient cycling, diseases
Benthos	Enhanced polyculture (e.g. with mollusks)	Changes in benthic species and production
Water column productivity	Enhanced production of invertebrates and finfish Shelter of	Predators Changes in community structure

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[49] GAO, K. and MCKINLEY, K. (1994) Use of macroalgae for marine biomass production and CO2 remediation: a review. *Journal of Applied Phycology,* 6**,** 45-60.

[50] http://www.fao.org/docrep/field/003/AB728E/AB728E05.htm

	fish fry , polyculture	

Some of the species used in algae production in Asia are similar, but not identical to the species that will need to be grown in Norwegian waters. All the research performed in Norway uses species that are native to the area, and the work is on developing these to commercially viable strains that are robust and have the optimal combination of traits for the desired products.

There is legislation in place for harvesting of natural (wild) seaweed under the Ministry of Fisheries and Costal affairs (Fiskeri- og kystdepartementet). There is currently no active legislation for algae production, but there is a bill for consultation that stipulates that the same regulation used for aquaculture, that the counties (fylkeskommunen) will have the granting authority and the approval of sites and the allocation of permits with the Ministry of Fisheries and Costal affairs also involved in the evaluation, and are currently those with the permitting competence.

There are a number of aspects of macroalgae production that will need to be evaluated by the local authorities in the counties along the coast where the algae will be grown. It is assumed that the algae production can be performed such that it is environmentally sustainable, but they need to be shown to be financially sustainable before the counties will be willing to approve areas for use. The seaweed production will need extensive areas for production, and most counties do not have this areas set off for this type of production in their plans. Algae producers will have to ensure that the areas where algae production is taking place also receive some of the benefits from the production. There will need to be clear frameworks for evaluation of permits at the local and national levels before any large scale macroalgae production begins along the coast of Norway. Although it may take some time to develop good systems, the local authorities are clearly positive to the introduction of a new industry along the coastline of Norway.

There are a number of European projects that are related to the sustainable production of macroalgae, for example:
BioMara - http://www.biomara.org/,
Energetic Algae - http://www.nweurope.eu/index.php?act=project_detail&id=4124
SuperGen - http://www.supergen-bioenergy.net/
EnAlgae http://www.enalgae.eu/index.htm

6 OTHER MARINE RESOURCES

Other marine resources, such as fish by-products, have been seen as a potential source of feedstock for biofuels. The by-products from Norwegian fisheries and aquaculture consist of viscera, heads, tails, shells etc from processing, gutting and de-heading. The by-product amount in 2011 was ca 815000 tons and about 620000 tons (76 %) of this was used in a number of different products including fish feed and fish oil. The current value is between 2 and 2.5 billion NOK.[51] The remaining fish by-products, which are mainly from cod fish, are now dumped in the sea and consist of about 50 % bones[42]. Cod bones consist of about 50 % mineral ash, 35 % proteins and only 3 % lipids[52], this is a composition that makes cod bones unsuitable for biofuel production. The numbers are shown in Table 16. The dumping of these fish by-products is not prohibited by Norwegian law. There is potential for use of this biomass if there is a feasible market, but logistic issues and price constraints that have hindered the development of a system for utilisation. Given the high protein content of fish, feed products are the most likely use of any additional by-product resources.

The Norwegian fishing fleet is divided into two types, the coastal fleet and the ocean-going fleet. The coastal fleet consists of thousands of fishing boats who offload in geographically dispersed docks. The coastal fleet goes to shore every day and any fish waste can be delivered daily with a minimum of extra storage costs, assuming that the docks have suitable receiving facilities to store and manage the by-products. For the ocean-going fleet the logistics are simpler since there are fewer boats and docks. But since these boats are longer at sea the boats will need facilities for conservation and storage of the by-products. Unless the price of the by-products is worth the investment for storage on the ship, the waste will not be made available. Both the ocean going fleet and the coastal fleet will most likely require above 1 NOK/kg[41] by-products to consider delivering the by-products.

The aquaculture industry has made use of most of the bi-products I the feed industry, with the exception of fish that die in the production area that cannot be used for fish feed. They can be used for mink feed, and there are efforts to utilise these products as biogas or fertiliser.[53]

Considerable efforts have been made to ensure that the by-products from the fish industry are utilised in profitable ways[54]. The focus of the development is on food and feed due to higher product prices. There is always the potential that if a biofuel producer could pay more than the current customer of the fish industry that there is tonnage available, but the amount would not be enough to base commercial biofuel production on. Given that fuel production generally needs to keep feedstock prices to a minimum, fish by-products are not a likely source of feedstock for bio jet fuel production at this point.

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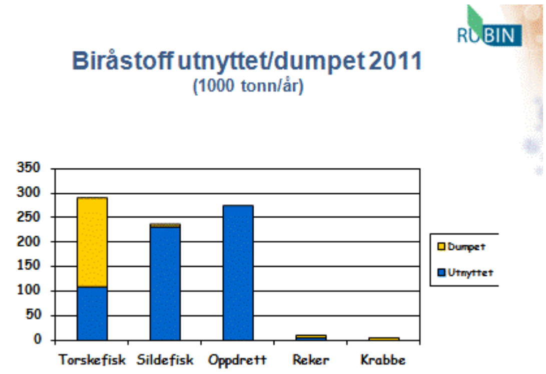
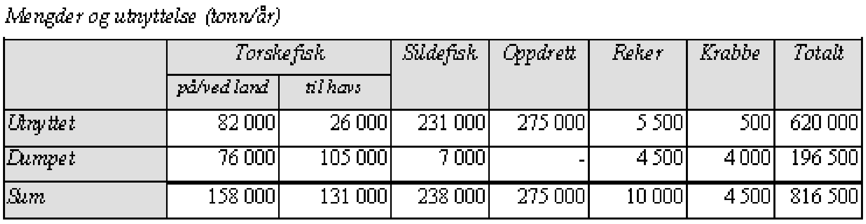
[51] Rubin foundation

[52] Toppe *et. al.* Comp. BioChem and Phys, Part B,2007, 146, p395-401

[53] http://miljolare.no/tema/forbruk/artikler/biprodukter.php

[54] Norwegian Seafood Federation, environmental report 2010 (only in Norwegian, Miljørapport)




Mengder og utnyttelse (tonn/år)

	Torskefisk		Sildefisk	Oppdrett	Reker	Krabbe	Totalt
	på/ved land	til havs					
Utnyttet	82 000	26 000	231 000	275 000	5 500	500	620 000
Dumpet	76 000	105 000	7 000	-	4 500	4 000	196 500
Sum	158 000	131 000	238 000	275 000	10 000	4 500	816 500

Table 17 Shows the ton/ year used (utnyttet) and discarded (dumpet) fish by-products in Norway.

7 LOOK TO THE FUTURE

Algae will probably not be a major source of biofuel before 2025. However, given the right political, research and business environment algae production and bio-refining could very well be a developing industry in Norway. There is potential for an industry that can sustainably produce a number of products, such as proteins and omega 3 oils for the aquaculture or food industry, pharmaceutical products and flavours and aromas as well as bioenergy.

There are considerable efforts being made on microalgae technology. There will most certainly be breakthroughs and improvements at all parts of the production chain. There is considerable venture capital, government research money and political incentives to promote the industry in various countries. The microalgae industry may be able to provide bio jet fuel in the international markets in the future. The current efforts in the Norwegian production are aimed at high value products and the species used will be adapted to Norwegian conditions. Government can help development through research grants and incentives. This market in Norway will grow if commercially viable, and if the production costs are considerably reduced, microalgae might contribute to jet fuel production also in Norway.

The production of macroalgae has the potential to become a successful industry in Norway. The production of biologically based industrial development can have similar development curves as other new industrial processes, but with algae specific problems to deal with. The industry in Norway that could be the basis for a comparison to speculate on the potential for the growth of an algae industry would be the aquaculture industry in Norway. The aquaculture industry has grown as a whole, but it has required an extended investment from individuals, companies and the government. There have been crisis years, new company structures, and continual improvement in all areas of the production chain over time. One parameter that illustrates the change is that the productivity per person/yr was more than quadrupled from 1992-2002 from 80 to 340 ton/ yr. Costs were brought down through increased competence that lead to better egg quality, less illness and death. [55] Since macroalgae is a biological raw material issues with the health and quality of the seaweed is likely to occur during the development of the macroalgae industry. Good control systems and government regulation of production conditions in the aquaculture industry in Norway is one of the key aspects as to why we have a thriving industry today. The same type of regime might be needed to develop a sustainable macroalgae industry.

One of the major differences between fish farms and macroalgae production will be the area needed for production. Fish farms are relatively high intensity and high value at the place of production. Algae production will need a centralized biorefinery and a very large area for growing and harvesting where the value creation may not be so large. Fish farms have had many challenges with location permits and local area conflicts, and algae producers can expect the same.

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[55] http://www.fiskeridir.no/statistikk/akvakultur/om-statistikken/om-statistikken-loennsomhet-matfiskanlegg

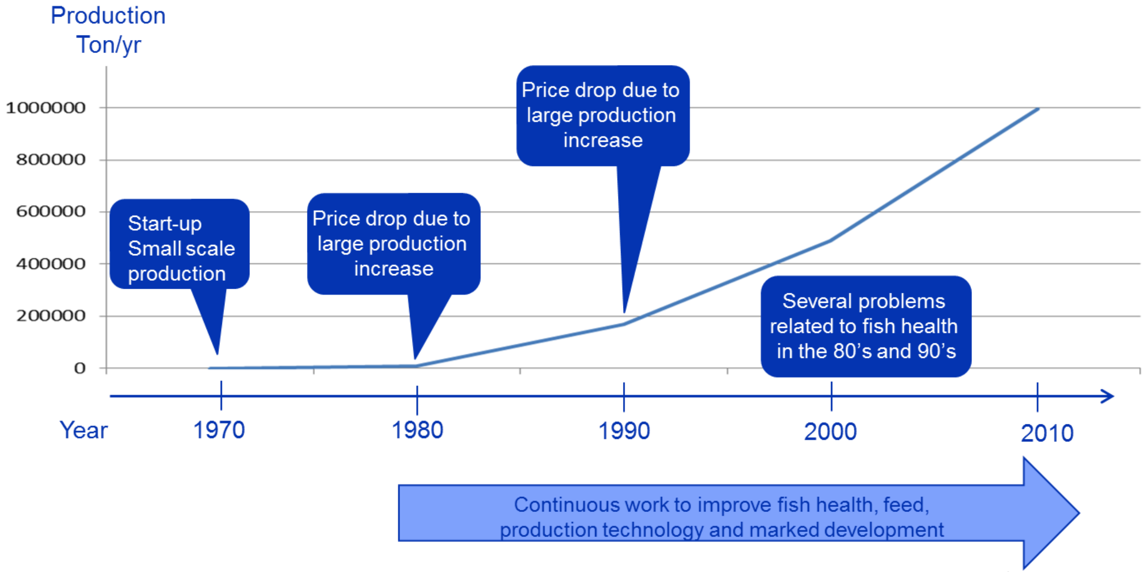

Figure 19 Development of the Norwegian aquaculture shown as ton produced fish per year[56].

If the aquaculture industry is any indication, 10 years of development can be expected before the industry is established in a moderate format. Another 10 years will be needed to learn from the first movers and start with larger areas of production. Increases in production and a viable industry will take another 20 years, as illustrated in Figure 19. In addition to technological development, a focus on understanding the marked development is crucial. Since the beginning in the early seventies, the aquaculture industry has received substantial governmental support, for instance to research and marketing efforts. Still the industry has experienced several crises years with drops of the prices, leading to closures. The success of algae production is also likely to depend on continual support from all stakeholders.

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[56] Numbers from Directory of Fisheries and the Norwegian seafood federation

8 CONCLUSIONS

In an international perspective, algae are a very interesting potential feedstock for biofuel production as they have the potential to provide biomass with little to no competition with other biomass production. There are two fundamentally different types of production: microalgae and macroalgae (seaweed).

Microalgae have provided feedstock for fuel used in aviation trials. The technical production is still developing, but production is feasible with current technologies. The major issue to date is price and the scaling up of production. There are a number of bottlenecks for scaling up algae for fuel production, including financing of projects. There is clearly a potential for production in certain areas, but suitable land, CO2 sources and water along with sunlight can be a challenge. The open pond technology, that has to date produced the most cost effective algae biomass for fuel, is not suitable for use in Norway due to weather conditions and lack of large flat land areas.

Microalgae production in reactors is feasible in Norway. There are possible locations for production on industrial sites that have CO2 release and excess heat. However, bioreactors have high investment and running costs and will only be commercially viable for high value products. There are many existing and potential products with high value and large markets. Currently bio jet fuel is seen a product of lower value. The competence centres in Norway are focusing on algae strains that have potential for producing high value products in Norwegian conditions.

All in all, there is in DNV’s opinion, little indication that microalgae will contribute to the supply of jet fuel in Norway by 2025-30.

Macroalgae (seaweed) is already an important commercial feedstock for products in Norway (alginate). The natural conditions in Norway are suitable for production of certain species of seaweed. The cultivation of macroalgae is under development and the aim is to have demonstration plot for algae production by 2015. As with microalgae, there are several issues that need to be resolved before seaweed can be produced and processed on a commercial scale.

Ethanol is the most likely fuel product from macroalgae production. Hence the most likely pathway for jet fuel production is the “ethanol to jet” conversion. According to the commercial stakeholders the first biorefinery for ethanol from seaweed will not be in place before 2020, at the earliest. Although there is potential for a thriving industry in the future, macroalgae are not likely to be a feedstock for commercial jet fuel production by 2025-30.

9 BACKGROUND LITERATURE

There are numerous reports on algae and the potential for biofuel production. Many contain similar information. There are many sources used in the report itself within the footnotes and are not included here. The reports here were those used for background reading.

The Potential Role of Biofuels in Commercial Air Transport – BioJetFuel
IEA Bioenergy Task 40, August, 2012 http://www.bioenergytrade.org/downloads/T40-Biojetfuel-Report-Sept2012.pdf

IEA Bioenergy (2011) Algal biofuels Status and Prospects, Annual Report 2010
International Air Transport Association. (2010) *IATA 2010 Report on Alternative Fuels.* 5th Edition. Motreal, IATA. Report number: 9709-03.
http://www.pewtrusts.org/uploadedFiles/wwwpewtrustsorg/Reports/Global_warming/DoD-Report%20FINAL.pdf

A Realistic Technology and Engineering Assessment of Algae Biofuel Production
Lundquist et al, 2010, Energy Biosciences Institute EBI, October, 2010
http://www.ascension-publishing.com/BIZ/Algae-EBI.pdf

Algae - the Future for Bioenergy?
IEA Bioenergy, October, 2009

Life-Cycle Assessment of Biodiesel Production from Microalgae
INRA,UR50 Laboratoire de Biotechnologie de l'Environnement
July, 2009

A Review of the Potential of Marine Algae as a Source of Biofuel in Ireland
Sustainable Energy Ireland
July, 2009
http://www.seai.ie/Algaereport.pdf

National Algal Biofuels Technology Roadmap
US DoE Biomass Program
June, 2009

Bio jet fuel from macro algae: a feasibility study into the end-to-end chain
Te Raa, H.R. Master thesis TU Delft 2010
http://repository.tudelft.nl/view/ir/uuid%3A03fbb394-6d1c-4adb-abe9 1c49301dbfa7

Macroalgae as a Biomass Feedstock: A Preliminary Analysis
G. Roesijadi, S.B. Jones, L.J. Snowden-Swan, Y. Zhu
September 2010 for the U.S. Department of Energy
http://www.pnl.gov/main/publications/external/technical_reports/pnnl-19944.pdf

Biofuels from *Algae*
www.parliament.uk/briefing-papers/POST-PN-384.pdf
Oilgae Report Academic Edition
www.oilgae.com

Appendix A Interviews

Table A.1: Interviews with microalgae manufactures in US and Australia

Name	Company	Role	Email
Jason Husk	Kiverdi	Director of Business Development	jason.husk@kiverdi.com
Philip Lee	Sapphire Energy	Group Leader – Crop Protection	phil.lee@sapphireenergy.com
Alexander Lindgren	Chingoo Research Partners	Founding Partner	alexanderblindgren@gmail.com
Tony St. Clair	MBD Energy Limited (Melbourne, Australia)	Agribusiness and Government Relations Director	tony.stclair@mbdenergy.com
Clayton Stearns	Chingoo Research Partners	Founding Partner	clayton.stearns@gmail.com
Xun Wang	Sapphire Energy	SVP of Research & Development	xun.wang@sapphireenergy.com

Table A.2: Interviews and contact with microalgae and macroalgae stakeholders in Norway, Sweden and Denmark

Telephone or personal interviews were held with :	Contacted /e-mail correspondence with
- **Seaweed Energy Solutions**	- Netalgae
- **Statoil**	- Havforskningsinstitutet
- **Sintef Havbruk**	- UiO
- **Sintef Bioteknologi**	- UiB
- **UMB**	- NIVA
- **UiT**	- Bioforsk
- **UiN**	- Norgesvel
- **Nordland Fylkeskommune**	- Biopharmia
- **Bellona**	- NTNU
- **Teknologisk Institutt Danmark**	- Stefan Kraan – Ocean Fuel
- **Swedish Biofuels**	- Scottish Marine Institute - SAMS
- **FMC**	

The interview notes are below.

A.1 Nordland Fylkeskommune v/ Jostein Angell

Dato: 6/8-12

Tildeling av områder til makroalgedyrking
Forslag om å inkludere tang og taredyrking i regelverket for aquakultur var på høring i 2011, men har ikke blitt innlemmet i regelverket ennå. Inntil videre er det Fiskeri- og kystdepartementet som har tildelingskompetanse for dyrking av tang og tare. Etter høringsforslaget vil godkjenning av lokaliteter og tildeling av tillatelser bli behandlet etter akvakultur regelverket med fylkeskommunen som tildelingsmyndighet. Fiskeri- og kystdepartementet har fortsatt saken til behandling.

Aspekter som må vurderes i forbindelse med tildeling av områder til makroalgedyrking:

- Dyrking av makroalger vil være miljømessig og biologisk bærekraftig. Det er usikkert i hvilken grad det også kan bli økonomisk bærekraftig.
- Algedyrking er arealkrevende siden det krever lys (kan kun gjøres i overflaten).
- Kommunene har per i dag ansvar for å planlegge områder til akvakultur, herunder også eventuelle dyrkingsområder for tare. De fleste kommuner i Nordland har avsatt moderat til lite areal til produksjon av laks og annen akvakultur.
- Kommuneplaner skal rulleres hvert fjerde år, men de fleste har en operativ levetid på 5-7 år. Avsetning av areal til algedyrking må gjøres ved revisjon av kommuneplan.
- Kommunene er generelt positive til ny næringsvirksomhet og det er viktig for dem å få noe igjen for områdene de åpner opp. Hvis makroalger dyrkes i flere kommuner, men at prosseseringsanlegg og arbeidsplasser ligger i kun en kommune, kan det være vanskeligere å få tildelt områder i kommuner som vil ha marginal nytte av ny virksomhet.
- Konflikt med annen næringsvirksomhet (bl.a. fiskeri, oppdrett). I Nordland er derfor områder som Lofoten og store deler av Vesterålen lite aktuelle for makroalgedyrking, men det finnes flere områder der dette ikke vil være et problem, f. eks Helgelandskysten.
- Konflikt med friluftsliv, ferdsel og fritidsbolig, primært pga støy og utseende på anlegg forekommer ofte ved behandling av akvakultursøknader
- Siden dyrking av makroalger ikke er en etablert industri, og ansvaret per i dag ikke ligger hos fylkeskommunen er det ikke utarbeidet rammeverk og metoder for behandling av slike saker.

Konklusjon: Det er trolig ingen uløselige og store hindringer for at man skal klare å finne og få tildelt områder som egner seg for makroalgedyrking. Derimot er tildeling av områder til makroalgedyrkning en uetablert prosess som kommer til å kreve en del tid. Blant annet må kommunene sette av areal til formålet.

Makroalger og fiskeoppdrett
Jostein Angell er skeptisk til dette og grunnene er:

- Lokaliseringen av oppdrettsnæringen er eksponert. Dette krever kraftig fortøyning og dermed kostnadskrevende investeringer i anlegg

- Fiskeoppdrett har en minimal negativ påvirkning på miljøet, og vil ikke bidra til store mengder næringsstoffer til å gjødsle algene[57]Skal man lykkes kommersielt med taredyrking, må man velge lokalisering og anleggsutforming som forutsetter moderate investeringskostnader og lavest mulig driftskostnader. Hensynet til dyrkingskonsept må derfor settes foran mulige marginale gevinster ved eventuelt å lokalisere anlegg i nærhet av lakseoppdrett.

Generelt om makroalgedyrkning

- Norge er et høykostland. Selv om det finnes tilgjengelig arealer i kystsonen, er det ikke sikkert at det er mulig å drive lønnsom algeproduksjon i Norge.
- Avhengig av hvilke typer tare man ønsker å dyrke, bør makroalger ha en mer skjermet lokalisering – dvs. i fjorder, der investeringskostnadene i anlegg er lavere
- En har ikke full kontroll på biologien i sjøen, andre alger og organismer kan begynne å vokse i anleggene. Dyrking av monokultur er derfor utfordrende.
- Logistikk er en utfordring med tanke på å oppnå lave driftskostnader.
- Makroalgedyrking kan ta lærdom av erfaringer fra dyrking av blåskjell. Prod.kost pr kg blåskjell er minimum 3-4 kr/kg. Avskrivinger anlegg er mellom 0,5-1,0 kr/kg. Anleggskostnadene for taredyrking i hengekultur vil være tilsvarende.
- Dyrking av stiklinger eller mikroalger kan eventuelt gjøres i forbindelse med industri som har utslipp av CO_2 og spillvarme. Elkem Salten har tidligere prøvd seg på roseproduksjon i forbindelse med anlegget sitt, dette var ikke levedyktig. Elkem Salten vurderer for tiden alternativ anvendelse av drivhusanlegget.

- [57] Risikovurdering – miljøpåvirkning av norsk fiskeoppdrett; Fisken og havet, særnummer 3-2011
- Vurdering av eutrofieringssituasjonen i kystområder, med særlig fokus på Hardangerfjorden og Boknafjorden; Rapport fra ekspertgruppe oppnevnt av Fiskeri- og kystdepartementet i samråd med Miljøverndepartementet (2011).

A.2 Telephone interview with Jostein Vea FMC

Date: 16.18.12

- FMC has harvested natural growth algae for over 50 years
- The sustainability of the harvesting is controlled by Fiskeridirektorate and that the harvest is sustainable is verified by Havforskningsinstituttet.
- The harvest from Rogaland to Sør- Tronderlag using “travtråling” all year , and the areas are harvested every 4-5 years
- 500 ton/ algae a day is used for alginate production; 150 000 to 160 00 ton a year is harvested
- They have several receiving areas, and receiving boat that treat the wet algae with formaldehyde to preserve the algae for use
- Other areas of the world the algae is dried (various methods depending on the climate) and ground into small particles. The stem is the most important part of the plant for alginate production. 30-35% of the dry weight is alginate. The production process uses a large amount of water, and the rest of the particles are so diluted in the water that trials to find commercially viable uses of these biomass particles have not been successful.
- The algae used for alginate is not the algae that is suitable for fermentation for biofuels.
- The current “lowest price” for algae is $300- $400 ton (and speciality algae can be $25000 ton)
- The potential for successful algae production in Norway is possible, but needs to have appropriate laws and regulations that do not hinder the industry (preferably promote the production of algae) and research and investor realism that this is a new industry and it will take some time and investments to develop commercially viable technologies and processes.
- Given investments – the production of algae in Norwegian waters could be feasible by 2020

A.3 Pål Bakken, CEO, Seaweed Energy Solutions

Date: 9.8.2012

- SES is a Norwegian company focused on large-scale cultivation and harvesting of large brown seaweed primarily for energy purposes.
- SES works closely with different partners like Sintef, Statoil, Aqualine, UMB and Cambi. The focus for the different projects is utilizing the algae's to ethanol or biogas.
- SES wants to industrialize cultivation of brown seaweed along the Norwegian coast line. The Norwegian coast line has good supply of nutrients and there is no need for growth supplements. SES has done trials outside the coast of Norway and Portugal in the open sea with good results of cultivation of seaweed. SES also does different trials for making the harvesting of the algae's less dependent on manual work. These trials are confidential
- SES currently has a 3 Ha cultivation site at Frøya and a Seaweed Breeding center and Nursery close to Trondheim. SES is scaling up production and the plan is to start building a large scale Demo-production area in in 2015. A possible timeline will be start up in 2016-2017 and with possible harvest of production algae in 2018.
- In Norway there are several factors to be considered before this new industry is viable; license and subsidies from the authorities, available areas, technology, facilities and cooperation with different partners.
- SES focus is use of algae for energy. For the rest of the biomass they see possibilities for animal food or chemicals.
- Uptake and storage of CO2 in the algae is an area of potential interest and is being looked at in projects
- Data from SES from their trials:
  -Yield of algae's: 200-250 tons wet algae/ha
  -Possible yield of ethanol: 43-50 l ethanol/ tons wet algae (to be confirmed with Statoil)
  -Possible to reach in the future: 20 €/ ton wet algae (In Asia today 25-30€/t wet algae, but this is for the food and medicine market and with more labour intensive methods)
  For a viable industry in Norway you will need to produce minimum 2 mill tons of algae's/year.

A.4 Teknologisk Institutt Danmark

Project title: The MacroAlgaeBiorefinery – sustainable production of bioenergy carriers and high value aquatic fish feed from macroalgae. (MAB3)
Concept: Producing biofuels (ethanol, butanol, biogas) from brown algae (*Saccharina latissima*, *Laminaria digitata)* in addition to fish feed from the fermentation residues.
Brown algae are chosen due to a high content of C-6 sugars and the protein composition.

Timeline: March 2012-March 2016

Goals for the project

"The main result of the project is development of an economically feasible solution to produce aquatic immune stimulating fish feed and energy carriers from macro algae."
This includes:

- Development of cultivation and harvesting techniques for algae
- Optimization of pre-treatment technologies (removal of water, drying and storage)
- Development of techniques for enzymatic treatment of algae biomass to fermentable sugars
- Development of fermentation processes for production of energy carries (ethanol, butanol and biogas)
- Pilot scale production of essential amino acids from residual products from the fermentation process
- Development and testing of fish feed from the fermentation residues (supplemented with amino acids and lipids from micro algae)
- Sustainability and LCA of the entire production from cultivation to products.

Current stage:

- Pilot stage cultivation of brown algae
- Pilot scale production of ethanol
- Lab scale trials with production of butanol

Fish feed:
The aim is to produce fish feed containing:

- Protein residues from the fermentation of algae to ethanol
- Aminoacids (isoleucin and arginine) from non-fermentable sugars
- Lipids (omega-3) from microalgae

A.5 University of Nordland

Date: 14.08.2012

Participants from UiN: Kiron Viswanath, Einar Skarstad Egeland, Sylvie Bolla.

UiN undertakes research on both microalgae (phytoplankton) and macroalgae. Their research on microalgae is mainly directed to benefit the aquaculture industry. They grow microalgae on a regular basis, to be used as live feeds for larval fish. In collaboration with the industry, UiN conducts research on microalgal ecology and the utilization of co-products from biorefinery of commercially produced microalgae. As for macroalgae, the effects of climate changes on their genetic responses are studied.

UiN has expertise on culture of microalgae, biochemical analysis and on application of microalgae for the food and feed industry. UiN is part of an international network of scientists and industry experts related to different aspects of algal technology. The collaborative efforts have resulted in publications including scientific papers and books, most recently “Phytoplankton pigments”, see www.cambridge.org/phytoplankton.

Current research activities at the faculty cover the following aspects:

- Distribution of marine microalgae in Saltfjorden (UiN funded)
- Influence of culture conditions on the chemical composition, particularly that of the pigments, lipids and amino acids in selected species of microalgae (UiN funded)
- Application of co-products derived from the biorefinery of commercially produced marine microalgae (Internationally funded; multiple projects since 2008; member of an US biofuels consortium). In cooperation with industries in US and in Asia, the potential of algal protein biomass as a feed ingredient has been demonstrated for prominent farmed aquatic species such as Atlantic salmon, Atlantic cod, common carp, tilapia and Pacific white shrimp. Further, the oils derived from algae are being explored as functional feed ingredients for fish.

The choice of an alga for commercial development depends on the needs of the industry. If biofuel is to be tapped from microalgae, the species or strain must have a high growth rate and a high content of lipid, which is rich in triglycerides. The defatted biomass could be a valuable ingredient in fish feeds, depending on the protein content, pigments and the residual polyunsaturated fatty acids. UiN believes that the commercial production of algae in Norway could initially be for food (e.g. omega 3 sources) feed and bioremediation purposes.

A.6 Statoil

Telephone meeting with Wenche Waage Fougner

Statoil has one algae project that involves several partners. Statoil has an overall co-ordinating role that ensures the research and development activities of the partners contribute to the goal of commercial production of algae as a feedstock for fuel and other products.

Growth: together with partners, SES / Pål Bakken is focused on concept development

Hope to have a 2000 ha demo by 2015 where harvesting techniques can also be tested

BAL – Statoil owns 20% - is performing research to find microbes such that more of the feedstock can be utilised

Need 10 000 ha algae to have enough feedstock for a biorefinery. (200 mil. L EtOH/yr)

Beat case – bio-refinery start in 2020

Studies show that there is enough nutrients in the water for good growth in many areas along the coast

Epiphytes are a challenge as will be the monoculture issues such as illness

May look at possible combination of species and growth alternatives

Statoil is used to dealing with permitting, but hope that the area planning and the law is in place to allow for an efficient process

Will need government support for building a demo refinery

A.7 SINTEF–Fiskeri og Havbruk - Marin Ressursteknologi

Meeting with Trine Galloway (Research Director), Jorunn Skjermo(Sen. Scientist, Macro algae, Matilde Chauton (Scientist, micro algae)

<u>Macro algae</u>

Sintef are working on small scale cultivation trials (landbased/laboratory phase and sea phase (exp.size 400m2), with aim to help new industry to upscale.

- Good results for algae growth both in fjord, coastal and offshore locations
- Algae on rope and other types of fixtures
- Sintef's numbers for the potential ethanol yield from algae is based on productivity of algae/m2, dry matter content, carbohydrate content, and the assumption that all the main carbohydrates types (alginate, laminaran, mannitol) can be converted to ethanol. The conversion of 80% carbohydrates to ethanol have been shown in labscale trials (Wargacki et al., 2012).

Macroalgae need nutrients, CO2 and light to grow.

- CO2 is abundant, exposure to light can be regulated by regulating dept. The amount of nutrients is growth rate determining
- Sintef have done simulations of nutrient content in the sea along Norway, and have found that there are many suitable location for macro algae cultivation, both near the coast and in more exposed offshore locations. It is possible to find enough suitable area for algae cultivation to energy. With that type of locations the yield of macro algae will be good and predictable.
- Low growth rate in summer due to lack of nutrients (nutrients are consumed by micro algae), and low growth rate near Trondheim in Des/Jan due to lack of light

Harvesting

- Harvesting best in June due to prevent degradation from fouling. Theoretical optimum in September with regards to carbohydrate content without fouling, but fouling in the summer leads to a reduction in the carbohydrate content.
- Sintef is working with design of cultivation sites, and the development of harvesting equipment/techniques
- The macro algae can and should be harvested once a year, before the plant become fertile.

Ecological impact

- Some fertile plants are observed, but as long as local species are used, algae cultivation will probably not have an undesired effect on the local marine ecology. This is an important issue if modified species of algae are to be used. Impact assessments will have to be done.
- Seaweed farms serve as shed for small marine animals and fish juveniles.

Challenges – to grow enough macro algae to make the macro algae industry economically viable

- A biorefinery concept with fuel as one of many products is more likely to succeed. It is important to have high value products

- Logistics is an issue, both with coastal and offshore locations
- CO2 emmisions from harvesting and processing has to be considered when evaluating fuel from macro algae
- Sintef expects that biofuel from macro algae will be commercially available (possible to buy algae-bioethanol in a few locations) in 5 years.

Estimates of production potential:

- Estimates of macro algae productivity (100 (75-140) ton algae/ha pr yr, wet weight; 10-20% dry matter > 20 ton dry weight/ha/year)
- Estimates of the amount of ethanol that theoretically can be produced from the macro algae (250-280 l ethanol/ton dry weight algae) (conversion of 80% of theoretically available carbohydrate, 60% carbohydrate content of dry weight)

Microalgae

Sintef works primary on micro algae as a source for feed for fish

- Working with microalgae that are readily cultivated and has a suitable nutritional content
- Lab experiments with small and medium scale production units

Cultivations requirements

- Micro algae need light, CO2 and nutrients. Light is the limiting factor, artificial light is needed when natural light is low to secure an efficient growth. If CO2 is added it is in small amounts (1-2% of the air that is added).
- The need for light makes Norway less suitable for growing micro algae – the need for artificial light leads to a high production cost, and one does not get more energy out than what is put into the cultivation process. However, since Norway has access to ample amounts of renewable energy (hydro power electricity), the LCA analysis for microalgal production for biofuels in Norway may be favourable.
- It is important to have a closed, controlled system for algae growth.

Micro algae is suited for production of high value products

- Micro algae should be processed in a biorefinery type process where Omega3 and protein for feed are the major products. Biofuel can be made from residual biomass, but the volumes will probably be too small for an efficient fuel production. In coarse numbers, the dry matter in microalgae contain about 30 % protein, 15-25 % lipids and the rest is mostly carbohydrates.

A.8 SINTEF –Biotechnology

Telephone meeting with Inga Marie Aasen (SINTEF, research scientist) 23.08.2012

Processing of macro algae

- SINTEF Biotech is working on fermentation of sugars from macroalgae to ethanol
    - SINTEF have done some lab scale (~1L) fermentation experiments in addition to theoretical calculations and evaluation of the process from macro algae to ethanol.
    - The sugars in macro algae is mainly laminaran, mannitol and alginate
    - Laminaran can be fermented with conventional (non-GMO) microorganisms.
    - Mannitol can be fermented by conventional microorganisms if oxygen is added during fermentation. The amount of oxygen must be carefully controlled, too much oxygen will lead to cell growth instead of ethanol production. The addition of oxygen will increase production cost.
    - Genmodified microorganisms are needed to ferment alginate to ethanol, and would be preferred for mannitol as well. The conversion of 80% carbohydrates in marcoalgae to ethanol have been shown in labscale trials (Wargacki et al., 2012) in US. SINTEF is working on finding suitable microorganisms and are looking into modification of these.
- Yield of ethanol from macro algae:
    - Theoretical maximum ethanol yield from Norwegian sugar kelp is based on carbohydrate content content.

    From laminaran and mannitol a yield of above 90 % is obtained in SINTEF experiments. If one assumes 70-80 % yield form alginate, the total yield will be (with 2/3 lamninaran + mannitol and 1/3 alginate) about 85 %

    - 80 % of teoretical: 365 l/ton Dry weight.
    - 85 % of teoretical: 388 l/ton Dry weight

- Processing
    - Wet algae can be processed directly, and will give a solution with a sugar content of about 100 g/L. This is close to an optimum sugar concentration (about 150g/L), but increasing the concentration before fermentation is a more expensive process than distilling off the ethanol from a more dilute solution after fermentation
    - Salts could pose a problem in the fermentation, but it should be possible to find microorganisms that can handle the salt concentration in a seaweed slurry.
    - Macroalgae requires less pre-processing before fermentation than lignocellolosic material due to the lack of lignin and laminaran is more easily hydrolysed than cellulose.
    - Storage of macroalgae will require preservation. An alternative to storage may be to establish production plants that can handle both macroalgae and other biomass (ex. lignocellulose), depending on season. A macroalgae biorefinery may produce a small amount of alginate, protein for feed, minerals like phosforus in addition to ethanol.

Microalgae

- SINTEF works primary on heterotroph microalgae as a source for fat
    - These microalgae use sugars to produce fats and this is done on an industrial scale today to produce omega3 fatty acids as dietary supplements. 50-60% of the dry matter is fatty acids.
    - The fat composition of the organisms used by SINTEF is suited for omega3, not for fuel production. Organisms that produces lipids more suited for biofuel exist, but to use sugars to produce fat for fuel is probably less likely to be an economically viable process than converting sugars to ethanol, since the fat production is an aerobic process, requiring higher investment costs. (men kan likevel være billigere enn å benytte fotosyntetiske mikroalger, dette vil være en interressant beregning å gjøre)
    - SINTEF has currently no projects with experimental work on photosynthetic microalgae

A.9 University in Tromsø

- Focus on research on microalgae, mostly diatoms in large scale pilot testing. Essential is to cultivate under controlled conditions in order to obtain reproducibility in the processes. The diatoms are interesting based on efficient growth at low light- up to doubling their weight per day. Tromsø cultivates in a scale of 600 litres with continuous adding of nutrition (continuous culture). The diatoms need in addition Si. The biochemical plasticity of the diatoms is very high. This means that the chemical content of the algae can be altered based on the different environmental cultivation conditions. The diatoms contain pigments, proteins, carbohydrates and lipids. The different species produce very different ratio of chemical compounds.
- UiT will try to continue the research in large scale pilot in cooperation with Finnfjord Smelteverk. They will use tanks of 10-100.000 litres. Nutrition will be added continuously and Finnfjord Smelteverk will use their excess of heat and CO_2 in the cultivation process. This will take place at controlled environments and thus a more predictable outcome of chemical compounds. The light added will be artificial light (LED-light) in addition to natural illumination. The artificial light will be lowered down in the tank together with sensors for observation of nutrition`s etc. (solid state control).
- Theoretically the outcome of lipids can be up to 30-40%, but more realistically it is around 25% lipid of dry weight algae.
- If the lipids are utilised to biofuel, the rest of the algae can be used for medical purposes and animal foodstuff.
- UiT believes that the most promising utilisation of algae production in Norway is for omega- 3 production and animal foodstuff.

A.10 Norwegian University of Life Sciences (UMB)

- UMB is doing research on macroalgae (brown algae-Saccharina latissima). Mainly focusing on enzyme technology and anaerobic degradation of sugars to methane or ethanol.
- From results in small scale at the laboratory the outcome of methane can be 70m3 (equivalent to 700 kWh) of methane from 1 ton wet algae (190 kg dry organics). For comparison, 50 litres of ethanol may be produced from the same amount of wet algae.
- UMB believes that the most promising utilisation of seaweed feedstock in Norway is production of methane in combination with feed and fertilizer.
- UMB has run several research projects related to seaweed together with different partners. One project is with Cambi where the goal is to utilize lignocellulosic substrates and macroalgae for biogas production. UMB has also been working closely with Sintef and SES on different projects where the focus was ethanol production from macrolagae.
- The natural stocks of brown seaweed is to small to support any large scale production of biofuel. Thus macroalgae must be cultivated in large marine farms. The brown algae has the highest content of carbohydrates in the autumn and the best time for harvesting is in October/November. One may use different species of brown algae to spread the time for cultivation and harvesting. The seaweed could be processed to biofuel on ships at sea or transported to facilities on land.
- With cultivation methods available today the outcome of algae can be 300 tons wet algae per hectare or 60 tons dry algae/hectare.

A.11 Swedish biofuels

Telephone conversation with Angelica Hull 14 /8-12

Swedish biofuels is working on the “Alcohol to jet” process in collaboration with (among others) Lanza tech. They have a “mini plant”/pilot plant with a production capacity around 10 ton/ year of jet fuel. The process simultaneously produces kerosene, diesel and gasoline, and it is possible to regulate the process adjust the production mixture.

Appendix B AlgaeValue™

AlgaeValue™ was developed at KEMA in 2009 and is an Excel/VBA (Visual Basic for Applications) model capable of calculating cultivation yields and costs/revenue indications for cultivation and conversion of algae for different product groups. Parameters on climate, economy, scale, algae species, cultivation system, conversion system and products are based on test- and literature data.

The advantage of the model is that interdependencies are captured in logical and pragmatic functions, which facilitate quick and well-organised outlining of concepts that are otherwise laborious. All possible production routes can be evaluated and specific parameters can be used to rate the production, for instance annual biomass yields, or net annual profit, and perform sensitivity analysis.

The projected location is the starting point for each assessment as this determines the relevant climatic parameters (like number of solar hours each year, the solar intensity and average temperature), as well as economic parameters like the prices of land and labour. The availability and price of commodities like sweet or salt water, CO_2, heat, nutrients and electricity are also required.

The specifics of the algae species that will be used are the next input. The fraction of lipids, carbohydrates, proteins, and other fractions and cultivation parameters like specific efficiency, temperature dependency, optimum temperature and maximum photosynthetic yield are needed.

Technical parameters that are needed for the cultivation and the conversion system are investment and maintenance costs, commodity consumption and efficiencies. The figure below gives an impression of the model and the relations between the various input parameters.

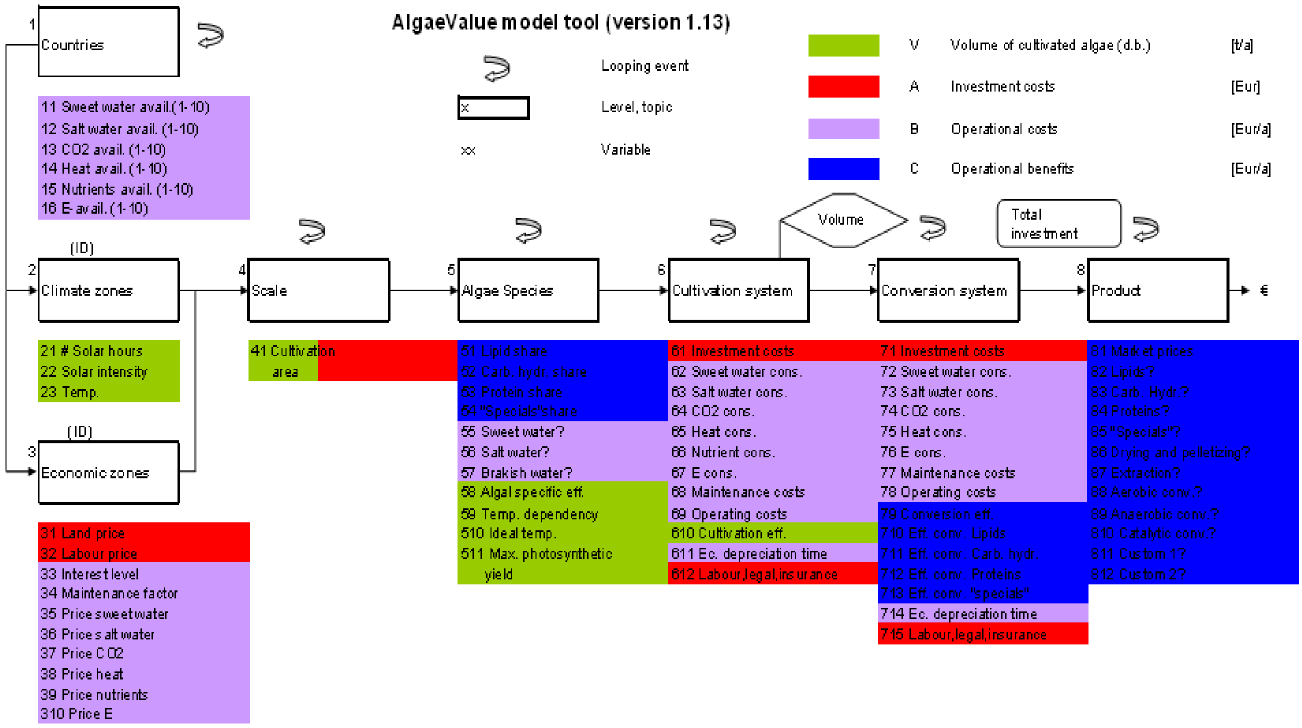

Figure B.1: Schematic representation of the AlgaeValue^{TM} model

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