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The purpose of the workshop was to inform the Executive Committee of the potential for using algae for energy purposes by stimulating a discussion with experts working both within and outside the Agreement. The workshop aimed to assess the current state-of-the-art, to consider the potential in the medium and long term, and to identify the major research and commercialisation challenges.

Algae – The Future for Bioenergy?

Summary and conclusions from the IEA Bioenergy ExCo64 Workshop

IEA Bioenergy

IEA Bioenergy: ExCo:2010:02

INTRODUCTION

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BACKGROUND

The last few years have seen a renewed interest and a great increase in activity in algae as a sustainable source of energy. Potentially algae can offer high productivity and production of biomass which avoids competition with other productive land uses. However, there is as yet no clear view of the potential for the technologies, nor any consensus about the optimum role for algae, with many algal strains and routes to energy under consideration. There is also an ongoing debate about technology readiness, with some parties pressing for scale-up and commercialisation, and others more cautious and stressing the need for R&D and careful step-by-step development.

The use of algae for energy purposes is currently being studied within Task 39 (Liquid Biofuels), Task 37 (Biogas), and Task 42 (Biorefineries) of the Agreement. Task 39 is carrying out a review of the area, led by NREL. This will build on experience in the USA, Australia, and other Member Countries, and should be completed in 2010. Once this review is complete, the need for further work on algae will be considered.

Given this background the workshop set out to answer the following questions:

- When is the technology likely to be ready for commercial exploitation?
- What are the critical development stages still required (R&D, trials, demonstrations)?
- What are the likely costs of producing energy from algae?
- What are the likely CO_2 savings?
- What are the main barriers to be overcome (technical and non-technical including financial)?
- What role can IEA Bioenergy best play?

The five sessions in the workshop addressed the following topics:

Session 1 – Overview and Scene Setting.
Session 2 – Marine Macroalgae.
Session 3 – Microalgae in Open Ponds.
Session 4 – Microalgae in Closed Reactors.
Session 5 – Discussion and Conclusions.

The main points made by the speakers are summarised below. All the presentations are available on the IEA Bioenergy website (*www.ieabioenergy.com*).

SESSION 1 – OVERVIEW AND SCENE SETTING

The Promises and Challenges of Algal-Derived Biofuels – Al Darzins, NREL, USA

In 2007, the USA passed a very aggressive Renewable Fuels Standard (RFS) that mandates the use of 36 billion gallons of advanced biofuels by the year 2022. Corn ethanol production during this time is currently expected to be limited to about 15 billion gallons per year. The remaining 21 billion gallons is to be made up of cellulosic ethanol and other advanced biofuels. While cellulosic ethanol addresses the gasoline market, which in the USA is currently about 140 billion gallons/year, it does not, however, address the need for higher energy density fuels that could be used to displace the combustion of petroleum-based fuels such as diesel and jet fuel. Biodiesel produced from current oilseed crops cannot come close to meeting worldwide diesel demand, which in the USA alone is 44 billion gallons/year. Alternative sources of renewable oils are therefore needed to meet the challenge of increasing demand for higher energy density liquid transportation fuels.

Microalgae represent an attractive feedstock for the production of higher energy density oils. Algae, in general, have the ability to produce a wide array of different chemical intermediates that can be converted into biofuels. Microalgae have the capability of producing hydrogen, lipids, hydrocarbons, and carbohydrates, which can be converted into a variety of fuels. In addition, the microalgal and macroalgal biomass itself could be used to produce methane through anaerobic digestion, or syngas and bio-oil through various thermochemical conversion processes such as gasification and pyrolysis.

Many species of microalgae are able to produce high levels of oil (up to 50% on a dry cell weight basis). Coupled with their rapid growth rate microalgae can produce 10-100 times more oil than terrestrial oilseed plants. They do not require the use of precious agricultural lands but instead can be cultivated on non-arable land which has little to no use. They are also capable of using a variety of different water sources including fresh, brackish, saline, and waste water, and can use waste CO_2 sources as a critical nutrient.

From 1979 to 1996, the US Department of Energy (USDOE) sponsored the Aquatic Species Programme (ASP), which was run by the National Renewable Energy Laboratory (NREL). During the early years of the ASP, scientists were focused on collecting microalgal strains from a variety of aquatic environments and characterising the best isolates for growth and oil production. During the mid portion of the project the ASP concentrated its efforts on studying the biochemistry and the physiology of lipid production. One major finding of the ASP was that nutrient deprivation stress (nitrogen depletion in green algae and silica depletion in diatoms) was found to trigger oil production, although it did so at the expense of growth.

In the latter years of the ASP the researchers focused on developing genetic engineering tools for microalgae. For example, they reported one of the first successful genetic transformations of a diatom and then went on to attempt

Cover Picture: *Courtsey Michele Stanley, Scottish Academy of Marine Science, Scotland.*

to genetically engineer a diatom to produce more oil by expressing the gene encoding the first committed step in fatty acid biosynthesis. In addition to these largely bench-scale studies, the ASP also conducted open raceway pond growth studies in California, Hawaii and New Mexico, demonstrating that it was possible to continuously grow microalgae. The ASP ended in 1996 largely because of federal budget cuts and because oil produced from microalgae could not compete with the price of petroleum oil, which at the time was US$20/barrel. The ASP final close-out report was published in 1998. It contained an excellent summary of the major accomplishments of the programme and highlighted some major recommendations for future research and development. The ASP report can be found at the following link: *http://www.nrel.gov/docs/legosti/fy98/24190.pdf*

Given the rejuvenated interest in developing microalgal biofuels over the last few years, some may ask what has changed since the end of the ASP in 1996. There have actually been several critical issues that combined have had a large influence on stimulating the resurgence of algal biofuels research. In this vein, the world has experienced record crude oil prices, increasing energy demand, environmental concerns over increased CO_2 release, a virtual explosion in biotechnology, and a substantial commitment to the development of algal biofuels by the industrial and governmental sectors. For example, there is growing interest in algal biofuels by oil companies: Chevron is currently working with NREL; Shell is working in Hawaii through a joint venture known as Cellana; Conoco Phillips is sponsoring algal biofuels research through the Colorado Center for Biorefining and Biofuels (C2B2) and Exxon Mobil recently announced a large investment in developing algal biofuels along with Synthetic Genomics. In addition to oil companies, there has been significant interest in the development of algal biofuels coming from end users, engine manufacturers, and the aeroplane manufacturing industry. The US Federal Government is also funding algal biofuels research. The Air Force Office of Scientific Research (AFOSR), the Department of Defence's DARPA programme, and USDOE all have active algal biofuels programmes. NREL re-established its algal biofuels research programme about three years ago and is currently focusing most of its efforts on algal biology as this pertains to oil production.

Current scenarios for producing substantial amounts of transportation fuels from microalgae are not unrealistic. However, despite the potential of algal biofuels there are still many technical challenges that need to be overcome before this technology can be commercialised at a sufficiently large-scale. These challenges span the entire length of the algal biofuels value chain, from algal biology to algal cultivation to biomass harvesting to extraction of lipids and finally to the conversion of the algal oil to fuels. Overarching this value chain is the need to produce algal-derived fuels sustainably from a land, water, and nutrient use perspective. Another important issue that the emerging algal biofuels industry is trying to address is some rather extravagant recent claims regarding algal oil productivities. Despite many enthusiastic predictions of 10,000 to 100,000 gallons of oil/acre/year, (93,500-935,000 litres/ha/year) oil production from microalgae must first and foremost obey the laws of thermodynamics and will ultimately be limited by the low efficiency of photosynthesis (1-5%). More realistic estimations of oil production in the future, which are largely dependent on the geographic location and amount of available sunlight, have been determined to be in the range of 1,000-5,000 gal/acre/year (9,300 to 46,500 litres/ha/year).

In recent years there have been several significant attempts to capture the state-of-the-art in the algal biofuels field through both reports and road mapping. The Energy Independence and Security Act (EISA) passed in the USA by President George Bush in December 2007 contained specific references to algal biofuels. Section 228 of the Act explicitly stated it required the Energy Secretary of the USA to present to Congress a report on the feasibility of microalgae as a fuel feedstock. NREL helped draft that important report, which was recently delivered to the USA Congress, and was also instrumental in helping the AFOSR hold a joint workshop on 'Algal Oil for Jet Fuel Production' in Arlington, Virginia in February of 2008. (*See http://www.nrel.gov/biomass/algal_oil_workshop.html*)

The USDOE sponsored an algal biofuels technology road mapping effort in December of 2008. NREL and Sandia National Laboratories helped plan and execute the workshop. The goal of this workshop was to define the activities needed to overcome key technology hurdles associated with commercial scale algal biofuel production. The input received as part of this workshop was used to draft a comprehensive national algal biofuels road map for the USA. The USDOE workshop addressed in detail several key barrier areas such as algal biology, cultivation, harvesting/dewatering, oil extraction, conversion to fuels, co-product generation systems integration, siting, resource management and regulation and policy. In the algal biology section, for example, subtopics discussed included strain isolation and screening, cell biology and physiology, the development of an algal genetic toolbox and the need for a systems biology approach to evaluating algal oil production. R&D support will be needed for all elements of the algal biofuels value chain including the various downstream processes such as harvesting, extraction, and fuel conversion. Techno-economic (TE) modelling and life cycle assessment (LCA) will be necessary to provide the emerging industry with the required insights as it moves along the critical path to eventual commercialisation.
TE analysis will help to specifically identify critical path elements that offer the best opportunities for cost reduction while allowing the industry to measure progress towards its R&D goals.

Based on a very preliminary cost analysis of algal oil production data obtained from the literature and several unpublished contributions, it is currently estimated that the cost of producing a gallon of algal oil is in the range of US$10-40 depending on whether open pond raceways or closed photobioreactors (PBRs) are used for cultivation. (The latter are more expensive to build and maintain than open raceway ponds.) The completed USDOE National Algal Biofuels Technology Roadmap containing a comprehensive discussion of the R&D barriers is expected to be publicly available by early 2010. A copy of the preliminary draft of the algal biofuels roadmap that was published as part of a Request for Information (RFI) on 30 June 2009, can be found at the following website: *http://www1.eere.energy.gov/financing/solicitations_detail.html?sol_id=276*

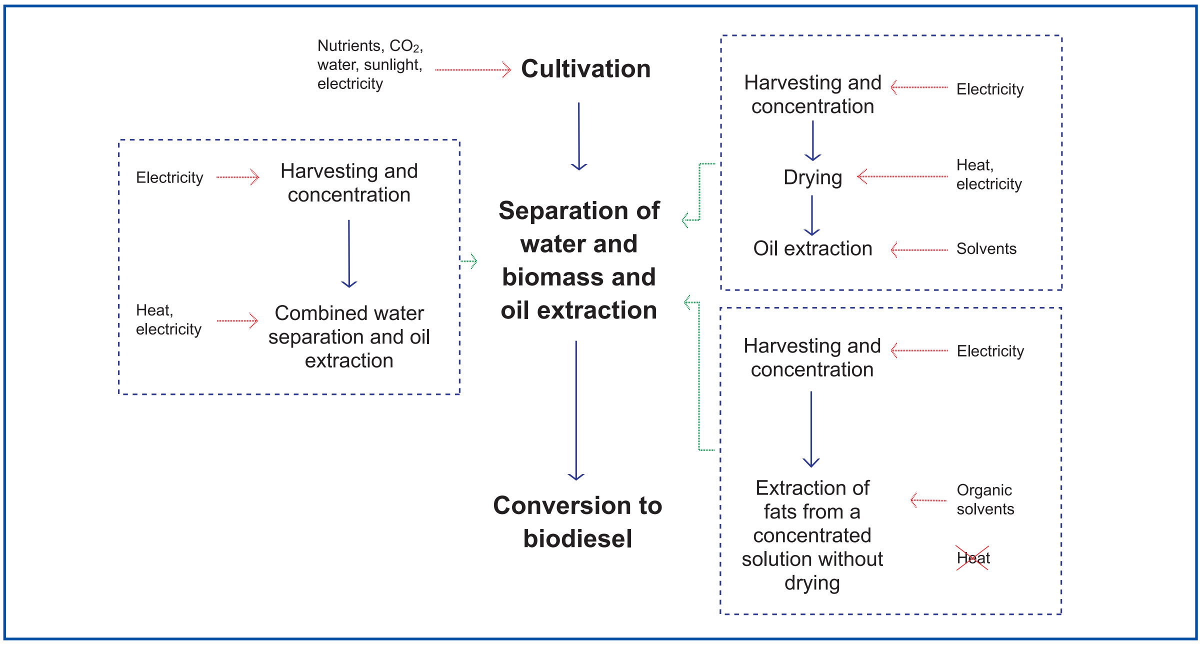

Figure 1. Algae biofuel production chain. Courtesy Pierpaolo Cazzola, IEA Secretariat, Paris.

Algae for Biofuel Production: Process Description, Life Cycle Assessment and Costs – Pierpaolo Cazzola, IEA Secretariat, Paris

Photosynthesis involves the metabolic synthesis of complex organic material using carbon dioxide, water, inorganic salts, and energy from solar radiation. The main factors limiting the productivity of photosynthesis include the availability of CO_2, water, mineral nutrients, and the ambient temperature.

Above a certain level of solar radiation, the atmospheric CO_2 concentration becomes the factor which limits biomass yields. Increasing the CO_2 level can increase the efficiency of the photosynthesis and lead to higher biomass yields per unit of land surface. Although enriching the CO_2 concentration is difficult for terrestrial plants, it is feasible in the case of microalgae where flue gases can be used.

The primary limiting factor in general is solar radiation. Typical efficiencies of photosynthesis in terrestrial plants are around 1%, and up to 3-4% in the best cases, such as sugar cane. This leads to typical biomass yields of below 10 g/m^2/day for terrestrial plants. In contrast, certain algal species have photosynthetic efficiency potential at least an order of magnitude higher than many terrestrial crop plants. Algae may achieve an efficiency of photosynthesis of 5%, and biomass yields above 20 g/m^2/day.

Two main solutions for algae cultivation have been adopted. These are open ponds (raceways) and photobioreactors (PBR). The characteristics of the two systems are summarised in Table 1 below.

Photobioreactors have mainly been developed since 1995. Analysis of published data shows that there is as yet no indication of significantly higher yields from PBR systems than from open ponds, notwithstanding the other advantages. Figure 1 shows the main process stages associated with producing energy from algae.

Table 1: Characteristics of the two systems used for algae cultivation.

Open Ponds	Photobioreactors
Demonstrated at a large, but not fully commercial scale	Developed to a laboratory scale, but not yet scaled up, not commercial
Large land footprint	Reduced footprint if there is sufficient light (e.g. when solar radiation is high) because the optimal illumination intensity for algae is below those typical of a sunny day in the tropics, and there are opportunities to extend PBRs vertically
Subject to contamination from predator strains	Allow single species culture
Subject to evaporative water loss	Water loss can be managed
Difficult to control temperature with day/night and seasonal variations	Can be more controlled but need larger amounts of energy for mixing and to maintain temperature
Lead to solutions with low biomass concentrations	Can lead to more concentrated solutions
Require larger amount of nutrients	Allow easier and more accurate provision of nutrients

Biomass yield averages around 20 g/m²/day, with peaks of 60 g/m²/day. This is considered indicative of average production across long periods of time. The average yield of oil suitable for the production of biodiesel is typically assumed to be between 20-50%. Oil yield can reach 90% for some species, under particular conditions, but high lipid fractions are generally associated with low overall biomass productivity, since plants tend to produce fats when they are under stress and therefore when their growth rates are limited. Taking a conservative estimated yield of 20% gives a production rate of close to 20,000 l/ha/year, about five times higher than the best yields achieved for the 'first generation' crops (e.g. palm oil in South East Asia). Higher yields may be obtainable.

Algae are produced in a water-rich solution, and the oily component needs to be extracted and then converted to fuel. This can be a very energy intensive process, so a number of alternatives are under consideration.

Drying is one option to achieve a higher biomass concentration in water, but this can be very energy intensive and could require around 60% of the energy content of algae. Strains with higher energy content might help reduce energy needs for drying, especially if the non-oil biomass residues are recycled for the generation of heat. Drying leads to concentrated biomass and oils, which can be separated using solvents.

The extraction of the oily component can also be done through chemical processes that require mechanical disruption of the biomass cells to free the lipid materials (generally contained in the cell walls) from the cellular structure. Such processes need high temperatures and pressures, and may require the use of solvents, applied in combination with a de-watering step and a drying phase before the oil extraction. Alternative processes which avoid the use of solvents are also under consideration. These combine oil extraction and water separation by using sub-critical water extraction. This takes advantage of the higher miscibility of oils in quasi-supercritical water and their easy separation once the temperature and the pressure of the solution are reduced. Another alternative is to extract the fats using organic solvents that are compatible with recycling of the algae in the bioreactor, without requiring high temperatures and pressures. Such processes are the subject of increased attention from companies that are patenting their developments while undertaking small-scale pilot tests.

Once the algal oil has been separated, the products are suitable for processes conventionally used for the conversion of vegetable oil to biodiesel, such as hydrogenation and trans-esterification. The extraction and simultaneous trans-esterification of oils using supercritical ethanol or methanol is emerging as a lower-cost, innovative approach to vegetable oil conversion. Its applicability to algae is not yet proven, but the pathway could be promising.

Technologies such as pyrolysis, gasification, anaerobic digestion, and supercritical processing allow the conversion of whole algae into fuels instead of first extracting oils and post-processing. Algae are also a potential feedstock for biomass gasification and conversion to fuels via Fischer-Tropsch (FT) synthesis. Since FT synthesis is an exothermic process, it could provide some of the heat needed for the drying phase.

If grown in the dark, some algae can convert sugars into ethanol and other alcohols (heterotrophic fermentation), as well as to hydrocarbons. Photosynthetic processes are suppressed once algae are grown in the dark, and the synthesis of hydrocarbons or alcohols occurs if the organisms are fed with sugars.

Life Cycle Analysis

A preliminary life cycle analysis for algae production has been carried out. The cultivation and the drying phase are particularly significant when the production of algae is analysed with respect to life cycle emissions, as shown in Figure 2.

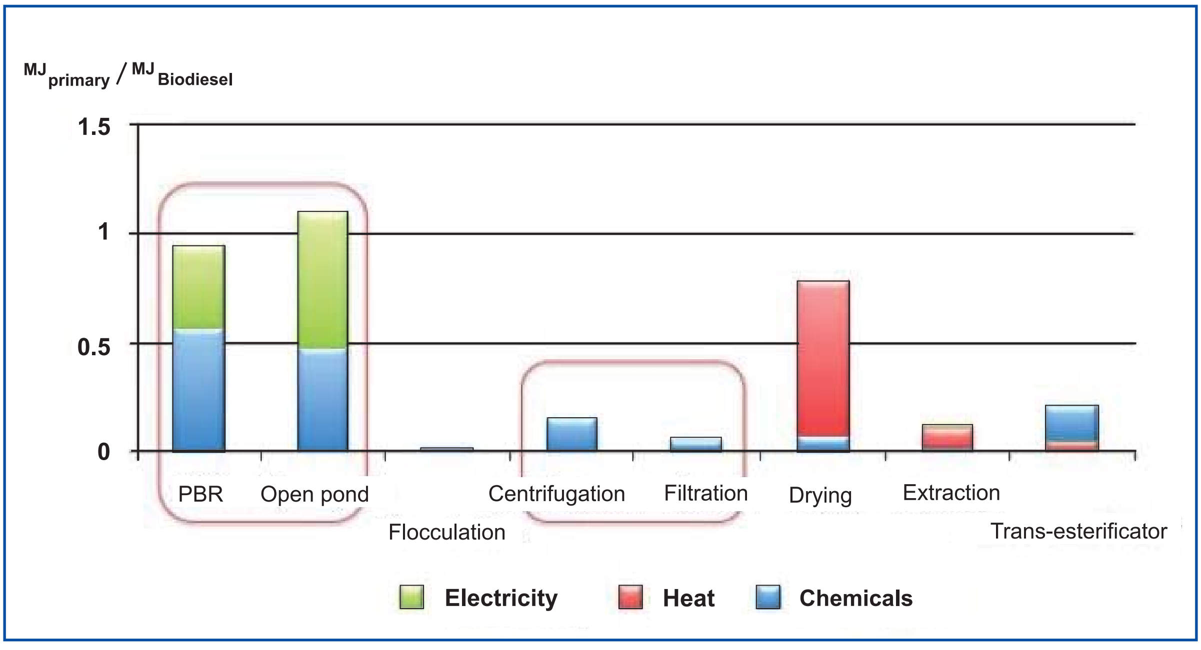

Figure 2. A preliminary life cycle analysis for algae production. Courtesy Pierpaolo Cazzola, IEA Secretariat, Paris.

Table 2: Life cycle analysis scenarios for sustainable algae-based biofuel production.

Scenario 1 'Base Case'	Scenario 2 'Dry Path'	Scenario 3 'Wet Path'
Production of algae biodiesel with drying before extraction of oil.	Production of algae biodiesel with drying before extraction of oil.	Production of algae biodiesel without drying before extraction of oil.
No use for residues of extraction and trans-esterification.	Extraction residues are burnt and the generated heat completely recovered.	Extraction residues are used for biogas generation via anaerobic digestion followed by heat and power generation via biogas-fuelled CHP. Some nitrogen is recovered after anaerobic digestion and is used for the cultivation phase. Trans-esterification residue (glycerol) is burnt and the resulting heat recovered.
Key assumptions: Algae biomass yield: 20 g/m²/day; Lipid content: 20% oil (on weight basis); Lower heating value of algal biomass after extraction: 11.25 MJ/kg dry biomass		

Optimisation of the chain, using the residues efficiently for local energy production, is necessary for sustainable algae-based biofuel production. The life cycle analysis considered three options, as shown in Table 2 below. Two scenarios are analysed in addition to a 'base case' (Scenario 1), in view of the importance of avoiding the drying stage. In Scenario 2, residual dry algal biomass is burned for heat recovery ('Dry path'). In Scenario 3, oil is extracted from wet biomass and the residues of extraction are used for anaerobic digestion, producing biogas, which is used in a CHP system to produce process heat and power, and also allowing the recycling of some of the nutrients used during cultivation.

The results of the preliminary analysis can be seen in Figures 3 and 4, which show the overall energy balance and greenhouse gas balances respectively. Scenarios 2 and 3 show significant improvements compared to the base case, and the energy balance for these two scenarios is positive. The analysis indicates that it is possible to reach GHG balances of 0.04-0.05 kg CO_2 equivalent per MJ of biodiesel produced. The 'well-to-wheel' emission for diesel is 0.087 kg CO_2 equivalent per MJ biodiesel. Algae biofuels are able to reduce emissions by 50% when replacing diesel.

Costs

There is relatively little information on costs of algae production in the literature. However the data available via techno-economic studies show a very wide range of estimates differing by orders of magnitude. The best studies indicate cost estimates of:

- US$2-2.5/L of oil produced in open ponds and fermenters producing algae grown in the dark; and
- US$5-6/L of oil produced in PBR.

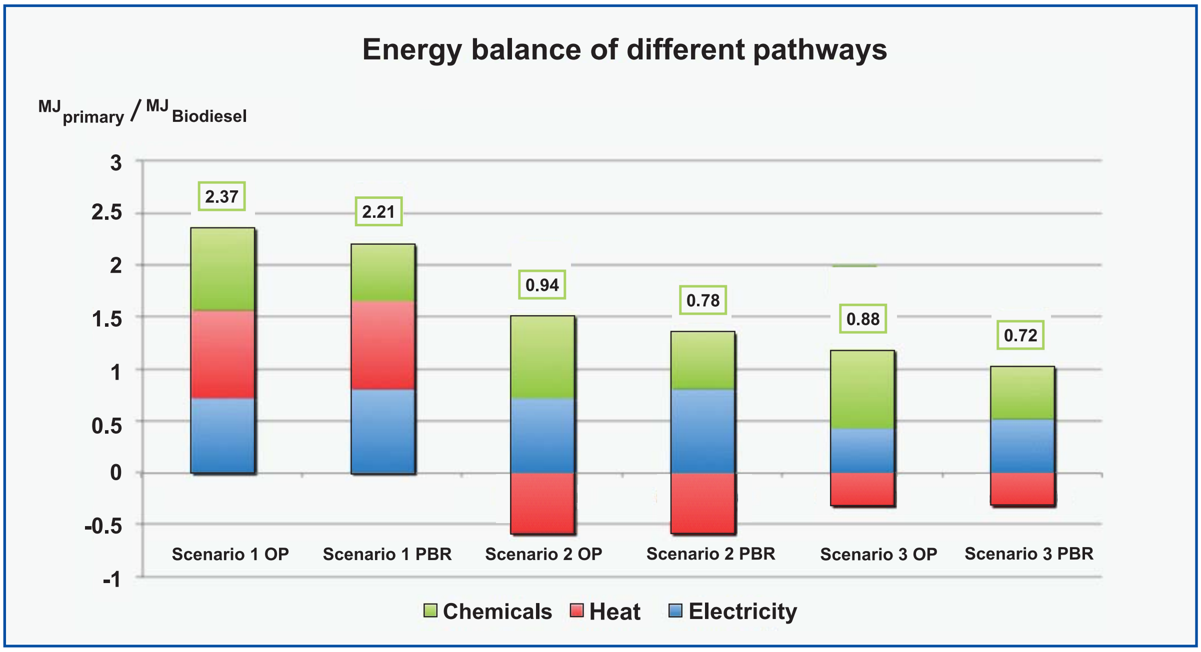

Figure 3. Preliminary results of energy balance. Courtesy Pierpaolo Cazzola, IEA Secretariat, Paris.

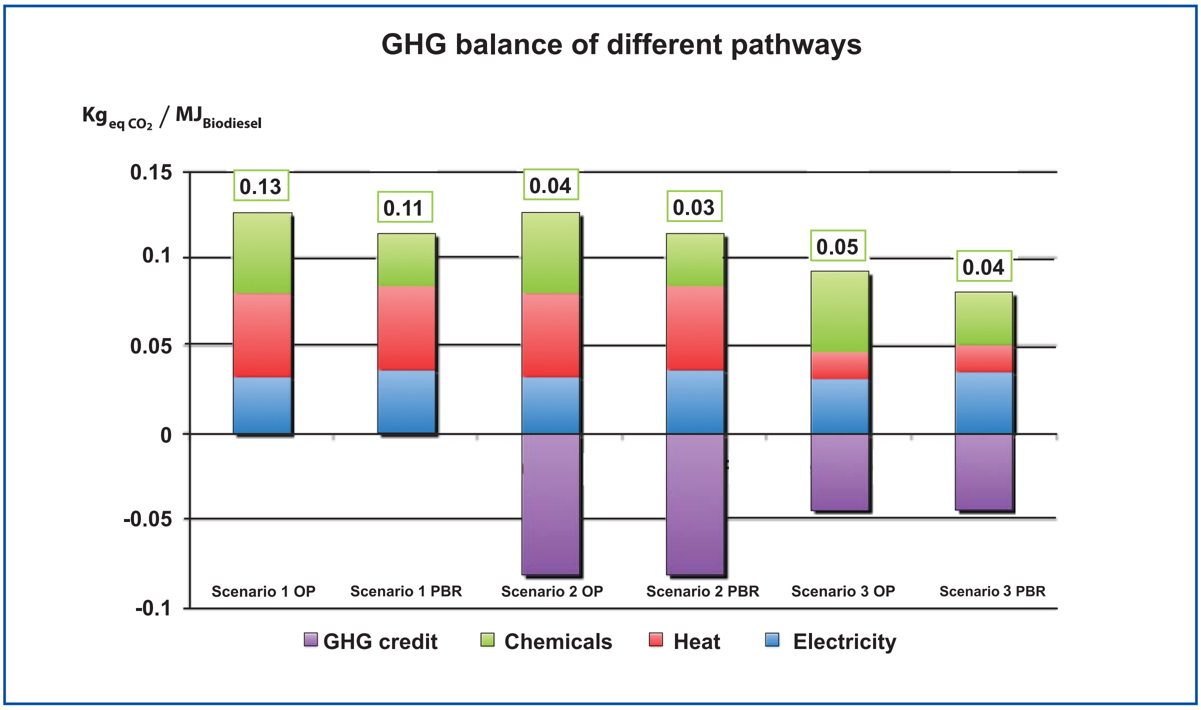

Figure 4. Preliminary results of GHG balance. Courtesy Pierpaolo Cazzola, IEA Secretariat, Paris.

However production processes are still under development and there is considerable scope to reduce costs and improve efficiency. Particular areas for improvement are the development of new strains of plants, optimised for biomass production or oil synthesis; and the development of extraction and conversion processes allowing the recycling of water, reduced energy consumption and even the recycling of the living organisms.

Future Work

The IEA Headquarters Secretariat will continue its analysis, focusing in particular on cost estimation and on overall potential worldwide. This will feed into an IEA biofuels roadmap, work on which will begin in late 2009 and go through 2010. This will include issues related to vehicles and fuels, and conversion and feedstock supply, and will also consider algae and other advanced biofuels. The results will be part of the Energy Technologies Perspective 2010 publication.

SESSION 2 – MARINE MACROALGAE

Fuel From the Sea – Michele Stanley, Scottish Academy of Marine Science, Scotland

Marine algae offer the potential to be a vast renewable energy source for countries around the world that have a suitable coastline. They are already farmed on a large scale in the Far East, mainly as a food source, to a much lesser extent in Europe, primarily in France, for alginate production and on a research scale in Scotland (Kelly and Dworjanyn, 2008; Sanderson *et al*., 2008). Utilising marine as opposed to terrestrial biomass for energy production circumvents the problem of switching agricultural land from food to fuel production. In addition, production of marine biomass is not limited by freshwater supplies, another of the contentious issues of increasing terrestrial biofuel production.

As a response to global warming, marine biomass as a means of mitigating CO_2 emissions is now being considered. According to Yokoyama *et al*. (2008) 0.9% of Japan's required CO_2 mitigation under the Kyoto protocol could be achieved by farming macroalgae on a large scale. However, it must be remembered that burning or decomposing macroalgal biomass, if used for energy production, will only recycle the carbon – the system is in fact a carbon neutral one. There are also potential benefits to fisheries by providing extra habitat but this must be viewed in the context of harvesting practices. The concept of marrying mariculture with offshore wind farms already has support in Germany, Denmark, the Netherlands, and the USA (Buck *et al*., 2004; Michler-Cieluch *et al*., 2009; Reith *et al*., 2005; McKay 1982; Hagerman and McKay, 2007).

The feasibility of producing methane from seaweed using anaerobic digestion (AD) has already been demonstrated. Research investigated the effects of varying several of the variables affecting the process as a whole e.g. separation of the juice and non-juice fractions, temperature, inoculums, nutrients, freshwater versus seawater dilution and non-dilution (Morand *et al*., 1991; Chynoweth *et al*., 1987). Advanced digester designs, process optimisation, and kinetics have now also been investigated. The results from this work demonstrated that in general brown algae are more easily degraded than green algae, and the green are more easily degraded than red. The AD process also involves at least two very distinct microbial consortia. For this reason some investigators have proposed separating these organisms into two separate phases. Whether methane production is performed with these phases combined or separated, the process as a whole is strictly anaerobic and must be performed in the absence of air (Chynoweth *et al*., 1987).

Seaweed contains two main storage sugars, mannitol and laminaran, which can be relatively easily extracted from milled seaweed. The Norwegian researchers (Moen *et al*., 1997) showed that these are the best substrates in seaweeds for the production of bioethanol. They are also both waste by-products of the alginate extraction industry. Initial attempts using microbes to convert these sugars into bioethanol have shown promising results (Horn *et al*. 2000a, 2000b). Both of the microbes used in these attempts were of terrestrial origin and, as expected, were found to produce sub-optimal conversion rates and yields of bioethanol. This is possibly attributable to the incompatibility of these terrestrial-origin microbes with a marine-based biomass, the relatively high concentrations of salts present in seaweed biomass limiting the conversion process.

The economic potential of bioethanol production from seaweed is enhanced by the facts that (i) the raw feedstock could be derived from waste produced by the alginate industry which is highly enriched in the sugars mannitol and laminaran, thereby dramatically cutting down on initial costs; and (ii) the time taken to achieve optimal bio-conversion rates and yields of bioethanol from seaweed is estimated to be years rather than decades as many technological hurdles have been overcome in the past 50 years of experience into converting bioethanol from lignocellulosic materials. The cost of enzymes for digesting complex biomass to make it more amenable to fermentation has fallen considerably, thus making ethanol from biomass more affordable and technologically less daunting.

In order to produce biofuels in the form of either methane or ethanol from macroalgae it will be necessary to:

- Optimise the pre-treatment to improve the performance of a substrate for AD.
- Overcome toxicity caused by high levels of phenols, heavy metals, sulphides, salts, and volatile acid compounds found in seaweeds, which can inhibit methanisation.
- Screen for bacteria that can be used in both methanisation and bioethanol production.
- Incorporate latest AD technology from terrestrial biomass digestion and design digestor's specifically for seaweeds.

Another key objective for marine biomass energy must be improvements in crop yield. There is the potential to increase the available macroalgal biomass through selective breeding programmes and the fact that yields can be greatly enhanced by providing the optimum nutrients in the growing regions. It has been suggested that an integrated approach would assist in attaining economic viability, so seaweeds grown for biomass could be simultaneously used as a means of pollution abatement, coastal protection, fertiliser production and the production of other raw materials or food. There is also a serious need to expand and enlarge existing culture banks and strain selection and maintenance facilities in the same manner that germplasm banks have been established for terrestrial plants and animals (Bird and Benson, 1987).

The €6 million BioMara project, started in January 2009, aims to address some of these issues. This is a collaboration between Scottish and Irish researchers coordinated from SAMS and funded by the EU Interreg IVA programme, Highlands and Islands Enterprise and the Crown Estate. Partners come from the University of Strathclyde; Queen's University, Belfast; the University of Ulster; the Dundalk Institute of Technology; and the Institute of Technology, Sligo.

The Biogas, Algae and Wetlands Project in Trelleborg – Sten Bjork, Trelleborg Municipality Environmental Department, Sweden

Between 2005 and 2007, Trelleborg City carried out a very comprehensive Integrated Coastal Zone Management (ICZM) analysis of the steps required to ensure the sustainable progress of society and the environment in our part of the Baltic Sea Region (BSR). The analysis concluded that the highest priority was to reduce considerably the release of nutrients from farming and agriculture production into the Baltic Sea, in order to preserve beach zones and fish reproduction areas from total eutrophication. It was also felt that it was essential to start to make all possible efforts to reduce air pollution from transport and heating activities in the same area.

Our community, together with our farmers, residents and businesses, quickly found the solution was to reduce the flow of nutrients into the sea by using algae. We plan to use algae found in nature, along with those grown in old and new wetlands and in newly constructed ponds connected to farmland ditches. We will construct a suitable system for algae collection and use them as a very economical and environmentally sound source of biogas production. This biogas can then replace other energy sources and so largely reduce industrial and consumer air pollution. Our EPA and Government fully support this initiative and this major biogas project has been recognised as having a high environmental value to our entire nation.

We had already started using CNG in our municipality in all our vehicles a few years ago, finding this to be the cleanest fuel presently available for modern engines. With our increased biogas production we will in the near future be able to shift over to biogas totally and run all land and sea vessels on what is at present the best and cleanest fuel available. A comprehensive CNG distribution system already exists, with pipelines covering the whole of southern Sweden. In the community of Trelleborg this is used for heating businesses and households in winter time.

This pipeline network makes the introduction of an increased capacity for biogas production relatively easy, since the sales and distribution systems as well as future customers are already in place. The shift from CNG to biogas will be very simple to arrange and therefore very cost effective, and can be done step-by-step until we have replaced all imported gas with totally green, locally produced and consumed gas for transport, electrical energy production, home heating and other uses. The latest proposal is to introduce methane as a fuel for our future continental ferries between Scandinavia and the European continent.

Biogas is easier to produce than other similar biofuels, using a simple fermentation process in a plant that is much easier to construct and run than other, more complicated fuel production systems. A significant advantage of biomethane was the possibility to mix it directly, without any technical difficulties, with either CNG or LNG.

Since 2004 our view has been that engine makers should adjust their engines to run on the best and most easily produced fuels, rather than expect society to produce less cost effective and more polluting fuels just to fulfil different engine makers' demands.

Working with the community and our farmers, the energy company EON's gas division have started to design a full-scale (350 GWh/year) biogas production plant pilot project, where all today's techniques and methods are being utilised, using harvests from restored and large newly-constructed wetlands, together with algae collected along the coastal zones.

The Trelleborg farmlands, situated on the south coast of Sweden, have the richest soils and also the largest farmland areas, covering 85% of the total community area. The geography of this lowland area is typical of the coastal zones of the southern Baltic farmland areas in Denmark, Poland, and Germany.

The collection of these harvests as a biogas source, both from wetlands and in the form of algae from the sea, will considerably reduce the total farmland effects on the Baltic Sea. As the biogas will be produced and also consumed locally, this pilot project will also make a significant contribution to decreasing the total CO_2 volumes from urban societies in the zone. CO_2 from the fermentation process is also sold to the farmers for greenhouse use (one of the CO_2 customers is the largest producer of tomatoes in Europe).

New harvesting techniques in the wetlands and for algae collection in the coastal zones have been developed and prototypes of the newly developed machines and tools are currently being tested in Trelleborg. All the tests have been very successful.

The logistics, transport methods, and collection making full use of algae, have been designed to be as efficient as possible, so it should be possible to replicate the systems in other places in the BSR.

The residue from the biogas production is pumped out as sludge in huge piping systems. A simple electrolytic pre-treatment process, which separates the heavy metals, ensures that the residue from the biogas production can be returned to the farmers and re-used as fertilisers.

The creation of such large biogas plants and the management of the wetland areas are huge projects, with long-term impacts which will have positive climate change impacts. The projects will be long-lasting and operate for many years to come. A step-by-step approach to investing in wetland management is being adopted, using existing rivers and ponds where possible. These measures will also contribute to preserving the wildlife diversity in our area.

With increased farmland productivity, which results from more intensive use of the farmland soils, it is very important that the farmers direct rainwater flows into wetlands, collection basins and ponds, and not into ditches, as the latter will transport the rainwater to the sea so much faster.

Close to the seashore, it is important to be aware that the Baltic Sea level may rise considerably in the coming decades due to climate change. This is taken into account when constructing the new wetlands and assembly ponds, which can be seen as equivalent to the Dutch solutions with channels, walls, and pumping systems.

This project, using algae for biogas production, is the only large-scale example which will reduce the flow of nutrients from farmlands into the Baltic Sea, especially where phosphorous reduction is concerned. With four systems of similar size, Sweden will be able to fulfil its obligations for reduction of nutrients flowing into the Baltic Sea under the HELCOM Agreement. We encourage all our neighbour nations around the vulnerable Baltic Sea to follow our example.

SESSION 3 – MICROALGAE IN OPEN PONDS

Algae Biofuels: Challenges in Scale-up, Productivity, and Harvesting – John R. Benemann, Benemann Associates, USA

Microalgae are currently cultivated commercially for high value nutritional supplements. Almost all this production uses shallow open ponds, mostly of the raceway-type with paddle wheel mixing. Around 10,000 tons are produced annually, with plant gate costs over $10,000/t. The goal for biofuels production is to produce millions of tons at under $1,000/t.

In order to achieve this goal, a number of challenges will have to be overcome. Microalgae are very small and grow as very dilute (<1 g/l) cultures in suspension. They have a very low standing biomass (<100 g/m^2), and require daily harvesting from large volumes of liquid. The harvested biomass must be processed immediately. Microalgae cultures require a source of CO_2, either purchased or 'free' from power plant flue gases, biogas or ethanol plants. Microalgae require a good climate with a long cultivation season.
For biofuel production algae must be produced at very high productivity, and the number of species available for cultivation must be increased.

The first algae production plant was constructed over 50 years ago on the roof of the MIT building. In this pioneering work, a pilot plant was used to produce the unicellular green alga *Chlorella*, during which Jack Myers and Bessel Kok identified some of the main issues for algae production which are still relevant today. In 1956 an engineering design study calculated the cost of a production plant at around US$2 million/hectare (in 2009 prices). During the 1950's, at the University of California Berkeley, Professor William Oswald and colleagues developed the raceway-type, mechanically mixed 'high rate' open pond design for waste water treatment. During the 1970's, the presenter, with Prof Oswald, Dr Joseph Weissman and colleagues, used two pilot-scale 0.1 hectare high rate ponds, with paddle wheel mixing, to demonstrate a process for algal biofuels (methane) production, using the low-cost, spontaneous settling ('bioflocculation') process for harvesting the algal biomass.

Currently four types of algae are produced commercially – *Spirulina, Dunaliella, Chlorella* and *Haematococcus*, all used primarily for human nutritional products ('nutraceuticals'). *Chlorella* was first produced in Japan in the 1960's using circular ponds, which were effective, but which cannot be scaled beyond 1000 m^2, because the speed at the tip of the mixing arm becomes too high. *Spirulina* is produced in about two dozen commercial plants worldwide, almost all in paddle wheel mixed raceway ponds of up to 5000 m^2. *Spirulina* is relatively easy to grow (due to its very alkaline medium) and harvest, as it grows as filaments. Cyanotech produces *Spirulina*, and *Haematococcus* in Hawaii, and has used CO_2 captured from a small biodiesel-fuelled power plant. *Dunaliella* is produced on a similar scale in Israel (by Ami Ben Amotz). It should be noted that currently even a large algae production plant is only about the size of a USA corn or alfalfa field. This is still a very small industry.

Algae can also be grown in enclosed photobioreactors (PBRs) of various designs, including tubes, bags, panels, etc. These systems are more amenable to experimental studies, however the productivity of PBRs and ponds are similar. Exceptions are where PBRs are erected vertically, which increases productivities per area of land, but not per m2 of PBR. Another advantage is that PBRs can be kept warmer in cold climates. However, PBRs are limited to a few hundred m^2 for individual growth units, compared to several hectares for ponds, and their costs are excessive even for high value nutraceutical products, let alone biofuels.

Open pond systems are more promising for biofuels production, with most design parameters, such as depth and mixing velocities, relatively well understood, but constrained by the limitations of parasitic energy use. The main process improvements will need to come from improved algal strains and cultivation techniques that minimise grazers and other challenges.

CO_2 supply is a key issue in algae production. Transport of flue gas and transfer of flue gas CO_2 into the ponds, present major cost and energy consumption issues. Some CO_2 is lost during transfer of flue gas into the algae ponds and through out-gassing before the algae grow. However the greater limitations are the daily and seasonal variations in productivity, i.e. the matching of the CO_2 requirements of algae with the emissions of large-scale fossil power plants, as even small power plants would require thousands of hectares of algae ponds. These limitations result in a likely maximum capture of CO_2 from a large power plant of plausibly around 10%. Adding this to the land and water limitations near most power plants indicates that, even ignoring climatic constraints, algae production is not a realistic mainstream option for significantly reducing emissions from large, centralised power plants. Where conveniently located, non-fossil sources of CO_2 (biomass power plants, pulp paper mills, ethanol, other agricultural processing plants and waste sources) are more promising for algae biofuels production, and such sources also avoid the further load of fossil CO_2 to the atmosphere inherent in using fossil-fuel derived CO_2 sources.

The best solution is the synergy of algae biofuels production with wastewater treatment, since wastes can provide a regular supply of water and nutrients (C, N, and P), which can be efficiently recovered by algae. Existing technology for algae wastewater treatment could be combined with biofuels production, with only modest development (e.g. bioflocculation harvesting).

Current technology for algae production could yield a maximum of around 70 t/hectare per year of biomass and about 15,000 litres of algae oil/hectare per year. These already rather optimistic estimates are well below many current commercial projections, most of which are overly ambitious, but still compare favourably with productivity levels for other biofuel systems. In the long-term, research might boost this level to around 60,000 litres/ha/year through strain improvements targeting photosynthetic efficiency, oil productivity, etc. One important opportunity in increasing photosynthetic efficiency will come from reducing the amount of the so-called light harvesting chlorophyll and other pigments per cell, which will thus allow better light penetration in the cultures and more efficient use of sunlight photons by the algae cultures. Aside from developing such more productive algal strains, many other challenges will need to be overcome to produce algae biofuels economically. However research into algae systems is promising because:

- Algae R&D can be carried out quickly since life cycles are very short (hours to days).
- The costs of algae research are relatively low since it can be carried out at a small-scale and fewer variables need to be considered than for higher plants.
- Growing algae can have multiple benefits when coupled with wastewater treatment, and with the production of protein and other co-products.
- Algae can use water (e.g. seawater) and land unsuitable for crop production.

The Economics of Algae Growing Systems: Global Feedback and Future Outlook – Peter van den Dorpel, Algaelink, Netherlands

Algaelink has focussed on the stage of the algae production chain involved in the primary production of algae, since this is the critical first stage, while others are focussing on downstream stages. Algae can produce materials that can serve a number of different markets. The food and feed markets could be of a significant scale and higher value than previously anticipated. Production of energy products along with co-products will be important and add robustness to business models. On the input side, algae production can have links to CO_2 absorption or links to waste water treatment. A diversified market is likely to develop with applications and product mixes varying with location. Figure 5 below illustrates the range of potential markets and likely price points.

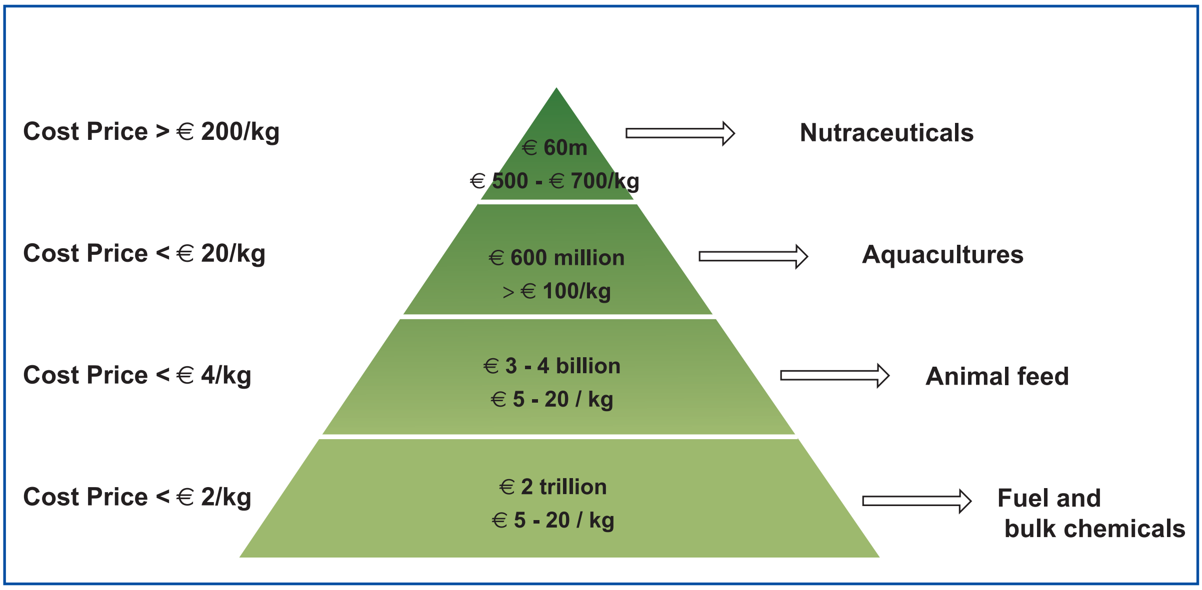

Figure 5. Potential market values and price points. Courtesy Peter van den Dorpel, Algaelink, Netherlands

Production cost estimates have reduced significantly in recent years, and can be as low as €2/kg in favourable circumstances where inputs can bring credits to the project economics. The situation depends on many factors – the location, climate, input costs, logistic costs, labour costs, and product mix. The required service levels are also very important to commercial arrangements.

Algaelink designs and sells photobioreactors, grows and sells algae, and provides consultancy and training associated with projects involving open and closed systems. The design of the photobioreactor is key, with more degrees of freedom than are found in open ponds. The system involves a transparent network of tubes, controlled and fed by a vessel with sensors and software, and a patented cleaning device. Depending on the climate and algae strain, density levels of up 1.5 kg/m^3 can be achieved. Between 50-150 tonnes/ha can be produced – potentially significantly higher than open ponds. There is currently a cost gap between open and closed systems, but the gap is closing. Hybrid systems, involving closed and open systems in combination, may offer an improvement by a factor of five in productivity at the cost of a factor of two in the relative cost, and so may prove more desirable.

Closed photobioreactors offer advantages compared with open ponds that include:

- better control of algae culture,
- large surface-to-volume ratio,
- reduction in evaporation of growth medium,
- better protection from outside contamination,
- higher biomass – can sustain higher cell density, and
- diverse algae species – because of reduced hydrodynamic stress more diverse algae species can thrive.

Algaelink has sold 35 systems worldwide, with significant interest from Australia, China, India and South Africa as well as Europe and North and South America. This has allowed a database of experience to be accumulated and fed back into reactor and project design and provides information for business planning. Yield is a complex issue, and high light intensity levels are not the only factor. Having a robust and reliable system is essential before moving on to large-scale operation, whatever product mix is to be produced. The Algaelink cleaning system addresses the biofouling issue and so maintains transparency and allows good levels of light absorption to be maintained, without regular downtime for maintenance. Another feature of the system is the automatic measurement system which then adjusts variables to optimise production, and enables learning at a rapid rate.

Now that the production system is in operation, work on the other steps is under way, including harvesting, drying (to a slurry with 18% solids), and extraction. The ultimate design will probably involve a hybrid system consisting of a number of photobioreactors feeding closed ponds which are used for flocculation. Development of lower cost photobioreactors coupled with likely increases in fossil fuel prices will lead to practical and economic algae projects.

SESSION 4 – MICROALGAE IN CLOSED SYSTEMS

Microalgae for the Production of Biofuels and Bulk Chemicals – Rene Wijffels, Wageningen, Netherlands

A recent economic feasibility study by the University of Wageningen was carried out for the electricity company Delta nv. This compared three different systems available today – a tubular reactor, a raceway pond, and a flat panel system. Two scales of operation were considered – a 1 ha system and a 100 ha system. A whole system analysis was carried out, using conservative but realistic estimates for costs and performance data – for example using solar conditions from the Netherlands, assuming current productivity rates, and allowing for purchase of all the necessary resources (such as CO_2 and nutrients). Although the resulting figures may be too high this allows sensitivity and optimisation studies to be carried out.

The results were not very sensitive to the type of reactor chosen. Taking the tubular reactor figures as an example, the production cost estimate was around €10/kg of dry biomass at the 1 hectare scale, with 50% of costs coming from labour and power costs. These costs are significantly reduced at a larger scale, leading to production costs of around €4/kg. Under these baseline conditions the system is still energy intensive due to pumping power demands and there is a negative energy balance. The energy cost of around €2/tonne is not so important when producing products with a value of approximately €100/tonne, but this becomes a critical factor if lower value energy products are the target.

The study also looked at the potential for improvements in costs and performance, for example:

- Providing CO_2 and nutrients at no cost (perhaps from a waste treatment plant).
- Increasing photosynthetic efficiency from the 3% obtainable in production processes to the 5% attainable in the laboratory.
- Shifting production to the Caribbean region, with better insulation levels.

These changes significantly reduce production costs to around €400/tonne. This is still too expensive for bulk energy production. The study also examined how the value of the algae could be increased by adopting a biorefinery approach and optimising the value of the lipid, protein and polysaccharide fractions, as well as gaining value from the oxygen produced along with some credit for nitrogen removal as shown in Table 3 below. Altogether these products lead to a value of €1,646/tonne of biomass, compared with the production cost of €400/tonne, indicating that only with a biorefinery approach is algae production likely to be economic.

This sort of analysis has been used to structure research programmes in Wageningen, via a number of projects funded by the Dutch and Belgium governments and the EU, and carried out with industry partners.

The work centres on closed photobioreactor designs, and on ways to maximise photosynthetic efficiency and the control of metabolism and productivity. This can be achieved by shading, using a vertical bioreactor design, or by increasing biomass density. High density cultures perform better with higher levels of mixing, but this requires more energy inputs, so a balance must be struck. Higher energy inputs can also lead to shear effects through bubbling or boiling, which can also lead to high levels of fouling. At high densities certain algae produce inhibitors, which need to be avoided. Other factors being studied include the use of light guides, and understanding the 'flashing light' effect as algae travels from light to dark zones. One key issue is the variation with light intensity, with the aim of maximising productivity when light levels are at the highest levels.

The O_2 produced by algae inhibits photosynthesis, so work is examining the maximum tolerable O_2 partial pressure and how this varies between algal strains. Examination of the combination of stress factors – for example high light levels coupled with high O_2 levels – is an important issue, along with work on O_2 removal techniques, since reducing O_2 is an energy intensive process. Energy efficient CO_2 supply is another important issue which can be addressed through strain selection, but also by working at high pH and salt levels, which encourage lipid formation.

Work on the control of primary metabolism aims to control metabolism to match reactor design and to maximise productivity, but also to optimise production of lipids or colourants. Genome-based metabolic network models are being developed to facilitate flux calculations to predict rates and primary metabolisms.

Work on harvesting and oil extraction focuses on the reduction of costs and energy demands by avoiding extra chemicals and by reusing mediums, and on examining mechanisms of bioflocculation for interesting algae.

In the next phase of work, the concept of an 'Algae Park' is being developed. This will allow a move to larger scale systems to allow development of the whole process chain and the accumulation of operational experience to provide information for the design of full-scale plants and the development and comparison of different systems. There is also a need to produce more algae products to test and develop downstream processes. The park will consist of a number of different reactors, including some 25 m^2 systems along with smaller scale reactors, and both open and closed systems. This will allow rapid testing of laboratory-based developments, enabling the move to larger scale testing as soon as possible.

Table 3: Biorefinery of microalgae: Bulk chemicals and biofuels in 1,000kg of microalgae.

Products	Product Value	Value €/tonne of biomass
400 kg of Lipids		
100 kg for chemical feedstock	2 €/kg lipids	200
300 kg transport fuel	0.5 €/kg lipids	150
500 kg of Proteins		
100 kg for food	5 €/kg protein	500
400 kg for feed	0.75 €/kg protein	300
100 kg of Polysaccharides	1 €/kg polysaccharides	100
Nitrogen removed – 70 kg	2 €/kg nitrogen	140
Oxygen produced – 1,600 kg	0.16 €/kg oxygen	256
Total		**1646**

The aim is to develop a comprehensive research portfolio covering the whole chain of process development in an integrated way, including fundamental biology, systems biology, metabolic modelling, strain development, bioprocess engineering, scale up, and biorefineries.

Overall the view is that microalgae are a promising source for bulk chemicals and biofuels production. The technologies are still immature, and a large-scale and comprehensive R&D effort will be required to bring the technologies to the market. A biorefinery approach, producing a range of products, will be essential for economic operation. University and industrial collaboration will be essential to the development of the sector, and such links are currently developing in a productive way.

Open Versus Closed Systems: Lessons Learned From Building Both Types of Systems – Marc Van Aken, SBAE Industries, Belgium

SBAE Industries was founded in 2006 as an algae production company, bringing together biological knowledge, and engineering know-how. The company has succeeded in obtaining support from four investment funds, including one of Europe's largest cleantech investment funds, and is focused on IP development.

'Algae' are a very ill-defined and diverse group of organisms, including blue-green, red, golden, yellow-green, and yellow algae. They include diatoms, which on their own include over 200,000 species. In fact algae are found within most of the major branches within the 'tree of life'. This illustrates the complexity of the area, and inevitably leads to complexity and diversity in cultivation and treatment processes. There are some areas of common ground, since algae need light, water, a carbon source (often CO_2), and nutrients (N, P, and K).

The study of algae is not a new topic, with early work by Martinus Willem Beijerinck leading to the isolation of *Chlorella* as early as 1890. In the 1960's production of algae in the sea was considered, and systems classified in three ways:

- the 'American' – closed circuit with circulating air;
- the 'German' – open circuit with circulating air; and
- the 'Japanese' – open circuit with rotating arms.

More recently the debate has polarised into an evaluation of the merits of 'open' versus 'closed' systems.

SBAE has developed algae production systems aimed at the aquaculture sector. Critical stages in the production process include air purification through freeze drying (to avoid contamination by air-borne micro-organisms including competitive algae), and water treatment. Algae are grown in photobioreactors which are typically between 80 and 300 litres in size. The resulting solutions are then subjected to post-processing treatments which include centrifuging, freeze drying, and post-production treatment to produce an algae powder. The various customer applications require mixes of algal products (typically involving four different species) depending on fish species. Algae are also used as food for rotifers, which are part of the food chain between algae and fish. The development of appropriate food mixes for fish larvae is one issue on the critical path to the evolution of sustainable aquaculture systems. The products can also be used in high value nutraceutical and cosmetic applications.

These techniques can be adapted to some extent to produce lower value algae for energy purposes by scaling up, using outdoor light sources, and modifying the reactor design. These steps will lead to some cost reductions. However the process will still have to be carefully controlled and this may limit the development potential.

Most work on algae has focussed on planktonic organisms which are free floating in water. The solution containing the organisms is circulated to gain exposure to light and nutrients and so facilitate growth. As an alternative approach, SBAE has been investigating the role of perifytonic organisms, which attach themselves to rocks etc., and which are widely found in nature. In systems using these organisms they can remain fixed to a medium, and the water bearing the nutrients circulated over them. The diatomic species involved offer a number of advantages including very high growth rates and productivity levels since they need only 6.5% of the energy required by typical planktonic algae, building their cell walls from silica rather than more energy intensive cellulose. They can also use a higher proportion of the sunlight spectrum. Using species which are indigenous to the production location leads to a more stable culture which is resistant to invasion by other algae and which poses no threat to the local ecosystem.

Attached algae also offer some advantages at the harvesting stage, since the culture medium can be extracted from the water easily, so reducing by a factor of 100 the need to handle and pump bulk volumes of dilute solutions. It is also easier to free the oil from within the diatom structure, since the silica cells essentially have a 'hinged lid'. When returned to atmospheric pressure after centrifuging, the structure is disrupted and the oil released. By stressing the cultures, an increase in triglyceride levels of between 20-30% can be induced. It will also be easier to scale these production processes since, when using indigenous species, untreated ocean water and unproductive lands can be utilised, and production should be possible in temperate as well as tropical areas.

The algae industry is very new, although rooted in a long tradition. The issues facing the development of the technology are wider than the debate between the proponents of open or closed systems. Solutions will have to address numerous challenges including contamination, stability, nutrient depletion, photic inhibition, self shading, and harvesting and concentration in an economical way. SBAE's 'Diaforce' approach is a novel way of addressing all of these issues.

The composition of diatoms includes essential amino and fatty acids, fytosterols, anti-oxidants, probiotics, and vitamins as well as 'energy molecules'. These materials can provide essential nutrients which could be used to supplement the diets of undernourished populations as well as providing feed for animals and an energy fraction. There are therefore choices to be made about where the really important issues lie, and what the role of algae systems in addressing them should be. There is also a timing issue. Given the importance of global warming, could innovative solutions such as Diaforce be fast tracked so as to provide some significant impact on emissions from energy production and on the climate in the near rather than the long term?

SESSION 5 – DISCUSSION AND CONCLUSIONS

The main points arising from the lively discussion sessions are summarised below.

- There is an extensive and well documented history of work on algae. There is a recent resurgence of interest in national programmes and industry with approximately 150 companies active in the area.
- There are currently several significant barriers to widespread deployment and many information gaps, but there is still lots of room for improvement and breakthroughs.
- Many different options are still being considered and this is likely to continue with different systems suited to different types of algae organisms, climatic conditions, and ranges of products. Much of the basic information related to genomics, industrial design, and performance is not yet defined.
- In principle, algae can offer productivity levels above those possible with terrestrial plants. Current estimates of practical productivity vary very widely (with some claims above the theoretical limit!).
- Similarly costs estimates vary widely, but the best estimates are promising at this stage of technology development.
- The use of algae to produce a range of products for the food, feed and fuel markets via a 'biorefinery approach' is likely to prove to be an attractive strategy offering better chances for economic operation than systems aimed at producing biofuel only.
- LCA analyses are inevitably difficult to do at this stage in the development of the technology. However these studies indicate that careful design of systems will be required to ensure that there is a positive energy and carbon balance associated with algae production. Excessive energy requirements for pumping, concentration, and drying must be avoided, along with efficient use of residues and any waste heat generated.
- A methodological issue was identified, which relates to how the credits for GHG reduction associated with algae production using CO_2 generated from fossil fuels should be allocated.

Marine Algae

- Marine algae are currently produced for food and added value chemical products and form the largest proportion of algae production today. The world production of seaweeds was some 8 million tonnes in 2003. The potential of marine biomass is increasingly discussed, given the size of the resource and that more than three quarters of the surface of planet earth is covered by water. These aquatic resources, comprising both marine and fresh water habitats, have immense biodiversity and the potential to provide sustainable benefits to all nations of the world. Maximum productivity may be 10 times higher for a seaweed stand than for a plankton population, and can be as high as 1.8 kg C/m^2/yr (Carlsson *et al.* 2007). An example is giant brown kelp (*Macrocystis pyrifera*), which has a high light absorptive capacity, and doubles its weight every six months.
- Marine algae-to-energy systems are most likely to be viable when supported by a secondary aim (such as production of a chemical substrate, or by generating environmental benefits by cleaning up water or absorbing waste nutrient flows). Large-scale deployment of these technologies could bring economic development opportunities to rural and maritime communities.
- In this sector there is a particular need for research, development, and demonstration to improve AD performance, and to improve harvesting and crop selection. There is also a need to evaluate and overcome environmental and political barriers to large-scale deployment.

Open Pond Systems

- Open pond systems are likely to be cheaper than photobioreactors. The cost and performance principles are well understood, although the scope for radical development and improvement is probably limited.
- Algae production is still too expensive for fuel production alone. There is a need to produce multiple products, including some higher value products which may have a restricted market, along with fuel and bulk chemicals at lower values.
- A CO_2 source is necessary, but the seasonal pattern of absorption does not match well with the constant level of emission from, for example, coal-fired power stations, so algae are unlikely to provide a complete solution to such emissions.
- There is good compatibility with waste water treatment options.
- There is a huge potential in choosing the most suitable types for energy production out of several hundred thousand algae species.
- There is scope for improvements in performance and productivity via genetically modified algae.

Closed Systems

- Many issues remain in optimising photobioreactor design.
- Systems analysis indicates that there could be significant economies of scale, but the economics remain challenging unless improvements in productivity and performance can be achieved, along with reductions in energy usage.
- The production of a range of co-products will be critical to cost viability, along with integration with existing waste water treatment operations.
- There are many different types of algae which can be considered and these may offer opportunities for novel approaches with lower costs and better performance. For example perifytonic diatoms alter the growth and separation paradigms and may offer systems which are industrially scalable, less dependent on favourable climatic conditions, and easier to break open.

In response to the questions posed by the Chairman at the beginning of the workshop, the following conclusions were drawn.

When is the technology likely to be ready for commercial exploitation?

Commercial exploitation will depend on the extent of R&D and demonstration activity, but some niche applications with co-product production could be available within 5-10 years, and bulk production in the longer term.

What are the critical development stages still required (R&D, trials, demonstrations)?
Given the wide range of unresolved issues, a balanced programme of fundamental research coupled with development and larger scale trials and demonstrations will be necessary. The use of algae to produce a range of products via a 'biorefinery' approach is likely to be an attractive option.

What are the likely costs of producing energy from algae?
Current estimates of productivity and cost estimates vary widely. While current costs often seem unattractive, there is considerable scope for reduction and optimisation, and for optimising co-product values. Best estimates of costs are promising at this stage of technology development.

What are the likely CO_2 savings?
There is significant potential for CO_2 absorption. A positive energy and greenhouse gas balance can be achieved, but this requires careful consideration of internal energy use and efficient use of co-products and waste heat. Matching seasonal absorption patterns to constant CO_2 sources (such as those from power plants) will be challenging.

What are the main barriers to be overcome (technical and non-technical, including financial)?
Currently there are a wide range of technical, institutional, and financial barriers, but there is plenty of room for improvements and breakthroughs. There are many different options available for consideration and these are likely to continue as different systems will fit various climatic conditions and ranges of products.

What role can IEA Bioenergy best play?
In the short-term IEA Bioenergy (Task 39) will provide an authoritative review of international activity and prospects (in 2010) and act as a focus for other activity within other IEA Implementing Agreements with an interest. IEA Bioenergy will then have a continuing role in facilitating coordination between national efforts to develop these technologies, and providing periodic updates on the prospects for commercialisation and deployment.

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The presentations from the workshop are available at *www.ieabioenergy.com*

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IEA Bioenergy

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