

Foresight Brief:

Seaweed & Algae as Biofuels Feedstocks

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This Foresight Brief was prepared by the Sea Change Management Unit of the Marine Institute to provide industry, Third Level researchers, government policy-makers and the general public about current topics of interest to the Marine Industry in Ireland. It is our objective to provide timely and concise reports which can have a beneficial impact on the overall Irish marine economy. We welcome any feedback you may have. Please feel free to contact us using the information at the end of this Foresight Brief if you have any questions or feedback. While every effort is reasonably taken to ensure the content is accurate, the subject matter is dynamic and emerging as the time of writing.

Introduction

Seaweed is a known potential carbon-dioxide (CO₂) neutral source of second generation biofuels. When seaweed grows it absorbs CO₂ from the atmosphere and this CO₂ is released back to the atmosphere during combustion. What makes seaweed, and in particular micro algae, so promising as a fuel source is their growth rates and high lipid (oil) content. Algae are among the fastest-growing plants in the world. Energy is stored inside the cell as lipids and carbohydrates, and can be converted into fuels such as biodiesel (in the presence of oils) and ethanol (in the presence of carbohydrates). Its high protein content implies that waste from the feedstock conversion process may yield a saleable waste stream as well.

The level of interest in the use of algae as a source of biofuels (primarily ethanol and biodiesel but also methane and hydrogen) is rising globally. Several factors appear to account for this. Firstly, despite earlier predictions of stability in world oil prices, such non-renewable hydrocarbon source fuels continue to spiral upwards (having closed at \$100 per barrel during Feb. 2008 for the first time) and there is a heightened awareness about the contribution of fossil fuels emissions to rapid climate changes. In this context, algae-based biofuels offer potential solutions since they are known to be a CO₂ sorbent and their harvesting may not have a negative CO₂ balance due to loss of CO₂ absorbing landmass which is the current topic of debate about first generation biofuels^{1,2}. The Marine Institute

¹ Searchinger, T., et. al., "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change", *Science* (Feb. 7, 2008).

² Fargione, Joseph, et. al., "Land Clearing and the Biofuel Carbon Debt", *Science* (Feb. 7, 2008).

of Ireland (www.marine.ie) has experienced a rise in interest in seaweed and algae as a potential feedstock for production of biofuels, reflected by requests for data concerning the properties and composition of algae and seaweed, from both the research and industrial communities over the past several months.

The following excerpts from the popular press illustrate some of the more sensational reports which undoubtedly contribute to awareness of this topic:

- Between 1978 and 1999 the U.S. Department of Energy funded a programme to investigate the development of diesel fuels from algae. This work resulted in the collection and storage of species of micro-algae with oil bearing potential. The work included detailed reviews of the physiology and biochemistry of algae; explored the options for using biotechnology to cultivate; cultivation methods and identified the high-cost of production as a barrier to commercialization. This initiative was closed-out due to the fact that low hydrocarbon fuels prices made algae uncompetitive (in 1999).³
- On Oct. 31, 2007 Chevron Corporation and the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) announced that they have entered into a collaborative R&D agreement to study and advance technology to produce liquid transportation fuels using algae. Chevron and NREL scientists will collaborate to identify and develop algae strains that can be economically harvested and processed into finished transportation fuels such as jet fuel. This will re-open the original programme (described above) which is now justified since the cost of hydrocarbon-base fuels has quadrupled since the programme was closed-out in 1999.⁴
- California-based Solazyme Inc. entered into an algae oil biodiesel feedstock development and testing agreement with Chevron USA Inc. Solazyme said it is currently producing thousands of gallons of algae oil. It is partnering with Chevron to accelerate the commercialization of its proprietary technology⁵
- On December 12, 2007 Royal Dutch Shell Plc announced it would fund a project aiming to produce transport fuel from algae, as biofuel production from palm oil and crops are increasingly criticised for causing deforestation and higher food prices. The company said it would build a pilot facility in Hawaii to grow marine algae from which it would extract vegetable oil that would be converted into a form of diesel for use in trucks and cars. The research plant, which is being built with Hawaii-headquartered HR Biopetroleum Inc., would only use non-genetically modified algae.⁶
- US firm PetroSun BioFuels Refining has entered a joint venture to build and operate a 30 MMgy biodiesel plant near Coolidge, Arizona. Algae grown at a proposed algae farm in the Arizona desert is the source of the oil. Producing a planned 150 million gallons of algae oil per year, the biodiesel plant is scheduled to begin production in the third quarter of 2008.⁷

³ Sheehan, J., et. al., U.S. Dept. of Energy, National Renewable Energy Laboratory, [A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae](http://www.nrel.gov/docs/legosti/fy98/24190.pdf), July 1998, (<http://www.nrel.gov/docs/legosti/fy98/24190.pdf>).

⁴ Chevron Corporation Press Release, "Chevron and National Renewable Energy Laboratory to Collaborate on Research to Produce Transportation Fuels Using Algae", Oct. 31, 2007 (<http://www.chevron.com/news/press/release/?id=2007-10-31>).

⁵ Solazyme Press Release, "Solazyme Unveils Renewable Biodiesel Derived from Algae via Scalable Process", Jan. 22, 2008 (<http://www.solazyme.com/news080122.shtml>).

⁶ Royal Dutch Shell plc Press Release, "Shell and HR Biopetroleum Build Facility to Grow Algae for Biofuel", Dec. 11, 2007 (www.shell.com).

⁷ PetroSun Press Release, "PetroSun Executes Algal Oil Feedstock Letter of Intent, Nov. 5, 2007 (<http://biz.yahoo.com/iw/071105/0324319.html>).

- A massive collaborative effort between Japanese researchers, industry and government is attempting to develop viable quick-growing seaweed nets for harvesting algae in the ocean to produce second generation biofuels. Working with scientists at the Mitsubishi Research Institute, Tokyo University, Mitsubishi Heavy Industries, Mitsubishi Electronics, Toshiba and NEC, the Japanese Government has provided a grant and is expected to give more when a pilot version of the giant seaweed farm opens. If proven successful in the pilot phase, the Japan Research Industries Association and will attempt to convince industry leaders that the idea is worth the 570 billion yen (£2.8 billion) needed to implement it on the grand scale (100 vast nets full of quick-growing seaweed, each measuring six miles by six miles). Furthermore, if this works, the Japanese government is considering the concept of fighting global warming through giant seaweed farms across the world's oceans, a strategy which could be included in the upcoming revision to the Kyoto Protocol.⁸
- On 30 Jan. 2008 the Florida Department of Agriculture announced investing \$415,520 to test a technology being developed by researchers at the Florida Institute of Technology's Vero Beach Marine Laboratory to convert green microalgae into a biodiesel fuel. Aurora Biofuels Inc., based in California, will also provide \$507,419 over two years towards the project and will work with the laboratory on the project. The researchers will enrich, isolate, screen and select algae strains with high oil content; test the performance of selected strains in outdoor ponds; demonstrate mass cultivation of the most promising strains; harvest the cells to yield a concentrated biomass content; and process the biomass to recover valuable co-products.
- In 2007, US-based GreenFuel Technologies Corporation, a leader in the development of algae bioreactor and renewable biofuels, signed a strategic alliance agreement with IGV, a private industrial research institute headquartered in Potsdam, Germany. IGV is a pioneer in micro-algae research and production with more than 80 commercial technology deployments worldwide. Through this and other alliances, GreenFuel is conducting commercial scale testing of algae to absorb CO₂ from coal burning plants and then to recycle the algae as a biofuel.^{9,10}
- Numbered amongst the many advantages cited for using microalgae mass cultures is biofixation of power plant flue gases and other concentrated CO₂ sources into biomass to produce methane, ethanol, biodiesel, oils and hydrogen; and the mitigation of emissions of fossil CO₂ and other greenhouse gases. "The increase in the concentration of atmospheric carbon dioxide is considered to be one of the main causes of global warming. As estimated by the Intergovernmental Panel on Climate Change (IPCC) criteria, about 10–15% of the gases emitted from the combustion coal being in the form of carbon dioxide. Microalgae...can contribute to the reduction of atmospheric carbon dioxide by using this gas as carbon source."¹¹
- "Eager to shrink its carbon footprint and wean itself from foreign oil, the U.S. aviation sector is leading the research push in biofuels made from algae oil, says an article in the

⁸ Lewis, L., The Times, "Seaweed to breathe new life into fight against global warming", May 14, 2005 (<http://www.timesonline.co.uk/tol/news/world/article522203.ece>)

⁹ GreenFuel Technologies Press Release, "Growth Rates of Emission-Fed Algae Show Viability of New Biomass Crop", Sept. 26, 2007 (http://www.greenfuelonline.com/gf_files/GreenFuel%20Growth%20Rates.pdf).

¹⁰ GreenFuel Technologies Press Release "Leading Algae-Based Biotechnology Companies in USA and Germany Team Up to Accelerate the Commercialization of Recycling Greenhouse Gases into Biofuels", Jan. 11, 2007 (http://www.greenfuelonline.com/gf_files/IGVAllianceGreenFuel.pdf).

¹¹ Greque de Moraes, M. and Vieira Costa, J.A., "Biofixation of carbon dioxide by *Spirulina* sp. and *Scenedesmus obliquus* cultivated in a three-stage serial tubular photobioreactor", Journal of Biotechnology, (Vol. 129, Issue 3, 1 May 2007), pp. 439-445.

Sept. 17, 2007 Aviation Week entitled 'Alternative Fuels for Jet Engines.' Plants such as algae that produce the fats used in biofuel not only can be grown locally but also spend most of their existence sucking up CO₂. Commercial airlines, the U.S. Air Force, the Federal Aviation Administration, and NASA are all on board with the idea of algae-based biofuels."¹²

- "Boeing is hoping that the first biojet fuel blend will be certificated by 2013. The oil harvested from algae cultivated in sewage represents up to 60% of its biomass, and the process has the added benefit of discharging clean water. Lifecycle CO₂ emissions for algae-derived biofuels would be up to 70% lower than conventional fuel, taking into account the CO₂ absorbed during cultivation in sewage water...The fuel could be used as a drop-in replacement for kerosene without requiring engine modifications."¹³
- Furthermore, microalgae is in widespread use for the production of high-value nutritional products (functional foods and nutraceuticals), in wastewater treatment as an algal feed source, and in aquaculture applications.

It must be emphasised that algae is seen as one of the least-proven technologies for biofuels applications. "Algae is at the far end of biodiesel. It is one of the 'out there' concepts," said Matthew Partridge, the head of global biofuels study at Wood Mackenzie, the investment research organisation. "But if biodiesel is going to become a reality in the long term, we are going to have to move up the technology curve. Someone has got to make the investment to do that."¹⁴

Algal Cultivation Systems

Globally, there are a number of technologies and processes used for the mass cultivation of microalgae. These include shallow lakes, constructed ponds and designed tubular cultivation facilities. "Extracting oil from algae is currently a cumbersome affair that involves drying and processing the plants. But some of the world's top genetic engineers want to create improved algae strains that will produce oil continually, eliminating the most difficult processing steps. "Farming and harvesting are both complex and expensive," says human genome pioneer J. Craig Venter, whose 2005 start-up, Synthetic Genomics, is experimenting with algal genes. Rival Solazyme in South San Francisco has engineered more than a dozen specialized strains and ramped up pre-commercial production. "We can easily make thousands of gallons [of algal biodiesel] a month," says Chief Operating Officer Jonathan S. Wolfson."¹⁵

Comparisons of these alternative technologies, point to open systems (such as ponds and raceway designs) as the least productive due to inefficient light utilization. Closed tubular systems, such as fence-tube reactors, consistently show higher real productivities compared to open systems. However, they too become limited by their ability to optimise photon utilization. When scaled algal cultivation for biofuels is considered, land cost and availability stands out as one of the key limiting factors.

Evidence pointing to the possible economical production of biofuels from algae exists. There are major gaps in knowledge about the most productive strains of algae, growth rates, and oil/carbohydrate and protein yields. By filling these gaps it will be possible to assess the commercial viability of algae-fuel production systems. There appears to be some years to go before it can be proven with certainty that algal biodiesel/bioethanol can be cost-effective on a large scale.

¹² "Here comes pond scum power", Business Week Europe, Dec. 3, 2007.

¹³ Doyle, A., "Boeing bullish on biofuels ahead of Virgin demo flight", Flight International, Feb. 20, 2008.

¹⁴ Fortson, D., "Shell starts algae biodiesel research site in Hawaii", The Independent, (Dec. 12, 2007).

¹⁵ "Here comes pond scum power", Business Week Europe, Dec. 3, 2007.

From algae to fuel

Fuels derived from algae generally fall into two groups; oils which are extracted from algae by a mechanical or chemical process; and ethanol resulting from the fermentation of algae in the presence of a yeast, and isolating the ethanol produced.

Oil extraction from algae is a hotly debated topic currently because this process is one of the more costly processes which can determine the sustainability of algae-based biodiesel. In terms of the concept, the idea is quite simple: Extract the algae from its growth medium (using an appropriate separation process), and use the wet algae to extract the oil. (Note: The algae need **not** be dried before oil extraction). There are three well-known methods to extract the oil from oilseeds, and these methods should apply equally well for algae too: they include, Expeller/Press, Hexane solvent oil extraction and Supercritical Fluid Extraction.

Estimates by Shell point to yields of 15 times more biofuel per hectare using algae versus conventional crops. Algae wins out over crops since it needs far less land than crop based biofuels; a hectare of maize can produce just over 2,400 litres of ethanol a year, and a hectare of soybeans just 600 litres. Given optimal conditions, algae grow rapidly and in theory a hectare of algae could produce about 40,000 litres of biofuel a year – and the organism can be harvested daily rather than annually. Additionally, algae have an extraordinary capacity for absorbing CO₂, owing to the organism's ultra-efficient photosynthesis. This efficiency is also the reason for its rapid growth. (It is also noteworthy that algae can feed on human waste streams, which has been the subject of some research into algae biofuels programmes, to explore all the potential benefits of such an initiative).

Issues likely to influence the development of algae biofuels

Researchers are looking at three strategies for the production of algae for biofuels. The first is the growth and harvesting of appropriate algae in ponds associated with agricultural systems. The second is similar growth in ponds but associated with electricity-generating power plants, using their CO₂ effluents to stimulate algal growth and their waste heat to maintain year-round constant temperatures in ponds. The third involves the harvesting of algae from existing waterways choked with high algal production due to nutrient-laden agricultural runoff.

Land based culture of algae appears to dominate in terms of large scale production systems. Since most of the algae-culture research so far concentrated on inland sites, this is not surprising. However a question that needs to be answered is: Can algae be cultivated in ocean environments for biofuels?

The open water growth of algae for biofuels may not be as attractive as land based production due to the challenges surrounding the control of the environment, which ultimately influences growth rates and hence yields. Just as the first generation of finfish aquaculture attracted opposition on various grounds, there are likely to be questions over environmental impacts (e.g., biodiversity) of dedicated culture of algae – whether on land or at sea.

The potential of wild algae species and particularly seaweed species as found in Irish waters is yet to be fully understood. Whilst there is some work on-going at the Martin Ryan Institute at the National University of Ireland, Galway (NUIG), there is little published information on issues relating to wild harvest and sustainability of species in Irish waters when used in fuel production.

Irish activity

The National University Ireland, Galway (NUIG)-campus company Eirzyme was set up to exploit research by Dr. Maria Touhy. The new company will produce low-cost enzymes to convert biological materials into bioethanol and biogas. The company attracted a €10 million investment from Canadian based firm Miromill System Inc. Initial research was supported by a grant from Enterprise Ireland.

An Irish bioethanol producer is undertaking feasibility assessments for large scale biofuels production plants in international locations in Europe, the Caribbean and Africa. Included in its project assessment activity is a review of algae for use in ethanol and biodiesel production. Company contacts also indicated that they launched a collaborative research programme with an Irish University during Dec. 2007 pertaining to algae bioethanol product development.

Ireland's Seaweed Centre at NUIG is also involved in SUPER-GEN Bioenergy II. This UK led research consortium is studying seaweed (together with other sources of biomass) as an energy source. This is a £6.3 million project that is scheduled to conclude in 2011 and involves 23 partners from research institutions and industry.

Some of the areas that Ireland could focus on include micro-algal cultivation methodologies (i.e., screening and developing culture methodologies for species with optimum characteristics for production of biofuels). Ireland has a number of aquaculture hatcheries and research groups who have specializations in this area so the expertise and infrastructure is in place but the goals (and probably the species) would be different.

Recent Algae Biofuels Funding Activities & Investment Opinions

Irish Funding Opportunities

Sustainable Energy Ireland

Sustainable Energy Ireland (SEI) launched a call for proposals to commission a study of the potential of marine algae as a source of biofuels for Ireland. It seeks to "Identify important research topics in order to realise the potential of marine algae for biofuels production in Ireland. These research topics should cover the complete supply chain from algae production through to delivery to the biofuel end user. Where possible, estimate the cost to carry out the required R&D and demonstration." For further information refer to this website: http://www.etenders.gov.ie/search/show/search_view.aspx?ID=FEB097511.

Science Foundation Ireland

Science Foundation Ireland (SFI) has a current EOI call for Strategic Research Clusters in areas of science or engineering research that underpin the biotechnology sector (and others) with a full proposal submission deadline (by invitations generated from EOI submissions) of 6 June 2008. These EI grants normally range from €500,000 to €1,500,000 in direct costs per year over a five year period. Details about this are available from their website http://www.sfi.ie/content/content.asp?section_id=706&language_id=1.

Marine Institute

The Marine Institute periodically has funding calls available to industry. As lead implementation agency for the national Sea Change Strategy, there is expected to be a call in 2008 under the NDP Marine Research Sub-Programme. Awards for individual companies or for collaboration initiatives between companies and research providers (universities, institutes of technology or other research institutes) are expected to be made during 2008. All funding will be posted on the agency website: <http://www.marine.ie/home/funding/>.

EU Funded Programmes

Interreg IVA – Ireland / Northern Ireland / Scotland (2007-2013)

The Interreg Programme has up to €182.7m in funding available. While this is not a research programme, there will be a submission including several institutes of technologies from Ireland and Northern Ireland seeking to demonstrate the feasibility and viability of producing biofuels from marine biomass derived from both macroalgal (seaweeds) and microalgal (single celled plants) sources. In particular they will be targeting specific questions designed to build on the current knowledge base available within this unique set of geographical regions to explore commercial opportunities.

FP 7 Energy Theme

The FP7 Energy Theme Programme will provide funding for upwards of €2.34 billion. Several projects proposals are known to have involved algae biofuels research projects from Spain, Italy, Germany, Belgium Portugal, Chile, Columbia, Austria, France, Czech Republic, Finland, Hungary, U.K. the Ukraine, Dominican Republic, Israel, Sweden, and others. Emphasis will be given to the following activities that may be relevant to algae biofuels projects:

- Renewable fuels production - fuel production systems and conversion technologies.
- CO₂ capture and storage technologies for zero emission power generation - technologies reducing the environmental impact of fossil fuel use by capturing CO₂.
- Knowledge for energy policy making - tools, methods and models to assess the economic and social issues related to energy technologies and to provide quantifiable targets and scenarios for medium and long term horizons.

Intelligent Energy Europe Programme

The Intelligent Energy Europe Programme has funded a wide range of non-R&D projects over the past several years (Mr. Matthew Kennedy, Sustainable Energy Ireland is the national contact point for Ireland). Their focus has been on capacity building; building and spreading of know-how, skills and methods; exchanges of experience; development of market and intelligence; policy input; awareness raising and information provision; and education and training. The IEE programme does not fund: "Hardware" type investments, demonstration projects, or technical research & development projects on energy efficiency and renewables. An example of a past project which should have but did not address algae biofuels was: "Assessment of biomass potentials for biofuels feedstock production in Europe: Methodology and results" (July 2007). The forthcoming call may have continuing topics for the following two areas pertinent to development of algal biofuels programmes:

- *Renewable fuel production:* "Integrated fuel production systems and conversion technologies to develop and drive down the unit cost of solid, liquid and gaseous (including hydrogen) fuels produced from renewable energy sources including biomass and wastes, while aiming at the cost effective production, storage, distribution and use of carbon-neutral fuels, in particular biofuels for transport and electricity generation."
- *Knowledge for energy policy-making:* Development of tools, methods and models to assess the main economic and social issues related to energy technologies and to provide quantifiable targets and scenarios for medium and long-term horizons (including providing scientific support for policy development).

This next call to be published in late February 2008 will be for:

1) European projects:

- At least 3 partner organisations from 3 different eligible countries.
- Maximum funding period 3 years.
- Budget usually between € 0.5 - 2.5 million (mainly staff costs).

2) Setting up of new local/regional energy agencies:

- Only local/regional public authorities can apply
- 1 authority = 1 proposal
- Maximum funding period 3 ½ years

U.S. Government

Dept. of Defence-DARPA

The U.S. Defence Advanced Research Projects Agency (DARPA) is currently soliciting innovative international collaborative research proposals in the area of technologies that enable the affordable production of a surrogate for petroleum based military jet fuel (JP-8) from aquacultural crops such as algae, that are non-competitive with food material.

"Algae offer the potential of a significant volume feedstock with extremely large yields per acre and which can be fundamentally non-competitive with the production of foodstocks. The affordable production of JP-8 surrogate from algae crop stocks

requires reducing the cost of algae triglyceride oil to the \$1-2/gal level. Current large scale production of algae crops, however, is limited to product applications that support crop costs significantly greater than \$20/gal. The key challenge in this area is the development of an integrated production system that combines advances in photo-bioreactor design, integrated closed-reactor and open-reactor concepts, algae nutrition management, cropstock selection, waste stream management, intermediate product extraction, and optimized conversion to JP-8." See full solicitation at <http://www.darpa.mil/STO/solicitations/baa08-07/index.html>.

U.S. Marine Corps.

On Dec. 10, 2007, the U.S. Marine Corps conducted a pre-solicitation for using algae at their 7.5 megawatt, natural gas-powered peaking plant which is located in the Mojave Desert and subject to future GHG regulations. A feasible solution they seek to fund is to capture the carbon dioxide emitted from the plant using algae. Carbon dioxide emitted from the power plant will become the source of carbon for the growing algae. The algae can then be used not only in carbon sequestration, but also as a feedstock in biodiesel, syngas or power production. See full solicitation at <http://www.fbo.gov/spg/DON/NAVFAC/N47408/N6258308R0022/-SynopsisR.html>.

Further Reading on this Topic:

Private Sector Investment Research

*Morgan Stanley Research Note
New Frontiers: Algae (Nov. 20, 2007)*

Research is currently being conducted by a number of firms including Algae Biofuels and XL Tech Group in partnership with AZTe, into the utilisation of micro-algae as an energy source, with applications being developed not only for Biodiesel but also for ethanol, methanol, methane and even hydrogen. Independent studies have varied significantly in their appraisal of algae's oil producing capabilities. According to the studies, an alga is capable of producing between 15 to 200 times more oil per hectare than the crops currently utilised for the production of biofuels.

Research focuses on the development of algae farms using large, open shallow pools. The algae feed on waste CO₂, and when developed, the algae are harvested and their oil is extracted. With high oil yields and fast growth rates, oil from micro-algae has clear potential, but at present the high cost of algae production remains an issue. The main factors that influence cost are biological, as contamination has been one of the biggest obstacles.

*Morgan Stanley Research Note
Biofuels: De-carboning Transportation Fuels (Oct. 16, 2007)*

An alga has compelling potential to serve as both a CO₂ capture technology and a fuel feedstock. An alga is energy dense and has very limited input requirements to grow rapidly. While entrepreneurs are still working on developing the right strain of algae and adequate breeding systems, we believe the potential is real and possible in the next 5-10 years. That said, we view algae as the riskiest of our feedstock bests since the method and cost to

manufacture are most unclear. Will algae be a viable feedstock? We believe algae are the best opportunity for an economical oil-based feedstock. That said, using algae for fuel is still very theoretical. If algae producers can significantly reduce costs (to exactly what, we are still unsure), there is the potential for it to be a scalable, low carbon feedstock.

Multi-client Market Research Study

Global Market Assessment of Algae Biodiesel Feedstock Trends to 2020, Emerging Markets Online, info@emerging-markets.com, <http://www.emerging-markets.com/>.

Books and Articles

BENEMANN, J. R. 2004. "Hydrogen and methane production by microalgae." In: Handbook of Microalgal culture: Biotechnology and Applied Phycology. Ed. A. Richmond. Blackwell Publishing.

BOROWITZKA, M.A. 1988. "Fats, oils and hydrocarbons." 257-287. In: Microalgal Biotechnology. Eds. Borowitzka & Borowitzka. Cambridge University Press, Cambridge.

HAAG, A. L. 2007. "Algae bloom again." Nature 447: 520-521.

HILLEN, L. W., Pollard, G., Wake, L. V. and White, N. 1982. "Hydrocracking of the oils of *Botryococcus braunii* to transport fuels. Biotechnology and Bioengineering" 24 (1): 193-205.

SHEEHAN, J., Dunahay, T., Benemann, J. and Roessler, P. 1988. A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel Production from Algae, National Renewable Energy Laboratory NREL/TP-580- 24190.

Internet Forums

<http://www.oilgae.com/>

<http://www.biodieselnow.com/forums/13.aspx>

http://tech.groups.yahoo.com/group/oil_from_algae/join

This Foresight Brief on marine industry opportunities and issues is provided by the Marine Institute's Sea Change Management Unit which is responsible for implementation of the Sea Change Strategy 2007-2013.



SEA CHANGE

A Marine Knowledge, Research & Innovation Strategy for Ireland
2007-2013



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