

**ADVANCED BIOFUELS FROM MICROALGAE:  
A REVIEW OF THE INDUSTRY IN THE USA &  
AUSTRALIA CONDUCTED THROUGHOUT 2010**

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- Develop technologically innovative, commercially scalable, socially and politically viable solutions

This program was established with the generous support of the Dow Chemical Company and Alcoa Inc.

## 1. EXECUTIVE SUMMARY

Advanced biofuels are derived from non-food feedstocks such as crop residues, wood waste, dedicated oil producing or energy crops, industrial and municipal waste, or cultivated or fermented organisms such as bacteria, yeast, fungi or microalgae. Advanced biofuels ideally should be “drop-in” fuels which are defined as fuels that are close substitutes for gas, diesel or jet fuel in today’s engines without creating the need to change vehicle and engine specifications, the technology of petroleum oil and gas refineries, or distribution infrastructure. Advanced biofuels must deliver significant savings in green house gas emissions and economic returns over the life cycle of the fuel at parity pricing to petroleum. Finally, it is ideal if an advanced biofuel technology platform can replace more than one fraction or product derived currently from a barrel of petroleum oil.

This report provides an independent analysis conducted throughout 2010 of the microalgal, advanced biofuels industry in the USA and Australia. It summarises the, scientific basis for microalgal biofuels as an alternative energy source, the state of development of the industry, the areas of uncertainty and opportunity, and the development of government policy. The analysis was conducted on the basis of non-confidential discussions with US and Australian experts across the entire algal biofuels supply chain and review of published reports and documents, company information and peer-reviewed literature.

Australia and the US have particular geospatial and climatic attributes that lend themselves to development of a successful microalgal biofuels industry. The industry is gaining momentum but at present microalgal biofuels are not economically competitive with fossil fuels.

Uncertainties about costs and yields right along the production system and about potential environmental impacts make it difficult to predict when the technical and economic gaps with conventional fuels will be closed. The best estimate is that it still faces a 5-10 year period of substantial investment in R&D and scale-up facilities to prove that it can produce advanced biofuels at parity pricing to petroleum and generate positive financial returns.

To build a successful industry, appropriate clusters of enterprises will need to be developed. These clusters will enable supply of other inputs into algal cultivation (e.g. water, nutrients and CO<sub>2</sub>) and provide the capacity to process the various outputs, including fuel and green chemicals. Near-term market opportunities provided by co-products and clear market signals for biofuels such as exhibited by the aviation industry are also critical success factors for the industry.

Also critical are innovation policy frameworks that provide: a playing field that is technology and feedstock neutral and applicable to multiple business models and company structures; well designed and delivered government funding and loan programs; tax codes, including taxes on carbon, that give certainty and clarity.

Replacing even a fraction of petroleum with advanced biofuels is an enormous global undertaking. It will require an array of biomass feedstocks, including microalgae. These petroleum alternatives will bring with them higher costs, at least initially, for

infrastructure and operation, uncertainties about technologies and business models, and steep learning curves for industry and government. These challenges are not unique to the biofuels industry. They apply equally to any of the low-carbon energy technologies, whether the technology is for electricity generation or replacement of petroleum fuels for transport.

## **2. A CENTURY OF COMPLEX CHALLENGES**

The 21<sup>st</sup> Century will be characterized by increasing global demand for energy, food, and water and decreasing supply of resources required for production of these staples (1). The world will reach peak oil extraction, peak agricultural land use, peak water consumption and peak human population (2). These peaks will amplify the predicted adverse effects of anthropogenic climate change induced to date. They also increase the urgency of finding solutions to the complex problem of how to foster growth in a national economy without concomitant consumption of scarce resources and growth in green house gas emissions.

This report will focus on the production of advanced biofuels from microalgae as one partial solution. Examination of even this microcosm of the energy space illustrates how such initiatives will affect our incumbent energy industry, economic systems, policy frameworks and societal structure. They will force us to embrace fundamental change, invest in initially higher cost forms of energy, progress along very long and steep learning curves, and ensure that industry sectors heretofore entirely separate, work collaboratively or at least in cooperative competition.

## **3. METHODOLOGY**

Throughout 2010, the author conducted non-confidential discussions with Australian and US experts across the entire algal biofuels supply chain. All gave generously of their time. Special mention should be made of the central role played in introductions in the USA by the Australian Trade Commission offices. Review of published reports, original studies and company information completed the analysis.

Experts interviewed represent a wide array of organizations in Australia and the US, including:

- Universities & Research Institutes
- National Research Organisations
- Companies ranging from early stage R&D to multinational corporations
- Investors- venture capital, private equity, bankers, superannuation funds
- State & Federal Governments
- Service Providers - legal, financial, strategic, engineering etc
- Industry Organizations and lobbyists
- Non-government Organisations
- Media/Trade Journals

## **4. REVIEW AND DISCUSSION**

### **a) Petroleum Oil Consumption**

The global, USA and Australian consumption of petroleum reported for 2009 by the U.S Energy Information Administration is shown in Table 1.

**TABLE 1. Annual Petroleum Consumption US, Australia and World, 2009**

	<b>Barrels/year</b>	<b>Barrels/day</b>	<b>Barrels/s</b>	<b>Litres/s</b>	<b>%</b>
Global	30,806,174,835	84,400,479	977	155,330	100
USA	6,865,654,015	18,810,011	218	34,659	22.3
Australia	346,671,160	949,784	11	1,749	1.1

Source: U.S. Energy Information Administration (3)

Corresponding volumes and percentages for the transportation fuels, gasoline, jet and diesel, for 2009 are shown in Table 2.

**TABLE 2. Annual Consumption of Petroleum Products for Transport, 2009**

	<b>USA</b>	<b>USA</b>	<b>Australia</b>	<b>Australia</b>
	<b>Barrels/day</b>	<b>% Total</b>	<b>Barrels/day</b>	<b>% Total</b>
Motor gasoline	8,996,521	47.8	325,781	34.3
Jet fuel	1,393,189	7.4	108,411	11.0
Distillate fuel	3,631,079	19.3	320,389	33.7
Total petroleum	18,810,011	100	949,784	100

The percentage consumption by the transportation sector is predicted to rise by 2035 because of increasing demand by developing countries (4, 5).

Direct replacements for crude oil will be critical to the energy portfolios of all countries in order to manage volatile and/or rising prices, scarcity of supply, rising carbon dioxide emissions and carbon pricing and trading schemes.

## **b) Advanced Biofuels**

The first generation biofuels industry in the USA mostly comprises production of ethanol from corn as a replacement for gasoline and of biodiesel from cooking oil, tallow and rapeseed oil. The bio-ethanol industry in Australia is mostly derived from waste streams, primarily from sugar cane and wheat crop waste.

Advanced biofuels are derived from non-food feedstocks such as crop residues, wood waste, dedicated oil producing or energy crops, industrial and municipal waste, or cultivated or fermented organisms such as bacteria, yeast, fungi or microalgae. Advanced biofuels ideally should be “drop-in” fuels which are defined as fuels that are close substitutes for gas, diesel or jet fuel in today’s engines without creating the need to change vehicle and engine specifications, the technology of petroleum oil and gas refineries, or distribution infrastructure. Advanced biofuels must deliver significant savings in green house gas emissions and economic returns over the life cycle of the fuel at parity pricing to petroleum. Finally, it is ideal if an advanced biofuel technology platform can replace more than one fraction or product derived currently from a barrel of petroleum oil.

The first generation and advanced biofuels industries operate in a complex environment in which different interests compete for inputs (e.g. land and water) and outputs around the “biomass wheel” (the “biomass wheel” – food, feed, fibre, fuels, fertilizers, feedstocks for chemicals) (6).

### (c) Microalgae

Microalgae constitute an enormous and diverse group of terrestrial, freshwater or marine, eukaryotic, unicellular organisms which grow in a myriad of environmental conditions across the globe. Microalgae are distinct from macroalgae (seaweeds) in that they do not develop defined anatomical structures such as leaves, stems or roots.

The prokaryotic organisms, which are organisms that lack membrane-bound nuclei, known as blue-green algae (also as cyanobacteria, blue-green bacteria, chloroxybacteria or cyanophytes), are not considered in this report.

Most microalgae are strictly photosynthetic and grow under autotrophic culture conditions using sunlight and CO<sub>2</sub>. Approximately 40% of global photosynthesis can be attributed to the macro and microalgal algal biomass (7, 8). Most algae use the C3 pathway to fix CO<sub>2</sub> which is incorporated into the 3-carbon compound, 3-phosphoglycerate. Marine diatoms use the C4 pathway to produce oxaloacetic acid (8).

The biodiversity of microalgae is enormous (algaebase.org). Estimates of the number of species vary widely from hundreds of thousands to millions. The US Department of Energy’s Aquatic Species Program collection and screening programs led to a collection of “over 3,000 strains of organisms” (9). A final collection of 300 oil-producing species was housed at the University of Hawaii.

The Australian National Algae Culture Collection at the Hobart laboratories of the Australian Commonwealth Scientific and Research Organisation (CSIRO) Marine and Atmospheric Research holds a significant collection of cultures of approximately 1000 living strains of more than 300 species, some of which are prokaryotic ([csiro.au/places/Australian-National-Algae-Culture-Collection--ci\\_pageNo-1.html](http://csiro.au/places/Australian-National-Algae-Culture-Collection--ci_pageNo-1.html)). Smaller collections are held in various organizations around the country.

A Summary Report for the Australian Biological Resources Study in 2002 noted that “it is more accurate to say that the majority of species in Australia are yet to be described” (10). Compilations of marine and freshwater algae continue to be updated by various Australian Herbaria, Botanic gardens and research groups (11, 12). The taxonomic checklists and descriptions from these various sources are entered into the Australian Plant Name Index ([anbg.gov.au/apni/index.html](http://anbg.gov.au/apni/index.html)) and the Atlas of Living Australia ([ala.org.au](http://ala.org.au)).

The genetic sequences of different algae species can be very diverse. The genomes are relatively large and contain numerous stretches of identical bases. *Chlamydomonas reinhardtii* is about 40 times bigger than the human genome. To date, fewer than 20 microalgal chloroplast and/or nuclear genomes have been sequenced and characterized. Progress has been chronicled in reports such as

those from Grossman (13, 14), Radakovits (15) and by the Department of Energy, Joint Genome Institute ([jgi.doe.gov](http://jgi.doe.gov)).

Modern genomics, proteomics, metabolomics, rapid, high throughput culture and screening methods, computational technologies and bioinformatics are being applied to microalgae by laboratories around the world to accelerate identification and characterization. These global intensive research programs aim to rapidly increase fundamental knowledge about the biology of microalgae and their photosynthetic conversion efficiencies, metabolic capabilities and biofuel production capacity (15) with a view to development and growth of a microalgal biofuels industry.

#### **(d) Biofuels from Microalgae**

##### **(i) The microalgal feedstock platform**

Microalgae produce a range of commercially interesting products such as fatty acids, hydrocarbons, oils, sugars and bioactive compounds (16). Others produce hydrogen or ethanol. Bioactive compounds include carotenoids (e.g. beta carotene), fatty acids (e.g. omega 3 fatty acids) and phycobilins (e.g. food colourings and chromophores). Many of these bioactive compounds have been produced at commercial scale for decades.

Biofuels can be produced from microalgae via three main pathways which are discussed in detail in the National Algal Biofuels Technology Roadmap (17). They are:

- Harvesting algal products such as ethanol, hydrogen, methane or paraffins
- Processing the whole algal biomass
- Processing lipid or carbohydrate extracts into biofuels.

Typically, the oil produced by microalgal species is in the form of neutral storage lipids such as triacylglycerols (TAGs) which comprise 16 or 18 carbon fatty acids incorporated into a glycerol backbone. Stored TAGs are energy dense and can easily be converted into a variety of fuels including biodiesel.

Photoautotrophic microalgae have been studied over several decades as a source of advanced biofuels because of the following attributes:

- Use solar radiation and CO<sub>2</sub> to produce biomass
- Can capture waste CO<sub>2</sub> from industrial emitters
- Can use recycled waste nutrients from industrial or agricultural sources
- Cultivation systems do not need to compete for arable land
- High growth rate per unit area per day
- High energy-dense lipid production and storage under appropriate conditions
- Can use and remediate water from a variety of non-potable sources, including waste water
- Provide a platform feedstock for production of valuable co-products in addition to biofuels.

(ii) The microalgal biofuels industry

A comprehensive research program on the production of biofuels and other co-products from microalgae was undertaken in the US under the U.S. Department of Energy's *Aquatic Species* Program which ran from 1978 -1996 and provided an important foundation stone for all future work (9).

A relative funding hiatus followed after this program closed until the early 2000s when spikes in oil price, concerns about energy security, food security and climate change, and improved tools for molecular and cell biology re-kindled interest in the field.

To bring the field up to date from the close-out of the Aquatic Species Program, the U.S. Department of Energy published the National Algal Biofuels Technology Roadmap in 2010 (17). This report documents the R&D and commercialization challenges associated with the development of an algal biofuels industry. It concludes "that many years of both basic and applied science and engineering will likely be needed to achieve affordable, scalable, and sustainable algal-based fuels. The ability to quickly test and implement new and innovative technologies in an integrated process will be a key component to accelerating progress."

Three other comprehensive, analytical reports also published in 2010 (18-20) agree that at this stage, production of biofuels from microalgae is not cost-competitive with fossil fuels or other biofuels.

Darzens et al (18) conclude that "the production of liquid transportation fuels from algal biomass is technically feasible. However there is a need for innovation in all elements of algal biofuels production to address technical inefficiencies, which represent significant challenges to the development of economically viable large-scale algal biofuels enterprises."

Lundquist et al (19) conclude that "the major area for long term cost improvements is in biology: the goal being to at least double biomass and oil productivity through strain selection and genetic modification. These strains must then be cultivated reliably in the outdoor ponds and harvested cheaply – major challenges and may required a decade's effort or longer to become practical."

Thurmond (20) conclude that "as of mid-2009, it remains to be seen if algae can be mass produced for biodiesel, although some last minute breakthroughs and announcements may bring a commercial market faster than most expect" and that commercialization was most probable in the 4-6 year range.

A sample of comments from various interviews conducted by the author illustrates a greater divergence of views.

"Algal farming is only a venture capital phenomenon; even under perfect conditions, the fuel will cost \$650/gallon; I see 15 biomass opportunities a week and don't invest in any of them; most guys don't have a cost structure that is competitive; only Silicon Valley is investing; algae are horribly negative, they use more energy that they get from fuel; it will only ever be a niche opportunity; the resource potential of microalgae

will always be modest; algae will be part of the solution; algae hold promise but are still 10 years out; theoretically, algae kills everything else; all we need to do is industrialise algae, which we know how to do with many other crops; algae harness evolution rather than fighting it; if we are going to use a biological source, it has to be algae; algae will be produced at commercial scale within one year". Waltz presents a similar spectrum (21).

The consensus view is that the industry is gaining momentum but still faces a 5-10 year period of substantial investment in R&D and scale-up to produce neutral or low-carbon, advanced biofuels at parity pricing to petroleum products and to achieve financial returns.

The following sections of this report outline some of the specific initiatives being taken to move the industry forward.

(iii) Progress towards scale-up and commercialization

Most companies are cultivating photoautotrophic microalgae in open ponds. Some are using relatively closed photo bioreactors outdoors or indoors (Table 3).

**TABLE 3. Companies Deploying Photoautotrophic Algae Systems**

<b>Company</b>	<b>Country</b>	<b>Cultivation</b>	<b>Microalgae</b>
Aurora Algae	USA & Australia	Open Pond	Photoautotrophic
Heliae Development	USA	Photo bioreactor	Photoautotrophic
MBD Energy	Australia	Open Pond & Photo bioreactor	Photoautotrophic
Muradel	Australia	Open Pond	Photoautotrophic
PetroAlgae	USA	Open Pond	Photoautotrophic
Sapphire Energy	USA	Open Pond	Photoautotrophic
Solix Biofuels	USA	Photo bioreactor	Photoautotrophic
Synthetic Genomics	USA	Open Pond	GM/Photoautotrophic

Open pond cultivation incurs a relatively low cost of capital for cultivation but harvesting and dewatering are expensive. In addition, the land must be co-located with sources of CO<sub>2</sub> and nutrients and preferably brackish or salt water to avoid the need to use fresh water sources. Other issues include less control of growing conditions and potential contamination by predators and pathogens.

Closed systems have the advantage of being similar to industrial systems for organisms such as bacteria, fungi or cells, including genetically modified organisms. Their disadvantages include high capital and operating costs and energy intensity.

To achieve profitability, most companies whether using open or closed systems or not are seeking to market a range of high value products in addition to biofuels. Market value models indicate that production of algal biofuels will be best suited to a facility where cultivation, primary biofuel refining and conversion to co-products are co-located (17).

In 2009, the Obama administration's economic stimulus package appropriated additional funding of \$480 M for integrated pilot and demonstration scale biorefineries, \$176.5 M of which was for commercial scale biorefineries and \$100 M of which was for basic research to underpin demonstration projects. Such projects are considered to be first-of-kind projects with technology and capital risks that are too high to be fully funded by private investment.

A total of \$180 M of this funding was awarded for algal projects in 2010, including part of the \$45 M awarded to the National Alliance for Advanced Biofuels and Bioproducts (NAABB). The NAABB ([naabb.org](http://naabb.org)) will conduct a series of interdisciplinary projects that span the entire production and value chain and address identified technical and/or cost bottlenecks. Progressive techno-economic and life cycle analyses are integrated into the research plans.

In 2009, General Atomics signed a \$43 M contract with the Defense Advanced Research Projects Agency (DARPA). The funding is for a three year program "to develop scalable processes for the cost-effective large-scale production of algae triglyceride oil and an algae-derived JP-8 jet fuel surrogate" ([ga.com](http://ga.com)).

The Algal Biomass Organization (ABO; [algalbiomass.org](http://algalbiomass.org)) estimates that the private sector has invested \$2 BN into the algae industry. The bulk of this investment represents the engagement by multinational corporations such as Exxon Mobil, Shell, BP and Chevron.

Significant venture capital fund investments also have been made in the U.S. in PetroAlgae, Aurora Algae, Heliae Development and Sapphire Energy and Solazyme.

Solazyme, Inc is unique pursuing a different approach in that it ferments heterotrophic algae with plant-based sugars. The strains of algae are engineered for high oil yield and oils designed to specifications, such as chain length and saturation. In August 2010, the company raised \$52 M in Series D funding and on 11 March 2011 filed its Initial Public Offering with the Securities and Exchange Commission. Regarded as the most successful microalgal company, Solazyme is generating revenue from sales of jet fuel to the US military, albeit at prices that reflect costs of production and are not at parity with petroleum oil. The company has developed several near-term market opportunities in the form of co-products such as cosmetics and nutraceuticals.

The Australian Government's National Collaborative Research Infrastructure Strategy (NCRIS) provided AU\$5 M to the construction and operation of a pilot scale photo bioreactor facility based at the South Australian Research and Development Institute's (SARDI) Aquatic Sciences Laboratories in Adelaide. This facility was completed in October 2009.

SARDI also formed a collaborative research alliance through the Algal Fuels Consortium™ (with Flinders University and CSIRO to develop a ten hectare pilot and pre-commercial scale production facility on Torrens Island.

The Second Generation Biofuels Research and Development Program (Gen2) of the Australian Government Department of Resources, Energy and Tourism (DRET)

awarded AU\$3.97 M to fund algal biofuels programs including the Algal Fuels Consortium™ Microalgal Research Alliance. DRET is currently establishing the AU\$20 M Australian Biofuels Research Institute (ABRI).

CSIRO, primarily through its Energy Transformed Flagship and Marine and Atmospheric Research Division, supports a range of algal programs. These include: the Australian National Algae Culture Collection; an integrated group that undertakes techno-economic and life cycle analysis; consulting services to third parties interested in cultivating algae; and collaborative programs to establish and test production systems from pilot to demonstration scale.

In December 2010, Murdoch University and the University of Adelaide, in conjunction with their commercial partner SQC Pty Ltd, announced the formation of Muradel Pty Ltd. The company commissioned its AU\$3.5 million open pond pilot plant in Karratha, Western Australia in November 2010. Initial funding of AU\$1.89 M for this plant was provided by the Australian Government as part of the Asia-Pacific Partnership on Clean Development and Climate.

The U.S. Company, Aurora Algae, Inc is also establishing open pond facilities in Karratha. “The combination of a perfect climate and the right blend of resources—including abundant seawater, industrial CO<sub>2</sub> and skilled labor—made Northwestern Australia an ideal location for our initial, high-yield commercial facility” (aurorainc.com). It is expected that a pilot facility will be opened in April 2011.

The Advanced Manufacturing Cooperative Research Centre and the Queensland State Government provided MBD Energy Ltd with a total grant of AU\$6.5 M towards the construction of R&D facilities at James Cook University and small photobioreactor systems at three coal-fired power plants along the East Coast of Australia. The MBD facilities will use waste water, waste CO<sub>2</sub> and waste nutrients. The first project, a one hectare pilot plant, is being constructed at the Tarong power station in Queensland. MBD expects that this pilot plant will produce 400 tonnes of algae per year starting from Q2 2011 at an operating cost of AU\$1.5 M. In addition to grants, MBD has raised AU\$18 M of private capital in part through a cornerstone investment in 2009 by Anglo American.

Founded two years ago, Algae.Tec Limited recently raised AU\$5.1 M under an initial public offering and listed on the Australian Stock Exchange on 13 January 2011. The company plans to cultivate algae in its proprietary McConchie Stroud photo bioreactor growth and harvesting system. Planned products include oil, ethanol, and jet fuel.

All companies have patent portfolios and proprietary information relating to their algal strains, cultivation, harvesting and extraction processes, machines, manufacture or composition of matter. Most patent filings are still undergoing prosecution.

#### (iv) The aviation industry

Commercial aviation is taking a lead in stimulating the advanced biofuels industry for a number of reasons. Fuel represents the single largest component of their operating costs. Rising costs of jet fuel can make the difference between profit and loss.

Aircraft engines will require liquid fuels for a long time into the future. Airlines also have no choice but to reduce their green house gas emissions. In 2005, the peak industry body, the International Air Transport Association (IATA), set a target for carbon neutral growth beyond 2020 and intermediate goals such as 10% of fuel being renewable by 2017.

In 2006, the Commercial Aviation Alternative Fuels Initiative (CAAFI) was formed by U.S. Airlines, Manufacturers and US Government sponsors to serve as a catalyst for technology development and deployment of alternative aviation fuels worldwide. The U.S military which has similar targets for sustainable fuels is also a key stakeholder in CAAFI.

U.S. airlines consume about 416 million barrels of jet fuel annually in worldwide operations. The U.S. military consumes about 59.5 million barrels annually. Through CAAFI, they engaged with the American Society for Testing and Materials (ASTM) process to enable the certification in 2009 of aviation turbine fuels containing synthesized hydrocarbons (D7566-09). This is the first new jet fuel to be certified in 20 years. It is expected that Hydrotreated Renewable Jet fuel (HRJ or HEFA), for which the feedstock can be any animal oil or any plant oil including algal oil, will be certified within the next twelve months.

On 4-6 March 2011, the author and Richard Altman, Executive Director of CAAFI, convened the Alternative Aviation Fuels Forum at AVALON 2011, The Australian International Aerospace & Defence Exposition ([ussc.edu.au/events/past/Avalon-2011-Alternative-aviation-fuels-forum](http://ussc.edu.au/events/past/Avalon-2011-Alternative-aviation-fuels-forum)). Presenting at the Forum, UOP LLC reported that it had processed more than 600,000 gallons (2,271,247 L) of bio-SPK (synthetic paraffinic kerosene) in 2010, from tallow, Camelina and Solazyme algal oil.

The aviation industry in the US is engaged with the Farm to Fly Initiative that was announced in 2009 (22). This five-year, nationwide project aims to engage all of the components of the supply chain and bridge the gap between agriculture and aviation.

In its report on 15 Dec 2010, the first recommendation under the heading of Environment by the US Department of Transportation Future of Aviation Advisory Committee (FAAC) was to “exercise strong national leadership to promote and showcase U.S. aviation as a first user of sustainable alternative fuels” ([dot.gov/faac](http://dot.gov/faac)).

The aviation industry in the US was one of the co-founders of the National Algae Association ([nationalalgaeassociation.com](http://nationalalgaeassociation.com)) and the Algal Biomass Organization (ABO; [algalbiomass.org](http://algalbiomass.org)). These provide focal points for information sharing, debate and progress. The recently released ABO Draft Guidance Document: Algal Industry Minimum Descriptive Language released in 2010 seeks the “voluntary adoption of uniform descriptive language” across the industry with a view to unifying research and accelerating growth (23).

In Australia, the algae-specific representative organization is the Biotechnological and Environmental Applications of Microalgae and Rural Industries Research and Development Corporation (BEAM-RIRDC) Algae Biofuels Group ([bsb.murdoch.edu.au/groups/beam/BEAMHOME.html](http://bsb.murdoch.edu.au/groups/beam/BEAMHOME.html)).

A number of airlines and associated manufacturers, including The Boeing Company, have formed the Sustainable Aviation Fuel Users Group (SAFUG). Industry consortia in Australia and the US are preparing roadmaps under the SAFUG banner. The Australian Roadmap Study is due to report early in 2011. It will focus on the opportunities and challenges in Australia of building a sustainable aviation fuel industry.

The Queensland Sustainable Jet Fuel Initiative was established in May 2010 by a consortium of partners including the University of Queensland, James Cook University, Queensland Government, Boeing Company, Amyris, Inc, Virgin Blue Airlines Group, IOR Energy and Mackay Sugar Ltd.

The Initiative has the primary objectives of:

- Performing a multi-pathway techno-economic and lifecycle analysis of sustainable aviation fuel production from three feedstocks - sucrose, oilseeds, algae
- Making the data publicly available to foster information sharing and debate
- Using systems and synthetic biology to improve production of jet fuel

In December 2010 and January 2011, Qantas airlines announced its plans to undertake feasibility studies with Solena Group and Solazyme, Inc, respectively.

(v) Success factors for commercial production of biofuels from microalgae

The success factors for commercial production of biofuels from any biomass include:

- Net positive energy return
- No depletion of carbon sinks in soil and existing vegetation or adverse impact on land use
- No reduction in food security
- No effect on existing local economic activity and quality of life
- No effect on water supply and quality
- No effect on air quality
- Minimal net consumption of non-renewable resources such as phosphorus
- Positive greenhouse gas balance for the entire production chain
- No impact on existing biodiversity or ecosystems
- Net positive economic return

Detailed analyses of all of these metrics are being performed for microalgal production systems but there will be many uncertainties until informed data are derived from pilot and demonstration facilities.

In regard to net positive energy return, the first law of thermodynamics means that the rate of incident solar irradiance on the photoautotrophic microalgal production area must be no less than the rate of storage of chemical energy as oil and biomass. In practice, the sunlight conversion efficiency of photosynthetic organisms is low, so that the yield of captured energy is a small percentage of the incident radiation. It is not certain yet that photosynthetic microalgae intrinsically can biosynthesize more

energy on an annualized basis than terrestrial crops or indeed have a net energy return (24-27).

Using an estimate of the theoretical limit of photosynthesis and taking into account unavoidable losses, Lundquist et al estimated the potential production from microalgae of 20,600 – 52,500 L oil /ha-yr (19) under a range of field conditions. They conclude that the economics are most favourable for microalgae production of biofuels when it is in conjunction with wastewater treatment and that “the resource potential of microalgae biofuels will always be modest, mainly due to the lack of sites having all the needed resources, in particular available CO<sub>2</sub>.”

The International Energy Agency presented yield data from 14 open pond and 23 photo bioreactor projects. Yields ranged from 20,000 to 100,000 L oil/ha-yr (28). Stephens et al calculated practical yield maxima of ~ 60,000 – 100,000 L oil/ha-yr at a photosynthetic conversion efficiency of 6.5% (29).

Darzins et al forecast that the yield from algae could reach 58,000 L oil/ha-yr (18). At that productivity, they concluded that using “the same amount of land currently devoted to the US soybean crop (75 M acres), microalgae could produce more than enough feedstock for biodiesel or green diesel to meet the current U.S. diesel fuel usage.” The report also concludes that “a 5% contribution of algal biofuels to total US biofuels by 2030 would require the construction of 170 x 1200 million litre facilities” ... and that these “could conceivably be operational by 2030.”

Borowitzka and Moheimani (25) estimate that the total land area required (including raceway ponds, roads, buildings and other infrastructure) to produce 100,000 barrels (bbl) of lipids per year is 5-14 km<sup>2</sup>. Calculating the yield using an average of 100,000 bbl per 9.5 km<sup>2</sup> gives a productivity of 16,736 L lipid /ha-yr, which is at the low end of the range of figures quoted above. To replace 10% of Australia’s consumption of distillates per year (320,389 x 365 = 117 million barrels per year - from Table 2) requires 111,100 ha or 1111 km<sup>2</sup> at a production rate of 16,736 L lipid/ha-year, assuming 100% conversion efficiency of oil to biodiesel. This represents 0.014 % of Australia’s total land area of 7,692,024 km<sup>2</sup> (ga.gov.au/education/geoscience-basics/dimensions/area-of-australia-states-and-territories.html).

Australia and the US have particular geospatial and climatic attributes that lend themselves to development of a successful microalgal biofuels industry. However, while maps of solar irradiance and climate are available, maps that detail the right type of land for microalgal cultivation (flat, height above sea level, available) in the right area (near saline water, CO<sub>2</sub> and nutrient sources etc) are not. The National Algal Biofuels Technology Roadmap (17) included an analysis of the National inventory of potential sites in the US amongst its recommendations for future work. In Australia, individual companies and some States already have begun to gather this information.

To date, life cycle analyses (LCAs) of green house gas emissions have been hampered by the lack of quantitative data gathered under field conditions at reasonable scale (17, 18, 29-31).

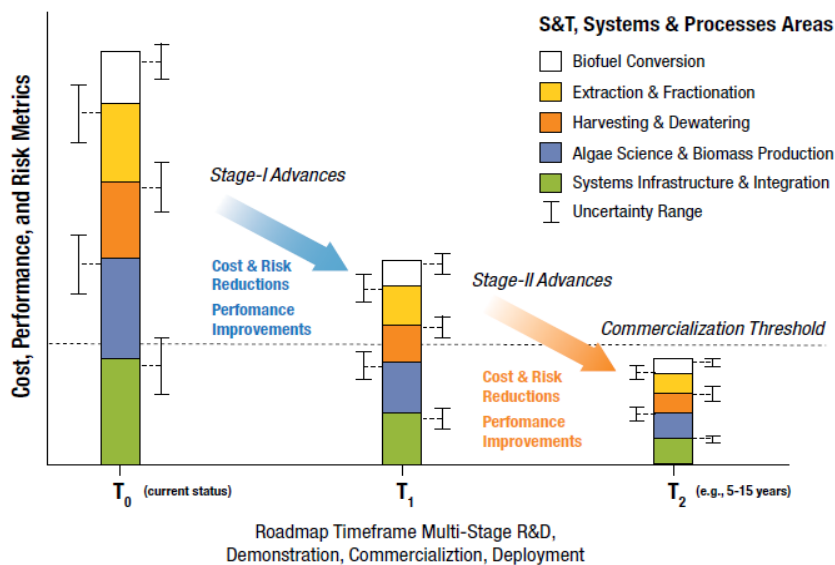
The Partnership for Air Transportation Noise and Emissions Reduction Project 28 reported detailed systems analyses of life cycle greenhouse gas emissions from alternative jet fuels in June 2010 (31). The Report noted that because of uncertainties surrounding many of the assumptions “the life cycle GHG emissions resulting from the production and use of HRJ from renewable algae oil range from 0.16 to 2.2 times those from conventional jet fuel”.

If algal biofuels do in fact achieve a net reduction in CO<sub>2</sub> generation compared with the alternatives, a price or tax on carbon and stringent controls on CO<sub>2</sub> emissions will be important factors in the economic viability of the industry.

In regard to net economic return, The National Algal Biofuels Technology Roadmap (17) concludes that there is at present “a general lack of demonstrated operating parameters and widely varying basic assumptions on a number of parameters from algal productivity to capital depreciation costs, operating costs and co-product credits.” Cooney et al concur (27).

Exhibit 10.2 from the Roadmap outlines its timeframe during which it expects that answers will be delivered to assure sufficient certainty to reach the commercialization threshold (17).

**Exhibit 10.2** Systems and Techno-Economic Modeling and Analysis as a decision-support tool  
It can track and assess performance, and evaluate investment cost/benefit/risk tradeoffs to inform both technical and programmatic decisions



Biofuels Digest (biofuelsdigest.com) regularly publishes a downloadable project database that provides forward estimates of the production capacity of advanced biofuels by companies across the globe and for the entire range of technology platforms, including microalgae. In the October 2010 update (biofuelsdigest.com/bdigest/2010/10/07/advanced-biofuels-capacity-to-reach-3-917-billion-gallons-by-2015-free-downloadable-project-database) Solazyme was the only company using microalgae for which forward estimates were at any scale (150,000 gallons is 2011 based on announced Navy contracts and 100 million gallons as the 2012/13 target).

(vi) US and Australian Federal Government policies

The biofuels industry in the US would not have come into existence but for successive federal government policies and incentives, including a subsidy for blending biofuel with gasoline and a tariff on imported ethanol (Congressional Research Service Reports, 2007 & 2010 (32,33)). The political support is based on a number of factors including geography (for rural economic development, primarily in the Southeast, Pacific Northwest, and Midwest), energy security (including for defence forces) and reduction of greenhouse gas emissions.

Creating scale across the production system from the farm to the consumer has reinvigorated the rural and manufacturing sectors and stimulated the development of green materials science and related economic development.

To promote the development of non-food feedstocks for biofuels, the US Energy Independence and Security Act of 2007 capped ethanol production from corn at 15 billion gallons per year by 2022. At the same time, the Act set the production target for biofuels at 36 billion gallons by 2022 meaning that 21 of the 36 billion gallons of biofuels are to be produced as advanced biofuels. The new Renewable Fuels Standard (RFS2) also sets the limits on green house gas emissions from the various generations of biofuels (33).

Algal biofuels companies must compete with each other, with other companies seeking to commercialise different advanced fuel technologies such as Amyris, Codexis, Coskata, Gevo, Joule, LanzaTech, LS9 and Virent. To ensure that all technologies are given parity from a policy perspective, early and subsequent Bills in the US have been enhanced through a bipartisan coalition to include algae-based biofuels. In 2010, the US House of Representatives passed H.R. 4186, the Algae-based Renewable Fuel Production Act, which gives algae-based biofuels tax parity with cellulosic biofuels (\$1.01 per gallon production tax credit and a 50 % bonus depreciation for biofuel plant property).

Importantly in the US, the federal government's biofuels programs are coordinated in a whole of government approach by the President's executive and the Departments of Energy, Agriculture and Environment. The Board is co-chaired by officers from the USDA and DOE, selected by the Secretaries of Agriculture and Energy, respectively. The Biomass R&D Board, which is similarly coordinated, provides oversight to the Biomass Research and Development Initiative ([eere.energy.gov/biomass](http://eere.energy.gov/biomass)).

In 2007, the history and current policy instruments in Australia for biofuels nationally and in the states were summarised in a Rural Industries Research and Development Corporation publication (34). The report recommended future assessment of second generation biofuels such as algae and an industry roadmap for implementation of these technologies. This was followed in 2008 by a report from The Australian Academy of Technological Sciences and Engineering ([atse.org](http://atse.org)) on Biofuels for Transport: A Roadmap for Development in Australia (35).

In March 2009, DRET flagged the development of an Energy White Paper and in September 2010 its proposal to form an Alternative Fuels Strategic Issues Group (AFSIG) to address the issues related to production of competitively priced

alternative fuels (including biofuels and natural gas) and their reliable supply, appropriate quality and consumer acceptance. AFSIG, which is due to report by September 2011, will focus on issues relating to industry, structure, technology and infrastructure challenges but will not address excise regimes. AFSIG will coordinate a whole of government approach, including States & Territories.

The potential and actual environmental impacts of industrial scale cultivation of endemic or non-endemic microalgae, including genetically modified microalgae, for biofuel production touch many areas of policy, standards and regulation in both countries. "Being a nascent industry, there are no existing standards for various aspects of algal biofuels production" in the US (17). The situation is similar in Australia.

From the environmental point of view, specific issues that arise for nationally and internationally include: lack of characterization of the number and characteristics endemic microalgal species, the effects of predators or infectious agents on large-scale microalgal cultures and the effects of large-scale cultures on biodiversity and surrounding ecosystems.

In the US, many of these environmental impact policies lie within the Coordinated Framework for the Regulation of Biotechnology which involves four lead Federal regulatory agencies - National Institute of Health (NIH), Environmental Protection Agency (EPA), Department of Agriculture (USDA) and Department of Health and Human Services Food and Drug Administration. Other Federal, State and Local requirements and permits will also pertain depending on the cultivar, whether or not the organism is genetically modified, obligations for reporting, management, storage, containment, use and disposal, effects on endangered species and/or biodiversity, and site ownership and location.

The frameworks are similar in Australia where the lead Australian Government agencies are the Department of Sustainability, Environment, Water, Population and Communities, Department of Agriculture, Forestry and Fisheries, Department of Resources, Energy and Tourism and the Department of Health and Aging.

## **5. CONCLUSIONS**

Australia and the US have particular geospatial and climatic attributes that lend themselves to development of a successful microalgal biofuels industry. The industry is gaining momentum but at present microalgal biofuels are not economically competitive with fossil fuels.

Uncertainties about costs and yields right along the production system and about potential environmental impacts make it difficult to predict when the technical and economic gaps with conventional fuels will be closed.

The best estimate is that it still faces a 5-10 year period of substantial investment in R&D and scale-up facilities to prove that it can produce advanced biofuels at parity pricing to petroleum and generate positive financial returns.

To build a successful industry, appropriate clusters of enterprises will need to be developed. These clusters will enable supply of other inputs into algal cultivation (e.g. water, nutrients and CO<sub>2</sub>) and provide the capacity to process the various outputs, including fuel and green chemicals.

Near-term market opportunities provided by co-products and clear market signals for biofuels such as exhibited by the aviation industry are also critical success factors for the industry.

Equally important will be the extent to which government policy drives the introduction of renewable energy alternatives such as microalgal biofuels, and provides certainty and clarity over the long term for investors.

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