Algae as a Feedstock for Biofuels

An Assessment of the Current Status and Potential for Algal Biofuels Production

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Introduction

In 2010, the IEA Advanced Motor Fuels Implementing Agreement and the IEA Bioenergy Task 39 both commissioned reports on the status and potential opportunities for Algal Biofuels. While there were substantial similarities in the findings of the two reports, each report provides unique perspectives on different aspects of the technology and the opportunities. This summary draws on both of those reports.

The Task 39 report (Bioenergy Algal Biofuels.pdf) was authored by Al Darzins and Philip Pienkos (NREL, US) and Les Edye (BioIndustry Partners, Australia). Contributions of text and figures were provided by Wade Amos, John Benemann, Eric Jarvis, John Jechura, Anelia Milbrant, Matt Ringer, Kristi Theis, and Bob Wallace.

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The Opportunity

The demand for energy is growing worldwide, especially in many of the rapidly developing countries such as China and India and, as worldwide petroleum reserves diminish due to consumption exceeding discoveries, many countries are becoming increasingly dependent upon imported sources of oil. Furthermore, the continued combustion of fossil fuels has created serious environmental concerns over climate change due to the increased release of greenhouse gases (GHG).

The pursuit of a stable, economically-sound, and environmentally-friendly source of transportation fuel has led to extensive research and development (R&D) efforts focused on the conversion of various feedstocks into biofuels.

One of the recent concerns with respect to increased biofuels production is the availability of land. It is recognized that the GHG benefits of biofuels can be offset if land with existing high carbon intensity is cleared for the production of biofuel feedstocks. Biofuels that could readily be produced without large increases in arable land, and thus eliminating any competition for food production, as well as any need for reductions in tropical rainforests, could be very attractive in the future.

Algae may offer that opportunity. Its use as a feedstock for biofuels has led to much excitement and initiative within the energy industry. Algae are highly diverse, single- or multi-cellular organisms comprised of mostly lipids, protein, and carbohydrates, which may be used to produce a wide variety of biofuels. Algae offer many competitive advantages over other feedstocks, including:

- They grow rapidly and have a higher solar conversion efficiency than most terrestrial plants;
- They can be harvested batch-wise or continuously almost all year round (where climatically favourable);
- Algal production facilities can be co-located on otherwise non-productive, non-arable land;
- They can utilize salt and waste water sources that cannot be used by conventional agriculture;
- They can use waste CO_2 sources thereby potentially mitigating the release of GHG into the atmosphere; and,
- They can produce a variety of feedstocks that can be used to generate biofuels and valuable co-products.

Although algae species collectively present many strong advantages (although one specific species is unlikely to possess all of the advantages listed), a sustainable algal biofuel industry is some time away from maturity, and no economically viable, commercial scale operations currently exist. Several technical and economic barriers must first be overcome before algal biofuels can compete with traditional petroleum-based fuels:

- Algae systems with significantly higher productivity need to be developed and demonstrated;
- Improvements are needed to reduce the cost in all segments of the production spectrum (e.g., harvesting, dewatering, extracting of oil, etc.);
- Further research to identify strains with high production rates and/or oil yields, and the characteristics required for the finished fuels may also improve competitiveness within the market;
- Suitable locations that have the required climate, CO_2 resource base, land, and opportunities for economies of scale need to be identified and their potential productivity assessed;
- The sustainability of these improved production chains needs to be assessed and documented.
- Initiatives to seamlessly integrate algal biofuels into the existing transportation infrastructure will be required.

Algae

Algae belong to a large group of simple photosynthetic organisms. They are subdivided into two major categories based on their size. Microalgae, are small free-living microorganisms that can be found in a variety of aquatic habitats and macroalgae, which have defined anatomical structures resembling leaves, stems, and roots of higher plants.

Microalgae were among the first life forms on earth. They are capable of fixing large amounts of carbon dioxide (CO_2) while returning significant quantities of oxygen to the atmosphere, thereby helping to support the majority of life on our planet. Microalgae are highly productive on a global scale, with cell doublings of 1-4 per day. While microalgae make up only 0.2 percent of global biomass generated through photosynthesis, they account for approximately 50 percent of the total annual global fixed organic carbon (Field et al., 1998). Most microalgae, like terrestrial plants, grow and multiply through photosynthesis, a process whereby light energy is converted into chemical energy by "fixing" atmospheric CO_2 by the following reaction:

$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 \text{ (sugars)} + 6O_2$$

The sugars formed by photosynthesis are converted to all the other cellular components (lipids, carbohydrates, and proteins) that make up the microalgal cell mass (biomass).

Microalgae, due to their simple structure, are particularly efficient converters of solar energy. Because microalgae do not need to generate elaborate support and reproductive structures, they can devote more of their energy into trapping and converting light energy and CO_2 into biomass. Microalgae can convert roughly 6 percent of the total incident radiation into new biomass (Benemann et al., 1978). By comparison, sugar cane, one of the most productive of all terrestrial crops, has a photosynthetic efficiency of 3.5 to 4 percent (Odum, 1971).

This distinguishing feature is one of the main drivers in the development of microalgal diesel fuels. Table 1 shows the potential oil yields from microalgae under three different productivity scenarios (Darzins et al, 2010). The first scenario with 10 $g/m^2/day$ matches long term productivity observed in Roswell, NM during the US DOE Aquatic Species Program (1978-1996), despite the fact that the open ponds occasionally froze during the winter. The more productive scenarios would require warmer climates (or availability of waste heat) to maintain productivity during winter months and higher yield strains, but they are far below the theoretical maxima based on photosynthetic efficiency (Weyer et al. 2009).

	Demonstrated at Roswell	Higher oil content	Higher productivity
$g/m^2/day$	10	10	50
lipid content	15	40	40
operating days/year	330	330	330
percent land devoted to ponds	70	70	70

Source: Darzins et al (2010)

Table 1 Microalgae Potential Yields

Under all three scenarios, the productivity of algae could be significantly higher than that of soybeans (450 L/ha/yr) (Table 2). Algae productivity could range from 65% of oil palm (6000 L/ha/yr) to surpassing that crop by nearly an order of magnitude.

Crop	Oil Yield (Litres/ha/yr)
Soybean	450
Camelina	560
Sunflower	955
Jatropha	1,890
Oil palm	5,940
Algae	3,800-50,800[a]

Source: Darzins et al (2010)

Table 2 Comparison of Oil Yields from Biomass Feedstocks

Algae Industry Overview

The overall concept for producing biofuels from oil-containing algal strains will involve similar process steps to those used for other biofuels. Typically, the algae will be cultivated in open ponds or closed photobioreactors (PBRs), harvested, and then their oil will be extracted and converted into a suitable biofuel. The wastewater and growth nutrients are recycled as

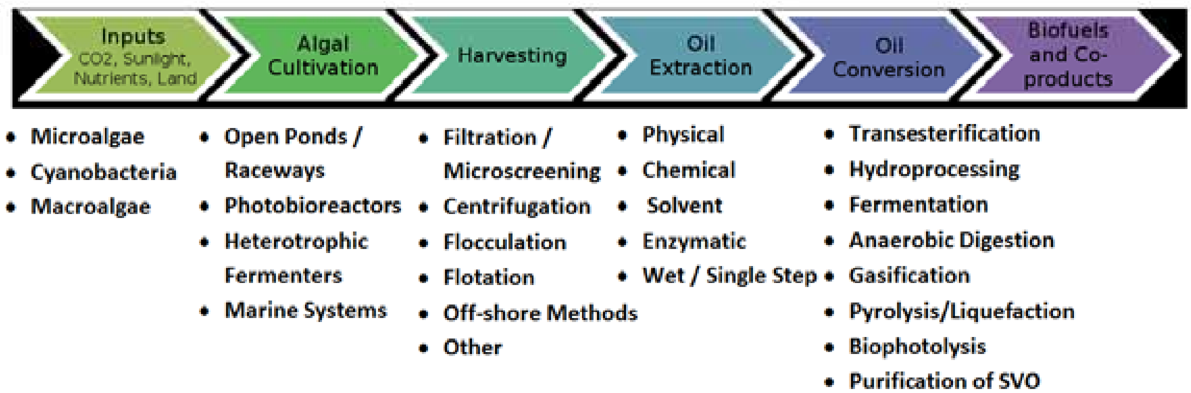

Figure 1 Simplified Schematic Diagram of Major Stages Involved in Producing Algal-derived Liquid Biofuels.

much as possible, and the extracted residual algal cell mass can be sold as animal feed or used to produce additional energy or chemical products.

This industry is still considered to be in its infancy and algal biofuels are not currently being produced at the industry scale. Considerable amounts of R&D are underway and pilot plants are up and running worldwide, testing promising new methods for improving system efficiency and cost-competitiveness with traditional fuel industries. As the industry matures and production ramps up, the portfolio of techniques is expected to naturally consolidate to address scalability, cost, and demand issues.

Current Industry

- **Size.** By mid 2010, an estimated 200 companies were directly participating in algal biofuels production, rising from virtually no companies at the start of the decade.
- **Value.** In a span of approximately ten years, the algal biofuel industry grew from miniscule in value to on track to reach an estimated market value of 271 million USD in 2010.
- **Production Level.** Algal biofuel is not currently being produced at commercial scale due to early technology production costs. Instead, numerous companies have set up demonstration and pilot scale plants that produce a variety of fuels in relatively small quantities for use by limited companies.
- **Production Costs.** Recent cost estimates for today's algae biofuel production range from 5 to 30 USD/gal (~1.2 to 7.9 USD/litre) equivalent to $200 to $1200 US/bbl of crude oil.

Projected Industry

- **Size.** Pilot facilities that demonstrate sustainable and economic solutions in the algae to biofuels industry are expected to transition into commercial scale facilities within the next one to two decades.
- **Value.** SBI Energy estimates a total algal biofuels market worth of 1.6 billion USD in 2015. This indicates a forecasted 43% annual growth rate between 2010 and 2015.
- **Production Level.** Announcements by algal biofuel companies have resulted in production projections of between 100 million and 1 billion gallons (380 to 3,800 million litres) of algal biofuels by 2015 (Emerging Markets Online). Pike Research, however, projects only 61 million gal (230 million litres) of algal biofuels produced by 2020.
- **Production Costs.** Recent cost estimates for future algae biofuel production are as low as 1 USD/gal (0.26 USD/L) equivalent to about 60 USD/bbl of crude oil.

Technology Assessment

Each stage in the algal biofuels production system is the subject of ongoing research and development. The successful algal biofuels companies will be those that optimize the whole production system and not necessarily those with the highest oil producing strain or the best extraction process.

Strain Selection

Algae are ubiquitous on earth, have adapted to diverse environments and have greater photosynthetic CO_2 fixation efficiencies than terrestrial plants when comparisons are made based on land area productivities. The prospects of commercial algal biofuels production are strengthened by this diversity, versatility and efficiency. Some physiological limits to algae growth may eventually be overcome or circumvented to a limited extent by advances in molecular biology. However, at present, there are significant gaps in our understanding of algae biology that are salient to the rate at which sustained commercial production of algal biofuels can be achieved.

Over 40,000 separate species of algae have been identified, and that number almost certainly represents a small fraction of the true population (perhaps as high as 10,000,000 different species) (Hu et. al., 2008).

Most algae are photoautotrophs, meaning that they can derive all of their energy from photosynthesis and all of their carbon requirements from the fixation of CO_2. Consequently, they require only sunlight, CO_2, and simple inorganic nutrients to thrive. Some genera (e.g., Chlamydomonas) are capable of growing heterotrophically in the dark, which means that they can utilize exogenous carbon sources and can be cultivated in standard fermenters, much like yeast, rather than in ponds or photobioreactors. Heterotrophically grown algae offer certain advantages in terms of elimination of contamination problems and higher volumetric productivity, but they eliminate the primary thermodynamic advantage of algal biofuels that derives from the algal cell's ability to harness light energy to drive CO_2 fixation.

There are inherent limitations to photosynthetic growth. Principal among these is the level of solar flux or solar radiation. Based on the understanding of the energetics of photosynthesis and CO_2 fixation, it is possible to determine the maximum theoretical growth rate for algae. In areas of high solar radiation (receiving >6 $kWh/m^2/day$), the theoretical maximum growth rate for algae is approximately 100 $g/m^2/day$. This theoretical maximum will be lower in areas receiving less solar radiation input. There are other limitations that further reduce the growth rate, but it is thermodynamically impossible to exceed this rate in sunlight regardless of whether the algae are grown in ponds or in photobioreactors. Observations of algal growth at a rate of 50 $g/m^2/day$ have been made both in natural blooms (Field et al., 1998) and in open pond systems (Sheehan et al., 1998), but these were not sustainable over an extended period. High values of productivity observed over extended periods in both open and closed systems tend to fall within the range of 20-30 $g/m^2/day$ based on illuminated culture surface area (Lee, 2001).

Other limitations to the growth of algae include:

- **Biosynthetic rates.** It is necessary for an algal cell to synthesize enough of the essential cellular components for two separate cells before it can divide. All of these components derive from CO_2 and simple inorganic nutrients. It is thought that growth rates are limited not by photosynthesis or CO_2 fixation, but rather by subsequent steps of conversion of precursor sugars to biomass (Lee and Low, 1992; Ma et al., 1997).
- **Temperature.** Algae, like all living organisms, have a narrow optimum temperature range for growth. As water temperature decreases or increases beyond the optimum range, growth is inhibited, then halted, and then cell death occurs.
- **CO_2 limitation.** The rate at which atmospheric CO_2 can diffuse into an algal culture would significantly limit growth. This can be overcome by sparging algal cultures with CO_2.

- **Other nutrient limitations.** Algae require nitrogen, phosphorous, sulphur, and other trace nutrients to grow; diatoms also require silicon for construction of the cell wall. It must be noted that nutrient requirements, like growth temperature, must be maintained within an optimal range to promote maximal growth. Too little of a nutrient will reduce the growth rate and too much can prove toxic. Nutrient limitation, as discussed previously, can result in increased overall lipid content in algal cells, but it comes at the expense of overall productivity.
- **Self-shading.** In high cell density cultures, cells nearest to the light source absorb all incoming light, preventing it from reaching the more distal cells. This limitation is reduced somewhat by providing good mixing to prevent cells from spending too much time in the shade and high surface-to-volume ratios for ponds and photobioreactors.
- **Light saturation and photoinhibition.** Algae can absorb more light than they can utilize for energy via photosynthesis and light saturation occurs at lower levels of light than found at high solar radiation areas, thus the measured growth rate will be lower than the maximum predicted by thermodynamic calculations.

From a techno-economic perspective, growth rate and maximum cell density are important parameters. Growth rate determines how quickly the biomass can be produced and maximum cell density determines the amount of water that must be processed to recover the oil. Due to the higher surface-to-volume ratios of closed photobioreactors, the volumetric cell densities can reach levels greater than 4 g/L, more than 10 times higher than that achieved in open ponds (Chisti, 2007). Compare this value to 100 g/L, which is more routinely achieved in commercial Escherichia coli or yeast fermentations.

Successful commercial algal growth will require the development of strains and conditions for cultures that allow rapid production of biomass with high lipid content and minimal growth of competing strains. Microalgae can thrive in a broad range of environmental conditions but specific strains are more limited by climatic conditions than most terrestrial crops. Various approaches are being implemented to identify potential production strains.

Strain selection may also depend on the technology chosen to convert the algal oil to transportation fuels. In the case of biodiesel, many properties of the feedstock vegetable fuel are retained in the finished fuel as some of the vegetable oil properties have a great impact on the properties of the fuel that emerges from the process.

Properties of vegetable oils tend to vary with the type of vegetable. Freezing point, viscosity, and cetane number of finished fuels can vary greatly depending on the selection of plants from which the oils are derived. For example, oils from tropical plants, such as coconut and palm, have the highest cetane numbers but also the worst cold flow properties.

Canada's Institute for Marine Biosciences analyzed the fatty acid profiles of several algae strains and made rough estimates of the qualities of finished fuels if made from these algae strains by the transesterification process. Table 3 below illustrates the differing fatty acid profiles of several samples by separating the fatty acids by degree of saturation.

Algae Species	Saturated (%)	Mono-unsaturated (%)	Poly-unsaturated (%)	Other (%)
Botryococcus braunii	0	74	8	18
Chlorella vulgaris	21	14	51	14
Neochloris oleoabundans	18	18	44	20
Phaeodactylum tricornutum	24	25	31	20
Nannochloropsis granulata	21	29	32	18
Isochrysis galbana	32	29	36	3
Soybean oil	15	27	54	8
Canola oil	7	61	21	11

Table 3 Summaries of Fatty Acid Profiles of Algal Strains obtained by NRC Canada's Institute for Marine Biosciences

Biodiesel produced from Botryococcus braunii is likely to have the best cold weather properties of the strains identified in the table, whereas Chorella vulgaris is expected to produce a product with a higher cetane value.

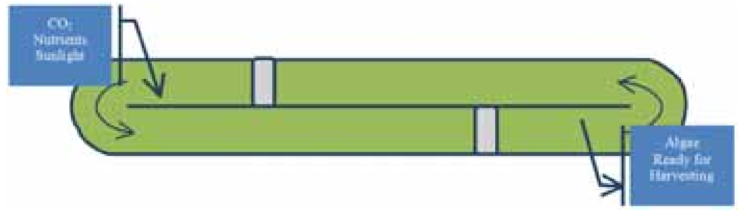

Figure 2 Single algae raceway with two motorized paddles

Cultivation

Once an algal strain (or set of strains) has been selected for production, a growth environment must be chosen. For traditional microalgae cultivation, open ponds / raceways and closed photobioreactors, or PBRs filled with water are the two most common designs. Each of these methods requires the same general inputs – light, nutrients, and CO_2 – and algae grown in these ponds or vessels are sent downstream to be harvested once they reach the desired level of maturity or lipid capacity. Heterotrophic fermentation is a less traditional approach, where algae thrive in vessels by feeding on sugar and nutrients (no light required) until they are ripe for harvesting. Finally, macroalgae is most often cultivated in marine settings where water and space are abundant.

Open Ponds / Raceways

Shallow, artificial ponds of water have been used for cultivating algae for decades and have been subject to extensive study. They can be designed in a multitude of shapes and sizes (e.g., tanks, circular ponds), but “raceway ponds” have become the most popular open model for efficiently growing algae since motorized paddlewheels can be used to continuously circulate the culture and keep algae suspended in the water. A basic schematic of a raceway pond is provided in Figure 2. Ponds are usually no more than 30 cm in depth to ensure sufficient exposure to sunlight. CO_2 and nutrients must be fed into the system on a regular basis (Wageningen, 2010).

Often, single raceways and ponds are aligned side-by-side to create expansive algae farms, such as Cyanotech’s outdoor pond facility in Kailua, Kona, Hawaii that is shown in Figure 3. An outlet for algae to be harvested is also usually incorporated into the design. Commercial scale open ponds typically produce approximately 20 tons of biomass/ha/year (Wageningen, 2010).

Figure 3 Aerial view of Cyanotech’s outdoor algae pond cultivation facility in Kailua Kona, Hawaii (Image Source: Cyanotech Corp.)

The most distinguishing characteristic of ponds and raceways is that they are open to the elements. As a result, operators benefit from free sunlight and some nutrients or salt from the earth. However, they must continuously battle water evaporation, possible contamination by bacteria or invasive algae strains, potentially large swings in pH and temperature, severe weather, and loss of CO_2 into the atmosphere. Furthermore, paddlewheels are generally less efficient at stirring contents than PBR systems, leading to uneven light exposure, lower mass transfer rates and, hence, inferior algae productivity.

This uncontrolled environment is not suitable for all algal strains, including monocultures and genetically-modified strains that cannot tolerate contamination. Furthermore, strains with high oil yields tend to be less hardy than those with higher amounts of proteins and carbohydrates and, therefore, do not thrive in uncontrolled open systems.

While the simplistic design of open ponds and raceways leads to low capital and operating costs, extensive acreage may be needed to accommodate commercial scale up. Site selection should take the length of the growing season into consideration, among several other factors, since the growing season may be limited to warmer months, unless the pond is artificially heated. Approximately half of all companies that produce algae for biofuel purposes use open ponds and raceways.

Relative to PBRs, the initial investment needed to build an open pond facility and bring it online is considered to be significantly less expensive. While much analysis has been conducted on whether open ponds or PBRs are most cost-effective, experts are still split on their overall conclusions.

Photobioreactors

Photobioreactors (PBR) are closed systems of transparent tubes, plates, bags or hemispherical domes. A variety of PBR designs are shown in Figure 4. Individual tubes generally range from 3-10 cm in diameter, allowing sufficient light to reach the centre of the tubes, and are often 25-100 meters in length (Wageningen, 2010).

Figure 4 Various designs of PBRs used in industry. From left to right: Brite Box PBR (Source: Natural Resources Canada); Tubular PBR (Image Source: Bioprodukte Prof. Steinberg); Wrapped PBR (Source: The University of Georgia); High Density Vertical Bioreactor (Source: Vertigro Products, Inc.).

Photobioreactors improve yields compared to open ponds by protecting productive strains to some extent from contamination, pathogens, and predators, offering the benefits of some temperature control and eliminating climate related impacts of open ponds (viz. rainfall, evaporation, and diurnal and seasonal temperature fluctuations). While better mixing in photobioreactors may provide slight area productivity gains, claims of productivity, which refer to the area or footprint of the growth vessel, can be extremely high when the reactors are configured vertically, which is misleading. Vertical photobioreactors must be situated far enough from each other so as to not shade and, consequently, the basic limitation on productivity remains the same for both open ponds and closed photobioreactors. Common biomass production rates achievable with PBRs are estimated at 20-60 ton/ha/yr (Wageningen, 2010).

Surface fouling due to bacteria, other organisms and, in particular, algae, is a major problem with photobioreactors and cleaning can be a major design and operational problem. Where CO_2 input and O_2 evolution must be optimized for maximum productivity, gas transfer, which is restricted to the surface area of gas-liquid interfaces, can limit scalability of photobioreactor designs.

The added benefits of PBRs come with increased costs. Relative to open pond systems, the initial investment needed to build a PBR facility and bring it online is generally much more expensive. However, less property area is typically required since biomass production concentrations and lipid yields are often higher in PBRs than in open pond systems. Operating costs are also generally higher for PBRs relative to open ponds. Roughly half of all companies that produce algae for biofuel purposes use PBR systems.

Heterotrophic Fermentation

In heterotrophic fermentation, algae are generally contained in a dark vessel where they ingest and metabolize sugars (e.g., glucose) or other organic substances, which are then converted into triglycerides (Figure 5). These high-quality triglycerides almost identically resemble the composition of common vegetable oil, which can then be converted into a variety of end-use biofuels. In this process, the sugar provides the carbon and energy requirements for the cell, substituting for photosynthesis. At least one company has claimed to reach as much as 75% of the dry weight of the cells in the form of oil (U.S. DOE, 2010), which leads to larger quantities of oil produced per day per litre than open pond or PBR systems. Other research suggests more conservative estimates of up to 50% (ITTC, 2008).

Figure 5 Heterotrophic fermenter (Source: Wageningen University, 2010).

Heterotrophic fermentation can be carried out in either batch or continuous mode. For batch mode, a fermenter is filled with a medium, inoculated, and emptied once the algae culture is ready for harvesting. Impellers are sometimes incorporated to ensure an evenly mixed medium. Heterotrophic fermentation of algae typically yields at least 20 g of dry biomass per L/day, although 302 g/L/day have been reported in laboratory settings (Theriault, 1965; BCIC, 2009).

The high level of productivity achievable through heterotrophic fermentation helps to outweigh its investment and operating costs. Only a fraction of the water used in a PBR or open pond is needed in heterotrophic fermentation, and the algae that grow in this process do not require CO_2 absorption.

Since fermentation requires sugar, this process does not fully address the land issues that face conventional biofuels. Solazyme has become the most popular player in the area of heterotrophic fermentation using genetically-engineered algae that do not require light. They are building a pilot-scale biorefinery capable of processing 13 metric tons of dry feedstock per day with a capacity of 300 KGY of purified algal oil. End use products derived from this oil are expected to include biodiesel and renewable diesel (U.S. DOE, 2010).

Marine Systems

Macroalgae are typically cultivated in off-shore or near-shore marine environments. For cultivating large volumes of macroalgae, the seaweeds need to be attached to a support structure, like an anchored rope or a net, to keep them from drifting away. The foundations of off-shore wind farms are being considered to serve as anchoring points for these support structures. The concept of combining seaweed cultivation with off-shore wind farms already has support in Denmark, Germany, the Netherlands, and the United States (IEA BIA, 2010).

Besides cultivating seaweeds on off-shore or near-shore structures, it is also possible to harvest wild seaweed stocks and seaweeds that are washed ashore. However, the quantities of seaweed that could be harvested these ways may be too small for a significant biofuel production, and the impact on natural ecosystems needs to first be clarified for harvesting wild seaweeds. Cultivated seaweed would therefore be the most likely source for biofuels from seaweed.

Harvesting

In continuous production the concentration of algae in a pond or photobioreactor is likely to be less than 0.1% mass on a dry basis. Notionally, after harvesting and concentration, the algae will be in the form of a wet paste at 10% to 20% solids. Consequently, the harvesting and concentrating processes require the removal of between 100 t and 200 t of water for each tonne of algae wet paste produced and must be accomplished at low cost and with minimum energy input. There are a number of proposed and practiced harvesting and concentration methods that either are dependent on the properties of the chosen algae species (specific harvesting methods) or are generally applicable to most if not all algal species (general harvesting methods).

Examples of specific harvesting methods include

- Filtration with >25 microns-opening screens, used for filamentous algae, e.g. spirulina;
- Simple settling (gravity thickeners without flocculants) used for *H. pluvialis* after it reaches the red cyst stage;
- Absorption to a hydrophobic material (polystyrene) coupled to an iron filament, which is then captured on a high gradient magnet. This is used for *Dunaliella* harvesting in Australia.

General harvesting methods include the use of gravitational (sedimentation) or dissolved air floatation (DAF) thickeners with the aid of flocculants (viz. lime, alum, ferric chloride, or ionic polymers), centrifugal dewatering, membrane filtration and screening (Benemann and Oswald, 1996). With the exception of membrane filtration, all these general harvesting methods are used to some extent in sewerage treatment to remove suspended solids in treated water from oxidation ponds. Centrifugation is used for harvesting *Chlorella* in Japan and Taiwan. The cost of flocculants to aid sedimentation and DAF thickeners is considered to be too high for algal biofuel production.

Membrane filtration of microalgae has been suggested as an economical way of harvesting large quantities of algae, but it has not yet been demonstrated at any significant scale.

In commercial production of high value algal products many of these harvesting methods have some application. For example, *Dunaliella* cells, when grown under extreme salinity conditions, acquire a hydrophobic surface and can be harvested by adhesion to a hydrophobic material (as practised in Australia). In India, the *Dunaliella* harvested with alum is extracted into vegetable oils for production of a carotenoid extract. In Israel, the *Dunaliella* product is used directly as a food supplement. The use of alum or other chemical flocculants is not possible so it is harvested by centrifugation (a more expensive process). In fact, the centrifuges used in Israel cost several-fold more than the cultivation system itself, in part because the fragility of these cells (lacking a cell wall) requires a much slower flow rate than possible with Chlorella or other hardier algae. Clearly, the harvesting method of choice depends on not only the algal species, but also the cultivation conditions and the use of the product (and, in the case of biofuels production, the intended use of the co-products).

Bioflocculation refers to the characteristic of some algae to form clumps or spontaneously flocculate when grown to high cell densities. Since these clumps are much easier to harvest than unicellular algae, this characteristic could significantly reduce harvesting costs. For algal species with this characteristic, bioflocculation and sedimentation appears to take between 6 and 10 hours and produces a primary concentrate of between 2% and 4% solids. Further concentrating by centrifugation is required to yield a wet algal paste (10% to 20% solids). For example, Seambiotic (Israel) favour bioflocculation followed by basket and decanter centrifugation for harvesting *Nannochloropsis* for biofuel production and claim this is a low cost process.

A similar approach was adopted by Benemann *et al.* (1978, 1982) in their pilot-scale work and was the basis for their much cited engineering and economic analyses of algae biofuels production. They argued that this was the only process that was of potentially low enough cost for biofuels production, and that bioflocculation was prevalent in natural ecosystems. However, not much is known about the mechanism of bioflocculation, and so enhancement of this trait or transfer to commercially interesting oil producing strains may require significant basic research.

Technology for low-cost harvesting of microalgae has not yet been demonstrated at any significant scale. If algae oil is to become a viable future energy source, this fundamental problem will need to be overcome. It is essential that harvesting process development take place in an integrative manner with strain development and cultivation scale up, because all three are interdependent. Harvesting processes still need to be more fully developed and engineered to demonstrate economic and technical feasibility.

Oil Extraction

Most algal biofuels are produced by processing specific cellular components that must first be separated from the rest of the cell. Before oil-based biofuels (e.g., biodiesel) can be processed, for example, lipids housed within the algal cells must be isolated. Separating the various cell components can be achieved through physical, chemical, enzymatic, or other extraction methods.

Conventional Solvent Extraction

Solvents, such as hexane, have been used to extract and purify soybean seed oils, high-value fatty acids, and specialty nutraceutical products. These types of solvent-based processes are most effective with dried feedstocks or those with minimal free water. The cost of drying the feedstock significantly adds to the overall production cost and requires significant energy. A limited number of solvents have been evaluated for large scale extraction of algal biomass with some success but, at the time, no effort was made to determine the process economics or material and energy balances of such processes (Nagel and Lemke, 1990). The drying of algae wet pastes for large-scale organic solvent extraction may not be economically feasible or sound in terms of embodied energy for biofuels. Nevertheless, it is frequently used in economic assessments of algal biofuel production as it is known technology and, at least for oil seeds, is practiced on a large scale with well established economics.

Supercritical Fluid Extraction

Supercritical CO_2 (SFE) has been used in manufacturing to remove caffeine from coffee, to separate high-value oils from plants, and in the laboratory to transesterify lipids into biodiesel from domestic sewage sludge (Dufreche *et al.*, 2007). Literature describes successful extraction of algal lipids with supercritical CO_2, albeit on a small-scale (Couto *et al.*, 2010), and the resulting conversion into biodiesel. The ability of SFE to operate at low temperatures preserves the algal lipid quality during the extraction process and minimizes the need for additional solvent processing.

Heated Oil Extraction

Benemann and Oswald (1996) proposed contacting algae wet paste from a gravitational thickener with heated oil and then combining centrifugal dewatering with oil extraction in a three phase centrifuge which could separate oil, water, and solids (i.e., residual biomass). In this extraction, a fraction of the oil is returned to the heater and then to extraction, and the remainder is fed forward to biofuel production. While this extraction method has never been demonstrated, preliminary analysis suggests it may be viable.

Mechanical Extraction

Mechanical treatments, such as ultra sonication (disruption with high-frequency sound waves) and homogenization (carried out by rapid pressure drops), may be used to disrupt cell walls and lead to enhanced oil recovery. Systems based on sonication process and centrifugation may provide economic solutions for algal lipid recovery.

Biological Extraction

Biological methods used to capture and extract lipids offer low-tech and low-cost methods of harvesting and lipid extraction. Demonstrations in large open ponds of brine shrimp feeding on microalgae to concentrate the algae, followed by harvesting, crushing and homogenizing the larger brine shrimp to recover oil, have been successful (Brune and Beecher, 2007). Using crustaceans to capture and concentrate microalgae would appear to be a promising solution for algae oil recovery. The use of enzymes to degrade algal cell walls and reduce the energy needed for mechanical disruption has also been investigated.

Fractionation

Low costs and high yield lipid extraction processes are unlikely to generate a feedstock clean enough to be converted directly to fuel. A crude lipid extract is likely to have a mixture of TAGs, free fatty acids, phospholipids, glycolipids, chlorophyll and other pigments, and perhaps hydrophobic proteins. Free fatty acids, phospholipids and glycolipids can interfere with transesterification by causing the formation of soaps and gums. Pigments and proteins are also likely to interfere with the transesterification process. Phosphorous and metal ions (e.g. magnesium from chlorophyll) can interfere with hydrotreating (for conversion to green diesel or jet fuels) by poisoning catalyst (with consequent increased processing costs). In either case, it will be necessary to consider process options that result in feedstock streams sufficiently clean to generate biofuels.

Fuel Production

Algae and its cellular components have been considered as feedstocks to be processed to create a variety of end-use energy products, which include a wide range of liquid and gaseous transportation fuels. Such fuels include biodiesel; renewable gasoline, diesel, and jet fuel; ethanol; methane; synthesis gas; hydrogen; and straight vegetable oil (SVO). In the biophotolysis fuel production route, algae (or cyanobacteria) are not used as feedstock, but they are the actual producers of the fuel (hydrogen), which means that the algae are not consumed in this process. In addition to transportation fuels, dry algal biomass can also be directly combusted to create heat or electricity.

Transesterification

Overwhelmingly, the transesterification process is used today to make most biodiesel fuels from lipids. This process is not severe since it runs at atmospheric pressure and quite low temperatures of approximately 60°C (140°F) (Hussain, 2010). Algal lipids have similar makeup to land-based crop oils, and transesterification has been proven effective for converting these oils into biodiesel.

Biodiesel production via transesterification can be performed continuously or in batch. Dry triglycerides (three fatty acid molecules esterified with a glycerol molecule) are mixed with methanol or another alcohol in the presence of a catalyst. In the reaction, the triglycerides are converted to diglycerides, then monoglycerides, and finally into glycerol while three fatty acid methyl ester (FAME) molecules (biodiesel) remain.

Transesterification is a well understood method for producing biodiesel and has been used for many decades. The end-use product (biodiesel) is non-toxic, biodegradable, and emits significantly less greenhouse gas (GHG) emissions than traditional diesel. Transesterification of oils results in biodiesel with a higher cetane number than traditional diesel, so it contributes to easy cold starting and minimal idle noise. The high lubricity of the biodiesel also enhances engine life. Transesterification also carries much of the feedstock oil characteristics over to the finished fuel; the feedstock therefore has a broad range of parameters that can impact end-use suitability.

Hydroprocessing

A rising trend in the biofuels market involves catalytic hydroprocessing of lipids to produce "drop-in" hydrocarbon fuels with very similar chemical structures and energy contents as standard gasoline, diesel, and jet fuel. As a result, these green fuels can be blended with their petroleum-derived counterparts without any necessary adjustments to the vehicles, distribution system, or fuelling infrastructure.

Hydrotreating and hydrocracking are the two main forms of hydroprocessing that can be used to upgrade oils to transportation fuel quality. Both methods remove undesired elements and contaminants (e.g., sulphur, nitrogen, metals), use similar hardware, and hydrogenate the oil. In recent decades, hydrotreating has become much more commonly used in this industry than traditional hydrocracking. In hydrotreating, only minimal molecular changes occur, and the process occurs at a lower temperature (approximately 300-390°C) and pressure (approximately 50-150 bar).

The greatest advantage of hydroprocessing algal oil is that the resultant renewable fuel can simply be mixed with petroleum-based fuels since they essentially have the same chemical structure. No adjustments to existing vehicles or infrastructure are required. The fuels are also compatible with existing fuel standards. Hydroprocessed end-use fuels are actually higher quality than petroleum-based fuels because they are virtually free of sulphur and nitrogen compounds. They also have higher energy contents than biodiesel or alcohol.

Fermentation

The concept of fermentation can be applied to multiple algae-to-fuel pathways. For example, certain strains of algae are grown in closed bioreactors by ingesting sugar fed into the system, reaching high volumes of oil to be processed into biodiesel and other end-use fuels. Other strains are instead selected for fermentation because their carbohydrates are capable of directly producing alcohols, such as ethanol, presenting one of the most direct pathways from algae cultivation to biofuel.

Alcohol can be produced through fermentation by one of two primary ways:

- With light, where starch is created and stored through photosynthesis and fermented intracellularly. Resulting ethanol is excreted into the medium.
- Without light, where sugar is fed to the system, which is anaerobically fermented (in absence of oxygen) with the aid of microorganisms (e.g., bacteria or yeast). The fermented mixture is then processed into alcohol and CO_2.

The greatest advantage of using heterotrophic fermentation to produce ethanol is that it eliminates the need to dewater the algal culture, extract oil, and process the oils. Also, if photosynthesis is used to drive fermentation ("with light" option), large volumes of CO_2 can be redirected from industry sources and fed into the system as opposed to being released into the atmosphere, although it will be released later when the biofuel is combusted in a motor vehicle engine.

If light is not used, relatively small amounts of water are needed in heterotrophic fermentation, and the algae that grow in this process do not require CO_2 absorption. However, sugar must be fed into the system and concern has been voiced that this process may add to the "food vs. fuel" debate where this process could be displacing food for the purposes of fuel production.

Anaerobic Digestion

Anaerobic digestion is a biochemical reaction that reduces complex organic compounds, such as algae, down to methane and CO_2 in the absence of oxygen. The resultant methane gas can be compressed and used as a motor fuel in the form of natural gas. Traditionally, three separate groups of bacteria are used during anaerobic digestion. Assuming whole algal cells enter a digester, lipids must first be broken down to fatty acids, carbohydrates to monosaccharides, and proteins to amino acids.

This step, referred to as hydrolysis, usually entails a collection of enzymes excreted by hydrolytic and fermentative bacteria. Next, acetogenic bacteria are responsible for converting these acids and alcohols into acetate, CO_2, and hydrogen. Finally, methanogenic bacteria complete the conversion of these products into CO_2 and methane.

Anaerobic digestion removes certain barriers associated with other algal biofuel processes. For example, dewatering of algal cultures and extracting of oils are unnecessary in anaerobic digestion, which may reduce production costs. Furthermore, anaerobic digesters are less selective of algal strains compared to other methods, so measures to reach high lipid yields are not as important. Therefore, settings where various strains are growing uncontrolled, such as wastewater treatment plants, may be ideal for digestion.

Because methane gas has a greenhouse effect 21 to 25 times that of CO_2, the biogas created in anaerobic digestion needs to be controlled. Since the reaction occurs in totally enclosed systems, the level of control needed can be accommodated. Furthermore, methane can be combusted or otherwise converted into products with lower CO_2 intensities. Compost material and nutrient-rich water, the two primary byproducts of anaerobic digestion, hold considerable market value in the agricultural industry and can be reused as fertilizer materials.

Gasification

Algal biomass can be converted into a syngas in a thermochemical process called gasification. The versatile syngas that results is primarily comprised of carbon monoxide (CO), CO_2, and hydrogen, but can also include nitrogen, methane, water, tar, and ash particles. Several of these syngas components can act as intermediates in the production of transportation fuels, such as hydrogen, ethanol, and methanol. The gases can also be directly combusted in turbines to produce electricity or converted to liquid alkanes via Fischer-Tropsch synthesis. Product proportions vary with the characteristics of the feedstock (e.g., moisture content) and gasifier (e.g., temperature, pressure, catalyst).

In conventional gasification, dry algal biomass (less than 15-20% moisture content) is reacted at temperatures ranging from 800°C to 1,000°C with a controlled amount of oxygen or water.

The greatest benefit of gasification is the wide variety of end-use fuels and valuable byproducts that can be derived from the syngas. Opportunities for synergies exist when considering algae as a feedstock for gasification. For instance, excessive heat from the reactor can be redirected with a heat exchanger to help dry algae in preparation for gasification.

Several challenges of gasifying algae are present, at least in the near term. First, in order for the process to be cost-efficient, large-scale production is likely necessary. Second, reactor operations and system inputs would need to be tailored to optimize syngas characteristics. Finally, regardless of feedstock type, removal of tar accumulation and other unwanted byproducts in conventional gasification adds steps to the overall process.

Pyrolysis

Pyrolysis is a thermochemical pretreatment that can be applied to organic material under high temperature and high pressure to produce an intermediary bio-oil of low viscosity, which can then be hydroprocessed to produce renewable diesel, gasoline, and jet fuel.

In pyrolysis, dry biomass is thermally decomposed in the limited presence of oxygen. When cooled, bio-oil, wastewater, and CO are the key outputs (additional byproducts, including charcoal and phenol-formaldehyde, can be used in fertilizer and animal feed production). Flash, or “fast,” pyrolysis can be performed between 350-500°C for less than 2 seconds if the feedstock is finely ground. This is more efficient than the conventional slow pyrolysis and results in higher quality bio-oil.

Biophotolysis

A number of microalgae and cyanobacteria are able to split water into hydrogen and oxygen, using light as the energy source, in a process called biophotolysis. This is different from other options of algae for biofuels, where the algae are converted into liquid fuel. In biophotolysis, the algae are naturally producing the fuel. Direct biophotolysis is the simplest form of photobiological hydrogen production. It can be considered the biological equivalent of electrolysis of water.

Biophotolysis is still mostly in the research phase, but the production of hydrogen by microalgae and cyanobacteria via biophotolysis has been demonstrated in laboratory settings. Some industries are teaming up with universities and other research institutes.

Purification of SVO

Most commonly, extracted algal oil is esterified to produce biodiesel. However, if left unrefined, algal oil can act as straight vegetable oil (SVO) and, therefore be used in SVO applications. SVO can directly be used as a fuel in diesel engines although modifications to the engine are required. Prior to use as a fuel, algal oil should be purified to remove excess water, solvents, and/or impurities. Methods for oil purification include filtration and distillation.

SVO varies significantly from biodiesel. SVO has a much higher viscosity than biodiesel or other petroleum-derived diesel, and the additional thickness more rapidly results in wear and tear on an engine compared to the more "fluid" biodiesel. Adverse effects of using SVO in a standard diesel engine may include piston ring sticking; deposits in the injector, combustion chamber, and fuel system; degraded power and fuel economy; and increased exhaust emissions. SVO also has different combustion properties than biodiesel and petroleum-derived diesel, which result in different combustion characteristics.

Sustainability

Sustainability is the subject of much discussion at international scientific and governmental forums on biofuels. Emerging from this discussion is a consensus that sustainability is of foremost importance as an overarching principle for the development of biomass-to-energy agro-industrial enterprises. While sustainability criteria that are agreeable to all nations are still being expounded, the generally accepted principles of sustainability include that;

- the greenhouse gas balance of the production chain is positive;
- the biomass production is not at the expense of carbon sinks in existing vegetation and soil;
- the biomass production does not endanger the food supply and existing local business activity (i.e. local supply of energy, medicines and building materials);
- the biomass production has no impact on biodiversity (protected or vulnerable biodiversity is not affected or if possible strengthened);
- soil and soil quality are retained or improved;
- ground water and surface water are not depleted and water quality is maintained or improved;
- air quality is maintained or improved; and
- the production and processing of biomass contributes to local prosperity and to the social well being of employees and the local population.

While the literature on the sustainability of algal biofuels is sparse, recent analyses appear to raise concern with respect to the claims of superiority of algal production systems when compared to terrestrial crops. It should be stressed that these LCA studies are based on hypothetical operating scenarios, not real production systems. The purpose of the studies is to highlight inefficiencies in the production systems that need to be addressed to create sustainable microalgae-to-biofuel enterprises. Nevertheless, these studies created debate in the scientific community and the exchange of comments published in subsequent editions of the journals.

To acquire knowledge about how large-scale algal biofuel systems operate, several pilot projects are underway and are expected to increase in number. Pilot projects should be adapted to local circumstances such as climatic conditions and native algae species, the availability of water, and potential markets. Real-world experience will help remove the uncertainties, and will also help clarify which practices are feasible and which are not.

Siting

Climate conditions, availability of CO_2, other nutrients (nitrogen and phosphorous), and water resources greatly affect algae productivity. In addition, land considerations, such as topography, use, and stewardship help define the land available for algae production. The perceived availability of water (of low quality with few competing uses), CO_2 and non-arable land resources in suitable climates are significant drivers for the development of algal biofuels.

Autotrophic algae, like terrestrial plants, depend upon sunlight for growth. However, algae evolved to thrive in a low light environment have maximized their photosynthetic apparatus accordingly. While crop plants grow optimally in full sunlight, high solar radiation can inhibit algal growth and even cause cell death. The following figure illustrates the yearly sum of global solar irradiance averages over the period of 1981 to 2000. Solar radiation of ca. 1,500 kWh·m^{-2}·yr^{-1} is considered adequate for algae production, which means the majority of the earth's land surface would appear to be potentially suitable for algae production.

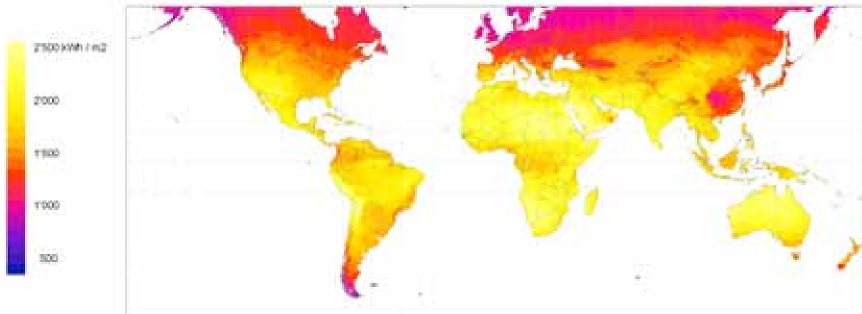

Figure 6 Global Solar Irradiance (Image source Meteotest; database Meteonorm (www.meteonorm.com))

Generally, all plant species grow well when maintained in a narrow temperature range (defined by adaptation to the ecosystem from which they are derived). Algae suspended in water are less responsive to fluctuation in air temperature since the water temperature will be a function of solar heating, evaporative cooling, and other process factors in open ponds. However, once climatic conditions drive the temperature of the water in open ponds outside of the physiological range for the algal strain production will cease or be challenged by invasive algal species. Consequently, while temperature has a direct affect on growth rate, ambient temperature range or climate defines the effective growing season for an algal production system.

Ambient temperature is strongly linked to economic feasibility. It is generally considered that year round production in open ponds may be achievable where average monthly temperatures of the coldest month exceed 15 °C. There will likely be seasonal production in more temperate climates, with a consequent requirement to shut down and re-establish production on an annual basis.

One of the major benefits of growing algae is that unlike terrestrial agriculture, algal culture can utilize water with few competing uses, such as seawater and brackish water from aquifers, oil and natural gas wells, and coal seams. While coastal land is obviously suitable for algae production, relatively little is known about saline groundwater resources. An improved knowledge base is needed to better define global distribution, quantity, physical and chemical characteristics of groundwater resources and to predict the effects of its extraction on the environment (Alley, 2003).

The following figure depicts the location of large stationary sources of CO_2. The most obvious characteristic of this distribution is that very few of these large CO_2 emitters are in close proximity to regions identified as being most suitable for year round large scale open pond production systems (dry tropical coastal regions). Large point sources of CO_2 are concentrated in proximity to major industrial and urban areas.

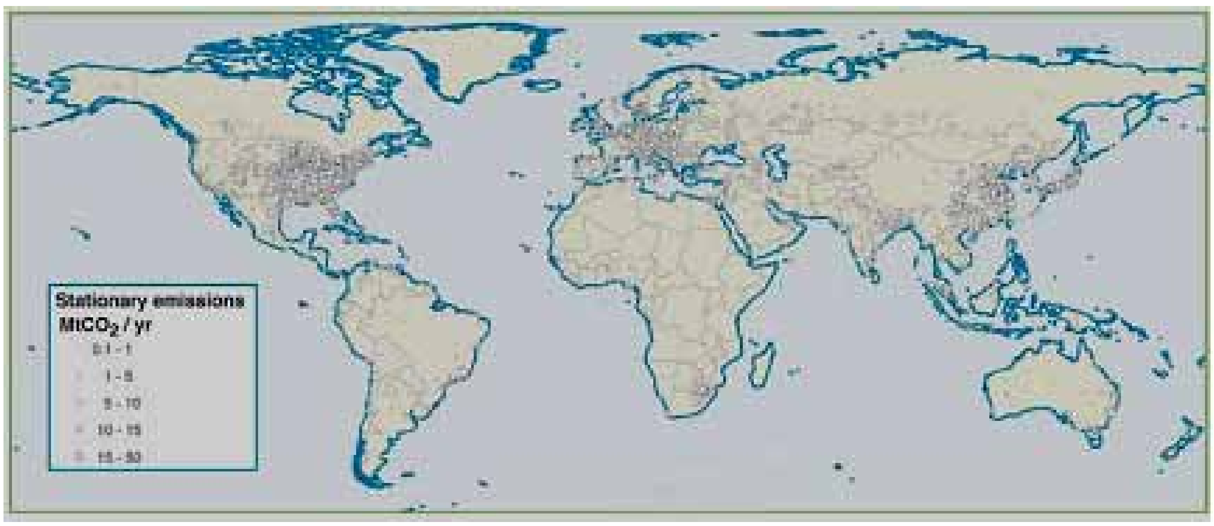

Figure 7 Point Source CO_2 Emissions

Optimal algae growth occurs in a CO_2 enriched environment. Since CO_2 capture and geo-sequestration (or carbon capture & storage, CCS) is likely to become a necessary activity for stationary energy providers and other large volume industrial CO_2 emitters, it would seem that algae production plants could provide an alternative CCS.

Undoubtedly, land and water in suitable climates for large scale algal biofuels production exist, but the economics of production, and the embodied energy and GHG mitigation of the biofuel will be influenced by the proximity of these resources. It is less obvious that the CO_2 is available in regions most suited to year round algal growth. Optimal siting of large scale algal biofuels production facilities will require that the resources exist in close proximity, or that there are drivers to ensure the provision of the missing resource (most likely CO_2). However, much more effort is required to develop a more complete picture of ideal locations for algae growth.

Economics

Like many aspects of algal biofuels production, there is great uncertainty with respect to the economics of future commercial scale algal production. Two distinct estimates of the economics were developed, the first is an update of the techno-economic analysis completed for the US Aquatic Species Program employing new process information and current cost data, and the second is a ground up analysis based on large open pond systems in an Australian context.

Three open pond scenarios were modelled in the US, the best demonstrated performance of the Roswell, NM ponds operated in the 1990s, a higher oil, aggressive productivity scenario, and a maximum productivity case. The parameters assumed are shown in the following table.

	Current Case	Aggressive Case	Maximum Case
Dry Algae			
Areal Productivity (g/m^2/day)	**20**	**40**	**60**
Volumetric Productivity (g/m^3/day)[a]	**50**	**133**	**200**
Lipid			
Mass Fraction (% of algae)	**25%**	**50%**	**60%**
Areal Productivity (g/m^2/day)	**5**	**20**	**36**
Volumetric Productivity (g/m^3/day)[a]	**13**	**67**	**120**
Carbon Dioxide			
Carbon Dioxide Consumption (g/m^2/day)	**50**	**100**	**150**

[a] Represents a pond that is 30 cm deep

Table 4 Algae Production Analysis Scenarios

The following figure shows the costs of producing 46.9 ML/year of lipids under each scenario. The significance of the capital cost is shown. Approximately 46.9 ML/yr of lipids is required to produce 37.8 ML/yr of biodiesel.

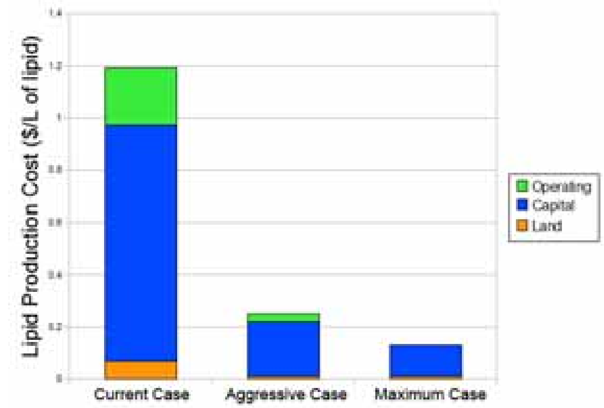

Figure 8 Cost to Produce 46.9 ML/yr of Algal Derived Lipids at the Three Different Algae Growth Scenarios

Photobioreactors have been discussed as a potential alternative to raceway ponds. A photobioreactor has the potential to produce significantly higher quantities of lipids per volume of water. Higher volumetric productivity occurs because the photobioreactor has higher surface area per volume of algae/water mixture than typical raceway ponds. The result of this higher volumetric efficiency is a reduction in water consumption, which can have a significant impact on the technical and economic feasibility of the algae-to-fuels process.

A reasonable approximation for closed photobioreactor cost is $1 million/hectare (ha) ($400,000/acre). The case was also run with a photobioreactor cost of $500,000/hectare ($200,000/acre). The results from this sensitivity analysis for the production of 37.8 ML/yr of biodiesel are shown in the following figure.

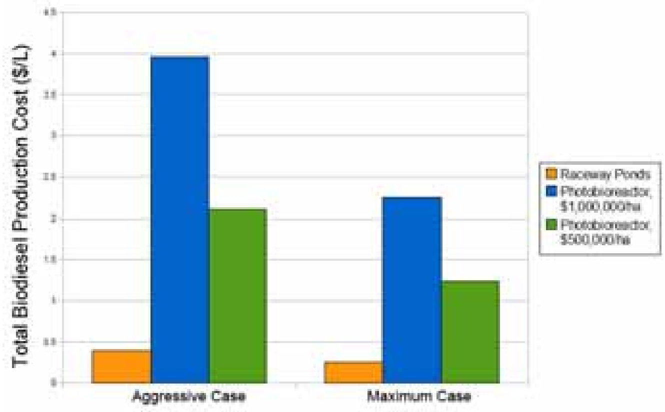

Figure 9 Comparison of Raceway Ponds and Photobioreactors, With Different Photobioreactor Cost

The use of photobioreactors causes the production cost of biodiesel to be significantly higher than when raceway ponds are used. The economic results presented show that at high enough algae growth rates and lipid contents, biodiesel could be produced at prices that compete with current petroleum derived diesel. However, at current algae productivities, the costs for production of fuels are prohibitively high. An aggressive and perhaps long term research effort will be necessary to achieve an economically viable process.

A dynamic material balance and economic model was developed based on large scale ponds located in Australia. The same basic productivity assumptions where algal productivity is 60 $g \cdot m^{-2} \cdot d^{-1}$ and algal biomass is 60% lipid are used. The facility is situated in the dry tropics where low rainfall and high ambient temperatures allow for more than 340 days of operation in each pond. The land is flat and the soil is clay so pond liners can be avoided and capital costs are comparatively low. Seawater is provided to the pond system by tidal flow and the CO_2 source is close to the facility. An emission trading system (and a carbon emissions price of $100 tCO_2 $equiv^{-1}$) drives nearby industry to capture CO_2 and the algae are able to grow in ponds with direct feeding of flue gas. Algal cake is sold as an animal feed and returns $300 t^{-1} dry basis (effectively $600 t^{-1} protein content). Other higher value products are extracted and sold but markets for these products are no longer as attractive due to oversupply. The 100 ML facility is profitable at a diesel price of $0.63 l^{-1} ($100 bbl^{-1}) with after tax IRR between 20% and 23% depending on co-product values.

Findings and Recommendations

Algae feedstocks for alternative fuels production are not economically competitive with fossil fuels at the present time. Furthermore, it has not yet been demonstrated that algae production systems offer improved sustainability characteristics.

Algae does have potential as a feedstock for biofuels. Depending on their composition, different algae species may be suitable for a range of biofuels. Additionally, algal biomass productivity per hectare could eventually be higher than for terrestrial energy crops. Last but not least, algae can be cultivated at sea or on non-arable land, so there is no competition with current food production.

These reasons justify attention to algal biofuels from researchers, industries and (governmental) policy makers. The research that forms the basis of this report leads to the conclusion that the following issues are important to consider in policymaking on algal biofuels:

1. Algal biofuels are in an early stage of development. Current expectations for the future are based on estimates and extrapolation of small-scale production and results of laboratory work. Progress needs to be demonstrated that higher productivity, commercial scale systems, exhibiting improved economics and sustainability attributes are achievable.
2. It is too early to select preferred algal fuel pathways and technologies. In practice there will not be one preferred production method for all situations. Different local circumstances, such as climatic conditions, the availability of fresh or salt water, and the proximity of suitable CO_2 resources will likely have different optimum solutions.
3. Algae production will not be possible in quite a few regions of the world. High productivity rates will require good solar irradiance, a narrow and suitable temperature range, good water supply, adequate CO_2 resources, and sufficient flat land. The locations where all of the appropriate resources are available need to be identified.
4. Sustainability criteria must be developed for algal biofuels. Besides the energy, environmental, and ecological issues that are addressed in this report, criteria should be defined on issues not addressed in this report such as economic prosperity and social well-being.
5. It has been shown that under specific conditions, the algal biofuel production and distribution chain may have a net energy output, but further energy analysis of many different algae fuel chains is needed.
6. Algal biofuel policies and projects should aim to reduce fossil energy consumption and the environmental burden compared to conventional fuels. In parallel, these efforts should result in acceptable impacts on ecosystems. Therefore, many government agencies that fund pilot projects are requiring a complete sustainability analysis prior to construction and operations. During the execution of the project, energy consumption and emissions should be measured to ensure that actual measurements are consistent with those in the sustainability analysis and to collect inputs for later LCA analyses.
7. Based on the high level of innovation demonstrated within the algal biofuels industry in just the past decade, it is likely that new, refined, or even breakthrough technologies will continue to be introduced in the future. In fact, the introduction of these innovations will be critical if the sector is ultimately going to achieve commercial success. It is important that industry stakeholders and policymakers remain open to new algal species, processes, and fuels besides the ones that are being considered today.

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