Perspective

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The promise and challenges of microalgal-derived biofuels†

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Abstract: Microalgae offer great promise to contribute a significant portion of the renewable fuels that will be required by the Renewable Fuels Standard described in the 2007 Energy Independence and Security Act of the United States. Algal biofuels would be based mainly on the high lipid content of the algal cell and thus would be an ideal feedstock for high energy density transportation fuels, such as biodiesel as well as green diesel, green jet fuel and green gasoline. A comprehensive research and development program for the development of algal biofuels was initiated by the US Department of Energy (DoE) more than 30 years ago, and although great progress was made, the program was discontinued in 1996, because of decreasing federal budgets and low petroleum costs. Interest in algal biofuels has been growing recently due to increased concern over peak oil, energy security, greenhouse gas emissions, and the potential for other biofuel feedstocks to compete for limited agricultural resources. The high productivity of algae suggests that much of the US transportation fuel needs can be met by algal biofuels at a production cost competitive with the cost of petroleum seen during the early part of 2008. Development of algal biomass production technology, however, remains in its infancy. This perspective provides a brief overview of past algal research sponsored by the DoE, the potential of microalgal biofuels and a discussion of the technical and economic barriers that need to be overcome before production of microalgal-derived diesel-fuel substitutes can become a large-scale commercial reality. Published in 2009 by John Wiley & Sons, Ltd

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Introduction

As petroleum supplies diminish, the USA will become increasingly dependent on crude oil from unstable regions of the world. The USA currently imports more than 60% of its petroleum. Of that, two-thirds is used for the production of transportation fuels, such as 140 billion gallons per year (gal yr^{-1}) of gasoline and 44 billion gal yr^{-1} of on-road diesel.[1] Soaring energy demand in developing nations is beginning to create intense competition for the world's dwindling energy resources. In addition, the combustion of fossil fuels has created serious concern about global greenhouse gas (GHG) accumulation and its effects on world economies and human habitat.

In response to these global concerns, President Bush signed into law the 2007 Energy Independence and Security Act (EISA). EISA contains provisions designed to increase the availability of renewable energy that decreases GHG

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emissions, and also establishes a very aggressive Renewable Fuels Standard (RFS). This RFS calls for the production of 36 billion gallons by 2022 of which at least 21 billion gallons must be advanced biofuels (i.e., non-corn ethanol). While cellulosic ethanol is expected to play a large role in meeting the EISA goals, a number of other advanced biofuels show significant promise in potentially helping to achieve the 21 billion gallon mandate. Of these candidates, biofuels derived from algal biomass feedstocks are generating considerable interest around the world. It is with this in mind that micro-algal-derived lipids could serve as a major contributor to our goal of energy independence. There are several aspects of algal biofuel production that have combined to capture the interest of researchers and entrepreneurs around the world. These include: i) high per-acre productivity, ii) algal feedstock based on non-food resource, iii) use of otherwise non-productive, non-arable land, iv) utilization of a wide variety of water sources (fresh, brackish, saline, and wastewater), v) mitigation of GHG release into the atmosphere, and vi) production of both biofuels and valuable coproducts.

Nevertheless, while the basic concept of using algae as an alternative source of biomass feedstock for biofuels has been explored over the past several decades, a scalable, commercially viable system has yet to emerge. Despite the huge potential of algal feedstocks to replace significant quantities of petroleum-based fuels, the technology is still regarded by many in the field to be in its infancy. There are many both basic and applied R&D milestones that need to be achieved before algal-based fuels can be produced at a commercial scale. Production at a cost that is competitive with petroleum-based fuels increases the challenge substantially. In this perspective, we will provide a brief overview of past algal research, explain the economic and environmental impacts of using algal biomass for the production of liquid transportation fuels, and describe the current status of algae R&D. Finally, we will identify some of the critical technical barriers that must be overcome in order for algal biomass to be used in the production of economically viable advanced biofuels.

Past algal biofuels research efforts

The Aquatic Species Program (ASP) funded by the Department of Energy (DoE) from 1978 to 1996 represents the most comprehensive research effort to date on fuels from algae. DoE invested approximately $25 million over an 18-year period to study a variety of aquatic species for use in renewable energy production, including microalgae, macroalgae, and cattails.[2] ASP was successful in demonstrating the feasibility of algal culture as a source of oil and resulted in important advances in the technology. These advances were made through algal strain isolation and characterization,[2] studies of algal physiology and biochemistry,[3-4] genetic engineering,[5-6] engineering and process development, and outdoor demonstration-scale algal mass culture[7] (Fig. 1). Technoeconomic analyses and resource assessments were important aspects of the program, to guide limited financial resources to the most important scientific and technical barriers. While ASP made significant progress over its 18-year existence, the program was discontinued due to decreasing federal budgets and because the potential cost of algal oil production was estimated in the $40–$60 per barrel range compared to $20 per barrel for crude oil in 1995. The program highlighted the need to understand and optimize the biological mechanisms of algal lipid accumulation and to find creative, cost-effective solutions for culture and process engineering development to isolate lipids from very dilute biomass suspensions. In 1998, a comprehensive overview of the project was completed.[2] In the years immediately following ASP and until recently, support for algal biofuels research was rather limited, and as a result little progress was made. In the last few years, however, interest in algae has increased dramatically, and although federal agencies are beginning to show signs that increased support is imminent, many new groups have begun to explore this area in academic, industrial (especially small entrepreneurial organizations), and national laboratories, largely funded by private investors and industrial sources. This work is not limited to the USA since significant efforts are now taking place in Europe, the Middle East, Australia, New Zealand, and many other parts of the world.

Benefits of microalgal oil production

Microalgae include a wide variety of photosynthetic micro-organisms capable of fixing CO_2 from the atmosphere to produce biomass more efficiently and rapidly than terrestrial plants. Numerous algal strains have been shown in the laboratory to produce more than 50% of their biomass as

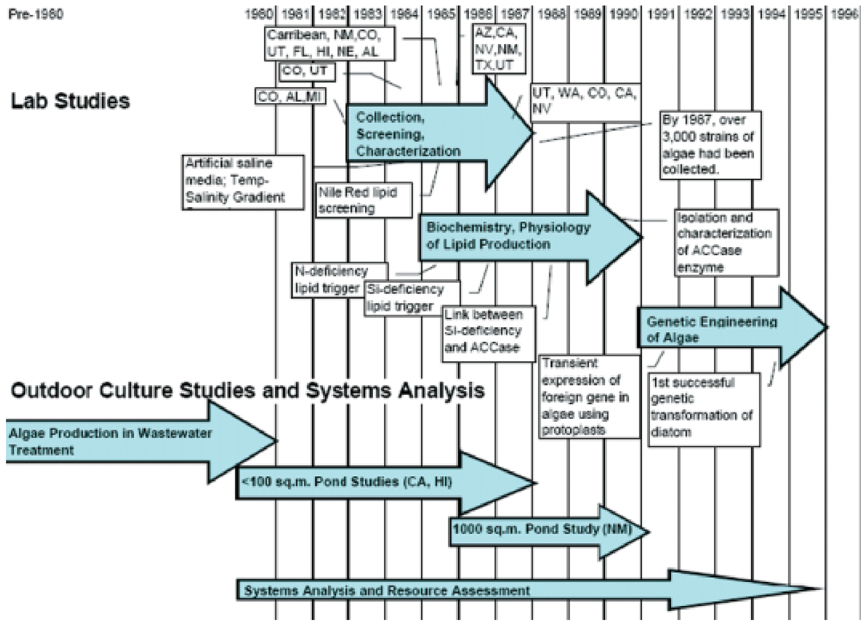

Figure 1. Summary of the Aquatic Species Program's research activities.

lipid [8-9] with much of this as triacylglycerols (TAGs). It must be stated that the methodology for lipid analysis (largely based on solvent extraction and gravimetric analysis) has not been standardized and so literature values must be approached with a healthy level of skepticism. TAGs are the anticipated starting material for high energy density fuels such as biodiesel (produced by transesterification of TAGs to yield fatty acid methyl esters [10]), green diesel, green jet fuel, and green gasoline (produced by a combination of hydroprocessing and catalytic cracking to yield alkanes of predetermined chain lengths).[11] Most of the observations of high lipid content come from algal cultures grown under nutrient (especially nitrogen, phosphorous, or silicon) limitation. Lipid content varies in both quantity and quality with varied growth conditions.[8] While high lipid content can be obtained under nutrient limitation, this is generally at the expense of reduced biomass productivities. Nevertheless, the possibility that algae could generate considerably more oil per area than typical oilseed crops must certainly be evaluated further.

The development of biofuels from traditional oil crops and waste cooking oil/fats cannot realistically meet the demand for transportation fuels.[12] If the entire 2007 US soybean oil yield, representing almost 3 billion gallons produced on 63.6 million acres of farm land (Soy Stats™, American Soybean Association, available at http://www.soystats.com) were converted to biofuel, it would replace only about 4.5% of the total petroleum diesel (~66 billion gallons). If that much land were used to cultivate algae, the resulting oil could, even at a conservative projected productivity (10g m^{-2} day^{-1} at 15% TAG), replace approximately 61% of the petroleum diesel used annually (Table 1), as well as capturing approximately 2 billion tons of CO_2 in the biomass. CO_2 capture, however, should not be confused with CO_2 sequestration since a portion of the CO_2 captured and partitioned in the oil will be released when the algal-derived fuel is combusted, and the remaining biomass will likely be used as a feedstock for a byproduct that will ultimately be converted to CO_2. Algal capture of CO_2 for biofuels applications really amounts to a 'recycling' of the CO_2 for at least one additional use prior to be released during burning of the fuel. Under this scenario there is no permanent CO_2 capture unless the algal biomass is completely isolated from the environment and stored.

Improvements in either areal productivity or lipid content could significantly reduce the amount of land needed to produce this much biofuel (Table 1). After removal of the lipid component, the remaining residual biomass (largely carbohydrate and protein) can also be used for the generation of energy, more liquid or gaseous fuels, or for higher value by-products (Fig. 2). Algal biofuels also offer the promise of being more sustainable than bioethanol derived

Table 1. Productivity comparisons for soybeans and algae

	Soybean	Algae		
Productivity		Low Productivity	Medium Productivity	High Productivity
		10 $g/m^2/day$	25 $g/m^2/day$	50 $g/m^2/day$
		15% TAG	25% TAG	50% TAG
gal/acre	48	633	2637	10,549
Total acres	63.6 million	63.6 million	25 million	6.26 million
gal/year	3 billion	40 billion	66 billion	66 billion
% Petrodiesel	4.5%	61%	100	100

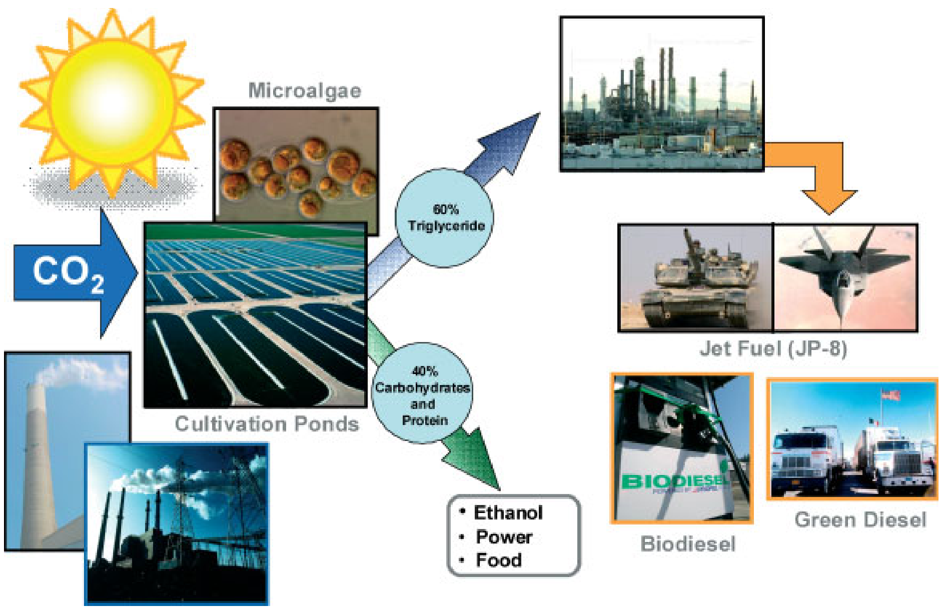

Figure 2. Algal biomass product streams.

from corn and sugarcane and biodiesel derived from terrestrial oil crops and even possibly more sustainable than cellulosic ethanol.[13] Algae can be cultivated on otherwise non-productive land that is unsuitable for agriculture. It can also be grown in brackish, saline, and waste water that has little competing demand, offering the prospect of a biofuel that does not further tax already limited resources. Even so, a detailed life cycle assessment (LCA) and environmental impact analysis will be necessary to confirm sustainability.

Algae require approximately 2g of CO_2 for every g biomass generated and thus have a tremendous potential to capture CO_2 emissions from powerplant flue gases and other fixed sources. In the future, an algal-based biorefinery could potentially integrate several different conversion technologies to produce many biofuels including biodiesel, green diesel and green gasoline, aviation fuel (commercial and military), ethanol, and methane as well as valuable coproducts including oils, protein, and carbohydrates (Fig. 2). In some ways algal strains with promise for biofuel production are comparable to food crops utilized prior to the agricultural revolution – they have enormous potential for further development and improvement. Unlike first-generation biofuels, however, advanced biofuels, like those derived from algae, are likely to effect a much higher overall reduction in fossil fuel use.

Algal cultivation

There are currently no microalgae biofuels produced commercially in the USA. Only a small amount (approximately 5000–10 000 tons worldwide) of algal biomass is produced commercially today, mainly for the production of high-value, low-volume food supplements and nutraceuticals.[14] Commercial algae production facilities employ both open and closed cultivation systems. Each of these has advantages and disadvantages, but both require high capital input. Closed photobioreactors are significantly more expensive to construct, but have not been engineered to the extent of other reactors in commercial practice, and so there may be opportunities for significant cost reductions. Neither open ponds nor closed photobioreactors are mature technologies. Therefore, until large-scale systems are built and operated over a number of years, many uncertainties will remain. Cultivation issues for both open and closed systems, such as reactor construction materials, mixing, optimal cultivation scale, heating/cooling, evaporation, O_2 build-up, and CO_2 administration, have been considered and explored to some degree, but more definitive answers await detailed and expensive scale-up evaluations.

Successful commercial algal growth will require the development of strains and conditions for culture that allow rapid production of biomass with high lipid content and minimal growth of competing strains. The economics of continuous algal propagation can be severely challenged by the growth of contaminating algal species as well as the presence of grazers and pathogens. The rapid growth rate of algae and year-round cultivation will allow for opportunities briefly and will periodically shut down production for cleaning and maintenance to deal with competitors, grazers, and pathogens. Unlike terrestrial crops whose failure costs an entire growing cycle, an algal pond can be reinoculated to resume production in a matter of days. Microalgae can thrive in a broad range of environmental conditions, but specific strains are more limited by climatic conditions than terrestrial crops. In areas of high solar radiation, the theoretical maximum for algal productivity has been calculated to be on the order of 100g m^{-2} day^{-1}.[15] Most reports of high levels of sustained productivity in both open ponds and closed photobioreactors fall in the range of 20–30g m^{-2} day^{-1},[16] but peak productivities approaching 50g m^{-2} day^{-1} have been observed in both open ponds[2] and in natural algal blooms.[17] Maximal volumetric productivities can be higher in a closed photobioreactor than in an open pond because the surface-to-volume ratio can be higher, but in large scale, both open pond and closed photobioreactors are limited by the amount of incident sunlight on the Earth's surface and cannot exceed a maximum of 100g m^{-2} day^{-1}. [15]

Algal harvesting

Among the various unit processes involved in producing algal biomass, the aspect of harvesting cells is an important economic factor. Gudin and Thepenier[18] estimated that harvesting can account for 20–30% of the total production cost. The concentration of algal biomass per liter when grown phototrophically is typically 0.5–1.0g L^{-1} for open pond and approximately 5–10g L^{-1} for closed systems.[8] Even the upper end of this range is still low compared to that of bacterial or yeast fermentations, which can achieve cell densities in excess of 100g L^{-1}. At 1g L^{-1} algal biomass, 1000kg of water must be processed to capture 1kg of biomass. Even if the biomass contains 50% TAG, nearly 1800 gallons of culture will be needed to produce a single gallon of algal oil. The challenge for algal biomass harvesting is to take the very low cell density and concentrate it to a point where lipid extraction is possible (as much as 1000X) using the lowest possible cost and process options. Therefore, energy-intensive processes such as centrifugation may be feasible for high-value products but are far too costly in an integrated system producing lower-value products, such as algal oils for biofuels applications. In the case of algal-derived biofuels, the most promising low-cost approach is to take advantage of gravity settling – possibly enhanced by flocculation, without benefit of chemical flocculants.[19] Other mechanisms exist including the autoflocculation process which depends on the coprecipitation of algal cells with calcium carbonate and other precipitates that form in hard waters subject to high pH. Aside from settling, in some cases the algal biomass will float, either due to buoyancy (e.g., high oil content) or by using a dissolved air flotation process, as widely used in chemical flocculation. The use of small amounts of chemical flocculants to aid in such a process could be cost effective, depending on the amount used. Nevertheless, a significant engineering research effort aimed at developing cost-effective algal harvesting techniques will be required.

Extraction of algal oils

The differences between microscopic algal cells and the seeds of oil-bearing plants demand that different processes be employed for recovery of the oil. The most likely technology for algal oil recovery involves some form of solvent extraction (although other methods such as mechanical extraction, electroporation, supercritical CO_2 fluid extraction, ultrasonics and 'algae milking' in two-phase systems with dodecane[20] have been proposed). Processes built upon dry biomass are unlikely to be economical due to the energy inputs involved, and so methods that work with algal slurries or wet paste are preferred.[21] Once the algal oil is recovered and refined, downstream processing to biodiesel or green diesel is well understood, although complications in fuel conversion may still arise from differences in overall lipid content (i.e., relative levels of TAGs, phospholipids, and glycolipids) that may occur with changes in algal populations and climatic variations. Although the cost contribution for inorganic nutrients is not a significant burden to the overall economics of biofuel production (PT Pienkos, unpublished results), the energy input is significant.[21] Byproduct credits must also be considered as part of the overall economics of biofuel production. Substantial byproduct credit can be obtained from algal waste-water treatment, conversion of residual biomass to energy (through combustion, gasification, pyrolysis, or ethanolic fermentation), higher value animal feed, and veterinary nutraceuticals (Fig. 2). The high protein content of algal biomass suggests that delipidated biomass could command a higher market price than distillers' dried grains (a byproduct of corn-ethanol production) as an animal feed due to higher nutritional content. Wherever possible, inorganic nutrients in algal biomass should be recycled back to the cultivation system for maximum process efficiency.

Fuel production from algal feedstocks

Historically, the emphasis on fuel products from microalgae has been on the high-energy lipids. Microalgal oils contain fatty acid and triglyceride compounds, which like their terrestrial seed-oil counterparts, can be converted into alcohol esters (i.e., biodiesel) using conventional transesterification technology. The transesterification reaction is well-understood; however, there are still numerous approaches to optimizing the reaction for different feed compositions and different downstream processing requirements.

Alternatively, the oils can be used to produce a renewable or green diesel product by a process known as catalytic hydroprocessing. Vegetable oils and waste animal fats are being processed in a limited number of petroleum refineries to make renewable fuels. Gasoline, jet fuel, and diesel are generally described as 'renewable' or 'green' if the source material is from a biological source (such as biomass or plant oil), and all have essentially the same chemical analysis as those from crude oil. A major characteristic of petroleum-derived fuels is a near-zero oxygen content. Typical biofuels such as ethanol and biodiesel have very high oxygen contents as compared to crude oil. The primary goal of making renewable gasoline, jet fuel, and diesel is to minimize the oxygen in the final fuel while maximizing the final energy content.

Algal biofuels funding

Since the end of DoE's ASP, funding for algal research in general has been sparse and sporadic. Federal funding for algal biofuels R&D is currently split between the Department of Defense (DoD) and DoE. Recent initiatives, such as the two major Defense Advanced Research Projects Agency (DARPA) solicitations for affordable alternatives to petroleum-derived JP-8 jet fuel, the Air Force Office of Scientific Research (AFOSR) algal biojet program, DoE's Office of Energy Efficiency and Renewable Energy and Office of Fossil Energy Small Business Innovative Research (SBIR) programs specifically targeting algal-derived biofuels (2007/2008 awards and 2009 proposed topics) and the recent DoE announcement on the selection of two university-led algal biofuels projects suggest that funding levels are beginning to increase.

State funding programs have also generated approximately $10 million for algal biofuels research while a similar amount has been allocated over the past few years for research on algal biofuels at a number of US national labs including the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), the National Energy Technology Laboratory (NETL), Los Alamos National Laboratory (LANL), the Pacific Northwest National Laboratory (PNNL), and Oak Ridge National Laboratory (ORNL).

Private investment to support algal biofuel commercialization comes from both the investment community and the petrochemical industry. More than 150 small companies have been formed (mostly in the past two years) to participate in algal biofuel commercialization. According to the numbers reported by the Cleantech Group (http://cleantech.com), algae biofuels companies raised approximately $180 million through the first nine months of 2008. With the recent announcement that approximately $850 million will be invested to make ethanol from cyanobacteria,[22] it is now estimated that more than $1 billion has been committed by the private sector to develop algal-based fuels.

Technoeconomic analysis and resource assessment

While an aggressive and long-term research effort will be necessary to demonstrate economic feasibility, it is clear that a detailed review of algae-to-fuels research, development, and commercialization would not be complete without an investigation of the potential costs for the technology. The economics of algal biofuels production is highly dependant on the TAG feedstock price. Price and yield, as well as many other factors, will help to determine how algal-derived lipids will fare in the competitive marketplace. Three production scenarios are being explored: open pond, closed photobioreactor (or some combination of the two, known as 'hybrid' systems), and dark fermentation (based on heterotrophic growth of algae in fermentors using sugars rather than CO_2 as the carbon source).[23]

At NREL we have focused on open raceway pond technology, because we believe that this is the most cost-effective option to generate algal biomass (although it must be said that this approach exacerbates productivity issues such as cell density, predation species control and water loss through evaporation). We use a low-capital-cost process model proposed by Oswald and Benemann[24] as the basis for our technoeconomic analysis. This process (Fig. 3) envisions continuous open-pond cultivation of algae with a chemical flocculant to concentrate the biomass. The biomass slurry would be extracted with hot diesel oil to recover the lipids and that stream would be sent to a three-phase centrifuge to separate the oil, water and spent biomass. Although centrifugation is in general thought to be too expensive for an algal biofuel process, the biomass concentration step using flocculant will reduce the amount of water to be processed by approximately 100-fold and thus reduce the size of the centrifuge needed, bringing the capital and operating costs down to an acceptable level. The extraction step using hot diesel and the resulting biomass slurry also reduces operating costs by eliminating the need for bringing the biomass to dryness. It also eliminates the cost of pure solvents, providing a lipid stream that can be sent directly to biofuel processing. In our process configuration, the spent biomass is to be sent to an anaerobic digester for the production of methane to be used for power and heat generation.

We have constructed a technoeconomic model based upon this production process, to estimate the cost of production for algal lipids. Using the same productivities described in Table 1, we estimate a cost ranging from $25 per gallon for low productivity (10g m^{-2} day^{-1} at 15% TAG) to $2.50/gal for high productivity (50g m^{-2} day^{-1} at 50% TAG) (Fig. 4). It is only at the high productivity projections that the price of

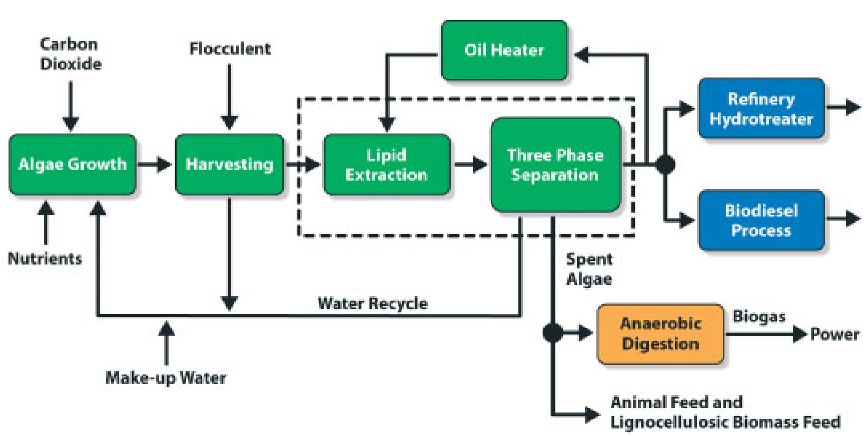

Figure 3. Process flow diagram for a model algal lipid production system.

algal oil is competitive with the price of soybean oil. Even this price cannot compete with the current price for petroleum (<$50 per barrel in December, 2008), but can compete with oil priced at >$110 per barrel. Clearly, the challenge facing algal oil commercialization is to achieve high productivity while reducing capital and operating costs still further.

Microalgae are feedstocks for advanced biofuels that have a small ecological footprint –this technology enables productive use of arid and semi-arid lands and saline water, resources that are not suitable for agriculture and other biomass technologies. Intensively managed microalgal production facilities are capable of fixing several-fold more carbon dioxide per unit area than agricultural crops or trees. Although CO_2 will still be released when biofuels derived from algal biomass are combusted, integration of microalgal farms with power plants for flue-gas capture can increase the amount of energy produced per unit of CO_2 released by as much as 60%. Materials derived from microalgal biomass also can be used for other long-term uses, serving to sequester CO_2. Flue gas from powerplants has the potential to provide sufficient quantities of CO_2 for large-scale microalgae farms. Full LCAs with broad boundaries should continue as the technologies evolve for production, extraction, conversion, and use to ensure maximum environmental and ecological benefits principally regarding water use and quality.

Additionally, as with any biomass-based technology, the algae-to-fuels concept needs to be analyzed from a resource perspective so that critical requirements, such as CO_2, nutrients, sunlight, and water, can be aligned with their availability. The availability of these resources is a significant driver for the development of algal biofuels. Many factors need to be considered when investigating the resources required for algae production. A preliminary survey of the resource requirements and availability for large-scale algal cultivation has been conducted, with special attention paid to climate, land, water, and CO_2 availability. The results in Fig. 5 show that adequate land, CO_2, water, and sunlight exist at several locations throughout the USA; but more work is needed to integrate all of the information to identify the areas with maximum potential for siting algae farms (Anelia Milbrandt, NREL, unpublished results).

Future research focus

All of the elements for the production of lipid-based fuels from algae have been demonstrated. Algae can be grown in large outdoor cultures and harvested. The algal lipids can be extracted and converted to biodiesel or other transportation fuels. The relevant question is not whether biofuels from algae are possible, but rather whether they can be made economically and at a scale sufficient to help contribute to US fuel demand. There are, however, a number of major technical challenges that will need to be overcome to achieve this goal. Significant attention and support should be given to both basic and applied research on algae for biofuels applications and the engineering of sustainable microalgal systems. Our technoeconomic analysis indicates that algal productivity is the primary production cost determinant and so efforts should be focused on various aspects of algal biology that can have the greatest impact on growth rate and lipid biosynthesis. However, this work cannot be done

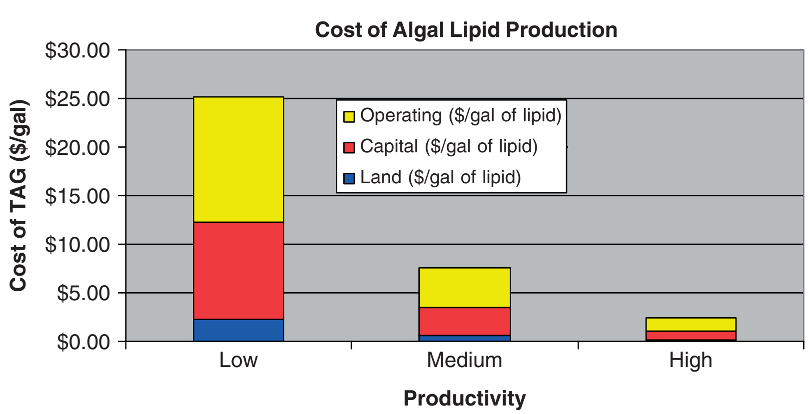

Figure 4. Cost contributions for algal lipid production.

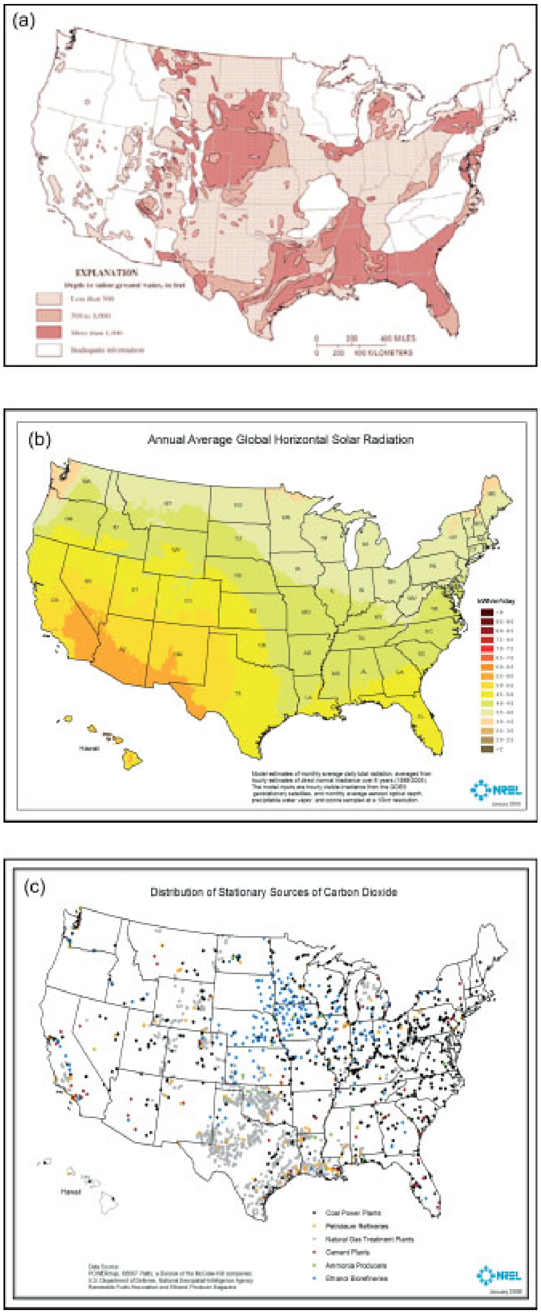

Figure 5. Resource availability for large-scale algal cultivation (a) Depth to saline groundwater[25]; (b) Annual average solar radiation; (c) Select large stationary sources of CO_2.

in isolation, and it would be a mistake to equate progress in productivity made at the bench scale with success in large-scale cultivation. Hence, attention must be paid to growth under conditions that model commercial production (including climate, and input sources), with data exchanged between biologists and process engineers. In anticipation of success of this revolutionary approach to a novel twenty-first-century concept of agriculture, and if using land that has never been developed for any purpose, it is essential to complete a detailed LCA and ecological impact analysis in advance of any large-scale deployment to ensure a smooth path to commercialization. An LCA should also include a very detailed assessment of the energy recoveries for algal biofuels production (i.e., net energy being recovered in the algal fuel compared to the energy input from fossil fuels in order to produce the renewable fuels). Based on recently published energy calculations, microalgal biofuels have the potential to be produced sustainably. Energy ratios, which range from 3.3 to 7.5, are dependent on a variety of parameters such as algal cell oil yields, areal biomass productivity, biogas yield resulting from an anaerobic digestor, harvesting and extraction processes, waste-water treatment, and fertilizer/nutrient recycling.[21]

Conclusions

Although lignocellulosic biomass is currently the frontrunner for biofuel production, oil-rich, CO_2-utilizing photosynthetic microalgae are technically viable and attractive alternatives. Even though ethanol derived from corn and cellulosic feedstocks addresses the world gasoline markets, there is a need for higher energy density biofuels from algal-derived feedstocks to displace our significant petroleum diesel and jet fuel usage. Research and technology development on the production of liquid transportation biofuels from photosynthetic microbes began in earnest in the 1980s and continues to this day, with interest and investment ramping up rapidly in the US and elsewhere in the world. Reaping the energy independence and security benefits of algal feedstocks will require critical innovation related to fundamental algal physiology and algal mass culture, together with process and overall system engineering to ensure that technical and economic feasibility are reached. Finally, it must be noted that the promise of algal biofuels comes with the vision of a novel form of large-scale agriculture likely to be deployed in areas that have not previously been developed for agricultural or industrial uses. It is therefore critical to consider the ecological impact of this work as well as regulatory issues, public acceptance and societal effects while this technology is in the early days of development.

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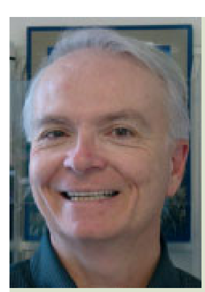

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