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# Technical and Economic Analysis of Liquid Fuel Production from Microalgae

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# TECHNICAL AND ECONOMIC ANALYSIS OF LIQUID FUEL PRODUCTION FROM MICROALGAE

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## ABSTRACT

Under the sponsorship of the U.S. Department of Energy (DOE), the Solar Energy Research Institute (SERI) has conducted a technical and economic evaluation of the production of fuels from a microalgal feedstock. This effort was divided into two areas: feedstock production and subsequent conversion of the feedstock into fuels. An Algal Production and Economic Model (APEM) was developed to estimate capital and operating costs for mass culture facilities. This model estimates that if today's technology were applied on a large scale (e.g., 20-ha modules in a facility of 1000 ha), a microalgal feedstock suitable for conversion to fuels could be produced at a cost of $436/t (1984 dollars). Sensitivity analysis demonstrates that the production cost could be reduced to $224/t by a series of improvements such as increased salinity tolerance, increased photosynthetic efficiency, increased lipid content, and decreased losses from water evaporation and $CO_2$ outgassing. Based on these microalgal production cost estimates, integrated refinery options for conversion of the microalgae to high-energy liquid fuels are evaluated. This portion of the analysis is based on preliminary data for processes that were developed for feedstocks similar but not identical to microalgae. Of the three major algal components (lipid, protein, and carbohydrate), the lipid component was determined to have the greatest potential as a source of fuels to replace conventional hydrocarbons. Two processes were examined—one based on the conversion of triglycerides into methyl fatty esters, which are being extensively investigated as potential diesel fuel substitutes, and a catalytic reduction process for the production of hydrocarbons, primarily in the gasoline range. The estimated costs of these fuel products compare favorably with the projected costs of conventional fuels at the turn of the century, as long as the presumed improvements in lipid yields are achieved.

# TECHNICAL AND ECONOMIC ANALYSIS OF LIQUID FUELS PRODUCTION FROM MICROALGAE

## INTRODUCTION

Microalgae offer significant opportunities as sources of renewable high-energy liquid fuels. Among the qualities that make microalgae a unique feedstock for energy production are high biomass productivities. The current limits of commercial technology are 25 g $m^{-2}$ $d^{-1}$ (60 t $ha^{-1}$ $yr^{-1}$) (Benemann et al. 1984), but yields up to 46 g $m^{-2}$ $d^{-1}$ (annualized to 110 t $ha^{-1}$ $yr^{-1}$) have been sustained over a one-month period (Laws 1984). Considering the infancy of this technology, the probability exists that still higher yields could be achieved. Microalgae also have the unique ability to accumulate large quantities of storage lipids. A lipid content over 60% of ash-free dry weight (AFDW) has been found in some species (Tornabene et al. 1984). Also, many microalgae strains survive and grow well in waters of moderate to high salinity, which usually have low or even negative economic value compared with fresh water. This paper presents the results of a technical and economic evaluation of two potentially promising fuel production options from microalgae. The evaluation is based on the results of an economic analysis of intensive mass culture production of a microalgal feedstock suitable for conversion to fuel products. Preliminary data on conversion processes are used to determine the comparative potential of the fuel options.

## FEEDSTOCK CHARACTERISTICS AND COSTS

### Chemical Composition of Microalgae

Microalgae are composed of proteins, carbohydrates, and lipids, with smaller amounts of ash and metabolic intermediates. The amounts and types of these components vary widely depending on species, environmental factors (e.g., temperature, illumination, nutrient levels), and method of culture (Tornabene et al. 1984; Tornabene 1984; Ben-Amotz 1984). Of the various algal components, lipids have by far the highest specific energy (energy per unit of mass): about 39 MJ/kg (17,000 Btu/lb), compared to 24 MJ/kg (10,500 Btu/lb) for protein, the next highest energy component. Lipids are chemically similar to hydrocarbons, especially aliphatics, which have long carbon chains but no rings. Lipids also resemble hydrocarbons in their low oxygen content, which is 15% or less, compared with 50% oxygen in carbohydrates. Because of their high energy content as well as their chemical resemblance to hydrocarbons, lipids from microalgae are an important potential source of substitutes for hydrocarbon fuels.

Algal lipids are recovered sequentially by extraction with the solvents hexane, benzene, chloroform, acetone, and methanol (Figure 1). The chloroform, methanol, and benzene fractions are the most relevant to this examination of fuel product alternatives, so they will be discussed first. The algal triglycerides and fatty acids identified to date (found in the chloroform fraction) are generally longer in average chain length and higher in degree of unsaturation than the oils of conventional agricultural crops such as corn and sunflower (Tornabene et al. 1984; Hill and Feinberg 1984). The tendency for polyunsaturated compounds to polymerize into waxy solids could create a problem with long-term storage of triglyceride-derived fuels. Further investigation of the triglyceride components will determine the degree to which polyunsaturation is a limitation on their suitability as fuel substitutes. Phospholipids (methanol fraction), although primarily present in the cell membrane, might also be of interest because of their fatty acid chains. Components of the benzene fraction have been less well characterized than the triglycerides, but it is known that olefins and aromatics

| Solvent | Major components of extract | Range of Typical content |
|---|---|---|
| Hexane | Paraffins | 10% |
| Benzene | Olefins<br>Aromatics<br>Isoprenoids | 10-50% |
| Chloroform | Mono-, di-, triglycerides<br>Fatty acids | 5-35% |
| Acetone | Glycolipids | 10-50% |
| Methanol | Phospholipids | 5-40% |



**Figure 1. Major Lipid Fractions as Recovered via Sequential Solvent Extraction**

are present, as well as isoprenoids (compounds which contain multiple units of isoprene: 2-methyl-1,3-butadiene). With regard to the remaining lipid fractions, the glycolipid fraction is generally associated with the membrane and is extremely variable in composition. Although the hexane fraction contains straight-chain hydrocarbons of 17-34 carbons, it is rarely present in quantities that are useful as a refinery feedstock. Although further characterization work will be required on all algal lipids, sufficient preliminary information is available to evaluate the feasibility of fuel production options. However, the production of a suitable microalgae feedstock must first be examined; then the cost of the algae feedstock, added to the fuel processing cost, will determine the final cost of the microalgae-derived fuel products.

## Economics of Microalgal Production

The design and operation of a mass algal culture facility depends on many resource-, biology-, and facility design-related parameters. Important resource-related parameters are the salt and water balance (e.g., evaporation rate), source water characteristics such as salinity and nutrient levels, and land characteristics such as soil permeability and surface contours. Biological parameters include the algal chemical composition, salinity tolerance of the cultured alga, and photosynthetic efficiency. Facility design-related parameters include nutrient addition rates, outgassing losses (from carbon dioxide and ammonia), culture pond geometry (length/width ratio), and type of harvesting equipment. A computer model has been developed at SERI that uses these and other parameters as input and calculates capital and operating costs for the resulting algal production facility (Hill 1984). This Algal Production and Economic Model (APEM) was used as a tool to evaluate sensitivities of algal production cost to the most critical parameters and to identify critical research issues.

The analysis of the economics of microalgae production begins with the establishment of a base or reference case. The reference case is a consistent set of input parameters that represent a consensus of SERI researchers and other experts on what values might be expected if mass culture technology were implemented today in the southwestern United States. Based on current knowledge of mass culture facilities, the reference case is a point of departure for further evaluation of cost improvements that could be achieved through continued research and technical progress. All cost figures are reported in 1984 dollars. Briefly, the mass culture facility is sized at 1000 hectares (ha) (2500 acres), about 85% of which is occupied by the culture ponds; the remainder is required for support facilities such as harvesting systems, buildings, laboratories, access roads, and piping. There are forty-three 20-ha single modules, or ponds. Each module is a meandering channel 300 m long by 30 m wide, with a culture depth of 0.2 m. Mixing is accomplished by paddlewheels located at the end of each channel. The reference-case harvesting system consists of two stages: a microstrainer followed by a centrifuge, which together increase the product solids concentration from its initial value of 0.05% (500 mg/L) to 10%.

Carbon, the major nutrient, is supplied in the form of gaseous carbon dioxide, which is obtained from power plant flue gas. The $CO_2$ is scrubbed, compressed, and transported by pipeline to the algal culture facility. The model determines the quantity of carbon dioxide required to support the specified productivity level and then, based on transport distance, calculates the delivered $CO_2$ cost. In the reference case, with a transport distance of 80 km, the calculated $CO_2$ cost is $\$0.14/m^3$ ($\$4.00/10^3$ SCF). The biomass productivity is calculated from the depth, culture density, and detention time (total culture volume divided by flow rate). With a culture density of 500 mg/L and a detention time of 4 days, the reference system has a productivity of 25 g $m^{-2}$ $d^{-1}$. The reference-case photosynthetic efficiency (based on the photosynthetically active radiation [PAR]) is 7%. The algal composition is 30% lipid, 20% carbohydrate, 32% protein, 10% metabolic intermediate, and 8% ash; the resulting gross energy content, calculated from the specific energies of each component, is 24.9 GJ/t (10,730 Btu/lb). The cost of the source water is $\$0.067/m^3$. The reference parameters used in the APEM are listed in Table 1.

The total production cost was estimated to be \$436/t of algae. The breakdown of the total cost into capital costs (both depreciable and nondepreciable) and operating costs is shown in Table 2. Two important points are identified from the table. First, capital costs represent only 16.4% of the total product cost; reducing the capital cost is therefore less critical than reducing the operating costs. The depreciable portion of capital investment, the culture system and the harvester system, accounts for 75% of the total capital cost. Second, nutrients account for over half of the operating costs; they are the only raw materials supplied to the system besides saline water and free solar energy. In fact, of the total nutrient costs, carbon dioxide represents 80.5%, or 38.2% of the total product cost, which makes clear the need to maintain stable $CO_2$ costs.

Based on detailed sensitivity analysis of the various input parameters which the APEM uses to determine the total algal production cost, the two parameters with the most potential for cost reduction were found to be microalgal productivity and chemical composition. The combined effects of these two variables were analyzed by varying photosynthetic efficiency and lipid content. Photosynthetic efficiency was increased from the reference value of 7% to 12% to 18%. The 12% value represents what has been achieved in short-term studies (Laws 1984), while 18% represents a value toward which research could be targeted. Theoretically, the maximum achievable photosynthetic efficiency, based on PAR, is in the range of 23%-29%, depending on the photosynthetic products produced (Bassham 1980). Based on the biochemical composition of Platymonas sp. (Laws

**Table 1. Reference Parameter Values for Microalgae Systems** (1984 $)

| RESOURCE PARAMETERS | | FACILITY DESIGN PARAMETERS | |
|---|---|---|---|
| Evaporation | 0.0035 m/d | Effective culture area | 86% of total size |
| Salinity of source water | 8 g TDS/L | Effective culture downtime | 10% of total size |
| Nitrogen in source water | 13 $g/m^3$ | Module size | 20 ha |
| Phosphorus in source water | 0.5 $g/m^3$ | Channel width | 30 m |
| Potassium in source water | 46 $g/m^3$ | Depth of culture | 0.2 m |
| Carbon in source water | 100 $g/m^3$ | Carbon in medium | 12 $g/m^3$ |
| Land cost | $1245/ha | Nitrogen in medium | 1.4 $g/m^3$ |
| Energy cost | $0.05/kWh | Phosphorus in medium | 3.1 $g/m^3$ |
| Water cost | $0.067/$m^3$ | Potassium in medium | 5 $g/m^3$ |
| Ammonia cost | $203/t | Carbon losses | 0.5 $g\ m^{-2}\ d^{-1}$ |
| Superphosphate cost | $281.6/t | Nitrogen losses | 0.5 $g\ m^{-2}\ d^{-1}$ |
| Potassium muriate cost | $102/t | Mixing velocity | 0.2 m/s |
| Distance to $CO_2$ source | 80 km | Mixing system efficiency | 65% |
| $CO_2$ cost | $0.14/$m^3$ | Harvester solids removal | 90% |

| BIOLOGY PARAMETERS | |
|---|---|
| Salinity tolerance | 35 g TDS/L |
| Phosphorus cell content | 0.007 g/g dry wt |
| Growing season | 320 days |
| Photosynthetic efficiency on PAR | 7% |

1984) and Phaeodactylum tricornutum (Terry et al. 1984), lipid content was varied between 20% and 60% of total biomass. Protein and carbohydrate contents were adjusted accordingly, with the protein content being fixed at an estimated minimum level (13%) required to support normal cell function. Proximate compositions for the various cases (low-lipid, reference, and high-lipid) are shown in Table 3, along with the calculated gross energy content for each case.

Based on the APEM output for each combination of photosynthetic efficiency and lipid content, Table 4 presents biomass productivity (the total dry weight of microalgae produced at the culture facility) and the algal production cost (expressed both in $/t and $/GJ) for these cases. Remember that the reference case has a total production cost of $436/t; dividing this cost by the gross energy content of 24.9 GJ/t gives a production cost of $17.51/GJ ($18.50/$10^6$ Btu) of algal energy produced. The biomass productivity for the reference case is 62,000 t/yr. Table 4 shows that production costs can be reduced and productivity increased by increasing photosynthetic efficiency at constant lipid content. Productivity can also be increased by decreasing lipid content at constant photosynthetic efficiency. Since constant photosynthetic efficiency implies constant net energy production, higher lipid content is associated with lower biomass productivity (because of higher gross energy content) and vice versa. However, increasing lipid content also serves to decrease the energy-based production costs per unit; the high-lipid cases have at least 13% lower production costs (in $/GJ) than the other two cases. The case with 18% photosynthetic efficiency and 60% lipid has neither the highest productivity nor the lowest production cost per ton but does have the lowest cost per GJ ($8.74/GJ or $9.20/$10^6$ Btu) and therefore is the most promising case from the fuel production standpoint.

**Table 2. Summary of Algal Production Facility Capital Cost and Operating Costs for Reference and Attainability Cases (1984 $)**

| Cost Category | Reference Case | | Attainability Case | |
|---|---|---|---|---|
| | $/t | Percentage of Category | $/t | Percentage of Category |
| Capital Costs | | | | |
| Culture system | 36.0 | 50.3 | 16.9 | 51.3 |
| Harvester systems | 18.3 | 25.6 | 8.1 | 24.7 |
| Engineering fees | 5.9 | 8.3 | 2.7 | 8.2 |
| Contingency fees | 9.1 | 12.7 | 4.1 | 12.6 |
| Land costs | 2.1 | 2.9 | 1.0 | 3.1 |
| Total capital cost | 71.5 | 100.0 | 32.8 | 100.0 |
| Operating Costs | | | | |
| Labor and overhead | 56.1 | 15.4 | 26.2 | 13.7 |
| Utility costs | 18.6 | 5.1 | 5.2 | 2.7 |
| Nutrient costs | 206.8 | 56.8 | 120.7 | 63.2 |
| Water costs | 17.8 | 4.9 | 9.4 | 4.9 |
| Operating costs | 26.9 | 7.4 | 12.4 | 6.5 |
| Maintenance costs | 37.9 | 10.4 | 17.4 | 9.1 |
| Total operating cost | 364.1 | 100.0 | 191.3 | 100.0 |
| Total feedstock cost | 436.0 | | 224.0 | |

**Table 3. Microalgal Proximate Chemistry and Resulting Energy Content**

| Case | Lipid (%) | Carbohydrate (%) | Protein (%) | Gross Energy Content[a] (GJ/t algae) |
|---|---|---|---|---|
| Low-Lipid | 20 | 49 | 13 | 21.6 |
| Reference | 30 | 20 | 32 | 24.9 |
| High-Lipid | 60 | 9 | 13 | 30.1 |

[a]Ash (8%) and intermediates (10%) are constant for all cases.

SI conversion: 1.0 GJ/t = 430.9 Btu/lb.

The APEM-derived estimates of algal production cost presented to this point were based on variations of photosynthetic efficiency and lipid content, with all the other parameters held constant. Several of these other parameters could also be improved through continued research and development. Carbon dioxide cost could be reduced to $\$0.08/m^3$ ($\$2.30/10^3$ SCF) by locating the algal facility closer to a coal-fired electric power plant. This would also reduce the cost of electric power from $0.05 to $0.03/kWh. Other nutrient costs could be reduced by as much as 10% to reflect contract prices available to a large user. Other parameters for which improved values were chosen include higher source water salinity, wider salinity tolerances, and decreased outgassing losses. The algal production cost for this integrated attainability case (using the improved values) decreased from $263 to $224/t (from $7.80 to $7.43/GJ) (Table 2). This was not the lowest estimated cost at which a microalgae feedstock for energy production could be

**Table 4. Effect of Photosynthetic Efficiency and Lipid Content on Algal Production Cost (1984 $)**

| Photosynthetic Efficiency (PAR %) | Lipid Content (%) | Biomass Productivity ($10^3$ t/yr) | Production Cost | |
|---|---|---|---|---|
| | | | $/t | $/GJ |
| 7 | 20 | 72 | 381 | 17.63 |
| | 30 | 62 | 436 | 17.51 |
| | 60 | 52 | 466 | 15.48 |
| 12 | 20 | 119 | 278 | 12.87 |
| | 30 | 105 | 316 | 12.69 |
| | 60 | 87 | 337 | 11.20 |
| 18 | 20 | 181 | 220 | 10.19 |
| | 30 | 157 | 253 | 10.16 |
| | 60 | 130 | 263 | 8.74 |

SI conversion: $1.00/GJ = $1.055/$10^6$ Btu.

produced. A lower estimate was developed based on locations where excess $CO_2$ is available (both from flue gas and natural sources), but such locations would be the exception and would be available for limited applications. The $224/t cost represents a production associated with an extensive technology.

## MICROALGAL REFINERY SCENARIOS

### Methodology

The concept of a microalgal refinery as developed here is similar to the typical petroleum refinery. A crude microalgae feedstock is received from a culture facility, its composition is determined by analysis, and it is then characterized as suitable for producing a specific slate of products. Various processing options may be considered, and the final choice is a function of the feedstock, the seasonal changes in fuel demand, the availability of essential equipment, and, ultimately, economics. In this section, two different production schemes are developed, and both center around production of hydrocarbon substitute fuels produced from microalgae that are high in lipids. The characteristics of the proposed products, and those required of the feedstock, are examined in some detail, thereby establishing the basis for further analysis.

A simple model was developed that prepares preliminary capital and operating cost estimates for each set of conditions. The fuel production options discussed below were first matched with all combinations of lipid content and photosynthetic efficiency (holding all other parameters constant). The capital and operating costs for fuel production, plus the algal production cost, produce a final fuel product cost (in real 1984 dollars per unit of product). The microalgal refinery is assumed to be located near the microalgal culture facility. In addition to the case in which the refinery is sized to match the capacity of the culture facility, a case is examined in which the refinery is sized to serve ten culture facilities, thereby realizing significant improvements in conversion costs and thus in the final selling price of the product.

### Transesterification

Conversion of triglycerides to methyl or ethyl fatty esters (the transesterification process) is employed commercially in the production of fatty alcohols

(Technical Insights 1980). The process has recently been the subject of extensive investigation in the context of fuel production (Freedman and Pryde 1982; Kusy 1982; Clark et al. 1984). The product of the transesterification reaction, referred to here as ester fuel, is being considered as a substitute for petroleum-derived diesel fuel. Oxygenated diesel fuel substitutes such as vegetable oils and ester fuels are not yet complete replacements for diesel fuel, but interest is especially high in the agricultural sector. The diesel engines in use today have been optimized for the properties of hydrocarbon-based fuels. Ester fuel is not a perfect substitute, but it outperforms the vegetable oils under essentially all conditions.

The viscosity of any diesel fuel is critical to its efficient combustion; the viscosity of most vegetable oils is higher than ester fuel and No. 2 diesel, which is the most common grade of diesel for auto, truck, and farm use, by an order of magnitude. Ester fuels perform almost as well as No. 2-D in indirect-injection (IDI) diesels, but not as well in direct-injection (DI) engines (Ryan et al. 1984). Ester fuels also typically have higher cetane numbers than No. 2-D, although the applicability of the cetane rating for oxygenated fuels is subject to some question at this time (Pryde 1984).

The two main drawbacks of ester fuel are its tendency toward injector fouling (especially in DI engines) and its relatively high pour point (about $0^{\circ}C$), making it less suitable for use at ambient temperatures below $5^{\circ}C$. Solutions to both of these problems, either through the development of additives or some modification to the fuels themselves, are technically feasible as research and development continue. Fuel value of ester fuel can be as much as 10% lower than diesel on a volumetric basis, leading to slightly higher fuel consumption; ester fuel would presumably have to be sold at a discount relative to diesel to make up for the lower energy content.

Figure 2 shows how the transesterification process might be applied to microalgae. The extraction of the lipid feed would presumably be accomplished in a single step using a suitable solvent or solvent system (e.g., chloroform-methanol). A dewatering step may be required before extraction; however, since the necessity for dewatering has not been established, these costs have not been included. The esterification reaction is accomplished by adding excess alcohol

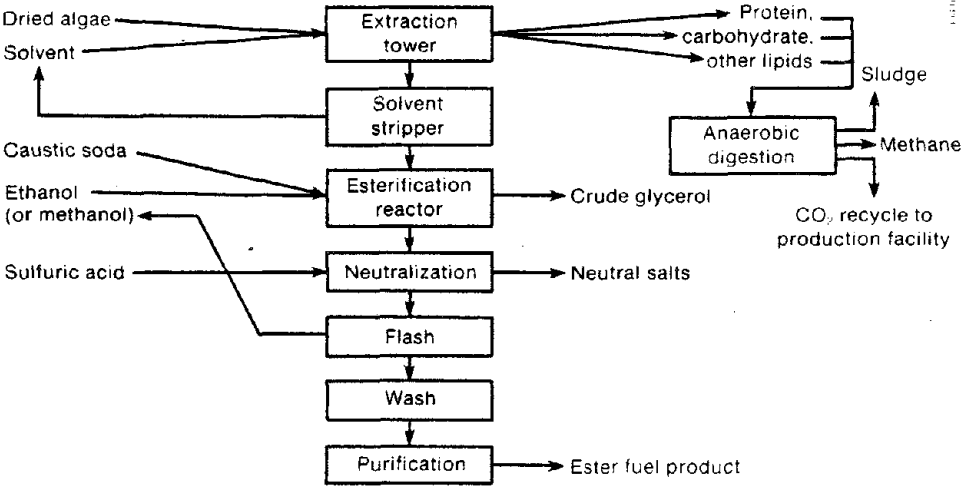



**Figure 2. Schematic of Transesterification Process**

(generally double the stoichiometric minimum) plus an alkaline catalyst. One mole of glycerol is produced for each 3 moles of esters; the glycerol can be recovered and then purified in a separate unit for substantially less than its current market value of over 70¢/lb ($1540/t). Besides glycerol and the refined ester fuel, other by-products are produced. In the microalgal refinery concept we hope to maximize the energy production, so all the organic material not extracted for ester fuel production is anaerobically digested to produce biogas (a methane-carbon dioxide mixture) and a disposable sludge. Sulfur and carbon dioxide are removed from the biogas. The resulting methane is a pipeline-quality fuel gas (requiring compression if it is to be transported over long distances), and the carbon dioxide is suitable for recycling to the culture facility. Credits are also taken for the water and soluble nitrogen (as ammonia), which are recycled to the algal production facility.

One of the most critical parameters in the evaluation of the transesterification process is the utilization efficiency of the algal lipids. As microalgae allocate larger percentages of their cell mass to lipids, larger percentages in turn become storage lipids—those not associated with membranes. At 20% lipid content, only 30% of the total lipids might be suitable for transesterification (i.e., triglyceride and possibly phospholipid). At 30% lipids, this proportion will be about 40%, and at 60% lipids about 50% will be available for processing. A modified allocation of carbon might increase the lipid fraction available for transesterification to as high as 75%. Conversion from triglyceride to ester fuel is assumed constant at 98%, which is routinely achieved industrially (Technical Insights 1980). A brief summary of the relationships between photosynthetic efficiency, lipid content, lipid availability, and ester fuel production is shown in Table 5. Increasing the lipid content (and thus the lipid availability) from the reference value of 30% to 60% doubles the ester fuel production and halves the cost. Increasing the photosynthetic efficiency from 7% to 12% would again decrease the production cost by half, to just under $3.00/gal.

The analysis of ways to reduce ester fuel cost is accomplished by setting up an attainability case for the refinery and integrating it with that of the culture facility. Three different fuel cost reduction strategies could be employed to reduce the algal production cost of $224/t. First, using the lipid availability estimate of 75%, the production cost can be reduced to $1.94/gal based on annual production of 16.4 million gal (up from 10.9 million). Second, the ester fuel cost can be calculated for a refinery processing the feedstock from ten 1000-ha culture facilities. Ester fuel cost from this 109 million gal/yr plant (using the feedstock at $224/t) would be $2.47/gal. Third, incorporating both scale and efficiency

**Table 5. Transesterification: Effects of Photosynthetic Efficiency, Lipid Content, and Lipid Availability on Ester Fuel Cost** (1984 $)

| | Photosynthetic Efficiency (PAR %) | Lipid Content (%) | Lipid Available (%) | Ester Fuel Production ($10^6$ gal/yr) | Ester Fuel Cost ($/gal) |
|---|---|---|---|---|---|
| Reference case | 7 | 30 | 40 | 2.1 | 11.90 |
| Other cases | 7 | 60 | 50 | 4.3 | 5.67 |
| | 12 | 60 | 50 | 7.3 | 3.97 |
| | 18 | 60 | 50 | 10.9 | 2.96 |
| Attainability case[a] | 18 | 60 | 75 | 163 | 1.63 |

[a]Processes microalgae feedstock from ten 1000-ha culture facilities; others each process feedstock from one 1000-ha culture facility.

improvements into a facility (producing 163 million gal/yr) reduces ester fuel cost to $1.63/gal.

The capital and operating costs for the reference and attainability cases are shown in Table 6. Capital costs are listed separately for each of the three major process units (ester fuel, glycerol, and methane), while the operating costs are the combined totals for all three. The effect of increased plant scale is apparent from this table; although the ester fuel production is 80 times higher in the attainability case, capital investment and operating expenses have only increased by a factor of 12.

One important caveat in this evaluation of algae-derived ester fuel is the sustainability of the market for by-product glycerol. In the reference case, the glycerol production is 760 t/yr, but in the attainability case it increases to 60,000 t/yr, which is 40%-50% of the current domestic market (International Trade Commission 1982). Clearly, a new 60,000-t glycerol facility would have a dramatic impact on the market price. Natural glycerol (derived from animal and vegetable triglycerides as a by-product of soapmaking), like algae-derived glycerol, is produced for much less than its current $1540/t market value and would be able to withstand price decreases. However, synthetic glycerol (made from petroleum-derived propylene), has a production cost much closer to the

**Table 6. Summary of Reference and Attainability Capital and Operating Costs for Ester Fuel Production** (1984 $)

| | Case | | | |
|---|---|---|---|---|
| | Reference | | Attainability | |
| Capital Costs ($10^6$) | | | | |
| Main process unit | 10.4 | | 142.4 | |
| Glycerol by-product unit | 1.8 | | 23.1 | |
| Methane by-product unit | 5.2 | | 38.7 | |
| Total | 17.2 | | 204.2 | |
| | $10^6$/yr | $/gal | $10^6$/yr | $/gal |
| Operating Costs | | | | |
| Raw materials[a] | 27.4 | 13.05 | 319.6 | 1.95 |
| Utilities | 0.4 | 0.19 | 12.0 | 0.07 |
| Labor, maintenance, taxes | 1.7 | 0.81 | 46.9 | 0.29 |
| Depreciation | 1.7 | 0.81 | 20.4 | 0.13 |
| Return on investment | 0.6 | 0.29 | 5.8 | 0.04 |
| Total (gross) | 31.8 | 15.14 | 404.7 | 2.48 |
| Credits from By-Product Sales | | | | |
| Methane | (4.2) | (2.00) | (35.5) | (0.22) |
| Glycerol | (1.1) | (0.52) | (92.4) | (0.57) |
| Other | (1.3) | (0.62) | (10.3) | (0.06) |
| Subtotal (credits) | (6.8) | (3.24) | (138.2) | (0.85) |
| Main Product Cost | 25.0 | 11.90 | 266.5 | 1.63 |

[a]Includes algae feedstock at cost shown in Table 2.

market value, most likely ranging from $1000 to $1200/t. Synthetic glycerol facilities would be caught in a cost-price squeeze. It is possible that the very first 60,000 t glycerol-from-microalgae facility would be able to claim a credit of $1540/t by displacing the most expensive synthetic production, but it is doubtful that subsequent facilities could sustain a credit that large. The result is a negative effect on the economics of ester fuel from microalgae: each 10¢/lb ($220/t) decrease in the glycerol credit will further increase the ester fuel cost by $0.08/gal. A credit of only $380/t ($0.40/lb) thus increases the ester fuel cost $0.24 to $1.87/gal. Smaller facilities that produce 4000 t/yr or less should not suffer any adverse affects, at least for the first 10-20 facilities.

## Catalytic Conversion

The next process to be examined is based on a zeolite-catalyzed methanol-to-gasoline process developed by Mobil Research and Development Corporation (Voltz and Wise 1976). Mobil also investigated some oxygenated feedstocks larger than methanol, notably corn oil (Weisz et al. 1979). As Figure 3 shows, almost 60% of the product from corn oil is in the gasoline range, and the majority of that amount is aromatics of 6 to 8 carbons (i.e., benzene, toluene, and xylene, the major aromatic octane enhancers). Another 28% consists of 3- and 4-carbon compounds, primarily paraffins, which yield a product similar to liquefied petroleum gas (LPG). The light-end product would be suitable as a fuel gas, either for blending with the digester-produced methane or by itself. The heavy-end product, with 11+ carbons, could be suitable for use as a diesel fuel. The process itself is basically a catalytic reduction; most or all of the initial oxygen present is removed, resulting in the production of hydrocarbons, which, unlike ester fuel, are direct substitutes for petroleum-derived products. Figure 4 is a flow diagram based on Mobil's process. As in the ester fuel case, lipid extraction precedes the main process and anaerobic digestion follows it. The possible efficiencies for dewatering and lipid extraction depend on the requirements of the process and more detailed characterization of the products.

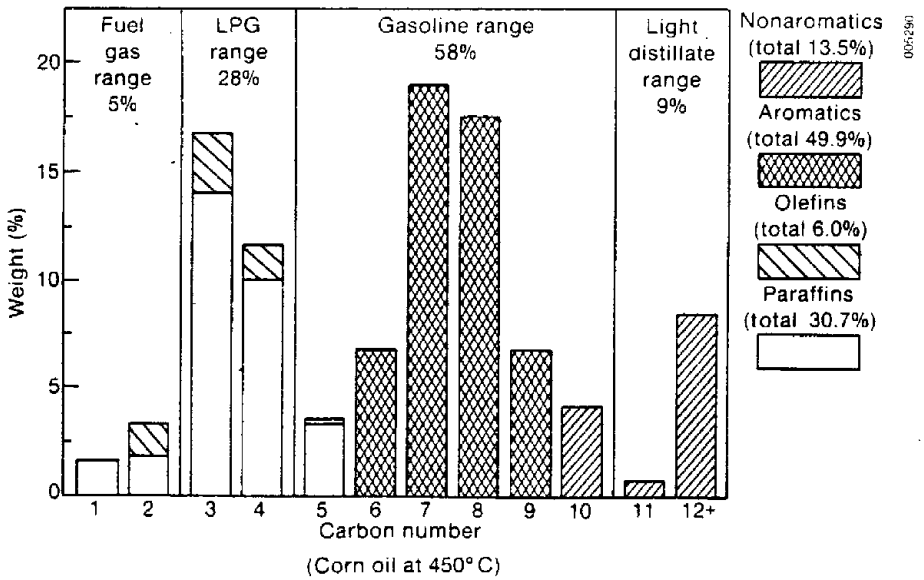



**Figure 3. Product Distribution from Catalytic Conversion of Triglycerides** (Source: Weisz et al. 1979)

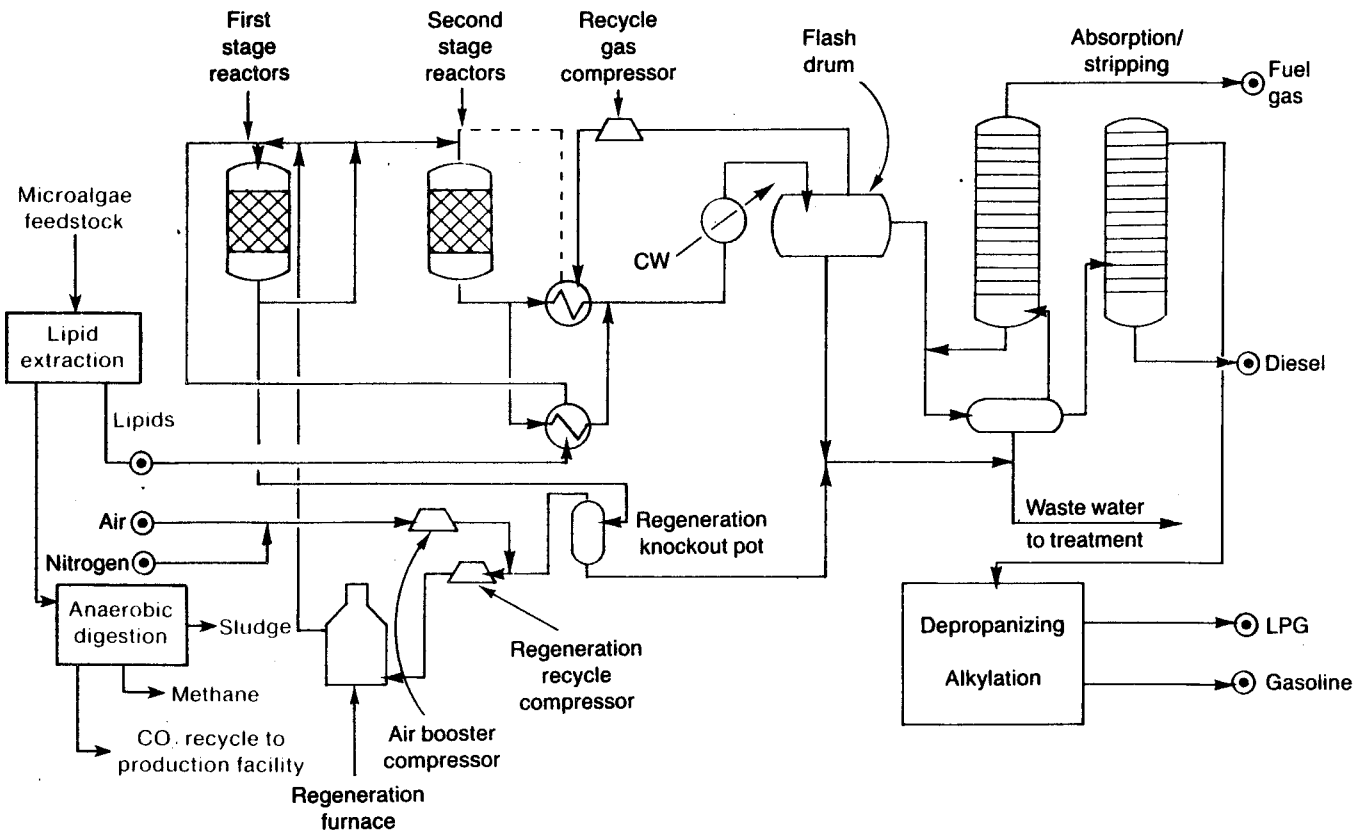



**Figure 4. Mobil M-gas Process Adapted for Microalgal Lipids**
(Source: Voltz and Wise 1976)

The effects of photosynthetic efficiency, lipid content, and lipid availability on the cost of catalytically produced gasoline are briefly summarized in Table 7. Again, these cases need to be matched with the appropriate algal production cases from Table 4, plus the integrated attainability case. The analysis assumes slightly higher lipid availability fractions compared to transesterification—50% available at 20% lipid content, 60% available at 30% lipids, 80% available at 60% lipids, and 90% of total lipids available in the attainability case. These higher availabilities are consistent with those assumed for the transesterification studies. Besides triglycerides, free fatty acids and phospholipids, hydrocarbons (aliphatics and aromatics), and isoprenoids could all potentially be converted in this process. The assumed conversion efficiency is 90% on an energy basis, which is conservative since Mobil achieved 90%-95% conversions (in the original methanol process).

The economic effects of increasing photosynthetic efficiency, lipid content, and lipid availability are favorable, just as they were in the other process scheme examined. At constant 7% photosynthetic efficiency, doubling the lipid content to 60% (with an associated increase in lipid availability) decreases the gasoline cost by over half; further increases are then achieved by increasing photosynthetic efficiency. In the case of 18% photosynthetic efficiency and 60% lipids, either the efficiency attainability (increasing the lipid availability from 80% to 90%) or the scale attainability (sizing the catalytic conversion unit for ten culture facilities rather than one) has the effect of reducing the gasoline cost to about $1.90/gal. This is a different effect than was seen for the ester fuel, where efficiency improvement decreased the cost much more than the scale improvement. Combining the efficiency improvement with the scale improvement, the gasoline cost can be reducted to $1.72/gal.

Summaries of capital and operating costs for both the reference and attainability cases are presented in Table 8. Capital costs in particular are estimated to be substantially lower than those of the transesterification process, primarily because the latter requires interstage solvent recovery and neutralization steps. With regard to the capital cost estimates presented here, two points need to be noted. First, these estimates are based on preliminary data. Second, fluctuations in capital costs will have relatively minor effects on the operating costs, since depreciable capital contributes less than 10% to the total product cost of either process. Another positive factor in this process is that all the major by-products are fuels: fuel gas (including methane), LPG, and diesel fuel. No major nonfuel (i.e., demand-limited) by-products are required for commercial feasibility.

**Table 7. Catalytic Conversion: Effects of Photosynthetic Efficiency, Lipid Content, and Lipid Availability on Gasoline Cost** (1984 $)

| | Photosynthetic Efficiency (PAR %) | Lipid Content (%) | Lipid Available (%) | Gasoline Production ($10^6$ gal/yr) | Ester Fuel Cost ($/gal) |
|---|---|---|---|---|---|
| Reference case | 7 | 30 | 60 | 1.9 | 12.63 |
| Other cases | 7 | 60 | 80 | 4.2 | 5.31 |
| | 12 | 60 | 80 | 7.1 | 3.62 |
| | 18 | 60 | 80 | 10.6 | 2.62 |
| Attainability case[a] | 18 | 60 | 90 | 120 | 1.72 |

[a]Processes microalgae feedstock from ten 1000-ha culture facilities; others each process feedstock from one 1000-ha culture facility.

**Table 8. Summary of Reference Attainability Capital and Operating Costs for Gasoline Production (Catalytic Conversion)** (1984 $)

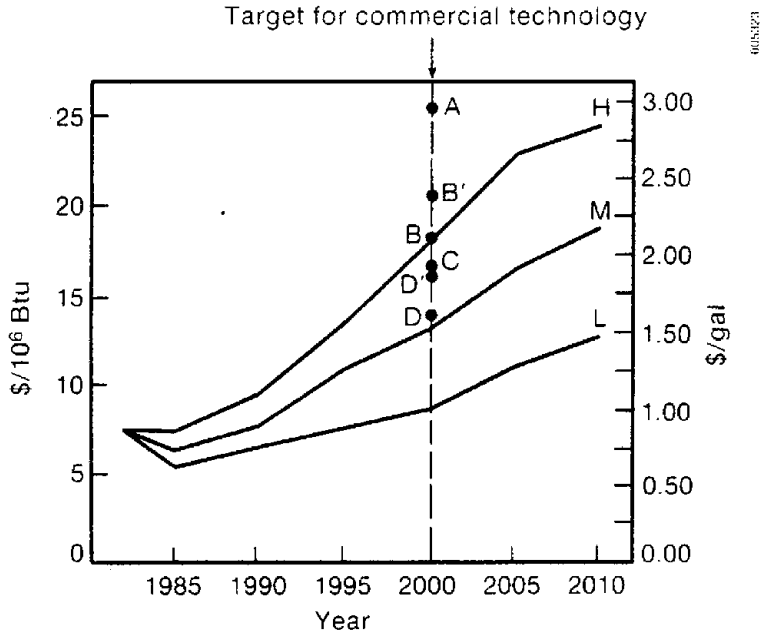
| | Case | | | |
|---|---|---|---|---|
| | Reference | | Attainability | |
| Capital Costs ($10^6$) | | | | |
| Main process unit | 6.3 | | 75.9 | |
| Methane by-product unit | 4.8 | | 32.1 | |
| Total | 17.2 | | 204.2 | |
| | $10^6/yr | $/gal | $10^6/yr | $/gal |
| Operating Costs | | | | |
| Raw materials[a] | 27.4 | 14.20 | 291.3 | 2.43 |
| Utilities | 0.4 | 0.21 | 11.8 | 0.10 |
| Labor, maintenance, taxes | 1.0 | 0.53 | 10.3 | 0.09 |
| Depreciation | 1.1 | 0.58 | 10.7 | 0.09 |
| Return on investment | 0.5 | 0.26 | 3.7 | 0.03 |
| Total (gross) | 30.1 | 15.84 | 327.9 | 2.74 |
| Credits from Product Sales | | | | |
| Methane | (3.6) | (1.89) | (31.1) | (0.26) |
| LPG | (0.8) | (0.42) | (50.5) | (0.42) |
| Diesel | (0.5) | (0.26) | (34.4) | (0.29) |
| Other | (1.2) | (0.63) | (6.6) | (0.06) |
| Subtotal (credits) | (6.1) | (3.21) | (122.6) | (1.02) |
| Main Product Cost | 24.0 | 12.63 | 205.3 | 1.72 |

[a]Includes algae feedstock at cost shown in Table 2.

## SUMMARY OF ATTAINABLE FUEL PRODUCT COSTS

A comparison of the cost of production of ester fuels (Figure 5) and catalytically produced gasoline (Figure 6) with the predicted prices for the products based on NEPP forecasts indicates commercial feasibility by the year 2000. Most optimistic estimates indicate that at least fifteen years are required to develop a technology with the required improvements for production at these lower costs. The cost of diesel fuel (Figure 5) is estimated to be $13.27/$10^6$ Btu ($12.58/GJ). For ester fuel, which has 10% lower heat of combustion than diesel, this cost becomes $1.55/gal. Based on the optimistic (low world oil price) and pessimistic (high world oil price) scenarios, diesel fuel price ranges from $8.84 to $18.02/$10^6$ Btu ($8.38 to $17.08/GJ), for an ester fuel cost of $1.03-$2.10/gal. These values are the low-range and high-range forecasts, respectively.

All points on Figure 5 represent the high lipid content of 60%. Point A shows the 50% lipid availability for the 1000-ha facility size, which has an ester fuel cost of $2.96/gal (Table 5). Point B shows the effect if the ester fuel production facility were sized to match the output of ten 1000-ha algal culture ponds. In this case, the cost could drop to $2.11/gal if the glycerol credit remained at $1540/t, which just reaches the NEPP high-range forecast for the year 2000. Such facilities, however, would produce up to 40,000 t/yr of glycerol,



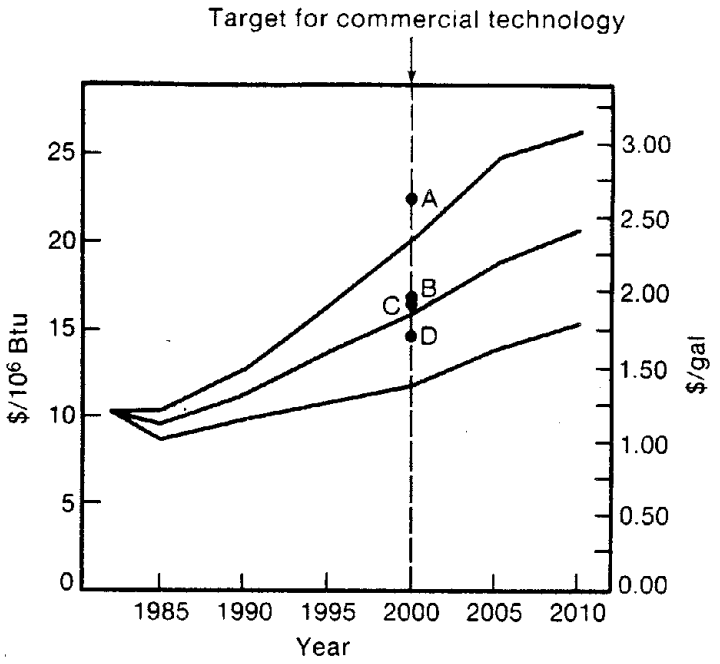

Projected fuel costs
H — High-range projection
M — Mid-range projection
L — Low-range projection

Microalgae-based fuel costs
A — 1000 ha, 50% lipid availability
B — 10 × 1000 ha, 50% lipid availability
C — 1000 ha, 75% lipid availability
D — 10 × 1000 ha, 75% lipid availability
B' and D' are the same as B and D but with $770/t glycerol credit.

**Figure 5. Comparison of Attainable Ester Fuel Costs with Projected Price of Diesel Fuel** (Source: Department of Energy 1983)

more than the current market structure could absorb. With a more likely glycerol credit of $770/t (half the current value), ester fuel cost would be $2.40/gal (Point B'). Point C shows the case in which the lipid availability increases to 75% without scale-up; the glycerol credit remains at $1540/t, so the ester fuel cost drops to $1.94/gal, between the mid-range and high-range forecasts. Point D shows the case that incorporates both increased availability and plant scale, with the ester fuel cost of $1.63/gal. This cost almost reaches the mid-range cost projection. If the full glycerol credit is again taken away and is replaced with the $770/t credit, ester fuel cost increases to $1.91/gal (Point D').

Another way to analyze the glycerol situation of Figure 5 is to say that some additional period of time will be required for the development of additional glycerol markets, and that the full glycerol credit of $1540/t (or at least a value between $770 and $1540/t) would then be sustainable over larger annual production. If the $1540/t credit of Point D were to be available in 2005, for example, the $1.63/gal ester fuel cost would then actually fall below the mid-range projection (since the costs are all in real 1984 dollars with no inflation assumed).




Projected fuel costs
H — High-range projection
M — Mid-range projection
L — Low-range projection

Microalgae-based fuel costs
A — 1000 ha, 80% lipid availability
B — 10 × 1000 ha, 80% lipid availability
C — 1000 ha, 90% lipid availability
D — 10 × 1000 ha, 90% lipid availability

**Figure 6. Comparison of Attainable Catalytically Produced Gasoline Costs with Projected Price of Gasoline** (Source: Department of Energy 1983)

Figure 6 shows an even more encouraging situation for gasoline. Point A represents the high-lipid case with 80% lipid availability, which has a gasoline price of $2.62/gal, somewhat higher than the high-range projection of $2.37/gal. Point B (scale-up to ten culture facilities at 80% lipid availability) and Point C (90% lipid availability with the smaller scale) are just above the mid-range projection at $1.93 and $1.91/gal, respectively. The year 2000 mid-range projection, based on a typical lower heating value for gasoline of 116,500 Btu/gal is $1.84/gal. Finally, Point D', which includes 90% lipid availability plus scale-up, is between the low and middle range at $1.72/gal. Unlike Figure 5, there are no qualifying statements concerning market limitations of important by-products. All by-products from the catalytic conversion process are fuels and can be valued at their NEPP mid-range projected values ($13.27/$10^6$ Btu for diesel, $7.40/$10^6$ Btu for methane, and $9.25/$10^6$ Btu for LPG). Thus there are several scenarios in which the catalytic conversion process could be successful in producing competitive liquid fuels from microalgae by the turn of the century.

## CONCLUSIONS

Microalgae are unique feedstocks that could be a competitive source of renewable liquid fuels by the early 21st century. Their two most important attributes to be exploited are their potentially high biomass productivities and higher lipid yields.

Even at this preliminary stage of evaluation, two processes have been identified that offer potential for commercial development. The major fuel products produced by these processes are catalytically produced gasoline and ester fuel, an oxygenated diesel fuel substitute. Maximum production of liquid fuels in the former process is estimated at $2.5 \times 10^{12}$ J $ha^{-1}$ $yr^{-1}$ (60% of which is gasoline), while maximum ester fuel production is estimated at $2.0\ 10^{12}$ J $ha^{-1}$ $yr^{-1}$. Economic success of the transesterification process depends to a significant degree on the utilization of by-product glycerol, which could be produced in sufficiently large quantities to affect its market structure. There are no such problems with the gasoline process, since all by-products are either fuels themselves (with no assumed upper market limit) or are returned directly to the algal culture facility.

Neither microalgal mass culture technology nor the processes for conversion of microalgae to high energy liquid fuels are in a mature stage of development. Both require substantial continued research efforts before commercialization can occur.

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