AgBioForum, 13(2): 119-130. ©2010 AgBioForum.

The Economics of Microalgae Oil

James W. Richardson, Joe L. Outlaw, and Marc Allison
Texas A&M University

A Monte Carlo simulation model for a commercial-scale microalgae farm in the US desert Southwest was developed and used to compare costs of producing algal oil with two levels of technology. Ranges of input and output coefficients in the microalgae literature were used to simulate a farm using conventional wisdom regarding production and extraction. An alternative scenario was simulated using experimental data for an actual microalgae farm in the Southwest. The total costs of algal oil ranged from $0.85 to $3.67/pound, with an average of $1.61 (with by-product credits) for the conventional wisdom input/output coefficients. The costs using the test farm's coefficients ranged from $0.15 to $0.45/pound, with a mean of $0.25 (with by-product credits). Improvements in algae strains, feeding, CO_2 efficiency, and harvesting are responsible for the improved cost efficiency on the test farm.

Key words: cost algal oil, economic viability, microalgae oil, simulation.

Introduction

Unintended consequences of ethanol and biodiesel production have led to increased corn, sorghum, and sugarcane acres at the expense of food production and possibly loss of acres of timber in the Amazon and Southeast Asia. Production of cellulosic ethanol could potentially have these same consequences, as much of the feedstock will be grown on land presently producing agricultural crops. Reduced prices and profits for ethanol and biodiesel and increased concerns about environmental quality and climate change will likely decrease future investment in renewable fuels facilities using corn as the feedstock. Policymakers are increasingly turning to second-generation biofuels with very few issues with direct and indirect land use and small carbon footprints. Algae production is one of the very few biofuel alternatives with almost no problems with direct and indirect land use, and it potentially uses more carbon than it takes to produce it.

A 1998 report from the National Renewable Energy Laboratory (NREL) summarizes 18 years of research on using algae to produce natural oils for use in biodiesel (Sheehan, Dunahay, Benemann, & Roessler, 1998). Algae are single-cell organisms that thrive in brackish water and convert CO_2 into carbohydrates, protein, and natural oils. For some algae species, as much as 75% of their body weight is made up of non-edible natural oils. Through transesterification (process of adding three molecules of alcohol to one molecule of natural oil), the algae natural oils can be used to produce renewable fuels. Along with biodiesel, other, more advantageous, "drop in" transportation fuels are also possible that have equivalent or better energy density than the petroleum fuels we currently use and are also compatible with the existing energy infrastructure, including the existing network of refineries, pipelines, and terminals and the existing fleet of cars, trucks, and jets (Business Opportunities, 2009).

Burning biodiesel production from algae

- provides a means to re-use CO_2 in large volumes,
- utilizes land area not suitable for biodiesel feedstock crops,
- reduces emissions of CO_2 and SO_x but produces higher levels of NO_x,
- yields much higher levels per acre than all other biofuel sources, and
- degrades in the natural environment much faster than petrodiesel.

Production of biodiesel from algae is of interest in the United States and other countries because it is renewable, can reduce energy dependence on imported petroleum, and generally does not compete with traditional agricultural crops for land and water.

Algae can be produced in many climatic zones, but it performs best in more temperate areas, such as the desert Southwest. Agricultural production in the US Southwest is confined to grazing and a limited amount of irrigated crop production. The algae varieties identified by NREL as high oil producers prefer brackish water that is not used for crop production or human consumption and is in plentiful supply in the desert Southwest.

The laboratory experiments showed that the production of algae oil was feasible in 1998 (Sheehan et al., 1998). However, we have yet to see any full-scale algae farms because three issues have yet to be addressed.

- An efficient process to harvest the algae has not been demonstrated.
- An efficient process to separate the natural oil from the algae has not been created.
- The economic viability of algae farms at realistic prices has not been proven.

Research has been conducted around the world to find the best strains of algae for different climates/seasons, to develop the best growth medium, to develop the best pond structure, and to test harvesting and separation technologies (Sheehan, et al. 1998). Presently this NREL research is being continued by researchers in industry, university, and government laboratories.

Research into the use of microalgae as a source of oil for fuel reached its height under the US Department of Energy's Aquatic Species Program in the 1980s and early 1990s. The program was discontinued in the mid 1990s for funding reasons and stabilized oil prices. Research since has continued, but not on the scale of the Aquatic Species Program, especially in the United States. Research abroad focused on many parts of microalgae, but one of the more popular subjects was its use as a high-value nutraceutical. Some of the more recent research has focused on microalgae's ability to use carbon, especially the carbon dioxide found in flue gas from coal plants. This emphasis has been the result of growing concerns regarding climate change. No major breakthroughs in harvesting and extraction techniques have been reported in the literature, while some improvements in productivity have been reported. Closed photobioreactor systems, which are more conducive to high-value microalgae production, have also been popular research topics. However, because of the high costs associated with such systems, they are not included in our analysis.

Recently, Chisti (2007) discussed the production potential of microalgae and the area necessary to replace 50% of all US transportation fuels. Chisti showed how minute those areas are when compared to current sources of biodiesel. He also addressed various oil-content levels based on different strains of algae and the variations within each strain. Production facility designs, both raceways and photobioreactors, are discussed, with Chisti analyzing the area needed to produce 100,000 kg of algal biomass. For those same designs, Chisti estimated a microalgal biomass cost of $2.95 (photobioreactor) and $3.80 (raceway) per kg. These estimates assumed CO_2 is available at no cost. When 30% oil content is assumed, algal oil cost was reduced to $1.40 (photobioreactor) and $1.81 (raceway) to produce the biomass necessary for 1 liter of oil. Chisti also included a recovery process cost estimate of 50% of the final oil price.

Huntley and Redalje (2007) addressed a hybrid system using both raceways and photobioreactors in which the microalgae initially were grown in the photobioreactors. Once the microalgae reached a certain concentration, they were moved to the raceways for further growth. Huntley and Redalje (2007) estimated a cost of $84/barrel of oil, based on raceway costs of $74,782 per hectare and photobioreactor costs of $197,000 per hectare. This assumed that 80% of the production facility area was for raceways while the remaining 20% was for photobioreactors. Huntley and Redalje (2007) concluded that a 75% reduction in photobioreactor costs would put costs at $51/barrel. They also reported updates on the growth patterns of the microalgae depending on climatic conditions.

The previous pieces of literature offer great insight into the current state of the microalgae industry and also the direction in which it is heading. Continuing to build on the research of the Aquatic Species Program and research around the world will allow us to pursue a much more productive alternative fuel source.

Presently, the US Department of Energy has requested proposals to fund a three-year research project for inter-disciplinary consortiums to rapidly advance our ability to produce economical biodiesel from algae. Several consortiums have been formed with the top algae researchers in the United States and a large number of industrial partners. The charge is to develop the science to support a sustainable algae industry in the United States. This turn of events confirms there is continued interest in producing algal oil.

The purpose of this article is to provide a review of literature surrounding the relevant variables needed for an economic analysis and to report an estimate of the costs of producing algae oil for a commercial-size algae farm based on both conventional wisdom and recent production coefficients.

Methodology

The cost of production for algae will be estimated using a Monte Carlo simulation methodology. Ranges of values for variables critical to algae production will be used to define probability distributions for these variables. A simulation model will be developed using the stochastic values for the critical input variables, with the sole purpose of simulating the distribution of probable costs of production for algae oil. The model will be simulated 500 times to estimate the probability density functions (PDF) for the algae cost of production, algae oil production, and other key output variables (KOVs).

Two algae-farm scenarios will be reported. First will be a scaled-up commercial algae farm that uses the algae and oil yields and production costs reported in the literature. The second commercial algae farm will be constructed based on research from a promising ½ acre experiment in the Southwest which has demonstrated significant progress in producing microalgae oil. Due to non-disclosure agreements, the name of the facility and its location cannot be revealed at this time.

Key Input Variables

The key input variables (KIV) for modeling the economics of an algae farm are described below and are summarized in Table 1.

- The *evaporation rate* variable is the meters of water lost to evaporation and/or soaking into the ground for unlined raceways. This variable is used to calculate the amount of water that must be replaced daily. This variable is treated as a stochastic variable for the analysis. Evaporation ranges up to one inch per day but a reasonable range is 0.08-1.0 inch per day (Table 1).
- The *water cost* variable is the cost per gallon or cubic meter of water. The variable is used to calculate the cost of filling the raceways and maintaining them at the proper depth. It is heavily influenced by fuel costs for pumping water. The literature shows a cost of $0.012-0.26/cubic meter of water.
- The *water depth* variable is the average depth of water in raceways. The value can range from 4-12 inches and is a management control variable. Water depth is optimized by balancing evaporation losses (deeper raceways mean smaller % of H_2O lost) and a greater potential for algal shading problems (which hinders algae growth and oil productivity). The literature shows water depths of 0.1-0.3 meter.
- The *days of operation* variable is simply the number of days the farm has water and algae in the raceways. The number of days is dependent on the location of the farm and the algae strain(s) being grown. Some farms can operate for the full year and others cannot due to extreme temperatures. This is a management control variable and could range from 300 to 365 days according to the literature (Table 1).
- The *medium cost* variable is the cost per cubic meter of the algae food or "algae chow." The medium is a mix of different chemicals and trace minerals and will depend on the variety of algae, location, and season. This is a stochastic variable due to the uncertainty of prices for the ingredients, but the literature suggests a range of $0.027-0.58/kg of biomass produced.
- The *carbon dioxide* variable is bubbled into the raceways to feed the algae. The amount of CO_2 used is a management control variable and is closely related to algae production. The literature indicates ranges of CO_2 use by micro algae of 1.65-3.7 kg/kg of biomass produced. CO_2 costs range from $0.0035-0.313/kg of biomass produced.
- The *algae production rate* variable is the measure of net harvested algae without the water and is measured in grams per square meter per day. The average appears to be 30 $g/m^2/day$, but the range in the literature is 10-60 for outdoor raceways. By the nature of farming, this is a stochastic variable.
- The *oil content of the algae* variable is the fraction of the cell weight that is natural oil. Oil content fraction is used to calculate the quantity of natural oil extracted from the algae sludge. There appears to be a large number of studies reporting oil content at 25-35%, however several studies show oil content at 60% in the extreme. Oil content also varies based on the strain of algae, medium contents, and climatic conditions.

Scenarios Analyzed and Model

Two hypothetical commercial-size algae farms are analyzed for this article. Different production assumptions are used to reflect two possible microalgae farms in the Southwest. The management control variables that help define the algae farms are summarized in Table 2. The first farm is defined by using the input/output information found in the literature for the KIVs in Table 1 supplemented with local prices and observations. The second farm uses values for the KIVs that have been

Table 1. Key input variable range estimations.

	Range	
Evaporation rate	**Inches per day**	**Notes**
Brown (personal communication, 2008)	1.00	Personal communication with researchers from September 2008 visit
Weissman, Tillett, and Goebel (1989)	0.13-0.14	Rates from 1989 Solar Energy Research Institute study in Roswell, NM, in 3m^2
Simpson (personal communication, 2009)	0.50	Personal communication with researchers from May 2009 visit
Neenan, Feinberg, Hill, McIntosh, and Terry (1986)	0.08-0.39	Reference value of 0.0335; water depth
Production rate	**Grams/m^2/day**	**Notes**
Benemann, Goebel, & Weissman (1988)	30	Water was 20 cm deep; strain was Chlorella
Huntley and Redalje (2007)	36	Strain was Haematococcus pluvialis; 35% oil content assumed
Putt (2007)	20	Strain was Chlorella; 100 acre facility w/raceways w/ paddlewheels
Schulz (2006)	30	Strains were Spirulina, Haematococcus, Chlorella, and Dunaliella
Patil, Tran, and Giselrod (2008)	24	Strain was Dunaliella
Schenk et al. (2008)	20	From Seambiotic (Israel)
Schenk et al. (2008)	30-60	
Schenk et al. (2008)	10-25	Operated at depth of 15-20 cm and biomass concentrations of 1 g biomass/dry weight per liter
Schenk et al. (2008)	62	Strain was Tetraselmis suecica w/30% lipid content
Carlsson, van Bellen, Möller, and Clayton (2007)	30	
Neenan et al. (1986)	10-60	Minimum and maximum rates for outdoor raceway productivity from National Renewable Energy Laboratory
Weissman et al. (1989)	3.2-13.1	Small lined ponds in September-December production
Lee (2001)	25	
Benemann (1994)	30-60	Lower estimate was the projected rate for the project and the larger estimate was the theoretical maximum
Chisti (2007)	35	
Production days	**Days**	**Notes**
Putt (2007)	300	No production in darker and colder months of December and January; located in Alabama
Neenan et al. (1986)	200-365	Min & max growing days, with 250 days used as reference value
Tapie and Bernard (1988)	300	Photobioreactor experiment
Stepan, Shockey, Moe, and Dorn (2002)	365	
Oil content	**Percentage**	**Notes**
Neenan et al. (1986)	20-60	30% used as reference case
Li, Xu, and Wu (2007)	40-50	
Dote, Sawayama, Inoue, Minowa, and Yokoyama (1994)	30-70	
Benemann (1994)	50	
Demirbas (2007)	50	Considers this estimate to be at the higher end of the spectrum
Chisti (2007)	15-77	Depends heavily on strain of algae, with 20-50% being common
Carlsson et al. (2007)	15-75	Depends heavily on strain of algae, with 30-50% being common
CO_2 usage	**Kg/kg biomass**	**Notes**
Molina-Grima, Belarbi, Acien-Fernandez, Robles-Medina, and Chisti (2003)	3.70	kg CO_2 per kg of biomass produced @ cost of $0.4706/kg in photobioreactor

Table 1. Key input variable range estimations.

Chisti (2007)	1.83	kg CO_2 per kg of biomass produced
Doucha, Straka, and Livansky (2005)	1.65-1.83	kg CO_2 per kg of biomass produced
Benemann et al. (1988)	1.83	kg CO_2 per kg of biomass produced
CO_2 cost	**$/kg algal biomass**	**Notes**
Tapie and Bernard (1988)	0.200	For a photobioreactor facility
Singh, Croiset, Douglas, and Douglas (2003)	0.0035-0.0053	CO_2 captured for use at a microalage facility using two different harvest processes; about 40¢/kg
Water cost	**$/m^3**	**Notes**
Neenan et al. (1986)	0.05-0.20	Reference value of $0.067 in 1984 dollars
Weissman et al. (1989)	0.012-0.26	Cheaper source is saline groundwater at 800 gallons per minute (gpm) and more expensive source is city water
Molina-Grima et al. (2003)	0.0294	Water used in photobioreactor
Singh et al. (2003)	0.0100	Cost of cooling water
Medium cost	**$/kg algal biomass**	**Notes**
Molina-Grima et al. (2003)	0.5883	Takes 2.5 kg of medium to produce 1 kg of algal biomass in photobioreactor
Tapie and Bernard (1988)	0.2700	For a photobioreactor
Stepan et al. (2002)	0.0190	Only accounts for cost of additional nutrients; some nutrients are received from CO_2 flue gas
Electricity cost	**$/kWh**	**Notes**
Neenan et al. (1986)	0.04-0.10	Reference value of $0.065 in 1984 dollars
Molina-Grima et al. (2003)	0.0588	3.81 kWh used to produced 1 kg of algal biomass in photobioreactor
Benemann, Goebel, Weissman, and Augenstein (1982)	0.1000	
Stepan et al. (2002)	0.0150	$0.0107 per kg of algal biomass produced; 0.715 kWh per kg of algal biomass produced
Labor	**$/kg algal biomass**	**Notes**
Neenan et al. (1986)	0.0400	For a 1,000 ha facility, 43 employees
Tapie and Bernard (1988)	0.3920	For a photobioreactor facility
Benemann et al. (1982)	0.0253	
Stepan et al. (2002)	0.0056	Assuming annual production of 886,000 tons and annual salaries of $5,000,000
Water depth	**Meters**	**Notes**
Benemann et al. (1982)	0.20	
Neenan et al. (1986)	0.10-0.30	
Weissman et al. (1989)	0.15	
Lee (2001)	0.13-0.15	
Benemann (1994)	0.20-0.30	
Chisti (2007)	0.30	Considers this to be typical raceway depth
Huntley and Redalje (2007)	0.10-0.20	
Stepan et al. (2002)	0.10-0.90	

obtained for a small-scale algae test farm in the desert Southwest.

The simulation model is a stochastic budget for one year. Costs for producing microalgae oil is simulated using stochastic values for variables management cannot control. The result is an estimate of the probability density function (PDF) for the cost of producing algae oil. The resulting PDFs will give us a better estimate of the range of costs of production for the two different production models.

Where the literature is widely divergent on the input variables we assumed they are stochastic. The stochastic variables are simulated using a GRKS probability distribution (named for its developers, Gray, Richardson, Klose, and Schuman; Richardson et al., 2007). The distribution is used to simulate random variables with a minimum of information: a minimum, a middle value, and a maximum. The GRKS distribution assumes 50% of the observations are less than the middle value. Also, the distribution draws 2.28% of the values from below the minimum and 2.28% above the maximum. Random values drawn outside of the minimum and maximum values account for low-frequency rare events that could significantly impact a business, i.e., Black Swans. The GRKS distribution does not force the minimum and maximum values to be equal distance from the middle so the GRKS can simulate a skewed distribution. The random prices in the model are simulated as a multivariate empirical probability distribution using the method reported by Richardson et al. (2000). The MVE parameters were estimated from annual data for 1989-2008, and the Food and Agricultural Policy Research Institute (FAPRI) January 2009 Baseline was used for forecasted average prices in 2010.

The algae simulation model was programmed in Microsoft® Excel using the Simulation and Econometrics to Analyze (Simetar©) add-in. Simetar© provides a library of functions for parameter estimation, simulation of random variables, statistical validation tests, and ranking risky scenarios (Richardson, Schumann, & Feldman, 2002). Random variables were simulated using the Mersenne Twister pseudo-random number generator and a Latin hypercube sampling method.

Input Data

Data for the model were collected through an extensive literature review and through personal communication with microalgae researchers at Texas A&M University and other microalgae test farms in the Southwest. The microalgae farms described for this study are hypothetical, based on research results from the local researchers and a range of values in the literature.

The simulated farms are assumed to have a land area of 1,000 acres for raceways, with the amount of water surface area depending on the size of the raceways (Table 2). Land is assumed to cost $500 per acre. Total investment in the two farms is about $78,000 and $44,000 per acre, respectively, for the base and Scenario 2 farms. The life of the depreciable assets for the facility is assumed to be 10 years, and the initial investment is financed for 20 years at 7.5% interest rate.

Scenario 1 is a West Texas algae-oil production facility built using production expectations found in the microalgal literature. This facility is assumed to operate 10 months per year (300 days). The other two months are not suitable for production based on temperature; these months will be used for pond maintenance and cleaning. Raceways are 20 meters wide and 1,000 meters long with plastic liners and paddlewheels. Space between raceways is assumed to be 3 meters, and space for the burn in the center of the raceway is assumed to be 2 meters. This is the reason that water surface area (867 acres) is not the same as total land area. Such allowances are necessary as facility operators must be able to travel between raceways for monitoring and maintenance purposes. Pipe to deliver nutrients, carbon dioxide, and water to the individual raceways is estimated at $10.00 per foot based on current prices for pressured pipe. Pipe requirements are estimated at nearly 350,000 feet based on the facility design. Water depth is 0.2 meters (approximately 8 inches), based on research by Weissman, Goebel, and Benemann (1988) as well as research by Neenan et al. (1986). Evaporation ranges from 0.25 to 1.0 inches per day, with a middle estimate of 0.5 inches per day (Table 2). These estimates are based on communication with researchers in Pecos, Texas (L. Brown & J. Brown, personal communication, September 24, 2008). Water will also be lost in the harvesting and extraction process, estimated by Simpson at 10% loss per harvest. Water costs are based on per-gallon pumping costs for farmers in the Pecos Valley. Labor requirements come from research by Neenan et al. (1986) and annual salaries are based on a range of salaries for similar jobs in the local region.

Algae production for the base-scenario farm is based on the range of production values suggested by the literature, which indicates a range of 20-30 g/m^2/day (Table 2). Wide ranges for oil content are observed in the literature. The parameters to simulate oil content are a minimum of 20, a middle value of 30, and a maximum of 40%. Costs for harvesting (539 kWh/ton biomass) and extraction (1,000 kWh/ton biomass) are electricity requirements reported by Stepan et al. (2002).

The assumed proportions of nutrients fed in the microalgae chow are based on a study by Stepan et al. (2002). The study was used because there is very little information available on microalgae nutrient feed ration, as everyone is very secretive about their feed mixtures. The prices of nutrients (ammonia, potash, and diammonium phosphate) are stochastic based on the his-

Table 2. Summary of all input assumptions for two microalgae farms.

Variable name	Scenario 1	Scenario 2
Facility assumptions	**Assumed value**	**Assumed value**
Facility land size (in acres)	1,000	1,000
Pond width (in meters)	20	100
Pond length (in meters)	1,000	1,000
No. of paddle wheels per pond	2	10
Meters for slope on side of raceway	2	0
Meters for separation between raceways	3	3
Water depth (in meters)	0.200	0.275
Water loss in harvest % of harvest volume	0.100	0.050
Days of operation	300	365
Years to depreciate fixed assets	10	10
Land for buildings and plant	20	20
Price of land $/acre	500	500
Cost of a well 600-900 gpm	80,000	80,000
Annual repair and maintenance per well	3,500	3,500
Annual administrative expenses (fraction variable costs)	0.010	0.10
Interest rate for operating expenses (fraction)	0.085	0.085
Interest rate to finance investment (fraction)	0.075	0.075
Fraction of year finance operating costs	0.083	0.083

	Scenario 1			Scenario 2		
Random variables	**Minimum**	**Middle**	**Maximum**	**Minimum**	**Middle**	**Maximum**
Microalgae production sludge (g/m^2/day)	20.0000	25.0000	30.0000	18.0000	22.0000	25.0000
Evaporation rate (meters/day)	0.0064	0.0127	0.0254	0.0050	0.0051	0.0051
Oil content (fraction)	0.2000	0.3000	0.4000	0.4000	0.5100	0.6000
Kg of medium fed per kg biomass	0.1200	0.1463	00.1800	0.0900	0.1097	0.1350
Cost to pump water ($/gallon)	0.0018	0.0021	0.0024	0.0004	0.0007	0.0009
Kg of CO_2 per kg of sludge	1.6500	1.8300	1.9000	0.0000	0.0000	0.0000
Price of CO_2 ($/kg)	0.1500	0.1800	0.2000	0.0000	0.0000	0.0000
Avg. price of algae protein $/ton		250.0000			250.0000	
Avg. price of electricity ($/kWh)		0.0500			0.0000	
Avg, price of ammonia ($/ton)		575.0000			575.0000	
Avg. price of potash ($/ton)		780.0000			780.0000	
Avg. price of diammonium phosphate ($/ton)		500.0000			500.0000	
Electricity used kWh/kg of biomass		0.7150			0.0000	

Table 2. Summary of all input assumptions for two microalgae farms.

	Scenario 1			Scenario 2		
Labor costs	**Minimum**	**Middle**	**Maximum**	**Minimum**	**Middle**	**Maximum**
Project manager salary	105,000	112,500	123,750	140,000	150,000	165,000
Operations manager salary	105,000	112,500	123,750	140,000	150,000	165,000
Administrative assistant salary	67,500	75,000	82,500	90,000	100,000	110,000
Procurement salary	--	--	--	90,000	100,000	110,000
Marketing salary	--	--	--	90,000	100,000	110,000
Field operators salary	45,000	50,000	55,000	90,000	100,000	110,000
Aquatic biologist salary	67,500	75,000	90,000	90,000	100,000	120,000
Fisheries biologist salary	--	--	--	90,000	100,000	120,000
Algae ration as tons of chemical/ ton biomass		**Assumed value**			**Assumed value**	
Ammonia		0.04779			0.0358425	
Potash		0.0173			0.012975	
Diammonium phosphate		0.08116			0.06087	
Annual costs to maintain culture		50,000			50,000	
Costs of harvesting and extraction						
Harvesting cost kWh/ton biomass		539			250	
Extraction cost kWh/ton biomass		1,000			500	
Number of employees						
Project manager		1			1	
Operations manager		1			1	
Admin / sect		1			1	
Procurement		0			1	
Marketing		0			1	
Field operations		9			6	
Aquatic biologist / lab manager		1			1	
Fisheries biologist		0			1	

torical variability of these prices. Prices of $575 per ton for ammonia, $780 per ton for potash, and $500 per ton for diammonium phosphate are used as the mean prices.

Carbon dioxide costs for Scenario 1 are based on research by Tapie and Bernard (1988) and Weissman et al. (1988). Carbon dioxide usage per unit of algal biomass produced is based on research by Weissman et al. (1988), Doucha et al. (2005), and Chisti (2007). The minimum, middle, and maximum price for CO_2 of $/ton is $0.15, 0.18, 0.20/kg, based on local price quotes for bulk delivery of compressed CO_2.

It is assumed that both microalgae farms produce algae oil and by-product protein, which is dried and sold in bulk as an animal feed commodity.[1] Protein by-products are priced based on the 2008 projected average market price for soybean meal. The relative price risk for the by-product is assumed to be proportional to the risk for soybean meal.

Electricity cost was calculated based on stochastic electricity prices and the amount of electricity used in the different aspects of growing, harvesting, and extracting microalgae oil. The electricity consumption values reported in the literature were used to arrive at the values in Table 2.

---

1. *Algae by-products have a range of potential uses, from nutriceutials to fertilizer and animal feed. Algae by-products have been tested at more than 48% protein, making it a good substitute for soybean meal. To avoid making the test farms appear overly profitable, it is assumed that the algae by-product will be dried and sold to dairy cattle and beef cattle in Southwest feedlots.*

Scenario 2 employs a much more aggressive approach to growing micro algae and facility design. The experimental version of the farm modeled in Scenario 2 has operated for more than 18 months with the same strain of micro algae and has production records to support annual production of more than 4,500 gallons of algae oil per acre per year. The test farm has records to support the assumption that oil content is greater than 50%.

Raceways are 20 meters wide and 1,000 meters long with two paddlewheels per raceway. Pond design used for the experimental farm is based on discussions about alternative pond configurations. To maximize water volume and reduce liner welds and dirt moving expenses, there will be five raceways in one large raceway, with concrete blocks separating the individual raceways. Pipe costs for nutrient and water inflow are reduced to $5.00 per foot due to using gravitational flow to deliver water and nutrients. Pressurized CO_2 pipes are not necessary for the farm, as the farm aggressively bubbles in air and does not use compressed CO_2.[2] This practice results in a significant cost savings from not purchasing CO_2.

Water needs are cut by reducing evaporation through technology improvement and by decreasing the amount of water lost in harvesting and extraction to 5%. Nutrient costs are reduced by 25% by optimizing the ingredients in the medium mixture, using a proprietary mix of ingredients. Much more emphasis is put on the quality of labor in this scenario, as a fisheries biologist and an aquatic biologist are added to the labor force. Employees are expected to have advanced degrees and knowledge of the industry and in turn will be compensated more generously. Algae biomass production is slightly lower than the base but is expected to improve considerably. Harvesting and extraction costs are reduced, as the experimental farm has demonstrated the benefits of new technology to improve these processes.[3]

Electricity costs are cut almost 100%, as electricity is supplied through wind energy and photovoltaic cells to run pumps, paddlewheels, and harvesting/extraction equipment. Investment in wind energy, photovoltaic cells, and associated equipment reduces variable costs while increasing fixed costs only slightly, making this an economical decision. No revenue is assumed to be generated by selling surplus electricity, although it is expected to occur based on the prevailing wind patterns in the region. Solar-generated electricity will be adequate for driving the paddlewheels and bubbling atmospheric oxygen because these activities only need to be done during daylight hours when photosynthesis is taking place.

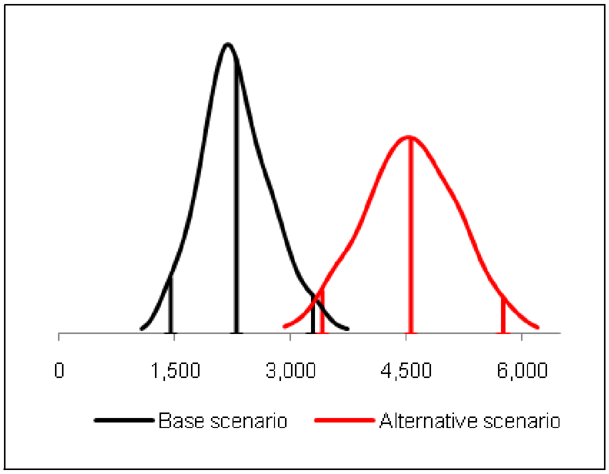

Figure 1. PDF of algae oil production (gallons/acre).

Results

The results of the simulation analysis are summarized in Table 3 and Figures 1-3. Starting with Figure 1 we see that algae oil production is highly variable. For the base scenario, production ranges from 1,073 to 3,736 gallons per acre, and for Scenario 2, the range of production is 2,927 to 6,297 gallons per acre (Figure 1). The mean production levels are 2,286 and 4,557 gallons per acre per year (Table 3), respectively. The increased oil content of the micro algae more than offsets slightly lower levels of microalgae production for Scenario 2.

Production costs per pound of microalgae oil—with a credit for the protein produced as a by-product—are summarized in Table 3 for both scenarios and in Figures 2 and 3. For the conventional microalgae farm (based on the parameters in the literature), the average total cost per pound is $1.605, with a range of $0.85 to $3.67. The PDF for the base scenario microalgae costs per pound is skewed to the right, with 5% of the observations greater than $2.48 per pound. Production costs for Scenario 2 are estimated to be much lower; the average is $0.253

---

[2] *The literature does not show that atmospheric CO_2 is adequate to support microalgae production. However, repeated visits to the test farm have confirmed that aggressive bubbling in atmospheric CO_2 will produce a healthy algae population that is capable of high levels of oil production per acre.*

[3] *The test farm has experimented with several harvesting and extraction technologies. They have developed their own harvesting equipment, which has increased efficiency of studge recovery and reduced energy requirements. Similar advances in extraction of algal oil from the studge have been made.*

Table 3. Comparison of production and costs for conventional and advanced technology microalgae farms.

Variable	Conventional	Advanced
Investment $/acre	77,095	42,774
	Production tons/acre	
Mean	33.35	35.23
Std. dev.	3.34	2.85
Coef. var.	10.01	8.09
Min	23.36	24.46
Max	44.79	43.25
	Production gallons/acre	
Mean	2,286.16	4,557.85
Std. dev.	455.25	602.87
Coef. var.	19.91	13.23
Min	1,073.66	2,927.83
Max	3,736.12	6,197.50
	Variable cost $/lb	
Mean	1.45	0.25
Std. dev.	0.35	0.03
Coef. var.	23.84	13.59
Min	0.70	0.18
Max	3.50	0.41
	Fixed costs $/lb	
Mean	0.46	0.13
Std. dev.	0.10	0.02
Coef. var.	21.14	13.91
Min	0.27	0.09
Max	0.94	0.19
	Total cost without credit $/lb	
Mean	1.91	0.38
Std. dev.	0.43	0.05
Coef. var.	22.50	13.43
Min	0.99	0.28
Max	4.25	0.60
	Total cost with credit $/lb	
Mean	1.61	0.25
Std. dev.	0.37	0.04
Coef. var.	23.02	16.62
Min	0.85	0.15
Max	3.67	0.45

per pound with a range of $0.15 to $0.44 per pound. The PDF of costs per pound for the second scenario also shows costs are skewed to the right, with 5% of the costs exceeding $0.35 per pound.

The average costs reported here for the test farm—$0.253/pound—are much lower than costs of production reported in the literature, after adjusting their costs for changes in the consumer price index. Neenan et al. (1986) reported a cost of algal oil in the range of $0.67 per pound in 2009 dollar equivalents. Chisti (2007) reported an algal oil cost of $0.95 per pound in 2009 dollars. Hassannia (2009) reported a cost of production of about $0.82 per pound. However, all of these cost estimates are lower than the $1.60 per pound for the base scenario. Examining the three studies closely showed that each one assumed either higher production or lipid content than reported in Table 1.

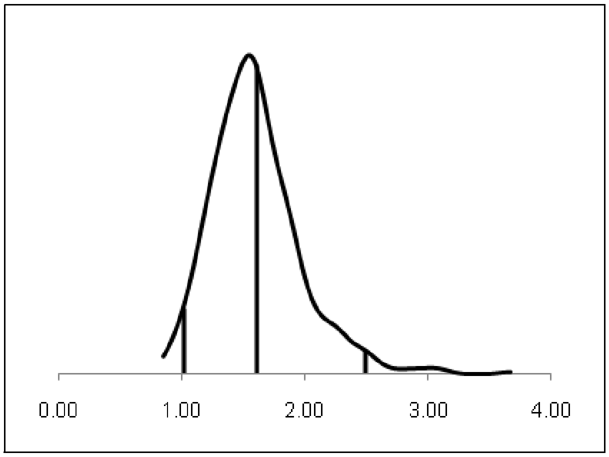

Figure 2. PDF of total costs/lb (base scenario).

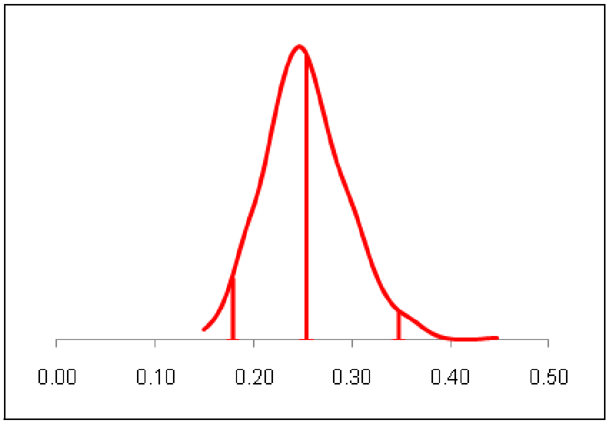

Figure 3. PDF of total costs/lb (Scenario 2).

The total costs per pound of microalgae oil with and without a protein credit are presented in Table 3. The protein credit is worth about $0.30 per pound of microalgae oil for the base scenario and $0.13 per pound for the second scenario. The higher protein value for the base results from the assumption that oil content is a lower percentage of body weight.

Due to much higher investment cost and lower oil content under the base scenario, the fixed costs per pound of oil for the base are three times larger than for

Scenario 2 (Table 3). Variable costs per pound of oil are about six times higher for the base scenario ($1.45 per pound vs. $0.25), due largely to the differences in costs for nutrient, water, CO_2, and electricity for pumping, harvesting, and extraction. Using wind to generate the electricity needs of the farm will result in much lower costs, which are more than sufficient to pay for the necessary wind turbines and photovoltaic cells.

Summary

The literature for microalgae oil is quite extensive on the production of microalgae oil, but few studies offer estimates of the costs to produce oil. Using the ranges in the literature for critical input and production variables, a commercial size microalgae farm of 1,000 acres was simulated to estimate algae oil costs of production. Using the same methodology, a similar size farm was analyzed, but this time the input and output parameters were based on results for an experimental farm in the desert Southwest.

Results of a Monte Carlo simulation for the two hypothetical farms indicate that the total cost for producing microalgae oil is highly variable for both farming systems due to the inherent risks associated with growing micro algae in open raceways. The average cost of production, with the protein credit, for the conventional farm is estimated at $1.61, per pound while the cost for the second scenario is $0.25 per pound. The May edition of F.O. Licht's World Biodiesel Price Report (2009) reported that the crude soybean oil price for FOB Gulf in the United States ranged from $0.35 to $0.38 per pound. At these prices, the more productive microalgae farm can compete with soybean oil. A rough estimate of the price of biodiesel made from algae oil is $2.35 per gallon, just slightly higher than current diesel prices, but far below diesel prices a year ago.

Microalgae oil production is economically feasible at this time, but only if the results for the best small-scale experiment the authors have seen are scalable to a commercial size farm. Their research is very promising, but the issue of scaling it to 1,000 acres is still a question.

References

Benemann, J.R. (1994, September). *Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass*. US Joint Technical Meetings, Albuquerque, NM.

Benemann, J.R., Goebel, R.P., & Weissman, J.C. (1988). Photobioreactor design: Mixing, carbon utilization, and oxygen accumulation. *Biotechnology and Bioengineering, 31*, 336-344.

Benemann, J.R., Goebel, R.P., & Weissman, J.C., & Augenstein, D.C. (1982, December). *Proceedings of the SERI biomass principal programs investigators' review meeting—Aquatic species program reports* (SERI/CP-231-1808). Golden, CO: Solar Energy Research Institute, US Department of Energy (DOE).

Business opportunities and climate policy: Statement before the US Senate Committee on Environment and Public Works Hearing, 111th Cong. (2009, May 19) (testimony of C.J. Warner).

Carlsson, A.S., van Beilen, J.B., Möller, R., & Clayton, D. (2007). EPOBIO: Realizing the economic potential of sustainable resources—Bioproducts from non-food crops. In D. Bowles (Ed.), *Micro and macro algae: Utility for industrial applications*. Newbury, UK: University of York, CPL Press.

Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances*, *25*, 294-306.

Demirbas, A. (2007). Importance of biodiesel as transportation fuel. *Energy Policy*, *35*, 4661-4670.

Dote, Y., Sawayama, S., Inoue, S., Minowa, T., & Yokoyama, S. (1994). Recovery of liquid fuel from hydrocarbon-rich microalgae by thermochemical liquification. *Fuel*, *73*, 1855-1857.

Doucha, J., Straka, F., & Livansky, K. (2005). Utilization of flue gas for cultivation of microalgae (Chlorella sp.) in an outdoor thin-layer photobioreactor. *Journal of Applied Phycology*, *17*, 403-412.

F.O. Licht. (2009). *World biodiesel price report*. London: Informa UK, Ltd.

Hassannia, J. (2009). Algae biofuels economic viability: A project-based perspective. *Diversified Energy Newsletter*, *20*(April), 1-4.

Huntley, M.E., & Redalje, D.G. (2007). CO_2 mitigation and renewable oil from photosynthetic microbes: A new appraisal. *Mitigation and Adaptation Strategies for Global Change*, *12*, 573-608.

Lee, Y-K. (2001). Microalgal mass culture systems and methods: Their limitation and potential. *Journal of Applied Phycology, 13*, 307-315.

Li, X., Xu, H., & Wu, Q. (2007). Large-scale biodiesel production from microalga chlorella protothecoides through heterotrophic cultivation in bioreactors. *Biotechnology and Bioengineering*, *98*, 764-771.

Molina-Grima, E., Belarbi, E-H., Acien-Fernandez, F.G., Robles-Medina, A., & Yusuf, C. (2003). Recovery of microalgal biomass and metabolites: Process options and economics. *Biotechonolgy Advances*, *20*(7-8), 491-515.

Neenan, B., Feinberg, D., Hill, A., McIntosh, R., & Terry, K. (1986, August). *Fuels from microalgae: Technology status, potential, and research requirements* (SERI/SP-231-2550 DE86010739). Golden, CO: Solar Energy Research Institute, US DOE.

Patil, V., Tran, K-Q., & Giselrod, H.R. (2008). Towards sustainable production of biofuels from microalgae. *International Journal of Molecular Sciences*, *9*, 1188-1195.

Putt, R. (2007). *Algae as a biodiesel feedstock: A feasibility assessment*. Auburn, AL: Center for Microfibrous Materials Manufacturing (CM3), Department of Chemical Engineering, Auburn University.

Richardson, J.W., Herbst, B.K., Outlaw, J.L., & Gill II, R.C. (2007). Including risk in economic feasibility analyses: The case of ethanol in Texas. *Journal of Agribusiness*, *25*, 115-132.

Richardson, J.W., Klose, S.L., & Gray, A.W. (2000). An applied procedure for estimating and simulating multivariate empiracal (MVE) probability distributions in farm-level risk assessment and policy analysis. *Journal of Agricultural and Applied Economics*, *32*, 299-315.

Richardson, J.W., Schumann, K., & Feldman, P. (2002, July). *Simulation for Excel to analyze risk*. College Station, TX: Department of Agricultural Economics, Texas A&M University.

Schenk, P.M., Thomas-Hall, S.R., Stephens, E., Marx, U.C., Mussgnug, J.H., et al. (2008). Second generation biofuels: High efficiency microalgae for biodiesel production. *Bioenergy Research*, *1*, 20-43.

Schulz, T. (2006, December). *The economics of microalgae production and processing into biofuel*. Department of Agriculture and Food, Government of Western Australia.

Sheehan, J., Dunahay, T., Benemann, J., & Roessler, P. (1998). *A look back at the US Department of Energy's aquatic species program—Biodiesel from algae* (NREL/TP-580-24190). Golden, CO: National Renewable Energy Laboratory (NREL), US DOE.

Singh, D., Croiset, E., Douglas, P.L., & Douglas, M.A. (2003). Techno-economic study of CO_2 capture from an existing coal-fired power plant: MEA scrubbing vs. $0_2/CO_2$ recycle combustion. *Energy Conversion and Management*, *44*(19), 3073-3091.

Stepan, D.J., Shockey, R.E., Moe, T.A., & Dorn, R. (2002, February). *Carbon dioxide sequestering using microalgal systems* (2002-EERC-02-03). Pittsburgh, PA. NREL, US DOE.

Tapie, P., & Bernard, A. (1988). Microalgae production: Technical and economic evaluation. *Biotechnology and Bioengineering*, *32*, 873-885.

Weissman, J.C., Goebel, R.P., & Benemann, J.R. (1988). Photobioreactor design: Mixing, carbon utilization, and oxygen accumulation. *Biotechnology and Bioengineering*, *31*, 336-344.

Weissman, J.C., Tillett, D.M., & Goebel, R.P. (1989, October). *Design and operation of an outdoor microalgae test facility* (SERI/STR-232-3569). Golden, CO: Solar Energy Research Institute, US DOE.