Economic Feasibility of Commercial Algae Oil Production in the United States

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While corn ethanol and biodiesel from soybeans were early sources of renewable fuels, concerns over competition for agricultural land for fuel has led to further research into other sources. In addition, the Renewable Fuel Standard (RFS2) set maximum fuel production from conventional sources at 15 billion gallons per year. There are also concerns of worldwide land use change (e.g. the destruction of rainforests for conversion to farmland) and the overall efficiency of renewable fuels from food crops. This has encouraged government research into second generation feedstocks.

In the 1980s, the U.S. Department of Energy's Aquatic Species Program examined the potential of microalgae as a source of renewable fuels. While declining oil prices in the 1990s led to decreased investment in microalgae research, interest in microalgae has increased in recent years. In the past year, the Department of Energy has committed approximately $75 million in research funding for algae fuels to several groups, including the National Alliance for Advanced Biofuels and Bioproducts. Producing a renewable fuel from microalgae will not be widely accepted until it becomes cost effective.

Objective

The objective of this analysis is to examine the viability of a commercial microalgae production facility for the purpose of producing algae oil in the United States. Using Monte Carlo simulation, the paper examines the net present value (NPV) and cost per gallon of algae oil produced in the southwestern United States under several alternative cultivation assumptions. In addition, the research evaluates the sensitivity of NPV to key variables that researchers and algae farmers should optimize.

A Monte Carlo simulation model was constructed to estimate fixed and variable costs for an algae farm over a ten-year horizon. The model is scalable based on the desired size of the facility. For the model to be scalable, it is based on a general, open-pond facility design, which resulted from a combination of the literature, research, and interviews with current microalgae facility operators. The scalability of the model allows it to automatically recalculate fixed costs, variable costs, and production when inputs are changed. The model is designed to adapt to any facility design, improvement in technology, or change in production.

Background

Much of the microalgae research in the United States is based on work completed from 1980 to 1998 as part of the U.S. Department of Energy's Aquatic Species Program. This program was developed in reaction to high energy prices in the 1970s and work continued into the 1990s. As energy prices subsided and federal funding began to tighten, the Aquatic Species Program came to an end with much valuable information but no definitive production systems. Much uncertainty surrounded the production ability of microalgae, the cost of production, and the methods by which the oil can be extracted from the algae cells; concerns remain today (Sheehan et al., 1998).

With the increase in energy prices, alternative fuel sources, including microalgae, are once again the focus of much research. Microalgae offers a variety of benefits as a fuel source if the algae production, harvest, and extraction processes can be proven economically viable. Microalgae can be produced in an environment that is not suitable for most agricultural crops. Flat, dry, warm parts of the United States (and the world)—for example, the Desert Southwest and other southern areas—are favorable for microalgae production. Research indicates that microalgae are more productive in warmer climates because they enable year-round operation (Neenan et al., 1986).

Microalgae Production

Microalgae are commonly produced using two methods: raceway ponds and photobioreactors. Raceway ponds are the production system assumed in this analysis. The algae travels around the raceway until it is harvested or moved to another raceway. A series of raceways are grouped together to form a single pond. Alternatively, photobioreactors produce algae using a long series of tubing in which the algae grow. Photobioreactors have higher production and growth rates and their growth environments are easier to control; however, photobioreactors are not considered in this research because of concerns over cost effectiveness.

Thousands of microalgae strains exist throughout the world. Selecting the ideal strain for oil production is based on a variety of factors, some controlled by the facility operator's preferences and others controlled by the environment in which the facility is operated. Microalgae should be able to withstand high salinity because the proposed areas of production in the Southwest have higher concentrations of saline water than many other areas. Microalgae strains with high lipid content are the most desirable because the lipid is algae oil and can be refined for transportation fuel. Resistance to predators and contaminants is another desired characteristic of the microalgae due to the open-air nature of the raceway pond production system. Lastly, although the harvesting and extraction process has not yet been completely refined, buoyancy and behavioral characteristics that enhance harvesting are desirable as well (Neenan et al., 1986).

Data Methods

Risk is prevalent in economic modeling. A model without risk—known as a deterministic model—predicts only a single value based on input values. A deterministic model gives no indication as to what might happen if circumstances or markets change, even though they are constantly changing. Incorporating risk allows the analysis of the probabilistic effects of changes in factors that affect the algae-to-biofuels pathways and the firm's profitability.

Risks in the Algae Industry

In the algae simulation model, risk is present in production (biomass accumulation, lipid content, and protein yield), input prices (labor, CO_2, nutrients, water, and maintenance), output prices (fuel oil, high valued oil for human consumption,[1] and protein meal), climate (temperature, hours of sunlight, and rainfall), and resource availability (water, CO_2, and land). Although more sources of risk exist, these are the major risks affecting the viability of the algae industry. Simulating these random variables will aid in determining the economic feasibility of microalgae production. Without incorporating risk in the model, the outcomes for alternative pathways will not be robust enough to make a decision in a risky economic environment.

Simulation Model Development

Simulation facilitates the analysis of alternative pathways by using alternative input values the manager can control to estimate the outcomes of key output variables (KOVs) and their distributions (Richardson, 2008). Once the simulation model is developed, it is solved a large number of times (e.g. 500 iterations) to statistically represent all possible combinations of

[1] "High valued oil" is the conventional name given to fatty acids available from algae that are commonly used as supplements for humans. Omega-3 is probably the most familiar of these high valued oils.

the random variables in the system. The results of a simulation process are empirical probability distributions for each of the KOVs important to the decision maker. The empirical probability distributions quantify the risk associated with the KOVs and can be compared from one scenario to the next. The goal of simulation modeling is to imitate how the real systems would respond to exogenous changes in management variables and policies. The KOVs of interest in this paper are NPV and cost per gallon of algae oil. The cost per gallon estimates are net of byproduct sales, including high value oils and protein meal replacements.

Scenarios

Scenario analysis allows a decision maker to evaluate the KOVs for alternative input levels that define specific pathways. By simply changing the level of inputs between scenarios, the analyst can compare the effect individual inputs have on the firm's economic viability. This paper addresses eleven scenarios representing possible major input variables important to the profitability of an algae facility. All scenarios are for an algae farm located in the Desert Southwest. The variables varied across the scenarios are designed to address the cost and/or production implications of potential production systems or production designs.

This paper examines technological improvements needed to ensure a 90 percent likelihood of economic success. The model was used to develop a benchmark pathway based on accepted values from the literature; this pathway is labeled Literature in Table 1. These variables were simultaneously changed until the algae farm had a 50 percent probability of economic success; this pathway is labeled Base. An infinite combination of improvements in these variables could have led to the Base pathway; the values below were chosen based on what appear to be reasonable given current algae production practices. Table 1 also shows the inputs for water depth and production levels that increase the likelihood of economic success from 50 percent in the Base case to 90 percent.

Table 1: Inputs for Base and Literature Pathways; Inputs for Water Depth and Production Level Pathways that Provide a 90 Percent Probability of Economic Success

Scenario	**Literature**	**Base**	**Depth**	**Depth**	**Production**
Facility Size (Acre Feet of Water)	**500**	**500**	**500**	**500**	**500**
Water Depth (inches)	8	12	14	16	12
High Value Oil (%)	2.00	5.00	5.00	5.00	5.00
Production Levels (g/L/day)					
Min	0.039	0.097	0.097	0.097	0.106
Mid	0.049	0.122	0.122	0.122	0.133
Max	0.059	0.146	0.146	0.146	0.159
Oil Contents (%)					
Min	27	36	36	36	36
Mid	30	40	40	40	40
Max	33	44	44	44	44

Table 2 shows the inputs for facility size, lipid content, and high value oil content that increase the likelihood of economic success from 50 percent in the Base case to 90 percent.

Table 2: Inputs for Facility Size, Lipid Content, and High Value Oil Content Pathways that Provide a 90 Percent Probability of Economic Success

Scenario	**Facility Size**	**Facility Size**	**Lipid Content**	**High Value Oil Content**
Facility Size (Acre Feet of Water)	**1,725**	**1,750**	**500**	**500**
Water Depth (inches)	12	12	12	12
High Value Oil (%)	5.00	5.00	5.00	6.12
Production Levels (g/L/day)				
Min	0.097	0.097	0.097	0.097
Mid	0.122	0.122	0.122	0.122
Max	0.146	0.146	0.146	0.146
Oil Contents (%)				
Min	36	36	41.60	36
Mid	40	40	46.22	40
Max	44	44	50.84	44

Table 3 shows the inputs for the Combination and Maximum improvement scenarios. The Maximum scenario used the improvement needed in each input to achieve a 90 percent probability of economic success (i.e. 6.12 percent for high value oil content) as input values. The Combination scenario is an average of the Base and Maximum pathways.

Table 3: Inputs for Combination and Maximum Improvement Pathways

Scenario	**Literature**	**Base**	**Maximum**	**Combination**
Facility Size (Acre Feet of Water)	**500**	**500**	**1,750**	**1,125**
Water Depth (inches)	8	12	16	14
High Value Oil (%)	2.00	5.00	6.12	5.56
Production Levels (g/L/day)				
Min	0.039	0.097	0.106	0.102
Mid	0.049	0.122	0.133	0.127
Max	0.059	0.146	0.159	0.153
Oil Contents (%)				
Min	27	36	41.60	38.80
Mid	30	40	46.22	43.11
Max	33	44	50.84	47.42

All eleven scenarios have several inputs in common. For example, all scenarios assume conventional energy sources (electricity) to power the facility. In addition, groundwater is used to meet water requirements (as opposed to other sources, such as recycled water from an outside source). In building the model, a range of input cost estimates were obtained. Production level parameters are established in g/L/day and oil content parameters are given as percentages. Rather than using the algae meal for energy production (e.g. gasification or pyrolysis), these scenarios assume it will be sold as animal feed. All scenarios face the same risk for weather, evaporation, market prices, and input inflation rates.

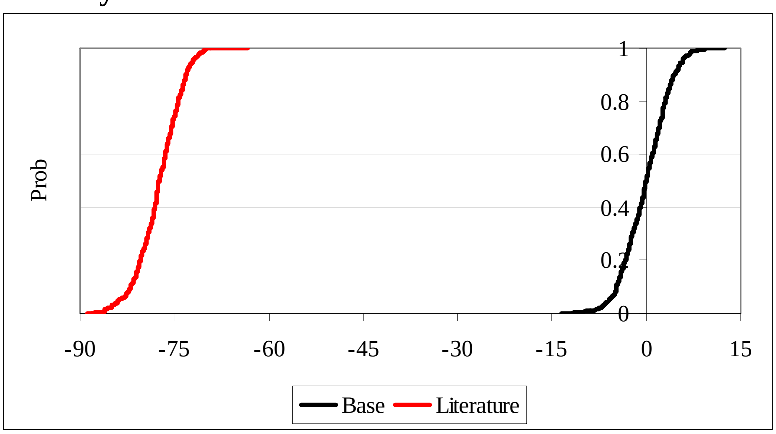
Results

The eleven scenarios were simulated 500 times and the results from those iterations are presented below. The cost per gallon estimates in the figures that follow are annual averages over the 10-year planning horizon and are net of byproduct sales, including high value oils and protein meal replacements.

Base Case

As shown in Figure 1, using parameters from the Literature pathway, there was no chance of economic success (i.e. NPV has no chance of exceeding zero). To improve to a 50 percent chance of economic success, water depth had to increase from 8 to 12 inches (50 percent increase), percent high value oil had to increase by 150 percent, percent lipid content had to increase by 33 percent and production had to increase by 148 percent (Table 1). Again, other combinations of improvements could have been evaluated for developing the Base pathway. Average NPV was -$77.43 million and $0 under the Literature and Base pathways, respectively.

Figure 1: Cumulative Distribution Functions of Net Present Value for Base and Literature Pathways

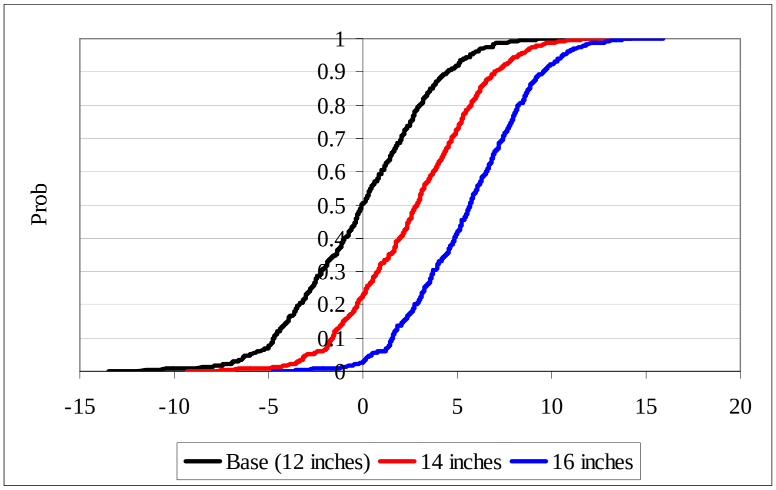


The average total cost per gallon of algae oil in the Literature pathway is $98 per gallon but falls to $1.52 in the Base pathway, further highlighting the infeasibility of producing algae under the Literature pathway. The Base pathway is the point of comparison for the remaining pathways.

Water Depth

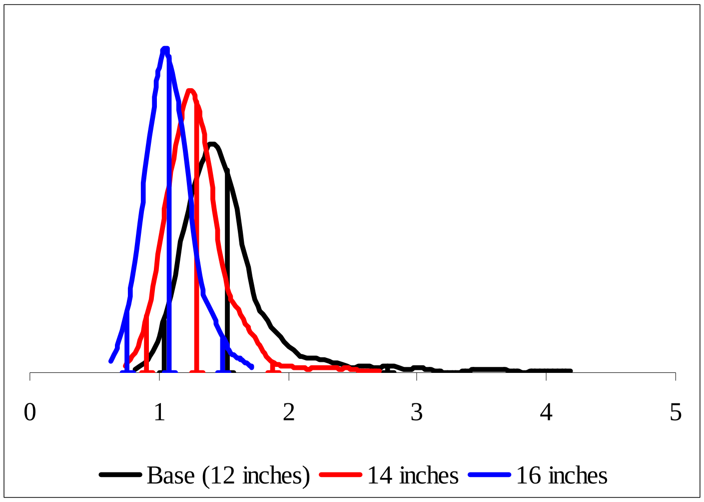
To increase the probability of economic success from 50 percent in the Base case to 90 percent, water depth had to increase from 12 inches to between 14 and 16 inches, an increase of at least 16.7 percent (Figure 2). Increasing water depth from 12 inches to between 14 and 16 inches resulted in an average NPV between $2.76 million and $5.61 million.

Figure 2: Cumulative Distribution Functions of Net Present Value for Alternative Water Depths that Increase the Probability of Economic Success to 90 Percent



As shown in Figure 3, at a water depth of 14 inches, the estimated per gallon cost of algae oil ranged from $0.74 to $2.70 with an average of $1.29 per gallon. At a water depth of 16 inches, cost per gallon estimates ranged from $0.63 to $1.72 with an average of $1.08 per gallon.

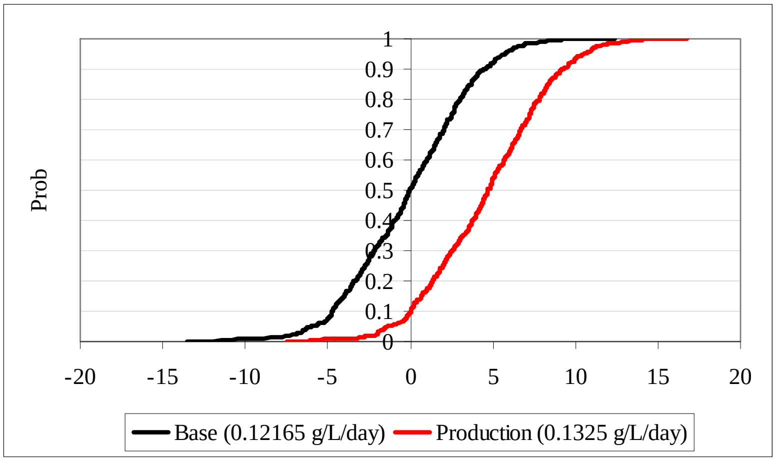
Figure 3: Probability Density Functions of the Estimated per Gallon Cost of Algae Oil for Alternative Water Depths that Increase the Probability of Economic Success to 90 Percent



Production

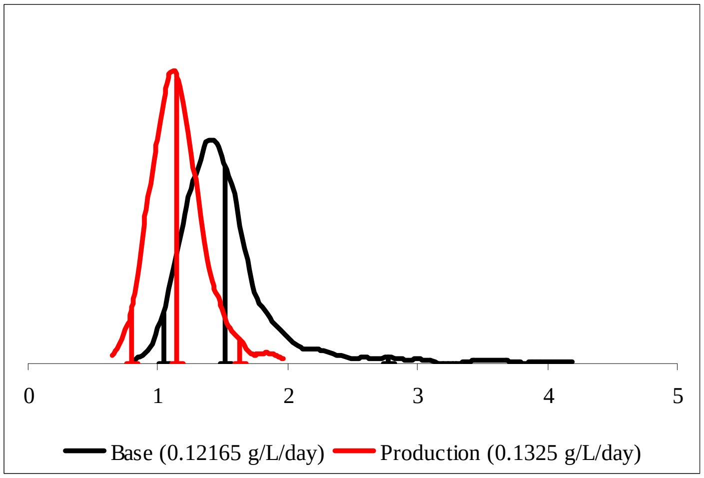
To increase the probability of economic success from 50 percent in the Base case to 90 percent, the facility had to increase production from 0.122 g/L/day (or 37.08 g/m^2/day) to 0.133 g/L/day (or 40.39 g/ m^2/day), an increase of 8.92 percent (Figure 4). At 500 acre feet, this would amount to increasing total annual facility output from 1.77 million to 1.93 million gallons (3,860 gallons per acre) of oil per year, an increase of 160,000 gallons per year on average. This increase in production resulted in an average NPV of $4.65 million.

Figure 4: Cumulative Distribution Functions of Net Present Value for Alternative Production Levels that Increase the Probability of Economic Success to 90 Percent



As shown in Figure 5, at the higher algae production level, the estimated per gallon cost of algae oil ranged from $0.64 to $1.97 with an average of $1.15 per gallon, an improvement of $0.37 per gallon over the average cost of $1.52 in the Base pathway. The higher algae production levels most notably reduce the risk by cutting off the extreme values in the right hand tail of the Base cost distribution.

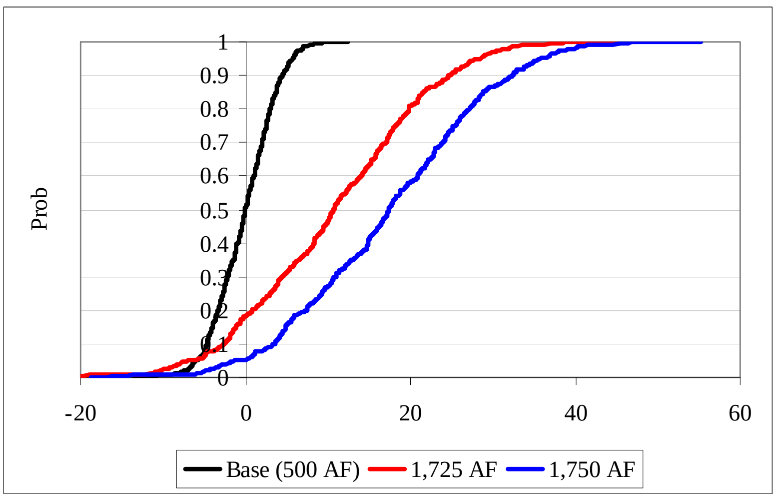
Figure 5: Probability Density Functions of the Estimated per Gallon Cost of Algae Oil for Alternative Production Levels that Increase the Probability of Economic Success to 90 Percent



Facility Size

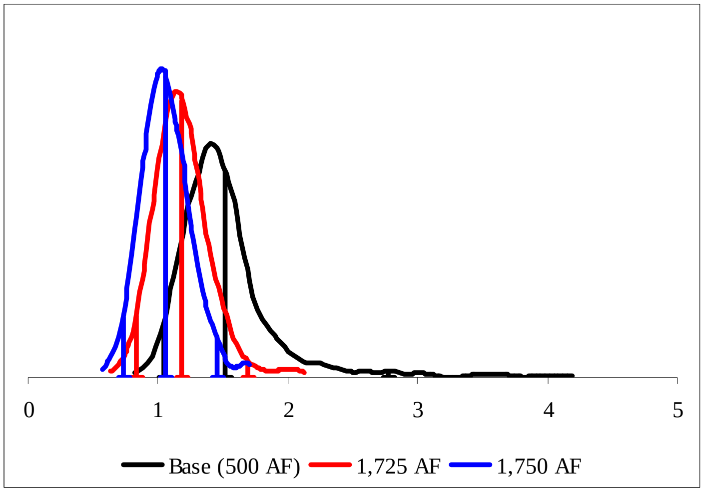
To increase the probability of economic success from 50 percent in the Base case to 90 percent, facility size had to increase from 500 acre feet to between 1,725 and 1,750 acre feet, an increase of between 245 percent and 250 percent (Figure 6). This increase in size resulted in an average NPV between $10.73 million and $17.43 million. As compared to other inputs, drastic increases in facility size would be required to make algae production feasible if other inputs are held at Base levels. It is worth noting, however, that increasing size alone was sufficient to make the algae farm economically viable, suggesting the presence of economies of size.

Figure 6: Cumulative Distribution Functions of Net Present Value for Alternative Facility Sizes that Increase the Probability of Economic Success to 90 Percent



For the 1,725 acre feet facility, the estimated per gallon cost of algae oil ranged from $0.64 to $2.12, with an average of $1.19 per gallon (Figure 7). In the 1,750 acre feet facility, cost per gallon estimates ranged from $0.57 to $1.71, with an average of $1.06 per gallon. The 1,725 and 1,750 acre feet facilities represented an improvement of $0.34 and $0.46 per gallon, respectively, over the Base pathway average cost of $1.52 per gallon.

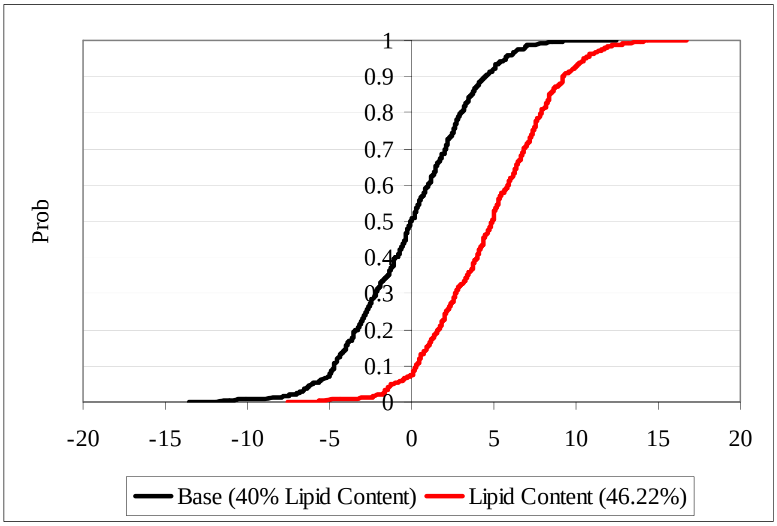
Figure 7: Probability Density Functions of the Estimated per Gallon Cost of Algae Oil for Alternative Algae Facility Sizes that Increase the Probability of Economic Success to 90 Percent



Lipid (Oil) Content

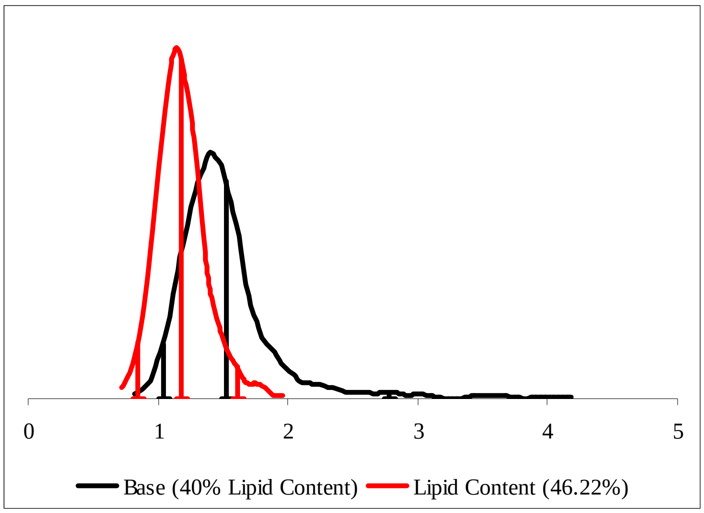
To increase the probability of economic success to 90 percent, lipid content had to increase from 40 percent to 46.22 percent (Figure 8). This increase in lipid content resulted in an average NPV of $4.82 million.

Figure 8: Cumulative Distribution Functions of Net Present Value for Alternative Lipid Contents that Increase the Probability of Economic Success to 90 Percent



At a lipid content of 46.22 percent, the estimated per gallon cost of algae oil ranged from $0.72 to $1.96 with an average of $1.18 per gallon, an improvement of $0.34 per gallon over the Base pathway (Figure 9).

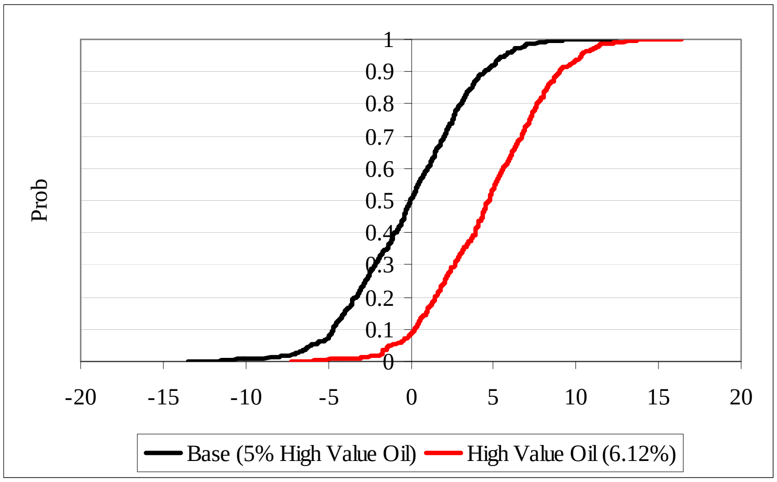
Figure 9: Probability Density Functions of the Estimated per Gallon Cost of Algae Oil for Alternative Lipid Contents that Increase the Probability of Economic Success to 90 Percent



High Value Oil Content

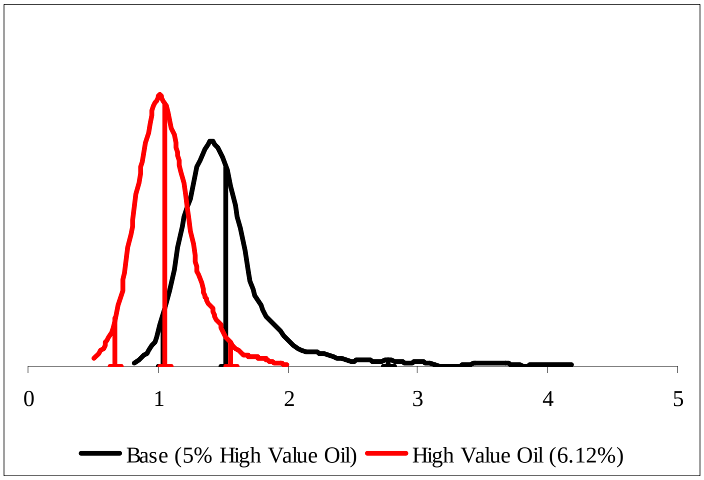
To increase the probability of economic success from 50 percent in the Base case to 90 percent, high value oil content had to increase from 5 percent to 6.12 percent (Figure 10). This increase in high value oil content resulted in an average NPV of $4.65 million.

Figure 10: Cumulative Distribution Functions of Net Present Value for Alternative High Value Oil Contents that Increase the Probability of Economic Success to 90 Percent



At a high value oil content of 6.12 percent, the estimated per gallon cost of algae oil ranged from $0.50 to $1.99 with an average of $1.06 per gallon, an improvement of $0.47 per gallon over the Base pathway (Figure 11).

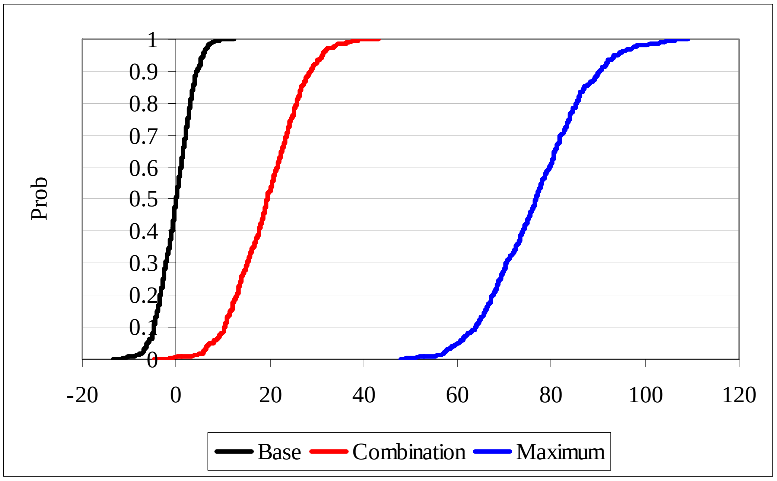
Figure 11: Probability Density Functions of the Estimated per Gallon Cost of Algae Oil for Alternative High Value Oil Contents that Increase the Probability of Economic Success to 90 Percent



Combination of Improvements

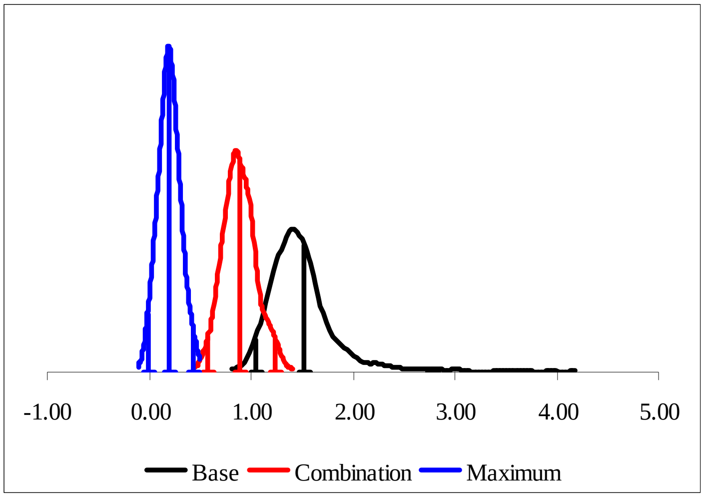
If all improvements are implemented simultaneously (as in the Maximum pathway), there is a 100 percent probability of economic success (Figure 12). Improvements need not be made in all areas for commercial algae production to be economically viable. The Combination scenario—which averages the Base and Maximum scenarios—still results in a greater than 99 percent probability of economic success. The Maximum pathway resulted in an average NPV of $76.75 million while the Combination pathway resulted in an average NPV of $19.41 million.

Figure 12: Cumulative Distribution Functions of Net Present Value for Base, Combination, and Maximum Pathways



As shown in Figure 13, the estimated per gallon cost of algae oil for the Combination pathway ranged from $0.46 to $1.41 with an average of $0.89 per gallon. There is a 77.8 percent probability that total expenses will be less than $1 per gallon of algae oil produced. Cost per gallon estimates for the Maximum pathway ranged from -$0.11 to $0.50 with an average of $0.20 per gallon. In other words, there is a 3.22 percent probability that revenue from co-products alone will more than offset the total expense of producing algae oil in the Maximum pathway.

Figure 13: Probability Density Functions of the Estimated per Gallon Cost of Algae Oil for Base, Combination, and Maximum Pathways



Discussion

Many factors are critical to the economic viability of algae as a renewable fuel, including algae oil/lipid content, high value oil content, production/growth rates, pond water depth, and facility size. While profitable commercialization of algae biomass production likely is still out of reach—evidenced by the fact that we do not see thousands of acres of production—many pathways still need to be identified and researched before we can optimize cultivation, harvesting, and extraction systems for profit.

A stochastic simulation model was developed to estimate the profitability and viability of a microalgae facility in the Desert Southwest. The model estimated both the fixed and variable costs of the facility for a ten-year horizon, including the inflation of variable costs. Using simulation, the model forecasted costs of construction and operation over a ten-year horizon for eleven scenarios. The differences between the scenarios were designed to analyze potential changes to the facility production system or to the operational aspect of the facility to achieve a 90 percent probability of economic success.

Improving significantly upon previous research is important for achieving even a 50 percent probability of economic success. Improving that outlook to a 90 percent probability of economic success will require even greater increases in production levels, percent lipid content, and percent high value oil content, along with increasing pond water depth. However, maximum improvement on all fronts is not required for achieving economic success. Successful ventures will avoid optimizing one variable at a time, but will rely on a systems approach. There is a significant need for continued research on strain selection, cultivation, harvesting, and extraction.

While the current model examines a raceway pond design for commercial facilities, work is underway to expand the model to account for photobioreactors and offshore algae facilities. In addition, the model will be expanded to account for small scale algae farms with cooperatively-owned oil extraction facilities. The projected cost of production per gallon of oil using current input levels is high, but that is typical for an immature industry like microalgae. As the technology and production levels improve, so too will the unit cost of production for microalgae oil.

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