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Working Paper 13-2

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Introduction

The NAABB consortium has analyzed a host of alternative technologies for producing algae biomass, harvesting algae, and extracting oil from the biomass. Many questions remain, such as: Which of the alternative technologies will be best for reducing the costs of producing algae crude oil? What is the best combination of technologies for cultivation, harvesting, and extraction that will provide algae producers greater than a 90% chance of economic success? If changes can be made in algae farming, what changes would have the greatest impact on increasing profits? The tool for answering these and many more questions related to the profitability of algae farming and the costs of algae crude oil is technoeconomic analysis.

Technoeconomic analysis of alternative pathways to produce algae crude oil can provide a projection of the probable economic viability of an algae oil industry in the short run and in the longer run as the industry reaches maturity. Several technoeconomic analyses have emerged recently (e.g., Davis, et al.; Richardson, Johnson and Outlaw; Norsker, et al.; and Chisti). Davis et al. find minimum selling prices for algal lipid of \$8.52/gal for open ponds and \$18.10/gal for PBRs to achieve a 10% internal rate of return in a facility producing 10 MG/year. Richardson, Johnson, and Outlaw also evaluate a production facility producing 10 MG/year and finds that open ponds have a lower cost of production at \$12.74/gal as compared to PBRs which have a cost of production of \$32.57. Norsker, et. al, estimates the production costs to be 4.95, 4.16, and 5.96 €/kg of biomass for open ponds, horizontal tubular PBRs, and flat panel PBRs, respectively, for a 100 hectare facility. Chisti estimates the cost per gallon of production to be \$2.95 and \$3.80 for PBRs and open ponds, respectively, for a facility producing 100,000 kg of biomass annually.

These analyses largely rely on data which is dated and does not reflect the innovations from the NAABB consortium. The purpose of this paper is to conduct a comprehensive technoeconomic analysis of alternative technologies developed/reported by the NAABB consortium in the areas of biology, cultivation, harvesting and extraction.

Objective

The objective is to estimate the financial feasibility for six alternative pathways to produce crude oil from microalgae. The pathways to be analyzed are based on the research conducted by the NAABB consortium.

Methods

A Monte Carlo simulation model for analyzing the financial feasibility and economic viability of algae to crude oil pathways is used to analyze the six alternative NAABB pathways. The Farm-level Algae Risk Model (FARM) was developed for the NAABB project and is used for the analysis. FARM is a Monte Carlo firm level simulation model designed to simulate the annual cultivation, harvesting, extraction, and financial/economic activities of an algae farm. The model is designed to facilitate researchers analysis of the economic returns and costs of crude oil production for an algae farm under alternative management systems. The model can be thought of as an integrated systems compilation of many techno-economic models for different phases of an algae farm.

Information to simulate the six alternative pathways comes from research funded by the Department of Energy. Alternative cultivation systems, biology assumptions, harvesting systems, and extraction methods are analyzed in the report. The results provide estimates of the probability of economic success for each pathway, as well as the costs of production for algae crude oil and the sensitivity of the costs of production to changes in CAPEX and OPEX.

The FARM model simulates an algae business recursively for 10 years. This means that the ending cash flow position of the business in year 1 is the beginning cash flow position for year 2, and so on. The 10 year planning horizon is repeated 500 times (iterations) using different stochastic prices, rates of inflation, and production values for each year. By simulating the 10 year planning horizon for 500 iterations, the model is able to simulate most all combinations of the stochastic variables, (i.e., the best and worst cases and those in between) based on their respective probabilities of being observed. The resulting 500 values for the key output variables are estimates of empirical probability distributions for these variables and are used to calculate probabilities of financial and economic sustainability. For a detailed description of FARM see Appendix A.

FARM requires that all input for an algae farm be entered in the INPUT worksheet and most all calculations are in the MODEL worksheet. The model is simulated by drawing annual stochastic prices, production, and costs randomly from known probability distributions. The parameters for the distributions are provided as input by the researcher. Analysts must enter all of the data to describe the scenario to simulate for a farm. This includes data for the type of cultivation, harvesting, extraction, and use of co-products.

FARM is programmed to accommodate many different production systems. One option in the production system is the source of the biomass production data; Pacific Northwest National Laboratory (PNNL) pre-loaded regional production data can be elected or the user can specify their own monthly biomass growth rates with assumed risk. Additionally, water recycle and batch harvesting can be selected. The analyst must also enter information regarding the size of the production facility, i.e., acre feet per harvested pond, grams per liter density of the harvested culture, days of operation, number of harvests per month, and pond crash probability. FARM then draws values at random from the probability distributions to determine the algae growth rate each month, the number of harvests per month and whether there was a pond crash or not each month. Combining the growth rate with the area under cultivation, pond crashes, and number of harvests per month allows FARM to compute the amount of biomass produced annually.

Additionally, the analyst must enter information regarding the harvesting and extraction system used on the farm. There are pre-programmed options for both harvesting and extraction. For harvesting they are: chemical flocculation, centrifuge, and electrocoagulation (EC). For extraction the pre-programmed options are: wet solvent extraction, Hydro-Thermal Liquefaction – Catalytic Hydro-thermal Gasification (HTL-CHG), and Pyrolysis. Capital Expenses (CAPEX) and operating expenses (OPEX) for the farm must be entered as well. The analyst must also specify the financial and debt financing information for the farm. This information is used in ProForma Financial statements to calculate principal payments, interest costs, and investor dividends.

Based on parameters entered by the analyst, the annual production of lipid, lipid extracted algae, methane, or other selected co-products are calculated. These annual production figures, combined with the stochastic market prices for the products (algae crude oil, high valued oils, and lipid extracted algae) are used in calculating the annual receipts for the farm. These values are then used in the Income Statement.

After receipts are calculated all costs for the farm are calculated on an annual basis based on information entered in the INPUTS page by the analyst. Net water loss is calculated based on stochastic precipitation, evaporation, and water recycled. Then, the stochastic cost of acquiring new water is paired with the net water loss to determine the cost of water for the farm. The analyst can provide operating costs in two ways: an annual sum for the operating cost category or by providing ratios of consumption or use per short ton of algae produced or processed. If an annual value is entered for an operating cost category it is inflated over the farm's 10 year span and then summarized in the Expenses section of the Income Statement. If a ratio is instead entered the cost is calculated in the model as well. For example, if one pound of CO_2 is required for each pound of biomass produced then the total pounds of CO_2 required for the farm will be calculated based on that year's stochastic biomass production. Once the total amount of material is calculated it is multiplied by that year's inflated price for the input to determine the annual expense to the farm for the operating cost category. The operating cost categories include, but are not limited to, CO_2, media, water, harvesting and extraction chemicals and catalysts, and natural gas. The costs from each of the operating expense categories also flow to the Income Statement and are used to calculate the operating loan interest costs as well as the annual net cash income.

Scenarios

The six scenarios selected for the present analysis were specified to highlight the research results from the NAABB consortium. The different combinations of biology, cultivation, harvesting and extraction are summarized in Table 1. Scenario 1 reflects the early stages of NAABB with reduced algae production rates and uses conventional methods for cultivation, harvesting, and extraction. Scenario 2 is provided to highlight the economic contributions of using electrocoagulation (EC) in place of centrifuges for harvesting. The comparison of Scenario1 to Scenario 3 allows one to quantify the economic gains of HTL-CHG over using wet solvent extraction and conventional algae production and harvesting parameters. Scenario 4 combines the improvements in harvesting (EC), extraction (HTL-CHG), and algae productivity. The total economic gains in scenario 4 can be compared to scenario 1 to evaluate the improvement since the beginning of NAABB. Scenario 5 is used to highlight the economic contributions of the ARID cultivation system and its associated increased productivity to the open pond cultivation system with unimproved growth productivity. Scenario 6 is the same as Scenario 5 but with the same assumed increase in biomass production as in Scenario 4. The three new processes from the NAABB consortium that are evaluated in the scenarios are summarized in Table 1.

Table 1. Summary of the Technologies Analyzed for the Alternative Scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Products	Algae Crude Oil & LEA	Algae Crude Oil & LEA	Algae Crude Oil & Methane	Algae Crude Oil & Methane	Algae Crude Oil & Methane	Algae Crude Oil & Methane
Cultivation	Open Pond w/ Liners	Open Pond w/ Liners	Open Pond w/ Liners	Open Pond w/ Liners	ARID	ARID
Biology	Generic	Generic	Generic	GMO	Generic	GMO
Harvesting	Centrifuge	Electrocoagulation (EC)	Centrifuge	EC	EC	EC
Extraction	Wet Solvent Extraction	Wet Solvent Extraction	HTL-CHG	HTL-CHG	HTL-CHG	HTL-CHG
Nutrient Recycling	No	No	Yes	Yes	Yes	Yes
Biomass Production (Tons/Yr)	119,883	119,883	119,883	316,831	152,215	378,591
Crude Oil Production (Gallons/Yr)	4,679,762	5,095,741	13,505,602	42,320,555	20,332,113	50,570,129
Location	Pecos, TX	Pecos, TX	Pecos, TX	Pecos, TX	Tucson, AZ	Tucson, AZ

Each Scenario in Table 1was programmed in FARM as a separate farm so as to eliminate the chance of crossing the technologies during the analysis. Basic information for the algae farms comes from the CAPEX and OPEX cost information provided by Davis, et al. (2012) DOE harmonization report as this is a standard for comparison. Changes to the DOE baseline CAPEX and OPEX were made to account for the differences in costs for the alternative technologies summarized in Table 1. The biggest changes were those associated with

Scenario 5 and 6 as the ARID system is quite different from the open ponds used for the other scenarios. Where CAPEX, OPEX, and biomass production differ for ARID from open pond, information was provided by researchers at the University of Arizona (U of A).

The Davis et al. DOE Harmonization report included capital and operating costs for an algae farm, a diesel plant, and an anaerobic digester. For the present study the final products were crude algal oil and lipid extracted algae (LEA) or methane, so Davis' capital and operating costs for the diesel plant and anaerobic digester were not included. In the DOE harmonization analysis the algal oil facilities produced 10.4 MG/year of diesel on each representative farm.

Algae farms for Scenarios 1-4 are assumed to be located in Pecos, Texas, and the fifth and sixth farms are located in Tucson, Arizona. The fifth and sixth farms are located in Tucson, Arizona, because that is the only location where the ARID raceway system has been tested. The baseline monthly biomass production for both farm locations was simulated by the Pacific Northwest National Laboratory (PNNL)'s Biomass Assessment Tool (BAT) for the DOE study. The BAT model produced monthly biomass yields for 30 years based on simulated monthly weather data for the farm sites. Additionally, the BAT model produced 30 years of lipid production and net water requirements. The 30 years of monthly data from the BAT model was used to estimate a multivariate probability distribution of monthly biomass, lipid and water consumption. The multivariate distributions of biomass production and water consumption are used in the FARM model to simulate stochastic biomass production, lipid production and net water requirements for the representative farms. CAPEX and OPEX costs in the Davis, et al. study were scaled for each of the six farms based on the average annual biomass production levels for the six farms. The BAT biomass probability distributions were scaled up on a relative basis to accommodate the increased biomass production for Scenarios 4-6.

Electrocoagulation harvesting utilizes metal ions, which are released during electrolysis between two metal plates submerged in the media. A number of metals can be used including aluminum and stainless steel. Aluminum plates release aluminum ions with a +3 charge, while stainless steel electrodes release iron ions with a +2 charge. The positively charged metal ions attract the negatively charged algae and create a floc. The floc then settles to the bottom of the media and is separated by decanting the clear media from the top, which can be recycled to the cultivation process. The algae are concentrated from approximately 1 g/L in cultivation to around 8% solids (80 g/L) in the sediment. The capacity of the electrocoagulation unit is determined by the size of the plates, the electrode material, and the volume of the reactor chamber. Stainless steel electrodes were evaluated to avoid ion release that reduces the value of LEA for animal feed. Electro-flocculation has the advantage of leaving no ions in the algae residue, a potential issue for downstream processing.

HTL-CHG is a process in which algae biomass is transformed into oil and methane or electricity. Other output streams from this process include phosphate, CO_2, water, and other nutrients that can be recycled back to the ponds. The harvested algae are brought in and are made into a slurry for the process. The algae slurry is heated and pressurized. The output from this step is an oil formation consisting of oil and effluent water, along with a solid precipitate, phosphate. The phosphate can be recovered and sent for remake, after which it can be recycled to the ponds. Once the oil and water are separated the oil can be upgraded just like crude oil. The effluent water is then sent on to CHG for further processing. Once the effluent water reaches the CHG process it is again made into a slurry that is heated and pressurized to produce a liquid and precipitate, phosphorus, that can be processed and recycled. The liquid is then combined with a catalyst in the gasifier to produce CH_4 and CO_2. This CH_4 can be sold or turned into electricity, heat or CNG. The CO_2 can be recycled to the ponds and the remaining gas/water mixture can be further separated to obtain the CO_2 from the water and nutrients mixture, all of which can then be recycled to the ponds.

The ARID cultivation system was designed to improve temperature control and increase the algae production rate. The ARID system includes a deep canal and a serpentine flow path through shallow channels. Temperature is regulated by varying the water surface area between day and night. Removing the water from the serpentine channels at night reduces long wave radiation to the night sky and convective heat loss. The ARID system reduces energy input through recirculation of water in the channel area and only drops water into the canal when necessary for temperature management, cleaning, or harvesting. A significant advantage to ARID is its reduced CAPEX relative to conventional open ponds (Table 2).

Table 2. Key Input Parameters and Operating Costs for Six Scenarios.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
	Centrifuge – Wet Solvent	EC – Wet Solvent	Centrifuge – HTL-CHG	EC – HTL-CHG	ARID EC-HTL-CHG	ARID Increased Productivity
Location	Pecos, TX	Pecos, TX	Pecos, TX	Pecos, TX	Tucson, AZ	Tucson, AZ
Cultivation	Open Pond	Open Pond	Open Pond	Open Pond	ARID	ARID
Total Hectares of Land	4,850	4,850	4,850	4,850	4,850	4,850
Total Hectares of Ponds	4,050	4,050	4,050	4,050	4,050	4,050
Total Volume of Ponds (AF)	9,855	9,855	9,855	9,855	2,941	2,941
Total Volume of Ponds (Mil. L)	12,156	12,156	12,156	12,156	3.63	3.63
Days of Operation	330	330	330	330	330	330
Harvesting	Centrifuge	Electrocoagulation	Centrifuge	Electrocoagulation	Electrocoagulation	Electrocoagulation
Throughput Capacity (L/Hr)	113,560	408,780	113,560	408,780	408,780	408,780
Capital Cost (M$s/Unit)	0.275	0.65	0.275	0.65	0.65	0.65
Number of Units	2,231	620	2,231	620	185	185
Total Harvesting Capital Cost (M$s)	613.5	403.35	613.5	403.35	120.6	120.6
% Solids	10%	8%	10%	8%	8%	8%
Harvesting Chemicals OPEX (M$s/Yr 5)	0	19.52	0	19.52	5.83	5.83
Extraction	Wet Solvent	Wet Solvent	HTL-CHG	HTL-CHG	HTL-CHG	HTL-CHG
Throughput Capacity (L/Hr)	394,314	394,314	39,583	39,583	39,583	39,583
Capital Cost (M$s/Unit)	23.57	23.57	10.20	10.20	10.20	10.20
Number of Units	1	1	7	21	3	8
Total Extraction Capital Cost (M$s)	23.57	23.57	71.42	214.27	30.61	81.63
Extraction Chemicals OPEX (M$s/Yr 5)	14.09	14.09	0	0	0	0
Extraction Chemicals Startup Cost ($)	0	0	34.78	104.33	14.90	39.74
CAPEX (M$s)						
Land	35.9	35.9	35.9	35.9	35.9	35.9
Construction	6.7	6.7	6.7	6.7	158.98	158.98
Liner	205.2	205.2	205.2	205.2	156.94	156.94
Paddlewheels	138.6	138.6	138.6	138.6	0	0
Total CAPEX	1,211.9	1,001,8	1,259,8	1,192,5	1,109.3	1,070.3
Unallocated CAPEX (M$s)						
Labor & Overhead	4.9	4.9	5.0	5.2	6.4	6.5
Natural Gas	477.2	418.7	3.7	8.9	5.0	10.7
Electricity	5.5	5.4	6.0	7.1	2.3	3,9
Maintenance	41.7	17.0	43.2	25.2	18.1	20.4
Insurance	2.6	2.0	2.5	2.4	2.0	2.1
Interest	260.9	224.1	95.5	63.8	82.4	54.2
Total OPEX Year 5	812.4	713.0	162.2	140.9	143.9	126.7

Scenario 1

The Baseline Scenario uses an open pond cultivation system with a liner and produces crude algal oil and LEA. The farm requires 2,231 centrifuges for harvesting along with one wet solvent extraction system. The centrifuges have a throughput capacity of 113,560 liters/hour and produce an output that is 10% solids. There is no chemical cost associated with the centrifuge harvesting process. The centrifuges only require electricity. Each centrifuge costs $275,000, resulting in a total CAPEX of $613,525,000 for harvesting equipment. The extraction system can process 394,314 liters of 10% algae solution per hour. Only one extraction system is needed with a total extraction CAPEX of $23,566,667. Makeup solvent is required after each harvest, resulting in an annual cost for extraction chemicals. In the fifth year of operation the extraction chemical cost is $14,091,358.

Scenario 2

Scenario 2 uses a lined open pond cultivation system to produce crude algal oil and LEA. Electrocoagulation is used for harvesting with a wet solvent system for extraction. The EC units have a throughput capacity of 408,780 liters per hour so 620 EC units are required for harvesting. The capital cost for the EC units is $1,000,000 for the first unit and $650,000 for each additional unit. This results in a total CAPEX of $403,350,000 for the EC units. The output of the EC is 8% solids. The EC units require stainless steel plates which degrade over time and must be replaced, resulting in an annual replacement cost. In year five of operation the plate replacement cost is $19,517,998. Similar to the first scenario, only one wet solvent extraction system with a throughput capacity of 394,314 liters per hour is required at a cost of $23,566,667. The makeup solvent cost in year five for this farm is $14,091,358.

Scenario 3

In Scenario 3 algal crude oil and methane are produced using a lined open pond cultivation system. With a throughput capacity of 113,560 liters per hour, 2,231 centrifuge units are used for harvesting. The capital cost per centrifuge is $275,000, resulting in a total CAPEX for harvesting of $613,525,000. Algal oil is obtained from extraction when HTL-CHG is used. However, no LEA is produced as the co-product is methane. The HTL-CHG units have a throughput capacity of 39,583 liters per hour so more units are required as compared to the wet solvent extraction system. The capital cost of each unit is $10,203,472. Since the output from the centrifuge is 10% solids only 7 HTL-CHG units are required, resulting in a total CAPEX of $71,424,304. There is a one-time startup cost for catalyst associated with the HTL-CHG units. The total extraction catalyst startup cost is $34,775,342.

Scenario 4

The fourth Scenario uses HTL-CHG for extraction, so algal crude oil and methane are produced. The algae are grown in lined open ponds. However, this farm has increased biomass productivity as compared to the first three scenarios. NAABB biologists report that genetically modified algae strains are more productive with the same resources. In this scenario, biomass production is increased by 50% in the winter (October-February), 100% in the spring and fall (March, July-September), and 200% in the summer (April-June). Even though there is increased biomass productivity the number of EC units required does not change from Scenario 2, because the same amount of water is being used to produce more biomass. A total of 620 EC units are required at a price of $1,000,000 for the first and $650,000 for each unit after. The total CAPEX for harvesting is $403,350,000. The output of the EC is 8% solids and the cost of replacement for the stainless steel plates in year five is $19,517,998. For Scenario 4 HTL-CHG units with throughput capacities of 39,583 liters per hour are used for extraction. Due to the lower percent solids output of the EC compared to the centrifuges and the fact that the algae culture is a higher density 21 HTL-CHG units are required compared to the 7 in Scenario 3. Twenty-one HTL-CHG units are required at a price of $10,203,000 per unit, resulting in a total CAPEX cost of $214,272,912 for extraction. The extraction catalyst startup cost is also increased compared to the third scenario because of the additional HTL-CHG units. This startup cost for Scenario 4 is $104,326,026.

Scenario 5

The fifth Scenario is for an algae farm located in Tucson, Arizona, and uses the ARID cultivation system. BAT generated probability distributions of biomass production in Tucson, Arizona were adapted to actual biomass production records for ARID. At any point during the year when BAT open pond production is greater than ARID, the farm is operated as an open pond facility. The Scenario 5 farm produces crude algal oil and methane and uses EC for harvesting and HTL-CHG for extraction. Due to the reduced water use in the ARID system, less fluid has to be processed by the harvesting and extraction units. Thus, only 185 EC units with a throughput capacity of 408,780 liters per hour are required as opposed to the other scenarios which needed 620. Total CAPEX cost for harvesting is reduced to $120,600,000, which is significantly lower compared to all other scenarios. The stainless steel plate replacement cost for EC is reduced to $5,827,468. Additionally, only three HTL-CHG units are required for extraction resulting in a total CAPEX of $30,610,416. The startup catalyst cost is also reduced to $14,903,718 since only three units are required.

Scenario 6

The sixth Scenario is also for an algae farm located in Tucson, Arizona, using the ARID cultivation system. However, this farm has increased biomass productivity as compared to the fifth scenario that is also located in Tucson, Arizona. NAABB biologists report that genetically modified algae strains are more productive with the same resources. In this scenario, biomass production is increased by 50% in the winter (October-February), 100% in the spring and fall (March, July-September), and 200% in the summer (April-June). Even though there is increased biomass productivity the number of EC units required does not change from Scenario 5, because the same amount of water is being used to produce more biomass. At any point during the year when BAT open pond production is greater than ARID, the farm is operated as an open pond facility. This farm produces crude algal oil and methane and uses EC for harvesting and HTL-CHG for extraction. 185 EC units with a throughput capacity of 408,780 liters per hour are required. Total CAPEX cost for harvesting is $120,600,000. The stainless steel plate replacement cost for EC is reduced to $5,827,468. Additionally, eight HTL-CHG units are required for extraction resulting in a total CAPEX of $81,627,776. The startup catalyst cost is also $39,743,248 since eight units are required.

The major cost items in CAPEX and OPEX are also listed in Table 2. Land, construction, liner, and paddlewheels costs are the largest cost categories for the six farms. These cost categories are constant for Scenarios 1-4. Because the ARID system has a different design its CAPEX costs differ on construction and liner. The ARID system also does not require paddlewheels. Overall, the construction costs of the ARID system are more expensive than the open ponds, but the system saves in total CAPEX as fewer harvesting and extraction units are required. The total CAPEX for the ARID system is very comparable to the other four scenarios.

The largest OPEX categories are labor and overhead, natural gas, electricity, maintenance, and insurance (Table 2). There are many different processes on the algae farms that involve these cost categories, so these costs are unallocated to specific functions. The largest cost that is common to all of the scenarios is the interest cost due to high CAPEX costs. Interest costs are calculated assuming the farm has a 50% equity initially so

50% of all CAPEX is financed using a fixed interest rate for 10 years at 8% interest. In addition to paying interest for money to finance CAPEX, algae farms must pay a dividend to the investors who put up the money for 50% equity so the farm can qualify for a 50% equity loan.

In the scenarios where wet solvent extraction is utilized the natural gas costs are also noticeably high (Table 2). This is because the wet solvent system requires the use of natural gas to dry the LEA. Maintenance is also very high for the farms. The electricity, labor and overhead and insurance costs are low on a relative basis. The total OPEX for using wet solvent extraction is more than half a billion dollars. Even when the best case data are employed OPEX costs still total more than $150,000,000 dollars in year five.

Results

Results for analyzing the six scenarios over a 10 year planning horizon are summarized using a reduced number of key output variables from FARM. The overall profitability of an algae farm scenario is reported using the net present value (NPV) and probability of economic success.[1] Each farm scenario was simulated 100 times for all combinations of reducing CAPEX and OPEX in 10% increments from 0 to 90%. This results in a matrix of 100 average NPV's and probabilities of economic success. The resulting matrix provides a sensitivity analysis indicating the potential profitability if CAPEX and OPEX can be reduced by alternative fractions.

Additional key output variables used to summarize the farm scenario results are: average ending cash reserves in year 10, total cost per gallon of algae lipid, and marginal cost per gallon of algae lipid. All of the key output variables are presented using the 10 x 10 matrix for alternative reductions in CAPEX and OPEX. The values in the tables are color-coded using a stoplight scheme of red, yellow, and green for bad, marginal, and good.

Scenario 1 Results

Scenario 1 evaluates the financial feasibility of an algae farm with the base technology for the NAABB consortium. A lined open pond cultivation system, centrifuge harvesting, and wet solvent extraction were all utilized in this scenario. The average net present value for each fractional reduction in CAPEX and OPEX for Scenario 1 is summarized in Table 3. A negative average net present value means that on average the farm does not earn a return on its initial equity greater than the 10% discount rate. A positive average net present value indicates that on average the farm earned a return greater than the discount rate and that the average internal rate of return exceeded the discount rate. For the algae farm in Scenario 1 to obtain a positive average net present value both CAPEX and OPEX must be reduced by more than 90%. Investors in any farm that does not reduce CAPEX and OPEX by greater than 90% will lose all of their initial investment and more within 10 years.

[1] Net present value equals the sum of annual present values for dividends paid to investors plus the present value of ending net worth minus beginning net worth; all discounted using a 10% discount rate. The probability of economic success is the probability that the farm scenario generates a positive NPV, i.e., that the internal rate of return exceeds the 10% discount rate.

Table 3. Average Net Present Value for Scenario 1 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Net Present Value (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-4032.13	-3918.99	-3805.86	-3692.72	-3579.59	-3466.45	-3353.31	-3240.18	-3127.04	-3013.91
0.1	-3719.65	-3606.65	-3493.66	-3380.66	-3267.67	-3154.67	-3041.68	-2928.68	-2815.69	-2702.69
0.2	-3407.17	-3294.31	-3181.46	-3068.60	-2955.75	-2842.89	-2730.04	-2617.19	-2504.33	-2391.48
0.3	-3094.68	-2981.97	-2869.26	-2756.54	-2643.83	-2531.12	-2418.40	-2305.69	-2192.97	-2080.26
0.4	-2782.20	-2669.63	-2557.06	-2444.48	-2331.91	-2219.34	-2106.76	-1994.19	-1881.62	-1769.04
0.5	-2469.72	-2357.29	-2244.86	-2132.43	-2019.99	-1907.56	-1795.13	-1682.69	-1570.26	-1457.83
0.6	-2157.24	-2044.95	-1932.66	-1820.37	-1708.07	-1595.78	-1483.49	-1371.20	-1258.91	-1146.61
0.7	-1844.76	-1732.61	-1620.46	-1508.31	-1396.16	-1284.00	-1171.85	-1059.70	-947.55	-835.40
0.8	-1532.28	-1420.27	-1308.26	-1196.25	-1084.24	-972.23	-860.21	-748.20	-636.19	-524.18
0.9	-1219.80	-1107.93	-996.06	-884.19	-772.32	-660.45	-548.58	-436.70	-324.83	-212.95

The probability of economic success is calculated as the probability that net present values will be positive over the 500 iterations. So the probability of success is the probability that the farm will earn an average internal rate of return greater than the investor's discount rate (or opportunity return for investing in another business). The probability of economic success for each combination of fractional reductions in CAPEX and OPEX for the algae farm in Scenario 1 appears in Table 4. There are no combinations of reductions in CAPEX and OPEX that result in a probability of economic success greater than zero.

Table 4. Probability of Economic Success for Scenario 1 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5 reports the average ending cash reserves for each fractional reduction in CAPEX and OPEX for the algae farm in Scenario 1. None of the combinations of fractional reductions in CAPEX and OPEX result in positive average ending cash reserves in year 10 for Scenario 1.

Table 5. Average Ending Cash Reserves in Year 10 for Scenario 1 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Ending Cash Reserves in Year 10 (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-10238.03	-9966.43	-9694.83	-9423.24	-9151.64	-8880.04	-8608.45	-8336.85	-8065.26	-7793.66
0.1	-9427.53	-9156.30	-8885.07	-8613.84	-8342.60	-8071.37	-7800.14	-7528.91	-7257.68	-6986.44
0.2	-8617.04	-8346.17	-8075.30	-7804.44	-7533.57	-7262.70	-6991.83	-6720.97	-6450.10	-6179.23
0.3	-7806.54	-7536.04	-7265.54	-6995.03	-6724.53	-6454.03	-6183.53	-5913.02	-5642.52	-5372.02
0.4	-6996.05	-6725.91	-6455.77	-6185.63	-5915.49	-5645.36	-5375.22	-5105.08	-4834.94	-4564.80
0.5	-6185.55	-5915.78	-5646.01	-5376.23	-5106.46	-4836.68	-4566.91	-4297.14	-4027.36	-3757.59
0.6	-5375.06	-5105.65	-4836.24	-4566.83	-4297.42	-4028.01	-3758.60	-3489.19	-3219.78	-2950.37
0.7	-4564.56	-4295.52	-4026.47	-3757.43	-3488.38	-3219.34	-2950.29	-2681.25	-2412.20	-2143.16
0.8	-3754.07	-3485.39	-3216.71	-2948.03	-2679.35	-2410.67	-2141.99	-1873.31	-1604.63	-1335.95
0.9	-2943.57	-2675.26	-2406.94	-2138.63	-1870.31	-1602.00	-1333.68	-1065.39	-797.12	-528.98

Table 6 reports the total cost ($/gallon) of lipid and Table 7 reports the marginal cost ($/gallon) of lipid for each of the fractional reductions in CAPEX and OPEX for the algae farm in Scenario 1. The marginal cost ($/gallon) is the operating expense per gallon of lipid associated with producing the next gallon of lipid. Marginal cost assumes all fixed costs have been covered. The total cost ($/gallon) is the marginal cost plus interest and dividend payments and depreciation per gallon of lipid, so total cost takes into account fixed costs. In a mature industry the marginal cost per gallon would be the cost of producing an additional gallon of lipid and it will be the price that a consumer pays for a gallon of lipid. When there is no reduction in CAPEX and OPEX the total cost for lipid is very high and remains so even with a 90% reduction in CAPEX and OPEX. When there is no reduction in CAPEX and OPEX the marginal cost for lipid is also extremely high. Even with a 90% reduction in the OPEX the farm is still not feasible as the marginal cost exceeds $13/gallon. The marginal cost does not change significantly over the CAPEX reductions due to the fact that the marginal cost does not take into account fixed costs. The base technology that NAABB started with is not feasible for development into an economically viable industry.

Table 6. Average Total Cost of Algae Lipid for Scenario 1 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	230.63	224.28	217.93	211.59	205.24	198.89	192.55	186.20	179.85	173.51
0.1	212.99	206.65	200.31	193.98	187.64	181.30	174.96	168.62	162.28	155.94
0.2	195.36	189.03	182.69	176.36	170.03	163.70	157.37	151.04	144.71	138.37
0.3	177.72	171.40	165.07	158.75	152.43	146.10	139.78	133.46	127.13	120.81
0.4	160.09	153.77	147.45	141.14	134.82	128.51	122.19	115.87	109.56	103.24
0.5	142.45	136.14	129.83	123.53	117.22	110.91	104.60	98.29	91.99	85.68
0.6	124.81	118.51	112.21	105.91	99.61	93.31	87.01	80.71	74.41	68.11
0.7	107.18	100.89	94.59	88.30	82.01	75.72	69.42	63.13	56.84	50.55
0.8	89.54	83.26	76.97	70.69	64.40	58.12	51.83	45.55	39.26	33.02
0.9	71.91	65.63	59.35	53.08	46.80	40.52	34.25	27.97	21.81	16.92

Table 7. Average Marginal Cost of Algae Lipid for Scenario 1 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	132.21	132.15	132.09	132.03	131.97	131.92	131.86	131.80	131.74	131.68
0.1	118.99	118.93	118.88	118.83	118.78	118.72	118.67	118.62	118.57	118.51
0.2	105.77	105.72	105.67	105.63	105.58	105.53	105.49	105.44	105.39	105.35
0.3	92.55	92.50	92.46	92.42	92.38	92.34	92.30	92.26	92.22	92.18
0.4	79.32	79.29	79.25	79.22	79.18	79.15	79.11	79.08	79.04	79.01
0.5	66.10	66.07	66.05	66.02	65.99	65.96	65.93	65.90	65.87	65.84
0.6	52.88	52.86	52.84	52.81	52.79	52.77	52.74	52.72	52.70	52.67
0.7	39.66	39.64	39.63	39.61	39.59	39.57	39.56	39.54	39.52	39.50
0.8	26.44	26.43	26.42	26.41	26.39	26.38	26.37	26.36	26.35	26.34
0.9	13.22	13.21	13.21	13.20	13.20	13.19	13.19	13.18	13.17	13.17

Scenario 2 Results

Scenario 2 offers a comparison of the EC harvesting system and its impacts on financial feasibility. Other than the difference in harvesting systems, Scenario 2 is identical to Scenario 1. The average net present value for each fractional reduction in CAPEX and OPEX for Scenario 2 is summarized in Table 8. For the algae farm in Scenario 2 to obtain a positive average net present value both CAPEX and OPEX must be reduced by more than 90%. Compared to Scenario 1, Scenario 2 offers a slight improvement. By comparing the average net present values it is observed that the values for Scenario 2 are slightly less negative than the values in Scenario 1. This increase indicates an improvement in Scenario 2 over Scenario 1. Thus, in identical situations the EC harvesting system offers an improvement over the base technology centrifuge system.

Table 8. Average Net Present Value for Scenario 2 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Net Present Value (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-3778.12	-3685.60	-3593.09	-3500.58	-3408.06	-3315.55	-3223.04	-3130.52	-3038.01	-2945.50
0.1	-3468.81	-3376.41	-3284.01	-3191.62	-3099.22	-3006.82	-2914.42	-2822.03	-2729.63	-2637.23
0.2	-3159.50	-3067.22	-2974.93	-2882.65	-2790.37	-2698.09	-2605.81	-2513.53	-2421.25	-2328.97
0.3	-2850.19	-2758.02	-2665.86	-2573.69	-2481.53	-2389.36	-2297.20	-2205.03	-2112.87	-2020.70
0.4	-2540.88	-2448.83	-2356.78	-2264.73	-2172.68	-2080.63	-1988.58	-1896.54	-1804.49	-1712.44
0.5	-2231.57	-2139.63	-2047.70	-1955.77	-1863.84	-1771.90	-1679.97	-1588.04	-1496.11	-1404.17
0.6	-1922.26	-1830.44	-1738.62	-1646.81	-1554.99	-1463.17	-1371.36	-1279.54	-1187.73	-1095.91
0.7	-1612.95	-1521.25	-1429.55	-1337.85	-1246.15	-1154.44	-1062.74	-971.04	-879.34	-787.64
0.8	-1303.64	-1212.05	-1120.47	-1028.88	-937.30	-845.72	-754.13	-662.55	-570.96	-479.38
0.9	-994.33	-902.86	-811.39	-719.92	-628.45	-536.99	-445.52	-354.04	-262.57	-171.09

In Table 9 we report the probability of economic success for each combination of fractional reductions in CAPEX and OPEX for the algae farm in Scenario 2. There are no combinations of reductions in CAPEX and OPEX that result in a greater than zero probability of economic success. Even though the EC harvesting system has a positive impact on average net present value, it is not enough to offer any positive probability of economic success.

Table 9. Probability of Economic Success for Scenario 2 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 10 reports the average ending cash reserves for each fractional reduction in CAPEX and OPEX for the algae farm in Scenario 2. It will take more than a 90% reduction in CAPEX and OPEX to have a positive average of ending cash flow.

Table 10. Average Ending Cash Reserves in Year 10 for Scenario 2 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Ending Cash Reserves in Year 10 (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-9621.05	-9398.75	-9176.46	-8954.16	-8731.87	-8509.58	-8287.28	-8064.99	-7842.70	-7620.40
0.1	-8818.77	-8596.78	-8374.79	-8152.80	-7930.81	-7708.81	-7486.82	-7264.83	-7042.84	-6820.84
0.2	-8016.50	-7794.81	-7573.12	-7351.43	-7129.74	-6908.05	-6686.36	-6464.67	-6242.98	-6021.28
0.3	-7214.23	-6992.84	-6771.45	-6550.06	-6328.67	-6107.28	-5885.89	-5664.50	-5443.11	-5221.72
0.4	-6411.96	-6190.87	-5969.79	-5748.70	-5527.61	-5306.52	-5085.43	-4864.34	-4643.25	-4422.17
0.5	-5609.69	-5388.90	-5168.12	-4947.33	-4726.54	-4505.76	-4284.97	-4064.18	-3843.39	-3622.61
0.6	-4807.42	-4586.93	-4366.45	-4145.96	-3925.48	-3704.99	-3484.50	-3264.02	-3043.53	-2823.05
0.7	-4005.15	-3784.97	-3564.78	-3344.60	-3124.41	-2904.23	-2684.04	-2463.86	-2243.67	-2023.49
0.8	-3202.88	-2983.00	-2763.11	-2543.23	-2323.34	-2103.46	-1883.58	-1663.69	-1443.81	-1223.93
0.9	-2400.61	-2181.03	-1961.44	-1741.86	-1522.28	-1302.70	-1083.15	-863.65	-644.27	-425.23

Table 11 reports the total cost ($/gallon) of lipid and Table 12 reports the marginal cost ($/gallon) of lipid for each of the fractional reductions in CAPEX and OPEX for the algae farm in Scenario 2. When there is no reduction in CAPEX and OPEX the total cost for lipid is more than $200/gallon and remains high even with a 90% reduction in CAPEX and OPEX ($14.87/gallon). When there is no reduction in CAPEX and OPEX the marginal cost for lipid is also extremely high ($119.99/gallon). With a 90% reduction in the OPEX the marginal cost is still not feasible at nearly $12/gallon. Again, when Scenario 1 is compared to Scenario 2 it is demonstrated that by using the improved harvesting technology total cost ($/gallon) of lipid, marginal cost ($/gallon) of lipid, and total cost ($/ton) of biomass would be decreased.

Table 11. Average Total Cost of Algae Lipid for Scenario 2 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	198.48	193.73	188.99	184.25	179.50	174.76	170.02	165.28	160.53	155.79
0.1	182.47	177.74	173.00	168.26	163.52	158.79	154.05	149.31	144.58	139.84
0.2	166.47	161.74	157.01	152.28	147.54	142.81	138.08	133.35	128.62	123.89
0.3	150.47	145.74	141.02	136.29	131.56	126.84	122.11	117.39	112.66	107.94
0.4	134.46	129.74	125.02	120.30	115.58	110.86	106.15	101.43	96.71	91.99
0.5	118.46	113.74	109.03	104.32	99.60	94.89	90.18	85.46	80.75	76.04
0.6	102.45	97.75	93.04	88.33	83.62	78.92	74.21	69.50	64.79	60.09
0.7	86.45	81.75	77.05	72.35	67.64	62.94	58.24	53.54	48.84	44.14
0.8	70.45	65.75	61.06	56.36	51.66	46.97	42.27	37.58	32.89	28.35
0.9	54.44	49.75	45.06	40.37	35.68	30.99	26.31	21.67	17.66	14.66

Table 12. Average Marginal Cost of Algae Lipid for Scenario 2 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	119.85	119.81	119.76	119.72	119.67	119.63	119.58	119.54	119.50	119.45
0.1	107.87	107.83	107.79	107.75	107.71	107.67	107.63	107.59	107.55	107.51
0.2	95.88	95.84	95.81	95.77	95.74	95.70	95.67	95.63	95.60	95.56
0.3	83.90	83.86	83.83	83.80	83.77	83.74	83.71	83.68	83.65	83.62
0.4	71.91	71.88	71.86	71.83	71.80	71.78	71.75	71.72	71.70	71.67
0.5	59.93	59.90	59.88	59.86	59.84	59.81	59.79	59.77	59.75	59.73
0.6	47.94	47.92	47.90	47.89	47.87	47.85	47.83	47.82	47.80	47.78
0.7	35.96	35.94	35.93	35.92	35.90	35.89	35.88	35.86	35.85	35.84
0.8	23.97	23.96	23.95	23.94	23.93	23.93	23.92	23.91	23.90	23.89
0.9	11.99	11.98	11.98	11.97	11.97	11.96	11.96	11.95	11.95	11.95

Scenario 3 Results

Scenario 3 is a comparison of the HTL-CHG extraction system to the wet solvent extraction system in Scenario 1. Other than the difference in extraction systems, Scenario 3 is identical to Scenario 1. The average net present value for each fractional reduction in CAPEX and OPEX for Scenario 3 is summarized in Table 13. There are five combinations of CAPEX and OPEX reductions in Scenario 3 that return positive average net present values. For example, if CAPEX is reduced by 90% and OPEX is reduced by 60% a positive average net present value will be reached ($29.48 million). If investors greatly reduce CAPEX and OPEX they could see a return on their initial investment greater than the 10% discount rate. Compared to Scenario 1, Scenario 3 with an HTL-CHG extraction system offers an economic improvement over the base technology wet solvent extraction system.

Table 13. Average Net Present Value for Scenario 3 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Net Present Value (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-1241.06	-1124.71	-1008.36	-892.01	-775.66	-659.32	-542.97	-426.62	-310.27	-193.92
0.1	-1200.32	-1084.12	-967.92	-851.71	-735.51	-619.31	-503.11	-386.90	-270.70	-154.49
0.2	-1159.58	-1043.53	-927.47	-811.41	-695.36	-579.30	-463.25	-347.19	-231.13	-115.03
0.3	-1118.84	-1002.93	-887.02	-771.11	-655.20	-539.29	-423.38	-307.47	-191.52	-75.45
0.4	-1078.11	-962.34	-846.58	-730.81	-615.05	-499.28	-383.52	-267.71	-151.79	-35.83
0.5	-1037.37	-921.75	-806.13	-690.51	-574.89	-459.27	-343.61	-227.84	-111.92	1.01
0.6	-996.63	-881.16	-765.69	-650.21	-534.73	-419.22	-303.59	-187.82	-72.13	32.66
0.7	-955.89	-840.57	-725.24	-609.91	-494.54	-379.05	-263.43	-147.74	-34.49	64.36
0.8	-915.15	-799.97	-684.78	-569.56	-454.21	-338.73	-223.14	-108.04	-0.12	96.91
0.9	-874.41	-759.37	-644.28	-529.07	-413.72	-298.26	-182.90	-70.03	32.58	128.60

In Table 14 we report the probability of economic success for each combination of fractional reductions in CAPEX and OPEX for the algae farm in Scenario 3. There are seven combinations of reductions in CAPEX and OPEX that result in a greater than zero probability of economic success. One example of a positive probability of economic success is observed for a 80% reduction in CAPEX and a 90% reduction in OPEX. At this combination a 99.6% probability of economic success is achieved.

Table 14. Probability of Economic Success for Scenario 3 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	54.2%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
0.7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
0.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	48.6%	100.0%
0.9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%

Table 15 reports the average ending cash reserves for each fractional reduction in CAPEX and OPEX for the algae farm in Scenario 3. There are five combinations of CAPEX and OPEX reduction that have a positive average ending cash flow. CAPEX would need to be reduced 90% with a 60% or greater reduction in OPEX or if CAPEX was reduced by 80% and OPEX has to be reduced 90% or more.

Table 15. Average Ending Cash Reserves in Year 10 for Scenario 3 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Ending Cash Reserves in Year 10 (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-2995.58	-2715.96	-2436.34	-2156.73	-1877.11	-1597.49	-1317.88	-1038.26	-758.66	-479.10
0.1	-2889.91	-2610.67	-2331.44	-2052.20	-1772.96	-1493.73	-1214.49	-935.27	-656.08	-377.00
0.2	-2784.25	-2505.39	-2226.53	-1947.67	-1668.82	-1389.96	-1111.12	-832.31	-553.60	-275.75
0.3	-2678.59	-2400.11	-2121.63	-1843.15	-1564.67	-1286.21	-1007.77	-729.44	-451.94	-178.84
0.4	-2572.92	-2294.82	-2016.72	-1738.62	-1460.54	-1182.49	-904.54	-627.41	-354.02	-90.23
0.5	-2467.26	-2189.54	-1911.82	-1634.11	-1356.44	-1078.88	-802.17	-528.88	-262.51	-11.66
0.6	-2361.59	-2084.25	-1806.93	-1529.64	-1252.47	-976.19	-703.17	-435.63	-177.09	54.89
0.7	-2255.93	-1978.99	-1702.08	-1425.31	-1149.48	-876.83	-608.90	-347.96	-99.64	120.59
0.8	-2150.29	-1873.76	-1597.39	-1322.05	-1049.83	-781.93	-519.59	-265.91	-28.89	188.42
0.9	-2044.69	-1768.74	-1493.91	-1222.20	-954.63	-691.60	-435.23	-188.84	39.11	254.00

Table 16 reports the total cost ($/gallon) of lipid and Table 17 reports the marginal cost ($/gallon) of lipid for each of the fractional reductions in CAPEX and OPEX for the algae farm in Scenario 3. When there is no reduction in CAPEX and OPEX the total cost for lipid is very high (more than $28/gallon) and remains high unless there are substantial reductions in the CAPEX and OPEX. For example, if CAPEX and OPEX are reduced 80% each ($4.08/gallon). When there is no reduction in CAPEX and OPEX the marginal cost for lipid is also extremely high ($5.54/gallon). However, with a 60% reduction in the OPEX the marginal cost for lipid becomes feasible at $2.18/gallon. At this reduction level, algal lipid production could become competitive with fossil fuels. When Scenario 1 is compared to Scenario 3 it is observed that the total cost ($/gallon) of lipid, marginal cost ($/gallon) of lipid, and total cost ($/ton) of biomass can be decreased by using the improved extraction technology of HTL-CHG.

Table 16. Average Total Cost of Algae Lipid for Scenario 3 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	27.27	24.98	22.68	20.39	18.10	15.81	13.51	11.22	8.93	6.83
0.1	26.51	24.22	21.93	19.64	17.35	15.06	12.77	10.48	8.20	6.21
0.2	25.75	23.46	21.18	18.89	16.60	14.32	12.03	9.74	7.49	5.62
0.3	24.99	22.71	20.42	18.14	15.86	13.57	11.29	9.01	6.79	5.07
0.4	24.23	21.95	19.67	17.39	15.11	12.83	10.55	8.28	6.14	4.53
0.5	23.48	21.20	18.92	16.64	14.36	12.08	9.82	7.60	5.55	4.00
0.6	22.72	20.44	18.17	15.89	13.62	11.35	9.13	6.97	4.97	3.46
0.7	21.96	19.68	17.41	15.14	12.88	10.67	8.50	6.36	4.41	2.93
0.8	21.20	18.93	16.66	14.41	12.19	10.03	7.89	5.76	3.91	2.40
0.9	20.44	18.18	15.93	13.72	11.56	9.42	7.29	5.18	3.42	1.88

Table 17. Average Marginal Cost of Algae Lipid for Scenario 3 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	5.53	5.51	5.49	5.47	5.45	5.43	5.41	5.38	5.36	5.34
0.1	4.98	4.96	4.94	4.92	4.90	4.88	4.87	4.85	4.83	4.81
0.2	4.43	4.41	4.39	4.38	4.36	4.34	4.32	4.31	4.29	4.27
0.3	3.87	3.86	3.84	3.83	3.81	3.80	3.78	3.77	3.75	3.74
0.4	3.32	3.31	3.29	3.28	3.27	3.26	3.24	3.23	3.22	3.21
0.5	2.77	2.76	2.74	2.73	2.72	2.71	2.70	2.69	2.68	2.67
0.6	2.21	2.20	2.20	2.19	2.18	2.17	2.16	2.15	2.15	2.14
0.7	1.66	1.65	1.65	1.64	1.63	1.63	1.62	1.62	1.61	1.60
0.8	1.11	1.10	1.10	1.09	1.09	1.09	1.08	1.08	1.07	1.07
0.9	0.55	0.55	0.55	0.55	0.54	0.54	0.54	0.54	0.54	0.53

Scenario 4 Results

Scenario 4 is a comparison of the improved harvesting and extraction technologies examined in Scenarios 2 and 3, along with increased biomass productivity relative to the base technologies and growth rate in Scenario 1. The EC harvesting system and HTL-CHG extraction system are utilized along with an increased biomass growth rate in Scenario 4. In this scenario biomass production is increased by 50% in the winter (October-February), 100% in the spring and fall (March, July-September), and 200% in the summer (April-June); lipid content is increased to 50% and the probability of pond crashes is reduced 50%. Scenario 4 represents the best NAABB technologies developed for harvesting, extraction, and biology. The average net present value for each fractional reduction in CAPEX and OPEX for Scenario 4 is summarized in Table 18. There are 53 combinations of CAPEX and OPEX reductions in Scenario 4 that return positive average net present values. For example, if CAPEX is reduced by 40% and OPEX is reduced by 50% average net present value is $1.77 million. If investors greatly reduce CAPEX and OPEX they could see a return on their initial investment that exceeds the 10% discount rate. Compared to Scenario 1, Scenario 4 offers significant improvement. Comparing the average net present values it is observed that the values for Scenario 4 are positive or less negative than the corresponding values in Scenario 1. The increases in average NPV indicate an improvement in Scenario 4 over Scenario 1.

Table 18. Average Net Present Value for Scenario 4 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Net Present Value (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-611.24	-505.88	-400.94	-296.67	-193.76	-92.76	3.63	92.59	179.53	265.90
0.1	-560.09	-455.23	-350.96	-247.93	-146.65	-48.36	42.91	129.85	216.14	302.05
0.2	-509.24	-404.98	-301.91	-200.40	-101.35	-7.25	80.42	166.56	252.40	338.01
0.3	-458.70	-355.68	-254.11	-154.58	-58.47	31.06	117.24	203.02	288.50	373.73
0.4	-409.22	-307.59	-207.79	-110.55	-18.62	68.24	153.83	239.16	324.34	409.39
0.5	-360.74	-260.84	-163.09	-69.04	19.27	104.88	190.07	275.04	359.90	444.57
0.6	-313.58	-215.57	-120.39	-30.13	56.02	141.07	225.95	310.54	395.03	479.34
0.7	-268.01	-172.18	-80.39	7.22	92.31	176.86	261.35	345.60	429.60	513.38
0.8	-224.18	-131.08	-42.17	43.54	128.01	212.19	296.18	379.91	463.52	547.02
0.9	-182.21	-92.18	-5.34	79.10	163.11	246.79	330.33	413.76	497.10	580.34

In Table 19 we report the probability of economic success for each combination of fractional reductions in CAPEX and OPEX for the algae farm in Scenario 4. There are 59 combinations of reductions in CAPEX and OPEX that result in a greater than zero probability of economic success. One example is for a 40% reduction in CAPEX and a 50% reduction in OPEX that results in a 54.4% probability of economic success.

Table 19. Probability of Economic Success for Scenario 4 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	54.4%	100.0%	100.0%	100.0%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	5.6%	94.8%	100.0%	100.0%	100.0%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	39.4%	100.0%	100.0%	100.0%	100.0%
0.3	0.0%	0.0%	0.0%	0.0%	2.0%	89.2%	100.0%	100.0%	100.0%	100.0%
0.4	0.0%	0.0%	0.0%	0.0%	26.6%	100.0%	100.0%	100.0%	100.0%	100.0%
0.5	0.0%	0.0%	0.0%	0.8%	76.8%	100.0%	100.0%	100.0%	100.0%	100.0%
0.6	0.0%	0.0%	0.0%	12.4%	98.6%	100.0%	100.0%	100.0%	100.0%	100.0%
0.7	0.0%	0.0%	0.0%	58.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.8	0.0%	0.0%	5.2%	96.2%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.9	0.0%	0.0%	40.6%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 20 reports the average ending cash reserves for each fractional reduction in CAPEX and OPEX for the algae farm in Scenario 4. There are 48 combinations of CAPEX and OPEX reduction that have a positive ending cash flow.

Table 20. Average Ending Cash Reserves in Year 10 for Scenario 4 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Ending Cash Reserves in Year 10 (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-1429.29	-1188.58	-951.99	-719.99	-493.16	-271.56	-59.25	140.60	336.81	531.87
0.1	-1313.00	-1076.32	-843.94	-616.55	-394.27	-178.74	24.43	220.45	415.23	609.07
0.2	-1200.16	-967.41	-739.66	-516.70	-299.88	-92.49	104.42	298.50	491.81	684.25
0.3	-1090.35	-862.43	-639.24	-421.48	-211.07	-12.00	181.62	374.23	565.89	756.77
0.4	-984.93	-761.63	-543.48	-331.50	-129.48	64.53	256.23	447.25	637.88	828.24
0.5	-883.93	-665.91	-453.50	-248.49	-53.16	138.29	328.92	519.05	708.94	898.37
0.6	-788.55	-575.92	-369.43	-171.47	20.37	210.64	400.61	589.86	778.87	967.42
0.7	-698.57	-491.10	-291.04	-97.33	92.86	282.04	471.09	659.55	847.35	1034.56
0.8	-613.05	-410.98	-215.70	-25.02	163.98	352.29	540.13	727.29	914.12	1100.68
0.9	-531.53	-334.86	-142.88	45.64	233.58	420.67	607.40	793.82	980.01	1165.97

Table 21 reports the total cost ($/gallon) of lipid and Table 22 reports the marginal cost ($/gallon) of lipid for each of the fractional reductions in CAPEX and OPEX for the algae farm in Scenario 4. When there is no reduction in CAPEX and OPEX the total cost for lipid is greater than $7/gallon and with a 90% reduction in CAPEX and OPEX total costs are approximately $0.62/gallon. When there is no reduction in CAPEX and OPEX the marginal cost for lipid is $2.01/gallon. Even without reductions in OPEX, the marginal cost of lipid is feasible.   At this level, algal lipid production could become competitive with fossil fuels. When Scenario 1 is compared to Scenario 4 it is observed that the total cost ($/gallon) of lipid and the marginal cost ($/gallon) of lipid can be significantly decreased by using the improved harvesting, extraction, and biomass growth production technology.

Table 21. Average Total Cost of Algae Lipid for Scenario 4 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	7.20	6.55	5.90	5.26	4.65	4.10	3.60	3.16	2.75	2.34
0.1	6.96	6.31	5.66	5.02	4.43	3.88	3.40	2.97	2.55	2.15
0.2	6.72	6.07	5.42	4.79	4.21	3.68	3.21	2.77	2.36	1.95
0.3	6.48	5.83	5.19	4.56	3.99	3.49	3.02	2.58	2.17	1.76
0.4	6.24	5.59	4.95	4.34	3.80	3.31	2.83	2.39	1.97	1.57
0.5	6.00	5.36	4.72	4.14	3.62	3.13	2.65	2.20	1.78	1.37
0.6	5.76	5.12	4.51	3.95	3.44	2.94	2.46	2.01	1.59	1.18
0.7	5.53	4.90	4.32	3.78	3.26	2.76	2.28	1.82	1.39	0.98
0.8	5.30	4.70	4.14	3.61	3.08	2.58	2.10	1.63	1.20	0.79
0.9	5.09	4.52	3.97	3.43	2.91	2.40	1.92	1.45	1.01	0.60

Table 22. Average Marginal Cost of Algae Lipid for Scenario 4 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	2.00	2.00	1.99	1.98	1.98	1.97	1.96	1.96	1.95	1.95
0.1	1.80	1.80	1.79	1.78	1.78	1.77	1.77	1.76	1.76	1.75
0.2	1.60	1.60	1.59	1.59	1.58	1.58	1.57	1.57	1.56	1.56
0.3	1.40	1.40	1.39	1.39	1.38	1.38	1.37	1.37	1.37	1.36
0.4	1.20	1.20	1.19	1.19	1.19	1.18	1.18	1.17	1.17	1.17
0.5	1.00	1.00	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.97
0.6	0.80	0.80	0.80	0.79	0.79	0.79	0.79	0.78	0.78	0.78
0.7	0.60	0.60	0.60	0.59	0.59	0.59	0.59	0.59	0.59	0.58
0.8	0.40	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.39	0.39
0.9	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.19

Scenario 5 Results

Scenario 5 is a comparison of the ARID cultivation system with the improved harvesting and extraction technologies to the open pond cultivation system. An exact comparison cannot be made between ARID cultivation and open pond cultivation due to the difference in location of the scenarios. The average net present value for each fractional reduction in CAPEX and OPEX for Scenario 5 is summarized in Table 23. There are 27 combinations of CAPEX and OPEX reductions in Scenario 5 that return positive average net present values. For example, if CAPEX is reduced by 80% and OPEX is reduced by 50% a positive net present value would average $72.62 million.

Table 23. Average Net Present Value for Scenario 5 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Net Present Value (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-956.04	-848.48	-740.93	-633.37	-525.80	-418.21	-310.57	-202.85	-95.08	9.15
0.1	-920.70	-813.26	-705.82	-598.37	-490.89	-383.37	-275.77	-168.09	-60.63	37.59
0.2	-885.35	-778.03	-670.70	-563.33	-455.93	-348.45	-240.88	-133.28	-27.29	65.25
0.3	-850.01	-742.79	-635.54	-528.25	-420.89	-313.44	-205.92	-98.64	3.14	92.62
0.4	-814.64	-707.51	-600.33	-493.08	-385.75	-278.35	-170.95	-64.84	31.16	120.07
0.5	-779.24	-672.17	-565.04	-457.82	-350.53	-243.19	-136.23	-33.06	58.80	147.51
0.6	-743.78	-636.75	-529.65	-422.47	-315.25	-208.13	-102.38	-3.11	86.20	174.46
0.7	-708.23	-601.24	-494.18	-387.07	-279.99	-173.44	-69.92	24.90	112.94	200.82
0.8	-672.58	-565.64	-458.65	-351.66	-244.92	-139.70	-39.14	51.62	139.32	226.75
0.9	-636.86	-529.99	-423.11	-316.33	-210.40	-107.12	-10.41	77.89	165.05	252.05

In Table 24 we report the probability of economic success for each combination of fractional reductions in CAPEX and OPEX for the algae farm in Scenario 5. There are 27 combinations of reductions in CAPEX and OPEX that result in a greater than zero probability of economic success. One example of a positive probability of economic success is a 70% reduction in CAPEX and a 70% reduction in OPEX. At this combination there is an 75.8% probability of economic success for the algae farm.

Table 24. Probability of Economic Success for Scenario 5 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	73.8%
0.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	99.4%
0.2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.8%	100.0%
0.3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	57.6%	100.0%
0.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	98.2%	100.0%
0.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	100.0%	100.0%
0.6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	40.8%	100.0%	100.0%
0.7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	95.8%	100.0%	100.0%
0.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.2%	100.0%	100.0%	100.0%
0.9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	24.6%	100.0%	100.0%	100.0%

Table 25 reports the average ending cash reserves for each fractional reduction in CAPEX and OPEX for the algae farm in Scenario 5. There are 19 combinations of CAPEX and OPEX reduction that have a positive average ending cash, but they largely are associated with large reductions in CAPEX.

Table 25. Average Ending Cash Reserves in Year 10 for Scenario 5 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Ending Cash Reserves in Year 10 (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-2299.28	-2038.22	-1777.20	-1516.25	-1255.52	-995.40	-736.56	-480.43	-230.77	3.90
0.1	-2207.66	-1946.96	-1686.32	-1425.91	-1166.12	-907.53	-651.26	-399.85	-156.83	63.90
0.2	-2116.10	-1855.77	-1595.70	-1336.25	-1077.97	-821.76	-569.40	-323.61	-87.42	121.51
0.3	-2024.62	-1764.89	-1505.80	-1247.86	-991.83	-739.01	-491.41	-251.11	-24.71	178.19
0.4	-1933.48	-1674.76	-1417.18	-1161.43	-908.46	-659.72	-417.07	-181.74	33.17	234.98
0.5	-1843.14	-1585.94	-1330.53	-1077.59	-828.17	-583.68	-345.33	-116.87	90.39	291.76
0.6	-1754.15	-1499.11	-1246.31	-996.57	-750.78	-510.30	-276.23	-55.40	147.00	347.26
0.7	-1667.17	-1414.59	-1164.73	-918.08	-675.82	-439.03	-210.15	2.21	201.92	401.26
0.8	-1582.44	-1332.53	-1085.31	-841.68	-602.98	-370.36	-147.44	56.99	255.90	454.10
0.9	-1499.92	-1252.36	-1007.74	-767.34	-532.33	-304.24	-89.06	110.62	308.19	505.34

Table 26 reports the total cost ($/gallon) of lipid and Table 27 reports the marginal cost ($/gallon) of lipid for each of the fractional reductions in CAPEX and OPEX for the algae farm in Scenario 5. When there is no reduction in CAPEX and OPEX the total cost for lipid is more than $15/gallon, but is much lower with significant reductions in CAPEX and OPEX. With the assumed technologies the marginal cost is barely feasible without any reductions in OPEX. Although a direct comparison cannot be made between Scenario 5 and the other four scenarios, the ARID cultivation system does show it could be an economically viable alternative compared to the open pond cultivation system.

Table 26. Average Total Cost of Algae Lipid for Scenario 5 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	13.49	12.29	11.10	9.91	8.72	7.53	6.36	5.25	4.38	3.74
0.1	13.05	11.86	10.67	9.48	8.29	7.12	5.96	4.90	4.06	3.43
0.2	12.61	11.42	10.23	9.05	7.87	6.72	5.59	4.55	3.74	3.12
0.3	12.17	10.99	9.80	8.63	7.47	6.34	5.23	4.22	3.43	2.80
0.4	11.74	10.56	9.38	8.22	7.09	5.98	4.88	3.89	3.13	2.49
0.5	11.30	10.13	8.97	7.84	6.73	5.62	4.53	3.59	2.82	2.18
0.6	10.88	9.72	8.59	7.47	6.37	5.27	4.19	3.29	2.52	1.86
0.7	10.47	9.33	8.22	7.12	6.02	4.92	3.88	3.01	2.23	1.55
0.8	10.07	8.96	7.86	6.76	5.67	4.58	3.60	2.72	1.93	1.24
0.9	9.70	8.60	7.51	6.41	5.32	4.25	3.32	2.44	1.64	0.93

Table 27. Average Marginal Cost of Algae Lipid for Scenario 5 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	3.24	3.23	3.22	3.21	3.20	3.19	3.18	3.16	3.15	3.14
0.1	2.92	2.91	2.90	2.89	2.88	2.87	2.86	2.85	2.84	2.83
0.2	2.59	2.58	2.58	2.57	2.56	2.55	2.54	2.53	2.52	2.51
0.3	2.27	2.26	2.25	2.25	2.24	2.23	2.22	2.22	2.21	2.20
0.4	1.95	1.94	1.93	1.93	1.92	1.91	1.91	1.90	1.89	1.89
0.5	1.62	1.62	1.61	1.60	1.60	1.59	1.59	1.58	1.58	1.57
0.6	1.30	1.29	1.29	1.28	1.28	1.27	1.27	1.27	1.26	1.26
0.7	0.97	0.97	0.97	0.96	0.96	0.96	0.95	0.95	0.95	0.94
0.8	0.65	0.65	0.64	0.64	0.64	0.64	0.64	0.63	0.63	0.63
0.9	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.31

Scenario 6 Results

Scenario 6 is a comparison of the ARID cultivation system with the improved harvesting and extraction technologies and increased biomass productivity to Scenario 5. Like Scenario 4, the biomass production is increased by 50% in the winter (October-February), 100% in the spring and fall (March, July-September), and 200% in the summer (April-June); lipid content is increased to 50% and the probability of pond crashes is reduced 50%. The average net present value for each fractional reduction in CAPEX and OPEX for Scenario 6 is summarized in Table 28. There are 76 combinations of CAPEX and OPEX reductions in Scenario 6 that return positive average net present values. Compared to Scenario 5, Scenario 6 offers a significant improvement in the number of positive probabilities of economic success.

Table 28. Average Net Present Value for Scenario 6 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Net Present Value (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-402.25	-296.43	-193.41	-94.31	-0.18	89.86	178.97	267.88	356.50	444.90
0.1	-362.61	-258.77	-158.21	-62.04	30.01	119.23	207.88	296.38	384.60	472.81
0.2	-324.13	-222.74	-125.03	-30.96	59.51	148.02	236.30	324.47	412.57	500.39
0.3	-287.65	-188.74	-93.15	-0.88	88.33	176.46	264.44	352.37	440.07	527.54
0.4	-252.86	-156.09	-62.42	28.43	116.71	204.62	292.33	379.86	467.21	554.47
0.5	-219.67	-124.82	-32.53	57.01	144.89	232.46	319.74	406.97	494.10	581.06
0.6	-187.81	-94.48	-3.26	85.22	172.60	259.78	346.93	433.80	520.66	607.34
0.7	-156.99	-64.72	25.34	112.82	199.90	286.85	373.75	460.34	546.91	633.25
0.8	-126.91	-35.70	53.19	140.19	226.96	313.66	400.16	486.58	572.77	658.96
0.9	-97.60	-7.35	80.55	167.22	253.62	340.06	426.28	512.41	598.36	683.99

In Table 29 we report the probability of economic success for each combination of fractional reductions in CAPEX and OPEX for the algae farm in Scenario 6. There are numerous combinations of reductions in CAPEX and OPEX that result in a positive probability of economic success. One example of a positive probability of economic success is a 30% reduction in CAPEX and a 40% reduction in OPEX. At this combination there is a 57.4% probability of economic success for the algae farm.

Table 29. Probability of Economic Success for Scenario 6 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Probability of Economic Success

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.0%	0.0%	0.0%	0.4%	49.4%	100.0%	100.0%	100.0%	100.0%	100.0%
0.1	0.0%	0.0%	0.0%	3.6%	84.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.2	0.0%	0.0%	0.0%	15.4%	97.6%	100.0%	100.0%	100.0%	100.0%	100.0%
0.3	0.0%	0.0%	0.2%	48.4%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.4	0.0%	0.0%	2.6%	83.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.5	0.0%	0.0%	13.8%	97.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.6	0.0%	0.2%	45.6%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.7	0.0%	2.4%	80.4%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.8	0.0%	10.0%	96.6%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.9	0.2%	39.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 30 reports the average ending cash reserves for each fractional reduction in CAPEX and OPEX for the algae farm in Scenario 6. There are over 50 combinations of CAPEX and OPEX reduction that have a positive average ending cash, but they are largely associated with reductions in CAPEX of more than 30%.

Table 30. Average Ending Cash Reserves in Year 10 for Scenario 6 Assuming Alternative Fractional Reductions in CAPEX and OPEX (M$s).

Ending Cash Reserves in Year 10 (M$s)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	-999.98	-767.10	-541.37	-324.08	-115.48	87.24	288.62	489.49	689.61	889.19
0.1	-920.33	-692.65	-472.64	-261.19	-56.04	145.35	345.61	545.48	744.64	943.76
0.2	-843.93	-622.25	-408.40	-200.61	2.12	202.00	401.35	600.42	799.31	997.49
0.3	-772.60	-556.56	-346.69	-142.00	58.72	257.75	456.37	654.88	852.78	1050.08
0.4	-705.29	-493.70	-287.33	-84.83	114.25	312.75	510.73	708.24	905.32	1102.13
0.5	-641.64	-433.68	-229.59	-29.14	169.27	366.94	563.86	760.65	957.19	1153.29
0.6	-580.75	-375.49	-173.00	25.84	223.06	419.77	616.42	812.32	1008.22	1203.62
0.7	-521.96	-318.39	-117.74	79.29	275.79	471.97	668.03	863.25	1058.44	1253.01
0.8	-464.61	-262.82	-64.07	132.15	327.91	523.50	718.54	913.38	1107.65	1301.89
0.9	-408.86	-208.62	-11.39	184.16	379.00	573.94	768.33	962.47	1156.15	1349.01

Table 31 reports the total cost ($/gallon) of lipid and Table 32 reports the marginal cost ($/gallon) of lipid for each of the fractional reductions in CAPEX and OPEX for the algae farm in Scenario 6. When there is no reduction in CAPEX and OPEX the total cost for lipid is $5.60/gallon, but with reductions in CAPEX and OPEX it falls below $3.00/gallon for a majority of the combinations. When there is no reduction in CAPEX and OPEX the marginal cost for lipid is feasible relative to current fossil fuel prices.

Table 31. Average Total Cost of Algae Lipid for Scenario 6 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Total Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	4.86	4.39	3.96	3.58	3.23	2.90	2.60	2.32	2.05	1.78
0.1	4.69	4.22	3.80	3.43	3.09	2.76	2.45	2.17	1.89	1.63
0.2	4.51	4.06	3.65	3.29	2.95	2.62	2.30	2.02	1.74	1.48
0.3	4.34	3.90	3.51	3.15	2.80	2.47	2.16	1.87	1.59	1.32
0.4	4.17	3.75	3.37	3.01	2.66	2.33	2.01	1.72	1.44	1.17
0.5	4.02	3.61	3.23	2.87	2.52	2.19	1.86	1.57	1.29	1.02
0.6	3.87	3.48	3.10	2.73	2.38	2.04	1.72	1.42	1.14	0.87
0.7	3.73	3.34	2.96	2.59	2.24	1.90	1.57	1.27	0.99	0.72
0.8	3.60	3.21	2.82	2.45	2.10	1.76	1.43	1.12	0.84	0.57
0.9	3.46	3.07	2.69	2.32	1.96	1.62	1.29	0.97	0.69	0.42

Table 32. Average Marginal Cost of Algae Lipid for Scenario 6 Assuming Alternative Fractional Reductions in CAPEX and OPEX ($/Gallon).

Average Marginal Cost per Gallon for Lipid ($/Gallon)

Open Pond	Fractional Reductions in the CAPEX									
Fraction Opex	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	1.56	1.56	1.55	1.55	1.54	1.54	1.53	1.53	1.52	1.52
0.1	1.40	1.40	1.40	1.39	1.39	1.38	1.38	1.37	1.37	1.37
0.2	1.25	1.24	1.24	1.24	1.23	1.23	1.23	1.22	1.22	1.21
0.3	1.09	1.09	1.09	1.08	1.08	1.08	1.07	1.07	1.07	1.06
0.4	0.94	0.93	0.93	0.93	0.93	0.92	0.92	0.92	0.91	0.91
0.5	0.78	0.78	0.78	0.77	0.77	0.77	0.77	0.76	0.76	0.76
0.6	0.62	0.62	0.62	0.62	0.62	0.61	0.61	0.61	0.61	0.61
0.7	0.47	0.47	0.47	0.46	0.46	0.46	0.46	0.46	0.46	0.46
0.8	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.30	0.30
0.9	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.15	0.15

Sensitivity of Costs

A sensitivity elasticity[2] analysis was calculated for marginal cost, total cost, and net cash income in year five for key parameters to the algal production system in Scenario 4. The sensitivity elasticities show percentage change for the total cost ($/gallon) of lipid, marginal cost ($/gallon) of lipid, and net cash income in year five (Figures 1-3) for a one percent change in each of the selected exogenous variables. They also show the relative importance of further research. The sensitivity elasticities for marginal costs are summarized in Figure 1. The elasticity of marginal cost with respect to (wrt) EC plate replacement costs is 0.25, meaning that for every one percent increase in EC plate replacement the marginal cost for algae lipid increases 0.25 percent. The elasticity of marginal costs wrt the biomass production is inverted compared to the other elasticities. The elasticity of marginal costs wrt biomass production is -0.83; thus a one percent increase in biomass production will decrease the marginal cost by 0.83 percent. The elasticity of marginal costs wrt the biomass production is also 3.26 times larger than the elasticity of marginal costs wrt EC place replacement, the next largest elasticity.

[2] Sensitivity elasticities show the percentage change in key output variables, such as, total cost, to a one percent change in the cost of a particular input variable, all other things being held constant.

In terms of relative importance, the largest absolute elasticity is the most important and decreases with the absolute values of the elasticities. The three largest elasticities, and also the most important in terms of research, wrt marginal cost are for biomass production, maintenance (16%, which is a function of CAPEX) and EC plate life for harvesting (25%).

The sensitivity elasticities of total costs for algae lipids in Scenario 4 wrt to 12 input variables are presented in Figure 2. Total costs of algae are six and a half times more sensitive to harvesting CAPEX (E_s = 0.32) than maintenance costs (E_s = 0.04). For each one percent decrease in harvesting CAPEX we project that total cost would fall 0.32 percent.

The sensitivity of annual net cash income to 12 cost categories is summarized in Figure 3 assuming Scenario 4. For net cash income the elasticities are inverted, because for a one percent increase in costs we see a decrease in net cash income. A ten percent increase in harvesting CAPEX also decreases net cash income 8.08%. A one percent increase in biomass production leads to a 6.03 percent increase in net cash income; so a 10 percent decrease in biomass production decreases net cash income approximately 60 percent. The sensitivity of net cash income is low for costs such as: utilities (0.004%), harvesting electricity (0.01%), and insurance (0.09%). Thus, research efforts should not be concentrated in these areas where the absolute values of the elasticities are small. Research in biomass production will have the biggest impact and is the most important area to focus future research.

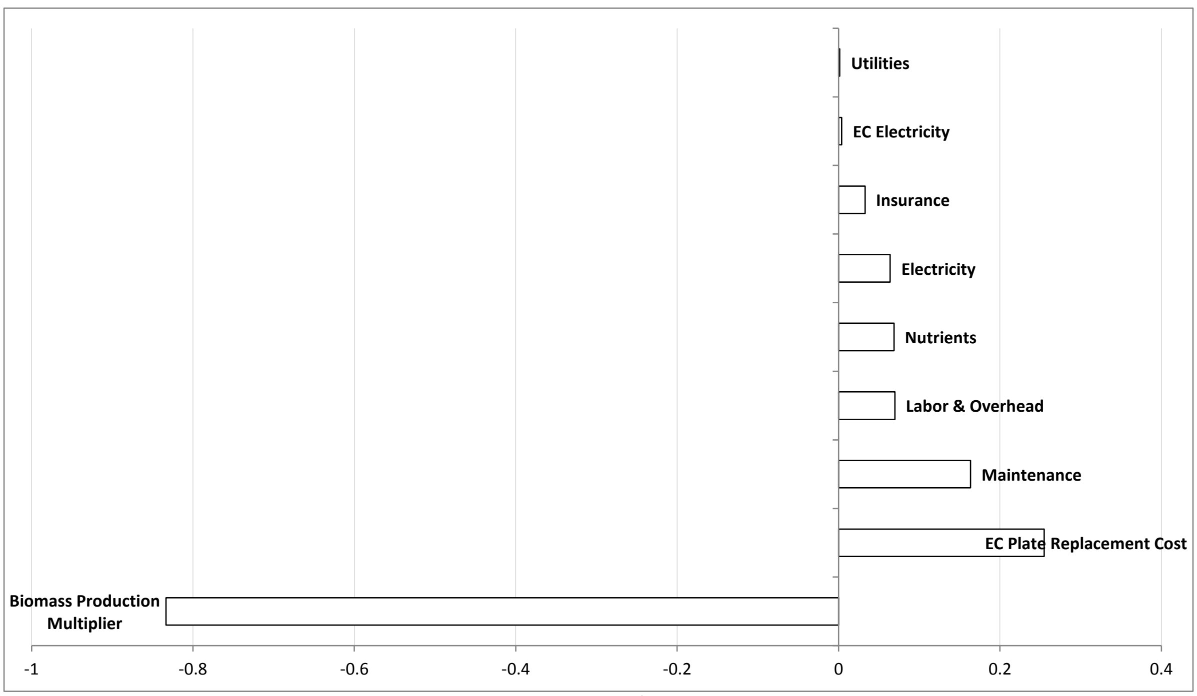

Figure 1. Sensitivity Elasticities of Marginal Cost ($/Gallon of Lipid) for Scenario 4.

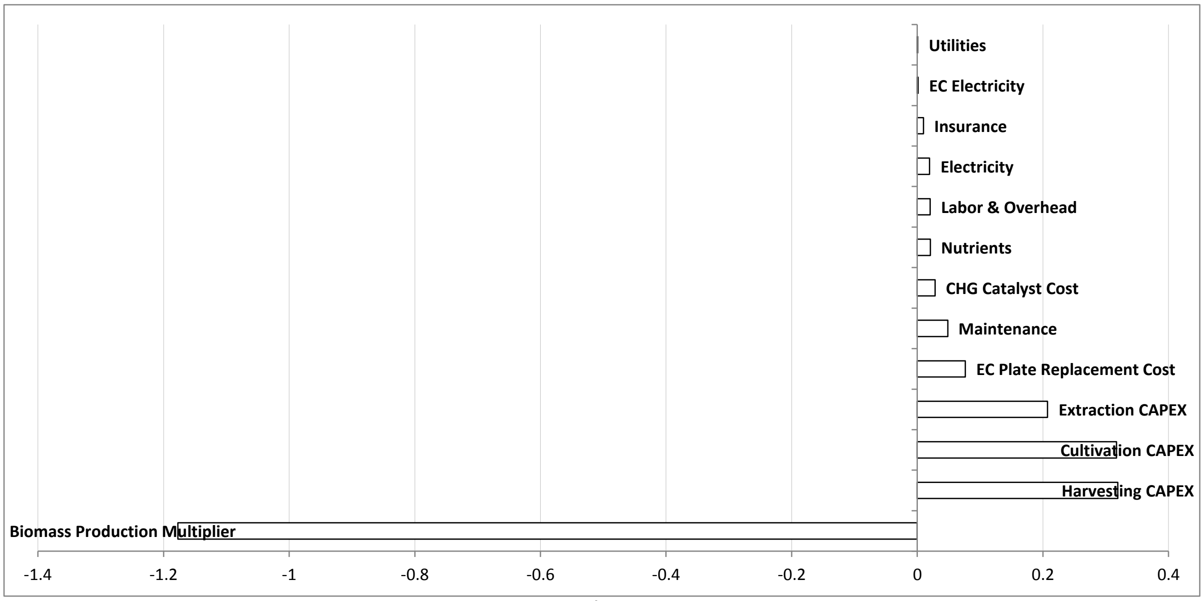

Figure 2. Sensitivity Elasticities of Total Cost ($/Gallon of Lipid) for Scenario 4.

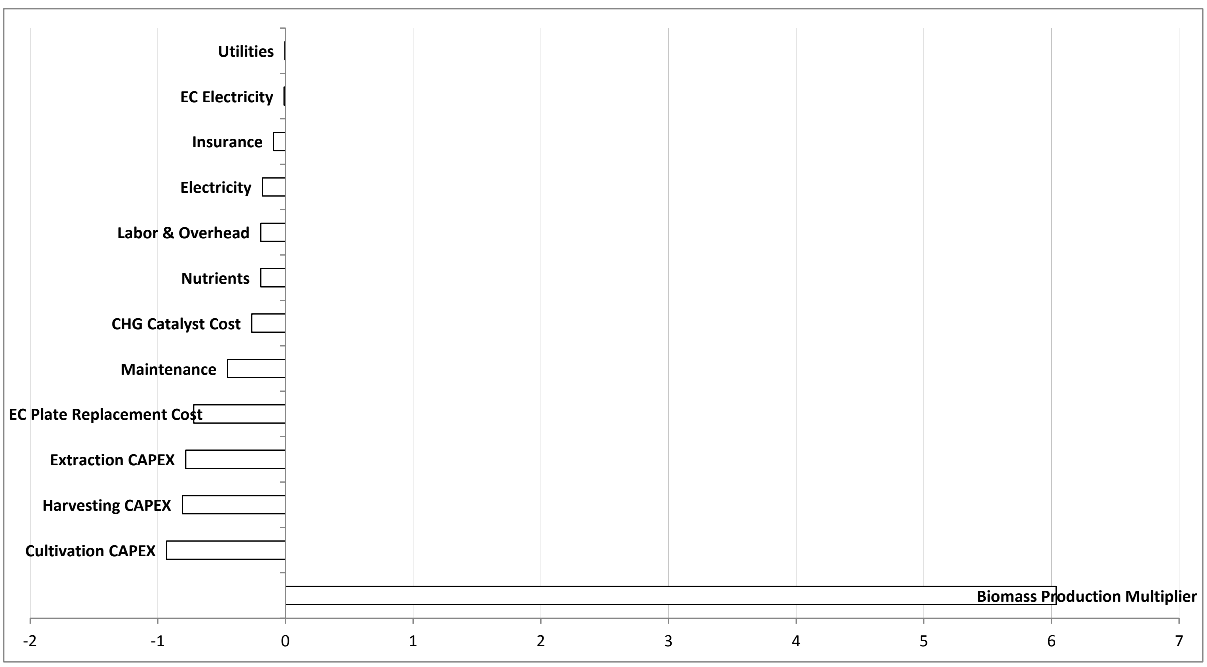

Figure 3. Sensitivity Elasticities of Net Cash Income ($/Gallon of Lipid) for Scenario 4.

Summary of Scenario Results

Table 33 summarizes selected results for the six scenarios. The reduction in CAPEX and OPEX rows list the respective reduction amounts needed for the algae farm to obtain a reasonable probability of economic success. There are two probabilities of success listed for each scenario, e.g., 0.0 – 57.2% (Scenario 4). The first probability of success listed is the probability of economic success for the farm when neither CAPEX nor OPEX is reduced. The second is the probability of economic success when the reductions in CAPEX and

OPEX from the above rows are used. In Scenario 4, for example, when the algae farm does not reduce its CAPEX or OPEX the farm has a probability of success of 0.0. However, when the farm reduces its CAPEX and OPEX by 40% each, the farm has a 57.2% probability of economic success. The average total costs ($/gal of lipid) are also listed for the 0% reduction in CAPEX and OPEX and the listed reduction. With a 0% reduction in CAPEX the total cost ($/gal of lipid) for scenario 4 is $7.03, and if CAPEX and OPEX are reduced 40% each the total cost ($/gal of lipid) is $3.64. The last two rows of Table 33 report the lower and upper confidence intervals (LCI and UCI) at the 95% level for total cost of production. For Scenario 1 the LCI is $8.84 and the UCI is $22.97 per gallon. The narrowest confidence interval is for Scenario 6, $2.74-$4.16 per gallon, assuming a 30% reduction in CAPEX and 40% reduction in OPEX.

Figure 4 shows the probability density functions of the total costs of lipid ($/gal) for the six scenarios at the CAPEX and OPEX reduction levels listed in Table 33. Scenarios 1 and 2 have the widest dispersion of costs. There is more risk in Scenarios 1 and 2 compared to Scenarios 3-6, which is depicted graphically in Figure 4 and the LCI and UCI ranges in Table 33. Scenarios 3-6 have smaller distributions associated with their total costs of lipid ($/gal) as well as lower average total costs compared to Scenarios 1 and 2 (Figures 5-10). The probability density charts for Scenarios 2 and 3 demonstrate the significant reduction in total costs and the risk on total costs from adopting EC and HTL-CHG, respectively (Figures 6 and 7). Note: the vertical line in each chart is the mean and the lines on either side of the distributions depict the range for a 95% confidence interval for cost of production, e.g., for Scenario 4 the 95% confidence interval on total costs per gallon for lipid is $2.93 and $4.35. The lowest cost of production is observed for Scenario 6 with a mean cost of $3.45/gallon, assuming significant reductions in CAPEX and OPEX. The Scenarios 3-6 have similar probability density functions, but it required different amounts of reduction in CAPEX and OPEX to achieve the low costs of production depicted in the charts (Figures 7-10). Scenarios 4 and 6 required a much small reduction in CAPEX and OPEX than Scenarios 3 and 5. Because of their small dispersions in total cost of lipid ($/gal) and lower reductions in CAPEX and OPEX, Scenarios 4 and 6 are much better than the other four scenarios (Figures 8 and 10).

Table 33. Summary of Results for Scenarios 1-6.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Reduction in CAPEX	90%	90%	80%	40%	70%	30%
Reduction in OPEX	90%	90%	80%	50%	60%	30%
P(Success)	0.0 – 0.0	0.0 – 0.0	0.0 – 48.6%	0.0 – 76.8%	0.0 – 40.9%	0.0 – 48.4%
Average Total Cost $/gal	230.63 – 16.92	198.48 – 14.66	27.27 – 3.91	7.20 – 3.62	13.49 – 3.29	4.86 – 3.15
Lower Confidence Interval TC $/gal	11.97	10.26	3.40	3.14	2.80	2.69
Upper Confidence Interval TC $/gal	24.28	21.42	5.07	4.44	4.13	3.87

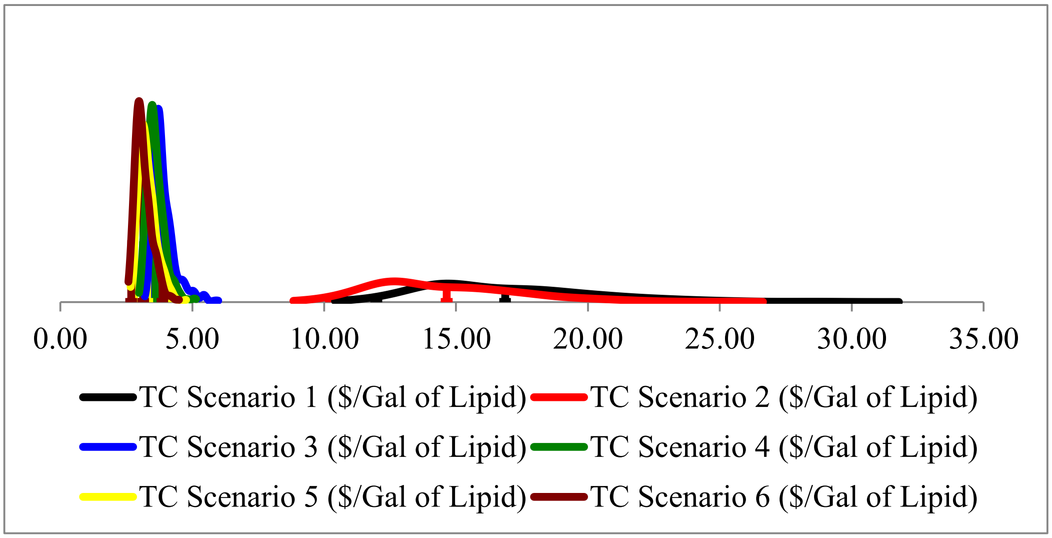

Figure 4. Probability Density Functions of Total Cost of Lipid ($/Gal) for Six Scenarios.

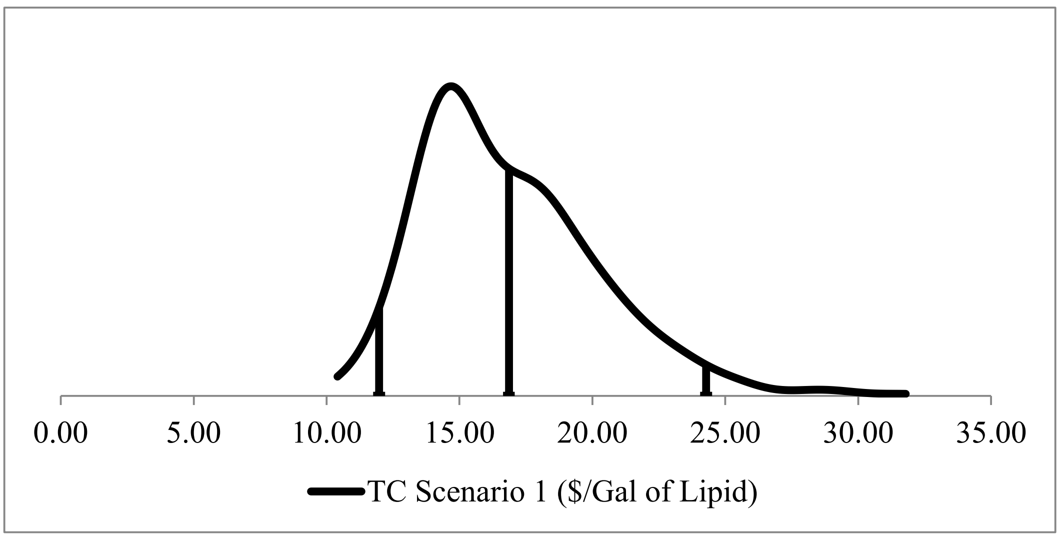

Figure 5. Probability Density Functions of Total Cost of Lipid ($/Gal) for Scenario 1.

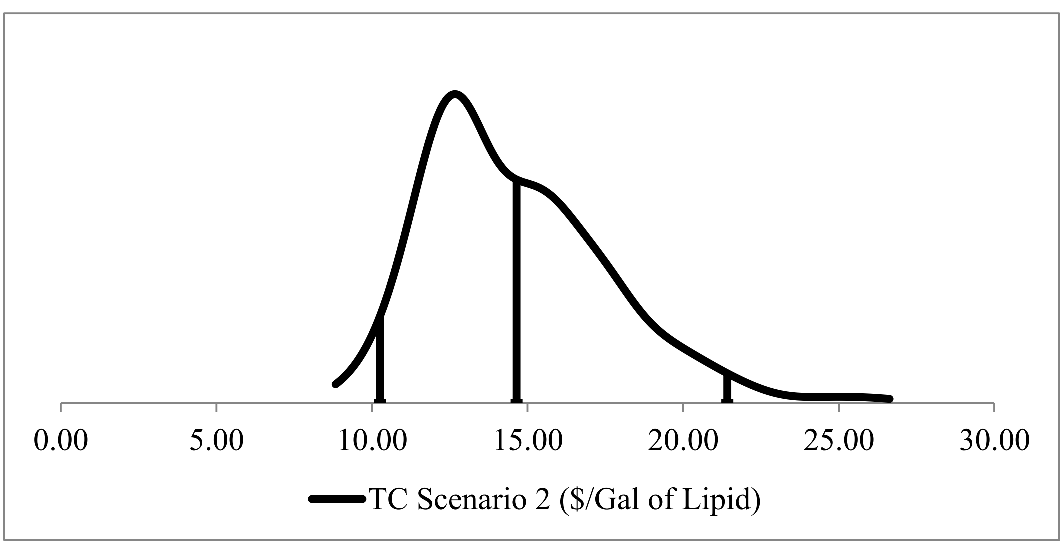

Figure 6. Probability Density Functions of Total Cost of Lipid ($/Gal) for Scenario 2.

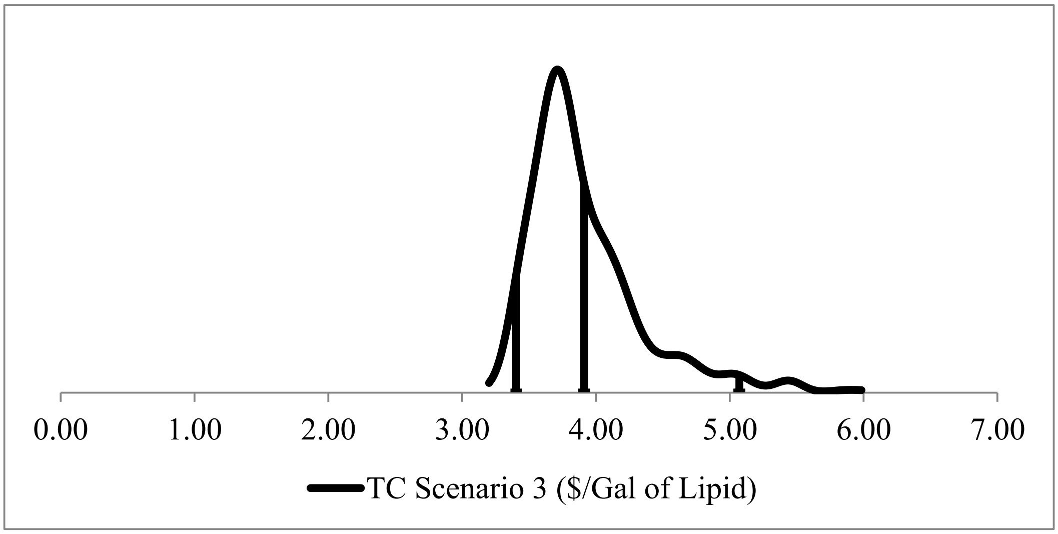

Figure 7. Probability Density Functions of Total Cost of Lipid ($/Gal) for Scenario 3.

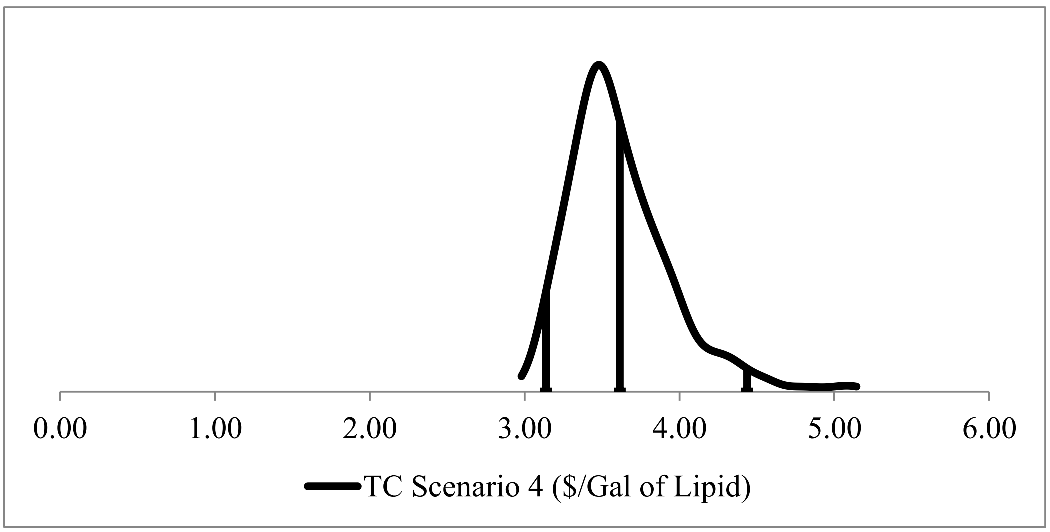

Figure 8. Probability Density Functions of Total Cost of Lipid ($/Gal) for Scenario 4.

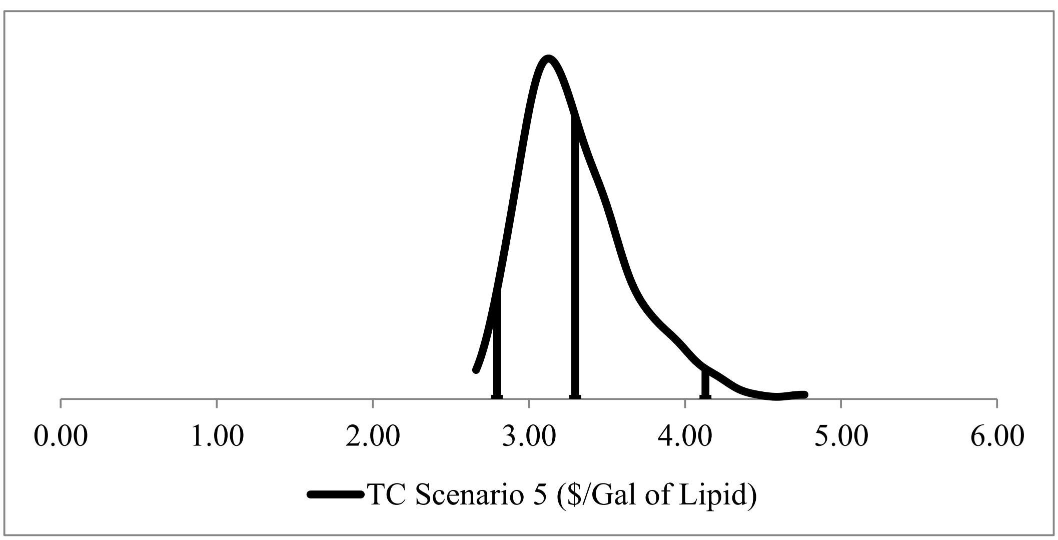

Figure 9. Probability Density Functions of Total Cost of Lipid ($/Gal) for Scenario 5.

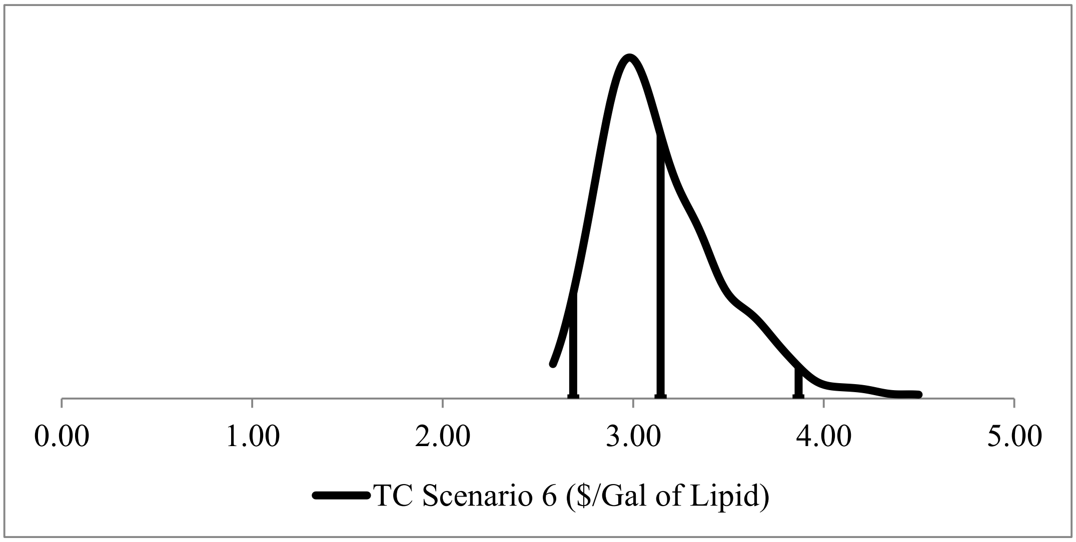

Figure 10. Probability Density Functions of Total Cost of Lipid ($/Gal) for Scenario 6.

Summary

The results from simulating algae farms with technologies developed by NAABB scientists suggest that algal lipid could be financially feasible if CAPEX and OPEX can be reduced further. However, the biological information remains untested in large outdoor raceways. Scenario 1, with the base technology, had a zero probability of economic success, even when CAPEX and OPEX were reduced by 90%. Scenario 2 utilized the EC harvesting system and showed an improvement over Scenario 1, although it was not enough to result in a positive probability of economic success, even with 90% reductions in both CAPEX and OPEX.

The use of the HTL-CHG extraction system in Scenario 3 offered a more significant improvement over Scenario 1 than Scenario 2. In Scenario 3 there were twelve positive probabilities of economic success but to achieve these, significant reductions in CAPEX and OPEX will have to be made. By combining the two improved technologies in harvesting and extraction with increased biomass productivity there were even more positive probabilities of economic success in Scenario 4.

The sensitivity elasticities from Scenario 4 showed areas in which research would have the biggest impact on the marginal cost ($/gallon) of lipid, total cost ($/gallon) of lipid, and net cash income in year 5. For improvement in marginal cost the top three areas of focus should be on biomass production, EC plate life, and maintenance. For improvement in total cost and net cash income the top three areas on which to focus research are biomass production and harvesting and cultivation CAPEX. Overall, the most important area to focus on is biomass production. Increasing biomass production will have an impact three times greater than the next closest variable.

Scenario 5 analyzed the use of the ARID cultivation system in Tucson, Arizona. With significant reductions in CAPEX and OPEX in Scenario 5 there were also several positive probabilities of economic success, as well as low marginal costs. Lastly, Scenario 6 analyzed the use of the ARID cultivation system in Tucson, Arizona, but with increased biomass productivity similar to Scenario 4. Similar to Scenario 5, with reductions in CAPEX and OPEX there were numerous positive probabilities of economic success. These results for Scenarios 5 and 6 offer evidence that the ARID cultivation system may be an improvement over the current open pond cultivation system.

It will still take further testing of biomass production and several more significant breakthroughs in cultivation, harvesting, extraction, and operations to ensure CAPEX and OPEX are reduced to a level where algae farming is financially feasible and appealing to investors. Great strides have been made by the NAABB consortium, but many more breakthroughs are needed in all areas of algal biology, cultivation, harvesting and extraction.

APPENDIX A: Description of FARM

FARM is programmed in Microsoft® Excel and depends upon the Simetar© add-in to incorporate risk. A flowchart of the model is presented in Figure A1. The flowchart shows that information from biology, extraction, harvesting, and cultivation are combined with stochastic processes for algal production, prices, interest rates, and inflation rates are used in the model to provide projections of economic profitability and viability of an algae farm.

The Excel workbook model for FARM is divided up into multiple worksheets that include: Input, Model, Simulation Results, Stochastic Production and Prices, and Reports. All input for an algae farm is entered in the INPUT worksheet and most all calculations are in the MODEL worksheet. Simetar is used to simulate the Excel model stochastically by drawing annual prices, production, and rates of inflation randomly from user specified probability distributions. The parameters for all probability distributions are estimated from historical or experimental data provided by the analyst.

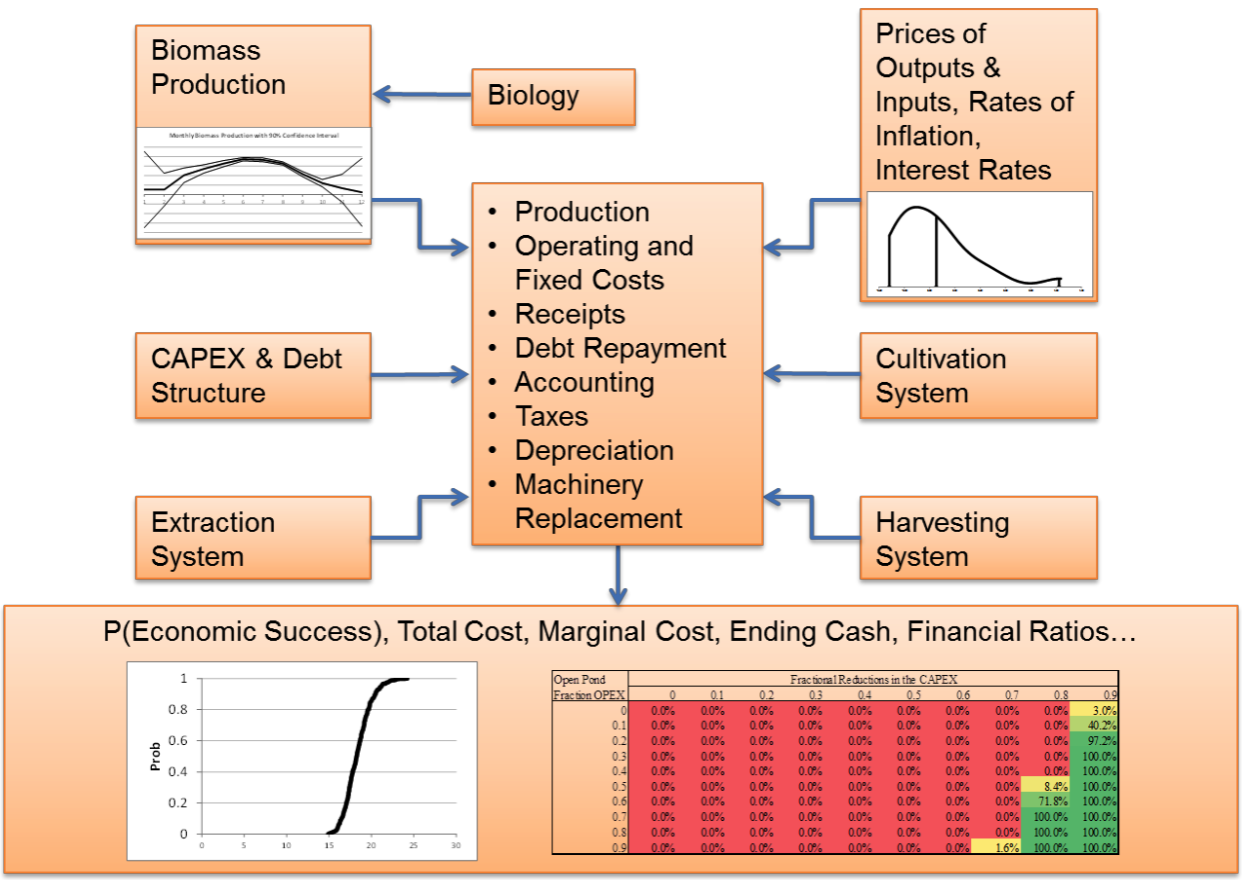

Figure A1. Flowchart of the Farm-level Algae Risk Model.

FARM Inputs

The analyst must enter all of the data to describe the algae business model. This includes data for the biology, cultivation, harvesting, extraction, and co-products. A base scenario can be defined and copied multiple times with slight variations in the many management control variables. Simetar can then simulate all of the scenarios at once using the same risk for all of the stochastic variables. In this manner one can be guaranteed that the scenarios can be compared directly and that the only differences between scenarios are the input data changes. In the subsequent sections we describe the types of data required as input for FARM.

- **Price Projections**

Projected annual average prices for soybean meal, electricity, nitrogen, phosphorous, CO_2, diesel, algae crude oil, and other inputs and products are provided for 10 years. Annual rates of inflation for input costs and interest rates are also provided as input. These data are used to calculate annual increases in input costs not associated with the stochastic variables.

- **Historical Price Data**

Historical prices for the stochastic price variables must be entered as input to FARM. The model requires 10 years of historical prices for the stochastic price variables so parameters for a multivariate probability distribution can be estimated and simulated.

- **Options for Farming System**

FARM is programmed to accommodate many different production systems. The first option is the source of weather history data, as weather directly affects algae production and water required to replace evaporation losses. The second option is the source of the biomass production data; Pacific Northwest National Laboratory (PNNL) pre-loaded regional production data can be elected or the user can specify biomass growth rates. The analyst can specify whether water will or will not be recycled.

Options are available to specify the harvesting and extraction systems. The last set of options for the model deals with the final products. The farm can produce multiple products, but the user must be cognizant that co-products are dependent on the type of extraction process selected. The pre-programmed harvesting systems are: chemical flocculation, centrifuge, and electrocoagulation. The extraction systems are: Solution Recovery Services (SRS), Hydro-Thermal Liquefaction – Catalytic Hydro-thermal Gasification (HTL-CHG), and Pyrolysis.

- **Algae Production Information**

The model simulates 10 years of monthly algae production for the 500 iterations using monthly biomass probability distributions developed from the PNNL/BAT model. The BAT biomass probability distributions can be easily modified to simulate stochastic biomass production for alternative assumptions regarding biology and cultivation systems.

- **Lipid Production**

A GRKS probability distribution parameterized by the analyst is used to simulate the average annual percent lipid value. The GRKS distribution requires the parameters: the mode, the minimum (2.5% quantile) and the maximum (97.5% quantile) so it is easily parameterized for experimental cultivation systems. The simulated stochastic annual percent lipid is multiplied by the total annual biomass to calculate total lipid production.

- **Debt Financing Information**

The user must specify the financial and debt financing information for the business. This information is used in *Pro Forma* financial statements to calculate principal payments, interest costs, and investor dividends.

- **Cultivation**

The cultivation input section of the model specifies the basis for the farm and is a key piece in the production and sizing of equipment for the farm. FARM has the capacity to simulate three cultivations systems: open ponds, ARID, and closed photo bioreactor (PBRs). CAPEX and OPEX associated with each system must be entered by the user. The user must specify the desired acre feet or liters of water for the algae production facility. The algae concentration (g/L) at harvest must also be entered, as this value is used to calculate the quantities of water and algae that move through the system. The number of days of operation per year must be specified.

- **Land Area**

The user must also specify the number of acres needed just for ponds and then for the whole facility. Land not required for ponds is used for space between the ponds, harvesting and extraction equipment, office or storage buildings, and anything else that might be needed.

- **Harvesting**

FARM has three alternative harvesting systems: centrifuge, polymer flocculation, and electrocoagulation. The model allows for each of the systems to be used as the sole harvesting system or to be used in combination. The user must specify what percent of the annual algae production will be harvested by each system. CAPEX and OPEX associated with each process, such as electricity, chemicals, and maintenance must be entered by the user. In addition, the user must also specify the throughput capacity (L/hr), harvest time (hours/day), effective recovery rate of harvested algae, and percent solids of the algae output. These parameters are used to determine the number of harvesting units needed for the facility. Effective recovery rate also allows the biomass actually harvested to be tracked so the extraction machinery can be sized appropriately.

- **Extraction**

In FARM, there are three different extraction options to choose from: Solution Recovery Services (SRS), Hydro-Thermal Liquefaction – Catalytic Hydro-thermal Gasification (HTL-CHG), and Pyrolysis. The CAPEX and parameters for the extraction systems are more specific than harvesting. However, parameters that remain constant between processes are: throughput capacity (tons/day) or (liters/hour), and extraction (hours/day) to determine the number of units needed, along with capital cost ($/unit), life of the machine (years), operating costs, and annual maintenance cost.

- **CAPEX**

Values for CAPEX are specified by the user. CAPEX categories are: dirt moving construction, raceway construction, photo bio-reactor (PBR) tubes or bags, sump construction, liner, perimeter fence, dividers between ponds, paddlewheels, CO_2 delivery system, nutrient storage and distribution, piping system, algae inoculum stations, water wells, storage buildings, anaerobic digester, power generation, electrical lines, office building, backhoes, motor graders, pond sweepers, lab building and equipment, field expenses, diesel plant capital cost, contingency costs, and other capital costs. CAPEX costs are summed and split into the appropriate machinery replacement categories based on useful life. These summations are used to compute the values of the machinery replacement loans and cash flow requirements for maintaining current equipment. CAPEX for extraction and harvesting equipment are entered on a per unit basis and FARM scales the total CAPEX for these functions based on the number of units required to handle the throughput of water and algae biomass.

- **OPEX**

There are several different operating cost categories so the analyst can customize input costs to match the business being simulated. In each category, the user may either enter a lump sum annual operating cost for that category or be more specific and enter information that will be used to calculate usage and costs. The OPEX categories are as follows: CO_2 , media, labor, electricity, water recycling, waste water disposal, natural gas, property tax rate, workman's compensation/unemployment tax, non-harvesting and extraction maintenance costs and crash cleanup costs, and harvesting and extraction costs.

- ***Pro Forma* Financial Statements**

FARM calculates three *pro forma* financial statements: income statement, cash flow, and balance sheet. These statements summarize the business activities carried on by the algae farm.

  - **Income Statement**

The income statement provides separate lines for each source of receipts, such as: algae crude oil, biodiesel, electricity, PUFAs, LEA, and whole algae. By reporting receipts by source the analyst can see where receipts are being generated and can make changes to input data as needed to insure proper simulation of the business being analyzed. The receipts in the statement are calculated elsewhere in the model and are only summarized in the income statement.

The second part of the income statement has separate lines for each cash expense. The cash expenses include: nutrients, labor, fixed costs, electricity, etc. Total cash expenses are used to calculate operating interest costs based on the projected annual interest rate.

Other interest costs included in the expenses section are interest for the initial loan for CAPEX and interest for cash flow deficit loans. The latter occurs when the business has insufficient cash reserves and net cash income to pay required cash outflows described in the cash flow statement. If a cash flow deficit exists in year t, then the interest for a short-term loan against the deficit is calculated and included as an interest expense in year t+1.

Net cash income equals total receipts minus total cash costs and total interest expenses. Net income equals net cash income minus depreciation. For this calculation depreciation is calculated using a straight-line method.

- **Cash flow Statement**

The cash flow statement is divided into two parts: cash inflows and cash outflows. Cash inflows include cash on hand January 1, net cash income for the year, and interest earnings on beginning cash reserves. Cash outflows include: investor dividends, principal payments, repayment of cash flow deficits, income taxes, and down payments for machinery and equipment replacement. These items are cash outlays but are not tax deductible so they do not appear in the income statement. The last line of the cash flow statement calculates the ending cash balance on December 31 as total inflows minus total outflows.

- **Balance Sheet**

The balance sheet is divided into assets and liabilities. The first asset is positive ending cash reserves for December 31. If ending cash is negative this value is zero. The ending cash value from this line is what becomes beginning cash reserves next year in the cash flow statement. Other assets include the market value of land, capital improvements, and machinery.

The liability section of the balance sheet shows the current balance for the original loan and the cash flow deficits if ending cash reserves are negative. Net worth is the final value in the balance sheet and equals assets minus liabilities.

Key Output Variables (KOVs)

The KOVs are the variables from the model that are sent to Simetar to collect during simulation and then calculate summary statistics after the last iteration. The KOVs include variables such as: net present value, rate of return on equity, annual net cash income, annual ending cash reserves, counter variable for positive annual cash reserves, present value of ending net worth, probability of increases in real net worth, annual cost of biomass, lipids, and diesel and marginal cost of biomass, lipids, and biodiesel. Any variable in the model can be included in the list of KOVs.

Costs of production are net costs calculated by subtracting credits for by-products which are sold. Credits for recycled water, nutrients, and CO_2 do not directly reduce costs because they do not generate cash to the business. The recycled inputs directly reduce costs to the extent that they reduce the cost of inputs.

Income Taxes

The income taxes for the business are calculated assuring the business is taxed as a corporation. The taxable income equals net cash income minus depreciation calculated based on IRS code for the reasonable life of each piece of machinery. The income tax rates in the IRS code for corporations are used directly. At this time there are no state income taxes being calculated for the model.

Model Output

Each time the input data changes the model must be re-simulated using Simetar. The simulation takes 3 to 45 seconds and the stochastic results are presented in the simulation results (SimData) worksheet. The results in SimData include summary statistics for each KOV and the 500 actual simulated values for each KOV.

Probability charts (PDFs, CDFs, Fan Graphs, and StopLight charts) are developed from the 500 simulated values of selected KOVs. Tables of the summary statistics for selected KOVs can be developed. The charts developed using data in SimData will automatically update each time the model is re-simulated by Simetar.

A policy working paper is designed to provide economic research on a timely basis. It is an interim product of a larger AFPC research project which will eventually be published as a policy research report. These results are published at this time because they are believed to contain relevant information to the resolution of current policy issues. AFPC welcomes comments and discussions of these results and their implications. Address such comments to the author(s) at:

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