THE FUTURE OF BIOFUELS: AN ECONOMIC ANALYSIS OF THE DESIGN AND OPERATION OF A MICROALGAE FACILITY IN TEXAS AND THE SOUTHWESTERN UNITED STATES

A Thesis

by

MARC S. ALLISON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Agricultural Economics

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Approved by:

Chair of Committee,	James W. Richardson
Committee Members,	Clair J. Nixon
	Joe L. Outlaw
Head of Department,	John P. Nichols

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ABSTRACT

The Future of Biofuels: An Economic Analysis of the Design and Operation of a Microalgae Facility in Texas and the Southwestern United States. (August 2010)

Marc S. Allison, B.S., Missouri State University

Chair of Advisory Committee: Dr. James W. Richardson

The world of energy is changing. With rising energy costs and concerns over the supply of energy materials, more research is being conducted into alternative sources of fuel and microalgae is one of the sources being researched, although much research had been conducted on it as a part of the Aquatic Species Program from the 1970s to the early 1990s. With the emergence of microalgae as a source of alternative energy, the need for an economic analysis of microalgae has arisen. This research studies the economic feasibility of the design and operation of a microalgae production facility in two Texas locations (Pecos and Corpus Christi) and in southeastern New Mexico using a stochastic simulation model. It examines the production levels needed for the facility to be profitable and also some facility designs necessary for that profitability. It also measures several annual financial indicators so that potential investors have some estimates of the future profitability of the microalgae industry.

The results show that for microalgae to become a viable commercial operation, production must be improved beyond the current levels and the levels suggested by the literature. Production needs to be at least 0.8 g/L/day with 40% oil content and 24” of

water depth. Production must be improved through increasing growth rates and oil contents at greater water depths. Production can be improved through nutrient and carbon dioxide usage, two elements that are being heavily researched. Water usage will become a major focus because of the limited resources and the quantities necessary to operate a commercial-scale facility. With the necessary improvements in technology and research, microalgae could prove to be a viable source of alternative energy.

ACKNOWLEDGEMENTS

First of all, I would like to thank my family, especially my parents, for the guidance, support, and advice they have given me through this process and throughout my life. I would not be where I am today without all of you. A special thanks to my cousin, Mr. Chris Eggerman, for steering me on the right path towards Texas A&M University. This is a very special place and my experiences down here are ones I will treasure the rest of my life.

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To everyone at the Center of Excellence for Hazardous Materials Management, especially Doug Lynn and Greg Brown, thank you for sharing your insight and your data with us. This model would not be possible without the help of all of you. It is always great to see what farming mixed with engineering can create.

Finally, to everyone else at Agricultural & Food Policy Center, thank you for your help, advice, and guidance. You all made me feel welcome and at home and I know that this group of people is one I will miss as I leave Texas A&M.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF FIGURES

Page

Page

Page

LIST OF TABLES

Page

Page

Page

CHAPTER I

INTRODUCTION

1.1. Problem Statement

With rising concerns over the perceived worldwide shortage of oil and the rising cost of oil affecting many sectors of the economy, the race is on to find an alternative source of fuel. Early sources have included corn ethanol and biodiesel from soybeans. Still, the concerns over competition for agricultural land area for fuel as opposed to food has led to further research into other sources. In addition to the food versus fuel argument, there are also concerns of worldwide land use (the destruction of rainforests for conversion to farmland) and the overall efficiency of renewable fuels from food crops (because those crops can only be harvested once per year). The U.S. Department of Energy created the Aquatic Species Program in the 1970's as a response to a similar situation with concerns over oil supplies and prices. This program examined the potential of aquatic species, microalgae in particular, to serve as a source of renewable fuels. However, after the oil market calmed, the program ended and research dwindled significantly. The interest in microalgae has begun to increase again in the recent years. Producing a renewable fuel from microalgae will not be widely accepted until it can become cost effective because the bottom line (profits and losses) tends to be the driving force for most ideas in the world today.

This thesis follows the style of the *American Journal of Agricultural Economics*.

1.2. Objective

The objective of this analysis is to examine the profitability and determine the viability of a microalgae production facility for the purpose of producing oil as a renewable fuel. This model will only address the profitability and viability of a microalgae facility in Texas and the southwestern U.S., more specifically, south Texas, west Texas, and southeastern New Mexico.

A simulation model will be built to estimate fixed and variable costs for a ten-year horizon. The life of such a facility is expected to be much longer than that but this industry is rapidly changing and because of that fact, the author felt that modeling beyond ten years would be ineffective. The model addresses the production potential of the facility, in both oil and by-products. Forecasts will be developed based on simulation to determine climatic conditions (evaporation and precipitation), which have an effect on multiple aspects of facility operation. Prices for variable inputs will be forecasted based off historical data and simulation. The model will also forecast potential prices of the facility outputs for the ten-year horizon, based on historical prices for comparable products and simulation. It will construct financial statements to examine the annual profitability and returns as well as profitability measurements for the ten-year horizon of the model.

The model will be scalable based on the desired size of the facility, which will be determined by a decision maker. In order for the model to be scalable, it will be based on a general facility design, which resulted from a combination of the literature, research, and interviews with people currently operating microalgae facilities. The scalability of the model will allow it to automatically recalculate fixed costs, variable costs, and production any time an input is changed. There will be many different design inputs at the discretion of the decision maker, such as the size of the facility in acre feet of water, the length of the raceways, and water depth.

Based on the inputs, outputs, forecasts, and results, the model will not only look at profitability/viability of a microalgae facility in Texas and the southwestern U.S., it will also examine areas of potential improvement which could improve the profitability of a facility, whether it be in facility design, fixed inputs, variable inputs, production, or technology.

The goal of this research is to build a broad ranging model with the ability to adapt to any facility design, improvements in technology, or changes in production. However, it should be noted that the facility designs are only approximate designs and that most of the cost information is only general because much this is an evolving industry. This model is designed to give a general cost idea and give general ideas about improvements that must be made within the industry. For a commercial scale microalgae facility to be built, a team of design and construction engineers would be needed to give a final design. It should also be noted that the microalgae industry is highly competitive due to the relatively young nature of the technology and the potential for significant government research grants. Therefore, information regarding production styles and facility designs was difficult to obtain. In exchange for some of the information and parameters vital to constructing a full-scale microalgae model, a confidentiality agreement was signed between the author and a group of individuals currently working in microalgae production.

1.3. Thesis Outline

The model begins with a background on biodiesel and the potential of microalgae as a source of biodiesel. It examines the benefits and drawbacks of biodiesel in addition to the current state of the industry. The history of microalgae and government programs is addressed as well as the characteristics of microalgae that make it suitable for renewable energy production.

The review of literature examines research already completed in the microalgae field, much of which comes from the Aquatic Species Program or research that began as part of the Aquatic Species Program. It is also worthy to note that a large amount of research on microalgae has been conducted outside the U.S. The review of literature addresses economic costs as well as facility design and microalgae production.

Chapter IV addresses the economics and mathematical basis for the model, examining risk, simulation, and the methodology for developing the model. Chapter V explains how the model was developed and how it functions. It also explains all the inputs at the discretion of the decision maker. Chapter VI discusses the results of the model and analyzes the potential of microalgae in Texas and the southwestern U.S. Chapter VII summarizes the research and analysis. The appendix section of the thesis provides additional summary statistics of the results and maps of suitable areas for microalgae production.

CHAPTER II

BACKGROUND

2.1. Biodiesel

With the rising cost of energy along with concerns regarding the climatic effects of traditional energy sources, researchers have once again been focusing on alternative energy sources. Biodiesel, as a replacement for petroleum-based diesel, and ethanol, as a replacement for gasoline, have become two major areas of research and policy discussion.

Biodiesel is currently mixed with traditional petroleum-based diesel because the biodiesel industry cannot meet current demand. According to Demirbas (2007), biodiesel offers a variety of benefits that make it at least a useful blending component. Unlike oil, biodiesel feedstocks come from renewable sources, meaning that potential supplies are much greater than the finite supply of crude oil and are readily available throughout the world. Several feedstocks, including soybeans, rapeseed, canola, and sunflowers, are produced domestically, which also reduces our dependence on foreign sources of petroleum.

Demirbas (2007) recognizes the much safer nature of biodiesel due to its biodegradability and higher flash point. The biodegradability allows the biodiesel to break down faster in natural conditions and also poses fewer risks when spilled. According to Zhang et al., this improved biodegradability is a result of the pure fatty acids naturally existing in biodiesel. The enzymes for breaking down fatty acids also naturally exist, meaning the biodegradation process can occur more rapidly. The rate of a catalyzed reaction is regulated by the amount of catalyzing enzymes that are present in the cell. Zhang et al. also shows that after 28 days in an aquatic environment, various biodiesels were 77-89% biodegraded, compared to only 18% biodegraded from petroleum diesel. The higher oxygen content of biodiesel also contributes to the improved biodegradability. Higher flash points result in less risk of explosions in fuel transportation.

Demirbas (2007) states that biodiesel's higher oxygen content improves the combustion process and decreases oxidation potential by increasing the homogeneity of oxygen with the fuel during combustion. Biodiesel is more engine-friendly than petroleum diesel due to its viscous properties. This results in engines being better lubricated, meaning they have a longer life expectancy.

Concerns surrounding climate change and the atmosphere have also added to the interest biodiesel. Demirbas (2007) indicates that sulfur levels in petroleum diesel are 20-50 times higher than in biodiesel. The combustion of biodiesel provides a 90% reduction in unburned hydrocarbons and a 75-90% reduction in polycyclic aromatic hydrocarbons. Compared to petroleum diesel, biodiesel also provides reductions in carbon monoxide and particulates.

Biodiesel does have its negative aspects as well. Demirbas (2007) explains problems related to higher cloud and pour points. The cloud point is the temperature at which the fuel begins to thicken, or become "cloudy." The pour point is the temperature at which the fuel continues to thicken and will no longer pour. The higher cloud and pour points associated with biodiesel mean that the diesel will gel more quickly and gel at colder temperatures when compared to petroleum diesel. This impacts a vehicle's ability to start and to run effectively in cold temperatures, one factor that discourages many from using pure biodiesel.

Although the improved viscosity does improve the lubrication qualities of the fuel, it also does create fuel pumping difficulties. According to Terry (2005), biodiesel causes the fuel pump seals to swell more than petroleum diesel. As the seals shrink back to their original size, there is a risk of fuel leaking or for air to be sucked into fuel lines. This can cause the fuel pump to fail, costing vehicle owner's money, not to mention the money lost and pollution created as a result of the leaked fuel. In addition to damaging the fuel pump, Terry (2005) states that biodiesel also creates problems because of its higher copper strip corrosion. Fuel system parts made from copper, bronze, or brass can be damaged by biodiesel, creating even more problems for vehicle owners. Although most current engines can withstand some of the biodiesel wear because most biodiesel is blended with petroleum diesel, pure biodiesel could require engine design modifications, creating more costs.

Biodiesel has lower energy content than petroleum diesel. Lower energy content creates less power for the engine, meaning more fuel will be needed to create power comparable to petroleum diesel. More fuel means higher costs. According to Demirbas (2007), biodiesel decreases power 5% when compared to petroleum diesel. Additional cost concerns result from the high production cost of biodiesel, which cannot be produced as cheaply as petroleum based diesel.

Biodiesel, like ethanol, comes from a variety of feedstocks. Agricultural crops, such as soybeans, rapeseed, canola, and sunflowers, are some of the more widely used sources of biodiesel, with soybeans being the most prevalent. Soybeans are one of the larger crops in the United States and South America. Legislation has encouraged the use of agricultural crops for fuel production. However, due to concerns regarding the competition between the fuel and food industries for agricultural crops and deforestation problems created by the demand for new agricultural land, researchers are exploring other potential alternative sources of fuel. In addition to the financial incentives involved, U.S. energy policy mandates so-called “advanced fuels” to meet future required levels. Microalgae oil is one of many sources of biodiesel in which research continues. However, because of previous exploratory research, new research can be focused on refining the process and making it economical.

2.2. Microalgae Overview

Much of the microalgae research in the United States centers around work completed in the period from the mid-1970s to the mid-1990s as part of the Aquatic Species Program conducted by the National Renewable Energy Laboratory, which is a division of the Department of Energy’s Office of Fuels Development. This program was developed as a reaction to high energy prices in the 1970s and work continued into the 1990s. As energy prices subsided and federal government budgets began to tighten, the Aquatic Species Program came to an end with much valuable information but no definitive production systems. Much of the uncertainty surrounded the production ability of the microalgae, the cost of production, and the methods by which the oil can be extracted from the algae cells. Those concerns remain the same today.

Specific strains of microalgae have much greater value in cosmetic and pharmaceutical uses. Research abroad, in addition to focusing on microalgae’s use as a potential fuel source, was also focused on high-value microalgae product. Research in

Australia and New Zealand, in addition to work by companies in Israel, is working to further the microalgae industry.

With the rise in energy prices, alternative fuels sources, including microalgae, are once again the focus of much research. Microalgae offers a variety of benefits as a fuel source if the algae harvest and extraction process can be designed in an economical manner. Microalgae can be produced in an environment that is not suitable for most agricultural crops. Flat, dry, warm portions of the United States (and the world), such as western Texas, parts of New Mexico and Arizona, and other southern areas, are favorable for microalgae production. Research indicates that the microalgae are more productive in warmer climates and the warmer climates offer the opportunity for year-round operation.

Maxwell, Fogler, and Hogg (1985) delve deep into the factors necessary for evaluation of a potential microalgae facility location. According to Maxwell, Fogler, and Hogg (1985), there are three primary parameters that should be evaluated: climate, water, and land. Climate and water tie into one another somewhat. Climate, specifically insolation and temperature, will affect the evaporation of the water in the raceways. The suitability of a facility site based on climate is exhibited in Figure 1 below. The raceway water needs to be maintained at a fairly constant level, meaning that areas with higher temperatures and insolation levels will require more water to replenish the raceways, meaning more groundwater will have to be pumped or the facility will have to find another water source. Figure 2 shows the suitability of land in terms of water factors in the southwestern U.S. as it pertains to the operation of a microalgae facility.

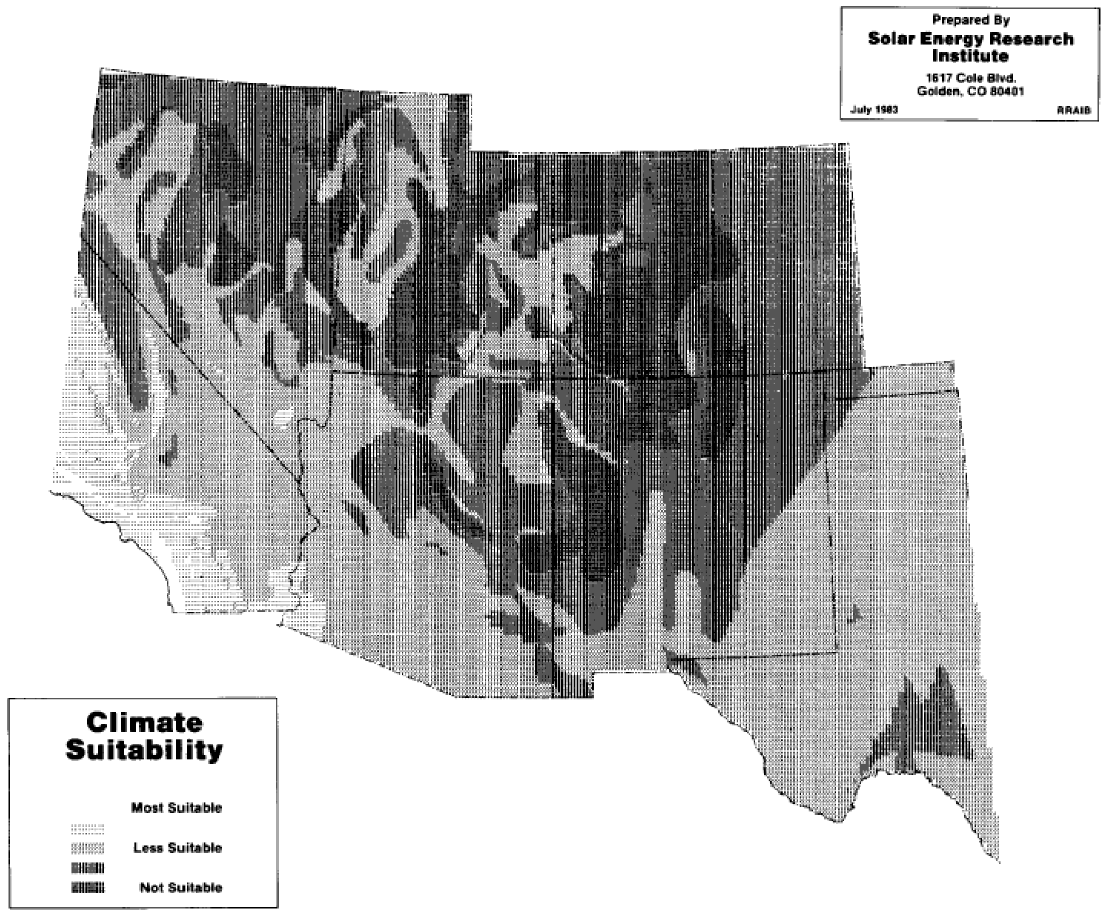

Figure 1. Zones of relative suitability for microalgae biomass production based on climate factors.
Source: Maxwell, Fogler, and Hogg (1985)

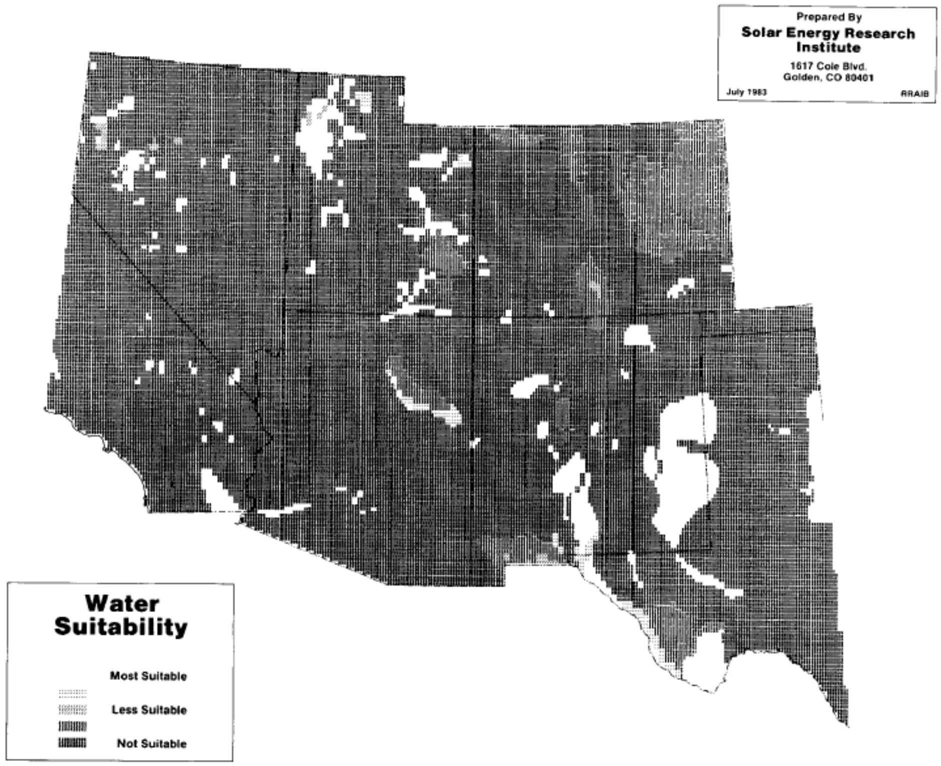

Figure 2. Zones of relative suitability for microalgae biomass production based on water. Source: Maxwell, Fogler, and Hogg (1985)

The precipitation of the location is important but could also be a detriment. Rainfall can replace water lost to evaporation. The same rainfall could also include contaminants that could be harmful to the microalgae. Another factor to consider when evaluating facility sites is the ownership of the water rights, which also ties into the land component. According to Maxwell, Fogler, and Hogg (1985), selecting a site based on land suitability is the final factor for consideration. Flatter topography is needed for the current raceway system designs. Flat land leads to less dirt moving during construction and lower construction costs. Land use is another important consideration when evaluating a site for a potential microalgae facility. Using land that is not already used in crop production agriculture means there is less competition between food and biofuels for the cropland. There is hope, but no proof, that the decline in competition between food and fuels will reduce the upward price pressure on agricultural commodities and food.

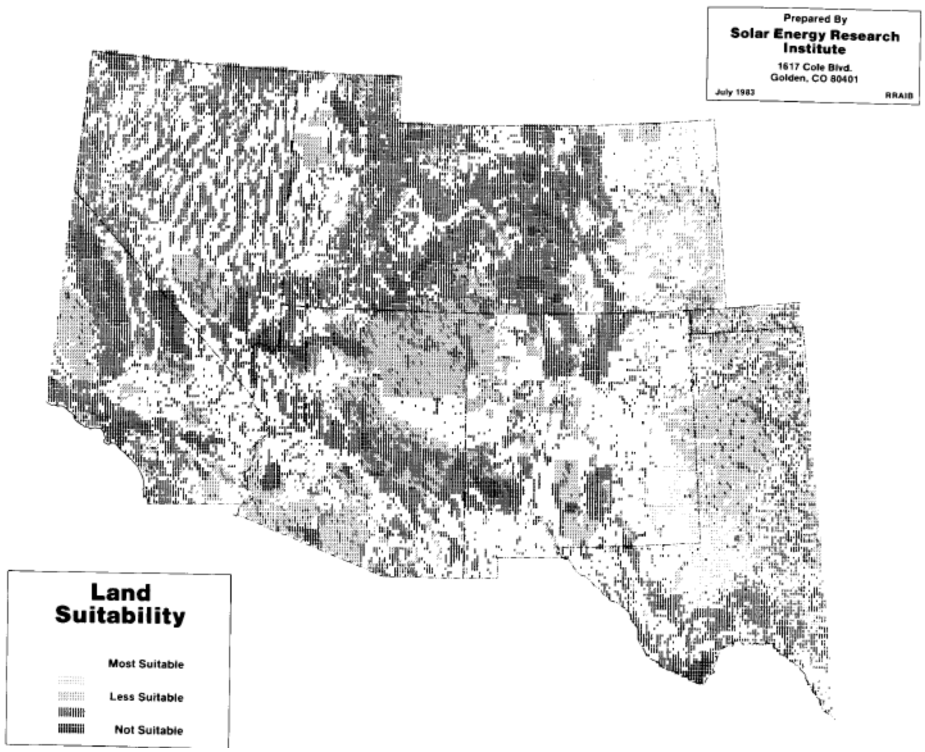

Figure 3. Zones of relative suitability for microalgae biomass production based on the availability and suitability of land resources.
Source: Maxwell, Fogler, and Hogg (1985)

Finally, the ownership of the land must be taken into account. Because of the potential size of the facility, continuous, flat land may be difficult to come by. It should also be noted that the U.S. government owns or manages large portions of land in the southwestern U.S. The suitability of a site for microalgae production based on land factors is reflected in Figure 3 above. Based on the factors mentioned above, Maxwell, Fogler, and Hogg (1985) were able to develop a suitability map for microalgae site selection in the southwestern U.S. It is shown in Figure 4 below.

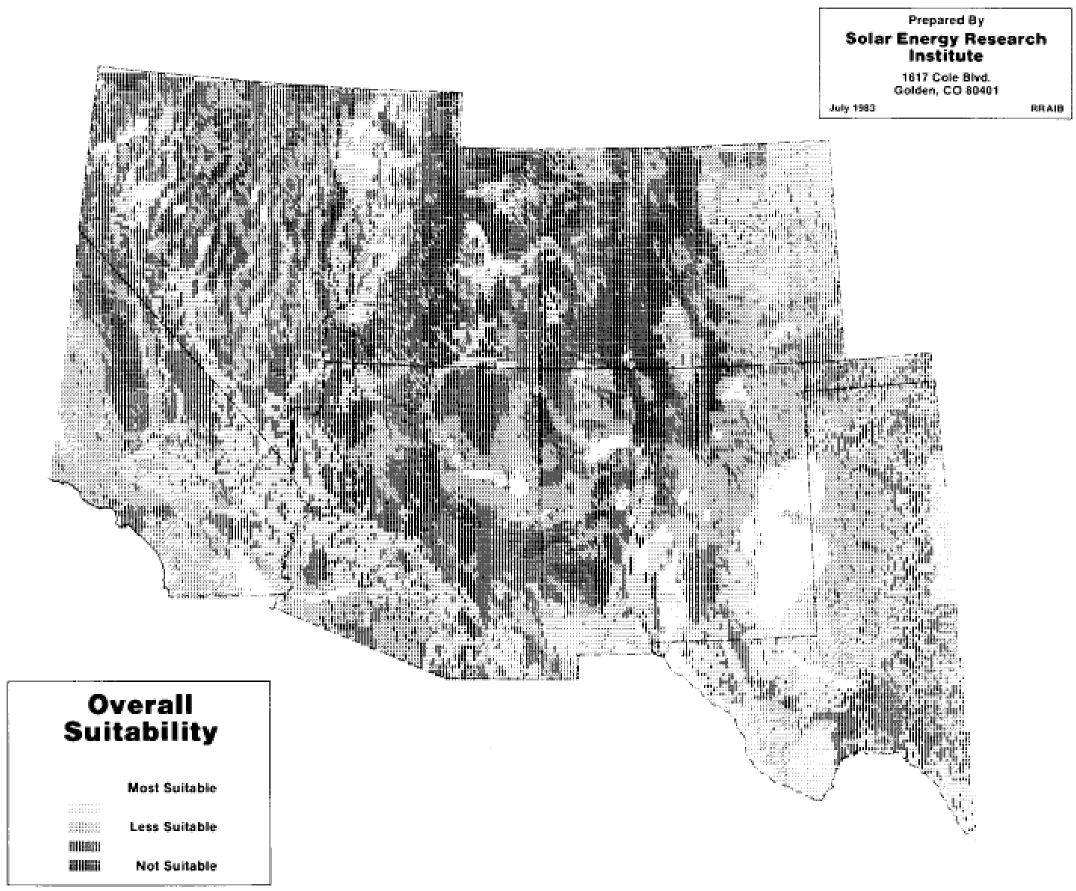

Figure 4. Zones of relative suitability for microalgae biomass production based on a compositing of climate, land, and water suitability maps.
Source: Maxwell, Fogler, and Hogg (1985)

In addition to being able to be produced on poorer quality land, algae can potentially produce much more fuel per acre than agricultural biofuels. Microalgae can be harvested many times throughout the year compared to one harvest for agricultural biofuels. Research has shown a variety of production cycles, ranging from being able to harvest every three days up to every two weeks. Algae growth rates have a large influence on the length of the production cycles. Microalgae, in the right climate, can also be produced year-round.

Microalgae is environmentally friendly, something that is a major area of focus in the energy world today. Although it does not reduce carbon emission, fuel from microalgae is considered to be carbon neutral. According to Scragg, Morrison, and Shales (2003), microalgae grow photosynthetically so no carbon source is required and any carbon dioxide released on combustion will have been previously fixed, meaning that the energy supply is carbon neutral. The carbon that is a by-product of the electricity used during the growing, harvesting, and extraction process will be offset by the carbon intake used in the growing process.

2.3. Microalgae Production

Microalgae are commonly produced using two methods: raceway ponds and photobioreactors. Photobioreactors produce algae using a long series of tubing in which the algae grow. Photobioreactors are not used in this research because of concerns with the cost effectiveness of such a system. If the costs were to be reduced in the near future, microalgae would be easier to produce in such a system. Photobioreactors have higher production and growth rates and are easier to control the growth environment for the algae. Contaminants, rain, and varying temperatures are not a threat in a photobioreactor production system because it is a closed system. If it is economical, photobioreactors can be built using vertical stands, meaning that much more algae can be produced in a smaller area. Currently, photobioreactors are more popular for producing the high value algae but they do offer some great potential for the future if such a system becomes cost effective.

Raceway ponds are the production system used in the current analysis. Although the system is not as productive, it is more cost effective at this time. Raceways are just as they sound, long channels with half circles at each end. A series of raceways are grouped together to form a single pond. The algae travels around the raceway until it is harvested or moved to another raceway. Some production systems use a series of raceways in which the algae starts out in smaller raceways and once it reaches a certain concentration, some of the algae is moved to a larger raceway while the remaining portion is left in the smaller raceway to start the next round of growth. The process continues through multiple sizes of raceways until the algae is ready to be harvested. This is referred to as a batch or terminal production system. Other raceway systems use the same size raceway and only have one level of production. Only a portion of the microalgae culture is harvested at each interval while the remaining culture continues to grow. This is known as a continuous production system.

The length and width of the raceway varies widely depending on design. To maximize land use area, larger raceways are preferred because less area is wasted in between each raceway. However, that fact must be weighed against the production preferences of the facility. Larger raceways also pose more loss risk if a raceway is contaminated. Larger raceways also require a larger form of moving system to keep the algae circulating in the raceways. Such factors must be balanced to determine the most effective raceway size.

Raceway and pond formation creates a significant cost in the microalgae production facility. Soil must be removed from the bottom of the raceway to create a lane in which the algae can flow. The bottom of the raceways must be level so that all the algae move freely. The depth of the raceways determines how much soil must be moved. This is another decision variable that comes into the design of the system. Deeper raceway ponds can create problems with shading, meaning that the algae on the bottom of the raceway do not receive the necessary light and in turn are not as productive or even die. Shading can be controlled by making sure the microalgae circulate through the raceway at a pace that ensures all algae receive the necessary light. Deeper ponds are able to combat evaporation more effectively because a smaller percentage of the water is lost when compared to more shallow ponds. Although it might seem that larger raceways would increase cost per unit of area, costs can actually be lower because larger construction equipment can be used and can move more soil at one time. In addition, larger equipment can use the precision equipment more efficiently, meaning lower costs associated with raceway pond leveling.

Microalgae circulation is an important component of raceway pond design. Most systems use one of two sources to circulate algae: gravity or paddlewheels. Paddlewheels, as shown in Figure 5 below, are large, electricity-driven wheels with paddles to circulate the algae. Paddlewheel cost varies based on the size of the paddles and the size of the motor necessary to drive the paddles. Larger and deeper raceways require large paddlewheels and motors for circulation. Larger paddlewheels tend to be more expensive. However, larger raceways could mean fewer numbers of paddlewheels necessary for the facility, depending on the raceway design.

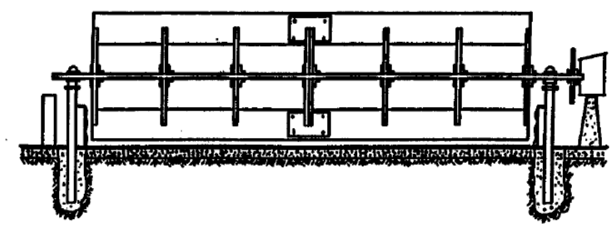

Figure 5. Microalgae paddlewheel.
Source: Green, Lundquist, and Oswald (1995)

Gravity is a more natural source of algae circulation. Raceway ponds must be designed with a very small decline to create the algal flow. This creates more costs for soil removal and for the precision with which the raceway pond decline must be created. Additional costs include the need for a pump to move the algae/water mix from the low end of the raceway back to the upper end to continue the circulation process. In addition to the initial cost of the pump, this also leads to additional electricity costs.

Although some research has experimented with unlined ponds, the common sentiment among researchers is that some kind of pond liner must be used. Neenan et al. (1986) states that pond liners reduce water loss by preventing water from seeping into the soil. Pond liners also keep contaminants from entering the production system through the soil. Liners vary in cost depending on the composition of the liner and the size of the liner rolls. This is another instance in which raceway pond design comes into play in that liner rolls can be used more efficiently for some designs. Smaller raceways mean more manipulation of liner rolls and more welds that must me made on the liners to ensure that there are no leaks. This increases the labor intensity necessary to build the ponds and the cost of raceway construction.

Thousands of microalgae strains exist throughout the world. Selecting the ideal strain for oil production is based on a variety of factors, some controlled by the facility operator's preferences and other controlled by the environment in which the facility is operated. In the United States, the proposed areas of production in the Southwest have higher saline concentrations than many other areas. For that reason, the microalgae should be able to withstand not only high salinities but also variations in salinity, according to Neenan et al. (1986). Neenan et al. (1986) also states that the strain should also be able to handle high temperatures. Higher photosynthetic efficiencies are desirable. Photosynthetic efficiency refers to the organism's ability to convert light into energy, which in this case leads to the production of oil by the algae.

To begin the microalgae production process, seed algae, the initial algae added to the raceway ponds to begin algae growth, must be grown in much smaller containers in a laboratory until a large enough supply is reached to inoculate the raceway ponds. In most instances, the microalgae first start in beakers and then progress until they are ready to be added to the raceways, a process that takes one to two weeks. Once you have the initial supply, no additional seed algae is needed because a portion of the algae is harvested while the algae remaining in the raceways begins the growth process again. It may be necessary to keep seed algae inoculants on hand in the event of a raceway contamination. However, because the seed algae is expected to be a one-time cost, it does not constitute a significant cost to the process and therefore is not heavily emphasized in the analysis. Even if multiple strains of microalgae are used in the system, the cost still remains small in relation to overall fixed costs.

The composition of the microalgae is important to yield. Microalgae, as shown in Figure 6, is composed of lipids, carbohydrates, protein, intermediates, and ash, with the first three making up the majority of the organism. Microalgae strains with high lipid contents are the most desirable because the lipid is oil. This is a major area of research because of its ability to increase production. A small increase in lipid content can a have a major impact in the overall productivity of the system. Resistance to predators and contaminants is another desired characteristic of the microalgae due to the outdoor nature of the raceway pond production system. The necessity for such a characteristic is enhanced by the expected location of the facilities because of the risk of wind-blown contaminants in addition to contaminants introduced through precipitation. Lastly, although the harvesting and extraction process has not yet been completely refined, buoyancy and behavioral characteristics that enhance harvesting are desired as well. (Neenan et al. (1986))

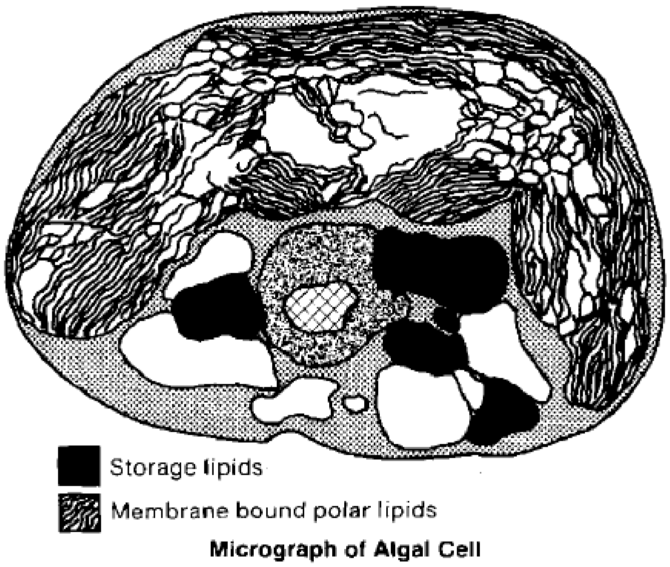

Figure 6. Microalgae cell.
Source: Neenan et al. (1986)

More than one algae strain can be used in a production system. Because there has yet to be one strain that possesses all of the necessary characteristics, depending on the climate, multiple strains may be needed to allow efficient year-round production. However, depending on the compatibility of one algae strain to another, the production system may need complete cleaning from one strain to the next. This creates down time for the entire system, creates additional labor for workers, increases the cost and decreases the system's efficiency. These factors must be weighed with the potential gains from increased productivity resulting from microalgae strain changes.

Microalgae strains are available from the University of Texas at Austin and the University of Hawaii. Researchers are working to develop strains of algae specifically for microalgae fuel production. Those strains, as mentioned earlier, are designed with higher lipid contents, photosynthetic efficiencies, and tolerance to a variety of climates and salinities. The ability to use one strain across all facilities and year-round will make the industry more efficient and only make it an even more viable alternative fuel source in the future. Choosing the correct strain of algae is a part of the process that is best left to a biologist rather, but with the assistance of economists.

Once the microalgae have been harvested from the raceway, it must be stored until the oil can be extracted, another process that needs significant research. The part of the process that is known is the necessity for storage facilities after the process. Once the water is separated from the algae from the raceways, it forms a sludge-like material. The separated water can be recycled back to the raceway ponds for further use. Some water loss due to the harvesting process is expected. Upon completion of the extraction process, two substances will be present: oil and the algae by-product. Oil storage tanks will be necessary, once again with their size depending on oil content and growth rates in addition to the number of days of oil harvests that will be stored before the oil is transported elsewhere for further processing.

The remaining microalgae by-product is of great interest for its potential as animal and aquatic species feed. The by-product will need a large storage facility in which it can dry completely until it forms into a dust-like consistency. It can be stored in similar conditions to conventional animal feeds and can be handled using a smaller skid steer or tractor with a loader. The byproduct could be pelletized to reduce loss in shipping and increase the ease in handling. The pellets could also be customized to the based on the needs of the end user, depending on the end user’s ability to digest such products. Depending on the location of the microalgae facility, the by-product, which is high in protein and carbohydrate content, could be used in beef or dairy rations or as shrimp or fish feed supplement. The by-product could be transported using conventional commodity trailers, similar to distiller's grains (by-product of corn ethanol production) or soybean meal (by-product of soybean biodiesel production). The by-product storage facility size would be determined by the oil content and growth rate of the algae in addition to the number of days of storage capacity necessary (how often the by-product will be transported to another facility or to a consumer).

A variety of nutrients are necessary to enhance the growth of the algae. Because the specific nutrients have a significant impact on the algal productivity, the exact formulations are a closely guarded secret, which creates difficulties in the cost analysis. The particular nutrients also depend upon what strain of microalgae is used. Either way, the nutrients still must be fed to the algae in the raceways at certain intervals. Depending on the size of the facility and the available labor, the easiest solution would be to have an automated mixing and piping system set on a timer to disperse the feed to the microalgae. The nutrient ration may also be tailored to the growth stage of the algae and the current climate conditions (i.e., temperature changes may warrant a change in algae nutrients). A larger facility will have an easier time justifying the cost for such a complex system. In addition to the cost of the pipe, laying the pipe creates more construction and labor costs. An automated monitoring system is still in the developmental stages and will be expensive when it becomes available. These costs must be compared to the potential labor costs resulting from having nutrients applied manually. Storage facilities will be needed and the amount of storage necessary will be dependent on the number of days of nutrients that facility operators plan to keep on hand, the size of the production facility, and the application rate of the nutrients.

The majority of the production process requires two other major inputs: labor and energy. Energy in the form of electricity will be required for the circulation, nutrient mixing, harvest, and extraction processes. The current analysis prices electricity based on current market rates. However, to make the facility and the process more environmentally friendly, there is a potential to use wind turbines as a source of energy generation. Wind energy is highly dependent on the location of the facility, another reason for locating the facility in the southwest where wind is abundant.

Microalgae production is presently a labor-intensive process. Competent, alert, and dedicated workers are essential to operating a successful facility. Labor needs depend heavily upon the size of the facility because the raceway ponds rely on daily monitoring to ensure the production process runs smoothly and efficiently. Pond operators must be alert for contaminants and other problems that arise in the system to ensure that the microalgae is able to be harvested and the oil extracted. If there are problems in the raceway ponds, an aquatic biologist with an advanced degree (Master's or Ph. D.) will be on staff to address the issue. A fisheries biologist with an advanced degree is necessary to determine nutrient mixes as the necessary ingredients may change based on the seasonal changes throughout the year. When real-time monitoring systems are perfected, the same number of well-trained biologists will be able to handle larger operations. Procurement will manage the harvesting and extraction process as well as the by-product storage. An operations manager will oversee the day-to-day operations of the facility, preferably someone with experience in management and engineering. A project manager will manage the larger aspects of the facility (purchasing, selling, and logistics) with help from a marketing specialist. Additionally, the marketing specialist will be responsible for expanding the profile of the facility's products as well as the overall profile of the microalgae industry. An administrative assistant will be necessary to help the project and operations managers in the overall operation of the facility.

CHAPTER III

REVIEW OF LITERATURE

3.1. Microalgae Costs

3.1.1. Microalgae Facility Costs

Research into microalgae as a potential fuel source has been revived in the past few years. No full scale commercial facilities for renewable fuels production are in operation today so it is very difficult to discover exact cost information for a commercial facility. The cost information reported here comes from a variety of publications, some of which contributed information regarding the necessary equipment for such a facility while the others indicated actual cost information. Because of concerns about overall inflation being different compared to the exact equipment necessary for the system, instead of inflating the cost values, potential sellers were contacted to obtain current prices regarding needed equipment. Cost estimates varied from one publication to another due to differences in production practices, facility locations, system design, and time of construction. When building the model, the estimated parameters were meant to reflect not only the literature but also the differences in the production system from those reflected in the literature.

Facility construction costs constitute a major portion of the overall system cost. The precise nature with which the facility must be constructed only enhances that cost. Larger raceway designs lend themselves to the use of larger equipment and therefore cheaper raceway construction costs. Huntley and Redalje (2007) estimate raceway costs in 2004 U.S. dollars to be near $75,000 per hectare of raceways, an estimate which includes all costs associated with the raceway, including construction and equipments considerations. The system analyzed differs from this model in that it also includes photobioreactors, at a ratio of four hectares of raceways for every hectare of photobioreactors. In addition, the raceways in this system are much smaller, being 76 m (~250 ft) long, 5.5 m (18 ft) wide, and 12 cm (4.72 in) in depth.

Putt (2007) estimates costs for two raceway design parameters: one acre ponds and ten acre ponds. Cost estimates are in 2007 U.S. dollars. Putt (2007) showed that the larger ten acre ponds are more cost effective because of the ability to use a carbonation pump in the system in place of a paddlewheel, significantly reducing costs. Land costs are estimated at $2,000 per acre ($4,942 per hectare) with pond costs of $1,600 per acre ($3,954 per hectare), with 800 m^3 (28,252 ft^3) of soil being moved per acre of raceway at a cost of $2.00/$m^3$ ($0.0566/$ft^3$). Paddlewheels are priced at $3,000 per pond for the one acre ponds and represent no cost to the ten acre ponds because the carbonation pump replaces the paddlewheel in Putt's system. There is no indication given of the exact dimensions of the raceways, only of their size in acres. This system also uses a larger, more complex carbon delivery system compared to the current analysis. Land prices are higher in Putt's (2007) analysis because this facility is assumed to be located in Alabama, where land prices are higher than some of the locations used in the current analysis.

Benemann (1994) models algae costs based on a one thousand hectare facility. Estimates are in 1994 U.S. dollars. Shown in Table 1, projected costs for raceway ponds are $27,500 per hectare ($11,129 per acre) based on 1994 prices and $33,000 per hectare ($13,355 per acre) based on theoretical maximums. Those projections for 1994 indicate productivity of 30 g/m^2/day and while theoretical maximums are estimated at 60 g/m^2/day. Raceway pond costs are combined into a single estimate and include earthworks, CO_2 sumps, and mixing cost. Benemann (1994)'s raceways are designed to be 10 hectares (24.71 acres) in size with paddle-wheel mixing and no pond liners. Benemann (1994) also assumes favorable site conditions in reference to land slope, availability of land, and water, all factors which are believed to be important in profitability analysis.

Table 1. Capital and Operating Costs for Microalgae Fuels Based on a 1,000 Ha Microalgae Production Facility.
Source: Benemann (1994)

Productivity Assumed: (ash-free dry weight)	Current Projected	Maximum Theoretical
Average Daily:	30 g/m^2/d	60 g/m^2/d
Annual:	109 mt/ha/yr	219 mt/ha/yr
Capital Costs ($/ha):		
Ponds (earthworks, CO_2 sumps, mixing)	27,500	33,000
Harvesting (settling ponds, centrifuges)	12,500	17,000
System-wide Costs (water, CO2 supply, etc.)	30,000	40,000
Processing (oil extraction, digestion)	10,000	20,000
Engineering, Contingencies (25 %of above)	20,000	27,500
Total Capital Costs ($/ha)	100,000	137,500
Capital Costs $/t-yr	920.00	630.00
Barrels of Oil/ha-yr (@ 3.5 bar./t)	380.00	760.00
Capital Costs $/Barrel-yr	260.00	180.00
Operating Costs ($/ha-yr):		
Power, nutrients, labor, overheads, etc.	1,000	15,500
Credit for methane produced	(3,000)	(6,000)
Net Operating Costs $/ha-yr	7,000	9,500
Net Operating Costs $/barrel oil	18.00	13.00
CO_2 Mitigation Credits ($60/tC)	(10.00)	(10.00)
Annualized Capital Costs (0.2 x Capital)	52.00	36.00
Total Costs $/Barrel	60.00	39.00
Land Area Required ha/MW	12.00	6.00

Assumptions: Algae organic composition: 50% lipid, 25% carbohydrate, 25% protein, 60% C, 5% N, heat of Combustion: 7.5 Kcal/g.
Avg. Annual Solar Insolation: 500 Langleys, 45% visible.

Definitions: g refers to grams; m refers to meters; d refers to days; mt refers to metric tons; ha refers to Hectares; t refers to tons; bar. refers to barrels; tC refers to tons of carbon; MW refers to megawatts

Weissman, Tillet, and Goebel (1989) estimated costs for a small-scale system and a large-scale system. Costs are in 1988 U.S. dollars, representing the period in which the research was conducted. The small-scale system was comprised of six 3 m^2 ponds with a total cost of $29,000. The large-scale system was comprised of two ponds, each 0.1 hectares (0.247 acres) in size. The lined pond had an estimated cost of $54,000 while the unlined pond was estimated at $46,100. The small ponds were 3.35 m (11 ft) wide and 15.5 m (51 ft) long. The large ponds were 14 m (46 ft) wide and 76.7 m (252 ft) long. Slope of the raceways was 0.0006, which aided in the ease of construction and draining and cleaning of the ponds.

A study by Stepan et al. (2002) estimates the total cost of raceways, including construction, mixing systems (4 per acre), and plumbing costs, to near $40,000 per acre ($98,840 per acre). Costs are in 1998-2001 U.S. dollars, representing the period in which the research was conducted. This estimate involves a facility design of approximately 420 acres (170 acres) with raceway pond depth of 3 ft. and compacted clay pond liners.

Neenan et al. (1986) breaks down raceway pond costs much more extensively. All estimates in their research are in 1984 dollars. Shown in Table 2, construction costs are estimated at $8,450 per hectare ($3,420 per acre), with those costs including site preparation, laser grading, and primary berm construction. Pond liners, which in this literature are granular covers over a clay bed instead of plastic or polymer liners, are estimated at an additional $5,000 per hectare ($2,023 per acre). It is also mentioned that not every site may be suitable for granular/clay liners and such a decision should be based on the permeability of the soil. Soils with high permeability will require the plastic or polymer liner, which, according to the study represents a much higher cost. Governmental environmental agencies may also have input in the use of liners, which may force facilities to use plastic or polymer liners. The circulation systems, which use paddlewheels, have an estimated cost of $2,500 per hectare ($1,012 per acre). Neenan et al. (1986) goes on to mention that an alternative air-lift pump could be used instead of the paddlewheel at the same cost but air-lift systems are much less efficient than paddlewheels. However, those same air-lift systems do serve a dual purpose in that they can be used to distribute CO_2 into the system. The decision of what circulation system to use is one that should be made by the system design engineer. The water and nutrient distribution system cost is estimated at $420,000 plus a deliver system of $21,000 per raceway pond. Land costs are estimated at $1,245 per hectare ($504 per acre).

Table 2. Summary of Reference Production Facility Cost Contributions for Annual Direct Cost and Capital Cost in 1984$.
Source: Neenan et al. (1986)

Cost Category	1984 $/yr (Million)	$/t[a]
Capital Costs		
Site preparation	0.796	24.00
Culture system	1.146	35.00
Harvester systems	0.395	12.00
Engineering fees	0.231	7.00
Contingency	0.356	11.00
Land	0.116	3.00
Total capital cost	3.040	92.00
Operating Costs		
Labor and overhead	2.354	70.00
Utility	0.713	21.00
Nutrients	3.374	102.00
Water	1.588	48.00
Operations	0.822	25.00
Maintenance	1.151	35.00
Total operating cost	10.002	301.00
Total feedstock cost	13.042	393.00

[a]33, 171 tons/year microalgae production.

Green, Lundquist, and Oswald (1995) address the power requirements for the paddlewheel motors. Although their research pertains to advanced integrated wastewater pond systems, the same concepts apply to microalgae raceways. According to Green, Lundquist, and Oswald (1995), power must be applied to overcome two types of head loss: frictional and kinetic. Kinetic head loss occurs in the bends as water flows around the 180° curve at the ends of the raceways. The formula for estimating kinetic head loss for raceways is as follows:

$$HL_{Kinetic} = \frac{K * V^2}{2g}$$

Where: *K* refers to the kinetic loss coefficient for 180° bends (which is theoretically equal to 2); *V* refers to the mean surface velocity in meters per second; and *g* is the acceleration of gravity, which is a constant of 9.81 meters per second squared

Frictional head losses occur along the channels of the raceways. They are calculated using Manning's Equation, which is defined in the following formula:

$$HL_{Frictional} = \frac{V^2 * N^2 * L}{R^{4/3}}$$

Where: *N* refers to Manning's n, which is a roughness factor held constant at 0.01; *L* is the channel length in meters; and *R* is the channel hydraulic radius

Unfortunately, Green, Lundquist, and Oswald (1995) did not define channel hydraulic radius. However, Putt (2007) defines channel hydraulic radius using the following formula:

$$R = W_{Channel} + 2\,D_{Pond}$$

Where: $W_{Channel}$ is the channel width and D_{Pond} is the pond depth

Total head loss is estimated using the equation below:

$$HL_{Total} = HL_{Kinetic} + HL_{Frictional}$$

Where: $HL_{Kinetic}$ is the kinetic head loss in meters and $HL_{Frictional}$ is the frictional head loss in meters

Green, Lundquist, and Oswald (1995) estimate the power (in Watts) necessary to overcome total head loss using the following equation:

$$P_{Watts} = \frac{9.8 * Q * W * HL_{Total}}{E}$$

Where: *9.8* is a conversion factor in Watts-seconds/kilograms-meters; Q is the channel flow in cubic meters per second; W refers to the unit mass of water which is constant at 998 kilograms per cubic meter; HL_{Total} refers to the total head loss in meters; and E refers to the efficiency of the paddlewheel drive system

Channel flow is estimated using the following equation:

$$Q = W_{Channel} * D_{Water} * V$$

Where: D_{Water} is the water depth in the raceway

Based on these formulas from Green, Lundquist, and Owsald, the model will estimate the size of the motor needed for powering the paddlewheels.

3.1.2. Algae Harvesting and Extraction

Upon production of the microalgae, it must be harvested and processed in some manner. This is one area in which research has struggled to find a cost-effective solution and an area which must see considerable improvement to make algal oil a commercially viable product. Putt (2007), with estimates in 2007 U.S. dollars, suggests using a three-step process involving flocculation, dewatering, and drying. Cellulose fibers and ferric nitrate are added by separate static mixers to cause the algae to agglomerate. As mentioned previously, Putt (2007) offers two production system designs: 100 one-acre ponds and 10 ten-acre ponds. Putt (2007) estimates the cost of each static mixer to be $10,000 for the smaller pond design and $5,000 for the larger pond design. Three pumps are also necessary for this process, one for harvesting the algae, one for pumping cellulose, and one for pumping ferric nitrate. For Putt’s (2007) smaller pond design, the harvesting pump cost is $30,000, the ferric nitrate pump cost is $35,000, and the cellulose pump cost is $7,700. For the larger pond design, the harvesting pump cost is $10,000, the ferric nitrate pump cost is $3,750, and the cellulose pump cost is $3,750. Once the cellulose and ferric nitrate have been added, the algal mixture is moved to settling tanks where the algae settles to the bottom and is then moved to a belt filter press for dewatering. Once the water has been removed, the algae would be dried and pressed into rolls. For the small pond design, the belt filter press and conveyor oven for drying have a cost of $40,000 each while the three settling tanks are priced at $50,000 apiece. For the large pond design, the belt filter press and drum dryer have a cost of $40,000 each while the three settling tanks are priced at $25,000 apiece. Putt (2007) offers no explanation as to how the oil will be removed once the algae have been pressed into rolls.

Tapie and Bernard (1988) estimate harvesting costs based on a ten hectare photobioreactor production system. Costs are in 1985 French Francs, represented by ₣.

Although the production system is different, it is assumed that the same or a similar harvesting system could be used in the current analysis. Therefore, the cost estimates are relevant to this literature review. Tapie and Bernard (1988) proposed a harvesting system using a centrifuge with some form of storage. Estimated costs are ₣1,330,000, converted to $133,000 using a conversion rate of ₣10:$1 as mentioned in the literature. This literature makes no mention of how the algae will be transported to the centrifuge or what will become of the products after oil extraction, two important costs associated with the harvesting and extraction process.

Grima et al. (2003) looks at the microalgae harvesting process but for a different purpose, the recovery of eicosapentaenoic acid, an essential fatty acid currently used as a neutraceutical and that emerging research is showing has therapeutic benefits in disease management. Although this is a different end product, it addresses various processes for harvesting algal biomass that are applicable to the current analysis. Like Tapie and Bernard (1988), Grima et al. (2003) uses a photobioreactor production system. Once the microalgae is ready for harvest, the water is removed using a centrifuge while the remaining biomass continues through the system where it goes through an extraction and esterification process, processes which are not applicable to a microalgae such as the one intended for the current analysis. However, Grima et al. (2003) does estimate cost information regarding the centrifugation process as shown in Table 3. All costs are in 2001 U.S. dollars. For 60 m^3 (2,119 ft^3) of photobioreactors (0.8 m^3 each), two 24-bowl centrifuges are needed at a cost of $123,949 each plus a feed pump for each centrifuge at a cost of $841 each. A preparation tank and a harvest broth storage tank are estimated to cost $34,814 apiece, with three of each being necessary. Two biomass storage silos are needed at a cost of $1,370 each. Harvest biomass conveyor belts, two of which are needed, are priced at $7,100 each. The remaining cost information provided by Grima et al. (2003) applies to further processing not applicable to the harvesting and extraction process in the current analysis.

Table 3. Major Equipment List and Costs for Algal Biomass Production.
Source: Grima et al. (2003)

Item	Delivered cost ($)	No. of units	Total cost	% of MEC
Photobioreactors (0.8 m^3)	3,524	75	264,300	30.0
Centrifuge (24 bowl, solids discharge, 2.99 m^3/h)	123,949	2	247,898	28.1
Medium filter unit (5.99 m^3/h)	18,014	1	18,014	2.0
Medium feed pumps (0.04 m^3/h)	349	75	26,175	3.0
Medium preparation tank (19.96 m^3)	34,814	3	104,442	11.9
Harvest broth storage tank (19.96 m^3)	34,814	3	104,442	11.9
Centrifuge feed pumps (2.99 m^3/h)	841	2	1,682	0.2
Air compressors (240 m^3/h)	26,103	3	78,309	8.9
Harvest biomass conveyer belts	7,100	2	14,200	1.6
Seawater pump station (5.99 m^3/h)	13,661	1	13,661	1.6
Carbon dioxide supply station (27.4 kg/h)	3,006	1	3,006	0.3
Weighing station	2,366	1	2,366	0.3
Biomass silos (0.07 m^3)	1,370	2	2,740	0.3
Total MEC ($)			881,235	

Definitions: m refers to meters; h refers to hours; kg refers to kilograms; MEC refers to major equipment costs

Neenan et al. (1986) bases its research on three harvester subsystems comprised of a microstrainer, a centrifuge, and a belt filter. The system consists of two stages, the first involving the microstrainer and the belt filter and the second using the centrifuge. Costs in the current analysis are not broken down between initial costs and annual costs but instead the initial cost is annualized. Estimates are in 1984 U.S. dollars. Total annual cost for the harvester system is estimated to be $395,000. This equates to a cost of $12 per ton of algal biomass based on a 1,000 acre facility with 33,171 tons of annual biomass production. According to Neenan et al. (1986), the harvesting system represents 13% of total capital investment and 25.7% of depreciable capital investment, as shown in Figure 7 and Figure 8.

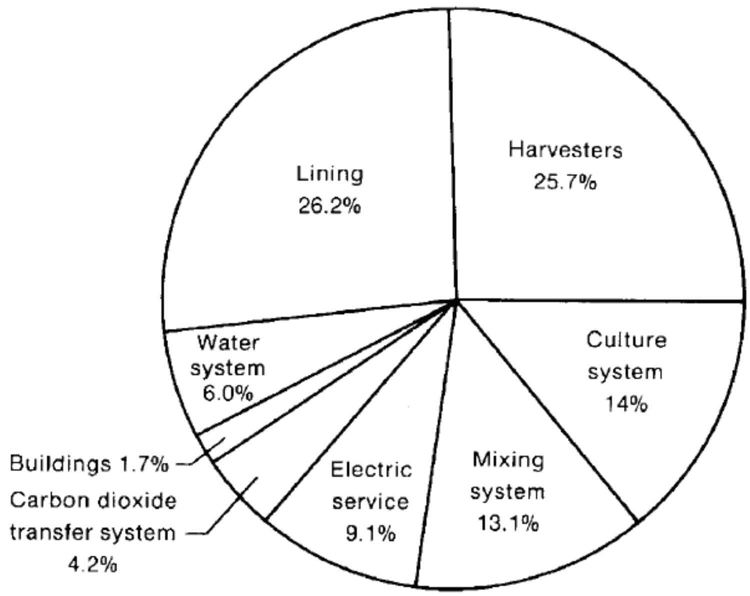

Figure 7. Cost contributions for depreciable capital investment.
Source: Neenan et al. (1986)

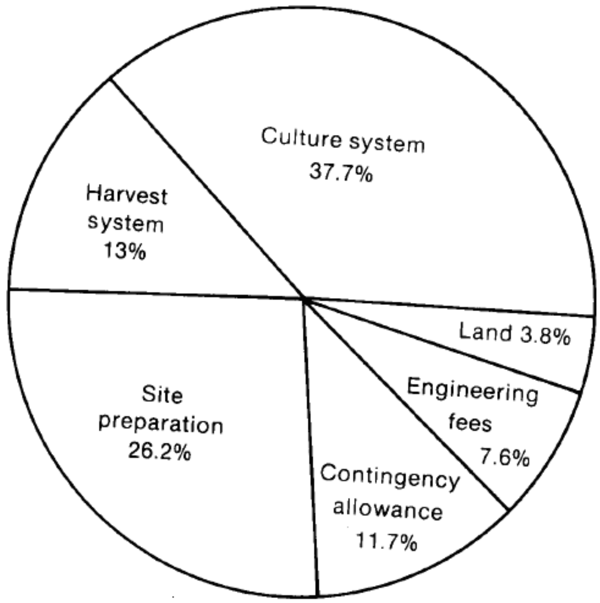

Figure 8. General cost contribution of capital cost categories.
Source: Neenan et al. (1986)

Stepan et al. (2002) estimates harvesting costs to be $20,000,000 for a facility with a production capacity of 2,136 dry tons of algal biomass per day. That estimate is in 1998-2001 U.S. dollars, reflecting the period in which the research was conducted. Their study proposes using a solids separation device such as a belt filter or a hydroclone for such a process. Stepan et al. (2002) also proposes drying the algae using waste heat from a power plant at a cost of $20,000. Their study does not give specific ideas for harvesting and extraction of the microalgal oil, choosing rather to incorporate a general cost estimate because such analysis is not the focus of their research.

3.1.3. Additional Facility Costs and Considerations

The final physical section of the facility is comprised of maintenance and operations buildings. Such a facility is necessary to house facility equipment, laboratories, offices, and storage space. Carlsson 2007 states that annual facility maintenance and operations cost, including those for buildings, roads, instrumentation, and machinery, to be $2,500 per hectare ($1,012 per acre). This literature also includes engineering and contingencies cost of 15% above all capital costs. This engineering and contingencies cost is 10% lower than the 25% above all capital costs estimated by Benemann (1994). Neither study specifically indicates the expectations for the outlays of such costs so it is difficult to compare the two to see which estimate is more appropriate.

Grima et al. (2003) estimates building costs to be $264,371 for a facility that produces 26,197 kg of biomass annually, a cost of $10.09 per kg of biomass, which is shown in Table 4. The cost is estimated at roughly 30% of major equipment costs, which include the previously mentioned costs of the production, harvesting, and extraction systems. Grima et al.'s (2003) analysis uses photobioreactors in place of raceways and the end product of this particular system is a much higher-value product. However, the 30% cost estimate is only for biomass production so it is a comparable estimate. Grima et al. (2003) includes another 20% of major equipment costs, or $176,247, for service facilities, exhibited in Table 4 on the previous page. Engineering and contingency costs are divided into two separate estimates. Engineering costs also include supervision costs and are estimated at 25% of major equipment costs, or $220,309. Contingency costs are estimate as 6% of total fixed capital investment, which not only includes all major equipment costs but also all other facility, installation, and construction costs. Contingency costs are $180,888. It should be noted that all estimates for this study were in 2001 U.S. dollars.

Table 4. Total and Annual Fixed Capital for Biomass Production.
Source: Grima et al. (2003)

Item	Cost ($)	% of A
Major purchased equipment (MEC)	881,235	29.2
Installation costs (at 0.3 MEC)	264,371	8.8
Instrumentation and control (at 0.1 MEC)	88,124	2.9
Piping (at 0.3 MEC)	264,371	8.8
Electrical (at 0.1 MEC)	88,124	2.9
Buildings (at 0.3 MEC)	264,371	8.8
Yard improvements (at 0.1 MEC)	88,124	2.9
Service facilities (at 0.2 MEC)	176,247	5.8
Land (at 0.06 MEC)	52,874	1.8
Engineering and supervision (at 0.25 MEC)	220,309	7.3
Construction expenses (at 0.1 Σ items 1 – 9)	216,784	7.2
Contractor 's fee (at 0.05 Σ items 1 – 9)	108,392	3.6
Contingency (at 0.06 total fixed capital investment)	180,888	6.0
Total fixed capital investment ($)	3,014,803	96.0

Definitions: MEC refers to major equipment costs; Σ refers to sum

Neenan et al. (1986) analyzes system costs based on a 1,000 hectare facility with a base of 1984 U.S. dollars. Neenan et al. (1986) does not directly address facility costs but does mention that buildings costs are included in the culture system costs, which represent 37.7% of total capital investment, as shown in Figure 8 earlier in this chapter. It is observed in Figure 9 that engineering fees are 15.5% of total non-depreciable capital investment, or $231,000 annually for the life of the facility, and contingency allowances are 20% of total capital investment plus engineering fees, or $356,000 annually for the life of the facility. Neenan et al. (1986) does note that contingency fees are normally estimated to be 10-15% but this does depend on the stage of development of the technology and whether prior experience has been obtained. Microalgae for fuel is considered to be in the early stages of development and no large scale production facility has been constructed, which warrants the authors to estimate a higher contingency allowance. This idea could also explain the difference in contingency costs from other research.

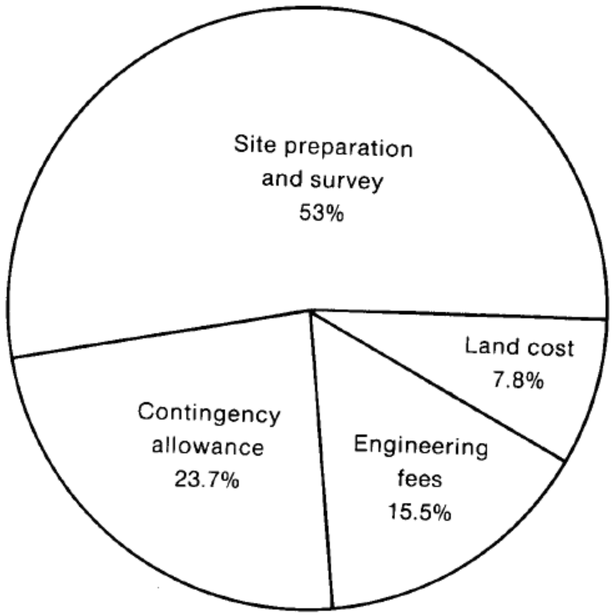

Figure 9. Cost contributions for nondepreciable portion of capital investment.
Source: Neenan et al. (1986)

Tapie and Bernard (1988) used concepts similar to the previous research in that cost estimates were based off of a percentage of the total principal equipment costs, which include equipment used in the daily production of microalgae. Costs are in 1985 French Francs, represented by ₣. Once again, although Tapie and Bernard (1988) use a photobioreactor production system, estimates are still relevant because the systems have similar concepts and have the same end result. Building expenses (including labor) are estimated at 10% of total principal equipment, which in this case ranges from ₣921,500-₣1,221,500 (converted to $92,150-$122,150 using a conversion rate of ₣10:$1 as mentioned in the literature) depending on which production design is used, while the actual buildings (including supplies and materials) constitute another 10%, with the cost being the same as the aforementioned values. Engineering cost is estimated at 30% of total principal equipment while contingencies are estimated at 15%.

Weissman, Tillet, and Goebel (1989) analyze the development of some small microalgae facilities in New Mexico. As shown in Table 5 below, two systems, one with six 3 m^2 raceways and one with two 0.1 hectare (0.247 acre) raceways, are discussed. Although no specifics are identified as far as building and other facility costs, engineering costs are assessed at $3,500 for the first year, $500 for the second year, and $3,600 for each additional year for the larger 0.1 hectare (0.247 acre) raceways. This equates to $14,164 per acre for the first year, $2,023 per acre for the second year, and $14,569 for each additional year afterwards. Although this may seem like a large cost, it must be considered that this is a very small facility. Costs are reported in 1988 U.S. dollars.

Table 5. Facility Development Plan.
Source: Weissman, Tillet, and Goebel (1989)

1st Year:	
Small-scale system (six 3-m^2 ponds)	29,000
Large-scale system	
Water to site	23,500
Power to site	5,600
One 0.1-ha growth pond (membrane-lined)	54,000
One 0.1-ha growth pond (earth-lined)	46,100
Power distribution network	2,700
Engineering	3,500
TOTAL:	164,400
2nd Year:	
Inoculum pond - 50 m^2	5,000
Chemical storage shed	2,000
Power distribution network	3,400
Engineering	500
TOTAL:	10,900
Subsequent Years:	
One 0.5-ha growth pond (earth-lined)	89,300
Electrical distribution network	4,600
Harvesting system (for all large ponds)	38,250
Engineering	3,600
TOTAL:	135,750

Note: Does not include labor by project personnel.

Definitions: m refers to meters; ha refers to hectares

3.2. Variable Input Costs

3.2.1. Carbon Dioxide

Carbon dioxide is a key ingredient to the production of microalgae and controlling carbon dioxide costs and losses are key to the subsequent success of a facility. The open air nature of raceways systems creates problems with CO_2 losses because some of the carbon dioxide escapes into the atmosphere to equilibrate the CO_2 levels between the atmosphere and the raceway. This process is known as outgassing. This creates additional concerns regarding climate change because of the CO_2 escaping into the atmosphere.

Research has shown that outgassing can be controlled by altering pH levels in the raceways. According to Weismann, Tillet and Goebel 1989, outgassing is also affected by concentration in the liquid and the resistance to movement though the gas-liquid interface. The latter two factors are adversely affected by decreasing pond depth. CO_2 also faces losses when it is injected into the raceway because of inefficiencies within the injection systems. Cost-effective sources of carbon dioxide for microalgae production are a major area of research in the United States and abroad.

Weissman, Tillet, and Goebel (1989) observed that CO_2 is absorbed much more effectively by the microalgae at a slightly basic pH. According to Weissman, Tillet, and Goebel (1989), at pH 7.5-7.8, 25% of CO_2 is lost to outgassing. If pH is raised to 8.0-8.3, outgassing falls to less than 10%. This is the suggested pH level to minimize outgassing, according the research. Their research also observed that outgassing was greater in unlined ponds when compared to lined ponds, due to the faster rate of renewal of surface resulting from greater bottom roughness. In other words, due to the rough nature of the raceway floors, the algae mixture circulated more and was exposed to the surface more, meaning higher losses of CO_2 in the form of outgassing. Weissman, Tillet, and Goebel (1989) injected CO_2 into the raceways using internal sumps that were 0.91 m (2.98 ft) deep and 0.62 m (2.03 ft) wide. The sumps had vertical walls and spanned the full width of the channel. CO_2 was sparged into the downflowing stream using porous polyethylene diffusers. To increase absorption efficiencies, the downflow velocity was matched with the average bubble rise velocity from the diffusers, creating long contact times, which results in higher absorption efficiencies. As exhibited in Table 6, overall injection efficiencies are estimated between 80-90%. The authors believe that percentage must be at least 90% or higher for the injection system to be viable.

Table 6. Carbon Utilization Efficiency in Lined Pond.
Source: Weissman, Tillet, and Goebel (1989)

	Carbon (kg)			Efficiency (%)	
	Injected	Biomass	Outgassed	Overall	Injection
9/8-9/22 pH = 7.5	121	55	40	45	78
9/23-10/13 pH = 7.5	220	142	66	65	95
10/14-11/14 pH = 7.8	174	107	36	62	82
11/15-11/28 pH = 7.5	83	27	46	32	87

A presentation in November 2007 by Dr. Philip Pienkos of the National Renewable Energy Laboratory touted the benefits of using flue gas, which contains CO_2 that would otherwise be released into the atmosphere, as a CO_2 supply source for a microalgae production facility. According to Pienkos (2007), such a system provides a double benefit in that CO_2 is necessary for algae production and it recycles fossil CO_2 instead of polluting the atmosphere with it. Pienkos (2007) also believes that carbon credits may become an economic driver for microalgae production facilities. According to Pienkos (2007), to produce the algal oil needed for 60 billion gallons of biodiesel annually, 1.4 billion tons of CO_2 (56% of U.S. power plant emissions) are necessary if the algae has a growth rate of 10 g/m^2/day and 15% lipid content. If those rates are raised to 50 g/m^2/day and 50% lipid content, 900 million tons of CO_2 (36% of U.S. power plant emissions) are needed. One potential downside to such an arrangement is location. The microalgae facility must be located near the power plant to harvest and use the flue gas. It may be difficult to find the land area necessary for such a facility within a reasonable vicinity of a power plant and locating a facility near a municipality will more than likely mean higher land prices and higher initial cost outlays.

Stepan et al. (2002) studied a power plant in Underwood, ND, and its flue gas emissions. According to their research, the flue gas was 12.1% CO_2 and 5.5% O_2, with a remaining composition of sulfur dioxide, nitrogen oxides, other trace gases, metals, and ash. Sulfur dioxide and nitrogen oxide are of particular concern because at certain concentrations, they can alter the pH of the algae mixture, which in turn inhibits algae growth and production. Sulfur dioxide become a problem at 400 parts per million (ppm), with the flue gas averaging 422.9 ppm in their study. Nitrogen oxides have a similar effect but not in the magnitude of sulfur dioxides. Stepan et al. (2002) states that microalgae have been shown to tolerate a medium containing up to 240 ppm of nitrogen oxides. Their study showed daily average nitrogen oxide levels of 123.6 ppm. In addition, the nitrogen oxides can serve as a nitrogen source for the microalgae. It observed that increased temperatures decrease the solubility of the gases in water, meaning that the temperature of the flue gas should be lowered before it is introduced to the production process. Stepan et al. (2002) goes on to discuss that carbon dioxide storage capacity in a growth medium is important because it determines how extensive a CO_2 delivery system must be and eventually how much money must be invested in such a system. CO_2 storage capacity depends upon the alkalinity and the pH range of operation for the growth medium. Stepan et al. (2002) discusses using a sump as the method of adding the carbon dioxide to the growth medium, similar to Weissman, Tillet, and Goebel (1989). However, it is noted that unpurified power plant flue gas would require a deeper sump, creating additional cost considerations.

Neenan et al. (1986) provides an in-depth look at carbon dioxide's importance and aspects of the system design that are important to maximizing the use and value of the CO_2. First of all, carbon dioxide is vital to microalgae production for fuel because it is the source of carbon for the synthesis of organic comlb such as oils. Neenan et al. (1986) states that atmospheric carbon dioxide is not an adequate source of CO_2 for microalgae production because it would require all the CO_2 in the air 50 m (164 ft) above the surface of the culture to produce 25 g/m^2/day of algal biomass. Such a system would be prohibited by costs and logistics. Another major factor affecting CO_2 loss is efficiency with which the CO_2 can be transferred to the culture. According to Stepan et al. (2002), if carbon dioxide is added as bubbles, large quantities can be lost if they reach the surface and burst. It is important that the bubbles be added in a counterflowing manner to the raceway because the counterflow keeps the bubbles from reaching the surface more quickly and as a result, more of the CO_2 can be utilized. The study estimates the cost of CO_2 using a power plant as the source, with the CO_2 being purified and compressed using an offsite facility with a potassium carbonate extraction system and transported to the microalgae facility via an 80 km pipeline. The delivered cost is estimated by calculating the 30-year amortized cost of the potassium carbonate extraction system and the amortized cost of the pipeline to transport the CO_2 to the facility. Table 7 shows the various scenarios for CO_2 costs. The resulting cost estimate is \$0.13/m^3, with a daily requirement of 83,000 m^3/day. If the microalgae facility was to be co-located with the power plant, CO_2 costs would fall to \$0.11/m^3 but that is the lowest possible cost. Overall production costs are shown to be sensitive to CO_2 costs as well, given Neenan et al.'s (1986) estimate of a \$6 decrease per ton of biomass produced per \$0.01 reduction in CO_2 costs. Neenan et al. (1986) notes that carbon dioxide costs contribute 26.7% of total costs and 78.6% of nutrient expenses. All costs are in 1984 U.S. dollars.

Table 7. Summary of Alternative Scenarios to Reduce CO_2 Costs to a Mass Culture Facility.
Source: Neenan et al. (1986)

Scenario	CO_2 Costs ($/$m^3$)	Algae Production ($/t)
Reference system	0.13	393.00
Power plant ownership increase scale	0.11	383.00
Increase scale and colocated plants	0.09	370.00
With plant ownership and colocated power plant	0.07	356.00
Several colocated power plants	0.05	345.00

Definitions: m refers to meters; t refers to tons

Neenan et al. (1986) addresses the potential demand for CO_2 in the west and southwest portions of the U.S. based on carbon dioxide's use in enhanced oil recovery. This could create competition for CO_2 resources. It is mentioned that higher oil prices created greater incentive for enhanced oil recovery, a fact is even more prevalent than it was when their research was conducted. However, the study notes that CO_2-based oil production is predicted to decline by 2010 due to reservoir depletion. This is the reasoning behind this concept's exclusion from the current analysis. It is also noted that the majority of CO_2 supply in the southwestern U.S. is in the form of flue gas from power plants.

Doucha, Straka, and Livansky (2005) suggest that 1.65-1.83 g of CO_2 is needed to produce 1 g of dry algal biomass. This research developed a formula for CO_2 supply in flue gas and CO_2 supply to a unit of culture area. The formula for rate of CO2 supply in flue gas is as follows:

$$M = \frac{Q_g * \rho_{CO_2} * C_{g,im}}{100}$$

Where: Q_g is the volumetric flow rate of glue gas in cubic meters per hour; ρ_{CO2} is CO_2 density in grams per cubic meter; $C_{g,in}$ is the CO2 content in the flue gas in percent volume before passing through the suspension

The rate of CO_2 supply to a unit of culture area is estimated by the following formula:

$$\frac{M}{A} = \frac{R_{CO_2} + \left(K_{L,CO_2} * \left(K_H * \left(p_{mean} - p^{+}\right)\right)\right)}{\left(DEC/100\right)}$$

Where: M is the rate of CO_2 supply in flue gas in grams per hour; A is the unit of culture area; R_{CO2} is the rate of consumption of carbon dioxide by the microalgae in grams of CO_2 per square meter per hour; $K_{L,CO2}$ is the liquid phase mass transfer coefficient in meters per hour for CO_2 transport from the suspension into the atmosphere; K_H is Henry's constant for CO_2 in grams of CO_2 per cubic meter per kilopascal; p_{mean} is the means pressure in kilopascals of the CO_2 in microalgal suspension; p^{+} is the partial pressure of CO_2 in kilopascals in an ambient atmosphere; and DEC is the degree in percentage of flue gas decarbonization after passing the gas stream through the suspension

Their research reinforced the conclusion of Stepan et al. (2002) that the presence of nitrogen oxides did not inhibit the growth of microalgae.

Grima et al. (2003) does not address CO_2 costs in depth but does provide some good cost information. Estimates are in 2001 U.S. dollars. For a photobioreactor facility 60 m^2 in size producing 26.2 metric tons of biomass annually, carbon dioxide costs are estimated at $45,620 at a price of $0.4706 per kilogram of CO_2 and annual consumption of 96,940 kg. A carbon dioxide supply station is estimated to cost $3,006 with a capacity of 27.4 kg/hour. No specifics are given regarding CO_2 losses, which will be lower because it is a photobioreactor, or what type of carbon dioxide delivery system is used in the system.

Putt (2007) proposes an environmentally-friendly system that uses animal litter digesters as a carbon source. Putt's design incorporates an anaerobic digester that produces methane and carbon dioxide. The methane is used to power an electric generator that provides power to the facility. The diesel exhaust from the generator would be used as a heat source for the dryer used in the harvesting and extraction process. The cool exhaust left over, which is rich in carbon dioxide, would then be stored in a carbonation pit and the CO_2 would be used in the algae raceways. Estimated costs for a algae facility with 100 one-acre ponds include $6,600 for the digester pit, $30,000 for the digester cover, $25,000 for the diesel generator, $1,000 each for a methane blower, an exhaust blower, and a litter pit. The carbonation pit has an estimated cost of $50,000. The costs are identical for a facility with 10 ten-acre algae ponds. Estimates are in 2007 U.S. dollars.

3.2.2. Water

Water availability and water sources are major concerns for a microalgae facility. Raceway algal production requires large amounts of water not only to fill the raceways but also to replace the water lost to evaporation and during the harvesting and extraction process. Facility location is one key in minimizing water costs and water losses because climatic conditions heavily influence evaporation and annual rainfall. Water for the raceways will have to be pumped from some source, whether it is from groundwater or some form of wastewater. Multiple wastewater sources have been proposed for such a facility, including the use of municipal wastewater and industrial wastewater used in cooling techniques. System design impacts water needs in that deeper raceways constitute the necessity for more water. However, deeper ponds lose a smaller percentage of their water to evaporation. Pond depth must be a combination of minimizing evaporation losses while maximizing the algae's exposure to sunlight.

Benemann (1994) discusses two raceway depth designs. The first, a shallower pond with depth of less than 30 cm (11.8 in), allows for better control over conditions. Additionally, less power is required to circulate the algae mixture because less water has to be moved when compared to the second raceway design. However, because the more shallow raceways cannot produce as much as deeper ponds, more raceways are necessary to produce the same quantity as the deeper raceways (of the second raceway design), which adds construction and equipment costs. The second design, more than 50 cm deep (19.7 in), allows for more production while using the same surface area as the shallower ponds. Concerns regarding the shading of microalgae at the bottom of the raceway, which inhibits algal growth because they are not receiving enough sunlight, do exist but a proper circulation design can help minimize such a risk. Another concern is the larger paddlewheels that will be necessary for the deeper ponds and additional energy will be needed because larger quantities of water will have to be circulated. Balancing these needs will allow for the optimal pond depth.

Neenan et al. (1986) offers a range of potential pond depths similar to other literature, with depths between 15-50 cm (5.9-19.7 in) mentioned. For their algal model, a low depth of 10 cm (3.93 in) is used, with the high being 30 cm (11.8 in), and a reference estimate of 15 cm (5.9 in). Neenan et al. (1986) discusses in length the effect of water salinity.

Microalgae have the ability to tolerate more saline waters, one reason southwest portions of the U.S., where saline water is prevalent, are under heavy consideration for microalgal production facilities. Land with water high in salinity is not suitable for crop production. Unfortunately, with open production systems experiencing evaporation, the salt does not evaporate and eventually builds up in the raceways. In such a case, a process known as blowdown can be used to lower the salinity within an acceptable range. However, blowdown creates the demand for additional water and additional costs. Table 8 addresses the advantages and disadvantages of using saline water.

Table 8. Tradeoffs Between Salinity Tolerance and Water Costs.
Source: Neenan et al. (1986)

Case A:	High cost ($0.20/$m^3$) / low salinity (10 g TDS/L) water		
Salinity Tolerance (g TDS/L)	Algae Cost ($/t)	Increase from Reference ($/t)	Equivalent Evaporation Rate
35	425	32.00	0.0009
50	420	27.00	0.0010
80	417	24.00	0.0012
120	415	22.00	0.0020
Case B:	Low cost ($0.05/$m^3$) / high salinity (25 g TDS/L) water		
Salinity Tolerance (g TDS/L)	Algae Cost ($/t)	Decrease from Reference ($/t)	Equivalent Evaporation Rate
35	381	12.00	0.0085
50	380	13.00	0.0090
80	380	13.00	0.0100
120	380	13.00	0.0150

The equivalent evaporation rate is that which restores algal production cost to the reference level, given the indicated level of salinity tolerance.

Definitions: g refers to grams; L refers to liters; m refers to meters; t refers to tons; TDS refers total dissolved solids

Water costs are estimated in $/$m^3$, with a low of $0.05, a high of $0.20, and a reference estimate of $0.067. In dollars per cubic foot, those estimates equate to a low of $0.0014, a high of \$0.0057, and a reference estimate of \$0.0019. These values are based on costs calculated for use in enhanced oil recovery but are appropriate for a microalgae facility because it is the same water being used. Evaporation rates range from 0.2 to 1.0 cm/day (0.078-0.393 in/day), with a reference value of 0.35 cm/day (0.138 in/day). It should be noted that these estimates are net evaporation rates, which includes annual rainfall total. Actual daily evaporation would be higher if rainfall were not included. Overall, water costs represent nearly 16% of total production costs, with total annual expenses of \$1,588,000, or \$48/ton of algal biomass assuming 33,171 tons of annual biomass production. Neenan et al. (1986) also shows that the salinity of the water source and the water supply costs have a significant effect on total costs. If the facility were to experience maximum evaporative losses, product costs rise by 12% while minimum evaporative losses only reduce costs by 3%. This disproportionate cost reduction is due to the high acquisition costs for makeup water and other nonevaporative water losses.

In a 2007 presentation entitled "The Potential of Biofuels from Algae," Dr. Philip Pienkos of the National Renewable Energy Laboratory highlighted the water needs for enough algal oil to produce 60 billion gallons of biodiesel per year. According to Dr. Pienkos, 120 trillion gallons of water would be used if the algae possessed a growth rate of 10 g/m^2/day and 15% oil content. If the growth rate is raised to 50 g/m^2/day and oil content is raised to 50%, only 16 trillion gallons of water are necessary. To put such estimates in perspective, Dr. Pienkos illustrates that roughly 22 million gallons of saline water are extracted annually in the U.S. while more than 4,000 trillion gallons of water are used annually to irrigate the U.S. corn crop. Dr. Pienkos does not discuss any raceway designs or evaporation rates used to make these estimates.

Weissman, Tillet, and Goebel (1989) addresses water needs and resources near Roswell, NM. Cost estimates are in 1988 dollars. For this project site, two water options are available: city water, at a cost of \$326/acre-foot or \$0.26/m^3 (\$0.0074/ft^3), or saline groundwater, with a capacity of 800 gallons per minute and a cost of \$75/acre-foot or \$0.012 m^3 (\$0.0003 ft^3). Estimated annual water cost is \$23,500 for two 0.1 acre (0.04 hectare) raceways. Weissman, Tillet, and Goebel (1989) compared evaporation for lined and unlined ponds, examined in Table 9. Nearly ½ cm per day (0.2 in per day) more water was lost in the unlined ponds compared to the lined ponds in initial testing. After thirty days, water loss in the ponds equalized at a rate of 0.4 cm per day (0.16 in per day). This is likely due to the natural sealing of leaks in the unlined pond as time passed. After the unlined pond was drained, it again exhibited higher evaporation rates for roughly a month. According to Weissman, Tillet, and Goebel (1989), under the worst possible conditions, water usage in the unlined pond would be 50% greater than usage in the lined pond. Operating depths for this research were 14 cm (5.5 in) but the authors did indicate that future research would include increasing depths to 18-20 cm (7.1-7.9 in) in the raceways.

Table 9. Average Daily Water Loss from Large-Scale Ponds in Centimeters/Day. Source: Weissman, Tillet, and Goebel (1989)

Date	Lined Pond	Unlined Pond	50 - m^2 Pond
9/2-2/17	0.32 (0.52)	0.79 (0.19)	--
10/9-11/13	0.36 (0.34)	0.40 (0.20)	0.37 (0.25)
11/28-12/26	0.11 (0.13)	0.43 (0.13)	0.16 (0.13)

Multiple sources made mentions of water depths and costs but went into very little explanation. Chisti (2007) describes a raceway design with a typical depth of 30 cm (11.8 in) but does not discuss the reasoning behind such an estimate. Huntley and Redalje (2007) have an even shallower raceway with a depth of only 12 cm (4.7 in). This specific design is a hybrid system that involves both a photobioreactor and a raceway. The raceway is more for experiment purposes but no justification is given for the raceway depth. Grima et al. (2003) discusses photobioreactors but does offer a cost (in 2001 U.S. dollars) of \$0.0294/m^3 for water used in its cooling system. Although it is not an exact estimate for water used in raceways, it does give insight into the cost of water that could be used as a replacement. Nagle and Lemke (1990) did microalgae research with raceways both indoors and outdoors. The outdoor test facility was comprised of 3 m^2 raceways 15 cm (5.9 in) in depth while the indoor test facility consisted of smaller 1.4m^2 raceways 20 cm (7.9 in) in depth. Schenk et al. (2008) notes that most open pond systems operate at a depth of 15-20 cm (5.9-7.9 in). Stepan et al. (2002) state that pond depths do not exceed 90 cm, an estimate that seems very excessive but it is just a limit. It uses 0.9 m (3 ft) as a pond operating depth.

3.2.3. Nutrients

Algal growth nutrients appear to be a closely guarded secret among researchers. Some make mention of what nutrients are used but not in what proportions. Others make general cost assumptions and suggestions but few are very specific. This is to be expected as the growth nutrients are key to algal production and in turn key to a researcher’s success. Assembling an effective growth medium is a huge step in microalgae-for-fuel research and in the current analysis was a difficult cost to quantify because of the vague nature of the research. In addition, different strains of algae respond differently to each growth medium and therefore not one growth medium solution exists. The availability of those nutrients is also key to their use in the growth medium.

Putt (2007) discusses carbon as a major nutrient, which has previously been addressed. Other major nutrients include nitrogen and phosphorus, both contained in animal litter. Animal litter recycling is a major focus of Putt's analysis. The current analysis does not focus on animal litter in depth because of its lack of availability in the regions analyzed. However, it is still important to note, as Putt (2007) does, that some animal litters are high in phosphate. When this litter is spread back onto the land, over the years the phosphate builds up and begins to run off into the natural water sources, such as the rivers, ponds, and lakes. The phosphate runoff is an important ingredient in the growth of the algae in these water sources.

Stepan et al. (2002) states that the basic nutrient requirements of microalgae include carbon dioxide, nitrogen, phosphorus, and trace minerals and metals. This research uses Bold's Basal Medium, shown in Table 10 below.

Table 10. Bold's Basal Medium - Major Nutrients.
Source: Stepan et al. (2002)

H_2O, mL	Chemical	Grams	940-mL Medium Add, mL
400	$NaNO_3$	10	10
400	$CaCl_2 \cdot 2H_2O$	1	10
400	$MgSO_4 \cdot 7H_2O$	3	10
400	K_2HPO_4	3	10
400	KH_2PO_4	7	10
400	NaCl	1	10

Definitions: mL refers to milliliters

Stepan et al. (2002) estimates the following daily nutrient requirements as well as the cost of those nutrients at the time of this research's publication. Ammonia use is estimated at 116 tons per day at a cost of $150/ton. Diammonium phosphate use is estimated to be 197 tons per day at a cost of $131/ton. Potash use is estimated at 42 tons per day at a cost of $78/ton. Based on these figures, total annual nutrient costs were estimated at $25 million for 420 acres of algae ponds 3 ft in depth producing 2,136 dry tons of algal biomass per day. They also assume 365 operating days per year. This equates to a nutrient cost of $32.07/ton.

Weissman, Tillet, and Goebel (1989) addressed the nutrients used during the research period but did not address the quantities or cost. Silica (in the form of sodium metasilicate pentahydrate), urea, phosphate (in the form of potassium phosphate dibasic), and sulfuric acid (to neutralize the sodium metasilicate) were mixed with deoinized water and fed into the raceways. Deionized water was used to prevent the formation of precipitates. Weissman, Tillet, and Goebel (1989) did address the microalgae's productivity under nitrogen and silicon deficient conditions. Experiments showed that nitrogen sufficiency ended when biomass nitrogen content fell below 8% and silicon sufficiency ended when biomass silicon content fell below 20%.

Neenan et al. (1986) observed that nutrient requirements are determined by basic biological requirements, nutrient quality, and the culture system design. Neenan et al. (1986) also noted that most nutrients required by the microalgae will be supplied through the addition of commercial fertilizers, although some nutrients, including potassium, nitrogen, and phosphorus, can be supplied in small quantities through the water source. Similar to Weissman, Tillet, and Goebel (1989), Neenan et al. (1986) listed the limiting nutrients necessary for microalgae production as nitrogen, phosphorus, silica, and iron. Nitrogen can be supplied from a variety of sources, including urea, ammonia gas or liquid, nitrate, or nitrite. At the time of their research, ammonia and urea were the two least expensive sources of nitrogen. Ammonia offered the advantage of being a liquid, which makes it easier to pump, and being 83% nitrogen by weight. Urea offers the advantage of containing a carbon molecule in addition to the nitrogen atoms. The carbon is released in the form of CO_2 when the urea is utilized. However, because urea is in crystal form, it adds handling costs and it contains only about half (42%) of the nitrogen by weight when compared to ammonia. Costs are in 1984 U.S. dollars. The reference ammonia cost is $185/ton, with a low of $165/ton and a high of $205/ton. The reference superphosphate cost is $254/ton, with a low of $225/ton and a high of $280/ton. The reference potassium cost is $92/ton, with a low of $80/ton and a high of $100/ton. Neenan et al. (1986) states that the amount of nutrients required is determined by the productivity levels within the system and the amount of nutrients naturally supplied by the source water. Overall, nutrient costs represent 33.7% of costs but only 7.2% of that can be attributed to nutrients other than carbon dioxide, which represents 78.6% of nutrient costs and 26.5% of overall costs. Total annual nutrient expenses were $3,374,000, or $102/ton of algal biomass assuming annual biomass production of 33,171 tons. That cost can be reduced by 3% if a more nutrient-rich water source is available.

Doucha, Straka, and Livansky (2005) offered insight into a medium used for microalgae produced in an outdoor open thin-layer photobioreactor. Although such a system is similar to a raceway system design, this system is designed for use in areas where year-round production is not viable, with growing seasons being closer to 150 days. In addition, this experiment took place in a laboratory setting rather than outdoors. For those reasons, this growth medium was not used in the present analysis. However, it is necessary to mention the particular nutrients to show the similarities to the previous literature. According to Doucha, Straka, and Livansky (2005), for every kilogram of produced biomass, the nutrients were as follows: macronutrients – urea (182 g), potassium dihydrogen phosphate (39.5 g), magnesium sulfate (29 g), ferrous sulfate (5 g); micronutrients – boric acid (137 mg), copper sulfate (158 mg), cobalt sulfate (100 mg), manganese sulfate (608 mg), ammonium molybdate (29 mg), zinc sulfate (440 mg), and ammonium vanadate (2.3 mg).

Grima et al. (2003) addresses the growth medium cost for microalgal biomass produced in photobioreactors. Unfortunately, their research does not discuss any specific contents of the medium. The following costs are in 2001 U.S. dollars. Based on total annual production of 26,197 kg of algal biomass, total growth medium cost is expected to be $65,500, which equates to $2.50 per kg ($1.14 per lb) of biomass produced. The cost of the medium is $0.5883 per kg ($0.267 per lb). It should also be noted that the end use of their algal biomass is eicosapentaenoic acid, a neutraceutical with potential for therapeutic benefits in disease management. Therefore, the medium may be different than one designed for optimizing oil production for the purpose of fuels.

Chisti (2007) lists microalgae’s essential elements as nitrogen, phosphorus, iron, and silicon (in some cases). According to Chisti (2007), minimal nutritional requirements can be estimated using the approximate molecular formula of the microalgal biomass. Chisti (2007) also stresses that phosphorus must be used in excess in a growth medium because the phosphates added complex with metal ions and therefore not all the added phosphorus is available. Ultimately, Chisti (2007) concludes that growth media are generally inexpensive.

3.2.4. Labor

Labor is a necessary component to any production facility. Although much of the facility could operate by automation and sensors, it is still necessary to have employees to operate that equipment and monitor daily production. Labor depends not only on the size of the facility and its automation; it also depends on the level of processing of the microalgae and also the marketing strategy of the facility. Efficient facility operation is dependent upon its operators.

Grima et al. (2003) estimated a total cost of $140,160 for producing algal biomass. This figure results from a per hour rate of $16, with one shift per day and three people per shift. Supervision is 20% of the labor cost, for a total of $28,032, and payroll is 25% of labor and supervision costs, for a total of $42,048. Total employee costs for this system are $210,240. It should be noted that this is a small photobioreactor facility with an end-product of something other than microalgal oil for fuel. However, the estimates for supervision and payroll are useful for other microalgal facilities.

Neenan et al. (1986) bases labor expenses on a 1,000 hectare (2,471 acres) raceway facility design. Production labor is estimated at $1,345 per hectare ($544 per acre) of total facility size, not of production area size. This labor estimate assumes salaries for the following employees: 1 plant engineer, 4 shift supervisors, 20 pond operators, 8 secondary harvesting operators, 8 processing operators, and 2 laboratory personnel. An additional cost of 75% of direct labor is included for overhead expense purposes. Exhibited in Figure 10, labor and overhead expenses represent 23.5% of direct operating and maintenance expenses and 18.0% of overall costs. Annual expenses are estimated to be $2,354,000 for the 1,000 hectare (2,471 acre) facility, with a per ton of algal biomass cost of $70, assuming annual production of 33,171 tons.

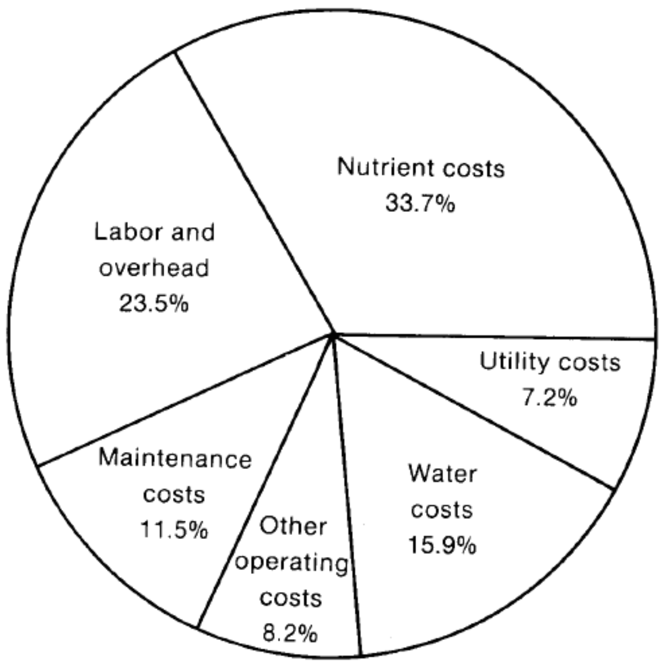

Figure 10. Cost contribution detail for direct operating and maintenance expenses.
Source: Neenan et al. (1986)

Putt (2007) estimates total annual labor expenses to be $260,000, with $200,000 for technicians and $60,000 for a foreman. The estimates do not differ from the separate system designs (100 one acre raceways or 10 ten acre raceways) and Putt (2007) gives no insight into the demands for labor for this facility. Stepan et al. (2002) gives a similarly vague estimate of total annual labor costs of $5,000,000. With an estimated annual production of 779,640 dry tons of algal biomass, the resulting per ton of biomass cost of labor is $5.64. No indication is given as to how many employees are necessary for the facility described in this research.

3.3. Microalgae Productivity and Composition

3.3.1. Algae Productivity

Previous sections of this literature describe inputs or designs (raceway and harvesting system design; carbon dioxide, water, nutrient, and labor inputs) that affect microalgal productivity. The microalgae form a biomass which contains oil that must be harvested and extracted in some manner as previously discussed. The important aspect is to maximize algal biomass production using a combination of the system design and inputs to maximize facility success. It should be noted that most all algal biomass productivities are reported in grams per square meter per day. It should also be noted that photobioreactors have higher productivity levels than raceways because they avoid input losses into the atmosphere. However, photobioreactor productivities are not considered in this literature review because the production system is different and cannot be compared to raceways when productivity levels are discussed.

Different opinions are offered on the current potential productivity levels but all seem to agree that the key to building a successful operation is to improve productivity. Productivity capability varies for each strain of microalgae and therefore it is difficult to simulate the potential productivity without knowing which strain is actually going to be used in this production system. In addition, it may be a completely new strain of algae for which we do not have data that is used in the system due to its characteristics favorable to microalgae production. Therefore, for the current analysis, the literature gave us some good indications about what levels of productivity were most likely to occur at this point in the industry.

Weissman, Tillet, and Goebel (1989) tested fifteen strains of microalgae in small 3m^2 fiberglass ponds but only six grew well enough to evaluate. Of those six strains, the annual average production was 16 g/m^2/day. The authors did mention that productivities were higher in the summer months (25-30 g/m^2/day) when temperature was higher. Productivity levels did reach 50 g/m^2/day on the best summer days but those levels were not sustainable throughout the 11 months of the experiment. As shown in Table 11, in comparison, the large 0.1 hectare (0.247 acre) raceways saw productivity levels of 10-11 g/m^2/day in their fall testing. Growth fell all the way to 2.1-5.0 g/m^2/day in the winter months, which the authors attributed to the cold weather, creating ice and slush in the smaller ponds.

Table 11. Large-Scale System Productivity in Grams of Ash-Free Dry Weight per Square Meter per Day.
Source: Weissman, Tillet, and Goebel (1989)

Date	Lined Pond	Unlined Pond	50-m^2 Pond	3-m^2 Pond
9/2-9/17	13.1	10.8	--	16.4
9/23-11/2	12.5	7.0	9.4	14.4
11/3-11/30	5.0	--	4.5	9.4*
12/1-12/26	3.2	2.1	1.8	3.5*

*1987 results.
Note: 50-m^2 pond is lined; 3-m^2 pond is fiberglass.

Stepan et al. (2002) estimated 2,136 tons per day of algal biomass production from 418 acres of raceways, which equates to nearly 1,150 g/m^2/day using conversion factors of 4,046 m^2 per acre and 907,185 grams per short ton (2,000 lb). This appears to be a very lofty expectation in that this estimate is more than ten times any reported productivity levels in any production system. However, it should be noted that these raceways are estimated at 3 ft (91 cm) in depth, about three times as deep as any of the other raceways mentioned in the literature. In addition, the productivity estimates were taken from microalgae produced in a 20-gallon fish tank with a 16-gallon operating volume. The authors also disclosed that light was also provided around the clock using a fluorescent “grow-light” bulb fixture mounted directly above the tank, meaning that there was more growing time for the microalgae and the algae received more light energy than that naturally occurring from the sun. In multiple ways, this research did not simulate conditions similar to outdoor raceway microalgae production, which does explain why the productivity estimate seems so large.

Putt (2007) bases his research off of microalgae growth at “economically practical rates,” which are considered to be average growth rates greater than 20 $g/m^2/day$ over a 300-day growing season. Putt (2007) expects a range of 10-30 $g/m^2/day$, with the lower estimates expected to occur in the cooler months and the larger estimates occurring in the warmer months. Total annual biomass production is estimate at 2,673 tons for a one hundred acre facility, or roughly 81 kg per acre per day, which does equate to roughly 20 $g/m^2/day$. It must also be taken into consideration that his facility is proposed in Alabama, where winters are milder than many states. Putt (2007) also offers the following formula for calculating productivity levels:

$$\frac{P}{D} = uC$$

Where: *P* is the pond growth rate in grams per square meter per day; *D* is the pond depth; *u* is the specific growth rate constant; and *C* is the microalgae concentration in grams per cubic meter

It should be noted that Putt (2007) assumes a growth rate constant of 2.4 grams per square meter per day based on using Chlorella microalgae that double every eight hours or less assuming they have adequate nutrients and light. Putt (2007) also assumes a pond concentration of 200 g/m^3. However, achieving those target concentrations is difficult to maintain on a consistent basis and the algal cell doubling time varies by strain, as evidenced by Putt's experimental results showing algal doubling time being about one-third of what the literature suggested. In addition, pond depths vary from one design to the next. Putt (2007) maintains the hypothesis throughout that the limited productivity is a result of nutrient deficiencies and adding sufficient nutrients will allow the target productivity levels to be achieved.

Neenan et al. (1986) uses three different productivity levels as algal model inputs. The low estimate of 10 g/m^2/day represents the productivity observed under less than favorable conditions. The high estimate of 60 g/m^2/day represents maximum productivity rates that were achieved under carefully controlled conditions where there is more emphasis on achieving high productivity levels as opposed to cost effectiveness. The reference estimate of 25 g/m^2/day represents a productivity level that has been consistently achieved and therefore is a reasonable estimate for the model. Sensitivity to production levels is exhibited by the fact that if levels are doubled from 25 g/m^2/day to

50 $g/m^2/day$, algal production cost follows suit by being cut roughly in half, from \$393/ton to \$192-195/ton (in 1984 U.S. dollars), depending on the lipid content of the microalgae. This is the primary reason why so much research has focused in the area of productivity capabilities and lipid content.

Huntley and Redalje (2007) conducted a year long study that involved a hybrid system in which microalgae was first grown in photobioreactors and then that microalgae was used to inoculate open raceways. This study ran from September 2000 to September 2001. Annualized productivity levels for the raceways were 15.1 $g/m^2/day$. Ponds were more heavily monitored during March 2001, in which the maximum biomass production was observed at a level of 36.4 $g/m^2/day$. Huntley and Redalje (2007) estimated that if photobioreactor productivity levels could be raised from 10.2 $g/m^2/day$ to 18.6 $g/m^2/day$ and photosynthetic efficiency and oil content could be improved, raceway productivity levels could rise to 70.4 $g/m^2/day$, nearly double the old maximum productivity levels.

Schenk et al. (2008) states that annual productivities range from 10-25 $g/m^2/day$ depending on the climate and the raceway design. Dr. Philip Pienkos of the National Renewable Energy Laboratory does not discuss productivity levels in depth but does use two examples in his 2007 presentation titled "The Potential for Biofuels from Algae." Dr. Pienkos uses 10 $g/m^2/day$ and 50 $g/m^2/day$ to illustrate the potential oil production from microalgae and also the potential demand for carbon dioxide and water. Chisti (2007) assumes an annual productivity of 35 $g/m^2/day$ for raceways based on proven methods of algal biomass production. Benemann (1994) projects an average daily productivity of 30 $g/m^2/day$ for a 1,000 hectare (2,471 acre) facility, which equates to

109 metric tons of annual production per hectare (269 metric tons per acre). Benemann (1994) also includes a scenario for a theoretical maximum of 60 g/m^2/day, which equates to 219 metric tons of annual production per hectare (541 metric tons per acre).

3.3.2. Algae Composition

Optimizing algal composition to produce the maximum end product of algal oil and algae feed is an area that has long been researched and will continue to be researched through genetic engineering as the industry continues to develop. Microalgae composition differs by strain and finding that strain which best fits a production system and the climate in addition to its suitability as an oil producer is difficult. Microalgae have three primary components: lipids (oil), protein, and carbohydrates. Lipids are the most important algae product but the biomass remaining after oil extraction has the potential to be a large revenue source as well. As the literature shows, improvements have been made in lipid production and the potential for more improvements in the future add to microalgae's appeal as a fuel source. Much of the literature makes assumptions of algal composition but does not specify an algae strain.

Benemann (1994) uses an assumption of 50% lipid, 25% carbohydrate, and 25% protein for a 1,000 hectare (2,471 acre) facility. Based on that assumption, a per barrel cost of algal oil of $39-60 is achieved (in 1994 U.S. dollars), with the range depending on the daily productivity levels. Benemann (1994) does include estimates for CO_2 mitigation credits that does lower the per barrel cost by $10 and very little water costs are included as well, which can make the cost estimate somewhat misleading.

Carlsson et al. (2007) lists sixteen different species of algae and their respective oil contents in Table 9. Oil contents range from a low of 7% in *Isochrysis sp.* to a high of 75% in *Botryococcus braunii*, with most of the oil contents occurring in the 25-50% range. It should be noted that wide ranges exist within the various species of algae based on multiple references. Dr. Philip Pienkos of the National Renewable Energy Laboratory uses oil content levels of 15% and 50% in analysis but very little explanation is given of why those particular content levels were used. Putt (2007) models an algae facility using a lipid content of roughly 20%.

Stepan et al. (2002) based algal composition off samples from microalgae experiments. Although the algae strain was not identified, lipid content was 26%, protein content was 41%, and the remaining portion (33%) was assumed to be carbohydrates. Based on the assumption of 2,136 tons of daily algal biomass production, this composition yields 876 tons of protein per day, 555 tons of lipids per day, and 706 tons of carbohydrates per day.

Chisti (2007) offers another compilation of microalgal oil contents in Table 12. In this table, oil contents range from a low of 15% in Tetraselmis sueica to a high of 77% found in Schizochytrium sp., with the majority of oil contents falling in the 25-50% range once again. Similar to the previous literature, ranges do exist within the individual algae species.

Table 12. Oil Content of Some Microalgae.
Source: Chisti (2007)

Microalga	Oil content (% dry weight)
Botryococcus braunii	25-74
Chlorella sp.	28-32
Crypthecodinium cohnii	20
Cylindrotheca sp.	16-37
Dunaliella primolecta	23
Isochrysis sp.	25-33
Monallanthus salina	>20
Nannochloris sp.	20-35
Nannochloropsis sp.	31-68
Neochloris oleoabundans	35-54
Nitzschia sp.	45-47
Phaeodactylum tricornutum	20-30
Schizochytrium sp.	50-77
Tetraselmis sueica	15-23

Estimated costs per liter of oil in 2007 U.S. dollars are \$1.81 (\$6.85 per gallon), but that assumes carbon dioxide is available at no cost and oil content is 30%. Table 13 shows Chisti's (2007) estimate that only 1.1% (2 million hectares or 4.942 million acres) of the existing U.S. cropping area would be necessary to supply 50% of all U.S. transportation fuel needs if oil content is 70%. If that oil content falls to 30%, an estimate that common in current algae species, still only 2.5% (4.5 million hectares or 11.12 million acres) are necessary to supply that same amount of fuel. The only other current source of biodiesel that comes close to that much oil production is palm oil, which would need 24% (45 million hectares or 111.2 million acres) of U.S. cropping area to produce 50% of all U.S. transportation fuels. This gives an illustration of the potential microalgae possesses.

Table 13. Comparison of Some Sources of Biodiesel.
Source: Chisti (2007)

Crop	Oil yield (L/ha)	Land area needed (M ha) [a]	Percent of existing US cropping area [a]
Corn	172	1,540.0	846.0
Soybean	446	594.0	326.0
Canola	1,190	223.0	122.0
Jatropha	1,892	140.0	77.0
Coconut	2,689	99.0	54.0
Oil palm	5,950	45.0	24.0
Microalgae [b]	136,900	2.0	1.1
Microalgae [c]	58,700	4.5	2.5

[a] For meeting 50% of all transport fuel needs of the United States.
[b] 70% oil (by wt) in biomass.
[c] 30% oil (by wt) in biomass.

Defintions: L refers to liters; ha refers to hectares; M refers to million

Hu et al. (2008) examines the lipid contents of oleaginous green algae. These algae exhibit an average total lipid content of 25.5%. However, as the algae are subjected to unfavorable conditions (photo-oxidative stress and nutrient starvation), lipid content nearly doubles to an average of 45.7%, with some lipid contents even tripling. Specifically, nitrogen and phosphorus limitation are the most important nutrients affecting oil content. This makes sense in that if the algae are fed fewer of those nutrients while maintaining the same carbon dioxide levels, carbon will become a larger part of the algal shell, meaning that oil contents will be higher as well. However, subjecting the algae to the unfavorable conditions negatively affects the growth rate and the quantity of biomass produced. More oil may exist in the algal cells but there will be fewer algal cells from which the oil can be extracted.

Huntley and Redalje (2007) assumes an oil content of 25% for *Haematococucus pluvialis* for a hybrid system using both photobioreactors and raceways. Similar to Hu, Huntley and Redalje (2007) noted that many other species have higher oil contents but higher oil contents usually indicate slower growth, which means lower overall oil productivity. Neenan et al. (1986) describes two kinds of microalgal lipids, exhibited in Figure 11 below.

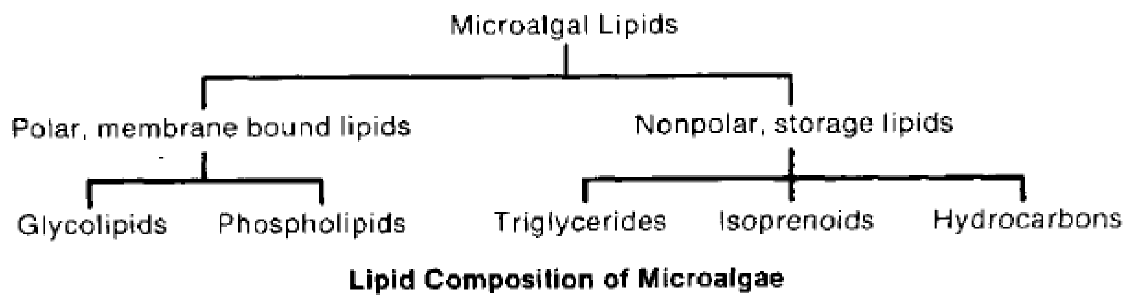

Figure 11. Lipid composition of microalgae.
Source: Neenan et al. (1986)

Polar, membrane bound lipids, such as glycolipids and phospholipids, are required for cell membrane integrity and constitute 50-70% of total cell lipids. Polar, membrane bound lipids are more difficult to extract. Nonpolar, storage lipids, such as triglycerides, isoprenoids, and hydrocarbons, are the lipids used for energy reserves. Those same energy reserves are the portion of the cell that is useful for oil and fuel production. Storage lipids are easier to extract than membrane lipids. Neenan et al. (1986) includes metabolic intermediates as a microalgae component in addition to lipids, carbohydrates, and proteins. Metabolic intermediates include any component of the cell biomass not extracted in one of the other three classes. The model included three separate algae compositions. The low lipid case, *Platymonas*, included 20% lipid, 13% protein, 49% carbohydrates, 8% ash, and 10% metabolic intermediates. The high lipid scenario, *Phaeodactylum tricornutum*, was composed of 60% lipid, 9% carbohydrate, 10% metabolic intermediates, 8% ash, and 13% protein. The reference case, of which the algal strain was not specified, contained 30% lipid, 20% carbohydrate, 32% protein, 8% ash, and 10% metabolic intermediates. Annual lipid yield for this 1,000 hectare facility is 71,012 barrels ($103 per barrel), with 33,171 tons of annual biomass production at a cost of $393 per ton. According to Neenan et al. (1986), as photosynthetic efficiency (the microalgae's ability to use sunlight in an effective manner) improves, lipid content improves, which is sensible because using sunlight more effectively will allow the algae to produce more lipids. This research conducted multiple sensitivity analyses involving improved photosynthetic efficiencies and lipid contents as shown in Table 14. The results show that per ton of algal biomass costs (in 1984 U.S. dollars) could fall to the $171-224 range and lipid costs could fall as low as $50 per barrel. To show the exact sensitivity to lipid contents (assuming a similar photosynthetic efficiency), per barrel costs rise 60% if lipid content falls to 20% while per barrel costs fall only slightly if lipid content rises to 50%.

Table 14. Summary Output for Attainability Microalgae Production Cases.
Source: Neenan et al. (1986)

		Attainability case[a]			
Parameter	Units	L30	L40	L50	A60
System algal yield	10^3t/yr	116	116	116	116
Productivity	g/m^2/d	50	50	50	50
Specific growth rate	d	0.37	0.37	0.37	0.37
PSE	% PAR	14.18	15.17	16.18	10.35
CO_2 demand	10^9 scf/y	3.24	3.24	3.24	3.24
Water demand	10^6 m^3/g	118	118	118	118
Capital investment	10^6 1984$	41.08	41.08	41.08	41.08
	$/ha[b]	48	48	48	48
Operating cost	10^6 1984$	17.32	16.94	16.59	16.59
Algal production cost	1984$/t	199	195	192	192
Lipid production cost	1984$/bbl	93	68	54	1344

[a] Cases L30, L40, and L50 correspond to assumed algal lipid contents of 30%, 40%, and 50%, respectively.
[b] For effective culture area (86% of facility size).

Defintions: t refers to ton; yr refers to year; g refers to gram; m refers to meter; d refers to day; PAR refers to photosynthetically active radition; scf refers to standard cubic feet; ha refers to hectare; bbl refers to barrel

Spolaore et al. (2006) lists eight different species of microalgae with lipid contents much lower than those previously discussed. Lipid contents range from 6-22%, with most occurring from 6-14%. Protein contents are considerably higher, ranging from 28-71%, with most being in the 40-60% range. Carbohydrate contents range from 10-57%, with all species having contents below 32% except one.

3.4. Algae By-products

The algal biomass remaining once the lipids have been harvested and extracted offer another revenue source for the microalgae facility. The remaining components, primarily carbohydrates and protein, could be used in animal or aquatic feed rations. Locating a microalgae production facility in the southwestern U.S., especially in west Texas and eastern New Mexico, adds the advantage of being close to hundreds of thousands, if not millions of cattle on feed, dairy cattle, poultry, and swine. Rather than hauling soybean meal, corn, or distiller's grains from the Corn Belt via rail or truck, some feed components can come from a closer source. In addition to serving as an animal feed source, aquaculture production covets the by-products of microalgae as a feed source because algae are a natural feed source for many of these organisms.

Becker (1994) notes that 30% of world algae production was sold for animal feed applications. Protein content is considered to be the most important component of the by-product but some alga also offer potential value in aquaculture because they add color to food products. One reason that live microalgae are not heavily used in current aquaculture production is the high cost and difficulty in using them as a feed. Using dried microalgae by-products would make such uses in aquaculture much more feasible. Becker (1994) goes on to discuss some benefits of microalgae to agriculture, specifically in poultry production. According to Becker (1994), poultry rations can safely contain 5-10% microalgae as a replacement for conventional proteins. Higher concentrations cause problems in poultry production. Becker (1994) states that the yellow color of broiler skin, shanks, and egg yolk are the most important characteristics that can be influenced by algae. Many of these ideas are the same echoed by Pulz and Gross (2004).

Certik and Shimizu (1999) address the benefits to agriculture production, both in physiology and animal appearance. Microalgae has shown to help immune response fertility in addition to improving weight control in animals. In addition, external appearance can be enhanced in the form of more healthy skin and a lustrous coat. Stepan et al. (2002) proposes that the protein recovered from microalgae production could be used as animal feed but gives no nutritional information or in what quantities it is planned to be used. Putt (2007) states that the meal remaining after oil extraction contains roughly 50% protein, comparable to soybean meal (the common animal feed that contains 48% protein), which makes it valuable as a feed ingredient.

CHAPTER IV

RISK AND SIMULATION

4.1. Risk

Risk is a concept that is prevalent in economic modeling. A model without risk, known as a deterministic model, only predicts a single value based on input values. This type of model gives no indication as to what might happen if circumstances or markets change, as they are constantly changing. Incorporating risk allows the presentation of alternative scenarios and the analysis of the probabilistic effects of changes on the system being modeled. Selecting the scenario that best fits the business and provides the best opportunity to achieve one's goals is important to a successful operation. Without risk in the model, the outcomes for alternative strategies will not be robust enough to make a decision in a risky economic environment.

Simulation facilitates the analysis of alternative scenarios by using alternative input values in the model to estimate the outcomes of key output variables (KOVs) and their distributions. The model then becomes known as a stochastic model because the outcome depends on the probability distributions for one or more of the input values. As Richardson (2008) states, "simulation is to teach us about a system and to facilitate better decisions, not to predict point estimates and make decisions."

4.1.1. Definition of Risk

Risk is the part of a business decision which cannot be controlled by a manager or operator. If there was no risk in an economic system, a manager would choose the strategy which offered the greatest economic return given a fixed set of input variables.

However, once risk is incorporated, a manager must consider the distribution of the economic returns (which includes multiple results based on the range of stochastic input variables) rather than a single value for economic return. One scenario may offer the highest mean return but involves a much wider distribution of returns that includes the potential for an economic loss while another scenario may offer a slightly lower mean return but a more narrow distribution of returns and no potential for a loss. Choosing between these alternatives will depend on a person's risk aversion.

Risk aversion is an individual's willingness to take on risk. An individual who is risk averse will be more likely to choose the safer scenario in which the distribution of outcomes is narrower and there is no risk loss but the potential for returns is lower. A risk loving individual will be willing to trade the downside risk of an economic loss and a wider distribution of outcomes in exchange for the potential for higher economic returns.

4.1.2. Sources of Risk

Risk is present throughout many aspects of an economic model. In this algae simulation model, risk is present in production (algal oil and protein yields), input prices (labor, CO_2, nutrients, water, construction, and maintenance), output prices (oil and protein meal prices), climate and location (days of operation and temperature), and resource availability (water, CO_2, and land). Although more sources of risk exist, these are the major sources of risk affecting the viability of such a project. Simulating these risky variables will aid in determining of the economic feasibility of microalgae operations.

4.1.3. Ranking Risky Alternatives

The ranking of risky alternatives for the current analysis primarily involves expected utility, which was first proposed by Von Neumann and Morgenstern (1944), and the concept that individuals wish to maximize expected utility. The utility function used to calculate expected utility depends on a vector of variables or the following:

$$U(X,\alpha)$$

Where: *X* is a random variable and *α* is a choice variable for decision makers. The utility function can also be written as:

$$U(Z)$$

Where: *Z* depends on *X* and *α*.

The utility function can then be rewritten as:

$$U(Z) = U(Z(X,\alpha))$$

Z is a measurement of wealth or net income for the economic decision. For a stochastic simulation model, the utility function is rewritten as:

$$U(Z_i) = U(Z_i(X,\alpha_i))$$

It is rewritten with i representing the alternative scenarios within the simulation. Expected utility holds that the decision maker will choose the scenario which maximizes expected utility. The outcome parameter is assumed to be monotonic in X and concave in α for all X and α. The restrictions on the utility function indicate that decision makers prefer more to less (as shown in the first restriction below) and that based on common behaviors, individuals tend to be risk averse (as shown in the second restriction below).

$$U'(Z) \geq 0; U''(Z) \leq 0$$

The most commonly used utility function is the negative exponential utility function, given as follows:

$$U(Z) = 1 - \exp(-r_a Z); and\ r_a = \frac{r_r}{Z}$$

Where: r_a is the absolute risk aversion coefficient and r_r is the relative risk aversion coefficient

The relative risk aversion coefficient hypothesizes that as individuals increase wealth or net income, they are willing to take on more risk. Multiple risk ranking procedures will be discussed in this chapter, including stochastic dominance, confidence premiums, certainty equivalence, stochastic efficiency with respect to a function, and risk premiums. However, not all of the procedures will be used in the analysis.

Stochastic dominance offers three forms of risk ranking procedures: first degree stochastic dominance (FSD), second degree stochastic dominance (SSD), and stochastic dominance with respect to a function (SDRF). FSD, proposed by Hadar and Russell (1969), ranks two risky alternatives ((F(z) and G(z)) in which F(z) is preferred to G(z) if [G(z) – F(z)] ≥ 0 for all z. FSD offers results in which the decision maker's risk preference has no effect as well. SSD, also proposed by Hadar and Russell (1969), addresses risk ranking for risk averse individuals. The sum of differences between F(z) and G(z) is calculated using:

$$S = \sum (G(z) - F(z))$$

If S is positive, F is preferred to G. If S is zero, F and G are indifferent. If S is negative, G is preferred to F. SDRF, which is also known as generalized stochastic dominance and was introduced by Meyer (1977), ranks risky alternatives for a class of decision makers who's utility is defined by a lower absolute risk aversion coefficient (LRAC or r_1) and an upper absolute risk aversion coefficient (URAC or r_2). The condition for F being preferred to G is:

$$\int [G(z) - F(z)]U'(z)dz \geq 0$$

The preferred risky alternative is calculated for both risk aversion coefficients (RACs) and if the same alternative is preferred, the result is an efficient set. If the preference is different at the two RACs, the decision maker is said to be indifferent between the two alternatives. SDRF is limited in that it can only compare two risky alternatives instead of ranking all alternatives simultaneously and that if the RACs are set too far apart, the procedure will not result in a consistent ranking.

Confidence premiums involve how much the decision maker values one alternative over another, as discussed in Mjelde and Cochran (1988). If F(z) is preferred to G(z) based on expected utility, a constant value (π) is subtracted from each F(z) value until the decision maker is indifferent between F and G at the LRAC. The value where indifference occurs is known as the lower confidence premium and is the minimum amount a decision maker would be willing to pay to switch from the preferred alternative (F) to the inferior alternative (G). The maximum premium a decision maker places on F relative to G is found by evaluating $F(z-\pi) = G(z)$ using URAC. If the confidence premium is small relative to the mean of F(z), then the stochastic dominance ranking is not strongly held or not very important for the type of decision maker represented by the RACs. It should also be noted that confidence premiums change when the RACs are changed so a decision maker should be cautious when setting these values.

Certainty equivalence uses the same basic principle as SDRF, which is more is preferred to less. Hardaker (2000) proposed that the expected utility for a risky alternative can be expressed through the inverse utility function as a certainty equivalence. The CE for a risky alternative, as defined by Freund (1956) is:

$$CE = Z - 0.5 r_a V$$

Where: Z is expected income or wealth, r_a is absolute risk aversion, and V is the variance of Z

Stochastic efficiency with respect to a function (SERF), discussed in Hardaker et al. (2004), is a combination of certainty equivalence and the use of a range of RACs. Instead of evaluating the certainty equivalence at an upper and lower RAC, it evaluates the certainty equivalence for many RACs between the upper and lower RACs. Additionally, it offers the convenience of ranking many risky alternatives at one time. The alternative with the highest CE at a given RAC is the most preferred alternative. However, because the CEs can change as the RACs change, the preference will change depending on the RAC. It is assumed that a rational decision maker will prefer a risky alternative over an alternative with zero return as long as the risky alternative's return is positive. If the risky alternative's return turns negative, it is assumed the alternative with no return is preferred. SERF can use seven different utility functions, with negative exponential and power utility functions being the most common. The negative exponential utility function is most useful when ranking risky alternatives for annual income. Because annual income can be positive or negative and is usually small compared to wealth, a constant absolute risk aversion utility function is assumed and the negative exponential utility function is the easiest one to use. The power utility function is most useful for ranking risky alternatives for a longer time horizon. It uses RRACs, which implies that as wealth increases, a decision maker is willing to take on more risk.

Risk premiums can be constituted from SERF analyses in that it uses all other risky alternatives and compares the premiums to a base alternative. One alternative is chosen as the base and the risk premiums are calculated for all other risky alternatives at multiple RACs. If the risk premium is positive, the alternative scenario is more valuable to the decision maker than the base scenario. If the risk premium is negative, the base scenario is more valuable than the alternative scenario. The risk premium values can be used to predict the utility-weighted payment necessary to persuade a decision maker to move from one alternative to another.

4.2. Simulation

Simulation is the process of solving a mathematical simulation model representing an economic system for a set of exogenous variables. A simulation model is a mathematical representation of a business or economic system that reflects sufficient detail of the system to address the questions at hand. Primarily, a simulation model answers the “What if…?” questions by allowing the management variables to change and discovering the results of those changes. Simulation models are used to analyze alternative business plans because experiments on the real system cannot be completed without harmful effects and generally take too long to see the effects. A simulation model is solved a large number of times (iterations) to statistically represent all possible combinations of the random variables in the system. The result of a simulation process is a large number of simulated values for KOVs important to the decision maker. The simulated values for a KOV represent an empirical estimate of the probability distribution for the variable and quantify the risk associated with the variable. The goal of simulation modeling is to imitate how the real systems would respond to exogenous changes in management variables and policy.

4.2.1. Stochastic Simulation

Stochastic simulation models are solved a large number of times using one value for X to generate a sample of outcomes for the dependent variable Y, recognizing that X has risk and because there is risk, Y must be forecasted using a probability distribution rather than a point estimate. The simulated distribution informs the decision maker of the riskiness of the forecast for the KOV, how skewed the outcome is, and the chances of a favorable outcome. The stochastic variables in the model are those which involve uncertainty even after the best forecast and those which the decision makers cannot control or predict. Stochastic models assume that future risk mimics historical risk so past variability is used to estimate the parameters for the probability distributions of risky variables in the model. Stochastic variables are crucial to the success of a business decision, out of the control of the decision maker, and can be specified by a probability distribution.

4.2.2. Iterations

An iteration is a set of random values or a state of nature. It represents one solution for all the equations in a model using one set of random values for all the random variables. Each additional iteration will draw a different set of random values (representing a different random draw) and the result of each iteration is recorded and used in estimating the distribution of the simulated results. All parameters must remain constant across iterations and none of the results of one iteration can be used as input to subsequent iterations.

The number of iterations necessary for simulating the model depends on the number of random variables, the number and type of equations in the model, the degrees of correlation among the random variables, and the sensitivity of the endogenous variables to the random variables. To determine the number of iterations necessary for an accurate model, multiple simulations using different numbers of iterations should be run and the summary statistics for the stochastic and key output variables should be compared. Specifically, the standard deviation of the KOVs changes until it reaches equilibrium and the iteration number where the standard deviation stabilizes should be the minimum number of iterations used for the model.

4.2.3. Probability Distribution Sampling

The Latin hypercube procedure is the preferred method of sampling probability distributions. This technique segments the distribution into N intervals and makes sure that at least one value is randomly selected from each interval. The number of intervals, N, is the number of iterations in the model. By sampling from N intervals, the Latin hypercube insures that all areas of the probability distribution are considered in the simulation. Latin hypercube is preferred to the Monte Carlo procedure because the Monte Carlo procedure randomly selects values from the probability distribution. As a result, the Monte Carlo procedure samples a greater percentage of the random values from the area about the mean and under samples the tails. Therefore, a larger number of iterations must be used to minimize the effects of under sampling the tails of the probability distribution.

4.3. Simulation Model Development

Richardson (2008) outlines an effective manner in which to build a useful simulation model. The key is to build the model from the top down, starting by determining the important variables for which results are desired and working backwards all the way to the stochastic variables within the model. In addition to building the model, the model and the variables must be validated.

4.3.1. Key Output Variables

The key output variables (KOVs) are any variables that the decision maker thinks are important to the decision. In the case of this model, two of the important KOVs are the total oil production from the microalgae and the cost per unit of producing the oil. Those two KOVs are inputs into the single most important KOV, the profitability of the facility. The entire purpose of this research is to determine the feasibility of a microalgae operation and identify the areas where improvement is needed through research and development to make the facility earn a profit or if it already turns a profit, to make it even more profitable. Financial statements, including an income statement, a cash flow, and a balance sheet, and financial ratios, such as payoff period, net present value, and debt and asset ratios, will be used in the evaluation of the financial feasibility of the project. The probability of positive annual cash flows and economic success will be examined using procedures suggested by Richardson and Mapp (1976). Different input and output variables are needed to create the financial statements and ratios necessary for evaluation.

4.3.2. Stochastic Variables

Production and cost estimates result from the development and inclusion of multiple formulas and equations in addition to model constants. The basis for many of those formulas and equations will be the output from the simulation of the stochastic variables. The model will include many stochastic variables, some of which will be forecasted from historical data using a multivariate empirical distribution, while others have very little information regarding them and therefore will be simulated using a Gray, Richardson, Klose, and Schumann (GRKS) distribution. Using the appropriate distribution is vital to building an accurate forecast for each variable and eventually an accurate forecast for the model. Upon the simulation of each stochastic variable, the variables must be validated ensure that the simulated variables are not statistically different from the historical variables.

4.3.2.1. GRKS Distribution

Oil content and growth/productivity rate are two of the most influential variables in the production of the algae. Those variables cannot be simply chosen by the facility but are rather the result of the strain of algae used, the climate and location of the facility, and the nutrients used in the production system. Since there is not one certain strain of algae for microalgae use, a range of oil contents will be simulated using a GRKS distribution. A GRKS distribution is the most applicable distribution because it is designed to simulated subjective probability distributions based on minimal input data. Existing data regarding microalgae oil contents is not abundant and the content varies from one strain to another and can even vary within the strain depending on the production system.

A GRKS distribution will be used for the production/growth rates because once again, those rates vary widely and not enough data is available to define a parametric distribution for the variable. A GRKS distribution requires three parameters: a minimum, a mid point, and a maximum. These three parameters are used to estimate the remaining parameters for the distribution based on the following assumed properties for GRKS: 50% of the observations are less than the mid point; about 95.6% of the simulated observations are between the minimum and the maximum; 2.2% of the simulated observations are less than the minimum and 2.2% are greater than the maximum; there are four equal distance intervals between the mid point and the minimum and the mid point and the maximum; and there are two intervals below the minimum and above the maximum and they have the same intervals as the parameters.

The harvesting and extraction of the oil creates additional needs for simulated variables because very little information exists on the process. The process used by this microalgae facility assumes a continuous production cycle, meaning that only a portion of the microalgae culture will be removed for harvest at each harvesting interval. In discussions with individuals who currently operate such a system, estimates of the percentage of the pond harvested at each interval were given but it was also stated that those percentages will vary. Consequently, a range of the percentage of the pond harvested at each interval was obtained and those range estimates became the minimum, mid, and maximum points for a GRKS distribution.

In addition to determining how much of the pond will be harvested at each interval, the model calculates how often the harvest interval will occur on an annual basis. The facilities currently in operation have not been harvesting and extracting oil from the algae for a long enough period to determine a concrete year-round harvesting schedule. However, they were able to estimate a range of the number of harvests for each pond on an annual basis, again creating a minimum, mid, and maximum point for a GRKS distribution to create a simulated number of harvests annually.

The final GRKS distributions pertained to the source of the water for the facility and revenues/expenses resulting from those potential water sources. The only water source that could potentially provide a source of revenue or create additional expenses would be water from oil companies (produced water). The individuals who discussed this idea are currently considering this for their small, pilot-scale facility. They have explored the subject and discussed it with the appropriate parties. Once again, a range of estimates was provided for the costs of processing the produced water from oil fields into a condition that would be appropriate for use in microalgae production. A range of estimates was also provided for the financial incentive received from the oil company in exchange for disposing of the produced water. Both of these ranges of estimates were provided in dollars per barrel of produced water. The range of estimates provides the points necessary for simulating using a GRKS distribution.

4.3.2.2. Empirical Distribution

According to Richardson (2008), empirical distributions are used when a random variable has too few observations to estimate parameters for a parametric distribution. The distribution has a finite minimum and maximum based on observed values. The shape of the distribution is defined by the data and interpolation between segments is done during simulation to create a continuous cumulative distribution function (CDF), which will be discussed later in this chapter. Richardson (2008) states empirical distributions are used in cases where few observations of a variable exist, which applies to several stochastic variables in this model, including commodity prices, inflation rates, interest rates, and weather.

It can also be proven which distribution is the most appropriate for any variable using the univariate parameter estimate (UPES) function in Simetar by simulating the variable using different distributions, and then conducting a CDFDEV test on each of the distributions. The UPES function estimates the parameters for simulating a random variable using the historical data and different assumed parametric distributions. After the parameter is simulated, the CDFDEV test determines how much the simulated parameter deviates from the actual distribution and estimates a scalar for each of the distributions. The distribution with the smallest CDFDEV estimate is the most appropriate distribution because its simulation most closely reflects the historical data. This process was carried out on every stochastic variable in the model and the results showed that each stochastic variable with historical data was best simulated empirical. The following is a list of all the stochastic variables in the model which use an empirical distribution: soybean oil, soybean meal, and natural gas prices; inflation rates for fertilizers, chemicals, services, wages, and electricity; long-term real, non-real, and savings account interest rates; and precipitation and evaporation for each of the three locations.

The stochastic variables mentioned above are simulated in groups because of their similarities to one another. Because there is more than one variable in each of the simulations, the model uses a multivariate empirical (MVE) distribution during parameter estimation. According to Richardson (2008), a MVE distribution has three components/parameters to be estimated: a deterministic component, a stochastic component, and a multivariate component for each of the variables. The deterministic component is the static projected value, which is based on mean, trend regression, or forecasted values from FAPRI (Westoff and Brown (2010)) for this model. Richardson (2008) states that the stochastic component for an MVE distribution is the measure of the dispersion about the deterministic component, which is measured as the vector of sorted deviations from the deterministic component, expressed as a fraction of the forecasted values at each historical period. The multivariate component is the correlation matrix of the random component for the random variables, according to Richardson (2008). The correlation matrix is calculated using the unsorted residuals, better known as the stochastic component of the MVE distribution.

4.3.3. Distribution Functions

Cumulative and probability distribution functions are the two used in Simetar. Cumulative distribution functions (CDFs) chart the cumulative results of a simulation. The x-axis of the chart assigns the appropriate quantitative values while the y-axis shows the cumulative probability of such a quantitative value occurring based on the simulation results. Figure 12 shows an example of a CDF.

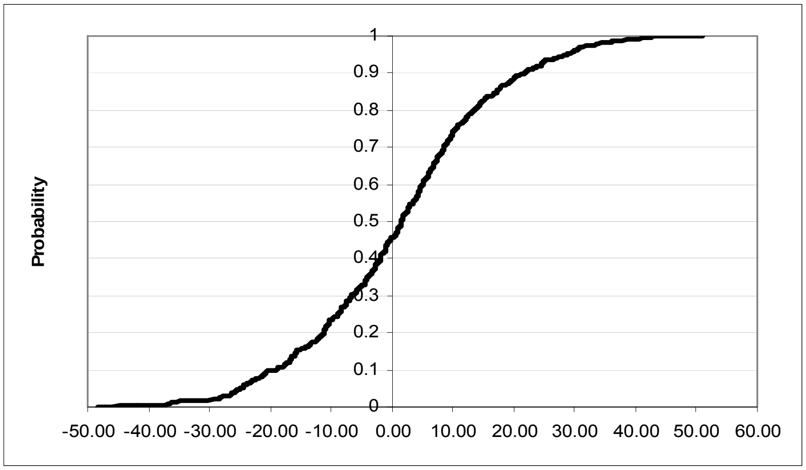

Figure 12. Example of a cumulative distribution function (CDF) graph.

Probability distribution functions show the distribution of the simulation results using a bell curve with means, lower, and upper tails. Such a graph is useful when comparing the results of alternative scenarios not only to compare the means and tails but also to compare the shape of the distributions. Figure 13 shows an example of a PDF.

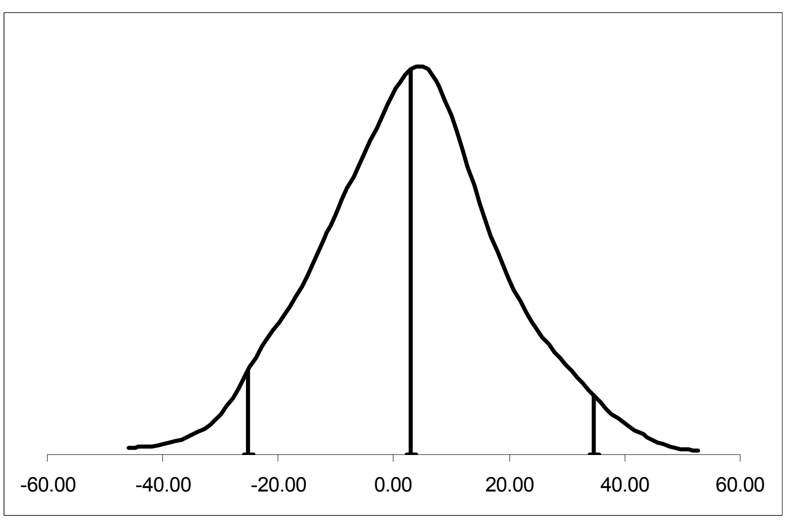

Figure 13. Example of a probability distribution function (PDF) graph.

4.3.4. Model Validation

According to Richardson (2008), validation is the process used to insure that the random variables are simulated correctly and demonstrate the appropriate properties of the parent distribution. The first step is to validate the stochastic component of the simulation model. The means, variance, and correlation must be validated for each simulation. For a multivariate probability distribution (i.e. MVE), Hotelling's T^2 test is used to simultaneously test whether the simulated vector means for the multivariate distribution are statistically equal to the vector of means for the original distribution. Box's M test of homogeneity for covariances is used to simultaneously test whether the covariance of the simulated multivariate distribution equals the covariance of the original multivariate distribution. To test the correlation for a multivariate probability distribution, the historical correlation matrix used to simulate the multivariate distribution can be tested against the simulated variables to determine if they are appropriately correlated using a Student's t-test. The Simetar function executes a Student's t-test on each of the coefficients in the correlation matrix. It should be noted that model validation also includes verifying each of the cells and formulas within the model once cell at a time.

4.4. Uncertainty

Uncertainty is risk which cannot be defined by a probability distribution. An uncertain variable is one which does not have a known distribution and therefore cannot be simulated directly. Uncertainty can be incorporated into models using one of two methods. The first is to use an example from a catastrophe theory and assume the worst outcome happens at random with a probability of P, which can be simulated using a

Bernoulli distribution. The second is to test the probability distributions for risky variables by making their means stochastic using a sensitivity analysis. A range of means for each distribution can be simulated to determine which is most critical to the business.

4.5. Scenarios

Scenario analysis allows a decision maker to evaluate the KOVs for viable alternative input levels. By simply changing the level of inputs between scenarios, the analyst can compare the effect of that individual input. The decision maker chooses which inputs he or she would like to alter from one scenario to the next and then sets up a table using the SCENARIO function in Simetar to program those alternatives. Because there are so many inputs into this model, the author has chosen a few important inputs which will change between the scenarios for comparison's sake.

This model addresses seventeen different scenarios representing possible major input values for the facility. Three locations will be addressed in the scenario analysis. The locations are southeast New Mexico, west Texas (Pecos), and south Texas (Corpus Christi). Each of these locations was chosen because of the current microalgae research being carried out there. Six scenarios will be used for both the southeast New Mexico and west Texas locations while five scenarios will be addressed for the south Texas location. A description of each of these scenarios will be presented in depth in Chapter VI. The model inputs that are varied across the scenarios and locations are designed strategically to address the cost and/or production implications of potential production systems or production designs. Although the research is only in its infant stages, much of the basis for this analysis was a combination of research from those three sites.

CHAPTER V

THE MICROALGAE MODEL

5.1. Model Overview

This model of a microalgae production facility for producing oil was built using a combination of ideas and concepts from the literature, from discussions with individuals currently working in the microalgae field, and from thoughts shared between the author, Mr. Bart Fischer, and Dr. James Richardson. It must be remembered that this is only a preliminary design for a commercial-scale facility and a final facility design would require consultation with a team of design engineers and construction experts. However, this model does address the major sectors of the design and operation of a commercial-scale microalgae production facility. As the industry continues to expand, design and operation concepts will be refined, which will in turn allow opportunities for this preliminary model to be not only refined but also significantly expanded. This model also addresses the viability/profitability component of the facility over a ten-year horizon by forecasting production, input prices, and output prices. The model consists of several main segments: costs, output prices, inflation rates, weather forecasts, and financial statements. The costs segment is the primary source for all the information necessary to run the model. It contains eight sections, including Model Inputs, Model Input Calculations, Conversion Factors and Constants, Raceway Calculations, Fixed Costs, Variable Costs, Facility Production, and Costs for Facility Inputs.

The model is designed to assess the viability of a microalgae facility for three primary locations: south Texas (Corpus Christi area), west Texas (Pecos area), and southeast New Mexico (Roswell-Carlsbad area). Data and cost information related to each general location is used to help analyze the overall viability in the selected regions. Since some of the cost information is more general than specific due to the general nature of the model, the model offers scenarios using the minimum, average, and maximum cost estimates for any cost inputs in the model. This input is referred to as the cost level input. Although it would make economic sense to use the minimum cost level inputs because the decision maker is most likely to use the product with the lowest price assuming all else is equal, this model also assess viability/ profitability for an average and maximum cost scenario to address the risk of rising input costs for supplies and materials with fluctuating costs (i.e. pipe, liner, and land). In addition, the model offers additional scenarios to assess the energy source for the facility, whether it is in the form of conventional power or in the form of renewable power, i.e. wind or solar energy. Due to the high cost of solar power and the high energy requirements for a microalgae facility, wind and conventional power were the only two sources analyzed. These various scenarios will allow the results to show what cost levels are necessary to build and operate a viable microalgae production facility.

The preliminary stages of model creation were spent reviewing designs and cost information from the literature and visiting facilities where actual microalgae research and facility operations were being performed. From this research, four major model components were identified: fixed costs, primarily resulting from facility design and construction costs; variable costs, primarily resulting from day-to-day operations of the facility; production, primarily dependent on microalgae growth rates and microalgae oil contents; and output prices, the source of revenue for the facility. After these major model components were identified, the fixed cost aspect of the model was addressed first, as some of the design specifications impacted the variable cost aspect of the model. After the variable cost component was completed, production was modeled using possible parameters from the literature and from conversations with people within the microalgae industry. Once production estimates were modeled, output prices were developed using simulation based on historical prices of comparable products. Following the creation of these price simulators, financial statements were constructed using previous components: fixed costs, variable costs, production estimates, and output prices. These financial statements will allow for addressing the profitability of a microalgae production facility over the foreseeable future.

5.2. Model Description and Design

5.2.1. Costs Segment

As mentioned earlier, the Costs segment is the most expansive portion of the model. It addresses all the cost components and generates the necessary fixed and variable costs based on the inputs given. This segment provides estimates for other segments of the model that will help develop profitability/viability measures for analysis.

5.2.1.1. Model Inputs Section

The model is based off a series of over one hundred input variables that pertain to the design and operation of the facility, input costs, output prices, and production and growth parameters for the facility. Many of the variable input price components only need current prices as inputs and then the model will inflate those current prices based on stochastic inflation estimates to reflect future cost implications for the facility. There are also decisions to be made about the production process, which in turn will affect the demand for input products and production potential of the facility. The production and growth inputs will eventually be replaced by a specific production and growth function but not enough data is currently available to build growth and production functions suitable to include in this model.

5.2.1.1.1. Production Inputs

The two primary production inputs are the Microalgae Growth Rate and the Microalgae Oil Content. Both of these inputs are a result of the scenarios, meaning that the decision maker must input these values into the scenario engine. However, the parameters are still at the discretion of the modeler. Because the information necessary to build production functions is not currently available, the growth parameters are simply given in grams per liter of water per day. Although much of the literature quotes growth parameters in grams per square meter per day, the parameters for this model are in units of volume rather than units of area. This is the result of the ability of the model to vary the water depth. A raceway with water eight inches deep is going to have higher productivity per unit of area than one with four inches of water. Therefore, it was determined that the growth parameters should be given in a unit of volume rather than a unit of area. The model also includes input parameters for a Stochastic Learning Curve. The Stochastic Learning Curve is a GRKS distribution of percentages to reflect the fact that microalgal oil for biofuels is still an emerging technology. It is designed to account for both risk about the annual gain in technology estimate and risk about the annual production estimate. Pertaining to the risk about the annual gain in technology, as time passes and more money and research are poured into the subject, technology capabilities will improve. However, because this is an emerging industry, the technology as a whole will need time to mature. This means that as time progresses, as a whole, the technology will improve but that does not mean the technology will not encounter setbacks from time to time. As the Stochastic Learning Curve pertains to risk about the annual production estimate, microalgae production is similar to farming and ranching with the idea that as farmers gain experience, they will be able to determine what works best for a particular location and climate, meaning they will become more productive as a whole. However, there are some factors that are out of the producer's control, primarily climate, meaning that although there will be improvement over the long run, production will vary from year to year. Demonstrating this risk is accomplished through the Stochastic Learning Curve. The improvement in technology is demonstrated by the input Annual Gain in Technology. Although this model assumes this gain is a constant factor, it could also a show a compounding effect as well, meaning that such a concept should be left up to the decision maker.

Oil content is simply the percentage of microalgae biomass that is in the form of oil. However, the oil produced can actually be broken down further into two main types of oil: that for used for renewable fuels and high-value oil that could be used for industrial and pharmaceutical purposes. The model is designed to allow the percentage of high-value oil to be inputted in the scenario engine section of the model while the oil for renewable fuels (which is in the same row) will automatically calculate itself based on the assumption that the remaining oil will be used for renewable fuels. The model uses the percentage of high-value oil as one of the parameters for scenario analysis because of the revenue potential from the high-value oil and the desire to analyze a variety of situations for the facility. Of the oil used for renewable fuels, roughly half of it can be directly used in the production of biodiesel while the remaining half must be hydrocracked, a process in which a long chain hydrocarbon can be added to form biodiesel, jet fuel, or gasoline. The model is prepared to handle the situation where all of the oil produced is used for renewable fuels. In speaking with industry representatives, it is believed that the high value oil will constitute between six and nine percent of the total oil produced. Model inputs are also set up to use a GRKS distribution to calculate a price for this oil based on a per gallon price inputted by the decision maker. Price data for such a product or a comparable product was not available and therefore high-value oil prices are simply calculated based on the model inputs at this time. As the market develops and a price is more easily discovered, a simulation could easily be added to the model to create a more sufficient price estimate for the high-value oil.

Unfortunately, the current harvesting and extraction technology cannot recover 100% of the oil, creating another input referred to as Percent Lipid Recovered During the Harvesting and Extraction Process. Because such technology is still in its developmental stages, this estimate will vary from one process design to the next and from one manufacturer to the next. The harvesting and extraction process requires two other inputs: the Number of Harvests Annually per Pond and the Percentage of the Ponds Harvested Each Cycle, both of which are at the discretion of the decision maker. Although the number of harvests annually will vary as climatic conditions vary throughout the year, the annual nature of this model allows a total number of harvests to be determined for the entire year rather than trying to create a monthly harvesting schedule. This model also assumes a continuous culture system in which only a portion of the microalgae culture is removed to allow the remaining microalgae to continue to grow. A terminal culture system in which the entire pond is removed for harvest and extraction was considered but would be much more labor intensive and require many acres of supporting growth ponds, which would nearly double all the inputs necessary for the facility, to refill the production ponds after harvest. The two aforementioned harvest inputs use a GRKS distribution because there is very little information available regarding them due to the relatively young nature of the industry. Once again, as more data becomes available, these parameters will be able to be further refined.

5.2.1.1.2. Facility Design Inputs

Designing an entire microalgae production facility requires a variety of design parameters. Although many of them may seem miniscule, they all play a role in the facility design and could affect production and its associated costs in addition to input costs. The decision maker must enter the design inputs of the facility and the model will determine all of the costs associated with these particular design parameters, from liner costs to the quantity of pipe necessary for the piping system. If such a facility as described in this model were to be constructed, engineers and construction experts would need to be consulted before a final design is determined.

5.2.1.1.3. Facility Area Inputs

The overall key input for facility design is the number of acre feet of water desired for production. The number of acre feet of water used for production is another of the inputs that must be specified in the scenario engine. This input was used in the scenario analysis because it allowed the modeler to analyze the potential scalability of a microalgae production facility and to determine what size of facility will be the most cost-effective and efficient give a current set of circumstances.

Once the number of acre feet of water and the dimension of the ponds are specified, the model automatically calculates the number of ponds necessary to achieve the desired acre feet of water. Once the model calculates the number of ponds necessary, it will determine the actual number of ponds to be constructed. If the number of ponds necessary has a square root that is a whole number, it will be equal to the number of ponds constructed. However, if the square root rule does not apply, then there may actually be a few more ponds than are necessary to achieve the desired number of acre feet of water. This is due to two factors. First of all, to get the exact number of acre feet of water would mean altering the dimensions of the ponds by miniscule amounts to get an exact number of acre feet of water. Secondly, this model is set up to calculate all facility dimensions and costs based on the idea of a square facility design, in the fashion of a grid layout. Although the grid may not be exactly square, the model is design to construct a facility as close to square as possible to try to minimize the amount of supplies used to build the facility because a square design is the most efficient way to do so. This means that the number of ponds wide will be within one of the number of ponds long. It also seemed to be common sense to make all the rows of ponds symmetrical. In addition to the amount of land needed for ponds for production, land will also be needed for support facilities, such as offices, harvesting and extraction facilities and machinery, by-product processing and product storage, maintenance facilities, and storage sheds. The model offers an input for the ratio of number of acres of ponds sustained by one acre of support facilities. A conceptual drawing of the microalgae facility is shown below in Figure 14.

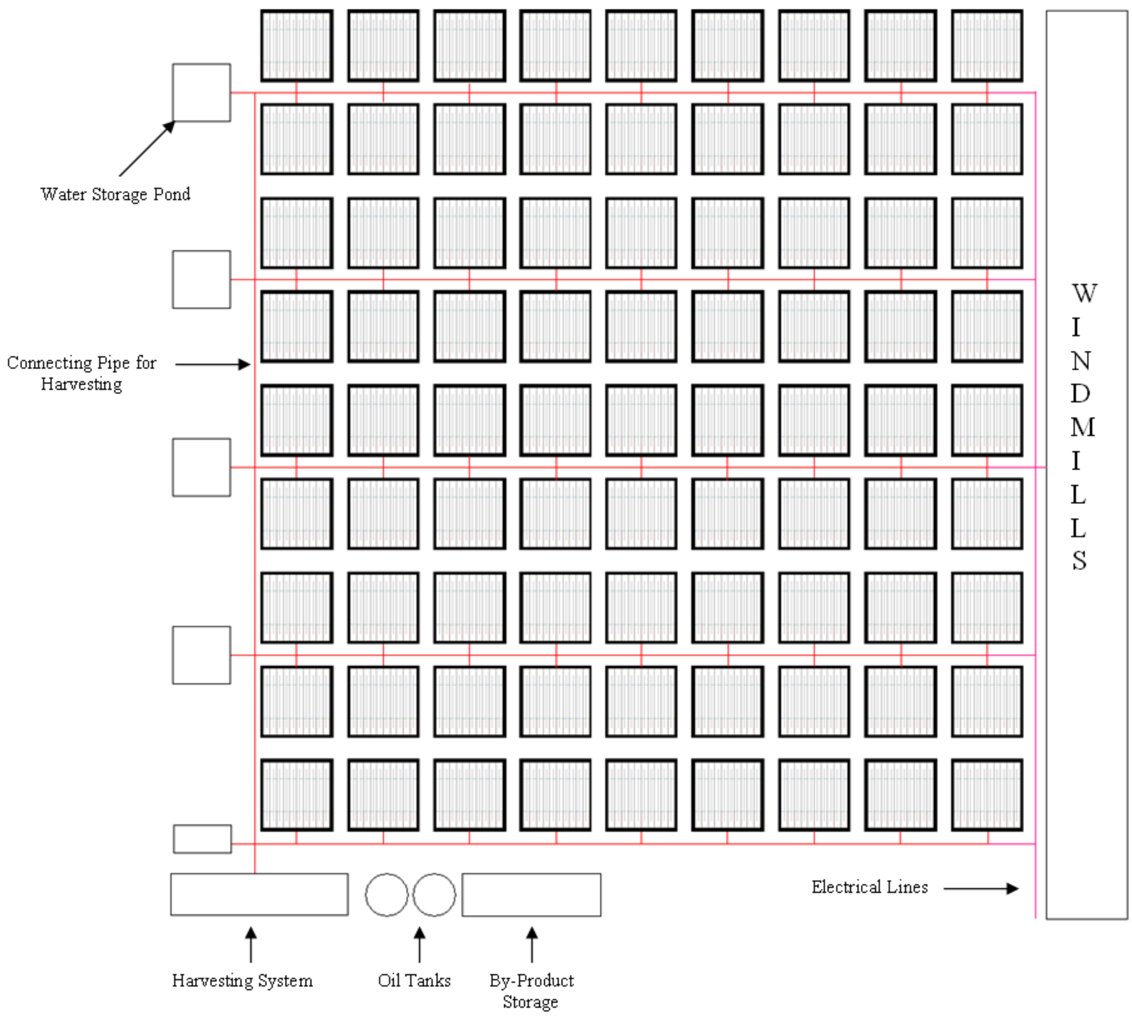

Figure 14. Microalgae facility design.

The facility will need to be enclosed by a perimeter fence. Microalgae can be very sensitive to a variety of contaminants. Although contaminants carried through the air and water cannot be protected against, contaminants introduced through wild animals, rodents, and even mischievous humans can be minimized. This same group can also pose a threat to the equipment and ponds used to produced and refine the algae. The decision maker can choose between nine and twelve gauge wire to be used for the fence and gates in addition to choosing the height of the fence, which can be either 6 or 8 feet.

5.2.1.1.4. Ponds and Raceways

Ponds of all sizes can be used to produce microalgae, but this model addresses the ponds by their length, depth, slopes of the edges, all of which can be determined by the decision maker. A conceptual drawing of an individual pond is shown in Figure 15 on the following page. The length and depth are the two major input parameters needed for pond design. The length of the pond is another input that must be specified in the scenario engine section of the model. This particular input is addressed in the scenario analysis because it will allow the modeler to determine the most efficient size of microalgae ponds, both in terms of production and construction costs. Although this particular input will not be addressed within this analysis, it will allow such an analysis to take place in the future. The width of the pond is not explicitly specified because the ponds are assumed to be determined by the width of raceways multiplied by the number of raceways per pond.

Ponds refer to a group of raceways, in which the number of raceways grouped together is a determinable variable. Similar to the pond length input, the number of raceways per pond is another input that is addressed in the scenario engine section. As mentioned before, addressing such an input in the scenario analysis will allow the modeler to determine the most efficient and effective pond design for a particular location, although such analysis is not carried out in this research. This design is employed to minimize the amount of soil that must be moved to create the ponds, to minimize the land area necessary for the facility, to minimize the amount of liner used in the ponds, and to minimize the risk of deterioration of the liner in the ponds. The grouping of raceways into ponds eliminates wasted space between individual raceways and eliminates the need for sloped berms on all sides of the raceways, instead creating the need for berms only on the ends and sides of the ponds. This reduces amount of liner used, the amount of soil moved, and the cost of liner installation. In addition, it increases the ease of liner installation. The reduction in the amount of liner used is preferred over other designs because the berms must be sloped, meaning that the liner will have to be laid over the berm, which creates opportunities for tearing because of the weight and force exerted on the liner on the crest of the berm over time.

Within the pond, the raceways will instead be divided by concrete blocks. The size of the concrete blocks is another determinable input in the model, with the model designed to use either 4”x 8”x 16” or 8”x 8”x 16” blocks. These blocks are sized in inches in height by width by length. The estimate in inches is converted to feet for ease of use in the model. This conversion is automatically completed by the model. The decision maker is also free to design his or her own paddlewheel platform using concrete blocks. This platform will serve as a support for the mixing device.

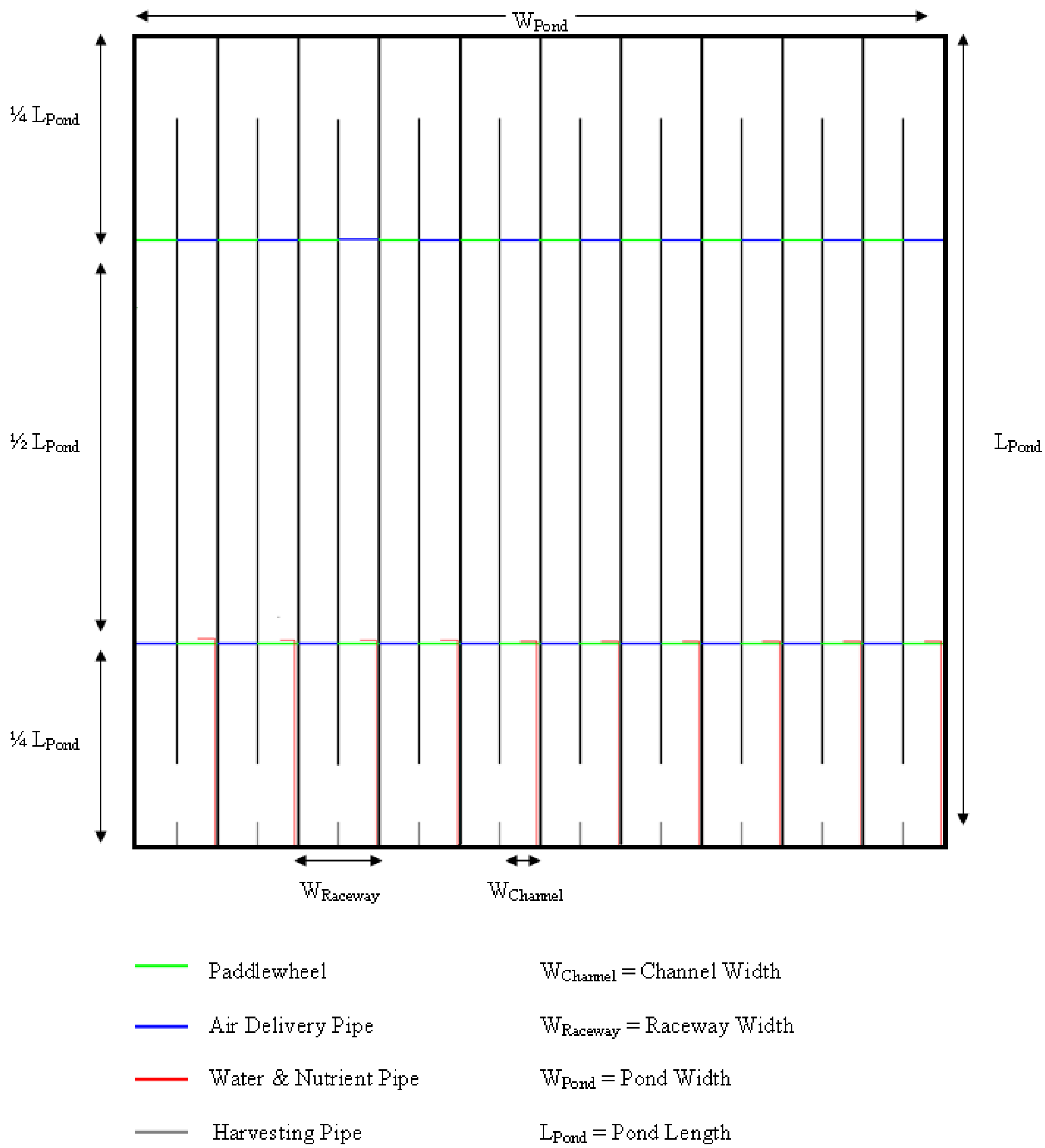

Figure 15. Individual pond design.

The decision maker must determine the number of blocks a worker can lay per day, how many workers will be used to lay those blocks, and the hourly wages of those workers. These inputs will be used to help calculate the cost of laying all the concrete blocks to divide the raceways within the ponds (dividing walls) and the concrete blocks to divide the raceways to allow the microalgal culture to flow in an oval pattern around center walls.

The length of the raceways is the same as the length of the pond but the width of the raceways depend on the ratio of length to width of the raceway. This is another input variable, with the current estimate based on the literature's suggestion that the raceway should be ten times as long as it is wide. To illustrate this entire example, assume the pond is 700 feet long and that there are ten raceways per pond. Based on the ratio, this indicates that each raceway should be 70 feet wide. The width of each raceway is multiplied by the number of raceways per pond, which in this case is ten. The result means that the pond will be 700 feet wide. If the number of raceways per pond was reduced to five, then the pond dimensions would be 700 feet long and 350 feet wide. It should also be noted that the raceway width must be divided by two to determine the channel width. The channel width is the width of the raceway in which the microalgae is moving in the same direction.

Pond depth is another important design input that influences cost, specifically soil moving costs. In order to minimize the amount of soil moved, a calculator was set up so that the amount of soil moved out of the bottom of the ponds could be piled up around the outside edges of the pond. In effect, this increases pond depth in two ways: by digging dirt out and building up dirt around the edges. Unfortunately, this optimization procedure must be recalculated using Excel's Goal Seek every time the depth of the pond is altered. This is done by setting the "Difference of Soil Moved and Removed" equal to zero by changing the "Optimal Depth of Soil Removed" cell. If this is completed correctly, the check cell "Optimal Soil Depth" will indicate "Yes". The soil depth used in this analysis is three feet because this will allow for expansion of water depth beyond current levels without the need for construction of new ponds. The End Anchor and Side Anchor inputs refer to the number of feet of liner that must be used at the edges of the ponds to anchor the liner. The Slope input indicates the slope of the berm on the outside edges of the ponds and is necessary to allow large cleaning equipment to be used in the ponds and to help anchor the liner in the ponds. The Space Between Ponds input allows the decision maker to determine how much space to allow to be able to drive in between the ponds and also space to lay pipe on top of the ground in order to avoid higher piping installation costs. The Center Wall input is a percentage to determine the length of the wall in the center of the raceway that divides it and allows the water to flow in an oval fashion. It is a percentage of the length of the raceway.

5.2.1.1.5. Water Inputs

Water inputs are vital to the success of a microalgae facility not only because it takes large quantities of water to fill all the ponds for microalgae growth, but also because the design of the water system has a significant effect on the evaporation that occurs in the ponds. Water depth is the single most important water input in the model and because of its importance, it is one of the input variables considered in the scenario analysis. Varying the water depth will allow the analysis to show the importance of increasing water depth as long as production levels are able to be maintained. Increasing water depth will help reduce both fixed and variable costs. Water depth directly affects all of the fixed costs (construction and construction materials primarily) because of the disproportionate relationship between the two. As water depth increases, more water can be contained in each pond, meaning it will require fewer ponds to meet the desired number of acre feet of water for the facility. In turn, fewer ponds leads to fewer supplies required to build the ponds and therefore fewer capital costs for the facility. Water depth also has a significant effect on evaporation, as the two are inversely related. As the water gets deeper, fewer ponds are needed to meet the desired number of acre feet of water, meaning there is less total water surface area exposed to the sun for the facility. Less water surface area exposed to the sun means less water will evaporate. Evaporation and water are two major constraints to the microalgae industry, as will be discussed throughout the rest of this chapter. Water depth must be tied to algae production so the model generates consistent, systems analysis answers when the production data regarding varying water depths become available.

The ability to deepen pond water levels will be a key variable in the future for reducing costs and improving the profitability of a microalgae production facility. This is a key reason for using ponds with three feet of depth in this analysis. It allows for future expansion of water depths while not creating the need to build new ponds (because the original ponds were too shallow) and creating additional capital costs down the road. The Center Wall Height is the height of the concrete block barrier in the center of the raceway. This input affects the number of concrete blocks purchased and installed. It does not necessarily need to be the same height as the depth of the pond because concrete blocks can be added later without making any additional alterations to the pond.

Days of Operation is included in the water inputs section, although it has an impact throughout the model. Days of Operation is the number of days the facility operates throughout the year, which has an impact on evaporation and in turn determines how much water will have to be supplied to replace the water lost to evaporation. If the facility is not operating, there is no use to replace the water lost to evaporation until the facility becomes operational again. Harvest Water Loss, which as an input is entered as a percentage, reflects the small water loss that occurs in the harvesting and extraction process. This once again is an input that is dependent on the harvesting and extraction technology employed for the facility.

Any water losses during the harvesting and extraction process create an additional demand source for replacement water for the microalgae ponds. The model is set up to use a combination of sources of water for the replacement water. Groundwater is considered to be the most obvious source in that it already exists on the property. Unfortunately, this water must be pumped out of the ground and into the ponds, creating a cost for installing and maintaining water wells and pumps, a cost for storing the water (which in this model consists of a number of deep lake-like lined storage ponds), and a cost of pumping the water to the microalgae ponds. The lined water storage ponds create more design inputs for the decision maker in that he or she must determine how deep the ponds are going to be and at what levels the water will be kept in those storage ponds. Similar to the microalgae ponds, the model is set up to calculate an optimal amount of soil to move for the water storage ponds in order to minimize soil moving costs and liner costs. The model is also designed to place a water storage pond in between every two rows of ponds.

In the case of a contaminated pond, replacement microalgae culture will need to be readily available. The model places a microalgae replacement culture station at each water storage pond. This simplifies the refill of a pond in that the replacement culture can be added to the pond in conjunction with the replacement water. Each station consists of fiberglass tanks stirred by trolling motors. The diameter of the tank and the number of tanks per station are both inputs to be determined by the decision maker. As the size of the facility increases, both the number of tanks and the diameter of those tanks should increase as well.

The enormous water demand from the microalgae facility creates a potential need to purchase water rights from adjoining land, creating an additional cost. There are several additional inputs associated with the use of groundwater for the facility. The number of wells needed is automatically determined by the model but an input is needed to determine the depth of the water wells. The expected depth of the wells can be determined by speaking to local well companies or local soil and water experts. The decision maker will also need to choose a water pump (or pumps depending on the size of the facility) based on its capacity. The horsepower associated with the particular water pump must also be added as an input as it is plays a role in determining how much energy will be required for its operation.

These cost factors combined with potential concerns from the public over water use create the need to explore additional water sources. These sources come in the form of city wastewater, oil, and food processing companies, the latter two which are prevalent in Texas and throughout the southwestern United States. Oil companies must dispose of the water they use in the process of oil well formation and maintenance, which is referred to as produced water. This water must be cleaned and injected back into the ground, creating additional costs for the oil company. This creates an opportunity in that the microalgae facility could clean this produced water and re-use as replacement water for the ponds. This would create an additional revenue source for the facility in that the oil companies would pay the facility to take the produced water. It would also create an additional cost for cleaning the water but in speaking with people within the microalgae industry, they believe the water can be cleaned for much less than they will be receiving from the oil companies for taking the water. The financial incentive only adds to the attractiveness of such a proposition because it will also reduce the strain on the groundwater source.

There is also potential to use water from food processing facilities, specifically vegetable and diary food processing facilities, as an additional water source. Unfortunately, the only financial incentive for using this source is the reduced cost of pumping groundwater. This idea is reflected in the following model inputs: Incentive for Using Produced Water; Cost of Cleaning Produced Water; Percentage of Produced Water Used in Water Recharge; and Source of Produced Water. The first two inputs are simply the financial cost and incentive the facility would receive for using produced water, if there is a financial incentive at all. This is estimated in dollars per barrel and uses a GRKS distribution due to the lack of data and information available about this potential process. The Source of Recycled Water Input determines if there is a financial incentive and cost involved, depending on which source (city wastewater, oil companies, or food companies). The input variable is found in the scenario inputs section of the model. It is important to consider the source of the recycled water in the analysis because water is such an important input and determining the best source will be very useful to the microalgae facility.

The Percentage of Recycled Water Used in Water Recharge is the percentage of water needed for the facility which the decision maker believes can be received from the alternative water sources. Such an estimate will require communication with local companies to determine the hypothetical amount of water that could be gained from the source. It should also be noted that another input to be considered is the distance from the recycled water source to the microalgae facility. If the quantity of water coming from the recycled water source (specifically city wastewater) is large enough, it would be advantageous to construct a pipeline from the source to the microalgae facility. The model requires the number of miles of pipeline necessary as an input in such a scenario. Microalgae growth rates will be affected by the source and quality of the water within the production system. The relationship between water quality and algae growth rates can be specified when these data become available.

The percentage of recycled water used is another input that is addressed in the scenario analysis section because of its affect on reducing the amount of water that will have to come from another source, i.e. groundwater. The source of the recycled water will affect profits because of its ability to create another revenue source and the percentage of recycled water used will affect not only how much energy will be necessary to obtain water from another source but also any potential need for purchasing water rights from adjoining properties.

5.2.1.1.6. Circulation Inputs

To keep the algae from settling and to keep the microalgae nutrients uniformly mixed, the microalgae culture must be constantly kept circulating in the raceways. The two sources of circulation employed in this model are paddlewheels and air blowers, although the air blowers serve an additional purpose to be addressed later in this chapter. Because of the constant need for circulation, one of these sources must be operated around the clock. The model offers the decision maker the opportunity to choose continuous air blowers and paddlewheels during the daylight hours or continuous paddlewheels and air blowers during the daylight hours from a dropdown list in the model inputs. The difference between the two choices lies in the energy demands from each of the sources of circulation. Ideally, the decision maker is likely to choose the circulation source which requires the least energy to operate constantly while using the source that requires more energy only during the daylight hours. However, that choice is left to the decision maker.

The paddlewheels are large rotating structures that push the water in one direction to keep it circulating. They move at a very slow pace to keep from damaging the microalgae and to keep the water from moving at too rapid of a pace. The decision maker must choose how many paddlewheels are necessary for each raceway, a factor that is based on the dimensions of the raceway and depth of the water. It should also be noted that concrete block platforms must be constructed for each paddlewheel, which is an additional input. The decision maker must also choose the size of the paddlewheels necessary, a factor which in addition to being dependent of the number of paddlewheels per raceway is also dependent upon the dimensions of the raceway and the depth of the water. The decision maker must determine the repetitions per minute (RPMs) of the paddlewheel motor and the desired RPMs for the paddlewheel. These two inputs create a reduction ratio that will help determine what size and kind of gear reducer is necessary to operate the paddlewheels. The model allows the decision maker to determine the size of the paddlewheel motor necessary by using the following inputs: the velocity of the culture (speed), the kinetic loss coefficient for 180° bends (which is taken from the literature for the sake of this model), and efficiency of the paddlewheel (also taken from the literature). Those factors can be determined once an actual microalgae facility is constructed.

Circulation will also be enhanced by the carbon dioxide source, which depends on the scenario. If the source is simply air, blowers will be used. These blowers will simply blow air in from the atmosphere through a piping system, which will allow the microalgae to clean some of the carbon dioxide out of the atmosphere while the blower helps the raceway circulate. If flue gas is the source of carbon dioxide, it will most likely be necessary to install a pipeline from the power plant to the facility to maintain a constant supply of carbon dioxide. Such a concept will require an input variable of the distance from the power plant to the microalgae facility to know how much pipeline will be necessary.

These concepts go against what much of the literature says in that the literature believes pure carbon dioxide must be introduced in some way. Not only will it cost money to install a system to deliver the pure carbon dioxide (similar to the piping system used in this concept), the facility will also have to purchase the carbon dioxide and store it in some fashion, which only creates additional price and storage risks. To compound on the problem of using pure carbon dioxide, not all of it is absorbed by the microalgae, meaning some of it is lost into the atmosphere through a process called outgassing. Although there are many factors that effect the level of outgassing in a system, the fact still remains that additional carbon dioxide is introduced into the atmosphere when using this process, which will not only damage the facility's ideal of creating a clean fuel that will do less harm to the environment but will also incur additional costs. The only major input associated with the air blowers is the number of cubic feet of air per minute to be blown into the raceway. The cubic feet per minute estimate will allow the model to determine the size of the blower necessary and in turn the cost of each blower. It also determines what size of motor (in horsepower) will be necessary, which will help determine energy demands for their operation.

The growth function will be affected by the source of carbon dioxide so model users should take the source of carbon into consideration when setting the parameters for the microalgae growth function. Unfortunately, definitive data on the affects of the carbon source on the growth functions parameters is not yet available for this model.

5.2.1.1.7. Piping System

A commercial scale microalgae facility will require an intricate piping system to maintain operations. As the size of the facility increases, the need for a piping system becomes more pressing. Smaller facilities could achieve some of the goals of the piping system by using manual labor (which can also be costly) but would still require some form of a piping system. For that reason, this model assumes that all things introduced into the ponds will be via a piping system rather than manual labor. Three sets of piping systems are needed for the facility: one for removing the microalgae for the harvesting and extraction process, another for blowing air into the raceways, and a final one for delivering nutrients and replacement water to the raceways. Figure 16 combines all three piping systems for display's sake.

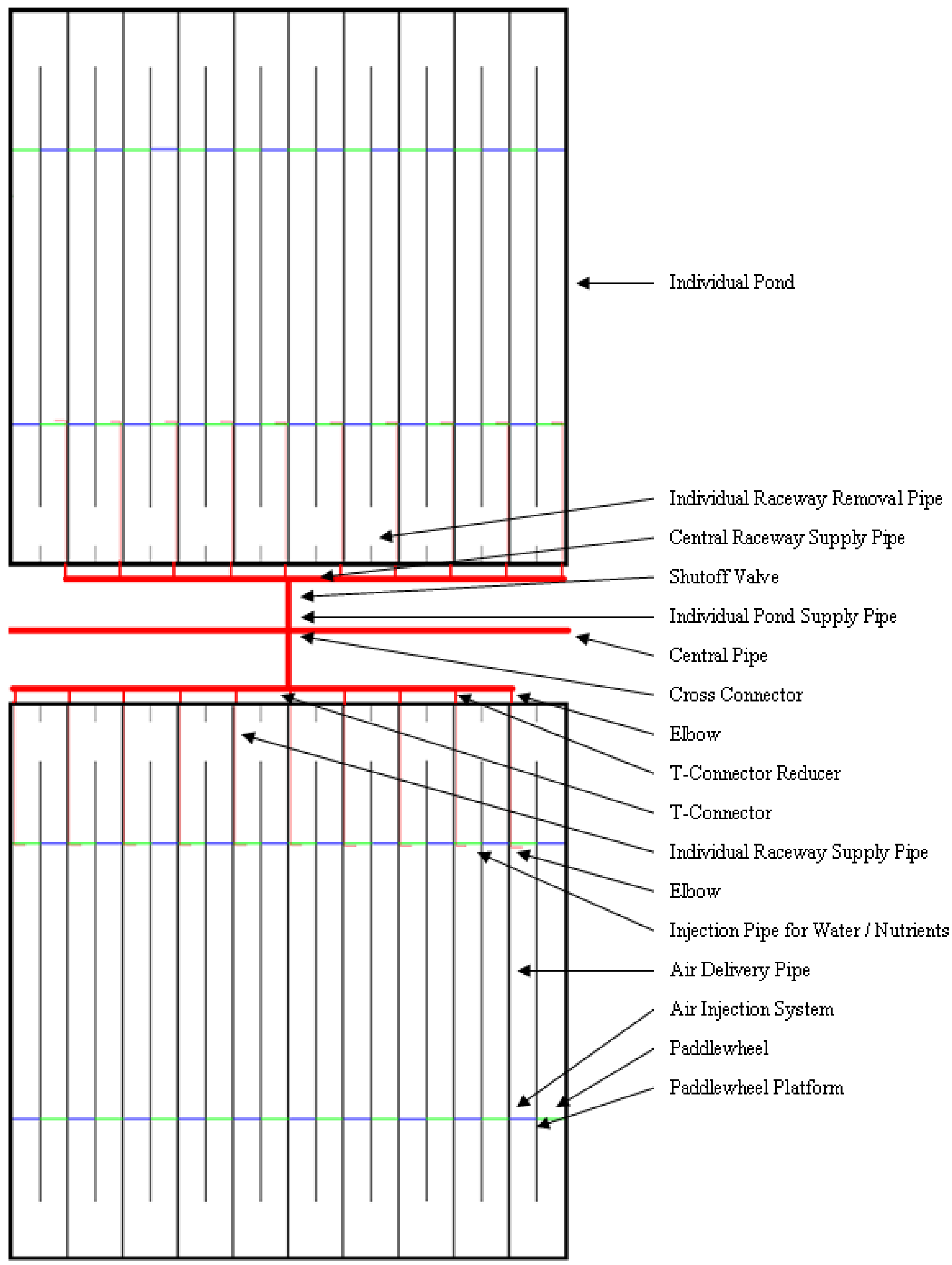

Figure 16. Paired pond design.

Two inputs affect all three systems. Standard pipe length can be discovered by simply contacting the pipe supply company. It is not a decision variable but one that is used to calculate necessary supplies for the system. Decision makers can choose between Schedule 40 and Schedule 80 pipe for their piping system. Schedule 40 is the cheaper of the two but is also the lighter-duty version of Schedule 80. The decision maker must weigh the cost benefits and the potential maintenance that each option might require.

5.2.1.1.7.1. Water & Nutrients Piping System

The piping system uses a paired design where one central pipe runs in between two rows of ponds. The standard pipe length input allows the model to determine the number of couplings necessary for the central pipe. In addition to the couplings, there are cross connectors and t-connectors to allow flow from the central pipe into the individual pond supply pipes. The individual pond supply pipe runs from the cross connector to the t-connector that joins the individual pond supply pipe to the central raceway pipe. The individual pond supply pipe also contains a shutoff valve that allows access to the entire pond to be cut off once water and nutrients reach the desired levels. The central raceway pipe runs along one end of each pond and uses T-connector reducers to join the central raceway pipe to the individual raceway supply pipe. The individual raceway supply pipe lies along the top of the concrete blocks that divide the raceways within the ponds. The individual raceway supply pipe eventually leads to the point where the water and nutrients are added to the individual raceways.

The model allows the decision maker to choose between 4”, 6”, and 8” as the size of the central pipe and the size of the individual raceway supply pipe. The model operates under the assumption that the individual pond supply pipe, the shutoff valve, the central raceway pipe, the t-connectors, the couplings, and the cross connectors are all the same size as the central pipe. Because the individual raceway supply pipe will not have to handle the quantity of water and nutrients that the rest of the pipe does, another input is provided to once again choose between 4”, 6”, and 8” pipe. This input will also apply to couplings used to connect the individual raceway supply pipe and the elbows at the end of the pipe where a downspout into the raceway is located. This creates an additional input to determine how long the pipe (in feet) from the individual raceway supply pipe into the raceway is. An input for the distance between the water storage ponds and the raceways is also necessary because the central pipe must extend to the water storage ponds. The last input for the water and nutrients piping system is a percentage that determines how far down the concrete block diving wall the pipe extends. The water and nutrients should be delivered somewhere near a mixing point so the nutrients are evenly distributed. Therefore, this input will most likely depend upon the placement of the paddlewheels.

5.2.1.1.7.2. Harvesting & Extraction Piping System

The harvesting and extraction piping system is very similar to the system used for water and nutrients. The major difference is that instead of having a pipe running along the top of the concrete barrier between the raceways, there will be one pipe with a downspout that is connected to the central raceway pipe. This will be referred to as the individual raceway removal pipe. The other classification change is that instead of an individual pond supply pipe, it will be referred to as an individual pond removal pipe. All the pipe sizes will remain the same as the water and nutrients pipe. The two inputs determined by the decision maker will be the length of the individual raceway removal pipe that extends from the central raceway pipe and the length of the downspout into the raceway.

In addition, because the algae must be moved to one central processing facility, an additional pipe must connect to the end of each central pipe in order to move the biomass back to the central processing facility. This does not require any additional inputs from the modeler but will require additional calculations and costs in the raceway calculations and fixed costs sections of the Cost segment.

5.2.1.1.7.3. Air Delivery Piping System

The air delivery piping system is the only piping system that changes depending on the scenario. The scenarios allow for CO_2 to be sourced from both flue gas and from the atmosphere. Pumping in air from the atmosphere and allowing atmospheric CO_2 to be used as the carbon dioxide source for the microalgae is much less complex than the alternative scenario. In this scenario, one air blower will be stationed at each raceway so the only pipe necessary will be that which runs from the blower to the points where the air is blown into the raceway. The model also designs the air delivery pipe to sit on top of the concrete block dividing wall. The decision maker can choose what size of pipe (4”, 6”, or 8”) to use. The location of the air injection can also be determined by the decision maker by inputting a percentage that represents the percent of the length of the dividing wall that the air supply pipe will extend. The concept for this model is that there will be two paddlewheels and two air injection systems for each raceway. Each paddlewheel will sit direct across the raceway from the air injection point and each circulation mechanism will move a similar amount of water. Using this idea, the air delivery pipe from the blower will have a t-connector a portion of the way down the raceway that will be used for one injection system while the rest of the air delivery pipe will extend to the other injection point where it will come to an end using an elbow. A pipe will extend hovering over the raceway with downspouts connected to the pipe by t-connectors. The downspouts will inject the air into the raceway. The length of the downspouts and the space between each downspout are two inputs that must be selected by the decision maker.

In the alternative scenario of piping flue gas from a power plant to the facility to be injected into the raceway, the concept for getting the CO_2 into the raceways will use the same piping design, only there will have to be a supporting piping system to get the flue gas from the power plant to the pipes along the tops of the concrete block dividing walls. This additional piping will be constructed in a manner similar to the harvesting and extraction piping system by using a connecting pipe to connect to the incoming flue gas source. The model requires an input for the size (in inches) of the connecting pipe the decision maker would like to use. From the connecting pipe, the flue gas will be distributed to the individual ponds using a series of central pipes, individual pond supply pipes, and central raceway pipes, in addition to the necessary connective piping (elbows, cross connectors, couplings, and T-connectors).

5.2.1.1.8. Harvesting & Extraction Inputs

The inputs necessary to calculate the variables for the harvesting and extraction process will be highly dependent on the process used. Inputs for the model using a specific harvesting and extraction technique were obtained from industry representatives. The inputs specific to this system are energy consumption per ton of biomass processed, natural gas usage per ton of biomass processed and the current natural gas price, chemical cost per ton of biomass processed, and the labor and maintenance cost per ton of biomass processed. These estimates are based off the current, proven technology. As the industry matures, more efficient and less expensive systems will be developed so the inputs necessary for the harvesting and extraction system will have to be tailored to an individual system.

5.2.1.1.9. Power Generation Inputs

Due to the need for continuous, flat land and because of potential odor concerns related to the facility, it is most likely that the facility will need to be located in a more remote area. The power source for the facility is an input determined in the scenario analysis section and can be one of three sources: conventional (purchasing power from the local power source), wind (wind turbines located at the facility), and renewable energy (using the microalgae by-products as a source of energy through the pyrolysis process).

Due to the undeveloped power grid that stretches over parts of Texas and the southwestern United States, this model includes inputs to help determine the cost and necessary supplies to bring power to a microalgae facility. This is another set of inputs that will need to be tailored to a specific location. It should be noted that these inputs are applicable if conventional energy is the power source for the facility. There are some general inputs that do need to be addressed. First of all, the decision maker needs to determine the distance from current grid power to the desired location. The decision maker will also need to determine the cost for power lines, both transmission and distribution lines, and input those estimates into the model.

The other two sources of energy require very specific inputs to determine both design parameters and the energy output of the systems. To help determine the land area necessary for the wind turbines, the model must have an input for the number of turbines per row (assuming the turbines are set up in a grid design) and the number of meters necessary between each turbine. If the energy source is the processing of the microalgae by-product, the energy content of the by-product (in BTUs) is an input as well as the number of hours of annual operation for the by-product processing system. This will allow the model to calculate annual energy output as well as how large of a power facility must be constructed.

Current electricity rates, in dollars per kilowatt hour, need to be inputted. This simple estimate can be obtained by contacting the company (or companies) that would potentially supply power to the facility. One final input, a cost for transformers, will apply to all the power sources.

5.2.1.1.10. Microalgae Products Storage

Once the oil and by-product have been harvested and extracted, they will need to be stored in some fashion. This model is set up to store the oil in tanks and the by product in commodity-style barns where it can complete the drying process. Because daily production of each of the products is estimated within the model, the decision maker must determine how many days of storage are necessary for each product and then the model will automatically determine how much storage space is needed. The decision maker must also input a factor that determines how many square feet of storage space are necessary for every ton of biomass. Such a factor can be ascertained by contacting building construction companies.

5.2.1.1.11. Financial Inputs

Depending on the size of the microalgae facility, it is more than likely that some internal source of financing will have to be generated to make the facility operational. First and foremost, an input for the percent equity in the facility is necessary because conversations with a lender who would handle a loan for such a project indicated that at least fifty percent equity in the facility is necessary before a loan could ever be made. The model assumes the use of a traditional loan with the loan life and the annual interest rate to be negotiated by the lender and the borrower. The model does assume that the annual interest rate is fixed and the loan payments will be constant for the life of the loan. The first year of the loan is simply the year in which the money is borrowed. The inputs for this model were determined through conversations with a large agricultural lender who has experience with renewable energy loans. However, the lender did emphasize that rates could change depending on the size and specifications of the facility and the demonstrated potential profitability. It was also noted that due to the current financial strains occurring within the renewable fuels industry, it might be difficult to obtain a loan for a microalgae facility. For the study, it is assumed that a loan would be readily available for such a project.

Much of the literature discussed an extra expense category referred to as engineering and contingency fees. This input is a percentage of annual expenses and represents costs not anticipated and any additional costs associated with the facility's day-to-day operations. In addition, because the project will require equity, the model assumes that the facility will pay annual dividends to the original investors. This amount is based on a percent of equity input, which is determined by the decision maker. There is an additional input for annual dividends to be paid if there is a positive net cash income. This percentage is another input that is determinable by the decision maker.

5.2.1.2. Model Input Calculations Section

The model input calculations section is designed to perform two major functions: determine the optimal quantity of soil to be move during pond construction and determine the exact amount of water to be contained in each pond in order to calculate the exact number of ponds necessary to achieve the desired water levels for the facility. Both of these concepts use a Riemann integral due to the sloped sides of the pond. Before the Riemann integral can be calculated, some supporting calculations must first be completed. Raceway width, which will be used to help calculate pond depth, must first be determined using the following formula:

$$W_{Raceway} = \frac{L_{Pond}}{Ratio\ of\ Length : Width\ of\ Raceway}$$

Where: L_{Pond} refers to pond length

Based on the raceway width, pond width, which will be used in the Riemann integral, is calculated using the formula:

$$W_{Pond} = W_{Raceway} * Q_{Raceways/Pond}$$

Where: $W_{Raceway}$ refers to raceway width and $Q_{Raceways/Pond}$ is the number of raceways in each pond

Once the supporting calculations are completed, the Riemann integral can be employed. The formula for the Riemann integral is as follows:

$$Q_{Opt.Soil/MA.Pond} = \int \left(L_{Pond} + \left(Slope * Q_{Ends} * D_{Pond}\right)\right)\left(W_{Pond} + \left(Slope * Q_{Sides} * D_{Pond}\right)\right)dx$$

Where: *Slope* is the slope of the pond berms; Q_{Ends} is the number of ends in the pond; D_{Pond} is the depth of the water or soil; W_{Pond} is the pond width; and Q_{Sides} refers to the number of sides in the pond

It should be noted that in the soil removal optimization calculation, the depth is the unknown for which is being solved. In the case of the water volume calculation, the depth is the depth of the water in the pond.

5.2.1.2.1. Pond Soil Removal Optimization

As discussed earlier, in order to minimize the amount of soil moved in pond formation, the soil removed will be piled on the outside edges of the pond, which not only creates the necessary pond depth by removing soil but also builds up the edges around it. Unfortunately, this cell must be re-calculated every time pond depth is changed but fortunately it can be solved with a simple Goal Seek. Because Goal Seek requires a cell set equal to a number value, a cell that calculated the difference between the soil removed from the existing ground and the soil moved to the edge of the ponds was formed so that it can be set equal to a value of zero. This creates a minimization point because all the soil removed will be piled around the edge of the ponds. Although the optimal amount of soil removed was an unknown, formulas to determine such an estimate were created from the existing pond dimension information provided in the Model Inputs section.

5.2.1.2.2. Pond Area

The actual land area required for each pond will be different based on the length of each pond because land area for the sloped berms, the anchors, and the space between ponds must be taken into account. Those additions are considered in this section of the model in order to determine accurate dimensions for pond surface area and pond land area. Pond surface area refers to the area of the pond capable of holding water, meaning the distance between the tops of the berms on each side and end. The length of the pond surface area is calculated by this formula:

$$L_{PSA} = L_{Pond} + ((D_{Pond} * Slope) * Q_{Ends})$$

The width of the pond surface area is determined by the equation:

$$W_{PSA} = W_{Pond} + ((D_{Pond} * Slope) * Q_{Sides})$$

Pond land area refers to the actual land area needed for each pond, meaning this estimate also accounts for the anchors and the space between ponds. The length of the pond land area is determined by this formula:

$$L_{PLA} = L_{PSA} + SBP + (L_{EndAnchor} * Q_{Ends})$$

Where: L_{PSA} is the length of the pond surface area; *SBP* is the space between ponds; and $L_{EndAnchor}$ is the length of the end anchor

The width of the pond land area is calculated using the following formula:

$$W_{PLA} = W_{PSA} + SBP + (W_{SideAnchor} * Q_{Sides})$$

Where: W_{PSA} is the width of the pond surface area and $W_{SideAnchor}$ is the width of the side anchor

5.2.1.2.3. Pond Water Volume

Pond water volume is vital to determine the number of ponds necessary to construct a facility with the desired number of acre feet of water. There are two steps to determining pond water volume. The first is to determine the pond water volume before the concrete blocks were laid, using this formula:

$$V_{PondInitial} = \int \left(L_{Pond} + \left(Slope * Q_{Ends} * D_{Water}\right)\right)\left(W_{Pond} + \left(Slope * Q_{Sides} * D_{Water}\right)\right)dx$$

Where: D_{Water} is the pond water depth

Following the Riemann integral, water displaced by the concrete blocks must be calculated to determine a true pond water volume.

Multiple concrete block calculations were necessary to calculate the total volume of water displaced. Such an estimate is dependent on a variety of factors. First and foremost, it is dependent on the number of raceways per pond because there will be one center wall in each raceway. There will also be dividing walls, the quantity of which is determined using this formula:

$$Q_{DW} = Q_{Raceways/Pond} - 1.0$$

It should be noted that the subtraction of one is used because there are already dividing walls on the sides of the pond in the form of the outside berms. Water volume lost to the dividing walls uses a fairly complex calculation as a result of the sloped berms at the ends of the pond. The formula is as follows:

$$V_{WLDW} = \left(Q_{DW} * L_{Pond} * D_{Water} * W_{Block}\right) + \left(Q_{DW} * D_{Water} * W_{Block} * Slope\right)$$

Where: Q_{DW} is the number of dividing walls and W_{Block} is the width of the concrete blocks

Water volume losses to the center walls use a more straightforward calculation because there are no slopes involved. The formula for determining water volume lost to center walls is:

$$V_{WLCW} = L_{Pond} * \%L_{CenterWall} * D_{Water} * W_{Block}$$

Where: $\% L_{Center\ Wall}$ refers to the percent length of the center wall in relation to the total length of the pond

Water volume will also be lost for the paddlewheel platforms. To determine that lost water volume, the model first calculates the width and length of the platform in addition to the length of the angled blocks. These calculations are set up for a platform with a design of that shown in Figure 17.

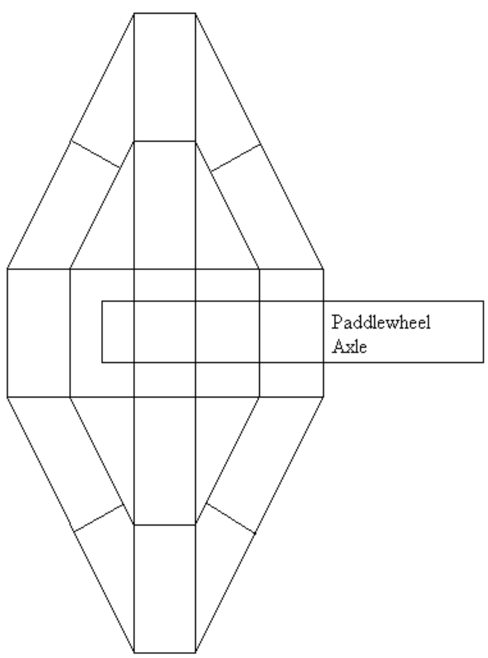

Figure 17. Paddlewheel platform design.

The formula for calculating platform width is:

$$W_{Plat} = W_{Blocks} * W_{\#Blocks}$$

Where: $W_{\#Blocks}$ is the number of blocks the platform is wide

The formula for calculating platform length is as follows:

$$L_{Plat} = L_{Block} * L_{\#Blocks}$$

Where: L_{Block} refers to block length and $L_{\#Blocks}$ is the length of the platform in number of blocks

The angled block length for the platform is determined by this formula:

$$L_{AB} = L_{Blocks} * L_{\#Ang.Blocks}$$

Where: $L_{\#Ang.Blocks}$ is the length of the angled corners of the platform in number of blocks

Total water volume lost as a result of the paddlewheel platforms is calculated by the following formula:

$$V_{WLPlat} = ((Q_{CW} + Q_{DW}) * Q_{Plat./Wall}) * \left(D_{Water} * \left((W_{Plat} * L_{Plat}) + \left(W_{Plat} * \sqrt{L_{AB}^2 - \left(\left(\left(\frac{W_{\#Blocks}}{2} \right) * W_{Block} \right)^2 \right)} \right) \right) \right)$$

Where: Q_{CW} is the number of center walls; $Q_{Plat./Wall}$ is the number of concrete block platforms per wall; W_{Plat} is the platform width in feet; L_{Plat} is the platform length in feet; L_{AB} is the length of the angled blocks in feet

It is also important to note that when the volume of water displaced is calculated, the model uses water depth and not pond depth because the water displaced by the concrete blocks only goes as deep as the water depth. Total pond water volume can be calculated once the supporting equations have been satisfied using the following formula:

$$V_{Pond} = V_{PondInitial} - \sum \left(V_{WLDW}, V_{WLCW}, V_{WLPlat} \right)$$

Where: $V_{PondInitial}$ is the water volume of the pond without reductions for concrete blocks: V_{WLDW} is water volume lost to dividing walls; V_{WLCW} is water volume lost to center walls, and V_{WLPlat} is the water volume lost to platforms

The answer will be given in cubic feet and will have to be converted to other units for use throughout the model.

5.2.1.2.4. Water Surface Area

Water surface area is calculated so it may be used to help determine facility net evaporation. It is necessary to estimate not only total evaporation but also total rainfall, which helps negate some of the evaporation. If the sides of the pond were vertical instead of being slanted, total water volume could be divided by water depth to determine water surface area. However, because the ends and sides of the ponds are sloped, such a calculation would understate the actual water surface area. Understating a water surface area by a minimal amount does not seem like it would have a large effect but it does. Understating water surface area will cause evaporation and rainfall to be understated because there will be less area over which evaporation and rainfall will occur. This will cause water demands and usage and electricity consumption to be stated incorrectly. Instead, water surface area is calculated using a series of equations. The first step is to calculate the water surface area without correcting for concrete block reductions by calculating length and width of the water surface area. To determine the true water surface area, the model also has calculations for the water surface area lost as a result of the concrete blocks. The formula for calculating water surface area length is:

$$L_{WSA} = L_{Pond} + \left(Q_{Ends} * Slope * D_{Water}\right)$$

The formula for calculating water surface area width is as follows:

$$W_{WSA} = W_{Pond} + \left(Q_{Sides} * Slope * D_{Water}\right)$$

Initial water surface area (without reductions for concrete blocks) is determined by this equation:

$$A_{IWSA} = L_{WSA} * W_{WSA}$$

Where: L_{WSA} is the water surface area length and W_{WSA} is the water surface area width

Three sources of water surface area reductions result from concrete blocks: dividing walls, center walls, and paddlewheel platforms. The formula for estimating water surface area lost to dividing walls is as follows:

$$A_{WSALDW} = Q_{DW} * L_{WSA} * W_{Block}$$

Water surface area lost to the center walls is calculated by the formula below:

$$A_{WSALCW} = Q_{Raceways / Pond} * \left(L_{Pond} * \%L_{CenterWall}\right) * W_{Block}$$

Water surface area lost to the paddlewheel platforms can be calculated fairly simply using some previous formulas. The formula for calculating water surface area lost to the platforms is below:

$$A_{WSALPlat} = \frac{V_{WLPlat}}{D_{Water}}$$

Once all the individual water surface area lost to concrete blocks has been determined, they are employed in the following formula, which determines the true water surface area:

$$A_{WSA} = A_{IWSA} - \sum \left(A_{WSALDW}, A_{WSALCW}, A_{WSALPlat} \right)$$

Where: A_{IWSA} is the initial water surface area (prior to reductions for concrete blocks); A_{WSALDW} is the water surface area lost to the dividing walls; A_{WSALCW} is the water surface area lost to center walls; and $A_{WSALPlat}$ is the water surface area lost to platforms

It should be noted that all of the calculations are completed in square feet.

5.2.1.3. Constants & Conversion Factors Section

The model offers many of the estimates and results in both metric and U.S. units, therefore creating the need for conversion factors and constants. The primary conversion factors used in this model involve volume and area, densities and weights, energy, and time. Many of these conversion factors are used to simplify the model in that the use of cell references for constants is much simpler than typing the value in each cell. If a mistake is made with the constants and conversions, it is much easier to change a single cell rather than having to search the model and change each cell individually.

The area conversion factors consist primarily of converting metrics to U.S. units or using conversion factors to aggregate smaller units into larger ones. Examples of these conversion factors include acres per hectare, square feet per acre, square feet per square meter, gallons of water per acre foot, and so on. There are also constants regarding area, including feet per mile and inches per foot.

Densities and weights are primarily used in the production section of the model to convert production into smaller units or more common units. Examples include pounds per short ton, kilograms per short ton, grams per kilogram, gallons per barrel, pounds of oil per gallon, etc.

Energy contents of both inputs and outputs of the model will be helpful in determining an energy balance for the facility. Many of these conversions play a very important role in the model, including watts per horsepower, watts per kilowatt, BTUs (British Thermal Units) per cubic foot of natural gas, BTUs per kilowatt hour, and BTUs per gallon of oil. A current energy estimate for microalgae oil is not yet available so the energy content for crude oil was used in for this conversion factor.

Time conversions were simply to break down estimates into smaller units or to aggregate them into annual data. Time conversions include hours per day, hours per year, days per year, minutes per hour, and minutes per day. An estimate for pi (mathematical unit) was also included.

5.2.1.4. Raceway Calculations Section

The model input calculations (which are based on an individual pond) and conversion factors are the basis for pond calculations for the entire facility. The key calculation in the Raceway Calculations section of the model is the minimum number of ponds necessary to satisfy the desired number of acre feet of water. This number of ponds is arrived at employing the following formula:

$$MIN\,Q_{Ponds} = \frac{Q_{Ac.Ft.Water} * Q_{Gal/Ac.Ft.Water}}{Q_{Gal.Water/Pond}}$$

Where: $Q_{Ac.\ Ft.\ Water}$ refers to acre feet of water in the facility; $Q_{Gal/Ac.Ft.\ Water}$ refers to the constant for number of gallons of water per acre foot; and $Q_{Gal.Water/Pond}$ refers to the number of gallons of water in the individual ponds

This number is set to round up to a whole number as it does not make sense to have a partial pond.

Once the minimum number of ponds is determined, using the square root rule discussed earlier, the model will calculate the number of rows of ponds and the number of columns ponds. The formula for determining the number of columns of ponds is:

$$Q_{PondColumns} = ROUNDUP\sqrt{(MIN\,Q_{Ponds})}$$

Where: $MINQ_{Ponds}$ is the minimum number of ponds

The formula for determining the number of rows of ponds is:

$$Q_{PondRows} = \frac{MIN\,Q_{Ponds}}{Q_{PondColumns}}$$

Where: $Q_{PondColumns}$ refers to the number of columns of ponds

The formula for determining the total number of ponds in the facility is:

$$Q_{Ponds} = Q_{PondRows} * Q_{PondColumns}$$

Where: $Q_{PondRows}$ refers to the number of rows of ponds

It is assumed the facility is square or as close to square as possible as it was the only way the author could determine that the model could calculate the pond layout on its own. It is possible that the number of rows and columns of ponds could be factored using whole numbers manually but the author was unable to determine a way that the model could complete such a calculation on its own. Fortunately, if the decision maker chose to enter the number of rows and columns of ponds manually, it would not affect other parts of the model. It should also be noted that a cell uses a series of If/Then statements to determine if the number of rows of ponds is even or odd. This will be used to help calculate electrical line quantities. Once the pond layout has been determined, the model will also calculate the dimensions of the facility based on the length of the ponds and other dimension inputs from the model inputs section. The formula for estimating facility length is:

$$L_{Facility} = (Q_{PondRows} * L_{PLA}) + SBP$$

Where: L_{PLA} is the length of the pond land area

The formula for estimating facility width is:

$$W_{Facility} = (Q_{PondColumns} * W_{PLA}) + SBP$$

Where: W_{PLA} refers to the width of the pond land area

The model calculates the total number of raceways for the facility using the equation:

$$Q_{Raceways} = Q_{Ponds} * Q_{Raceways/Pond}$$

<u>5.2.1.4.1. Piping System Calculations</u>

The piping system calculations require a complex set of formulas and If/Then statements in order to ensure that the model can be scaled effectively. Four estimates affect the piping system calculations through all three systems: the number of rows of pipe (both rounded and unrounded), the standard pipe length (from inputs), and a multiplier of two that represents that one central pipe will have a pond on each side. The rounded number of rows of pipe represents the number of central pipes that will be necessary, determined by the formula:

$$Q_{PipeRows(R)} = ROUNDUP\left(\frac{Q_{PondRows}}{2}\right)$$

The number of unrounded rows of pipe is also necessary because if the number of rows of ponds is an odd number, there will be one central pipe that will only have ponds on one side, therefore creating the need for a different set of piping supplies. It is represented by the formula:

$$Q_{PipeRows(UR)} = \frac{Q_{PondRows}}{2}$$

5.2.1.4.1.1. Water & Nutrients Piping System Calculations

The water and nutrients piping system will run from the water storage ponds (which will be located on the same side of the facility as the water wells) to the opposite side of the facility to supply water and nutrients to the individual ponds. As discussed earlier, one water storage pond and one central supply pipe will provide the necessary water and nutrients for two rows of ponds. The quantity of central pipe necessary per row will be calculated using the formula:

$$Q_{Cent.Pipe/Row} = L_{WSP\&MP} + \left(\left(W_{PLA} + SBP\right) * Q_{PondColumns}\right) - \left(\frac{W_{Pond}}{2}\right)$$

Where: $L_{WSP\&MP}$ refers to the distance between the water storage ponds and the microalgae ponds

Half the width of the last raceway is used because that is the point where the central pipe connects to the individual ponds supply pipe and there are no ponds beyond that point. The total number of feet of pipe is given by the formula:

$$Q_{Cent.Pipe} = Q_{Cent.Pipe/Row} * Q_{PipeRows(R)}$$

Where: $Q_{Cent.\ Pipe/Row}$ refers to the feet of pipe for one row of central pipe and $Q_{PipeRows(R)}$ refers to the rounded number of rows of pipe

Calculating the number of cross connectors and t-connectors employs this equation:

$$Q_{X-Connectors} = (Q_{PondColumns} - 1) * ROUNDDOWN(Q_{PondRows(UR)})$$

Where: $Q_{PondRows(UR)}$ refers to unrounded number of pond rows

The subtraction of one represents that a t-connector will be used at the end of each central pipe instead of a cross connector. This factor captures the fact that if there are an odd number of rows of ponds, the last row of central pipe will need to use t-connectors in place of cross connectors because there are ponds on only one side of the central pipe. There are two separate estimates to calculate the number of t-connectors, one to account for the ends of each central pipe and one to account for the t-connectors that will replace the cross connectors if there are an odd number of rows of ponds. The formula for the ends is:

$$Q_{TC.Cent.PipeEnds} = ROUNDDOWN(Q_{PipeRows(UR)})$$

Where: $Q_{PipeRows(UR)}$ refers to unrounded number of rows of pipe

The formula for the case of an odd row is:

$$Q_{TC.Odd} = ((Q_{PipeRows(R)} - ROUNDDOWN(Q_{PipeRows(UR)})) * Q_{PondRows}) - Q_{Elbows}$$

Where: $Q_{PipeRows(R)}$ refers to the rounded number of rows of pipe and Q_{Elbows} refers to the number of elbows

It must also be taken into consideration that an elbow must be used instead of a t-connector at the end of the central pipe if there are an odd number of rows of ponds. The formula for determining the number of elbows for the central pipe system is:

$$Q_{Cent.Pipe.Elbows} = Q_{PipeRows(R)} - Q_{TC.Cent.PipeEnds}$$

Where: $Q_{TC.Cent.PipeEnds}$ refers to the number of t-connectors for the ends of the central pipes

Once the number of cross connectors, t-connectors and elbows has been determined, the model will calculate the number of couplings necessary to connect all the central pipes. This will be completed by dividing the total number of feet of central pipe by the standard pipe length and then subtracting the number of cross connectors, t-connectors, and elbows.

The individual pond supply pipe that runs from the central pipe to the central raceway pipe is determined by this formula:

$$Q_{IPSP} = \left(\frac{SBP}{2}\right) * Q_{Ponds}$$

Dividing by two is used to indicate that the pipe will be laid an equal distance between the two rows of ponds. There is also a calculation for the number of couplings if the distance between the ponds is greater than the standard pipe length. The number of t-connectors necessary to connect the individual pond supply pipe and the central raceway pipe is simply the total number of ponds because there will be one t-connector for each pond. The quantity of central raceway pipe necessary is determined by the formula:

$$Q_{Cent.RW.Pipe} = \left(\frac{\left(W_{Pond} * \left(Q_{Raceways/Pond} - 1\right)\right)}{Q_{Raceways/Pond}}\right) * Q_{Ponds}$$

This accounts for the fact that the central raceway pipe will not need to stretch the entire width of the pond because the pipe will run along the top of the concrete block dividing walls. The number of t-connector reducers is calculated by the following equation:

$$Q_{T-Conn.Red.} = \left(Q_{Raceways/Pond} - 2\right) * Q_{Ponds}$$

Where: Q_{Ponds} is the total number of ponds in the facility

Subtracting two from the number of raceways per pond is necessary because elbows, not t-connector reducers, will be needed on each end of the central raceway pipe. The number of elbows necessary for the central raceway pipe is the result of the formula:

$$Q_{Cent.RW.PipeElbows} = Q_{Ponds} * 2$$

Once the number of t-connector reducers and elbows has been calculated, the number of couplings necessary for the central raceway pipe can be calculated using the following formula:

$$Q_{Cent.RW.Coup.} = \frac{Q_{Cent.RW.Pipe}}{SPL} - \left(Q_{T-Conn.Red.} + Q_{Cent.RW.PipeElbows}\right)$$

Where: $Q_{Cent.RW.Pipe}$ is the total number of feet of central raceway pipe; SPL refers to the standard pipe length; $Q_{T\text{-}Conn.Red.}$ refers to the number of t-connectors; and $Q_{Cent.RW.PipeElbows}$ is the number of elbows needed for the central raceway pipe

The number of feet of individual raceway supply pipe, which runs along the top of the concrete block dividing walls, is calculated using the equation:

$$Q_{IRSP} = \left(\% L_{WaterPipe} * L_{PSA}\right) * Q_{Raceways}$$

Where: $\% L_{Water\ Pipe}$ refers to the percent length of the raceway the water pipe extends and $Q_{Raceways}$ refers to the number of raceways

The couplings calculation is the same as described before except that there are no connectors or elbows to subtract out. An elbow is necessary at the end of each individual raceway supply pipe, meaning that Q_{Elbows} is equal to the total number of raceways. The number of shutoff valves is simply the total number of ponds because each pond has one shutoff valve.

5.2.1.4.1.2. Harvesting & Extraction Piping System

The harvesting and extraction piping system is very similar to the water and nutrients piping system. The calculations for the number of feet of central pipe are the same, as are the number of couplings, cross connectors, t-connectors, and elbows associated with the central pipe. The only difference between the pipe connecting the central pipe and the central raceway pipe is the name, which is individual pond removal pipe instead of individual pond supply pipe. One shutoff valve is located at every pond along with a t-connector to connect the individual pond removal pipe to the central raceway pipe. The number of feet of central raceway pipe will be the same, as will the number of t-connector reducers and elbows.

The major difference exists in that the individual raceway removal pipe will be centered in each raceway with a downspout into the raceway. The other major difference is the addition of one connecting pipe at the end of the central pipes. This connecting pipe will run from the end of the central pipe all the way to the harvesting and extraction facility. The number of feet is expressed in the following calculation:

$$Q_{Conn.Pipe} = (L_{PLA} + SBP) * (Q_{PondRows} - 1.0)$$

Subtracting one from the number of rows of ponds is used because the connecting pipe will only need to go as far as the last row of pipe, which will be located between the last two rows of ponds, meaning that the length of the pond for the last row can be subtracted. The number of elbows will be one and the number of t-connectors will be calculated using this equation:

$$Q_{TC.Conn.Pipe} = Q_{PipeRows(R)} - Q_{Conn.PipeElbows}$$

Where: $Q_{CP.Elbows}$ refers to the number of elbows on the connecting pipe

The number of couplings will be calculated the same way as mentioned earlier, instead using the quantity of connecting pipe instead of central pipe or central raceway pipe.

5.2.1.4.1.3. Air Delivery Piping System Calculations

The air delivery piping system calculations require a set of calculations similar to the previous two systems but more complex in that they require a series of If/Then statements because of the multiple sources of carbon dioxide determined in the scenario analysis section of the model. The series of formulas begin with the formula for the connecting pipe, which will connect the flue gas pipeline to the central pipes. The formula for the connecting pipe is as follows:

$$Q_{Conn.Pipe} = If\left(CO_2 = Air, 0, if\left(CO_2 = Flue\,Gas, \left(\left(L_{PLA} + SBP\right) * \left(Q_{PondRows} - 1.0\right)\right)\right)\right)$$

Where: CO_2 is the source of carbon dioxide from the scenario inputs; *Air* is if the source of the CO_2 is the air; and *Flue Gas* is if the source of the CO_2 is flue gas

The formulas use the same If/Then statements for the following estimates: $Q_{TC.Conn.Pipe}$, $Q_{Cent.Pipe}$, $Q_{X\text{-}Connectors}$, $Q_{TC.Cent.PipeEnds}$, $Q_{Cent.Pipe.Elbows}$, Q_{IPSP}, $Q_{Cent.RW.Pipe}$, $Q_{T\text{-}Conn.Red.}$, $Q_{Cent.RW.PipeElbows}$, and $Q_{Cent.RWCoup}$.

The air delivery piping system calculations are much simpler than those of the two previous piping systems only if the source of the carbon dioxide is air. The following calculations are necessary for either carbon dioxide source but the above calculations are required if flue gas is chosen as the carbon dioxide source. Because of the location of a blower at each raceway, the calculations only involve the pipe laid along the top of the concrete block dividers, the injection pipe, and the associated connectors. (If flue gas is the carbon dioxide source, the central raceway pipe will connect to the pipe laid along the concrete dividers instead of the pipe connecting to a blower). The number of feet of delivery pipe is determined using the formula:

$$Q_{Air.Del.Pipe} = L_{Raceway} * \% L_{AirPipe} * Q_{Raceways}$$

Where: $L_{Raceway}$ refers to raceway length and $\% L_{Air\ Pipe}$ refers to the percent of the length of the raceway that the air delivery pipe extends

The number of elbows to go on the ends of the air delivery pipe to connect to the injection pipe is simply the total number of raceways. The number of t-connectors to connect to the injection pipe is the same as well. The number of feet of injection pipe uses this equation:

$$Q_{Inj.Pipe} = W_{RWC} * 2 * Q_{Raceways}$$

Where: W_{RWC} is the width of the raceway channel

The number of endcaps necessary for the injection pipe is simply two times the number of raceways because there are two injection pipes per raceway. The number of t-connectors to connect the injection pipe to the downspouts is determined by the following formula:

$$Q_{TC.Inj.Pipe} = \left(\frac{W_{Channel}}{L_{BTW.Inj.Pipes}} - 1 \right) * Q_{Raceways}$$

Where: $W_{Channel}$ is the channel width and $L_{BTW.Inj.Pipes}$ refers to the distance between injection pipe downspouts

The number of feet of pipe for the downspouts is calculated using this equation:

$$Q_{Down.Pipe} = Q_{TC.Downspouts} * L_{Downspouts}$$

Where: $Q_{TC.Downspouts}$ is the quantity of t-connectors for downspouts and $L_{Downspouts}$ is the length of the individual downspouts

The length of downspouts input is found in the air delivery piping inputs section.

5.2.1.4.2. Electrical Line Calculations

The power requirements for a microalgae facility create the need for a complex electrical system, similar to the piping systems. Electricity will be necessary at three major points at each raceway: the paddlewheels, the air blowers, and the actuated shutoff valves. Similar to the piping system design, central electrical lines will be run along one side of the facility. Depending on the source of power, whether it is conventional or wind, the power will run from one central location along one side of the facility. If the power source is conventional, the electrical lines will run from one corner of the facility (assuming that is where the power source comes in to the facility from the substation) and branch out. The central distribution line will run perpendicular to the rows of ponds, similar to the connecting pipe for the harvesting and extraction piping system, and is calculated using the following formula:

$$Q_{CDL(C)} = (Q_{PondRows} - 1.0) * L_{PLA}$$

If the power source is wind turbines, the turbines will have to be located on the opposite side of the facility as the water storage ponds in order to avoid running electrical lines around the storage ponds. For a wind turbine power source, a central distribution point at the center of one side will be used in order to minimize the number of feet of electrical line used. This is the reason for determining if the number of rows of ponds is odd or even. If the number of rows of ponds is even, the formula used is:

$$Q_{CDL(WE)} = \left(Q_{PondRows} - 2.0\right) * L_{PLA}$$

If the number of rows of ponds is odd, the formula used is:

$$Q_{CDL(WO)} = (Q_{PondRows} - 1.0) * L_{PLA}$$

The central electrical lines will connect to the paired row distribution line that runs in between the rows of ponds, with one central line serving two rows. In this case, however, the electrical line will run the entire length of the row of raceways because of the need for power at the individual air blowers. The formula for calculating paired row distribution line is the same no matter the source of the power and is represented by this equation:

$$Q_{PRDL} = W_{Facility} * Q_{PipeRows(R)}$$

From the paired row distribution line, the individual raceway electrical line will run to the air blowers and along the top of the concrete block dividers to supply power to the actuated shutoff valves and the paddlewheels. The formula for calculating individual raceway electrical line is as follows:

$$Q_{IREL} = Q_{Raceways} * \left(\left(SBP / 2\right) + L_{EndAnchor} + \left(Slope * D_{Pond}\right) + \left(\% L_{AirPipe} * L_{Pond}\right)\right)$$

The total quantity of electrical line is calculated using the equation as follows:

$$Q_{EL} = \sum \left(Q_{CDL}, Q_{PRDL}, Q_{IREL} \right)$$

Where: Q_{CDL} is the number of feet needed for the central distribution line; Q_{PRDL} is the number of feet needed for the paired raceway distribution line; and Q_{IREL} is the number of feet needed for the individual raceway electrical line

5.2.1.4.3. Concrete Block Wall Calculations

The use of concrete blocks to divide raceways and create raceway channels may allow less land area and liner to be used and reduce risks associated with liner tearing but it also creates a huge undertaking in laying large quantities of concrete blocks. The concrete blocks will serve three purposes: to divide the raceways from one another (dividing walls); to divide the raceway into channels to allow the microalgae culture to maintain a continuous flow (center walls); and to serve as platforms for paddlewheels and injection pipes. It should be noted that the author did consider trying to pour concrete barriers but felt the liner could not withstand the activity and weight. It was also considered to employ used concrete highway barriers as dividers but cost and availability were determined to be prohibitive.

The total number of concrete blocks is dependent not only on the size of the facility in acre feet but also the length and depth of the ponds and raceways and the size of the concrete blocks. Once concrete block dimensions have been inputted, the model will calculate how many blocks tall both the dividing and center walls and the platforms must be. The model determines the number of blocks necessary for each pond and then multiplies that estimate by the total number of ponds to find the total number of blocks necessary for the entire facility. The number of blocks for the dividing wall is calculated using the following formula:

$$Q_{BlocksDW} = \frac{(Q_{Raceways/Pond} - 1) * L_{Raceway}}{L_{Block}} * H_{\#Blocks}$$

Where: $H_{\#Blocks}$ refers to the height of the wall in number of blocks

The number of number of blocks for the center wall is calculated in a similar fashion, employing this formula:

$$Q_{BlocksCW} = \frac{Q_{Raceways/Pond} * \%L_{CenterWall} * L_{Raceway}}{L_{Block}} * H_{\#Blocks}$$

The platforms are up to the design of the decision maker but once a design is chosen, the following formula is used to calculate the number of blocks necessary for the paddlewheel platforms for each pond:

$$Q_{BlocksPlatform} = L_{\#Blocks} * W_{\#Blocks} * H_{\#Blocks} * Q_{Walls} * Q_{PW/Raceway}$$

Where: Q_{Walls} is the number of walls and $Q_{PW/Raceway}$ is the number of paddlewheels per raceway

It should be noted that the number of walls represents the total number of walls, both dividing and center.

The model sums the total number of blocks per pond, using the following formula:

$$Q_{Blocks/Pond} = \sum \left(Q_{BlocksDW}, Q_{BlocksCW}, Q_{BlocksPlatform} \right)$$

Where: $Q_{BlocksDW}$ is the number of blocks needed per pond for the dividing walls; $Q_{BlocksCW}$ is the number of blocks needed per pond for the center walls; and $Q_{BlocksPlatform}$ is the number of blocks needed per pond for the paddlewheel platforms

The model then calculates the total number of blocks necessary for the facility, using the following formula:

$$Q_{Blocks} = Q_{Blocks/Pond} * Q_{Ponds}$$

Where: $Q_{Blocks/Pond}$ is the number of blocks required for an individual pond

After the total number of blocks necessary is determined, the model will calculate how many days will be needed to lay/stack the concrete blocks using this formula:

$$Q_{DaysBlocks} = \frac{Q_{Blocks/Worker/Day} * Q_{Workers}}{Q_{Blocks}}$$

Where: $Q_{Blocks/Worker/Day}$ is the number of blocks a worker can stack per day; $Q_{Workers}$ is the number of workers stacking blocks; and Q_{Blocks} is the total number of blocks for the facility

Assuming an eight-hour work day five days per week, the model calculates a total cost of laying/stacking all the blocks based on the hourly wage for those workers, which occurs in the fixed costs section.

5.2.1.4.4. Water Storage Tank Calculations

The massive water requirements for the facility make water storage ponds an absolute necessity for a microalgae facility. The model assumes one storage pond is located on one side of the facility in between two rows of ponds. In order to minimize cost, the model is set up to use the unrounded number of rows of pipe to determine water storage pond design. If there are an odd number of rows of ponds, there will be full size ponds for each pair of rows and then a half size pond for the single row.

The depth of the water storage ponds and the depth of the water stored in the ponds are design inputs left up to the decision maker. Once those have been determined, based on the annual water demands lookup table, the model automatically determines how much water the ponds must be able to store and what the dimensions of the storage ponds must be. This is another case where the model minimizes the amount of soil to be removed based on the same formulas as the pond soil removal minimization concept. This calculator also uses Goal Seek and must be reconfigured every time the storage pond dimensions are altered. The annual water demands lookup table is the result of annual water usage simulations for three different locations. The simulations take into account the following to generate a net evaporation estimate: harvest water losses, evaporation losses, and gains from rainfall. The values in the table represent the upper end of annual water losses, meaning that even in the worst case scenarios, the water storage ponds will have sufficient storage capacity to replenish the microalgae ponds. The water storage ponds are set up to store enough replacement water for two days of facility operation.

Based on the annual water demands and the capacity of each of the water wells, a VLOOKUP table was built to assign the number of wells necessary for the various sizes of microalgae facilities. The VLOOKUP table will be used later on in the model to assign the correct number of water wells and pumps for both the fixed cost component of the model in addition to variable costs associated with operating the wells and pumps on a daily basis.

<u>5.2.1.4.5. Paddlewheel Motor Sizing</u>

The paddlewheel motors are sized based on the formula from the Green, Lundquist, and Owsald literature. The formulas for estimating the quantity of power in Watts is set up in a series of equations in this section of the model. Since the formulas have already been stated in the literature, they will not be repeated in this chapter. However, it is necessary to convert the power in watts to a horsepower estimate, which is completed using the following formula:

$$HP_{PW.Motor} = \frac{P_{Watts}}{1000} * kW / HP$$

Where: P_{Watts} is the power in Watts required to overcome head losses and kW/HP is the number of kilowatts per horsepower

It should be noted that the necessary motor size is automatically rounded up to the nearest half or full horsepower because motors are not built in standard increments, such as 1/2, 1, or 1 1/2 horsepower. The rounding up is completed using a VLOOKUP table.

<u>5.2.1.4.6. Wind Turbines Required</u>

A VLOOKUP table to determine the necessary number of wind turbines for the various sizes of microalgae facilities was built based on the annual energy demands for the facilities and the annual energy output of the wind turbines. The following formula was used to determine that estimate:

$$Q_{Turbines} = ROUNDUP\left(\frac{Q_{Ann.kWhDem.}}{Q_{Ann.kWhProd/Turbine}}\right)$$

Where: $Q_{Ann.kWhDem}$ refers to annual energy demand for the facility and

$Q_{Ann.kWhProd/Turbine}$ refers to the annual energy production per turbine

$Q_{Turbines}$ was simulated across all the different size possibilities of the facility to determine the maximum number of turbines that should be installed to power the facility. The number of turbines for each location and each facility size was inputted into the VLOOKUP table, which will serve as a reference point for the number of turbines required when calculating fixed costs.

5.2.1.4.7. Nutrient Costs

Nutrient cost information was very difficult to obtain because the nutrient mixtures are guarded very heavily by people within the industry. This model bases the annual nutrient costs using an annual nutrient cost estimate from a microalgae facility currently in operation. Although it is not ideal, it was the best estimate that was obtainable. However, this annual nutrient cost estimate is for a ¼ acre foot of water microalgae raceway, meaning that it will have to be scaled up to make it comparable to the ponds designed in this model. The formula for the scalar is as follows:

$$Nutrient\ Scalar = \frac{Q_{Ac.Ft.Mod.Pond}}{Q_{Ac.Ft.ActualPond}}$$

Where: $Q_{Ac.Ft.Mod.Pond}$ is the size of the model ponds in acre feet and $Q_{Ac.Ft.ActualPond}$ is the size of the actual ponds (in acre feet) currently in operation

To determine the annual nutrient costs per pond, the nutrient scalar is multiplied by the original nutrient cost estimate. This estimate is based on the assumption that there no more or no less nutrients needed per unit of microalgae culture as the pond is scaled up in size.

5.2.1.4.8. Air Delivery/Carbon Dioxide Calculations

The air delivery/carbon dioxide calculations only apply if air is the source of carbon dioxide because that is the only situation in which blowers will be used in the model. Similar to the nutrient costs section above, estimates of the amount of air blown into the raceways was obtained from someone currently operating such system. However, because the blowers are for individual raceways and not ponds, the following formula is employed:

$$CO_2\,Scalar = \frac{Q_{Ac.Ft./RW}}{Q_{Ac.Ft.ActualRW}}$$

Where: $Q_{Ac.Ft./RW}$ is the size of the raceways in the model (in acre feet) and

$Q_{Ac.Ft.ActualRW}$ is the size of the raceways (in acre feet) currently in operation

The CO_2 scalar is multiplied by the estimate for the amount of air blown into the raceways to determine the amount of air necessary for the raceways in the model.

5.2.1.5. Costs for Facility Inputs Section

As indicated in earlier sections of the model, there are many different inputs necessary to complete construction of the microalgae facility. Based on the inputs that were determined to be necessary through the various stages of model development, primary data from potential suppliers in Texas and the southwestern United States was gathered regarding per unit costs. All of these costs were obtained either through telephone or e-mail communication or from company website. Many of the estimates were in a more general nature because the suppliers found it difficult to provide an exact cost estimate without specific facility design plans. In addition, due to the fluid price nature of some of the materials (specifically land, liner, and pipe costs), the price information may not be exact at the time of publication of this thesis.

Land costs were developed first as land is the first input necessary to start a microalgae facility. Land prices for the three general areas were gathered using a variety of sources. Land prices available from the U.S. Department of Agriculture reflected current farmland prices for a variety of classes of farmland in the three areas. The class of farmland that was used for comparison was flat grassland with below average quality soil. This soil is not able to be used in agricultural production because of the poor quality but offers a great opportunity for microalgae production assuming the land is flat. Other than the slope of the ground, the quality of the land has no bearing on the quality of the facility production because all the microalgae is produced in lined ponds. If unlined ponds were used, the percolation coefficient of the soil would have to be considered when choosing appropriate locations for a facility. The facility would need to be located on land with tighter soils to avoid too much water soaking into the ground. However, such a situation was not addressed in this analysis. The land price estimates were obtained from a variety of realtors and land brokers located in the general vicinity of a potential facility location. The realtors and land brokers contacted for land prices were kept primarily to those who dealt in large, continuous tracts of land in rural areas. Many of the estimates include both low and high cost estimates.

Once the land has been purchased, the next step in facility construction is the formation of the ponds. Because of the precise nature of the pond design (i.e. only remove a few inches of dirt, keeping the floor of the ponds level, and creating specific slopes for the outside edges of the pond), it was not easy to contact companies with such capabilities. The potential for hundreds or even thousands of acres of ponds causes list of companies with such capabilities to be narrowed even further. However, prices per cubic yard of dirt moved were obtained from multiple companies. Companies outside the general location area but within a reasonable distance were contacted as well due to the willingness of companies to move equipment depending on the size and scope of the project.

Upon construction of the ponds, plastic liner must be laid in order to create a barrier between the microalgae culture and the soil. Once again, due to the potentially large nature of the ponds, there were not a large number of companies with such capabilities. However, because the lined ponds are similar to those used in the oil industry, multiple companies did provide cost information. Cost data was collected on a per square foot basis and then extrapolated out into total liner costs. In addition, installation costs were also gathered on a per square foot basis. Prices for both polyethylene and ethylene propylene diene monomer (EPDM) liners in forty mil thickness (forty-millionths of an inch) were collected. As discussed earlier, the liner must extend several feet over the edges of the pond in order to anchor the liner in the ponds.

Upon installation of the liners, the concrete block diving walls, center walls, and paddlewheel platforms must be laid because of the potentially lengthy time period that it could take to lay the blocks, depending on the size of the facility. Two sizes of blocks were priced (dimensions in height by width by length): 4”x 8”x 16” and 8”x 8”x16”. The size of the concrete blocks is determined in the inputs section but that same cell is also tied to the price table so that the model will automatically price the correct size of blocks when the input is chosen. The price data comes from home improvement stores, block companies, and large concrete manufacturers located near potential facilities. Once again, the price is determined by the cost level input.

Depending on the size of the facility, the piping systems could be one of the most difficult aspects of facility construction. The piping systems are vital to maintaining and growing the microalgae in addition to the harvesting and extraction process. Pipe cost information was obtained from seven different pipe companies across Texas and the southwestern U.S. A pipe is priced in either dollars per foot (for pipe) or dollars per unit (for connectors and other specialty pieces). Polyvinyl chloride (PVC) pipe is offered in two main strengths: Schedule 40 and Schedule 80. Schedule 40 is not as heavy duty as Schedule 80 but tends to be cheaper. Allowing the decision maker to choose what schedule of pipe to use allows him or her to use the design they see as the best fit. Prices for 4", 6", and 8" pipe for both schedules allow the decision maker to choose the size of pipe necessary based on the size of the facility and the flow requirements necessary. In addition to the pipe costs, installation costs for each size and type of pipe were added to the model. The following is a list of the different piping supplies needed for the facility: pipe, couplings, elbows, t-connectors, t-connector reducers, endcaps, cross connectors, and shutoff valves. Although it was difficult to find more than two or three cost estimates for a couple of the piping supplies, all of the cost information is formatted into tables and uses an "If/Then" statement to determine which cost level input from the table to input into a lookup table. The lookup table summarizes all the cost information and sorts it by schedule and size so that it can eventually be inputted into the fixed costs section of the model.

Replacement culture stations will be located near each of the water storage ponds so they may be used in the case of pond contamination. By adding a heavily concentrated algae mixture to the replacement water, the pond could be back in the production cycle as soon as the contaminant is identified and the old microalgal culture is removed. The replacement culture stations consist of fiberglass stock tanks and a trolling motor to circulate the highly concentrated algae. Fiberglass stock tank prices for both 6' and 8' diameter tanks were gathered from farm supply stores and trolling motor prices were gathered from boat supply stores. Based on the diameter of replacement culture tanks input, the model will choose a price for the tanks and trolling motors based on the cost level input.

Costs associated with carbon dioxide delivery system depend upon the source. Air blowers for the air deliver system are included in a table similar to the pipe costs. The blowers are sorted by their capacity (in cubic feet per minute). The size of the motor (in horsepower) associated with each blower is entered in addition to the price. Similar to the piping system, the appropriate blower is chosen based on the cost level input. The associated blower price is inputted into a lookup table where the model will automatically determine which blower to use based on the capacity input from the inputs section. The model also uses an If/Then statement to select the motor size associated with the selected blower. The motor size associated with each individual blower is transposed into the lookup table as well. This information will help determine the energy demand for each blower based on the horsepower of the motor and how often the blower is operational. If flue gas is the source of carbon dioxide, a separate table is set up with a list of the cost of pipeline per mile. This cost will include the cost of buying, installing, and connecting the flue gas pipeline to both the power plant and the microalgae facility.

The other half of the circulation component of the model is a bit more complex. Not only does it require the paddlewheels but it also requires motors to run the paddlewheels and gear reducers to slow down the motor so that the paddlewheel can run at the appropriate speed determined in the inputs section. Paddlewheel prices are based on the cost of the facility building its own paddlewheels and information obtained from a group currently operating a microalgae facility and constructing paddlewheels. Price data for ½, 1, 3, and 5 horsepower motors was gathered based on the suggestion from industry representatives of those motors being the appropriate size for the paddlewheels. A large number of price estimates from a variety of small electric motor manufacturers was gathered along with the RPM associated with each motor. Once the model uses the inputs to determine the correct size of the motor and the correct cost estimate, it will determine the appropriate motor and the RPM associated with that particular motor and input to a lookup table. Based on the motor RPM and the desired paddlewheel RPM from the inputs section, the model will automatically choose the size of gear reducer necessary based on the reduction ratio, which is calculated using the following formula:

$$Reduction\ Ratio = \frac{RPM_{Motor}}{RPM_{Paddlewheel}}$$

Where: RPM_{Motor} is the RPM of the selected paddlewheel motor and

$RPM_{Paddlewheel}$ is the desired RPM of the paddlewheel

Gear reducers for all four sizes of electric motors were priced for a variety of reduction ratios ranging from 45-130. Based on the cost level input, once the reduction ratio is calculated, the model will choose the appropriate gear reducer from another lookup table.

Water well drilling and installation costs are priced on a per foot drilled basis. The pricing estimates are from drillers near potential facility locations for wells with at least 2,000 gallons per minute capacity. Water pumps are also included in the drilling costs. In speaking with these businesses, most stated that their estimates were general price quotes and they could not give an exact estimate without knowing the actual property where the well(s) would be drilled. This could lead to some cost escalation but the cost estimates are the best the drillers could give without knowing more detail. If the water source is something other than groundwater, a separate table with the costs of purchasing, installing, and connecting a water pipeline from the water source to the microalgae facility is included in the model.

Capital costs for bringing power from the current grid location to the microalgae facility were gathered from local power companies and their representatives and from representatives from renewable energy companies. Based on the size of the facility, a lookup table was built to determine the necessary number of miles of transmission and distribution lines in addition to power substation costs. This model uses multiple assumptions: the larger the facility, the more likely it is to be located further away from the grid, meaning it will need more transmission lines and a larger power substation; the smaller facilities will only need distribution lines to connect to the power grid because they will be located more closely to the grid; the south Texas location is more likely to be near a power grid because the area around Corpus Christi is more heavily populated; the west Texas and southeastern New Mexico locations are more likely to be located further away from the power grid because of their more remote location. These assumptions are evidenced by escalating costs and quantities for the transmission and distribution line estimates as well as the power substation costs found in the lookup table. The renewable energy source option comes in the form of wind energy and wind turbines. Cost estimates from for two brands of wind turbines (Northwind and Helix Wind) are based on a cost per kilowatt hour (kWh) of electricity generated. This cost per kWh is based on annual kWh generation estimates based on average annual wind speed data. There are multiple wind speed estimates for each turbine, meaning that higher wind speeds will be a best case scenario (minimum cost per kWh generated) and lower wind speed will be a worst case scenario (maximum cost per kWh generated). There are also estimates for area needed for individual wind turbines in order to help the model calculate additional acreage needed. Maintenance cost estimates were provided for only one of the brands of wind turbines but it does create a variable cost associated with annual kWh electricity consumption by the microalgae facility.

Harvesting and extraction construction and capital costs were obtained on a per gallon basis from a company that is currently building such technology. To determine the total cost for the harvesting and extraction facility, annual production was simulated and the upper end of annual production was multiplied by the cost per gallon of processing capacity to obtain a general cost estimate. This simulation was repeated multiple times to create a table of harvesting and extraction facility costs based on potential facility sizes. It should also be noted that the land area necessary for the harvesting and extraction facilities should be included in the additional facility area needed input in the model inputs section.

On-site storage facilities for both the oil and biomass by-product are priced based on their size. The microalgal oil is assumed to be stored in standard oil tanks and the capacity will be based on the daily production of the facility and the number of days of storage input. Price estimates come from tank companies primarily in Texas and represent a variety of sizes. A lookup table allows the facility to adjust the size of oil storage tank it uses as the size of the facility is altered. The biomass by-product storage barn is assumed to be similar to a commodity storage barn. The size of the barn is determined by this formula:

$$Q_{BarnCapacity} = \frac{Q_{TonsDMP}}{Ft.^2 / Ton\ of\ Meal} * Q_{DaysStorage}$$

Where: $Q_{TonsDMP}$ refers to daily meal production in tons; $Ft.^2/Ton\ of\ Meal$ refers to the area of storage needed for one ton of microalgae meal; and $Q_{DaysStorage}$ refers to the desired number of days of storage

Based on the number of square feet needed, the model uses a lookup table to obtain a per unit input cost, which will be inputted in the fixed costs section. The storage facilities for the outputs should also be included in the additional facility area needed input in the model inputs section.

Once all the sections of the microalgae facility have been constructed, a perimeter fence must be added to keep animals and trespassers away. Based on the wire gauge and fence height inputs and the desired cost level input, the model will determine a cost per foot of fence that will be used in the fixed costs section. The model assumes that the gates will be the same wire gauge and fence height as the fence. Based on that information and the desired cost level input, the model will also assign a cost per gate installed. There is an additional lookup table to determine the number of gates necessary on each side of the facility based on the final dimensions of the facility.

Labor cost estimates for the employment positions of the facility are included in a table as well. The data comes from U.S. Bureau of Labor Statistics (BLS) 2008 studies for both Texas and New Mexico. Although labor costs for some of the specific job titles were unavailable in the BLS studies, comparable jobs and their associated salaries were assigned in the table. Low, medium, and high salaries were assigned to each position in order to address the possibility of hiring employees with different education and experience levels, which could constitute different pay grades. A lookup table developed by the author based off literature and conversations with people within the microalgae industry helps the model determine the necessary number of employees for each position based on the size of the facility.

5.2.1.6. Fixed Costs Section

The previous components of the model (model inputs, model input calculations, raceway calculations, and costs for facility inputs) provide the information necessary to calculate fixed costs for the facility. Once the fixed costs have been verified, the total fixed cost estimate is automatically inputted into a loan calculator to determine annual loan payments based on a given interest rate and loan life.

Land costs for the microalgae facility are determined by calculating the total land area needed and then assigning a cost from the cost input section of the model. There are three or four different sections of the facility (depending on the power source) that creates the need for land: ponds, water storage tanks, operations facilities (harvesting and extraction facilities, maintenance buildings, etc.), and power facilities (in the case of using wind turbines). The acres of land needed for the ponds is calculated using the formula:

$$Q_{LandMA.Ponds} = \frac{L_{Facility} * W_{Facility}}{Ft.^2 / Acre}$$

Where: $L_{Facility}$ is the length of the facility; $W_{Facility}$ is the width of the facility; and $Ft.^2$ /Acre refers to the number of square feet in one acre

The area needed for water storage tanks involves a calculation that assumes the tanks will require land that runs the entire length of the facility and the extra width needed will be the width of the storage ponds added to the distance between the storage ponds and the microalgae ponds. The land area needed for water storage ponds is determined by the formula:

$$Q_{LandWSP} = \frac{L_{Facility} * (W_{WSP} + L_{WSP\&MP})}{Ft.^2 / Acre}$$

Where: W_{WSP} is the width of the water storage ponds

The area need for operations facilities is based on the input that assigns a ratio for the area needed for operations facilities per acre of microalgae ponds. To calculate the area, this formula is employed:

$$Q_{LandFacilities} = \frac{Q_{MA.PondAcres}}{Ratio\,of\, : MA\,Pond\,\,Acres / Acre\,of\,\,Support\,Facilities}$$

Where: $Q_{MA.PondAcres}$ is the total number of acres needed for the microalgae ponds

The formula for calculating land area needed for power facilities only applies if wind turbines are used as the power source. The formula is as follows:

$$Q_{LandPower} = \frac{Q_{Turbines} * Q_{Area/Turbine}}{M^2 / Acre}$$

Where: $Q_{Turbines}$ refers to the number of turbines necessary for the facility; $Q_{Area/Turbine}$ is the area needed for an individual turbine; $M^2/Acre$ is the number of square meters per acre

The square meters conversion is used because the area needed for each turbine is given in square meters. These estimates for land area then totaled and multiplied by a per acre land price (from the cost inputs section) to achieve a total land cost estimate using the following formula:

$$TC_{Land} = \left(\sum\left(Q_{LandMA.Ponds}, Q_{LandWSP}, Q_{LandFacilities}, Q_{LandPower}\right)\right) * \$ / Acre\,of\;Land$$

Where: $Q_{LandMA.Ponds}$ is the land area for the microalgae ponds; $Q_{LandWSP}$ is the land area for the water storage ponds; $Q_{LandFacilities}$ is the land area for the support facilities; and $Q_{LandPower}$ is the land area for the power source (if needed)

Soil removal costs are broken down by their source, soil removal for microalgae ponds and soil removal for water storage ponds. The total amount of soil moved for the microalgae ponds is calculated using the formula:

$$Q_{Tot.SoilMA.Ponds} = Q_{Opt.Soil/MA.Pond} * Q_{Ponds}$$

Where: $Q_{Opt.Soil/Pond}$ is the optimal amount of soil moved for an individual microalgae pond

The soil removed for the water storage ponds is determined by the formula:

$$Q_{Tot.SoilWSP} = Q_{Opt.Soil/WSP} * Q_{Ponds}$$

Where: $Q_{Opt.Soil/WSP}$ is the optimal amount of soil moved for a water storage pond This should be carried out for both the full size and half size water storage ponds and then totaled to get the correct value for the fixed costs section. Total soil moving costs are estimate using the following calculation:

$$TC_{SoilMoved} = \sum \left(Q_{Tot.SoilMA.Ponds}, Q_{Tot.SoilWSP}\right) * \$ / Ft.^3 \, of \; soil$$

Where: $Q_{Tot.SoilMA.Ponds}$ is the total soil moved for the microalgae ponds and

$Q_{Tot.SoilWSP}$ is the total soil moved for the water storage ponds

It should be noted that the cost of moving soil is on a per yard basis, meaning that the cost per cubic foot of soil moved is calculated using this conversion:

$$\$ / Ft.^3 = \frac{\$ / Yd.^3 \, of \; soil}{Ft.^3 / Yd.^3}$$

Where: $Ft.^3$ is cubic feet and $Yd.^3$ is a cubic yard

Liner costs create a complex calculation because the liner has to be laid on the slopes and edges of both the microalgae ponds and the water storage ponds. The liner for the microalgae ponds calculates the area needed for the floor of the pond using the following calculation:

$$A_{FloorLiner} = L_{Pond} * W_{Pond}$$

The area needed for the sloped sides and ends of the pond is calculated using Pythagorean's Theorem to determine the length of the sloped sides and ends (because pond depth and the slope of the berm are known) and the area needed for the corners of the ponds (because the length of the sides and ends are known). The formula used for the sloped berms is:

$$A_{BermLiner} = \left(\sqrt{D_{Pond}^2 + \left(Slope * D_{Pond} \right)^2} \right) * \left(\left(L_{Pond} * Q_{Sides} \right) + \left(W_{Pond} * Q_{Ends} \right) \right)$$

Where: D_{Pond} is the depth of the pond; Q_{Sides} it the number of sides; and Q_{Ends} is the number of ends

The formula used for the corners is as follows:

$$A_{CornerLiner} = \frac{\left(\left(\sqrt{D_{Pond}^2 + \left(Slope * D_{Pond} \right)^2} \right) * \left(D_{Pond} * Slope \right) \right)}{2} * 2 * Q_{Sides} * Q_{Ends}$$

This formula calculates the area of a triangle (length of berm multiplied by length of end and the product divided by two). It is multiplied by two because there are two triangles in each corner. The area needed for the anchors is determined by this formula:

$$A_{AnchorLiner} = \left(\left(L_{Pond} + \left(Q_{Ends} * Slope * D_{Pond} \right) \right) + W_{Anchor} \right) + \left(\left(W_{Pond} + \left(Q_{Sides} * Slope * D_{Pond} \right) \right) * L_{Anchor} \right)$$

Where: W_{Anchor} is the width of the anchor and L_{Anchor} is the length of the anchor

The total liner needed for the microalgae ponds is determined by the formula:

$$Q_{LinerMA.Pond} = \sum \left(A_{FloorLiner}, A_{BermLiner}, A_{CornerLiner}, A_{AnchorLiner} \right) * Q_{Ponds}$$

Where: $A_{FloorLiner}$ refers to the liner needed for the floor of a pond; $A_{BermLiner}$ is the liner needed for the berms of a pond; $A_{CornerLiner}$ refers to the liner needed for the corners of a pond; $A_{AnchorLiner}$ is the liner needed for the anchors of a pond

The same process is applied to the water storage ponds, only this time the dimensions for the water storage ponds, both half and full size, are used in the calculations. The total square footage of liner required is determined by the following formula:

$$Q_{Liner} = \sum\left(Q_{LinerMA.Ponds}, Q_{LinerWSP}\right)$$

Where: $Q_{LinerMA.Ponds}$ is the total liner needed for the microalgae ponds and $Q_{LinerWSP}$ is the total liner needed for the water storage ponds

However, that quantity does not reflect the exact amount of liner purchased. Liner must be obtained in full rolls, meaning that the following formula must be used to determine the number of rolls of liner to be purchased:

$$Q_{LinerRolls} = ROUNDUP\left(\frac{Q_{Liner}}{Ft.^2 / Liner\ Roll}\right)$$

Where: Q_{Liner} is the total quantity of liner needed in square feet

Total liner material cost is estimated by the formula:

$$TC_{LinerMat.} = Q_{LinerRolls} * \$ / Roll\ of\ Liner$$

Where: $Q_{LinerRolls}$ is the total number of rolls of liner purchased

The total cost of liner installation is calculated by this formula:

$$TC_{LinerInst.} = Q_{Liner} * \$ / Ft.^2\ of\ liner\ installed$$

It should be noted that the total area of liner purchased is not used in the installation cost calculation because not all the liner purchased will be installed, although it will only make a tiny difference in the overall cost of the facility. The cost of the liner, both material and installation, is determined by the following formula:

$$TC_{Liner} = \sum \left(TC_{LinerMat.}, TC_{LinerInst.} \right)$$

Where: $TC_{LinerMat.}$ refers to the total liner material cost and $TC_{LinerInst.}$ is the total liner installation cost

Concrete block costs result from two sources: material costs and block laying costs. The formula for materials cost is as follows:

$$TC_{BlockMat.} = Q_{Blocks} * \$ / Block$$

To determine the total cost of laying blocks, the following formula is employed:

$$TC_{BlockInst.} = Wages\left(\$ / hour\right) * Q_{Hours/Day} * Q_{Workers} * Q_{Days}$$

Where: $Q_{Hours/Day}$ refers to the number of hours worked per day; $Q_{Workers}$ is the number of workers per day; and Q_{Days} is the number of days necessary to complete the block laying

If the decision maker is interested in a per unit cost, it can be calculated using the formula:

$$\$ / Block = \frac{TC_{BlockInst.}}{Q_{Blocks}}$$

Where: $TC_{BlockInst.}$ refers to the total block installation (laying) cost

Total concrete block costs are determined by the following formula:

$$TC_{Blocks} = \sum \left(TC_{BlockMat.}, TC_{BlockInst.} \right)$$

Where: $TC_{BlockMat.}$ refers to the total block materials cost

Paddlewheel costs are dependent on two factors: the total number of raceways and the number of paddlewheels per raceway. The formula for calculating the number of paddlewheels, paddlewheel motors, and gear reducers to be purchased this formula:

$$Q_{Paddlewheels} = Q_{PW.Motors} = Q_{GearRed.} = Q_{Ponds} * Q_{Raceways/Pond} * Q_{PW/Raceway}$$

Where: $Q_{PW/Raceway}$ refers to the number of paddlewheels needed per raceway

Paddlewheel costs are determined by the formula:

$$TC_{Paddlewheels} = Q_{Paddlewheels} * \$/Paddlewheel$$

Where: $Q_{Paddlewheels}$ is the total number of paddlewheels for the facility

Paddlewheel motor costs are determined by the formula:

$$TC_{PW.Motors} = Q_{PW.Motors} * \$/Motor$$

Paddlewheel gear reducer costs are determined by the formula:

$$Q_{GearRed.} * \$/Gear\ Reducers$$

Total circulation costs from paddlewheels for the facility are calculated by the following formula:

$$TC_{Circ.-PW.} = \sum(TC_{Paddlewheels}, TC_{PW.Motors}, TC_{GearRed.})$$

Where: $TC_{Paddlewheels}$ is the total cost for the paddlewheels; $TC_{PW.Motors}$ is the total cost for the paddlewheel motors; and $TC_{GearRed.}$ is the total cost for paddlewheel gear reducers

Total costs for the other form of circulation, carbon dioxide, are given by formulas below. If air is the source of the carbon dioxide, the formula is:

$$TC_{Circ.-CO2} = (IF(CO_2 = Air, (Q_{Raceways} * \$/Air\ Blower), IF(CO_2 = Flue\,Gas, 0)))$$

If the CO2 source is flue gas, the formula is as shown below:

$$TC_{Circ.-CO2} = \left(IF\left(CO_2 = Flue\,Gas, \left(L_{CO2Pipeline} * \$ / Mile\right), IF\left(CO_2 = Air, 0\right)\right)\right)$$

Where: $L_{CO2Pipeline}$ is the length of the flue gas pipeline in miles and \$/Mile is the cost of the pipeline in dollars per mile

Total circulation costs for the facility are represented by this formula:

$$TC_{Circ.} = \sum\left(TC_{Circ.-PW.}, TC_{Circ.-CO2}\right)$$

Where: $TC_{Circ.-PW.}$ refers to total paddlewheel costs and $TC_{Circ.-CO2}$ is the total carbon dioxide equipment cost for the facility

The piping system fixed costs are broken down into the three individual systems: water and nutrients, air delivery, and harvesting and extraction. Unfortunately, there are no summary functions in Simetar where it will automatically sum a series of cells (i.e. sum all the 8" pipe cells or all the 8" couplings) based on the text or values within multiple cells. Therefore, it is up to the modeler to sum all the like piping materials for each system based on the schedule of the pipe and the diameter of the pipe. Once the total quantity of materials have been determined, the per unit cost is determined using a VLOOKUP formula that identifies the correct price from the lookup table in the cost inputs section based on the schedule and diameter of the pipe and the column of the table in which the per unit price for the specific material is located. This task is completed for all three piping systems and the lookup formulas are programmed for each specific piping material across the piping systems. The cost for each of the materials is determined by this formula:

$$TC_{PipeMat.} = Q_{PipeMaterial} * \$ / Unit\ of\ Material$$

Where: $Q_{PipeMaterial}$ is the total quantity of each material needed, in feet or number

This formula is applied to the following materials: pipe, couplings, cross connectors, t-connectors, t-connector reducers, elbows, endcaps, and shutoff valves. Total cost for each piping system is calculated using the following formula:

$$TC_{PipeSystem} = \sum \begin{pmatrix} TC_{Pipe}, TC_{X-Conn.}, TC_{T-Conn.}, TC_{T-Conn.Red.}, \\ TC_{Elbows}, TC_{Endcaps}, TC_{S.Valves}, TC_{Couplings} \end{pmatrix}$$

Where: TC_{Pipe} is total pipe costs; $TC_{X\text{-}Conn.}$ is the total cross connector costs; $TC_{T\text{-}Conn.}$ is total t-connector costs; $TC_{T\text{-}Conn.Red.}$ is total t-connector reducer costs; TC_{Elbows} is total elbow costs; $TC_{Endcaps}$ is total endcap costs; $TC_{S.Valves}$ is total shutoff valve costs; $TC_{Couplings}$ is total couplings costs

Total pipe costs for the facility are estimated using this formula:

$$TC_{Pipe} = \sum \left(TC_{Water/Nut.Pipe}, TC_{Harv.Pipe}, TC_{AirPipe} \right)$$

Where: $TC_{Water/Nut.Pipe}$ refers to the total cost for the water and nutrients piping system; $TC_{Harv.Pipe}$ refers to the total cost for the harvesting and extraction piping system; and $TC_{AirPipe}$ refers to the total cost for the air delivery piping system

It should be noted that pipe installation costs are included with the per unit costs estimates so there is no need for a separate installation cost calculation.

The total cost estimate for each piping system is compared to a cost estimate from the raceway calculations section (which also uses a VLOOKUP formula to determine unit costs) to make sure the two estimates are equal. A check cell will read “Yes” if the estimates are equal, meaning that there are no mistakes in the calculations. If the check cell reads “No”, mistakes have been made and the figures should be double-checked to determine and correct the source of the mistake.

Cost estimates for the microalgae replacement culture stations are composed of two components: tank costs and mixing mechanism costs. Tank costs are calculated by the formula:

$$TC_{MA.Rep.Tanks} = Q_{MA.C.R.S.} * Q_{Tanks/Station} * \$/\,Fiberglass\ Tank$$

Where: $Q_{MA.C.R.S.}$ is the number of microalgae culture replacement stations and $Q_{Tanks/Station}$ is the number of fiberglass tanks per station

The formula for determining total mixing mechanism costs is as follows:

$$TC_{MixMech.} = Q_{Tanks} * \$/\,Mixing\ Mechanism$$

Where: Q_{Tanks} is the total number of fiberglass tanks used for the station

It should be noted that the model assumes one mixing mechanism per tank, as implied by the number of tanks being equal to the number of mixing mechanisms. The total cost for the microalgae replacement culture stations is estimated by the formula:

$$TC_{MA.C.R.S.} = \sum \left(TC_{MA.Rep.Tanks}, TC_{MixMech.}\right)$$

Where: $TC_{MA.Rep.Tanks}$ refers to the total cost of the tanks and $TC_{MixMech.}$ is the total cost for the mixing mechanisms

The costs associated with the water equipment are dependent upon the use of recycled water for the facility. If no recycled water is used (i.e. water source is only the groundwater), water wells and pumps are all that are necessary. Water well and pump costs are dependent on the number of water wells and the depth of the individual wells. The formula for estimating water well and pump costs is as follows:

$$TC_{Wells} = Q_{WaterWells} * D_{Well} * \$ / Ft.Drilled$$

Where: $Q_{WaterWells}$ is the number of water wells in the facility and D_{Well} is the depth of the well in feet

However, if recycled water is used to recharge the ponds, the model will also calculate a cost for purchasing, installing, and connecting a water pipeline to the facility. This water pipeline is primarily associated with the use of water from city wastewater and wastewater from food processing facilities. The formula for estimate water pipeline costs is as follows;

$$TC_{WaterPipeline} = IF\left(Water = Food / City, \left(Q_{WaterPipeline} * \$ / Mile\right), 0\right)$$

Where: *Water* is the source of the recycled water, *Food/City* represents using city wastewater and wastewater from food processing facilities, $Q_{WaterPipeline}$ is the length of the water pipeline in miles, and *\$/Mile* is the cost of the pipeline in dollars per mile

Total water equipment costs are defined by the following formula:

$$TC_{WaterEquip.} = \sum\left(TC_{Wells}, TC_{WaterPipeline}\right)$$

Where: TC_{Wells} is the total cost for water wells and pumps and $TC_{WaterPipeline}$ is the total cost for the water pipeline (if needed)

The necessary capacity of the storage facilities for the microalgae oil and the biomass by-products are determined using a VLOOKUP formula that is based on the size of the facility (in acre feet of water) and the number of days of storage input from the model inputs section. Based on the total capacity needed, the model will determine the number of facilities (tanks in the case of the microalgae oil and commodity barns in the case of the biomass by-product) needed to store the products in even the most productive circumstances. It should also be noted that if the end-use of the microalgae by-product is energy rather than sales as a feed supplement, minimal by-product storage will be necessary because it will all be converted to energy. The formula for estimating the number facilities necessary is shown below:

$$Q_{Barns} = IF\left(BPUse = Sales, \left(\frac{Q_{Sq.Ft.Stor.Needed}}{Q_{Sq.Ft./Barn}} \right), 1 \right)$$

Where: *BPUse* refers to the end use of the algae by-product, *Sales* represents the use of the by-product as a revenue source, $Q_{Sq.Ft.Stor.Needed}$ is the total storage area needed for the algae by-product in square feet, and $Q_{Sq.Ft./Barn}$ refers to the size of each barn in square feet

It should be noted that even if the by-product is not used for sales, one storage facility is still included for any excess storage while using the by-product as an energy source. Once the number of facilities has been determined, there are two formulas for calculating storage facility costs. The formula for estimating barn costs is:

$$TC_{MealStorage} = Q_{Sq.Ft./Barn} * Q_{Barns} * \$ / Ft.^2\ of\ Construction$$

Where: Q_{Barns} is the number of storage barns in the facility

The formula for estimating oil tank costs is as follows:

$$TC_{OilStorage} = \frac{Q_{Gal.Ann.Prod.}}{Q_{Gal.Stor./Tank}} * \$ / Storage\,Tank$$

Where: $Q_{Gal.Ann.Prod}$ is the annual oil production for the facility in gallons and $Q_{Gal.Stor./Tank}$ refers to the storage capacity of an individual tank in gallons

Total facility product storage costs are calculated by the equation:

$$TC_{Storage} = \sum\left(TC_{OilStorage}, TC_{MealStorage}\right)$$

Where: $TC_{OilStorage}$ refers to the total oil storage facility costs and $TC_{MealStorage}$ refers to the total meal storage facility costs

Based on the decision maker's choice of the power source for the facility, the model will automatically calculate the necessary facilities to supply enough energy to the facility. In the case of using wind energy, the model calculates the number of turbines necessary by referencing the VLOOKUP table in Raceway Calculations section of the model. The formula is simulated to determine the maximum number of wind turbines needed for each location across a variety of facility sizes. The formula is as follows:

$$Q_{Turbines} = ROUNDUP\left(\frac{Q_{Ann.kWhDem.}}{Q_{Ann.kWhProd\,/\,Turbine}}\right)$$

Initial costs for the wind turbines are determined by the formula:

$$IC_{Turbines} = Q_{Turbines} * \$ / Turbine$$

Where: $Q_{Turbines}$ refers to the total number of turbines at the facility

The initial cost is reduced via the government incentives rebate that the federal government currently has for renewable energy facilities. To determine the value of the government rebate, the following formula is used:

$$Government\ Rebate(\$) = IC_{Turbines} * Government\ Rebate\ Rate(\%)$$

Where: $IC_{Turbines}$ is the initial cost for the wind turbines

The total cost of the wind turbines is then estimated by the formula:

$$TC_{Turbines} = IC_{Turbines} - Government\ Rebate(\$)$$

Additional costs are assigned for a substation, transformers, and distribution lines in order to get the power from the wind turbines to the facility. These costs, except for the transformers, are assigned from a power generation lookup table in the cost inputs section using a VLOOKUP formula based on the number of acre feet of water in the facility. The transformer cost is assigned based on annual energy demand and the capacity of an individual transformer. If the microalgae by-product is instead the source of the renewable energy for the facility, the model determines the size of the power facility needed (in megawatts) based on another VLOOKUP table. Total costs associated with using by-products as the energy source are calculated using the equation below:

$$TC_{BPEnergy} = Q_{MWPlant} * \$ / MW$$

Where: $Q_{MWPlant}$ is the size of the power facility in megawatts and *$/MW* is the cost of the power facility in dollars per megawatt of capacity

Total costs for renewable energy are determined by the following equation:

$$TC_{Renew.Energy} = \sum \left(TC_{Turbines}\ or\ TC_{BPEnergy}, TC_{Substation}, TC_{Transformers}, TC_{Dist.Lines} \right)$$

Where: $TC_{Turbines}$ is the total cost for the wind turbines; $TC_{BPEnergy}$ is the total cost for the power facilities for using algae by-products as an energy source; $TC_{Substation}$ is the total cost for a substation; $TC_{Transformers}$ refers to the total cost for transformers; and $TC_{Dist.Lines}$ refers to the total cost for distribution lines

It should be noted that an If/Then statement is used to determine whether wind or by-products are used as a source of energy. The If/Then statement is based off inputs from the scenario section of the model.

The conventional power source costs (except substations) are determined in a similar fashion, using VLOOKUP formulas also based on the size of the facility in acre feet of water to determine the quantity of materials necessary. The lookup table to which the formula refers is found in the cost inputs section. Costs for the power materials, which include transmission lines, distribution lines, and transformers, are calculated by the following formula:

$$TC_{Trans.Lines} = TC_{Substation} = TC_{Transformers} = TC_{Dist.Lines} = Q_{PowerMaterials} * \$ / Unit\ of\ Material$$

Where: $Q_{PowerMaterials}$ refers to the quantity of each of the materials needed

Costs for a substation are assigned solely based on a value from the VLOOKUP table. Once the cost for each of the materials has been determined, this formula is applied to determine total conventional energy fixed costs:

$$TC_{Conv.Energy} = \sum \left(TC_{Trans.Lines}, TC_{Substation}, TC_{Transformers}, TC_{Dist.Lines} \right)$$

Where: $TC_{Trans.Lines}$ refers to the total cost of transmission lines

The number of feet of electrical line is partially dependent on the source of energy for the facility, depending on the location from which the power enters the facility as discussed earlier. The formula for determining total electrical line cost is:

$$TC_{EL} = Q_{EL} * \$ / Ft.of\ Electrical\ Line$$

Where: Q_{EL} is the total quantity of electrical line needed for the facility

It should be noted that installation costs for the electrical line are included in the per unit price so a separate calculation for installation costs is not necessary. Total costs for the equipment and materials to supply energy to the facility are estimated by the following formula:

$$TC_{Energy} = (TC_{Renew.Energy} \; or \; TC_{Conv.Energy}) + TC_{EL}$$

Where: $TC_{Renew.Energy}$ refers to the total cost for the equipment and materials for renewable energy (wind or by-products); $TC_{Conv.\,Energy}$ refers to the total cost for equipment and materials for conventional energy; and TC_{EL} is the total cost for the electrical line

The harvesting and extraction facility capital cost is determined using a VLOOKUP formula based on the size of the facility in acre feet of water. The table from which cost information is retrieved is located in the cost inputs section. The cost is based on a per gallon harvest and extraction cost and the maximum annual production for a range of facility sizes.

Once all of the fixed costs have been calculated, they are cell referenced to a table at the end of the section so that the decision maker may look at the fixed costs collectively. The total fixed costs are estimated using the following formula:

$$TFC_{Facility} = \sum \begin{pmatrix} TC_{Land}, TC_{SoilMoved}, TC_{Liner}, TC_{Blocks}, TC_{Circ.}, TC_{Pipe}, \\ TC_{MA.C.R.S.}, TC_{WaterEquip}, TC_{Storage}, TC_{Energy}, TC_{H\&E} \end{pmatrix}$$

Where: TC_{Land} refers to total land costs; $TC_{SoilMoved}$ refers to total soil moving costs; TC_{Liner} refers to total liner costs; TC_{Blocks} is total concrete block costs; $TC_{Circ.}$ refers to total circulation costs; TC_{Pipe} is total pipe costs; $TC_{MA.C.R.S.}$ is total microalgae culture replacement station cots; $TC_{WaterEquip}$ refers to total water equipment costs; $TC_{Storage}$ refers to total product storage facility costs; TC_{Energy} is total costs for the equipment to supply energy to the facility, whether it is from renewable energy (wind) or conventional energy; and $TC_{H\&E}$ refers to total harvesting and extraction equipment costs

After the fixed costs are totaled, amount of the loan is determined by the following formula:

$$\$_{Loan} = TFC_{Facility} * (1 - \%Equity)$$

Where: $TFC_{Facility}$ is the total fixed cost for the facility and $\%Equity$ is the percent equity the facility must have to acquire a loan

The model assumes that the rest of the capital costs must come from some other sources of equity. The loan estimate is inputted into a loan calculator in the financials segment of the model to determine annual loan payments based on a given life of the loan and given interest rate.

5.2.2. Stochastic Forecasts

The model is set up to forecast the profitability/viability of a microalgae facility over a ten-year horizon. This creates the need to forecast inflation for a variety of variable cost inputs, interest rates, and output prices (which will be addressed later). In addition to inflation forecasts, there is also a need for weather forecasts because some of the variable costs are dependent on weather conditions (i.e. rainfall and evaporation). Creating accurate forecasts for these variable costs is important in building a model that can make accurate forecasts of profitability/viability.

5.2.2.1. Stochastic Weather Forecasts Segment

Based on the locations discussed earlier, precipitation and evaporation data from the nearest National Weather Service station was collected back as far as 1950. The data, which comes from the National Climate Data Center (1950-2008), was given on a monthly basis and an annual basis (when there were data points for all twelve months). Several of the years had a month or two missing from the data set. This problem was fixed by using seasonally-adjusted historical averages to represent monthly weather totals. Although this may not be the best method to fill in missing data points, this is the best data available for the model. It should also be noted that the weather station locations change throughout the sixty years of data. Some of the older stations were eliminated or phased out over time, therefore making it difficult to construct a continuous data set. The location next nearest to a potential microalgae facility site was used when sufficient data was no longer available from the previous site. In particular, this problem was most prevalent in the data for the southeastern New Mexico region.

The historical data were used to create forecasts assuming an empirical distribution, as discussed in the Chapter IV. A correlation matrix was created across all locations, correlating precipitation and rainfall. From the correlation matrix, correlated uniform standard deviates (CUSDs) and y-hats (deterministic forecasts) were created for each of the six variables (precipitation and evaporation for each of the three locations) across the ten-year horizon. The historical data showed no significant trend on four of the six variables, meaning the parameters would be estimated using an empirical distribution with percent deviations from mean. The y-hats were represented as the historical means of each of the variables. Using an empirical distribution, sorted deviations from mean and the associated probabilities were created for each location. Based on those percent deviations from mean and their associated probabilities, the y-hats (deterministic forecasts based on historical means), and the CUSDs, a forecast for precipitation and evaporation for each of the next ten years was created for each potential location. These forecasts will eventually be inputted into the variable costs section in order to determine how much replacement water will be needed to be pumped from the ground. Based on the pumping demands for water, a forecast of annual water pumping costs will be created. The model is set up to use the appropriate weather data from the respective locations based on the facility location input from the scenario section of the model.

The estimate for annual hours of daylight is calculated from data for the U.S. Naval Observatory. The U.S. Naval Observatory offers annual tables with daily sunrise and sunset schedules for any location. Those annual tables for each location were obtained and the daily hours and minutes of sunlight for a year were calculated by hand. Once the daily hours had been calculated, they were aggregated into monthly and annual estimates and eventually into a VLOOKUP table. The model is set up to automatically assign a value for annual daylight hours from the VLOOKUP table based on the facility location chosen in the model inputs section.

5.2.2.2. Stochastic Inflation Forecasts Segment

Forecasted annual inflation rates are needed for a variety of variable costs, including chemicals, electricity rates, labor, maintenance, and nutrients. Cost index data was obtained from the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri. It should be noted that the majority of the index data comes from the U.S. Department of Agriculture (USDA), more specifically the National Agriculture Statistics Service (NASS). The cost index data can be found in the Agricultural Prices Summary, published by NASS annually in July or August for the preceding year. The data only goes from 1995 to 2008 because much of the necessary data does not begin until 1995 and for the sake of forecasting, all the variables need to have a consistent number of data points. The data prior to 1995 is not nearly as specific as the data used in this analysis. Based on the data, annual inflation rates were calculated using the following formula:

$$I_T = \frac{IV_T - IV_{T-1}}{IV_{T-1}}$$

Where: IV_T is the index value for the current year and IV_{T-1} is the index value for the previous year

FAPRI (Westoff and Brown (2010)) also provides forecasts of index values for each of the variables through 2019, which allows the model to calculate forecasted annual inflation rates. Based on the calculated historical inflation rates, a simple regression is estimated. Three of the five variables exhibit trend. The residuals of the regression represent the deviation from historical means (risk). Using an empirical distribution to help estimate parameters, the residuals are sorted and assigned a probability value. In addition, a correlation matrix is estimated across all five of the variables. Based on the correlation matrix, CUSDs are estimated for each of the five variables across the ten-year horizon.

Based on the sorted deviations from trend and the CUSDs, the stochastic portion of the forecasted variables is developed. The stochastic portion is added to (or subtracted from) the deterministic FAPRI forecasted inflation rates to estimate the stochastic inflation rates. This method is employed because it is much easier than creating forecasted index values for the ten-year horizon.

5.2.2.3. Commodity Prices Segment

Microalgae oil and microalgae meal are the two major sources of revenue for the facility. (High value microalgae oil and produced water recycling are two other sources but they are simulated based off a GRKS distribution of input prices because historical data was not available for those particular sources of revenue.) Microalgae oil and meal are considered to be very similar to two oilseed products, soybean oil and soybean meal. It is believed that the microalgae oil will eventually be processed at a biodiesel plant in the same fashion as soybean oil. The protein composition in microalgae meal is similar to soybean meal, which is commonly used in animal feeding rations. Additional potential uses include aquaculture (shrimp and fish) feeding rations. Although more thorough research needs to be completed on including microalgae meal in feeding rations, another reason for locating a facility in Texas or the southwestern U.S. is the proximity to regions with high concentrations of feedlots (Texas and Oklahoma Panhandle and southwestern Kansas) and aquaculture farms (Corpus Christi and Coastal Bend of Texas).

Natural gas inflation rates were not available from the FAPRI forecast so natural gas prices were simulated with the commodity prices rather than inflating current prices based on simulated inflation rates. Using data from the Department of Energy, more specifically the Energy Information Administration's February 2009 Monthly Energy Review, historical natural gas prices were used to create a natural gas price forecast. It should be noted that all of the prices are in dollars per thousand cubic feet. Similar to the inflation rates, a simple regression was run on the historical data to look for trend. Based on the historical data, an empirical distribution was used to estimate sorted percent deviations from the mean of the historical natural gas prices and their assigned probabilities. An empirical forecast for each of the successive years is estimated using the historical mean, the sorted percent deviations from mean, and the assigned probabilities.

The microalgae oil and meal are priced based on soybean oil and meal. Historical data is available for both products in the 2009 Oilseed Yearbooks from the Economic Research Service (ERS) of the USDA. In the Comm. Prices segment of the model, historical data back to 1980 for soybean oil and meal and natural gas are assembled in chronological order and put through a simple regression to look for a trend in the data. Trend is present for two of the three variables at a 90% confidence interval, with the third being present at an 85% confidence interval. Using the historical data, a correlation matrix is developed across the three variables to be used to create CUSDs for the forecasted price data. The y-hats (deterministic price forecasts) for soybean oil and soybean meal come from the most recent Food and Agricultural Policy Research Institute (FAPRI) U.S. Baseline Briefing Book from March 2010. This is the most recent baseline available at the time of this research. The y-hats for natural gas are estimated using a trend regression.

Using the historical data and assuming an empirical distribution, sorted deviations from trend and their associated probabilities are formulated. Using these sorted deviations and their probabilities, the y-hats, and the CUSDs, a stochastic ten-year forecast of annual prices for soybean oil, soybean meal, and natural gas are simulated. These prices will be used to help calculate revenues in the Financials segment of the model and variable costs in the Costs segment of the model. It should also be noted that the simulated soybean oil prices are converted to dollars per short ton (it was originally in cents per pound) for the ease of use in the Financials section.

5.2.2.4. Interest Rates Segment

Interest rates for long-term real estate, non-real estate, and savings accounts were simulated to estimate interest rates for the horizon of the model. Based on FAPRI (Westoff and Brown (2010)), historical interest rate data from 1998 until 2009, a stochastic simulation was built to forecast interest rates for the ten-year horizon of the model. FAPRI (Westoff and Brown (2010)) has projected interest rates for each of the areas as far in the future as 2021. Using the FAPRI forecasts, this model develops simulated interest rates by using the FAPRI forecasts as the deterministic portion of the forecast while an empirical distribution is used to estimate the parameters for the stochastic portion of the forecast, resulting in stochastic interest rates around the FAPRI forecasts incorporating historical risk. This process is completed using the same steps used for simulating prices for soybean oil and meal. The simulated interest rates are added to (or subtracted from) the forecasted FAPRI interest rates to determine a stochastic interest rate forecast. The long-term real estate interest rate will be used to discount net worth, which will be discussed later in this chapter. The non-real estate interest rates will represent the operating interest rates used to calculate any operating loan expenses. Savings account interest rates will be used to calculate interest on cash surplus.

5.2.3. Variable Costs Section

The variable costs for this model represent the daily inputs required to help keep the microalgae growing and the facility operating. Variable costs include electricity, natural gas, chemicals, labor, maintenance, nutrients, and water. Each of these variable costs is tied to their respective stochastic inflation estimate in order to reflect the rising costs expected over the ten-year horizon of this analysis. The variable costs are tied to the size of the facility, evidenced by the fact that as the size of the facility grows, each of the variable costs grows as well.

Electricity costs represent a large portion of costs in that electricity is required to run the paddlewheels, blowers, water pumps, harvesting pumps, and harvesting and extraction equipment. Electricity consumption for the circulation equipment (paddlewheels and blowers) is partially based on the circulation schedule chosen in the inputs section (continuous air and paddlewheels during the day or vice versa) and partially based on the size of the motors running each of the blowers or paddlewheels. It should be noted that annual energy consumption for circulation will remain fairly constant over the ten-year horizon of the model. However, because of leap year and slight variations in annual hours of daylight, a schedule of annual average hours of daylight for each location was composed and then broken down to a daily basis. This ensures complete accuracy. The total annual hours of daylight were determined in another worksheet and then compiled into a VLOOKUP formula that assigns the proper daylight hour values based on location. Annual energy consumption by the paddlewheels is determined by this formula:

$$Q_{kWhPW} = HP_{PW.Motor} * kWh / HP * Q_{Ann.Hrs.Operation} * Q_{Paddlewheels}$$

Where: $HP_{PW.Motor}$ is the horsepower of the paddlewheel motor; kWh/HP is the number of kilowatt hours per horsepower; and $Q_{Ann.Hrs.Operation}$ is the number of annual hours of operation

Annual energy consumption by the air blowers is determined by the following formula:

$$Q_{kWhAB} = HP_{AB.Motor} * kWh / HP * Q_{Ann.Hrs.Operation} * Q_{AirBlowers}$$

Where: $HP_{AB.Motor}$ is the horsepower of the air blower motor and $Q_{AirBlowers}$ is the total number of blowers

The total annual electricity consumption for the circulation equipment is kept constant for the ten-year horizon and is determined by the formula below:

$$Q_{kWhCons.Circ.} = \sum \left(Q_{kWhPW}, Q_{kWhAB} \right)$$

Where: Q_{kWhPW} is the annual energy consumption by the paddlewheels and Q_{kWhAB} is the annual energy consumption by the air blowers

Electricity demand from water pumps is tied to the annual water loss for the facility. The model is set up to calculate energy consumption by determining the average number of hours of use per day based on annual water loss and the overall pumping capacity of the facility. The annual water loss is based off the stochastic weather simulations of both evaporation and rainfall. Once the annual estimate for evaporation and rainfall is calculated, the model converts those values into daily estimates in both inches and feet of water. The formula for calculating daily water evaporation in inches is:

$$Q_{In.Evap/Day} = \frac{Q_{In.Evap/Yr.}}{365}$$

Where: $Q_{In.Evap/Yr.}$ is the annual evaporation in inches for a particular location

The formula for calculating daily water evaporation in feet is:

$$Q_{Ft.Evap/Day} = \frac{Q_{In.Evap/Day}}{12}$$

Where: $Q_{In.Evap/Day.}$ is the daily evaporation in inches for a particular location

It is necessary for the daily evaporation estimate to be in feet because of the potential magnitude of the estimate and the ability to convert cubic feet of water to gallons. The formulas for daily precipitation are the same, except evaporation is replaced by precipitation.

Once daily evaporation and precipitation estimates are determined, the model determines evaporation losses and precipitation gains on a per pond and facility-wide basis. Daily evaporation water losses per pond are calculated in gallons using this formula:

$$V_{Evap/Pond/Day(G)} = Q_{Ft.Evap/Day} * A_{WSA} * Gallons\ of\ Water / Ft.^3$$

Where: $Q_{Ft.Evap/Day}$ is the daily evaporation in feet of water and A_{WSA} is the true water surface area

Daily precipitation water gain per pond is calculated in gallons using a similar formula, which is shown below:

$$V_{Precip/Pond/Day(G)} = Q_{Ft.Precip/Day} * A_{WSA} * Gallons\ of\ Water / Ft.^3$$

Where: $Q_{Ft.Precip/Day}$ is the daily precipitation in feet of water

Total daily evaporation for the facility in gallons is estimated using the following formula:

$$V_{WLE/Day(G)} = V_{Evap/Pond/Day(G)} * Q_{Ponds}$$

Where: $V_{Evap/Pond/Day(G)}$ is the daily pond evaporation in gallons

Total daily precipitation for the facility in gallons is determined by this equation:

$$V_{WGP/Day(G)} = V_{Precip/Pond/Day(G)} * Q_{Ponds}$$

Where: $V_{Precip/Pond/Day(G)}$ is the daily pond precipitation in gallons

It should be noted that the model simulates annual evaporation and precipitation estimates and those estimates are broken down into average daily evaporation and precipitation before they are inputted into the Variable Costs section of the model.

Daily water losses to harvest depend upon the harvest water loss input but it also depends upon the amount of the pond harvested each cycle, which will be discussed later in this section, the water recharge schedule, and any water gained from produced water. If water is recharged on a daily basis, the ponds will have a larger water volume at harvest, meaning that more water will be lost. The alternative is to recharge water after harvest, meaning that less water will be lost but the ponds will also not be as full. The literature revealed no research into any effects such a choice could have on production. This model leaves the choice to the decision maker. The model calculates daily water losses due to harvest for both scenarios and uses an If/Then statement to determine which estimate to use based on the choice of the decision maker. If the choice is to recharge water on a daily basis, daily water losses to harvest are calculated using the following formula:

$$V_{WLH/Day(DR)} = Q_{PondsHarv/Day} * \%V_{Mod.PondHarv.} * \%WaterLost\ to\ Harvest * V_{Pond}$$

Where: $Q_{PondsHarv/Day}$ is the number of ponds harvested per day and $\%V_{Mod.PondHarv.}$ is percent of the ponds harvested per cycle

If the choice is to recharge water only after harvest, the model first calculates the volume of the pond at harvesting using this equation:

$$V_{Pond(HR)} = V_{Pond} - \left(Q_{Evap/Pond/Day} * Q_{DaysBTWHarv.}\right)$$

Where: $Q_{DaysBTWHarv.}$ is the number of days between harvest cycles

Daily water losses to harvest under this choice are estimated using the following formula:

$$V_{WLH/Day(HR)} = Q_{PondsHarv/Day} * \%V_{PondHarv.} * \%WaterLost\ to\ Harvest * V_{Pond(HR)}$$

Where: $V_{Pond(HR)}$ is the volume of the pond if the water is recharged only after harvest

The microalgae facility has the potential for financial or physical gain or even both in the form of produced water from oil companies or excess water from food processing companies. Either way, the model will calculate any anticipated water from these sources based on the model inputs. The source of the water does not matter in this section of the model because financial gain is not addressed here. However, the percent of recycled water used for recharge does affect this section of the model. Before the model determines how much water will be replaced by the recycled water, it first determines water loss from both evaporation and harvest using the following formula:

$$V_{WL/Day(G)} = V_{WLE/Day(G)} + V_{WLH/Day(G)}$$

Where: $V_{WLE/Day}$ is the daily volume of water lost to evaporation in gallons and $V_{WLH/Day}$ is the daily volume of water lost to harvest in gallons

The model uses the previous calculation to determine the volume of recycled water used for the facility using this formula:

$$V_{WGRW/Day(G)} = V_{WL/Day(G)} * \%V_{RW}$$

Where: $V_{WL/Day(G)}$ is the daily volume of water lost in gallons and $\%V_{RW}$ is the percent volume of recycled water

Based upon these daily water loss and gain calculations, total daily net water loss is calculated using this formula:

$$V_{NWL/Day(G)} = V_{WL/Day(G)} - \sum\left(V_{WGP/Day(G)}, V_{WGRW/Day(G)}\right)$$

Where: $V_{WGP/Day(G)}$ is the daily volume of water gained from precipitation in gallons and $V_{WGRW/Day(G)}$ is the daily volume of water gained from recycled water in gallons

Based on the daily calculations, annual estimates can be determined by simply multiplying each of the formulas by the number of days of operation annually. Specifically, annual water loss is determined by the formula below:

$$V_{Ann.NWL} = V_{NWL/Day} * Q_{DaysOper.}$$

Where: $V_{NWL/Day(G)}$ is the daily net water loss for the facility and $Q_{DaysOper.}$ is the number of days of operation per year

Once annual net water loss is determined, the model can calculate the average number of hours the water pumps will have to operate on a daily basis using the following formula:

$$Q_{PumpHrs.Oper/Day} = \frac{\left(\frac{V_{Ann.NWL} / \left(Q_{WaterPumps} * V_{PumpGPM} \right)}{Q_{DaysOper.}} \right)}{Minutes / Hour}$$

Where: $V_{Ann.NWL}$ is the annual net water loss in gallons; $Q_{WaterPumps}$ is the number of water pumps for the facility; and $V_{PumpGPM}$ is the volume of the pump in gallons per minute

Total electricity demand from the water pumps can be determined using the following formula:

$$Q_{kWhCons.Water} = Q_{WaterPumps} * Pump\ HP * Q_{PumpHrs.Oper/Day} * Q_{DaysOper.}$$

Where: *Pump HP* is the horsepower of the motor for each pump and $Q_{PumpHrs.Oper/Day}$ is the number of hours of operation per day on average for the water pumps for the year

The electricity consumption resulting from harvesting and extraction does not remain constant. It is based on a kWh consumption constant per ton of microalgae biomass processed from the model inputs section and the total quantity of biomass processed annually, which will be addressed later on in this chapter. The formula for calculating electricity demand from the harvesting and extraction process is as follows:

$$Q_{kWhCons.H\&E} = kWh / Ton\ of\ Biomass\ \Pr ocessed * Q_{Ann.BM.Proc.}$$

Where: $Q_{Ann.BM.Proc.}$ is the annual number of tons of microalgae biomass processed

The three sources of electricity demand can then be combined to determine annual electricity consumption by the facility, using the following formula:

$$Q_{Ann.kWhCons.} = \sum \left(Q_{kWhCons.Circ.}, Q_{kWhCons.Water}, Q_{kWhCons.H\&E} \right)$$

Where: $Q_{kWhCons.Circ.}$ is the annual electricity consumption for microalgae circulation; $Q_{kWhCons.Water.}$ is the annual electricity consumption for water pumping; and $Q_{kWhCons.H\&E}$ is the annual electricity consumption for the harvesting and extraction process

However, because two of the scenarios offer alternatives where the electricity would be produced on site (wind and algae by-products), the model must determine how much energy will be generated from these alternative sources before determining how much energy must be purchased. It should be noted that the following formulas are only employed in the scenarios in which the appropriate renewable fuel source is used. This is carried out using a series of If/Then statements. If algae by-products are the source of renewable energy, the model first determines the annual by-product production from the Production segment of the model. The following formulas are used to determine the energy output from the by-products:

$$Q_{Ann.kWh\Pr od.BP} = \frac{Q_{Ann.MealProd.(E)} * Q_{MealBTU/Lb.} * Joules/BTU}{Joules/kWh}$$

Where: $Q_{Ann.MealProd.(E)}$ is the annual meal production (in pounds) used for energy generation; $Q_{MealBTU/Lb.}$ the energy content of the algae by-product in BTUs per pound; *Joules/BTU* is the conversion factor for the number of joules per BTU; and *Joules/kWh* is the conversion factor for the number of joules per kilowatt hour

On-site energy generation allows the facility to be energy-independent. Based on the energy generation from the wind turbines and the algae by-products, the model estimates the amount of energy to be purchased for the facility on an annual basis using this equation:

$$Q_{Ann.kWhPurch.} = Q_{Ann.kWhCons.} - \left(Q_{Ann.kWhProd.BP} + Q_{Ann.kWhProd.Wind}\right)$$

Where: $Q_{Ann.kWhCons.}$ is the annual energy consumption for the facility in kilowatt hours; $Q_{Ann.kWhProd.BP}$ is the annual energy production from the algae by-products in kilowatt hours; and $Q_{Ann.kWhProd.Wind}$ is the annual energy production from the wind turbines in kilowatt hours

In some situations, the facility will actually generate excess energy. The model determines if any excess energy is generated by the facility from the algae by-products using the equation below:

$$Q_{Exc.Ann.kWhBP} = Q_{Ann.kWhProd.BP} - Q_{Ann.kWhCons.}$$

The model also determines if any excess energy is generated from the wind turbines, if wind turbines are the chosen source of energy. The formula for estimating excess energy generation from wind turbines is shown by the following formula:

$$Q_{Exc.Ann.kWhWind} = \left(Q_{Turbines} * Q_{Ann.kWhGen./Turbine}\right) - Q_{Ann.kWhCons.}$$

Where: $Q_{Ann.kWhGen./Turbine}$ is the annual energy generation per wind turbine in kilowatt hours

Total annual excess energy generated by the facility is estimated using this equation:

$$Q_{Exc.Ann.kWh} = \sum \left(Q_{Exc.Ann.kWhBP}, Q_{Exc.Ann.kWhWind}\right)$$

Where: $Q_{Exc.Ann.kWhBP}$ refers to the excess energy generated from the algae by-products in kilowatt hours and $Q_{Exc.Ann.kWhWind}$ represents the excess energy generated from the wind turbines in kilowatt hours

It is assumed that any excess energy will be sold back a local energy provider. The exact amount of energy sold back is defined by the following formula

$$Q_{Ann.kWhSold} = Q_{Exc.Ann.kWh}$$

Annual electricity inflation rates are transposed from the Stoch Infl segment to escalate costs over the ten-year horizon. The model then uses a series of If/Then statements to determine the initial electricity cost based on the facility location and the source of the electricity. The cost for each successive year in the model is then determined using the formula:

$$\$/kWh_T = \$/kWh_{T-1} * (1 + Annual\ Inflation\ Rate)$$

Where: $\$/kWh_{T-1}$ is the electricity price from the previous year

Total purchased electricity costs can then be determined using the formula below:

$$TVC_{Electricity} = Q_{Ann.kWhPurch.} * \$/kWh_T$$

Where: $Q_{Ann.kWhPurch..}$ is the annual kWh consumption purchased for the facility and $\$/kWh_T$ is the simulated annual electricity price

In the case of the facility selling excess energy back to a local power company, the formula for calculating revenues is shown below:

$$TR_{Electricity} = Q_{Ann.kWhSold} * \$/kWh_T$$

Where: $Q_{Ann.kWhSold}$ is the total amount of energy sold back in kilowatt hours

Natural gas will be used as part of the harvesting and extraction process. Using the Natural Gas Usage per Ton of Biomass Processed constant from the model inputs section, the model calculates natural gas consumption in thousand cubic feet (TCF) by using a series of formulas that convert BTUs of natural gas into thousand cubic feet

(TCF) of natural gas. This conversion is necessary because natural gas is priced in dollars per thousand cubic feet. The series of formulas necessary is as follows:

Annual BTU Consumption:

$$Q_{Ann.BTUCons.} = Q_{Ann.BM.Proc.} * BTU / Ton\ of\ Biomass\ Processed$$

Annual TCF Consumption:

$$Q_{Ann.TCFCons.} = \frac{\left(\dfrac{Q_{Ann.BTUCons.}}{BTU / Ft.^3}\right)}{Ft.^3 / TCF}$$

Where: $Q_{Ann.BTUCons.}$ is the annual natural gas consumption in BTUs

Annual natural gas inflation rates are transposed from the Stoch Infl segment to escalate costs over the ten-year horizon. The model assigns a per unit natural gas cost for the first year based on the input value from the model inputs section. The cost for each successive year in the model is then determined using the formula:

$$\$ / TCF_T = \$ / TCF_{T-1} * (1 + Annual\ Inflation\ Rate)$$

Where: $\$/TCF_{T-1}$ is the natural gas price from the previous year

Total natural gas expenditures can then be determined using the formula below:

$$TVC_{Nat.Gas} = Q_{Ann.TCFCons.} * \$ / TCF_T$$

Where: $Q_{Ann.TCFCons.}$ is the annual natural gas consumption for the facility in thousand cubic feet and $\$/TCF_T$ is the simulated annual natural gas price

Chemicals will be used to help extract the algae from the biomass, although this model does not specify the exact chemicals due to the secretive nature of the extraction process. A chemical cost per ton of biomass processed, which was obtained from the company who's harvesting and extraction technology is used in this analysis, can be found in the model inputs section. To estimate the cost over the ten-year horizon, the original cost is used for the first year of operation and the cost for successive years is determined by inflating that original cost using the stochastic forecast from the Stoch Infl section and the following formula:

$$\$_{Chem} / TBP_T = \$_{Chem} / TBP_{T-1} * (1 + \textit{Annual Inflation Rate})$$

Where: $\$_{Chem}/TBP_{T-1}$ is the cost for chemicals per ton of biomass processed from the previous year

Because the chemical cost is estimated in dollars per ton of biomass processed, total chemical costs are determined using this equation:

$$TVC_{Chem.} = Q_{Ann.BM.Proc.} * \$_{Chem} / TBP_T$$

Where: $\$_{Chem}/TBP_T$ is the simulated annual cost for chemicals per ton of biomass processed

Labor and maintenance for the harvesting and extraction process is separated from the labor for the rest of the facility. Estimates for labor and maintenance costs for the harvesting and extraction process, found in the model inputs section, were provided for the technology which is currently being employed in microalgae facilities. Similar to the other variables involving information from the harvesting and extraction technology company, the original cost is assigned to the first year of operation and costs assigned to successive years employ the following formula:

$$\$_{LaborH\&E} / TBP_T = \$_{LaborH\&E} / TBP_{T-1} * (1 + \textit{Annual Inflation Rate})$$

Where: $\$_{LaborH\&E}/TBP_{T-1}$ is the cost for labor and maintenance for harvesting and extraction per ton of biomass processed from the previous year

The formula for estimating total annual labor and maintenance costs for the harvesting and extraction facility is similar as well, as shown below:

$$TVC_{LaborH\&E} = Q_{Ann.BM.Proc.} * \$_{LaborH\&E} / TBP_T$$

Where: $\$_{LaborH\&E}/TBP_T$ is the simulated annual labor and maintenance cost for harvesting and extraction per ton of biomass processed

It should be noted that this model chooses to separate the labor and maintenance for the harvesting and extraction process because the literature does not provide an estimate as solid as the one obtained regarding the current technology.

Similar to the chemicals used in the harvesting and extraction process, the nutrients used to promote microalgae growth are a closely guarded secret. Therefore, this model assigns a nutrient cost per pond per year, referenced to the estimate from the raceway calculations section of the costs segment. The original cost is applied to the first year of the model and costs for the remaining years of analysis are calculated using this formula:

$$\$ / Pond_T = \$ / Pond_{T-1} * (1 + Annual\ Inflation\ Rate)$$

Where: $\$/Pond_{T-1}$ is the nutrient cost per pond for the previous year

Total nutrient costs are calculated using the following formula:

$$TVC_{Nutrients} = \$ / Pond_T * Q_{Ponds}$$

Where: $\$/Pond_T$ is the simulated annual cost for nutrients per pond

This nutrient cost is a very fluid estimate as most of the industry is still trying to refine their microalgae growth medium to reduce costs while maintaining or improving microalgae productivity levels.

In speaking with individuals currently working within the microalgae industry, one of the most important resources for the facility is its employees. Similar discussions with those individuals along with suggestions from the literature were combined to create the labor requirement tables (found in the input costs section). Based on the size of the facility (in acre feet of water), a VLOOKUP table automatically determines the number of employees for each position the facility will need. Annual labor expenses are for each type of position are determined by the following formula:

$$TAS_{Position} = Q_{Emp./Position} * AS_{Position}$$

Where: $Q_{Emp./Position}$ is the number of employees for each position determined by the VLOOKUP table and $AS_{Position}$ is the annual salary for each position determined by the GRKS salaries simulation

The positions necessary for the facility are: project manager, operations manager, administrative assistant, procurement officer, marketing manager, field operators, aquatic biologist, fisheries biologist, and maintenance workers. Total annual labor expenses are then estimated using this equation:

$$TAS_{Facility} = \sum \begin{pmatrix} TAS_{Proj.Mgr.}, TAS_{Op.Mgr}, TAS_{AA}, TAS_{Proc.}, TAS_{Mkting.}, \\ TAS_{FieldOp.}, TAS_{AB}, TAS_{FB}, TAS_{Maint.} \end{pmatrix}$$

Where: $TAS_{Proj.Mgr.}$ is the total annual salary for the project manager(s); $TAS_{OP.Mgr.}$ is the total annual salary for the operations manager(s); $TAS_{AA.}$ is the total annual salary for the administrative assistant(s); $TAS_{Proc.}$ is the total annual salary for the procurement officer(s); $TAS_{Mkting.}$ is the total annual salary for the marketing manager(s); $TAS_{FieldOp..}$ is the total annual salary for the field operator(s); $TAS_{AB.}$ is the total annual salary for the aquatic biologist(s); $TAS_{FB.}$ is the total annual salary for the fisheries biologist(s); $TAS_{Maint.}$ is the total annual salary for the maintenance worker(s);

However, those annual salaries from the BLS database are in 2008 dollars so they have to be inflated using the stochastic forecast from the Stoch Infl section, in the process creating annual labor expenses for a ten-year horizon, which uses this formula:

$$TVC_{Labor(T)} = TVC_{Labor(T-1)} * \left(1 + Annual\ Inflation\ Rate\right)$$

Where: $TVC_{Labor(T-1)}$ refers to the annual labor expenses from the previous year

It should be noted that the first estimate for the annual labor expense ($TVC_{Labor(T-1)}$) is the total annual salary estimate ($TAS_{Facility}$).

Water costs are associated primarily with the cost of pumping the water. The water section of the model is used to calculate just how much water is lost in both the harvesting and extraction process and to evaporation on an annual basis. It allows the model to observe how much of a difference can be made by using different amounts of produced water instead of pumping groundwater. It also calculates the necessary capacity of the water storage ponds, which was simulated to determine a minimum size the ponds needed to be given a facility size. Those estimates were then inputted into a table in the cost inputs section that eventually is tied to the raceway calculations section which determines the necessary dimensions and the amount of soil to be moved for the water storage ponds.

After calculating each component of the variable cost section of the model, a total variable cost estimate is arrived at using the following formula:

$$TVC_{Facility} = \sum \left(TVC_{Electricity}, TVC_{Nat.Gas}, TVC_{Chem}, TVC_{LaborH\&E}, TVC_{Nutrients}, TVC_{Labor} \right)$$

Where: $TVC_{\ Electricity}$ is the total annual variable cost for electricity; $TVC_{\ Nat.Gas}$ is the total annual variable cost for natural gas; $TVC_{\ Chem}$ refers to the total annual variable cost for chemicals for harvesting and extraction; $TVC_{\ LaborH\&E}$ refers to total annual variable cost for labor and maintenance for harvesting and extraction; $TVC_{\ Nutrients}$ is the total annual variable cost for nutrients; $TVC_{\ Labor}$ is the total annual variable cost for labor

5.2.4. Facility Production Segment

Facility production is primarily dependent on three inputs: microalgae productivity rates, oil content, and the percent of the pond harvested. The production model is developed in steps, starting with simulated daily and annual biomass production and then determining daily and annual biomass harvested. Based on the daily and annual biomass harvested estimates and the simulated oil contents, daily and annual component (oil and biomass by-product) production is estimated. Those results are tied into the Financials segment of the model to determine annual revenues and expenses for the facility.

The production estimates for each year begin by simulating a microalgae production rate using the GRKS parameters of minimum, mid, and maximum from the inputs section. The microalgae production rate is classified in grams per liter of water per day. A Stochastic Learning Curve employs a similar concept, simulating a learning curve for each year using GRKS parameters that increase from their original levels annually by the annual gain in technology input estimate. This allows for a possible general increase each year but considers the possibility of taking steps back on a few occasions. Based on the simulated microalgae production rates and the Stochastic Learning Curve, model microalgae production rates are calculated using this formula:

$$Q_{Mod.MA.Prod(g/L/Day)} = Q_{Sim.MA.Prod(g/L/Day)} * SLC$$

Where: $Q_{Sim.MA.Prod(g/L/Day)}$ is the simulated microalgae production rates in grams per liter per day and *SLC* is the simulated stochastic learning curve

Daily pond production can then be determined using the following equation:

$$Q_{DailyProd/Pond} = \frac{Q_{Mod.MA.Prod(g/L/Day)} * V_{Pond(L)}}{Conversion\,Factor}$$

Where: $Q_{Mod.MA.Prod(g/L/day)}$ is the model microalgae production in grams per liter per day; $V_{Pond(L)}$ is the volume of the individual pond in liters; and *Conversion Factor* is the conversion to convert the estimate into the desired units, whether it is grams per kilogram, grams per pound, grams per ton, etc.

Overall daily facility production is calculated using the formula below:

$$Q_{DailyProd.} = Q_{DailyProd/Pond} * Q_{Ponds}$$

Where: $Q_{DailyProd/Pond}$ is the daily production per pond in the unit desired

Annual facility biomass production can be estimated using the following formula:

$$Q_{Ann.Prod} = Q_{DailyProd.} * Q_{DaysOper.}$$

Where: $Q_{DailyProd.}$ refers to the daily facility production in the unit desired

All of these estimates above are also converted into the desired unit(s) of measurement.

All of the biomass produced is not necessarily harvested because only a portion of the ponds are harvested at a time. Determining the number of ponds harvested each day and the percent of those ponds harvested is a drawn out process. First, the model simulates the number of harvests annually (using a GRKS distribution and the parameters from the model inputs section) and another Stochastic Learning Curve (designed the same as the one previously mentioned for production). Based on the simulate number of harvests annually and the Stochastic Learning Curve, the annual number of harvests is determined using the following formula:

$$Q_{Mod.Ann.Harv} = Q_{Sim.Ann.Harv.} * SLC$$

Where: $Q_{Sim.Ann.Harv.}$ is the simulated number of harvests annually

Based on that estimate, the number of days between harvests is determined by this formula:

$$Q_{DaysBTW.Harv.} = \frac{Q_{Mod.Ann.Harv}}{Q_{DaysOper.}}$$

Where: $Q_{Mod.Ann.Harv.}$ is the model number of harvests annually

The model is able to calculate the number of ponds harvested on a daily basis using the following formula:

$$Q_{PondsHarv/Day} = \frac{Q_{Ponds}}{Q_{DaysBTW.Harv.}}$$

Where: $Q_{DaysBTW.Harv.}$ is the number of days between harvests

It should be noted that the number of ponds harvested daily is rounded up to a whole number. The model determines what portion of the ponds is harvested each cycle. The model creates another Stochastic Learning Curve (just like the previous ones) and another GRKS simulated variable referred to as simulated percent of volume of pond harvested per cycle (based on the parameters from the model inputs section). Based on those two simulations, the percent of volume of ponds harvested per cycle is calculated using the following equation:

$$\%V_{Mod.PondHarv} = \%V_{Sim.PondHarv.} * SLC$$

Where: $\%V_{Sim.PondHarv.}$ is the simulated percent of volume of the pond harvested each cycle

These previous formulas are all necessary to determine the actual harvest quantities for the facility. First, the model determines the pond volume at the time of harvest based on this formula:

$$V_{Pond@Harv.} = Q_{DaysBTW.Harv.} * Q_{DailyProd/Pond}$$

Based on the pond volume at harvest, daily biomass harvested for the facility is determined by this formula:

$$Q_{BM.Harv./Day} = V_{Pond@Harv.} * Q_{PondsHarv./Day} * \%V_{Mod.Pond.Harv}$$

Where: $V_{Pond@Harv.}$ is the pond volume at harvest; $Q_{PondsHarv./Day}$ is the number of ponds harvested per day; and $\%V_{Mod.PondHarv.}$ is the model percent volume of the pond harvested each cycle

Annual harvest estimates can then be calculated simply using this formula:

$$Q_{Ann.BM.Harv} = Q_{BM.Harv./Day} * Q_{DaysOper.}$$

Where: $Q_{BM.Harv./Day}$ is the quantity of biomass harvested daily for the facility

The daily and annual harvest estimates are converted to other common units of measurement.

To determine daily and annual component production, microalgae oil content must first be simulated. Only microalgae oil content is simulated. Protein content is not simulated because protein content data was not available from the same source as the oil content. Protein content is determined using the following formula:

$$\%C_{Mod.Protein} = \frac{1.0 - \%C_{Mod.Oil}}{2}$$

Where: $\%C_{Mod.Oil}$ is the model oil content

This model assumes that roughly half of the biomass remaining after oil extraction is in the form of protein, which is the reason for dividing by two. This estimate is based partly off the literature but mostly off conversation with individuals currently operating a microalgae facility. Carbohydrates and trace minerals content is estimated using the same formula as protein, meaning that the two estimates should be equal. Microalgae oil content is modeled using a GRKS simulation based off the microalgae composition inputs. A Stochastic Learning Curve is also applied to the simulated microalgae oil content. Model microalgae oil content is estimated using the following formula:

$$\%C_{Mod.Oil} = \%C_{Sim.Oil} * SLC$$

Where: $\%C_{Sim.Oil}$ refers to the simulated oil content

This is done for each year.

It should also be noted that an estimate for the percent of lipid recovered in the harvesting and extraction process is included in the model. Current harvesting and extraction technology cannot recover all of the oil from the microalgae. The percent of lipid recovered during harvesting and extraction input is used for the first year and the following equation is used to calculate percent of lipid recovered for successive years:

$$\%LipidRec._{T} = \%LipidRec._{T-1} + Annual\ Gain\ in\ Technology$$

Where: $\%LipidRec._{T-1}$ is the percent lipid recovered during the harvesting and extraction process from the previous year

This assumes that the oil recovery can and will improve by changing technology and the chemicals used during the harvesting and extraction process.

Daily component production is divided between oil and the biomass by-product, referred to in the model as meal. The meal is broken down further into residual oil (the portion of the oil that cannot be recovered by the harvesting and extraction process), protein, and carbohydrates and trace minerals. The model includes a series of check cells to ensure that the quantity of biomass harvested is the same as the sum of all the components after harvest. Daily oil production is calculated using this formula:

$$Q_{OilProd/Day} = \%C_{Mod.Oil} * Q_{BM.Harv./Day} * \%LipidRec._{T}$$

Where: $\%LipidRec._T$ is the percent of oil recovered by the harvesting and extraction process

Annual oil production can be calculated using the following formula:

$$Q_{Ann.OilProd} = Q_{OilProd/Day} * Q_{DaysOper.}$$

Where: $Q_{OilProd./Day}$ is the daily oil production for the facility

Oil production is reported not only in kilograms, pounds, and tons, but also in liters and gallons. Daily meal production is calculated as a sum of the components remaining after oil extraction, using the following equation:

$$Q_{MealProd/Day} = \sum \left(Q_{Carb\&TM/Day}, Q_{Protein/Day}, Q_{Resid.Oil/Day} \right)$$

Where: $Q_{Carb\&TM/Day}$ is the daily carbohydrate and trace minerals production; $Q_{Protein/Day}$ is the daily protein production; and $Q_{Resid.Oil/Day}$ is the daily residual oil production not recovered during the harvesting and extraction process

The model then calculates annual meal production using this formula:

$$Q_{Ann.MealProd} = Q_{MealProd/Day} * Q_{DaysOper.}$$

Where: $Q_{MealProd./Day}$ refers to the daily meal production of the facility

It should be noted that each of these quantities is calculated in several different units of measurement, which is the reason a specific unit of measurement is not included in the formula.

Before the model can estimate meal production, the meal components must first be calculated. The daily residual oil is calculated by this equation:

$$Q_{Resid.Oil/Day} = \left(1.0 - \%LipidRec._{T}\right) * \%C_{Mod.Oil} * Q_{BM.Harv./Day}$$

Daily protein production for the facility is estimated by the formula:

$$Q_{Protien/Day} = \%C_{Protein} * Q_{BM.Harv./Day}$$

Where: $\%C_{Protein}$ is the protein content of the microalgae

Daily carbohydrate and trace mineral production is determined by this formula:

$$Q_{Carb\&TM/Day} = \%C_{Carb\&TM} * Q_{BM.Harv./Day}$$

Where: $\%C_{Carb\&TM/Day}$ is the carbohydrates and trace minerals content of the microalgae

Annual production estimates for each of these components can be estimated using the following formula:

$$Q_{Ann.Prod} = Q_{Prod./Day} * Q_{DaysOper.}$$

Where: $Q_{Prod./Day}$ is the daily production of each component (residual oil, protein, and carbohydrates and trace minerals)

These estimates are all offered in kilograms, pounds, and tons (both metric and short).

5.2.7. Financials Segment

The Financials segment of the model is the portion where the variables for profitability and analysis are formulated. The financial statements used in this analysis are income statement, cash flow, and balance sheet. Data from those statements will be used to calculate variables in the financial ratios and KOVs section of the worksheet. Those statements are also vital to construct the tax estimates for the facility. Four important supporting calculators/schedules also contained in the financials segment are the loan schedule calculator, the depreciation schedules, the income tax schedule, and the interest rate schedules.

5.2.7.1. Supporting Calculator/Schedules

The entire cost of constructing the microalgae facility will have to be financed in some fashion. The loan calculator, developed in Microsoft Excel, determines constant annual loan payments based on the amount borrowed, the desired life of the loan (in years), the annual interest rate (assumed to be fixed), and the first year of the loan, all of which can be found in the model inputs section. The calculator shows total interest paid over the life of the loan, the total cost of the loan, the interest and principal payment annually, the loan balance at the beginning and end of the year, and a cumulative cost of the loan to a specific date.

The depreciation schedule calculates an annual depreciation figure based off the original value of the item (from the Fixed Costs section), the salvage value of the asset (which is assumed to be zero) and the MACRS (Modified Accelerated Cost Recovery System) life of the item (in years). Depreciation is calculated using this formula:

$$Dep._T = Asset\,Value_T * \%Dep.Rate_T$$

Where: $Asset\ Value_T$ is the value of the facility asset at the specified time period and $\%Dep.Rate_T$ is the depreciation percentage rate for an asset for a given period of time

The percent value for depreciation comes from this formula:

$$\%Dep.Rate_T = \frac{1}{MACRS\ Life}$$

Where: *MACRS Life* is the MACRS life of the asset in years

The total annual depreciation is a sum of all the individual asset depreciation and is input into the taxable income formula.

The income tax schedule comes from U.S. tax law and uses a VLOOKUP formula to determine annual income taxes. Based on that annual income, a marginal tax rate is chosen and is used to help calculate total annual income taxes based on the following formula:

$$IT_T = BT_T + ((TI_T - IT_{Min}) * \%Tax_{Marg})$$

Where: BT_T refers to the base taxes due, which is the minimum taxes due for each particular income tax bracket; TI_T is the taxable income for the facility for a given time period; IT_{Min} is the lower bound of the income tax bracket based on taxable income; and $\%Tax_{Marg}$ is the marginal tax rate from the lookup table

The interest rate schedule exhibits interest inflation rates (from the Stoch Infl section of the mode), operating interest rates (based off the model input and inflated using interest inflation rates), and the three-month T-bill rate forecasts from the March 2010 FAPRI baseline.

5.2.7.2. Income Statement

The income statement evaluates receipts and expenses and estimates annual net cash income. The receipt section is composed of four sources of revenue as discussed earlier: microalgae oil, microalgae by-products (meal), high-value microalgae oil, and produced water recycling. The latter two sources may or may not be an actual source of revenue, depending on the inputs chosen by the decision maker. Annual microalgae oil revenues are calculated by the following formula:

$$R_{Oil} = \$ / Ton\,of\;Oil_T * Q_{Ann.OilProd.(ST)}$$

Where: *$/Ton of Oil*$_T$ is the microalgae oil price for a given period of time from the output price simulation and $Q_{Ann.OilProd.(ST)}$ is the annual oil production for the facility in short tons

Annual microalgae meal revenues are determined using this formula:

$$R_{Meal} = \$ / Ton\,of\;Meal_T * Q_{Ann.MealProd.(ST)}$$

Where: *$/Ton of Meal*$_T$ refers to the meal price for a given period of time from the output price simulation and $Q_{Ann.MealProd.(ST)}$ is the annual meal production for the facility in short tons

High-value microalgae oil revenues, if they are considered a source of revenue, are estimated using the following equation:

$$R_{H.V.Oil} = \$ / Gal.of\;H.V.Oil_T * Q_{Ann.OilProd(Gal)} * \%C_{H.V.Oil}$$

Where: *$/Gal.of H.V.Oil*$_T$ is the GRKS simulated price of the high-value oil; $Q_{Ann.OilPrd.(Gal)}$ is the annual oil production for the facility in gallons; and $\%C_{H.V.Oil}$ is the percent of the oil that is considered to be high-value, which is found in the model inputs

Produced water recycling revenues are calculated using an If/Then statement because revenues are only created if the companies pay the facility to recycle the water. If there is a revenue stream, it is calculated using this formula:

$$R_{RW} = \frac{V_{RW(Gal)}}{Gallons / Barrel} * \$ / Barrel_{T(Rev)}$$

Where: $V_{RW(Gal)}$ is the volume of recycled water used in gallons and $\$/Barrel_{T(Rev)}$ is the GRKS-simulated dollar incentive received for each barrel of water recycled for a given period of time

Total facility receipts are calculated using the formula below:

$$R_{Total} = \sum \left(R_{Oil}, R_{Meal}, R_{H.V.Oil}, R_{RW} \right)$$

Where: R_{Oil} is total annual receipts from oil; R_{Meal} is total annual receipts from meal; $R_{H.V.Oil}$ is total annual receipts from high-value oil; and R_{RW} is total annual receipts from recycled water

Each of these estimates is reported in dollars.

Expenses are comprised of variable production costs and interest expenses. Variable production costs include nutrients, labor, labor and maintenance for harvesting and extraction, chemicals for harvesting and extraction, natural gas for harvesting and extraction, electricity, and produced water recycling. Each of those except produced water recycling uses a cell reference to the variable costs section of the model because total expenses are already calculated there. The produced water recycling costs are calculated using the following equation:

$$TVC_{RW} = \frac{V_{RW(Gal)}}{Gallons / Barrel} * \$ / Barrel_{T(Cost)}$$

Where: $\$/Barrel_{T(Cost)}$ is the GRKS-simulated cost of recycling each barrel of produced water

Total variable expenses for the facility are determined by this formula:

$$E_{Var.Costs} = \sum \left(TVC_{Facility}, TVC_{RW} \right)$$

Where: $TVC_{Facility}$ is the total annual variable costs for the facility (calculated in the variable costs section) and TVC_{RW} is total annual variable costs for recycling water

Interest expenses result from three sources: operating interest (money borrowed for day-to-day operation), capital debt interest (money borrowed to build the facility), and carryover debt interest (money borrowed to cover a cash deficit at the end of the year). The formula for calculating total interest expenses is:

$$E_{Interest} = \sum \left(E_{Op.Int.}, E_{CDInt.}, E_{CODInt.} \right)$$

Where: $E_{Op.Int.}$ refers to annual operating interest expenses; $E_{CDInt.}$ is annual capital debt interest expenses; and $E_{CODInt.}$ refers to carryover debt interest expenses

Total facility expenses are calculated using the following formula:

$$E_{Total} = \sum \left(E_{Var.Costs}, E_{Interest} \right)$$

Where: $E_{Var.Costs}$ refers to total annual variable costs and $E_{Interest}$ is total annual interest expenses

Net cash income for the facility is measured using this equation:

$$NCI_T = R_{Total} - E_{Total}$$

Where: R_{Total} is total annual facility receipts and E_{Total} is total annual facility expenses

Net cash income is used throughout the Financial segment of the model.

5.2.7.3. Cash Flow Statement

Cash flow statements display the cash position for the facility for a period of time, which is a year for this model. Cash flows help determine when operating loans and carryover debt will have to be employed to keep the facility operational. Beginning cash is the cash on hand at the beginning of each fiscal year (which is the calendar year for this facility). It will never be a negative value. Other than the first value for beginning cash, it is always the value for ending cash for the previous year from the balance sheet. Net cash income is retrieved from the Income Statement and added into the cash inflow calculation. Interest earned is the result of having cash on hand at the beginning of the year and is estimated by the following formula:

$$IE_T = BC_T * \%I_{Savings}$$

Where: BC_T is beginning cash at a given point in time and $\%I_{Savings}$ is the simulated savings account interest rate

Total cash inflows are calculated using this equation:

$$CI_{Total} = \sum(BC_T, NCI_T, IE_T)$$

Where: NCI_T refers to net cash income for a given period of time and IE_T refers to interest earned for a given period of time

Cash outflows represent non-cash expenses to the facility. Capital debt repayment is the capital that is repaid on the loan for the original construction of the facility. It is a cell reference that comes from the loan calculation section. Deficit loan repayments represent any money that must be paid back as a result of having to borrow money to cover a cash flow deficit from the previous year. Deficit loan repayments are determined by the presence of any cash flow deficits found in the Balance Sheet from the previous year. Dividends represent payments to equity investors. In this model, dividends are paid on original equity and in years of positive net cash income. Dividends are estimated using the following formula:

$$DIV_T = \left(\$_{Equity} * \%DIV_{Equity}\right) + IF\left(NCI_T > 0, NCI_T * \%DIV_{NCI}, 0\right)$$

Where: $\$_{Equity}$ is the original equity in the facility; $\%DIV_{Equity}$ is the annual dividend rate as a percent of equity as specified in the financial inputs; $\%DIV_{NCI}$ is the annual dividend rate on positive net cash incomes

Income taxes refer to the calculation of any taxes that must be paid to the government when the facility earns a profit for the year. Taxable income is calculated using this formula:

$$TI_T = NCI_T - Dep._T - O.Ded._T$$

Where: $Dep._T$ refers to total depreciation for a given period of time and $ODed._T$ represent any other tax deduction for the facility for a given period of time

This cell is a cell reference to the taxes due calculation in the federal taxable income section of the worksheet. Total cash outflows are determined by this formula:

$$CO_{Total} = \sum\left(CDP_T, DLR_T, DIV_T, IT_T\right)$$

Where: CDP_T refers to capital debt payments for a given period of time; DLR_T refers to deficit loan repayments for a given period of time; DIV_T refers to dividends for a given period of time; and IT_T refers to income taxes for a given time period

Annual ending cash for the facility is estimate using the following calculation:

$$EC_T = CI_{Total} - CO_{Total}$$

Where: CI_{Total} refers to total cash inflows and CO_{Total} refers to total cash outflows

The balance sheet calculates the overall value of the facility at a point in time in the form of net worth. Net worth is calculated using the formula below:

$$NW_T = TA_T - TL_T$$

Where: TA_T is total assets at a given point in time and TL_T is total liabilities at a given point in time

Total assets for this model are determined by this equation:

$$TA_T = EC_T + Fac.\&\,Equip.Value_T$$

Where: EC_T is ending cash (from the cash flow statement) for a given period of time and $Fac.\&Equip.Value_T$ is the value of facilities and equipment at a given period of time

The value of facilities and equipment calculates the value of the facility if it was to be sold. For this model, it is assumed that the facility loses twenty percent of its value the first year and two and one half percent for each successive year for the ten-year horizon of this analysis. Total liabilities are the determined by the formula as follows:

$$TL_T = CD_{Total} + CFD_T$$

Where: CD_{Total} is total capital debt (from the loan for facility construction) and CFD_T refers to cash flow deficits (if ending cash is negative) for a given period of time

5.2.7.4. Financial Ratios

A series of financial ratios will be used to demonstrate the profitability/viability (or lack thereof) of the microalgae facility. A good overall indicator this model calculates is the present value of the ending net worth. Using a series of discount factors based on interest rates, the net worth in the final year of the analysis is discounted and the modeler can look at an overall increase or decrease in the net worth of the facility. The modeler can observe annual net return, which is estimated using this equation

$$NR_T = NCI_T - Dep._T$$

Total annual interest can easily be summed from the income statement. Annual return on interest, which is calculated using the following formula:

$$AR_{Interest} = \frac{E_{Interest} + NR_T}{NW_{Beginning}}$$

Where: NR_T is net returns for a given period of time and $NW_{Beginning}$ is beginning net worth

The present value of ending net worth estimates the net worth of the facility at the end of the ten-year horizon given the annual discount rate. The formula for calculating this value is as follows:

$$ENW_{PV} = \frac{ENW_T}{\left(1.0 + DR_T\right)^{10}}$$

Where: ENW_T is the ending net worth at a point in time and DR_T is the annual discount rate

Net present value (NPV) estimates the changing value of the facility and its sources of income over the entire ten-year horizon of the model. The formula for calculating NPV is:

$$NPV_T = -BNW + \sum\left(\left(DIV_T\right)_{PV}\right) + ENW_{PV}$$

Where: BNW refers to the beginning net worth for the facility; $(DIV_T)_{PV}$ refers to the present value of any dividends for the facility for each year; and ENW_{PV} is the present value of ending net worth

A counter for cash flow deficits helps determine the probability of negative cash flows for one and two consecutive years and is useful when the model is simulated.

5.2.8. Key Output Variables

The key output variables consist primarily of financial indicators, facility output and their associated prices, and facility input costs. Net present value, annual net cash income, annual ending cash balance, and annual net worth will allow the modeler to observe in which year the most financial risk occurs and where potential cash shortages could fall. The annual cost per gallon and pound of oil will demonstrate the facility's ability to become more productive and cost effective. Many of the rest of the KOVs simply demonstrate the simulations from other sections of the model but this allows the results to be available in one section in the model so that the modeler can observe them simultaneously.

CHAPTER VI

MODEL RESULTS AND ANALYSIS

6.1. Model Scenarios

The model was simulated for seventeen scenarios, six scenarios each for New Mexico and Pecos locations and five for the Corpus Christi location. Each location has a base scenario, which represents an assumed production level from the literature and the assumed design parameters for a microalgae facility. The input parameters for the algae facility are the same across each of the locations so the locations can be compared to one another. Each of the other scenarios includes parameters altered to reflect possible inputs, changes to the facility design, changes to the production system, changes to facility production levels, or changes to costs. This will allow the analysis to compare potential directions and designs for the future of the microalgae industry. The alternative scenarios were also intended to represent conceptual production systems and designs that could be possible in the near future resulting from discussions with people currently conducting microalgae research.

Facility design parameters were four of the inputs chosen for use in scenario analysis. The input parameters chosen were pond length, the number of raceways per pond, the power source for the facility, and the number of acre feet of water for the facility. The number of acre feet of water is important because it will allow for comparison of costs as the size of the facility grows. The length of the raceway and the number of raceways per pond are both very important design inputs in that they affect the number of raceways and ponds for the facility and therefore the quantity of supplies necessary. As the quantity of supplies used to construct the facility increases, it is expected that overall fixed costs will increase assuming all other things for the facility are equal. The power source for the facility was included in the scenario analysis to address the possibility of powering the facility using renewable energy, specifically wind and processed algae by-products. Each of the three locations are in areas with significant wind throughout the year and this offers an opportunity to compare electricity costs. It also makes the facility (and the use of the oil as a fuel source) more environmentally friendly, which has been one concern with other agricultural-based renewable fuels. The processing of the microalgae by-products also presents an opportunity for the facility to have an on-site power supply and making itself energy-independent.

Scenarios for two production system parameters are included in the analysis. The first is the water depth in the raceways. In addition to affecting facility construction costs, water depth also affects how much water is lost to evaporation and water must be pumped from the ground. Water pumping creates additional electricity consumption. If the water demands are greater than the capabilities of the facility's land, water rights from adjoining property may have to be purchased, which will create even more pumping and electricity requirements. The source of the carbon dioxide is another scenario choice. Because such research has not been carried out, the model does not discern between the production capacities based on the carbon dioxide source. However, the model does compare the costs associated with the two systems.

The production parameters for the model (microalgae growth rates and oil contents) are altered across the scenarios to help demonstrate the importance of improving those rates to the profitability of the facility. The parameters are those of a facility currently in operation in New Mexico while the other set of scenario parameters, although also very similar to the levels suggested by the literature, are the parameters from a Texas A&M University research facility in Pecos, Texas.

The final input variables included for scenario analysis are the cost level input and the percent of high value oil. The cost level input addresses the risk of rising input costs. The input allows the decision maker to use a minimum, average, or maximum cost estimate for the fixed input costs. The primary reason for inclusion of this scenario is the risk of rising input costs associated with land, pipe, and concrete blocks. In conversations with representatives for each of these cost components, the indication seemed to be that prices had been fairly volatile. The percent of high value oil addresses the possibility that some of the oil might have value for industrial or pharmaceutical purposes, meaning a higher price will be received for such a product, creating a more valuable source of revenue.

6.2. Model Assumptions

The model uses so many inputs that not all of them can be included as a part of the scenarios. Therefore, the model must include many different assumptions. Many of these assumptions may seem very small but all of them are necessary for the model to run.

The model assumes that the facility will be constructed in a square grid layout (or as close to a square as possible). This is to help minimize the number of supplies (primarily piping) used to build the facility. This also leads to the assumption that the facility will have the same number of ponds in each row, meaning that the desired number of acre feet of water will be minimum number of acre feet of water for the facility. The perimeter fence, which will enclose the entire facility (including the wind turbines if they are the power source) is assumed to use 12 gauge wire and to be 6' tall. The model also assumes that one acre of support facilities is necessary for every 20 acre feet of water. The facility is assumed to be in operation year-round (365 days).

It is assumed that the ponds will be 3' deep because it will allow for increases in water depth beyond current levels without creating the need to build new ponds. This is also partly based on discussions with individuals currently operating a facility and their assessment of future water depth limits. When the ponds are constructed, the model assumes that a minimum amount of dirt is moved from its current location to an outside berm to create the pond. A slope of 1:3 (33%) is assumed for the pond edges. This was the minimum slope suggested by individuals in the pond liner industry. This will also allow for equipment to be moved into the ponds for cleaning purposes.

The ponds are designed with liner anchors at each end and side. The length (or width) of those anchors is ten feet, at the suggestion of pond liner sales representatives. It is given that there will be 15' of space in between the ponds on all sides. This will allow for plenty of space for the pipe to be laid and plenty of space to drive equipment between the ponds. The raceways within the ponds are assumed to be ten times longer than they are wide (length to width ratio of 10:1), a value that is based on the literature.

Concrete blocks used for the dividing and center walls are assumed to be 4"x8"x16" (in height, width, and length). The blocks will be laid on top of the liner and on top of one another with no mortar. It is assumed that two hundred workers will lay blocks at a rate of four hundred blocks per day with wages of $10 per hour to complete the block laying. The center walls will be 24" high because that is the deepest water depth considered in this analysis. If the center walls needed to be taller if the water depth was increased, it would be very simple to add blocks on top of the existing blocks. This will also serve as an easy indicator of water depth to the facility operators so they know when to replenish the pond's water. The dividing walls will be the same depth as the pond, which is 3'.

The piping systems require many assumptions. It is assumed that the water and nutrients will be injected through a pipe located at 25% length of the facility, which coincides with the location of one of the paddlewheels. This is by design so the nutrients could be mixed more evenly by the paddlewheel. The carbon dioxide supply pipe is located at 75% length of the raceway because that is the location necessary for optimal water circulation (i.e. each of the circulation instruments is moving a similar quantity of microalgae culture). The pipe is assumed to be Schedule 40 in quality with a standard pipe length of 20'. The pipe quality necessary is based off discussions with individuals operating a similar piping system and the standard pipe length comes from discussions with pipe sales representatives.

For each of the three piping systems, the connecting and/or central pipes (and their related connectivity pieces) are 8" in diameter. In the case of the water/nutrients and carbon dioxide system, the pipes going into the raceways are assumed to be 6" in diameter, meaning the T-connector reducers in each of those systems will 8" to 6" reducers. Each of the systems includes some kind of downspout to either supply or remove the microalgae. The downspout length for the water/nutrients and carbon dioxide systems is 2' while the downspout length for the harvesting pipe is 2.25'. The length of the harvesting pipe (which extends from the T-connector reducer to the harvesting downspout) is 10'. For the water/nutrients pipe, it is assumed that the distance from the nearest microalgae pond to the water storage pond is 15' (the same as the distance between the ponds).

The circulation system assumes the carbon dioxide system is operated constantly while the paddlewheels are only operated during the day. The size of the blowers and the horsepower of the blower motors scaled to the facility and the distance from the carbon dioxide source. The paddlewheel assumptions include 2 paddlewheels per raceway and 2 paddlewheel platforms per raceway. Water velocity is assumed to be 0.15 meters per second (~6" per second) with a paddlewheel motor speed of 900 repetitions per minute (RPM) and a paddlewheel speed of 30 RPM. To help determine the paddlewheel motor size necessary, the model assumes a kinetic loss coefficient for 180° bends of 2.40 and a paddlewheel efficiency of 10%, estimates both taken from the literature.

The water system will require a well 200' deep with a 20 horsepower electric motor. Such a well will have a capacity of 2,000 gallons per minute pumping capacity. The water will be replenished on a daily basis. In addition to the evaporation losses, it is assumed that 0.5% of the water volume will be lost in the harvesting and extraction process. The in-ground water storage tanks will be 8' deep, with water being stored 7.5' deep. The microalgae replacement culture stations will be located at each water storage pond, with the culture tanks being similar to livestock tanks 8' in diameter and 2 tanks being at each water storage pond.

Storage facilities for the microalgae oil and by-products will have the necessary storage capacity for seven days of maximum production. It is assumed that 20 square feet of by-product storage space needed is needed to store one ton of by-product. This assumption was based on discussions with construction companies and individuals with similar facilities.

Power generation/sourcing for the facility operates on a number of assumptions because there are multiple power source alternatives. First of all, because west Texas and southeastern New Mexico are more remote locations, the distance from the power grid to the facility is much greater than the distance in the Corpus Christi area. The west Texas and southeastern New Mexico locations assume a 2 mile distance to the power grid while Corpus Christi has a distance of only 0.5 miles. The size of the facility will also affect this distance because as the facility grows, it will be more difficult to find contiguous, flat land suitable for the facility. This means that more remote locations will more than likely have to be considered. Electricity rates for each of the locations were acquired by contacting local power companies, which are as follows: 5.98¢/kWh for southeastern New Mexico; 7.02¢/kWh for Pecos, Texas; and 6.85¢/kWh for Corpus Christi, Texas.

If the facility employs a conventional power source, transmission lines will cost $500,000 per mile, distribution lines will cost $75,000 per mile, and transformers will cost $20,000 each. These estimates come from discussions with local power providers. If wind turbines are the source of energy generation, the main assumptions necessary are those needed for estimating the land area requirements. The number of turbines per row is 10 and 70 meters are needed between each row of turbines. These assumptions are based on correspondence with wind turbine companies. Finally, if by-product processing is the power source, the model assumes an energy content of 5,500 BTUs/lb. of by-product and 8,000 hours of annual operation for the by-product converter. These assumptions are based on discussions with Dr. Sergio Caparetta of Texas A&M University, who is currently researching such a energy system.

The assumptions for the harvesting and extraction system are based on estimates from a manufacturer currently making a proven system. Energy requirements per ton of biomass processed are assumed to be 9.63 kWh. Natural gas requirements are 3.69 MMBTUs per ton of biomass processed. Chemical costs for the harvesting and extraction process are $5.83 per ton while labor and maintenance expenses are $8.14 per ton of biomass processed. The model assumes a 90% lipid recovery the initial year of operation of the harvesting and extraction system. That efficiency level is assumed to improve by an annual gain of 0.5% due to technology.

The last set of assumptions involves the financial inputs. The fixed loan to finance the facility development is assumed to have a life of 20 years, with an annual interest rate of 10% and 2010 as the first year of the loan. The loan has a constant annual payment and will require 50% equity. These assumptions are based on discussions with an individual within the Farm Credit System who currently deals in renewable energy loans. Engineering and contingency fees are assumed to be 2.5% of annual expenses, a concept applied from the literature. Annual dividends are assumed to be 5% of the original equity in the facility and additional dividends of 5% of net cash income will be paid in years where net cash income is positive. The model operates on the premise that the investors will be able to raise the 50% equity needed to build the facility and will be able to readily secure a loan for the remaining portion of the initial costs. The model assumes that the 30% rebate on equipment for renewable energy generation (both wind and by-product processing) will continue in the future and will continue to apply to this facility.

In regard to the products of the facility, this analysis assumes that microalgae oil will continue to have use as oil and that by-products will prove safe to feed animals. This model assumes that the facility will comply with all governmental rules and regulations and that it will operate under the current U.S. corporate tax code.

Finally, several of the production (microalgae growth rates and oil contents) and cost parameters (nutrient costs and air injection rates) come from discussions with individuals or groups currently operating small scale microalgae test facilities. These facilities are very small compared to the commercial scale operation discussed in this analysis. This analysis operates on the premise that the production levels will be able to be maintained and the cost levels will stay the same per unit as facilities moved from pilot-plants to commercial scale. Although this is a very optimistic assumption, no information exists about the scalability of microalgae facilities because no facilities have ever been built on this scale.

6.3. Simulation Results

The analysis will be conducted for each location and then regional comparisons will be made. This section will compare not only means, minimums, and maximums, but will also use PDF, CDF, and SERF charts to explain what the risk results mean and how they affect the microalgae industry. It should be noted that across all scenarios, open raceways will stay the same size at 700’ in length with 10 raceways per pond. The cost level will also remain at the minimum bid prices for all inputs, across all scenarios.

6.3.1. Southeastern New Mexico Simulation Results

The southeastern New Mexico location includes six scenarios, with their assumptions shown in Table 15. The Base Scenario includes a 1,000 acre foot of water facility, a water depth of 24”, no recycled water, 2.5% high-value oil, the sale of the microalgae by-product, air as the source of carbon dioxide, a conventional electricity source, algae growth rate GRKS(0.10, 0.20, 0.30), and oil content GRKS(15%, 17.5%, 20%), raceways 700’ in length, 10 raceways per pond, and a minimum cost level input. The growth rates and oil contents considered in this scenario come from the Texas A&M research station in Pecos, TX, and the literature. These parameters will be used as a base to help demonstrate the importance of improving those production levels. The five remaining scenarios use increased production parameters (oil contents of 30%, 40%, and 50%; and growth rates of 0.6, 0.8, and 1.0 g/L/day). Total facility costs are $74.7 million for the Base Scenario.

Scenario 2 decreases the water depth to 14” and uses higher production levels. Total facility costs increase to $103.7 million, an increase of $29.0 million compared to the Base Scenario. Shallower water depths will require more ponds, more land area, and more support systems (piping), to reach the same number of acre feet of water as the deeper ponds, which explains the significant increase in facility costs. Scenario 3 is the same as the Base Scenario except for higher production levels and the use of wind as the power generation source. Facility costs are $117.7 million, an increase of $43.0 million over the Base Scenario. The increase in facility costs can be attributed to the cost of the wind turbines and the supporting power systems.

Table 15. New Mexico Scenario Assumptions.

Scenario Name	Base Scen.	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6
Description	Base	Med. Depth	Green	Small Size	Med. Size	High Prod.
Cost Level	Minimum	Minimum	Minimum	Minimum	Minimum	Minimum
Power Source	Conv.	Conv.	Wind	Conv.	Conv.	Conv.
Ac. Ft. of Water	1,000.00	1,000.00	1,000.00	100.00	500.00	1,000.00
Pond Length	700.00	700.00	700.00	700.00	700.00	700.00
Water Depth	24.00	14.00	24.00	24.00	24.00	24.00
% Recycled Water	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Source of Water	Ground	Ground	Ground	Ground	Ground	Ground
% High-Value Oil	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
Raceways/Pond	10.00	10.00	10.00	10.00	10.00	10.00
Prod. Levels (g/L/Day)						
Min	0.10	0.60	0.60	0.60	0.60	0.60
Mid	0.20	0.80	0.80	0.80	0.80	0.80
Max	0.30	1.00	1.00	1.00	1.00	1.00
Oil Contents (%)						
Min	0.15	0.30	0.30	0.30	0.30	0.30
Mid	0.18	0.40	0.40	0.40	0.40	0.40
Max	0.20	0.50	0.50	0.50	0.50	0.50
End Use of Algae Meal	Sales	Sales	Sales	Sales	Sales	Sales
CO2 Source	Air	Air	Air	Air	Air	Air
Total Facility Costs (Mil. $)	74.68	103.70	117.71	8.94	39.39	74.68
Total $ Financed (Mil. $)	37.34	51.85	58.86	4.47	19.69	37.34

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenarios 4, 5, and 6 use higher production levels and alter the size of the facility. Scenario 4, which uses 100 acre feet of water instead of the base of 1,000, has total facility costs of $8.94 million. It should be noted that this facility size does not include the cost of a power substation (~$3.0 million) while the other five scenarios do. This is due to the smaller electricity requirements for the facility. Scenario 5 includes a facility with 500 acre feet of water. Total facility costs are $39.4 million. Scenario 6 is the same as the Base Scenario except for the higher production, which explains why the total facility costs are equal. The total facility cost estimates do show some economies of scale because facility costs increase less than five times from Scenario 4 to Scenario 5 and costs less than double from Scenario 5 to Scenario 6.

The financial outlook for the Base Scenario is extremely discouraging based on the simulation results. Every year except year one offers a 100% probability of a negative ending cash balance (as shown by Figure 18), which is the result of escalating interest costs from the facility borrowing money to cover cash deficits. Over the ten-year horizon of the analysis, those costs create a snowball effect in that each year the facility loses money so they have to borrow additional money on top of the deficit loans they have already created. The facility would have to cease operations because it would be unable to obtain an operating loan year after year if it could not show any profitability. A 100% probability of a negative NPV, a 100% probability of losing real net worth, and a mean rate of return ranging from -18.4% to -20.9% are further evidence of the financial struggles for this scenario. A negative ending real net worth means that the facility does not make enough money to offset losses and the effects of the time value of money.

Table 16 shows mean net cash incomes are negative across all years, with only the early years of the facility even showing maximum net cash income being positive. Mean ending cash balances are more than -$128 million while mean ending net worth is -$66.5 million. Mean revenues range from $5.2-$6.1 million.

The mean cost of producing a gallon of oil is $17.59 in the first year, with the variable costs being $6.52 and fixed costs being $11.07. By the end of the ten-year horizon, the cost skyrockets to $193.88 per gallon of oil, with the costs split between $184.64 of variable costs and $9.24 of fixed costs. This is another statistic that exhibits

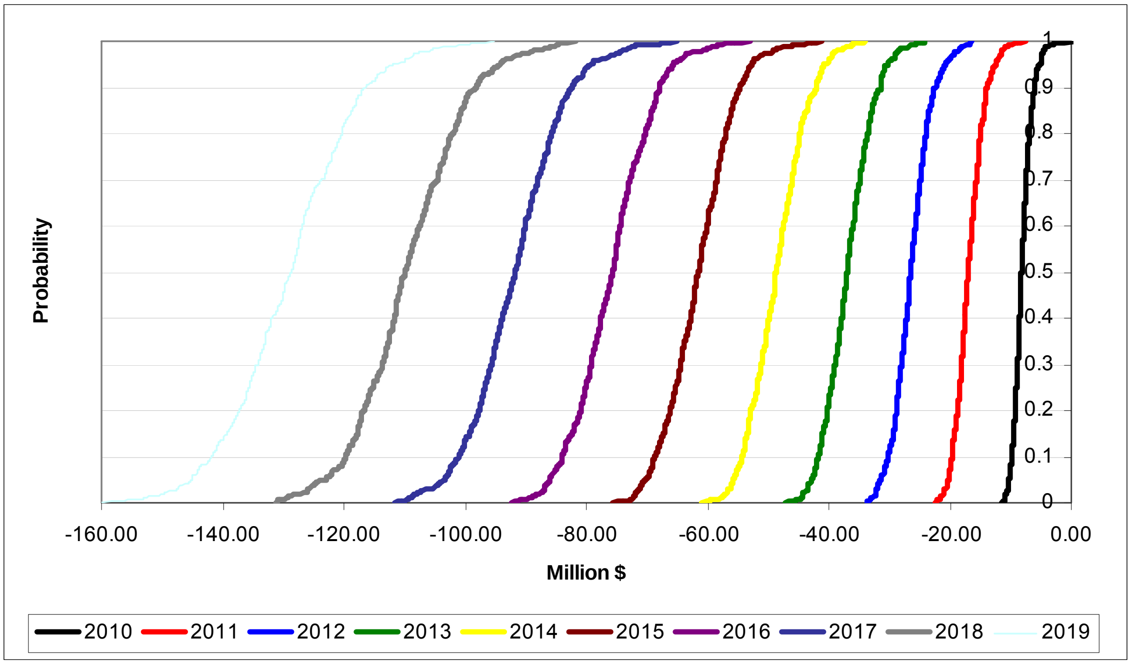

Figure 18. CDF of annual ending cash balances for New Mexico Base Scenario, with water depth of 24", 1,000 acre feet of water, and low production levels.

the effect of escalating debt-related expenses. Mean annual oil production for this facility is 574 gallons per acre foot of water while the mean by-product yield is 11.3 tons per acre foot of water.

All of these results, charts, and tables point to the fact that microalgae production must improve beyond current levels and the literature for a facility to become a profitable enterprise. The remaining scenarios will use production levels (growth rates and oil contents) at which the facility can have a possibility of being profitable while examining the affects of altering other variables.

Table 16. Averages and Probabilities of Key Output Variables for New Mexico Base Scenario, with Water Depth of 24", 1,000 Acre Feet of Water, and Low Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(89.38)
ERNW (Mil. $)										(66.46)
Prob. of Dec. RNW										100.0%
Prob. of Neg. NPV										100.0%
Prob. of Neg. ECB	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Total Rev. (Mil. $)	5.24	5.43	5.50	5.59	5.72	5.83	5.86	5.91	6.02	6.09
NCI (Mil. $)	(5.49)	(6.18)	(6.88)	(7.76)	(8.84)	(10.01)	(11.31)	(12.78)	(14.33)	(16.22)
Tx. Inc. (Mil. $)	(10.66)	(11.35)	(12.05)	(12.93)	(14.01)	(15.18)	(16.48)	(17.95)	(19.50)	(21.39)
Tx. Due (Mil. $)	-	-	-	-	-	-	-	-	-	-
ECB (Mil. $)	(8.01)	(16.77)	(26.31)	(36.80)	(48.46)	(61.40)	(75.73)	(91.65)	(109.25)	(128.88)
Net Worth (Mil. $)	15.05	5.51	(4.70)	(15.74)	(27.83)	(41.06)	(55.56)	(71.49)	(88.95)	(108.26)
Net Returns (Mil. $)	(10.66)	(11.35)	(12.05)	(12.93)	(14.01)	(15.18)	(16.48)	(17.95)	(19.50)	(21.39)
ROI	-18.4%	-18.9%	-18.9%	-19.1%	-19.2%	-19.5%	-19.9%	-20.2%	-20.4%	-20.9%
Interest Exp. (Mil. $)	3.77	4.30	5.00	5.79	6.83	7.89	9.06	10.42	11.89	13.59
Debt Exp. (Mil. $)	4.42	13.03	22.56	32.96	44.58	57.40	71.61	87.43	104.93	124.38
Var. Exp. (Mil. $)	7.00	15.95	25.55	36.14	47.93	60.98	75.33	91.30	109.02	128.72
Fixed Exp. (Mil. $)	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
Total Exp. (Mil. $)	13.25	22.20	31.80	42.39	54.19	67.23	81.59	97.56	115.27	134.97
Nut. % VE	9.4%	5.2%	2.9%	2.0%	1.5%	1.2%	1.0%	0.8%	0.7%	0.6%
Labor % VE	27.4%	12.0%	7.6%	5.5%	4.3%	3.4%	2.9%	2.4%	2.1%	1.8%
H & E L & M % VE	1.7%	0.8%	0.5%	0.4%	0.3%	0.2%	0.2%	0.2%	0.1%	0.1%
Chem. % VE	9.1%	4.3%	2.8%	2.0%	1.5%	1.2%	1.0%	0.9%	0.7%	0.6%
H & E NG % VE	38.3%	17.7%	11.4%	8.3%	6.5%	5.3%	4.3%	3.7%	3.1%	2.8%
Elec. Cons. % VE	11.0%	4.8%	3.1%	2.2%	1.7%	1.4%	1.1%	1.0%	0.8%	0.7%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	1.1%	0.7%	0.5%	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%
OI/DE % VE	0.5%	54.1%	71.0%	79.0%	83.8%	86.9%	89.2%	90.9%	92.2%	93.2%
H & E Exp. (Mil. $)	3.62	3.74	3.84	3.95	4.06	4.19	4.25	4.34	4.46	4.61
Var. Exp.% TE	52.3%	71.5%	80.2%	85.1%	88.4%	90.6%	92.3%	93.5%	94.5%	95.3%
Fixed Exp. % TE	47.7%	28.5%	19.8%	14.9%	11.6%	9.4%	7.7%	6.5%	5.5%	4.7%
Int. Exp. % TE	28.7%	19.5%	15.8%	13.7%	12.6%	11.8%	11.1%	10.7%	10.3%	10.1%
DLR % TE	0.0%	35.9%	52.6%	61.9%	67.8%	72.0%	75.2%	77.6%	79.5%	80.9%
Tx. Due % TE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
H & E Exp. % TE	26.6%	16.6%	12.0%	9.3%	7.5%	6.2%	5.2%	4.5%	3.9%	3.4%
$/Gal. Oil (VE)	6.52	21.83	37.65	54.56	72.65	93.20	113.63	134.19	208.67	184.64
$/Gal. Oil (FE)	11.07	10.92	10.63	10.44	10.23	10.19	9.92	9.60	12.54	9.24
$/Gal. Oil (TE)	17.59	32.75	48.28	65.00	82.89	103.39	123.55	143.79	221.21	193.88
Growth Rate (g/L/day)	0.20	0.20	0.20	0.20	0.20	0.20	0.21	0.21	0.21	0.21
Oil Content (%)	17.5%	17.6%	17.7%	17.8%	17.9%	17.9%	18.0%	18.1%	18.2%	18.3%
BM Prod. (1,000 ST)	14.71	14.92	15.04	15.21	15.35	15.52	15.64	15.76	15.92	16.04
BM Prod. (Tons/AF)	13.34	13.53	13.64	13.79	13.92	14.07	14.18	14.30	14.43	14.54
Oil Prod. (Mil. Gal.)	0.63	0.65	0.66	0.67	0.69	0.70	0.72	0.73	0.74	0.76
Oil Prod. (Gal./AF)	574	588	599	612	624	638	649	661	675	686
Meal Prod. (1,000 ST)	12.44	12.58	12.66	12.78	12.87	12.98	13.05	13.15	13.22	13.31
Meal Prod. (Tons/AF)	11.29	11.41	11.48	11.59	11.67	11.77	11.84	11.93	11.99	12.07
Water Loss (Bil. Gal.)	1.54	1.54	1.53	1.54	1.53	1.54	1.54	1.54	1.54	1.54
NG Cons. (Mil. TCF)	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41
Elec. Cons. (Mil. kWh)	12.47	12.48	12.48	12.49	12.49	12.50	12.50	12.51	12.51	12.52

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 2 is the same as the Base Scenario except for a water depth of 14” and the higher production rates previously discussed. The ending cash balance (Figure 19) reflects the differences in fixed costs and also the differences in the profitability resulting from the increased production levels. Mean ending cash balances have a 58.6% probability of being negative in the first year, but those probabilities rise to 77.8% in the final year. Investors would prefer that probability to fall, not to rise. As can be seen in Figure 19, Scenario 2 shows much more downside risk than upside risk on ending cash.

Total facility costs increase from $74.7 million in the Base Scenario to $103.7 million in Scenario 2, an increase of $29.0 million (Table 15). The results in Table 17 show that by decreasing the water depth, the mean annual fixed costs in year one is $9.26 million, about $3.0 million more than the Base Scenario. Throughout the horizon, fixed costs stay between $3.0 and $3.2 million higher than the Base Scenario. Over the ten year horizon, the total increase in mean annual fixed costs is $30.8 million by decreasing the water depth 10”.

Variable costs for Scenario 2 increase over the Base Scenario because more shallow water depths mean more ponds to get the same volume of water, which requires more circulation systems and electricity consumption. Table 17 shows annual mean electricity consumption is increased by 10.5 million kilowatt hours from the Base Scenario for an annual increase of 84.0%. Higher variable costs are largely offset by production increasing from 574 gallons per acre foot of water in the Base Scenario to 5,243 gallons per acre foot in Scenario 2. The additional production will require larger quantities of electricity for processing, so not all of the increase can be attributed to the decrease in water depth.

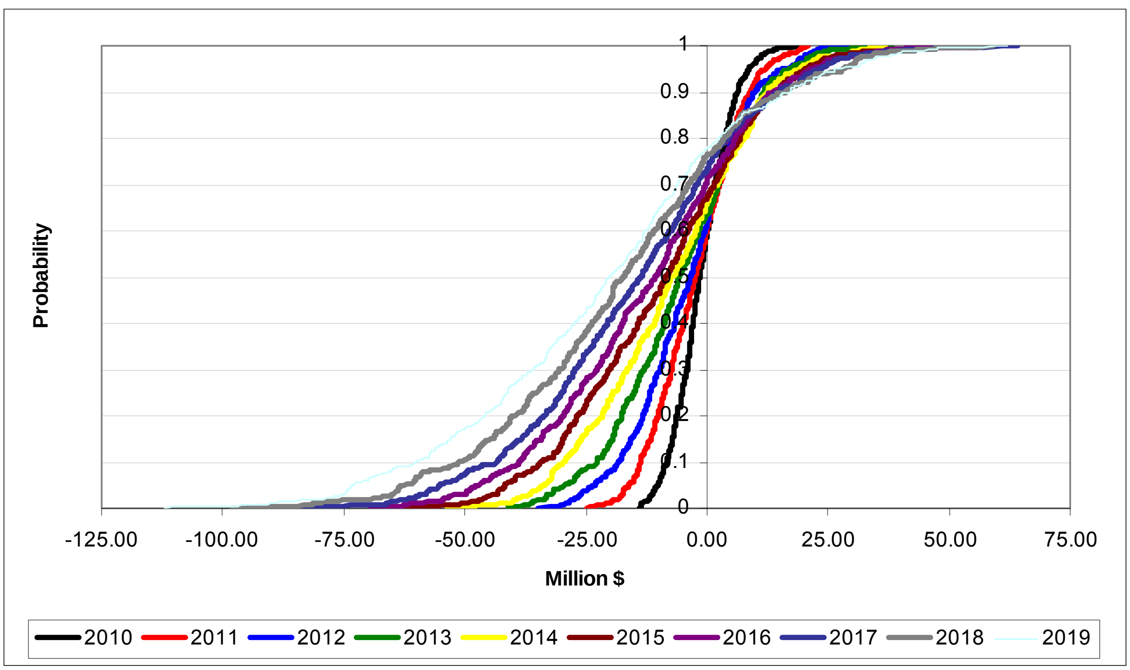

Figure 19. CDF of annual ending cash balances for New Mexico Scenario 2, with water depth of 14”, 1,000 acre feet of water, and high production levels.

Approximately 950 million additional gallons of water are required annually to replace evaporation and harvesting loss for Scenario 2, which equates to 62% more water. In addition to the mean water use being so different, Scenario 2 offers a much wider range of water usage, varying nearly 1.5 billion gallons between the minimum and maximum while the Base Scenario only varies 900 million gallons. Over the ten-year horizon, an addition 9.55 billion gallons of water are necessary.

The probability of losing real net worth at the end of the ten-year horizon is 99.8%. Scenario 2 has a positive real ending real net worth, $4.5 million, meaning the facility still maintained a portion of its initial net worth after adjusting for the time value of money. Mean NPV for Scenario 2 is -$25.6 million and the scenario has a 91.2% probability of a negative NPV or economic failure. The overall mean cost of producing oil is $5.27 per gallon, net of receipts for by-products. Overall mean variable and fixed costs per gallon of oil were both significantly lower in Scenario 2 due largely to the increase in production levels, with mean variable costs per gallon of $3.66 and mean fixed costs of $1.61.

Table 17. Averages and Probabilities of Key Output Variables for New Mexico Scenario 2, with Water Depth of 14”, 1,000 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(25.63)
ERNW (Mil. $)										4.54
Prob. of Dec. RNW										99.8%
Prob. of Neg. NPV										91.2%
Prob. of Neg. ECB	58.6%	59.6%	61.2%	63.6%	65.6%	67.0%	71.0%	73.0%	76.0%	77.8%
Total Rev. (Mil. $)	26.14	26.94	27.36	27.72	28.31	28.91	29.12	29.51	30.00	30.43
NCI (Mil. $)	3.01	2.95	2.88	2.67	2.62	2.60	2.29	2.12	1.98	1.62
Tx. Inc. (Mil. $)	(4.92)	(4.97)	(5.05)	(5.26)	(5.31)	(5.33)	(5.63)	(5.81)	(5.95)	(6.31)
Tx. Due (Mil. $)	0.37	0.43	0.46	0.45	0.43	0.50	0.46	0.40	0.44	0.46
ECB (Mil. $)	(1.07)	(2.31)	(3.73)	(5.43)	(7.28)	(9.33)	(11.80)	(14.53)	(17.60)	(21.24)
Net Worth (Mil. $)	30.94	28.63	26.28	23.81	21.37	18.90	16.21	13.46	10.60	7.40
Net Returns (Mil. $)	(4.92)	(4.97)	(5.05)	(5.26)	(5.31)	(5.33)	(5.63)	(5.81)	(5.95)	(6.31)
ROI	0.7%	0.9%	0.9%	0.6%	0.8%	0.9%	0.5%	0.3%	0.3%	-0.1%
Interest Exp. (Mil. $)	5.28	5.42	5.51	5.57	5.71	5.78	5.87	5.98	6.08	6.25
Debt Exp. (Mil. $)	6.19	9.34	11.42	13.41	15.75	18.10	20.59	23.24	26.21	29.79
Var. Exp. (Mil. $)	17.95	21.81	24.31	26.80	29.63	32.54	35.46	38.57	42.06	46.26
Fixed Exp. (Mil. $)	9.26	9.33	9.37	9.35	9.33	9.40	9.37	9.28	9.33	9.34
Total Exp. (Mil. $)	27.22	31.14	33.67	36.14	38.96	41.94	44.83	47.85	51.39	55.60
Nut. % VE	3.6%	3.8%	3.2%	2.9%	2.7%	2.5%	2.4%	2.2%	2.1%	1.9%
Labor % VE	10.8%	9.2%	8.6%	8.2%	7.9%	7.6%	7.3%	7.1%	6.9%	6.6%
H & E L & M % VE	2.6%	2.3%	2.2%	2.1%	2.0%	2.0%	1.9%	1.8%	1.8%	1.7%
Chem. % VE	14.1%	12.5%	12.0%	11.5%	10.9%	10.3%	10.0%	9.5%	9.1%	8.6%
H & E NG % VE	57.9%	50.3%	47.7%	45.8%	43.8%	42.2%	40.6%	39.2%	37.6%	35.9%
Elec. Cons. % VE	8.0%	6.8%	6.5%	6.2%	5.8%	5.6%	5.4%	5.1%	4.9%	4.7%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.1%	2.0%	1.9%	1.8%	1.8%	1.7%	1.6%	1.6%	1.5%
OI/DE % VE	0.5%	12.9%	17.9%	21.3%	25.1%	28.0%	30.7%	33.4%	36.0%	39.0%
H & E Exp. (Million $)	13.83	14.31	14.71	15.14	15.54	15.99	16.31	16.68	17.10	17.60
Var. Exp.% TE	65.4%	69.2%	71.0%	72.6%	74.1%	75.4%	76.6%	77.9%	78.9%	80.0%
Fixed Exp. % TE	34.6%	30.8%	29.0%	27.4%	25.9%	24.6%	23.4%	22.1%	21.1%	20.0%
Int. Exp. % TE	19.8%	17.9%	16.9%	16.1%	15.3%	14.5%	13.8%	13.1%	12.4%	11.8%
DLR % TE	0.0%	8.4%	12.1%	15.0%	18.0%	20.5%	22.7%	25.1%	27.4%	30.0%
Tx. Due % TE	1.2%	1.2%	1.3%	1.1%	1.1%	1.2%	1.0%	0.9%	0.9%	1.0%
H & E Exp. % TE	49.9%	45.8%	44.3%	43.2%	41.8%	40.7%	39.7%	38.7%	37.5%	36.2%
$/Gal. Oil (VE)	1.58	2.23	2.65	3.02	3.46	3.88	4.25	4.60	5.16	5.73
$/Gal. Oil (FE)	1.75	1.73	1.70	1.66	1.62	1.60	1.57	1.52	1.50	1.47
$/Gal. Oil (TE)	3.33	3.96	4.34	4.68	5.08	5.49	5.82	6.12	6.66	7.19
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	56.35	57.05	57.57	58.17	58.73	59.36	59.88	60.38	60.98	61.49
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	5.53	5.67	5.78	5.90	6.02	6.16	6.27	6.39	6.52	6.63
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	36.24	36.39	36.51	36.66	36.80	36.91	37.03	37.17	37.20	37.35
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	2.49	2.49	2.49	2.49	2.49	2.49	2.49	2.50	2.49	2.49
NG Cons. (Mil. TCF)	1.51	1.51	1.52	1.53	1.54	1.54	1.55	1.56	1.57	1.57
Elec. Cons. (Mil. kWh)	22.90	22.92	22.94	22.96	22.98	23.00	23.02	23.04	23.06	23.08

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 3 examines the economics of operating an algae facility with wind-generated electricity. Capital costs (and the associated financing costs) will be much higher because of the installation of wind turbines ($117.7 million compared to $74.7 million for the Base Scenario. Variable costs for electricity will fall because the energy will be generated on site. The probability of negative ending cash is reduced significantly from Scenario 2 in the first year and stays between 45.8%-48.6% over the nine remaining years (Figure 20).

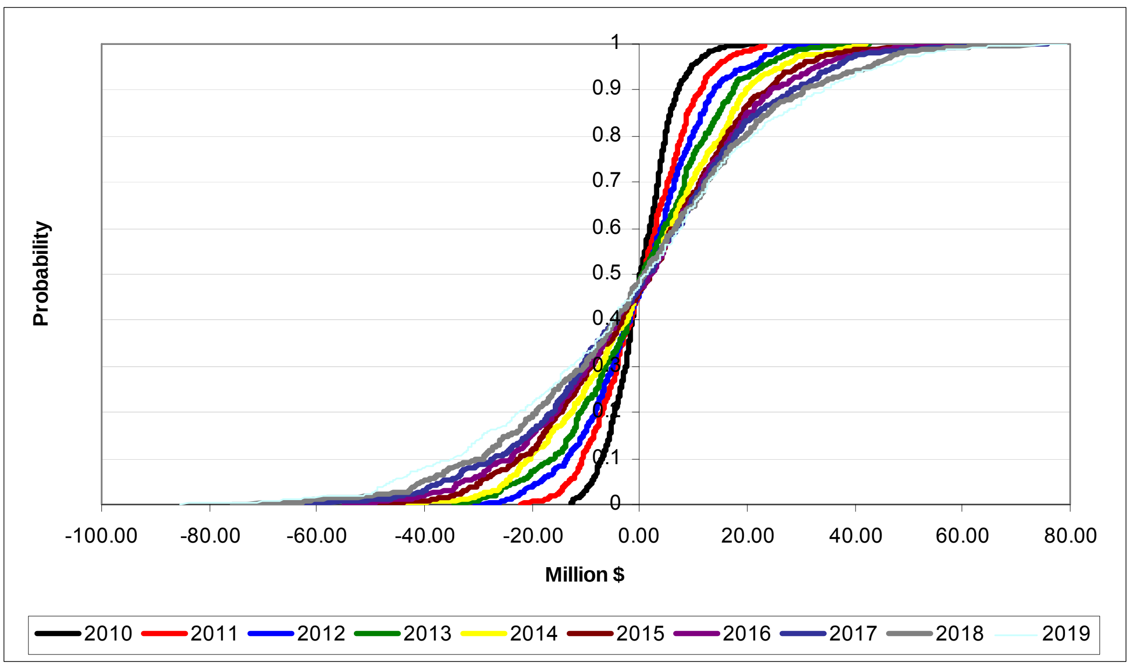

Figure 20. CDF of annual ending cash balances for New Mexico Scenario 3, with water depth of 24”, 1,000 acre feet of water, wind energy as the electricity source, and high production levels.

The probability of losing real net worth is still unacceptably high at 99.8%, with a mean ending real net worth of $20.0 million (Table 18). The probability of a negative NPV or economic failure is 79.6%, with a mean NPV of -$13.7.

Mean annual revenues for the facility range from $28.5-$33.2 million. Surplus electricity sales generate $1.3 million per year over the planning horizon. However, mean net cash incomes are similar to Scenario 6, with Scenario 6 having slightly higher revenues (by $0.2 million or less) in the first five years and Scenario 3 having slightly higher revenues (by $0.2 million or less) in the final five years. Mean returns on investment are range from 6.6% and 7.3% over the ten-year horizon.

The cost of producing algae oil is $4.01. The mean variable cost is $2.43 and the mean fixed cost was $1.59. Fixed costs per gallon are higher than the other scenarios with 24" of water depth and high production levels because of the cost of building a wind-generated power facility.

Table 18. Averages and Probabilities of Key Output Variables for New Mexico Scenario 3, with Water Depth of 24”, 1,000 Acre Feet of Water, Wind Energy as the Electricity Source, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(13.69)
ERNW (Mil. $)										19.98
Prob. of Dec. RNW										99.2%
Prob. of Neg. NPV										79.6%
Prob. of Neg. ECB	49.6%	47.4%	45.8%	48.6%	47.2%	46.4%	47.0%	47.6%	48.4%	47.8%
Total Rev. (Mil. $)	28.50	29.35	29.83	30.24	30.87	31.53	31.78	32.21	32.74	33.21
NCI (Mil. $)	5.24	5.30	5.40	5.36	5.52	5.69	5.60	5.69	5.82	5.78
Tx. Inc. (Mil. $)	(2.08)	(2.02)	(1.92)	(1.96)	(1.80)	(1.63)	(1.72)	(1.63)	(1.50)	(1.54)
Tx. Due (Mil. $)	0.66	0.75	0.79	0.79	0.81	0.87	0.92	0.82	0.91	0.92
ECB (Mil. $)	0.31	0.55	0.77	0.87	1.00	1.13	0.97	0.83	0.57	0.04
Net Worth (Mil. $)	36.66	35.67	34.84	34.07	33.51	33.18	32.77	32.60	32.57	32.55
Net Returns (Mil. $)	(2.08)	(2.02)	(1.92)	(1.96)	(1.80)	(1.63)	(1.72)	(1.63)	(1.50)	(1.54)
ROI	6.6%	6.8%	7.0%	6.9%	7.2%	7.3%	7.1%	7.1%	7.1%	6.9%
Interest Exp. (Mil. $)	5.98	6.05	6.05	6.01	6.01	5.95	5.88	5.79	5.67	5.58
Debt Exp. (Mil. $)	7.01	9.29	10.47	11.45	12.47	13.51	14.47	15.29	16.07	17.16
Var. Exp. (Mil. $)	17.38	20.38	21.93	23.39	24.89	26.49	27.85	29.11	30.40	32.09
Fixed Exp. (Mil. $)	10.81	10.91	10.96	10.95	10.99	11.05	11.11	11.01	11.10	11.12
Total Exp. (Mil. $)	28.19	31.29	32.89	34.35	35.88	37.54	38.96	40.11	41.51	43.21
Nut. % VE	3.9%	4.2%	3.6%	3.4%	3.2%	3.1%	3.1%	2.9%	2.8%	2.8%
Labor % VE	11.3%	9.9%	9.5%	9.3%	9.2%	9.0%	9.0%	9.0%	9.0%	9.0%
H & E L & M % VE	2.9%	2.6%	2.6%	2.5%	2.5%	2.4%	2.4%	2.4%	2.4%	2.5%
Chem. % VE	15.3%	14.0%	13.8%	13.6%	13.2%	12.9%	12.7%	12.5%	12.4%	12.2%
H & E NG % VE	62.6%	56.1%	54.6%	53.6%	52.7%	51.9%	51.3%	51.0%	50.6%	50.2%
Elec. Cons. % VE	1.1%	0.9%	0.9%	0.8%	0.8%	0.8%	0.7%	0.7%	0.7%	0.7%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.2%	2.1%	2.1%	2.0%	2.0%	2.0%	2.0%	1.9%	1.9%
OI/DE % VE	0.5%	10.0%	12.9%	14.6%	16.3%	17.9%	18.7%	19.5%	20.1%	20.8%
H & E Exp. (Million $)	14.44	14.95	15.36	15.81	16.23	16.70	17.03	17.43	17.86	18.38
Var. Exp.% TE	61.0%	64.3%	65.6%	66.8%	67.7%	68.7%	69.3%	70.2%	70.7%	71.3%
Fixed Exp. % TE	39.0%	35.7%	34.4%	33.2%	32.3%	31.3%	30.7%	29.8%	29.3%	28.7%
Int. Exp. % TE	21.7%	19.9%	19.0%	18.2%	17.4%	16.6%	15.8%	15.1%	14.3%	13.5%
DLR % TE	0.0%	6.0%	8.2%	9.5%	10.8%	12.1%	12.8%	13.6%	14.1%	14.8%
Tx. Due % TE	2.1%	2.2%	2.2%	2.1%	2.2%	2.3%	2.3%	2.0%	2.2%	2.3%
H & E Exp. % TE	50.4%	47.5%	46.9%	46.7%	46.3%	45.9%	45.8%	45.9%	45.8%	45.7%
$/Gal. Oil (VE)	1.32	1.80	2.03	2.22	2.41	2.62	2.76	2.84	3.04	3.24
$/Gal. Oil (FE)	1.73	1.71	1.67	1.63	1.60	1.57	1.54	1.49	1.48	1.44
$/Gal. Oil (TE)	3.05	3.50	3.70	3.84	4.01	4.19	4.30	4.34	4.51	4.68
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	58.86	59.59	60.13	60.76	61.35	62.01	62.55	63.07	63.70	64.23
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	5.78	5.92	6.04	6.17	6.29	6.43	6.55	6.67	6.81	6.92
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	37.85	38.01	38.14	38.30	38.44	38.55	38.68	38.83	38.86	39.01
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	1.54	1.54	1.53	1.54	1.53	1.54	1.54	1.54	1.54	1.54
NG Cons. (Mil. TCF)	1.57	1.58	1.59	1.60	1.60	1.61	1.62	1.63	1.64	1.64
Elec. Cons. (Mil. kWh)	15.63	15.65	15.67	15.69	15.71	15.74	15.76	15.78	15.80	15.82

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

NM Scenario 4 examines the possibility of a much smaller-scale facility, with 100 acre feet of water instead of 1,000 acre feet. This scenario is included to address the possibility of building a smaller commercial scale facility. The probability of a negative ending cash balance is highest in the first year at 44.4% and remains between 40.2% and 41.8% for the nine remaining years. As Figure 21 shows, the probabilities for a negative ending cash balance seems to be distributed evenly around a probability of 41%.

The probability of losing real net worth is 91.0% in this scenario, with a mean ending real net worth of $1.8 million (Table 19). The probability of a negative NPV is 62.0%, with a mean NPV of -$0.7 million. The cost per gallon of oil produced $3.78. The variable costs per gallon are $2.59 while fixed costs per gallon are $1.19.

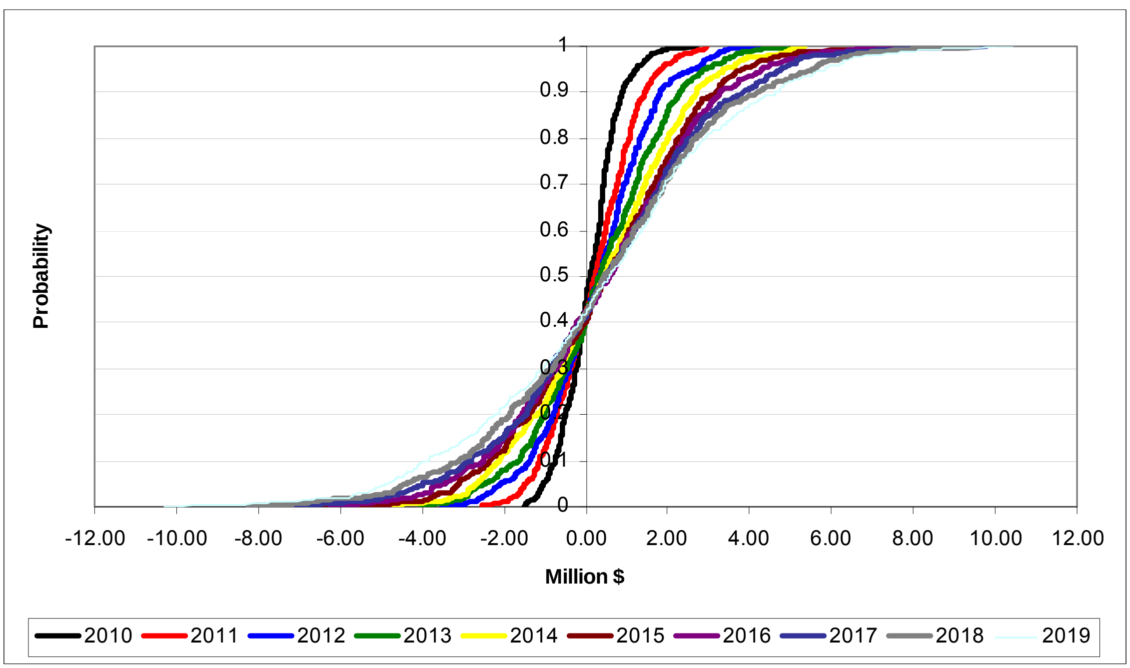

Figure 21. CDF of annual ending cash balances for New Mexico Scenario 4, with water depth of 24”, 100 acre feet of water, and high production levels.

Table 19. Averages and Probabilities of Key Output Variables for New Mexico Scenario 4, with Water Depth of 24”, 100 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(0.69)
ERNW (Mil. $)										1.80
Prob. of Dec. RNW										91.0%
Prob. of Neg. NPV										62.0%
Prob. of Neg. ECB	44.4%	41.6%	41.0%	40.6%	41.6%	40.2%	42.2%	41.2%	42.0%	41.8%
Total Rev. (Mil. $)	3.34	3.45	3.50	3.55	3.62	3.70	3.72	3.77	3.84	3.89
NCI (Mil. $)	0.54	0.54	0.54	0.52	0.53	0.53	0.51	0.50	0.50	0.47
Tx. Inc. (Mil. $)	(0.05)	(0.05)	(0.05)	(0.07)	(0.07)	(0.06)	(0.09)	(0.09)	(0.09)	(0.12)
Tx. Due (Mil. $)	0.11	0.11	0.12	0.12	0.12	0.12	0.13	0.11	0.12	0.12
ECB (Mil. $)	0.10	0.20	0.28	0.34	0.41	0.47	0.49	0.50	0.50	0.46
Net Worth (Mil. $)	2.86	2.86	2.87	2.86	2.88	2.90	2.90	2.92	2.93	2.93
Net Returns (Mil. $)	(0.05)	(0.05)	(0.05)	(0.07)	(0.07)	(0.06)	(0.09)	(0.09)	(0.09)	(0.12)
ROI	9.1%	9.4%	9.4%	9.0%	9.2%	9.2%	8.6%	8.3%	8.1%	7.5%
Interest Exp. (Mil. $)	0.46	0.47	0.47	0.47	0.47	0.47	0.47	0.46	0.46	0.45
Debt Exp. (Mil. $)	0.54	0.78	0.89	0.98	1.07	1.18	1.27	1.35	1.42	1.54
Var. Exp. (Mil. $)	2.36	2.68	2.85	3.00	3.17	3.34	3.49	3.63	3.78	3.98
Fixed Exp. (Mil. $)	0.89	0.90	0.90	0.90	0.90	0.90	0.91	0.89	0.90	0.90
Total Exp. (Mil. $)	3.24	3.58	3.75	3.90	4.06	4.25	4.40	4.53	4.68	4.88
Nut. % VE	3.5%	3.9%	3.4%	3.2%	3.0%	3.0%	2.9%	2.7%	2.7%	2.6%
Labor % VE	15.8%	14.2%	13.8%	13.6%	13.4%	13.2%	13.2%	13.2%	13.2%	13.2%
H & E L & M % VE	2.6%	2.4%	2.4%	2.3%	2.3%	2.3%	2.3%	2.3%	2.3%	2.3%
Chem. % VE	13.7%	12.9%	12.8%	12.6%	12.4%	12.1%	12.0%	11.8%	11.7%	11.6%
H & E NG % VE	56.5%	51.8%	50.8%	50.2%	49.7%	48.9%	48.5%	48.2%	48.0%	47.6%
Elec. Cons. % VE	5.1%	4.6%	4.5%	4.4%	4.4%	4.3%	4.2%	4.2%	4.2%	4.1%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.2%	2.2%	2.2%	2.1%	2.1%	2.1%	2.1%	2.1%	2.0%
OI/DE % VE	0.5%	8.0%	10.3%	11.4%	12.7%	14.2%	14.8%	15.5%	15.9%	16.5%
H & E Exp. (Million $)	1.77	1.83	1.88	1.94	1.99	2.05	2.09	2.13	2.19	2.25
Var. Exp.% TE	72.3%	74.5%	75.4%	76.2%	76.8%	77.5%	77.9%	78.8%	79.1%	79.6%
Fixed Exp. % TE	27.7%	25.5%	24.6%	23.8%	23.2%	22.5%	22.1%	21.2%	20.9%	20.4%
Int. Exp. % TE	14.6%	13.5%	13.0%	12.5%	12.1%	11.5%	11.0%	10.6%	10.0%	9.5%
DLR % TE	0.0%	5.4%	7.2%	8.1%	9.2%	10.4%	10.9%	11.5%	11.9%	12.6%
Tx. Due % TE	3.0%	2.9%	2.9%	2.7%	2.8%	2.8%	2.8%	2.4%	2.6%	2.6%
H & E Exp. % TE	53.7%	50.9%	50.4%	50.3%	50.0%	49.5%	49.3%	49.4%	49.3%	49.1%
$/Gal. Oil (VE)	1.67	2.08	2.27	2.41	2.56	2.75	2.87	2.94	3.10	3.29
$/Gal. Oil (FE)	1.29	1.27	1.25	1.22	1.20	1.18	1.16	1.12	1.11	1.08
$/Gal. Oil (TE)	2.95	3.35	3.51	3.63	3.76	3.92	4.03	4.06	4.22	4.38
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	7.21	7.30	7.36	7.44	7.51	7.59	7.66	7.72	7.80	7.87
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	0.71	0.73	0.74	0.76	0.77	0.79	0.80	0.82	0.83	0.85
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	4.63	4.65	4.67	4.69	4.71	4.72	4.74	4.75	4.76	4.78
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
NG Cons. (Mil. TCF)	0.19	0.19	0.19	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Elec. Cons. (Mil. kWh)	1.91	1.92	1.92	1.92	1.92	1.93	1.93	1.93	1.93	1.94

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

NM Scenario 5 is another variation on the size of the facility, with this scenario having 500 acre feet of water. Returns on investment are 9.1% in the first year and average 8.9% over the ten year horizon of the model (Table 20). The probability of a negative NPV is 59.8% and mean NPV remains negative at -$2.1 million. The probability of losing real net worth is 91.2%, with a mean ending real net worth of $8.8 million. The probability of a negative ending cash balance is 43.0% in the first year and decreases to 36.6% in the final year (Figure 22). Ending cash has an improved outlook when compared to Scenario 4 while not being quite as optimistic as Scenario 6. Less risk of a negative ending cash balance exists while the potential results on the positive side are higher in magnitude than Scenario 4.

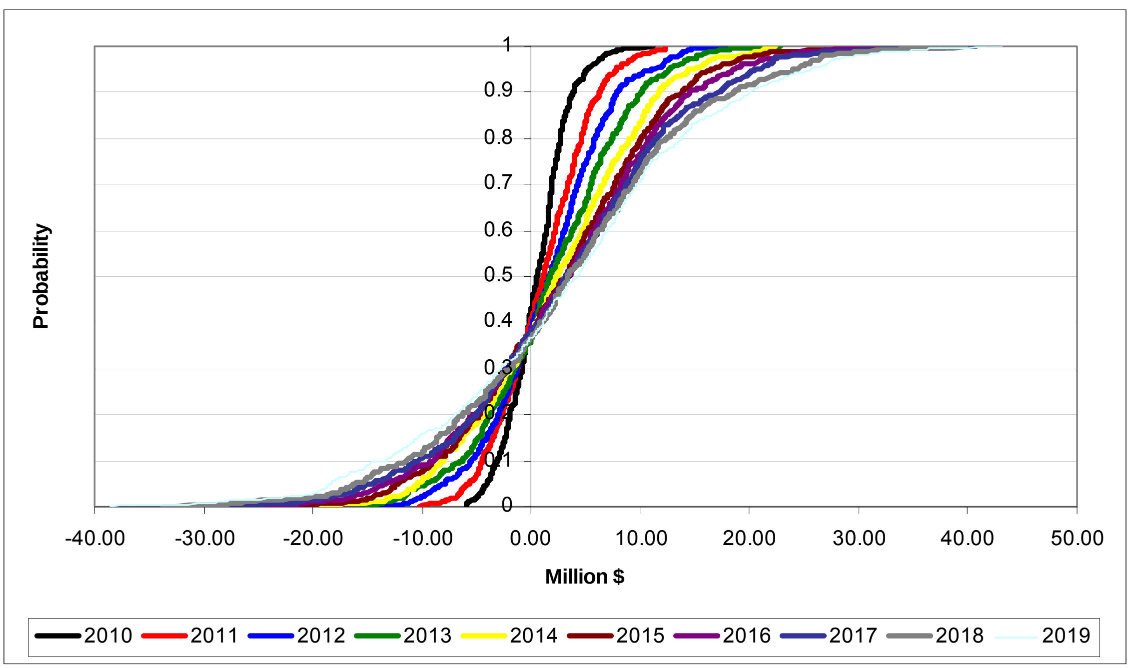

Figure 22. CDF of annual ending cash balances for New Mexico Scenario 5, with water depth of 24”, 500 acre feet of water, and high production levels.

The mean cost is $3.64 per gallon for algae oil, with variable costs of $2.39 per gallon and fixed costs of $1.25 per gallon. The $3.64 per gallon total cost is $0.14 lower per gallon than the 100 acre foot facility in Scenario 4.

Table 20. Averages and Probabilities of Key Output Variables for New Mexico Scenario 5, with Water Depth of 24”, 500 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(2.10)
ERNW (Mil. $)										8.84
Prob. of Dec. RNW										91.2%
Prob. of Neg. NPV										59.8%
Prob. of Neg. ECB	43.0%	40.4%	38.6%	36.6%	37.8%	37.6%	38.4%	38.2%	36.6%	36.6%
Total Rev. (Mil. $)	13.93	14.36	14.58	14.77	15.09	15.41	15.52	15.73	15.99	16.22
NCI (Mil. $)	2.44	2.45	2.46	2.39	2.43	2.48	2.39	2.38	2.40	2.33
Tx. Inc. (Mil. $)	(0.22)	(0.21)	(0.21)	(0.27)	(0.23)	(0.19)	(0.28)	(0.28)	(0.26)	(0.34)
Tx. Due (Mil. $)	0.44	0.48	0.50	0.49	0.50	0.52	0.55	0.49	0.53	0.53
ECB (Mil. $)	0.53	1.03	1.50	1.90	2.31	2.74	2.99	3.26	3.46	3.53
Net Worth (Mil. $)	12.69	12.78	12.90	13.01	13.19	13.46	13.63	13.89	14.17	14.41
Net Returns (Mil. $)	(0.22)	(0.21)	(0.21)	(0.27)	(0.23)	(0.19)	(0.28)	(0.28)	(0.26)	(0.34)
ROI	9.1%	9.4%	9.4%	9.0%	9.3%	9.4%	8.8%	8.6%	8.5%	8.0%
Interest Exp. (Mil. $)	2.02	2.06	2.06	2.05	2.06	2.04	2.01	1.98	1.94	1.91
Debt Exp. (Mil. $)	2.36	3.30	3.71	4.03	4.36	4.71	5.01	5.24	5.45	5.82
Var. Exp. (Mil. $)	9.52	10.83	11.46	12.05	12.64	13.29	13.82	14.29	14.78	15.49
Fixed Exp. (Mil. $)	3.88	3.92	3.94	3.94	3.94	3.97	4.00	3.94	3.98	3.98
Total Exp. (Mil. $)	13.41	14.75	15.40	15.98	16.59	17.26	17.82	18.22	18.76	19.46
Nut. % VE	3.6%	4.0%	3.5%	3.3%	3.2%	3.1%	3.1%	2.9%	2.8%	2.8%
Labor % VE	13.2%	11.9%	11.6%	11.4%	11.3%	11.2%	11.2%	11.3%	11.3%	11.3%
H & E L & M % VE	2.7%	2.5%	2.5%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.5%
Chem. % VE	14.2%	13.4%	13.2%	13.1%	12.9%	12.6%	12.6%	12.4%	12.4%	12.2%
H & E NG % VE	58.2%	53.5%	52.5%	52.1%	51.6%	51.0%	50.7%	50.7%	50.5%	50.3%
Elec. Cons. % VE	5.2%	4.7%	4.7%	4.6%	4.5%	4.5%	4.4%	4.4%	4.4%	4.4%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.2%	2.2%	2.2%	2.2%	2.1%	2.1%	2.1%	2.1%	2.1%
OI/DE % VE	0.5%	7.8%	9.8%	10.8%	11.8%	13.1%	13.5%	13.8%	14.0%	14.4%
H & E Exp. (Million $)	7.37	7.63	7.84	8.07	8.28	8.52	8.69	8.89	9.11	9.38
Var. Exp.% TE	70.6%	72.9%	73.7%	74.5%	75.2%	75.8%	76.2%	76.9%	77.2%	77.7%
Fixed Exp. % TE	29.4%	27.1%	26.3%	25.5%	24.8%	24.2%	23.8%	23.1%	22.8%	22.3%
Int. Exp. % TE	15.5%	14.4%	13.8%	13.3%	12.8%	12.2%	11.7%	11.2%	10.7%	10.1%
DLR % TE	0.0%	5.2%	6.7%	7.5%	8.4%	9.4%	9.7%	10.0%	10.3%	10.7%
Tx. Due % TE	3.0%	3.0%	3.0%	2.8%	2.9%	2.9%	3.0%	2.6%	2.8%	2.8%
H & E Exp. % TE	54.2%	51.4%	51.0%	51.1%	50.9%	50.5%	50.4%	50.8%	50.8%	50.7%
$/Gal. Oil (VE)	1.56	1.95	2.12	2.25	2.38	2.54	2.64	2.68	2.81	2.96
$/Gal. Oil (FE)	1.35	1.34	1.31	1.29	1.26	1.24	1.23	1.19	1.18	1.15
$/Gal. Oil (TE)	2.91	3.29	3.44	3.53	3.64	3.78	3.86	3.87	3.99	4.11
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	30.03	30.40	30.68	31.00	31.30	31.64	31.91	32.18	32.50	32.77
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	2.95	3.02	3.08	3.15	3.21	3.28	3.34	3.40	3.47	3.53
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	19.31	19.39	19.46	19.54	19.61	19.67	19.73	19.81	19.82	19.90
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.79	0.78	0.78
NG Cons. (Mil. TCF)	0.80	0.81	0.81	0.81	0.82	0.82	0.83	0.83	0.83	0.84
Elec. Cons. (Mil. kWh)	7.98	7.99	8.00	8.01	8.02	8.03	8.04	8.05	8.06	8.07

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 6 assumes a water depth of 24”, with 1,000 acre feet of water and the high productivity levels. The probability of a negative ending cash balance (Figure 23) is highest in the first year at 38.4% and falls to 26.6% in the final year. That is 10.0% better than Scenario 5 and 15.2% better than Scenario 4 in the final year, indicating that economies of scale will likely exist within the microalgae industry. The probability of losing real net worth is still relatively high at 86.0% but has improved over Scenarios 4 and 5 (Table 21). The mean ending real net worth is \$21.8 million. The probability of a negative NPV decreased to 45.8%, with a mean NPV of \$1.3 million. Mean rates of return are near 11.0%, or about 1.5%-2.0% higher than Scenarios 4 and 5.

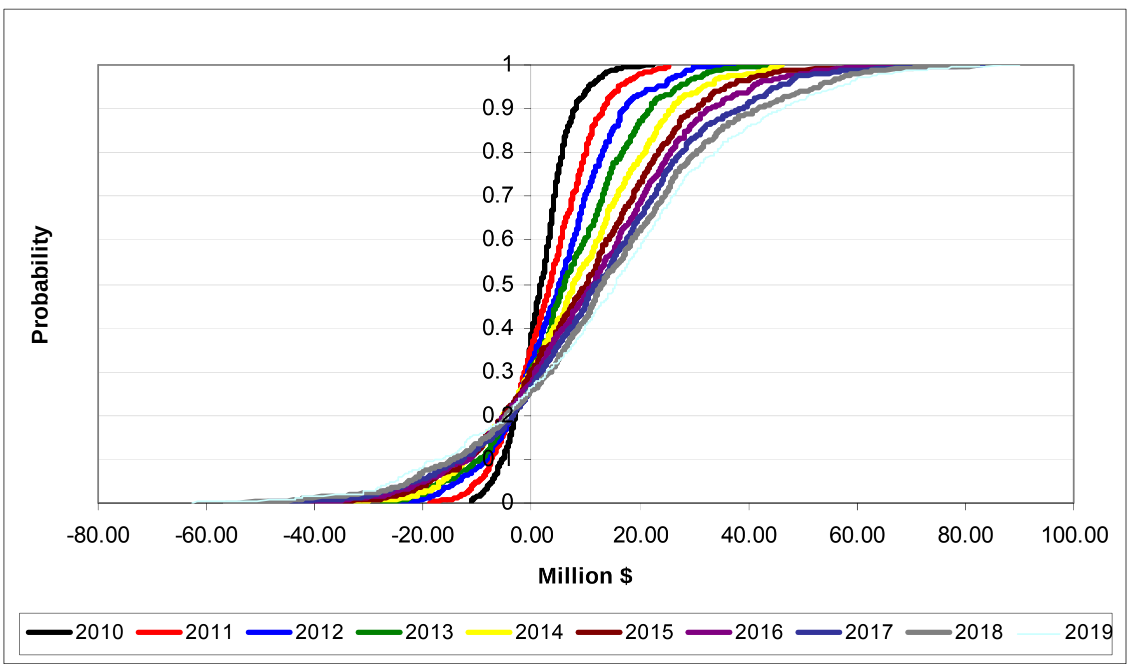

Figure 23. CDF of annual ending cash balances for New Mexico Scenario 6, with water depth of 24”, 1,000 acre feet of water, and high production levels.

Table 21. Averages and Probabilities of Key Output Variables for New Mexico Scenario 6, with Water Depth of 24", 1,000 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										1.30
ERNW (Mil. $)										21.76
Prob. of Dec. RNW										86.0%
Prob. of Neg. NPV										45.8%
Prob. of Neg. ECB	38.4%	35.4%	32.2%	30.6%	29.8%	30.2%	27.4%	26.6%	25.8%	26.6%
Total Rev. (Mil. $)	27.31	28.14	28.58	28.96	29.57	30.20	30.42	30.83	31.33	31.78
NCI (Mil. $)	5.42	5.46	5.50	5.41	5.53	5.66	5.53	5.57	5.65	5.55
Tx. Inc. (Mil. $)	0.25	0.29	0.33	0.24	0.36	0.49	0.36	0.40	0.48	0.38
Tx. Due (Mil. $)	0.98	1.05	1.09	1.09	1.10	1.15	1.22	1.11	1.20	1.19
ECB (Mil. $)	1.61	3.21	4.80	6.28	7.84	9.47	10.82	12.26	13.63	14.83
Net Worth (Mil. $)	24.67	25.50	26.41	27.34	28.47	29.80	30.99	32.41	33.94	35.45
Net Returns (Mil. $)	0.25	0.29	0.33	0.24	0.36	0.49	0.36	0.40	0.48	0.38
ROI	10.9%	11.2%	11.3%	10.9%	11.2%	11.4%	10.8%	10.7%	10.6%	10.1%
Interest Exp. (Mil. $)	3.83	3.88	3.87	3.84	3.82	3.75	3.68	3.58	3.48	3.39
Debt Exp. (Mil. $)	4.48	6.01	6.55	6.92	7.31	7.66	7.88	8.00	8.08	8.49
Var. Exp. (Mil. $)	18.16	20.41	21.36	22.25	23.14	24.06	24.71	25.29	25.90	26.95
Fixed Exp. (Mil. $)	7.54	7.61	7.66	7.65	7.67	7.72	7.81	7.69	7.78	7.77
Total Exp. (Mil. $)	25.69	28.02	29.02	29.90	30.81	31.79	32.52	32.97	33.68	34.72
Nut. % VE	3.7%	4.2%	3.7%	3.5%	3.4%	3.3%	3.3%	3.1%	3.1%	3.0%
Labor % VE	10.8%	9.8%	9.6%	9.6%	9.5%	9.5%	9.6%	9.7%	9.8%	9.8%
H & E L & M % VE	2.7%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.7%	2.7%
Chem. % VE	14.6%	13.9%	13.9%	13.9%	13.7%	13.5%	13.5%	13.5%	13.5%	13.3%
H & E NG % VE	59.9%	55.5%	55.0%	54.8%	54.6%	54.3%	54.3%	54.7%	54.9%	54.6%
Elec. Cons. % VE	5.4%	4.9%	4.9%	4.9%	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.3%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%
OI/DE % VE	0.5%	6.8%	8.1%	8.6%	9.2%	9.8%	9.7%	9.5%	9.1%	9.6%
H & E Exp. (Million $)	14.44	14.95	15.36	15.81	16.23	16.70	17.03	17.43	17.86	18.38
Var. Exp.% TE	70.3%	72.3%	73.0%	73.7%	74.2%	74.7%	74.9%	75.6%	75.7%	76.2%
Fixed Exp. % TE	29.7%	27.7%	27.0%	26.3%	25.8%	25.3%	25.1%	24.4%	24.3%	23.8%
Int. Exp. % TE	15.4%	14.3%	13.8%	13.3%	12.8%	12.3%	11.7%	11.2%	10.7%	10.1%
DLR % TE	0.0%	4.4%	5.5%	5.8%	6.3%	6.8%	6.7%	6.6%	6.4%	6.8%
Tx. Due % TE	3.5%	3.4%	3.5%	3.3%	3.4%	3.4%	3.6%	3.2%	3.4%	3.4%
H & E Exp. % TE	55.4%	53.0%	53.0%	53.3%	53.3%	53.2%	53.4%	54.1%	54.4%	54.4%
$/Gal. Oil (VE)	1.47	1.80	1.93	2.01	2.09	2.20	2.25	2.26	2.32	2.44
$/Gal. Oil (FE)	1.34	1.32	1.30	1.27	1.25	1.23	1.22	1.18	1.17	1.14
$/Gal. Oil (TE)	2.80	3.12	3.23	3.28	3.34	3.42	3.47	3.43	3.49	3.58
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	58.86	59.59	60.13	60.76	61.35	62.01	62.55	63.07	63.70	64.23
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	5.78	5.92	6.04	6.17	6.29	6.43	6.55	6.67	6.81	6.92
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	37.85	38.01	38.14	38.30	38.44	38.55	38.68	38.83	38.86	39.01
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	1.54	1.54	1.53	1.54	1.53	1.54	1.54	1.54	1.54	1.54
NG Cons. (Mil. TCF)	1.57	1.58	1.59	1.60	1.60	1.61	1.62	1.63	1.64	1.64
Elec. Cons. (Mil. kWh)	15.63	15.65	15.67	15.69	15.71	15.74	15.76	15.78	15.80	15.82

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

6.3.1.1. Comparisons Across New Mexico Scenarios

The cost per gallon of algae oil also suggests that economies of scale will be present in microalgae production. As shown in Table 22, the total cost per gallon in Scenario 6 is $3.32, which is $0.46 lower than Scenario 4 and $0.32 lower than Scenario 5. The majority of the difference is found in variable costs, with Scenario 6 having a variable cost per gallon of $2.08, $0.51 lower than Scenario 4 and $0.31 lower than Scenario 5. Scenario 6 has the lowest cost for producing algae oil across the six scenarios.

Table 22. Summary Statistics for Selected Key Output Variables for Six New Mexico Scenarios.

	Base Scen.	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6
Ac. Ft. of Water	1,000	1,000	1,000	100	500	1,000
Water Depth (Inches)	24.0	14.0	24.0	24.0	24.0	24.0
Electricity Source	Conv.	Conv.	Wind	Conv.	Conv.	Conv.
NPV (Million $)	(89.38)	(25.63)	(13.69)	(0.69)	(2.10)	1.30
ERNW (Million $)	(66.46)	4.54	19.98	1.80	8.84	21.76
Probability of Losing RNW	100.0%	99.8%	99.2%	91.0%	91.2%	86.0%
Probability of Neg. NPV	100.0%	91.2%	79.6%	62.0%	59.8%	45.8%
End. Cash Bal. (Million $)						
Mean	(60.33)	(9.43)	0.71	0.38	2.32	8.47
Min	(74.69)	(60.09)	(48.54)	(5.58)	(21.96)	(37.64)
Max	(41.71)	44.27	52.11	6.71	28.00	57.49
Total Exp. ($/Gal. Oil)						
Mean	103.23	5.27	4.01	3.78	3.64	3.32
Min	33.96	1.33	1.22	1.17	1.16	1.12
Max	3,123.34	16.38	12.96	12.24	11.82	10.66
Var. Exp. ($/Gal. Oil)						
Mean	92.75	3.66	2.43	2.59	2.39	2.08
Min	29.77	(0.40)	(0.70)	(0.49)	(0.56)	(0.60)
Max	2,915.65	13.80	10.86	10.74	10.23	9.73
Fixed Exp. ($/Gal. Oil)						
Mean	10.48	1.61	1.59	1.19	1.25	1.24
Min	3.95	0.89	0.89	0.67	0.72	0.71
Max	208.12	3.31	3.11	2.25	2.36	2.32

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

The effect of decreasing water depths can be exhibited by comparing the results between Scenario 2 and Scenario 6 because the only difference between the two is water depth. As shown in Figure 24, the NPV for Scenario 6 (water depth of 24") lies to the right of NPV for Scenario 2 (water depth of 14"), meaning that Scenario 6 will always be preferred by rational decision makers. The deeper water (Scenario 6) offers a higher NPV with less risk, assuming there is no loss in production due to increased water depths.

Annual mean water use increases from 1.5 billion gallons in Scenario 6 (24" of water depth) to 2.5 billion gallons in Scenario 2 (14" of water depth), a mean annual increase of 950 million gallons (62.2%) and 9.6 billion total additional gallons over the ten-year horizon. The shallower ponds require more water due to increased surface area and the resulting increase in evaporation loss.

Electricity use for deeper ponds (24") is lower than the 14" ponds due to less evaporation, resulting in less water being pumped, as well as fewer ponds. Annual mean electricity consumption increases from 15.7 million kWh in Scenario 6 to 23.0 million kWh in Scenario 2, an annual increase of 7.3 million kWh.

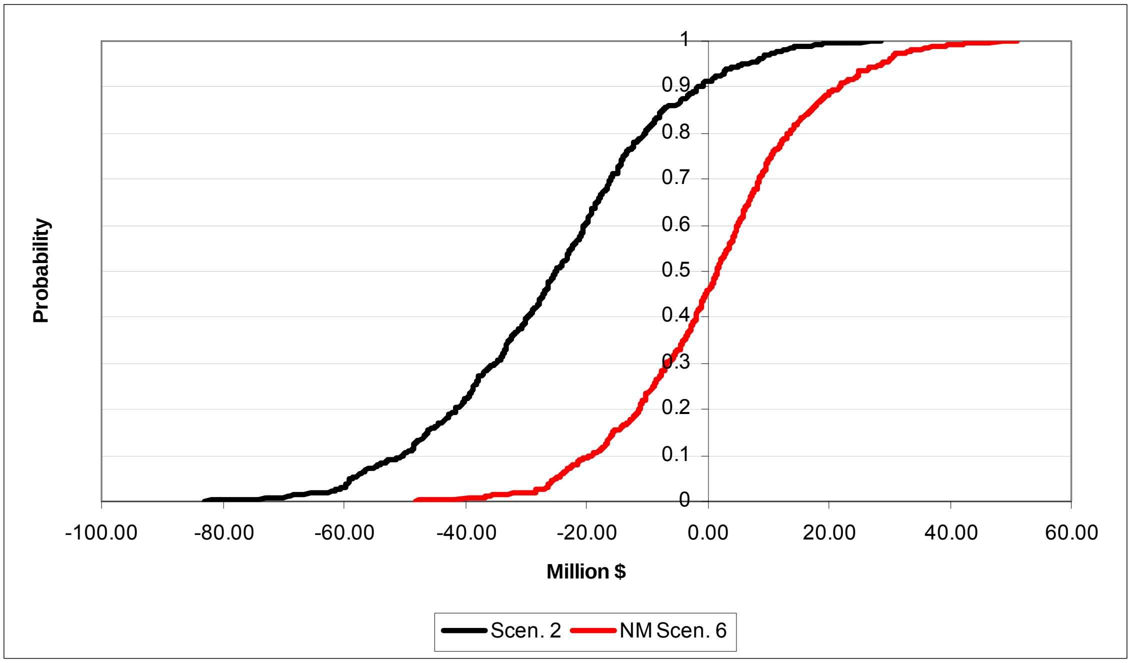

Figure 24. CDF of NPV for New Mexico Scenarios 2 & 6.

Figure 25 shows the SERF results for ranking the risky NPV distributions. The preferred scenario will depend on the decision maker's aversion to risk. Scenario 6 is preferred to all other scenarios at ARACs less than 0.0179. Scenario 6 is the only scenario that exhibits positive certainty equivalents, meaning this is the only scenario economically viable to a rational decision maker. However, only a risk neutral or normally risk averse decision maker would consider an investment in Scenario 6 because the certainty equivalents are negative at risk aversion levels greater than the ARAC for a normal risk averse decision maker . A rational investor would not invest in the Base Scenario, Scenario 2, Scenario 3, Scenario 4, or Scenario 5 because their certainty equivalents are negative across all levels of risk aversion. Scenario 4 is preferred to all other scenarios at ARACs greater than 0.0179 but a rational investor would not invest.

Scenario 3 is the fourth preferred scenario. Scenario 2 is the fifth preferred scenario while Base Scenario is the least preferred of the scenarios.

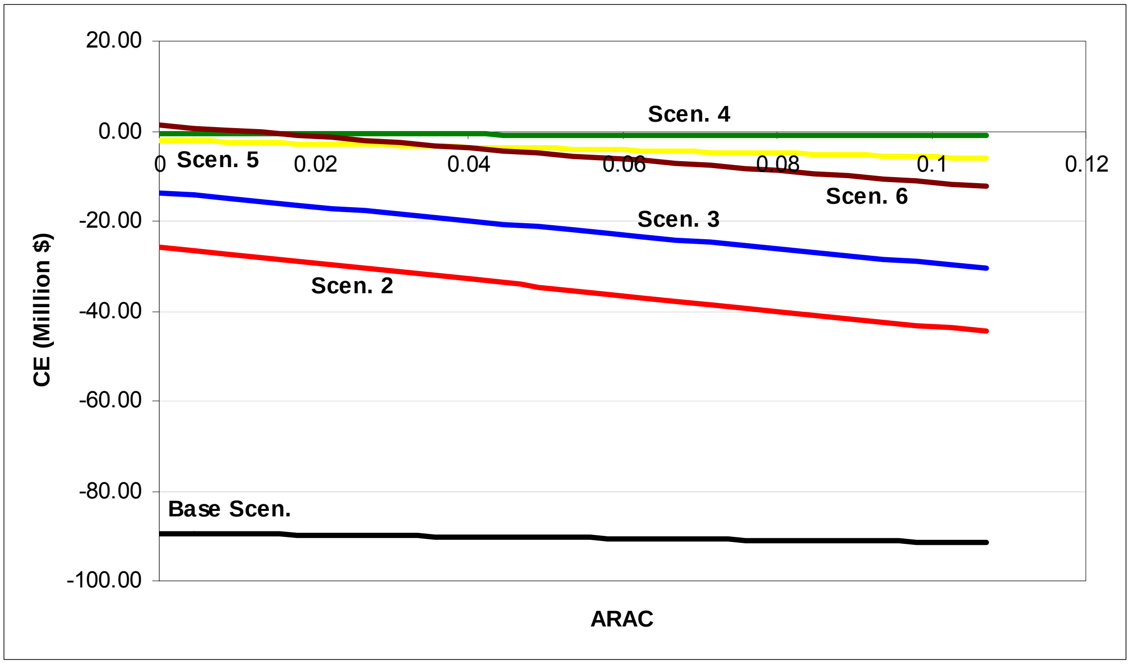

Figure 25. Stochastic efficiency with respect to a function (SERF) under a negative exponential utility function for NPV across six New Mexico Scenarios.

Figure 26 presents the CDFs for NPV across six scenarios, which show a risk-averse decision maker will prefer Scenario 6 because it offers the highest profit potential 57% of the time. The PDF of NPV (Figure 27) shows the risk associated with each of the scenarios. The larger facilities (with 1,000 acre feet of water) in Scenarios 2, 3, and 6 exhibit a wider distribution of results (i.e., more risk), noted by the shorter and wider distributions in the PDFs. The smaller facilities with 100 and 500 acre feet of water have narrower PDFs, indicating less risk. As facility size increases, the risk is compounded due to the greater input needs for: algae feed, total production, electricity used, and water used. All scenarios face the same stochastic prices and weather, so risk is a dis-economy to size. As expected, Scenario 4 exhibits the narrowest distribution of results for NPV because of the small size of the facility (100 acre feet of water). The Base Scenario and Scenario 5 demonstrate similar risk, with the Base Scenario showing a slightly more compact distribution, most likely the result of the low production that helped insulate the facility from end-product price risk. However, it is also important to notice that NPV is highly negative for the Base Scenario compared to Scenario 5, which has NPV results distributed around zero.

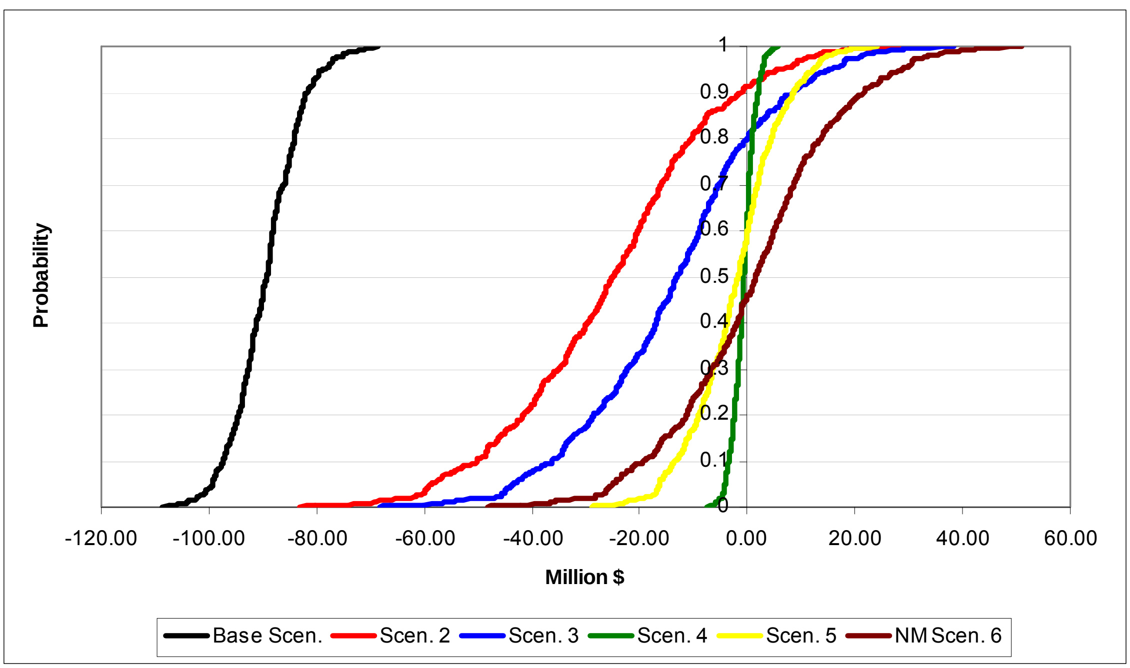

Figure 26. CDF of NPV for six New Mexico Scenarios.

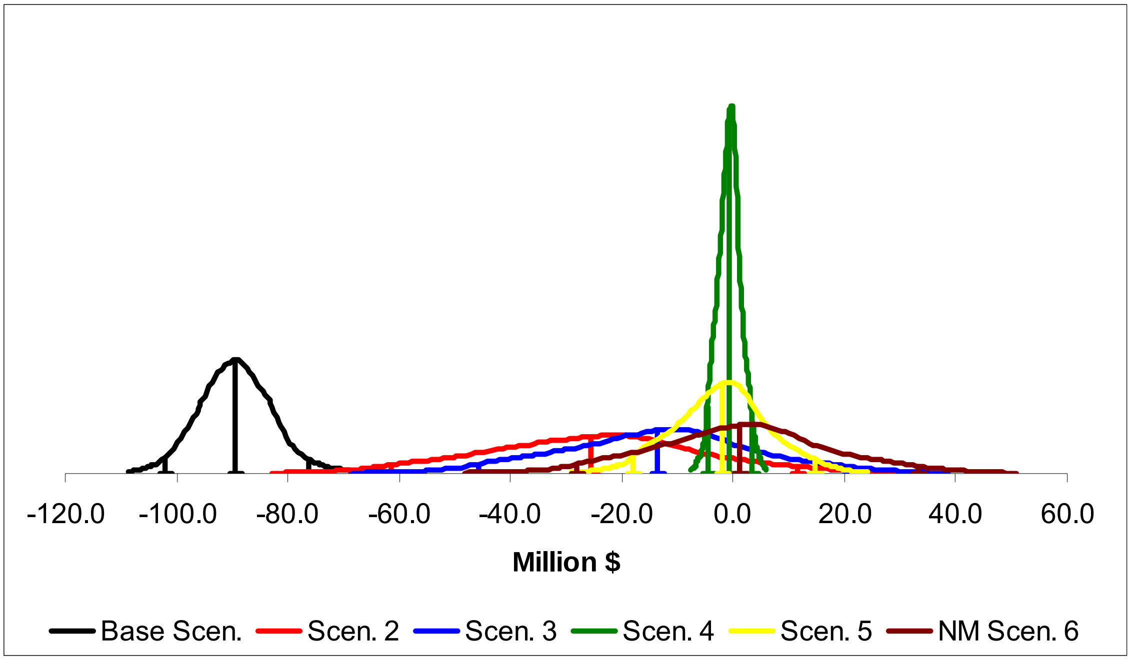

Figure 27. PDF approximations of NPV for six New Mexico Scenarios.

6.3.2. West Texas (Pecos) Simulation Results

Many of the scenarios for the Pecos, Texas, facility location were similar to the New Mexico scenarios (Table 23). The Base Scenario includes 1,000 acre feet of water, 24" of water depth, and the low production levels as suggested by the literature. The higher algae production levels are used across the remaining five scenarios. Total facility costs were also the same as the New Mexico Base Scenario at $74.7 million. Scenario 2 uses the higher production levels while decreasing water depth to 6". As a result total facility costs increase to $201.3 million, an increase of $126.6 million over the Base Scenario. Scenario 3 has a water depth of 12", with facility costs increasing to $112.8 million, an increase of $38.1 million over the Base Scenario. Scenarios 4, 5, and 6 are the same except for the variation in facility size. Scenario 4, with 100 acre feet of water, has a total facility cost of $8.9 million. Scenario 5, with 500 acre feet of water, has a total facility cost of $39.4 million. Scenario 6, with 1,000 acre feet o water, has a total facility cost of $74.7 million.

Table 23. Pecos, Texas Scenario Assumptions.

Scenario Name	Base Scen.	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6
Description	Base	Low Depth	Med. Depth	Small Size	Med. Size	High Prod.
Cost Level	Minimum	Minimum	Minimum	Minimum	Minimum	Minimum
Power Source	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.
Ac. Ft. of Water	1,000.00	1,000.00	1,000.00	100.00	500.00	1,000.00
Pond Length	700.00	700.00	700.00	700.00	700.00	700.00
Water Depth	24.00	6.00	12.00	24.00	24.00	24.00
% Recycled Water	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Source of Water	Ground	Ground	Ground	Ground	Ground	Ground
% High-Value Oil	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
Raceways/Pond	10.00	10.00	10.00	10.00	10.00	10.00
Prod. Levels (g/L/Day)						
Min	0.10	0.60	0.60	0.60	0.60	0.60
Mid	0.20	0.80	0.80	0.80	0.80	0.80
Max	0.30	1.00	1.00	1.00	1.00	1.00
Oil Contents (%)						
Min	0.15	0.30	0.30	0.30	0.30	0.30
Mid	0.18	0.40	0.40	0.40	0.40	0.40
Max	0.20	0.50	0.50	0.50	0.50	0.50
End Use of Algae Meal	Sales	Sales	Sales	Sales	Sales	Sales
CO2 Source	Air	Air	Air	Air	Air	Air
Total Facility Costs (Mil. $)	74.68	201.34	112.76	8.94	39.39	74.68
Total $ Financed (Mil. $)	37.34	100.67	56.38	4.47	19.69	37.34

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

The Base Scenario for West Texas was the same as the New Mexico Base Scenario except for the locations and weather risks. As can be observed from Figure 28, there is a 0% probability of a positive ending cash balance in every year for the Base Scenario. The mean ending cash balance in the tenth year of the analysis is -$128.5 million. Mean returns on investment range from -18.3% in the first year to -20.7% in the tenth year. As Table 24 exhibits, there was a 100.0% probability of a negative NPV or probability of failure and the facility has a mean NPV of -$89.2 million. Mean ending real net worth is -$66.2 million and there is 100% probability of losing real net worth.

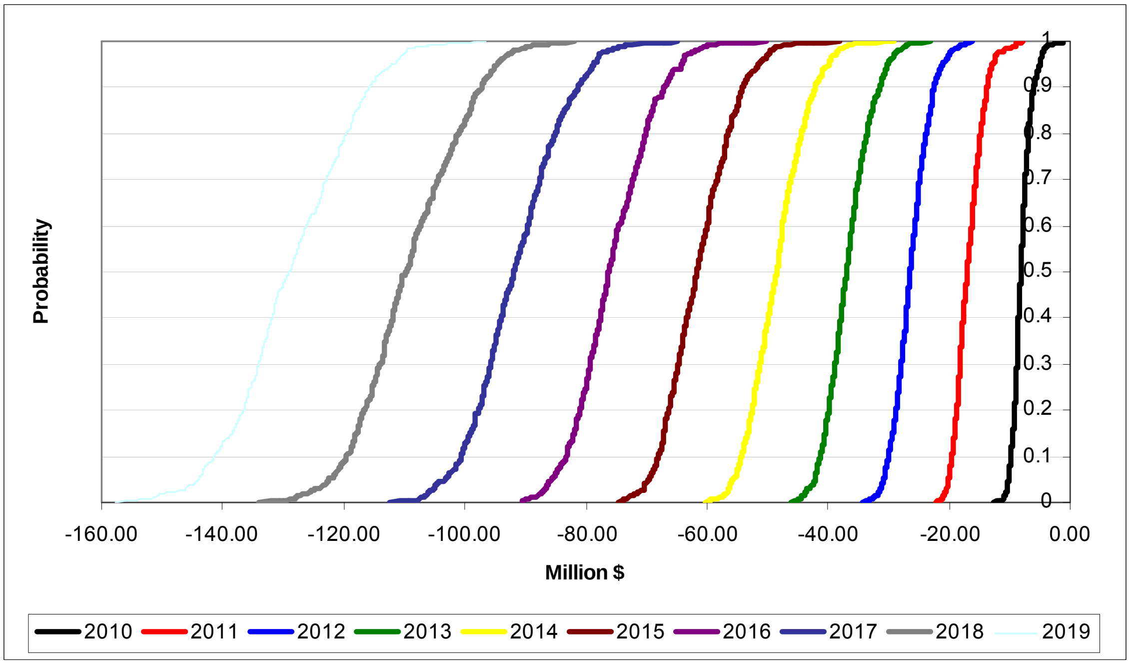

Figure 28. CDF of annual ending cash balances for Pecos, Texas Base Scenario, with water depth of 24”, 1,000 acre feet of water, and low production levels.

The average cost of producing a gallon of algae oil is $97.28, with costs of $17.54 in the first year and $193.22 in the final year of analysis. In the final year, $184.00 of the costs per gallon are accounted for by variable costs. Just like the NM Base Scenario, the escalating interest expenses due to servicing cash flow deficit loans year after year are the primary reason for the extremely high cost in the later years. It is again likely that the facility would not be able to obtain the necessary financing to continuing operating for the full ten-year horizon of the analysis.

Table 24. Averages and Probabilities of Key Output Variables for Pecos, Texas Base Scenario, with Water Depth of 24”, 1,000 Acre Feet of Water, and Low Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(89.16)
ERNW (Mil. $)										(66.24)
Prob. of Dec. RNW										100.0%
Prob. of Neg. NPV										100.0%
Prob. of Neg. ECB	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Total Rev. (Mil. $)	5.26	5.40	5.49	5.61	5.68	5.79	5.86	5.88	6.01	6.09
NCI (Mil. $)	(5.44)	(6.16)	(6.86)	(7.71)	(8.86)	(9.98)	(11.27)	(12.74)	(14.31)	(16.12)
Tx. Inc. (Mil. $)	(10.61)	(11.33)	(12.03)	(12.88)	(14.03)	(15.15)	(16.44)	(17.91)	(19.48)	(21.29)
Tx. Due (Mil. $)	-	-	-	-	-	-	-	-	-	-
ECB (Mil. $)	(7.96)	(16.71)	(26.22)	(36.67)	(48.35)	(61.25)	(75.54)	(91.42)	(109.00)	(128.52)
Net Worth (Mil. $)	15.10	5.57	(4.61)	(15.61)	(27.72)	(40.92)	(55.37)	(71.27)	(88.69)	(107.90)
Net Returns (Mil. $)	(10.61)	(11.33)	(12.03)	(12.88)	(14.03)	(15.15)	(16.44)	(17.91)	(19.48)	(21.29)
ROI	-18.3%	-18.8%	-18.8%	-19.0%	-19.3%	-19.5%	-19.8%	-20.1%	-20.4%	-20.7%
Interest Exp. (Mil. $)	3.77	4.30	4.99	5.78	6.82	7.88	9.04	10.40	11.86	13.56
Debt Exp. (Mil. $)	4.42	12.98	22.49	32.87	44.45	57.28	71.45	87.21	104.68	124.09
Var. Exp. (Mil. $)	6.97	15.86	25.46	36.02	47.78	60.79	75.14	91.05	108.75	128.35
Fixed Exp. (Mil. $)	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
Total Exp. (Mil. $)	13.22	22.11	31.72	42.28	54.03	67.04	81.40	97.30	115.00	134.61
Nut. % VE	9.5%	5.2%	2.9%	2.0%	1.5%	1.2%	1.0%	0.8%	0.7%	0.6%
Labor % VE	25.2%	11.1%	7.0%	5.0%	3.9%	3.2%	2.6%	2.2%	1.9%	1.7%
H & E L & M % VE	1.7%	0.8%	0.5%	0.4%	0.3%	0.2%	0.2%	0.2%	0.1%	0.1%
Chem. % VE	9.2%	4.3%	2.8%	2.0%	1.5%	1.2%	1.0%	0.9%	0.7%	0.6%
H & E NG % VE	38.5%	17.9%	11.5%	8.4%	6.5%	5.2%	4.3%	3.7%	3.2%	2.8%
Elec. Cons. % VE	13.0%	5.7%	3.7%	2.6%	2.0%	1.6%	1.3%	1.1%	1.0%	0.8%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	1.1%	0.7%	0.5%	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%
OI/DE % VE	0.5%	54.0%	71.0%	79.0%	83.8%	87.0%	89.2%	90.9%	92.2%	93.2%
H & E Exp. (Million)	3.62	3.74	3.85	3.97	4.08	4.17	4.27	4.35	4.49	4.60
Var. Exp.% TE	52.2%	71.4%	80.1%	85.1%	88.3%	90.6%	92.3%	93.5%	94.5%	95.3%
Fixed Exp. % TE	47.8%	28.6%	19.9%	14.9%	11.7%	9.4%	7.7%	6.5%	5.5%	4.7%
Int. Exp. % TE	28.8%	19.6%	15.8%	13.7%	12.6%	11.8%	11.1%	10.7%	10.3%	10.1%
DLR % TE	0.0%	35.8%	52.5%	61.9%	67.8%	72.1%	75.2%	77.6%	79.5%	81.0%
Tx. Due % TE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
H & E Exp. % TE	26.7%	16.8%	12.1%	9.3%	7.5%	6.2%	5.2%	4.5%	3.9%	3.4%
$/Gal. Oil (VE)	6.45	21.70	37.52	54.23	72.08	91.47	111.80	134.29	157.86	184.00
$/Gal. Oil (FE)	11.08	10.87	10.69	10.45	10.21	10.00	9.80	9.63	9.40	9.23
$/Gal. Oil (TE)	17.54	32.57	48.21	64.69	82.29	101.47	121.60	143.91	167.26	193.22
Growth Rate g/L/day)	0.20	0.20	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.21
Oil Content (%)	17.5%	17.6%	17.7%	17.8%	17.9%	17.9%	18.0%	18.1%	18.2%	18.3%
BM Prod. (1,000 ST)	14.74	14.89	15.02	15.24	15.30	15.47	15.67	15.71	15.93	16.04
BM Prod. (Tons/AF)	13.36	13.50	13.63	13.82	13.87	14.03	14.21	14.24	14.45	14.55
Oil Prod. (Mil. Gal.)	0.63	0.65	0.66	0.68	0.69	0.70	0.72	0.73	0.74	0.76
Oil Prod. (Gal./AF)	575	587	598	613	623	636	650	660	675	687
Meal Prod. (1,000 ST)	12.45	12.56	12.65	12.80	12.82	12.94	13.07	13.10	13.24	13.31
Meal Prod. (Tons/AF)	11.29	11.39	11.47	11.61	11.63	11.73	11.86	11.88	12.01	12.07
Water Loss (Bil. Gal.)	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46
NG Cons. (Mil. TCF)	0.39	0.40	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41
Elec. Cons. (Mil. kWh)	12.46	12.47	12.47	12.48	12.48	12.49	12.49	12.50	12.50	12.51

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 2 offers a comparison of altering water depths by decreasing the pond water depth to 6”. It should be noted that Scenario 2 does employ the high production parameters used throughout the five remaining scenarios for this location so profits and returns cannot be compared to the Base Scenario. Figure 29 shows the probability of negative ending cash balances, with a 92.8% probability in the first year and higher probabilities for additional years until the probability reaches 100% in year seven.

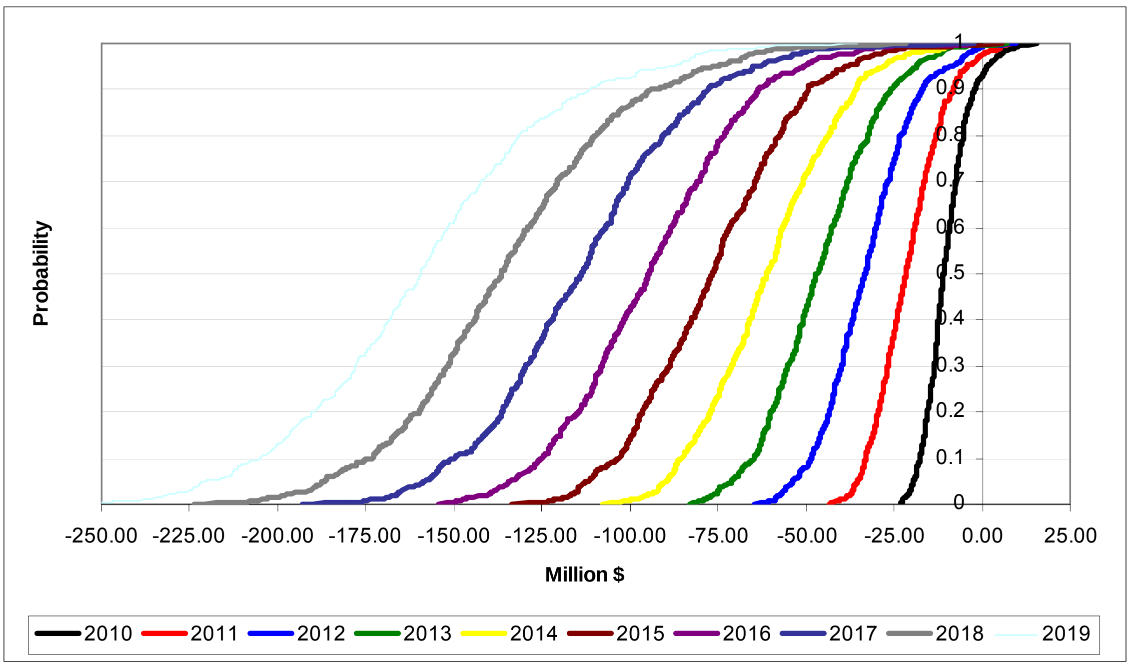

Figure 29. CDF of annual ending cash balances for Pecos, Texas Scenario 2, with water depth of 6”, 1,000 acre feet of water, and high production levels.

As Table 25 exhibits, the probability of a negative NPV is 100.0% with a mean NPV of -$124.8 million. Mean ending real net worth is -$63.4 million and there is a 100% probability of losing real net worth. Because of the shallow ponds, total facility costs rise significantly from the Base Scenario. Total facility costs are $74.7 million for the Base Scenario while Scenario 2 has total facility costs of $201.3 million (Table 23). Mean water use increases by 3.8 billion gallons annually over the Base Scenario, due to an increase in surface area open to evaporation. Such large quantities of water could become a major obstacle for the facility, even though it uses brackish water. Electricity use for the facility increases significantly, requiring an additional 21.9 million kWh annually and a total of 219.2 million kWh over the ten-year horizon, resulting in an average annual increase of 175.6% increase over the Base Scenario.

The mean cost of producing a gallon of algae oil for Scenario 2 is $5.18 in the first year and $29.76 in the final year, with an overall mean of $16.45. Mean variable costs constitute $1.79 of the cost in year one but increase to $26.94 in the final year. This is another case of mounting cash flow deficits (from negative net cash incomes) causing financial strain on the facility. Fixed costs per gallon of oil are $3.39 in the first year and fall to $2.83 in the tenth year of analysis as the facility is depreciated.

Table 25. Averages and Probabilities of Key Output Variables for Pecos, Texas Scenario 2, with Water Depth of 6”, 1,000 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(124.79)
ERNW (Mil. $)										(63.36)
Prob. of Dec. RNW										100.0%
Prob. of Neg. NPV										100.0%
Prob. of Neg. ECB	92.8%	97.4%	99.2%	99.6%	100.0%	99.8%	100.0%	100.0%	100.0%	100.0%
Total Rev. (Mil. $)	25.03	25.79	26.19	26.54	27.10	27.68	27.88	28.26	28.72	29.13
NCI (Mil. $)	(3.28)	(3.82)	(4.60)	(5.62)	(6.76)	(7.88)	(9.40)	(11.03)	(12.66)	(14.78)
Tx. Inc. (Mil. $)	(20.52)	(21.07)	(21.85)	(22.86)	(24.00)	(25.13)	(26.65)	(28.27)	(29.91)	(32.03)
Tx. Due (Mil. $)	0.01	0.02	0.03	0.05	0.02	0.03	0.02	0.01	0.01	0.00
ECB (Mil. $)	(10.15)	(21.02)	(32.87)	(45.96)	(60.39)	(76.21)	(93.81)	(113.33)	(134.82)	(158.81)
Net Worth (Mil. $)	52.01	39.05	25.40	10.82	(4.77)	(21.40)	(39.43)	(58.99)	(80.09)	(103.21)
Net Returns (Mil. $)	(20.52)	(21.07)	(21.85)	(22.86)	(24.00)	(25.13)	(26.65)	(28.27)	(29.91)	(32.03)
ROI	-10.3%	-10.2%	-10.2%	-10.4%	-10.4%	-10.3%	-10.6%	-10.6%	-10.7%	-10.9%
Interest Exp. (Mil. $)	10.17	10.78	11.53	12.38	13.58	14.72	16.02	17.56	19.14	21.05
Debt Exp. (Mil. $)	11.92	23.17	34.78	47.62	62.13	77.94	95.36	114.80	136.24	160.02
Var. Exp. (Mil. $)	18.24	30.18	42.22	55.57	70.59	86.95	104.79	124.69	146.66	171.06
Fixed Exp. (Mil. $)	16.94	16.95	16.95	16.96	16.92	16.94	16.91	16.90	16.89	16.88
Total Exp. (Mil. $)	35.18	47.13	59.17	72.53	87.51	103.89	121.70	141.59	163.54	187.94
Nut. % VE	3.3%	2.6%	1.7%	1.3%	1.0%	0.8%	0.7%	0.6%	0.5%	0.4%
Labor % VE	9.7%	6.1%	4.5%	3.5%	2.8%	2.4%	2.0%	1.7%	1.5%	1.3%
H & E L & M % VE	2.5%	1.6%	1.2%	1.0%	0.8%	0.6%	0.6%	0.5%	0.4%	0.4%
Chem. % VE	13.2%	8.7%	6.6%	5.2%	4.1%	3.4%	2.9%	2.5%	2.1%	1.8%
H & E NG % VE	54.5%	35.5%	26.8%	21.2%	17.1%	14.3%	12.2%	10.4%	9.1%	7.9%
Elec. Cons. % VE	13.8%	8.6%	6.5%	5.1%	4.1%	3.4%	2.8%	2.4%	2.1%	1.8%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	1.6%	1.2%	0.9%	0.7%	0.6%	0.5%	0.5%	0.4%	0.3%
OI/DE % VE	0.5%	35.4%	51.5%	61.7%	69.3%	74.5%	78.3%	81.5%	84.0%	86.0%
H & E Exp. (Million $)	13.28	13.74	14.13	14.54	14.92	15.36	15.66	16.02	16.42	16.90
Var. Exp.% TE	51.3%	63.2%	70.3%	75.5%	79.7%	82.9%	85.4%	87.5%	89.2%	90.6%
Fixed Exp. % TE	48.7%	36.8%	29.7%	24.5%	20.3%	17.1%	14.6%	12.5%	10.8%	9.4%
Int. Exp. % TE	29.2%	23.3%	20.0%	17.6%	15.9%	14.5%	13.4%	12.6%	11.8%	11.3%
DLR % TE	0.0%	21.1%	34.0%	43.4%	50.9%	56.6%	61.3%	65.2%	68.4%	71.0%
Tx. Due % TE	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
H & E Exp. % TE	37.1%	29.2%	24.3%	20.6%	17.7%	15.3%	13.4%	11.8%	10.4%	9.3%
$/Gal. Oil (VE)	1.79	4.07	6.31	8.69	11.33	14.06	16.89	19.89	23.45	26.94
$/Gal. Oil (FE)	3.39	3.34	3.27	3.20	3.13	3.08	3.01	2.94	2.90	2.83
$/Gal. Oil (TE)	5.18	7.42	9.58	11.89	14.46	17.14	19.90	22.83	26.34	29.76
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	53.95	54.62	55.12	55.69	56.23	56.84	57.33	57.81	58.39	58.88
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	5.30	5.43	5.53	5.65	5.76	5.90	6.00	6.11	6.24	6.35
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	34.69	34.84	34.96	35.10	35.23	35.33	35.45	35.59	35.62	35.76
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
NG Cons. (Mil. TCF)	1.44	1.45	1.46	1.46	1.47	1.48	1.48	1.49	1.50	1.51
Elec. Cons. (Mil. kWh)	34.32	34.34	34.36	34.38	34.40	34.42	34.43	34.46	34.48	34.50

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 3 is similar to Scenario 2, with a water depth of 12” instead of 6”. Although the results improve over those from Scenario 2, the financial status of the facility is still not at desirable levels for investors. In Figure 30, the probability of a negative ending cash balance is 66.2% in the first year and only worsens in successive years, with the final year having an 87.2% probability of a negative ending cash balance. Scenario 3 has a 100% probability of losing real net worth, with a mean ending real net worth -$2.1 million, meaning that the facility loses more than 100% of its initial investment after adjusting for inflation. Mean NPV is -$35.3 million, with a 95.8% probability of NPV being negative. Mean returns on investment were negative for all years, with returns ranging from -1.5% in the first year to -2.2% in the final year.

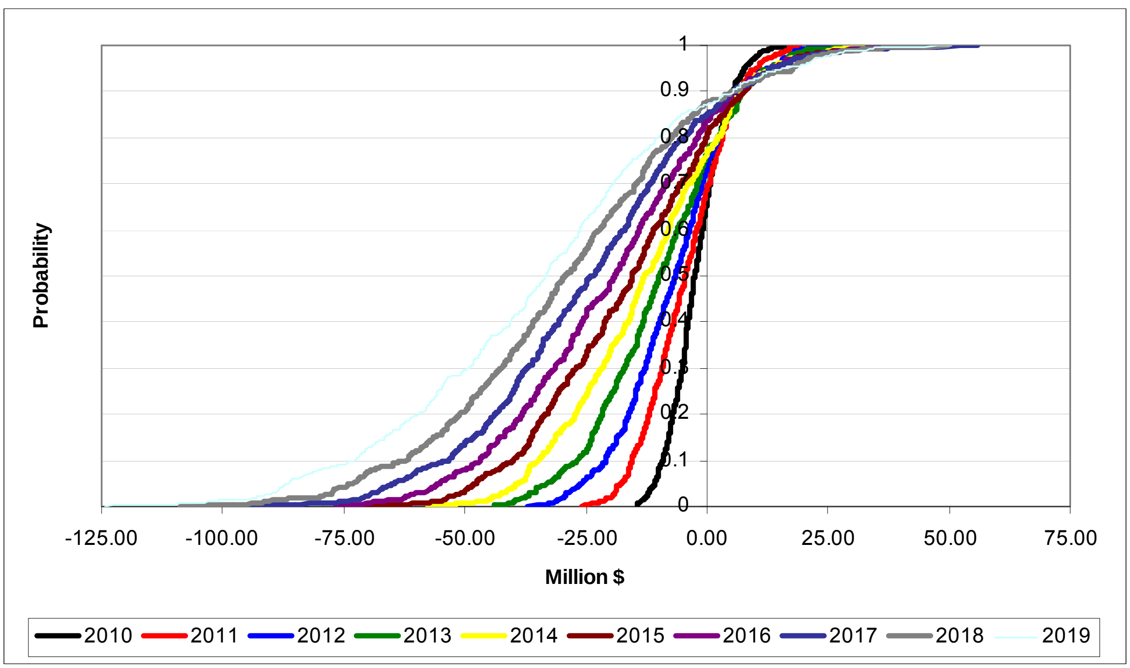

Figure 30. CDF of annual ending cash balance for Pecos, Texas Scenario 3, with water depth of 12”, 1,000 acre feet of water, and high production levels.

As Table 26 shows, mean net cash incomes are highest in year one at \$2.2 million and fall each year to \$0.03 million in the final year. Relative to the Base Scenario mean water usage increases in Scenario 3 by 1.2 billion gallons annually, which equates to an annual increase of 79.5%. Over the life of the analysis, an additional 11.6 billion gallons of water are used for Scenario 3, compared to the Base Scenario. Electricity usage decreases compared to Scenario 2, but is still higher than the base scenario, with Scenario 3 requiring an additional 6.5 million kWh annually over the base scenario, an average annual increase of 52.1%. Total additional electricity required over the ten year horizon is 65.0 million kWh over the Base Scenario.

The mean cost of producing a gallon of oil is \$6.31, which is a considerable improvement over Scenario 2 but obviously still not as efficient as the scenarios that use 24" water depths. Of that \$6.31, variable costs account for \$4.50 and fixed costs account for \$1.81. Over the ten-year horizon, annual mean fixed costs fall to \$1.64 per gallon while variable costs more than quadruple to \$7.65 from year one to ten because of debt servicing costs (Table 26). Over the time period, annual debt-related expenses rise from \$6.7 million to \$40.7 million.

Table 26. Averages and Probabilities of Key Output Variables for Pecos, Texas Scenario 3, with Water Depth of 12", 1,000 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(35.29)
ERNW (Mil. $)										(2.05)
Prob. of Dec. RNW										100.0%
Prob. of Neg. NPV										95.8%
Prob. of Neg. ECB	66.2%	68.6%	73.0%	76.4%	76.0%	80.2%	83.6%	84.8%	87.6%	87.2%
Total Rev. (Mil. $)	24.86	25.62	26.02	26.36	26.92	27.49	27.69	28.07	28.53	28.94
NCI (Mil. $)	2.19	2.11	1.98	1.72	1.58	1.48	1.09	0.80	0.53	0.03
Tx. Inc. (Mil. $)	(6.60)	(6.69)	(6.82)	(7.07)	(7.21)	(7.31)	(7.70)	(8.00)	(8.27)	(8.77)
Tx. Due (Mil. $)	0.24	0.29	0.31	0.31	0.27	0.34	0.29	0.25	0.27	0.29
ECB (Mil. $)	(2.03)	(4.27)	(6.75)	(9.58)	(12.65)	(16.02)	(19.90)	(24.20)	(28.97)	(34.47)
Net Worth (Mil. $)	32.78	29.38	25.89	22.22	18.50	14.68	10.55	6.23	1.68	(3.33)
Net Returns (Mil. $)	(6.60)	(6.69)	(6.82)	(7.07)	(7.21)	(7.31)	(7.70)	(8.00)	(8.27)	(8.77)
ROI	-1.5%	-1.4%	-1.4%	-1.6%	-1.5%	-1.4%	-1.7%	-1.8%	-1.9%	-2.2%
Interest Exp. (Mil. $)	5.73	5.90	6.04	6.16	6.38	6.53	6.72	6.96	7.18	7.51
Debt Exp. (Mil. $)	6.72	10.46	13.26	16.09	19.38	22.80	26.51	30.66	35.34	40.70
Var. Exp. (Mil. $)	17.03	21.45	24.64	27.95	31.71	35.66	39.77	44.35	49.53	55.48
Fixed Exp. (Mil. $)	9.86	9.91	9.94	9.93	9.89	9.96	9.92	9.86	9.88	9.89
Total Exp. (Mil. $)	26.90	31.36	34.58	37.88	41.60	45.63	49.69	54.21	59.41	65.37
Nut. % VE	3.6%	3.6%	3.0%	2.7%	2.4%	2.2%	2.1%	1.8%	1.7%	1.6%
Labor % VE	10.5%	8.6%	7.8%	7.3%	6.8%	6.5%	6.1%	5.7%	5.4%	5.1%
H & E L & M % VE	2.7%	2.3%	2.1%	2.0%	1.8%	1.8%	1.7%	1.5%	1.5%	1.4%
Chem. % VE	14.1%	12.2%	11.3%	10.6%	9.9%	9.2%	8.7%	8.0%	7.5%	6.9%
H & E NG % VE	58.1%	48.9%	45.3%	42.4%	39.8%	37.6%	35.4%	33.2%	30.8%	28.9%
Elec. Cons. % VE	8.2%	6.7%	6.2%	5.8%	5.4%	5.1%	4.7%	4.4%	4.1%	3.8%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.1%	1.9%	1.8%	1.7%	1.6%	1.5%	1.4%	1.3%	1.2%
OI/DE % VE	0.5%	15.7%	22.3%	27.4%	32.2%	36.1%	39.9%	43.9%	47.7%	51.2%
H & E Exp. (Million $)	13.19	13.65	14.03	14.44	14.82	15.25	15.56	15.92	16.31	16.79
Var. Exp.% TE	62.7%	67.5%	69.9%	72.0%	74.1%	75.7%	77.3%	79.0%	80.5%	81.9%
Fixed Exp. % TE	37.3%	32.5%	30.1%	28.0%	25.9%	24.3%	22.7%	21.0%	19.5%	18.1%
Int. Exp. % TE	21.7%	19.3%	18.1%	17.0%	16.1%	15.1%	14.3%	13.5%	12.7%	12.0%
DLR % TE	0.0%	10.0%	15.0%	19.1%	23.0%	26.4%	29.6%	33.2%	36.5%	39.7%
Tx. Due % TE	0.8%	0.8%	0.9%	0.7%	0.7%	0.8%	0.6%	0.5%	0.5%	0.5%
H & E Exp. % TE	48.2%	43.4%	41.3%	39.6%	37.8%	36.2%	34.7%	33.0%	31.2%	29.6%
$/Gal. Oil (VE)	1.57	2.38	2.94	3.49	4.13	4.75	5.33	5.93	6.82	7.65
$/Gal. Oil (FE)	1.97	1.94	1.90	1.86	1.82	1.80	1.76	1.71	1.68	1.64
$/Gal. Oil (TE)	3.54	4.32	4.85	5.36	5.95	6.55	7.08	7.64	8.50	9.30
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	53.59	54.25	54.75	55.32	55.86	56.45	56.95	57.42	57.99	58.48
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	5.26	5.39	5.50	5.61	5.72	5.86	5.96	6.07	6.20	6.30
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	34.46	34.61	34.72	34.87	35.00	35.10	35.21	35.35	35.38	35.52
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63
NG Cons. (Mil. TCF)	1.43	1.44	1.45	1.45	1.46	1.47	1.47	1.48	1.49	1.50
Elec. Cons. (Mil. kWh)	18.90	18.92	18.94	18.96	18.98	19.00	19.02	19.04	19.06	19.08

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 4 is the same as NM Scenario 4, decreasing the facility size from 1,000 acre feet of water to 100 acre feet of water, with water depth at 24". The probability of positive ending cash balances is centered around 39% (Figure 31). The probability distribution is the narrowest in the first year with each successive year having a wider distribution. This result reinforces the concept that the further out the forecast, the greater the amount of uncertainty that exists in the forecast. There is 59.0% probability of a negative NPV and a 90.0% probability of losing real net worth (Table 27).

Mean annual return on investment averages 9.5% and ranges from a high of 10.0% in the third year to a low of 8.3% in the final year. Table 27 shows mean annual net cash incomes of $0.5 million, with that value remaining steady across the ten-year horizon. It can also be observed that mean gross oil production ranges from 0.71 to 0.85 million gallons over the ten-year horizon, with steady increases each year. Ending real net worth has a mean of $2.0 million, while net present value has a mean of -$0.5 million. The overall mean cost for producing a gallon of oil is $3.66. Variable expenses account for $2.46 while the remaining $1.19 accounts for the fixed costs.

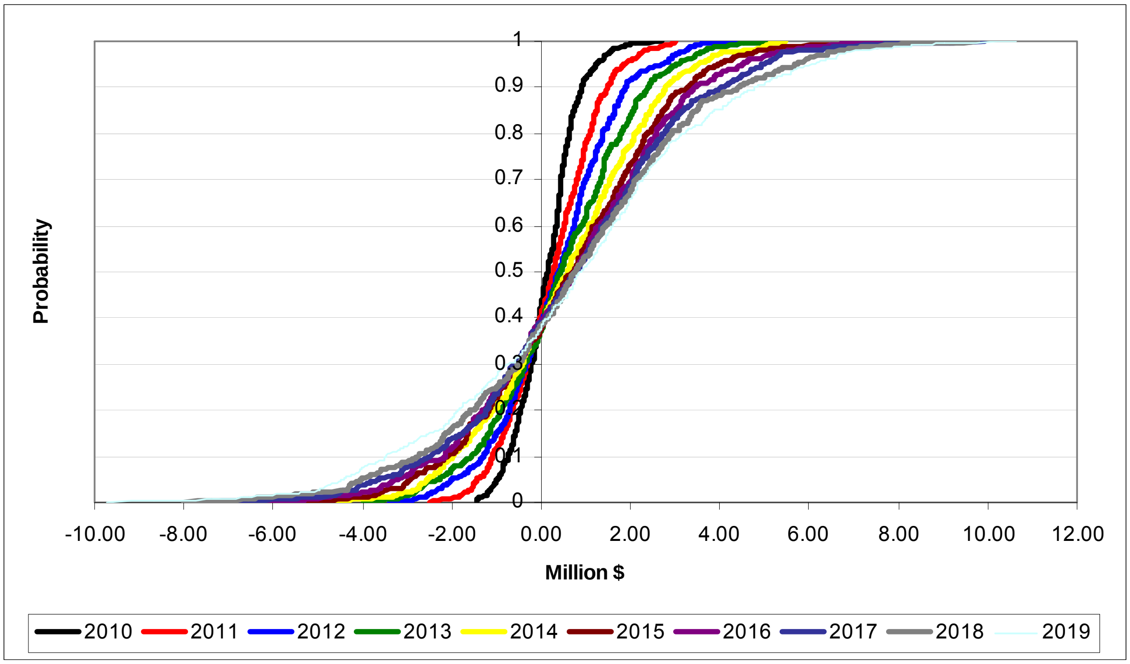

Figure 31. CDF of annual ending cash balances for Pecos, Texas Scenario 4, with water depth of 24”, 100 acre feet of water, and high production levels.

Table 27. Averages and Probabilities of Key Output Variables for Pecos, Texas Scenario 4, with Water Depth of 24”, 100 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(0.48)
ERNW (Mil. $)										2.00
Prob. of Dec. RNW										90.0%
Prob. of Neg. NPV										59.0%
Prob. of Neg. ECB	43.2%	40.6%	38.6%	37.2%	38.4%	37.8%	39.4%	38.8%	38.0%	38.4%
Total Rev. (Mil. $)	3.34	3.45	3.50	3.55	3.62	3.70	3.72	3.77	3.84	3.89
NCI (Mil. $)	0.57	0.57	0.57	0.55	0.56	0.57	0.55	0.54	0.54	0.52
Tx. Inc. (Mil. $)	(0.02)	(0.02)	(0.02)	(0.04)	(0.03)	(0.02)	(0.05)	(0.05)	(0.05)	(0.07)
Tx. Due (Mil. $)	0.11	0.12	0.12	0.12	0.12	0.13	0.13	0.12	0.13	0.13
ECB (Mil. $)	0.12	0.24	0.35	0.45	0.54	0.64	0.69	0.74	0.78	0.79
Net Worth (Mil. $)	2.88	2.91	2.94	2.97	3.01	3.07	3.10	3.16	3.21	3.26
Net Returns (Mil. $)	(0.02)	(0.02)	(0.02)	(0.04)	(0.03)	(0.02)	(0.05)	(0.05)	(0.05)	(0.07)
ROI	9.8%	10.0%	10.0%	9.6%	9.8%	9.9%	9.3%	9.1%	8.9%	8.3%
Interest Exp. (Mil. $)	0.46	0.47	0.47	0.47	0.47	0.47	0.46	0.46	0.45	0.44
Debt Exp. (Mil. $)	0.54	0.76	0.86	0.94	1.02	1.11	1.18	1.24	1.30	1.39
Var. Exp. (Mil. $)	2.33	2.64	2.79	2.94	3.08	3.25	3.37	3.50	3.62	3.79
Fixed Exp. (Mil. $)	0.89	0.90	0.91	0.90	0.91	0.91	0.92	0.90	0.91	0.91
Total Exp. (Mil. $)	3.22	3.54	3.70	3.84	3.99	4.15	4.29	4.40	4.53	4.70
Nut. % VE	3.5%	3.9%	3.4%	3.2%	3.1%	3.0%	3.0%	2.8%	2.8%	2.7%
Labor % VE	13.9%	12.5%	12.2%	12.0%	11.9%	11.8%	11.8%	11.8%	11.9%	11.9%
H & E L & M % VE	2.6%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%
Chem. % VE	13.9%	13.1%	13.0%	12.9%	12.7%	12.4%	12.3%	12.2%	12.1%	12.0%
H & E NG % VE	57.1%	52.6%	51.7%	51.2%	50.8%	50.1%	49.8%	49.7%	49.6%	49.3%
Elec. Cons. % VE	6.0%	5.5%	5.4%	5.3%	5.2%	5.2%	5.1%	5.1%	5.0%	5.0%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.3%	2.2%	2.2%	2.2%	2.1%	2.1%	2.1%	2.1%	2.1%
OI/DE % VE	0.5%	7.7%	9.7%	10.7%	11.8%	13.0%	13.5%	14.0%	14.2%	14.6%
H & E Exp. (Million $)	1.77	1.84	1.89	1.94	1.99	2.05	2.09	2.14	2.19	2.26
Var. Exp.% TE	71.9%	74.1%	74.9%	75.7%	76.3%	77.0%	77.3%	78.1%	78.4%	78.8%
Fixed Exp. % TE	28.1%	25.9%	25.1%	24.3%	23.7%	23.0%	22.7%	21.9%	21.6%	21.2%
Int. Exp. % TE	14.7%	13.6%	13.1%	12.6%	12.2%	11.6%	11.1%	10.7%	10.1%	9.6%
DLR % TE	0.0%	5.2%	6.7%	7.5%	8.4%	9.4%	9.8%	10.2%	10.5%	11.0%
Tx. Due % TE	3.1%	3.0%	3.1%	2.9%	2.9%	2.9%	3.0%	2.6%	2.8%	2.8%
H & E Exp. % TE	54.3%	51.5%	51.2%	51.2%	50.9%	50.5%	50.5%	50.7%	50.7%	50.6%
$/Gal. Oil (VE)	1.62	2.02	2.19	2.31	2.45	2.61	2.71	2.76	2.90	3.06
$/Gal. Oil (FE)	1.29	1.27	1.25	1.23	1.20	1.18	1.17	1.13	1.12	1.09
$/Gal. Oil (TE)	2.92	3.29	3.44	3.54	3.65	3.79	3.89	3.89	4.02	4.15
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	7.21	7.30	7.36	7.44	7.51	7.59	7.66	7.72	7.80	7.87
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	0.71	0.73	0.74	0.76	0.77	0.79	0.80	0.82	0.83	0.85
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	4.63	4.65	4.67	4.69	4.71	4.72	4.74	4.75	4.76	4.78
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
NG Cons. (Mil. TCF)	0.19	0.19	0.19	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Elec. Cons. (Mil. kWh)	1.91	1.92	1.92	1.92	1.92	1.93	1.93	1.93	1.93	1.94

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 5 examines the effects of a facility with 500 acre feet of water. Figure 32 shows the probability of a negative ending cash balance in the first year is 43.0%, with the probability falling steadily to 36.8% in the final year of the analysis. Mean ending cash balances begin at \$0.5 million and rise every year to \$3.4 million in the final year of the analysis, but the minimums and maximums widen as the forecast goes to ten years. The increased risk is also exhibited in the probability of negative ending cash balances (Table 28).

Table 28 shows total revenues for the facility have a mean of \$13.9-\$16.2 million while average net worth ranges from \$12.7-\$14.3 million. There is a 91.0% probability of losing real net worth. Ending real net worth has a mean of \$8.8 million. The mean

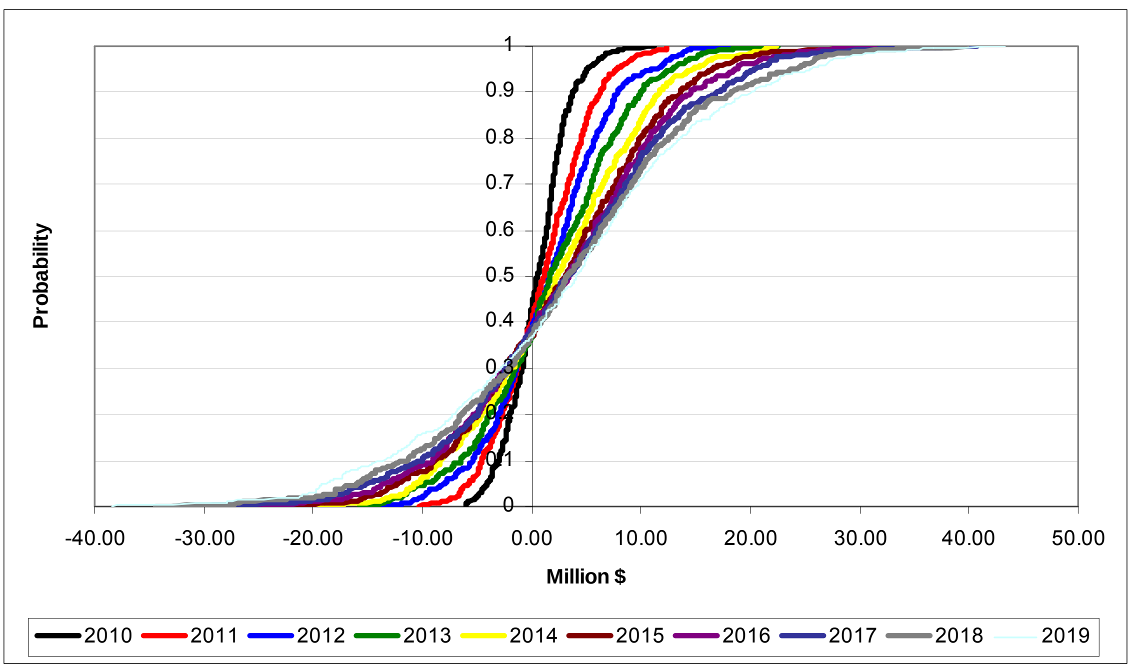

Figure 32. CDF of annual ending cash balances for Pecos, Texas Scenario 5, with water depth of 24", 500 acre feet of water, and high production levels.

cost of producing a gallon of oil is lower at $3.65, a decrease of $0.01 over Scenario 4, which indicates that economies of scale could exist for microalgae facilities. Mean variable costs per gallon fall by $0.06 while mean fixed costs rise by $0.06 per gallon.

Table 28. Averages and Probabilities of Key Output Variables for Pecos, Texas Scenario 5, with Water Depth of 24”, 500 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(2.16)
ERNW (Mil. $)										8.79
Prob. of Dec. RNW										91.0%
Prob. of Neg. NPV										60.0%
Prob. of Neg. ECB	43.0%	39.8%	38.6%	37.0%	38.2%	37.0%	38.4%	38.2%	37.0%	36.8%
Total Rev. (Mil. $)	13.93	14.36	14.58	14.77	15.09	15.41	15.52	15.73	15.99	16.22
NCI (Mil. $)	2.43	2.44	2.45	2.38	2.42	2.47	2.38	2.37	2.39	2.32
Tx. Inc. (Mil. $)	(0.23)	(0.22)	(0.22)	(0.28)	(0.24)	(0.20)	(0.29)	(0.29)	(0.27)	(0.35)
Tx. Due (Mil. $)	0.44	0.48	0.49	0.49	0.50	0.52	0.55	0.49	0.53	0.52
ECB (Mil. $)	0.52	1.01	1.48	1.87	2.27	2.69	2.93	3.19	3.38	3.44
Net Worth (Mil. $)	12.68	12.76	12.88	12.98	13.15	13.41	13.57	13.82	14.09	14.32
Net Returns (Mil. $)	(0.23)	(0.22)	(0.22)	(0.28)	(0.24)	(0.20)	(0.29)	(0.29)	(0.27)	(0.35)
ROI	9.1%	9.3%	9.4%	9.0%	9.2%	9.3%	8.8%	8.6%	8.5%	7.9%
Interest Exp. (Mil. $)	2.02	2.06	2.06	2.05	2.06	2.04	2.01	1.98	1.94	1.91
Debt Exp. (Mil. $)	2.36	3.30	3.71	4.03	4.37	4.73	5.03	5.27	5.48	5.85
Var. Exp. (Mil. $)	9.53	10.84	11.47	12.06	12.66	13.32	13.85	14.33	14.82	15.52
Fixed Exp. (Mil. $)	3.88	3.92	3.94	3.94	3.94	3.96	4.00	3.93	3.98	3.97
Total Exp. (Mil. $)	13.41	14.76	15.41	16.00	16.60	17.28	17.85	18.26	18.80	19.50
Nut. % VE	3.6%	4.0%	3.5%	3.3%	3.2%	3.1%	3.0%	2.9%	2.8%	2.8%
Labor % VE	12.4%	11.1%	10.8%	10.7%	10.6%	10.5%	10.5%	10.5%	10.6%	10.6%
H & E L & M % VE	2.7%	2.5%	2.5%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%
Chem. % VE	14.2%	13.3%	13.2%	13.1%	12.9%	12.6%	12.5%	12.4%	12.3%	12.2%
H & E NG % VE	58.1%	53.4%	52.5%	52.0%	51.6%	50.9%	50.6%	50.5%	50.4%	50.2%
Elec. Cons. % VE	6.1%	5.5%	5.5%	5.4%	5.3%	5.2%	5.2%	5.2%	5.1%	5.1%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.2%	2.2%	2.2%	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%
OI/DE % VE	0.5%	7.8%	9.8%	10.8%	11.9%	13.1%	13.6%	14.0%	14.1%	14.5%
H & E Exp. (Million $)	7.39	7.65	7.86	8.09	8.31	8.55	8.72	8.92	9.14	9.41
Var. Exp.% TE	70.7%	72.9%	73.8%	74.6%	75.2%	75.9%	76.3%	77.0%	77.3%	77.7%
Fixed Exp. % TE	29.3%	27.1%	26.2%	25.4%	24.8%	24.1%	23.7%	23.0%	22.7%	22.3%
Int. Exp. % TE	15.5%	14.4%	13.8%	13.3%	12.8%	12.2%	11.7%	11.2%	10.6%	10.1%
DLR % TE	0.0%	5.2%	6.7%	7.5%	8.4%	9.4%	9.8%	10.2%	10.4%	10.8%
Tx. Due % TE	3.0%	2.9%	3.0%	2.8%	2.9%	2.8%	3.0%	2.6%	2.8%	2.8%
H & E Exp. % TE	54.3%	51.5%	51.2%	51.2%	51.0%	50.6%	50.5%	50.9%	50.9%	50.8%
$/Gal. Oil (VE)	1.56	1.96	2.13	2.25	2.38	2.55	2.65	2.69	2.82	2.97
$/Gal. Oil (FE)	1.35	1.33	1.31	1.29	1.26	1.24	1.23	1.18	1.18	1.15
$/Gal. Oil (TE)	2.92	3.29	3.44	3.54	3.64	3.79	3.87	3.88	4.00	4.12
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	30.03	30.40	30.68	31.00	31.30	31.64	31.91	32.18	32.50	32.77
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	2.95	3.02	3.08	3.15	3.21	3.28	3.34	3.40	3.47	3.53
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	19.31	19.39	19.46	19.54	19.61	19.67	19.73	19.81	19.82	19.90
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
NG Cons. (Mil. TCF)	0.80	0.81	0.81	0.81	0.82	0.82	0.83	0.83	0.83	0.84
Elec. Cons. (Mil. kWh)	7.97	7.98	7.99	8.00	8.01	8.02	8.03	8.05	8.06	8.07

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 6 considers a microalgae facility with 1,000 acre feet of water and 24" of water depth. As shown in Figure 33, ending cash balances became positive at probabilities of 38.4% and greater in the first year and at probabilities less than 35.2% in the successive years, with the final year having a 26.2% probability of a negative ending cash balance. The mean NPV was $1.3 million, with a 44.6% probability of a negative NPV and economic failure (Table 29). The probability of losing real net worth was 86.2%. Mean annual net cash incomes for the ten-year horizon stayed between $5.4 and $5.7 million. Mean rates of return on investment ranged from 10.1% to 11.2%.

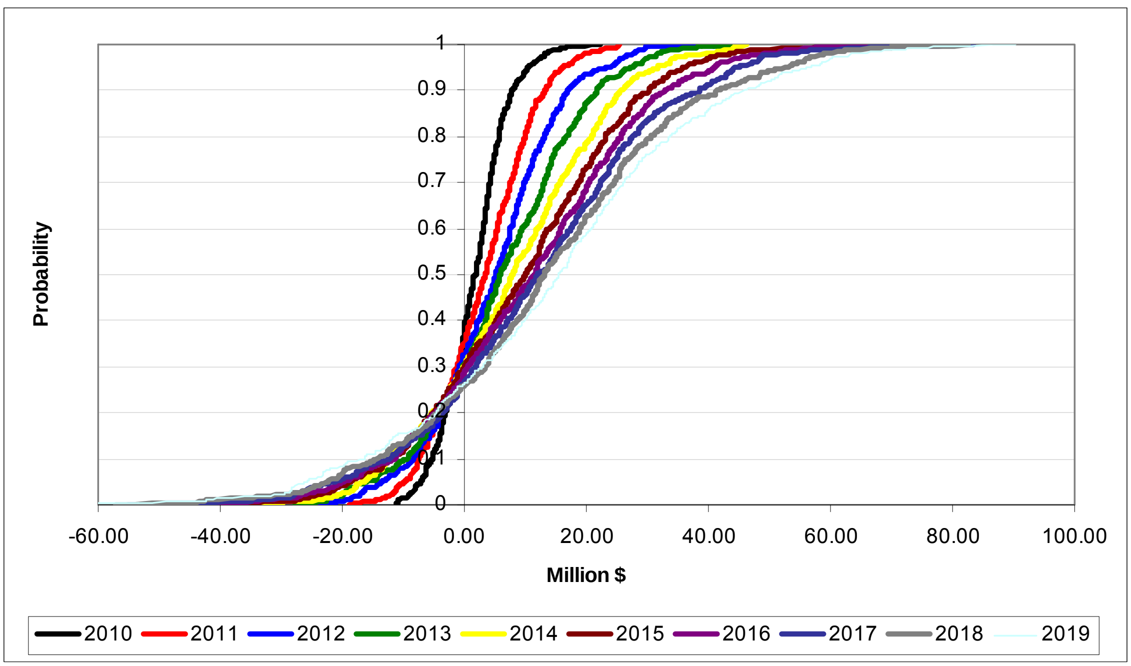

Figure 33. CDF of annual ending cash balances for Pecos, Texas Scenario 6, with water depth of 24", 1,000 acre feet of water, and high production levels.

Table 29. Averages and Probabilities of Key Output Variables for Pecos, Texas Scenario 6, with Water Depth of 24”, 1,000 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										1.27
ERNW (Mil. $)										21.73
Prob. of Dec. RNW										86.2%
Prob. of Neg. NPV										44.6%
Prob. of Neg. ECB	38.4%	35.2%	32.4%	30.4%	30.0%	29.8%	28.8%	26.8%	26.0%	26.2%
Total Rev. (Mil. $)	27.31	28.14	28.58	28.96	29.57	30.20	30.42	30.83	31.33	31.78
NCI (Mil. $)	5.41	5.46	5.50	5.40	5.53	5.65	5.52	5.56	5.64	5.55
Tx. Inc. (Mil. $)	0.24	0.29	0.32	0.23	0.36	0.48	0.35	0.39	0.47	0.38
Tx. Due (Mil. $)	0.98	1.05	1.09	1.09	1.10	1.15	1.22	1.11	1.19	1.19
ECB (Mil. $)	1.61	3.21	4.78	6.26	7.81	9.43	10.78	12.21	13.59	14.78
Net Worth (Mil. $)	24.67	25.49	26.40	27.32	28.44	29.76	30.95	32.37	33.89	35.40
Net Returns (Mil. $)	0.24	0.29	0.32	0.23	0.36	0.48	0.35	0.39	0.47	0.38
ROI	10.9%	11.2%	11.2%	10.9%	11.2%	11.3%	10.8%	10.7%	10.6%	10.1%
Interest Exp. (Mil. $)	3.83	3.88	3.87	3.84	3.82	3.76	3.68	3.58	3.48	3.40
Debt Exp. (Mil. $)	4.48	6.01	6.55	6.92	7.32	7.68	7.90	8.01	8.10	8.51
Var. Exp. (Mil. $)	18.16	20.41	21.37	22.26	23.15	24.09	24.74	25.30	25.93	26.97
Fixed Exp. (Mil. $)	7.53	7.61	7.66	7.65	7.67	7.72	7.81	7.68	7.78	7.77
Total Exp. (Mil. $)	25.70	28.02	29.03	29.91	30.82	31.81	32.54	32.98	33.71	34.74
Nut. % VE	3.7%	4.2%	3.7%	3.5%	3.4%	3.3%	3.3%	3.1%	3.1%	3.0%
Labor % VE	9.8%	9.0%	8.8%	8.8%	8.7%	8.7%	8.8%	8.8%	9.0%	8.9%
H & E L & M % VE	2.7%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.7%	2.7%
Chem. % VE	14.6%	13.9%	13.9%	13.9%	13.7%	13.5%	13.5%	13.5%	13.5%	13.3%
H & E NG % VE	59.8%	55.5%	55.0%	54.8%	54.6%	54.3%	54.3%	54.7%	54.9%	54.6%
Elec. Cons. % VE	6.3%	5.8%	5.8%	5.7%	5.7%	5.6%	5.6%	5.6%	5.6%	5.6%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.3%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%
OI/DE % VE	0.5%	6.8%	8.1%	8.6%	9.2%	9.8%	9.7%	9.5%	9.2%	9.7%
H & E Exp. (Million $)	14.49	14.99	15.41	15.86	16.28	16.75	17.09	17.48	17.92	18.44
Var. Exp.% TE	70.3%	72.4%	73.0%	73.7%	74.2%	74.7%	74.9%	75.6%	75.7%	76.2%
Fixed Exp. % TE	29.7%	27.6%	27.0%	26.3%	25.8%	25.3%	25.1%	24.4%	24.3%	23.8%
Int. Exp. % TE	15.4%	14.3%	13.8%	13.3%	12.8%	12.3%	11.7%	11.2%	10.7%	10.1%
DLR % TE	0.0%	4.4%	5.5%	5.8%	6.3%	6.8%	6.7%	6.6%	6.4%	6.9%
Tx. Due % TE	3.5%	3.4%	3.5%	3.3%	3.3%	3.4%	3.6%	3.2%	3.4%	3.4%
H & E Exp. % TE	55.6%	53.2%	53.1%	53.4%	53.4%	53.4%	53.6%	54.3%	54.5%	54.5%
$/Gal. Oil (VE)	1.47	1.80	1.93	2.01	2.09	2.20	2.26	2.26	2.33	2.44
$/Gal. Oil (FE)	1.34	1.32	1.30	1.27	1.25	1.23	1.22	1.18	1.17	1.14
$/Gal. Oil (TE)	2.80	3.12	3.23	3.28	3.34	3.43	3.47	3.43	3.50	3.58
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	58.86	59.59	60.13	60.76	61.35	62.01	62.55	63.07	63.70	64.23
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	5.78	5.92	6.04	6.17	6.29	6.43	6.55	6.67	6.81	6.92
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	37.85	38.01	38.14	38.30	38.44	38.55	38.68	38.83	38.86	39.01
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46
NG Cons. (Mil. TCF)	1.57	1.58	1.59	1.60	1.60	1.61	1.62	1.63	1.64	1.64
Elec. Cons. (Mil. kWh)	15.62	15.64	15.66	15.68	15.71	15.73	15.75	15.77	15.79	15.81

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

The overall mean cost for producing a gallon of algae oil was \$3.32, with a range of \$2.80 to \$3.58 over the ten-year horizon. Of that \$3.32 per gallon of oil, \$2.08 was attributed to variable expenses and the remaining \$1.24 was attributed to fixed expenses.

6.3.2.1. Comparison Across Pecos, Texas Scenarios

Table 30 exhibits further evidence of economies of scale for microalgae facilities. When comparing Scenarios 4, 5, and 6, as the facility size (in acre feet of water) increases, algae production costs per gallon fall. The same pattern is seen when water depths are increased in Scenarios 2, 3, and 6. Costs per gallon fall from \$16.45 at 6" of water depth (Scenario 2) to \$6.31 at 12" of water depth (Scenario 3) to \$3.32 at 24" of water depth (Scenario 6). It can also be observed that NPV and ending real net worth estimates improve as water depths are increased.

Table 30. Summary Statistics for Selected Key Output Variables for Six Pecos, Texas Scenarios.

	Base Scen.	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6
Ac. Ft. of Water	1,000	1,000	1,000	100	500	1,000
Water Depth (Inches)	24.0	6.0	12.0	24.0	24.0	24.0
NPV (Million \$)	(89.16)	(124.79)	(35.29)	(0.48)	(2.16)	1.27
ERNW (Million \$)	(66.24)	(63.36)	(2.05)	2.00	8.79	21.73
Probability of Losing RNW	100.0%	100.0%	100.0%	90.0%	91.0%	86.2%
Probability of Neg. NPV	100.0%	100.0%	95.8%	59.0%	60.0%	44.6%
End. Cash Bal. (Million \$)						
Mean	(60.17)	(74.74)	(15.88)	0.53	2.28	8.45
Min	(74.46)	(128.64)	(65.69)	(5.42)	(22.17)	(37.91)
Max	(40.88)	(2.25)	38.27	6.81	27.94	57.47
Total Exp. (\$/Gal. Oil)						
Mean	97.28	16.45	6.31	3.66	3.65	3.32
Min	34.31	3.98	1.38	1.16	1.16	1.12
Max	391.15	39.70	18.98	11.89	11.83	10.70
Var. Exp. (\$/Gal. Oil)						
Mean	87.14	13.34	4.50	2.46	2.40	2.08
Min	29.99	1.72	(0.39)	(0.52)	(0.55)	(0.64)
Max	346.04	33.68	15.84	10.42	10.26	9.21
Fixed Exp. (\$/Gal. Oil)						
Mean	10.14	3.11	1.81	1.19	1.25	1.24
Min	3.88	1.47	0.98	0.67	0.72	0.71
Max	45.92	6.71	3.78	2.25	2.36	2.31

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

SERF analysis using NPV scenario rankings shows results similar to the New Mexico location (Figure 34). Scenario 6 is preferred to all other scenarios across ARACs less than 0.0179. Scenario 6 is the only scenario that exhibits positive certainty equivalents, meaning this is the only scenario economically viable to a rational decision maker. However, only a risk neutral or normally risk averse decision maker would consider an investment in Scenario 6 because the certainty equivalents are negative at risk aversion levels greater than that. A rational investor would not invest in the Base Scenario, Scenario 2, Scenario 3, Scenario 4, or Scenario 5 because the certainty equivalents are negative across all levels of risk aversion.

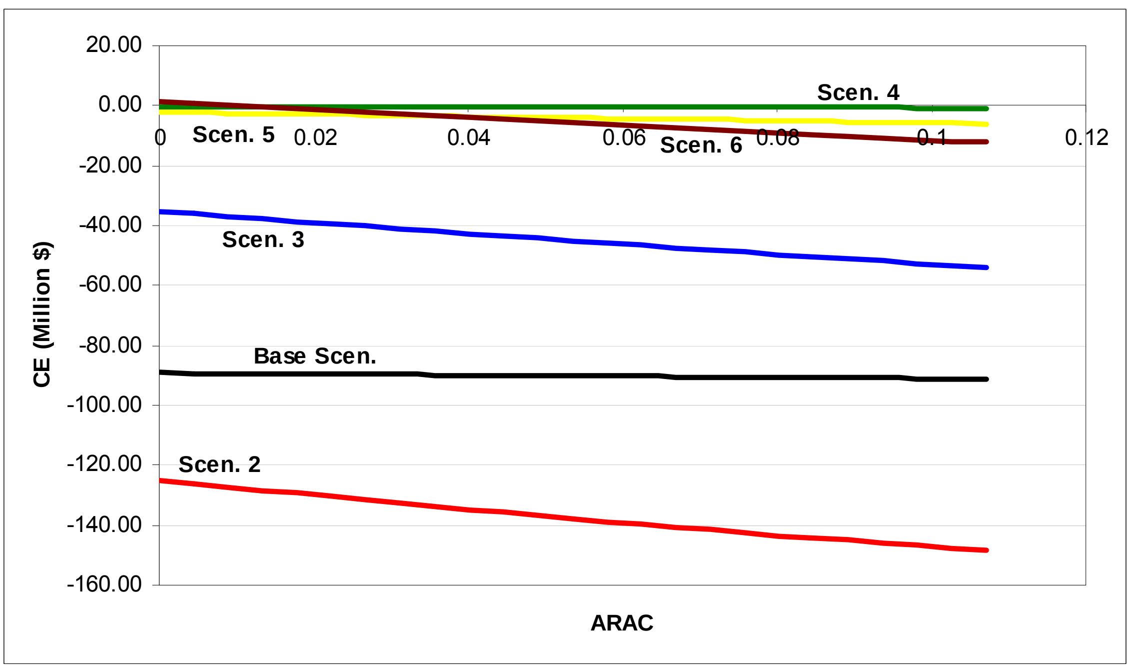

Figure 34. Stochastic efficiency with respect to a function (SERF) under a negative exponential utility function for NPV across six Pecos, Texas Scenarios.

PDFs of NPV show the relative risk for the alternative scenarios. Scenario 6 has the highest mean and upper quantile, with Scenario 4 having the second highest mean NPV and Scenario 5 having the third highest mean NPV (Figure 35). Scenario 6 has the most risk, indicated by its wide distribution. Scenario 4 has the least risk, indicated by its narrow distribution. The risk for Scenario 5 lies in between the previously mentioned scenarios. Scenario 3 has a relatively risky distribution, and the majority of the results are negative. The Base Scenario shows less risk than all scenarios except Scenario 4, but the results are all negative. Scenario 2 is the riskiest scenario.

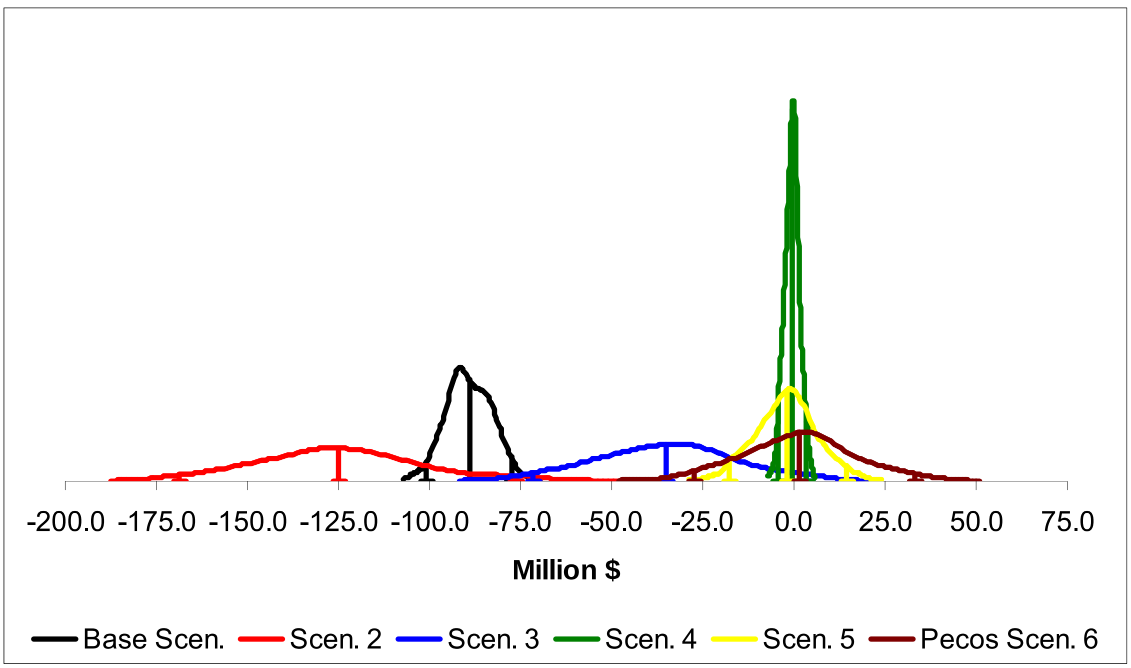

Figure 35. PDF approximations of NPV for six Pecos, Texas Scenarios.

6.3.3. South Texas (Corpus Christi) Simulation Results

The Base Scenario for Corpus Christi, Texas includes the same parameters as the previous two base scenarios (Table 31). The facility has 1,000 acre feet of water, 24" of water depth, low production levels, an electricity source of conventional power lines, and a carbon dioxide source of ambient air. The remaining four scenarios all use higher production levels. The Base Scenario has a total facility cost of $75.1 million. Scenario 2 uses 14" of water depth, which causes the facility costs to rise to $104.4 million, an increase of $29.3 million over the Base Scenario.

Scenario 3 is the same as the Base Scenario except that the carbon dioxide source used is flue gas from a local power plant. Total facility costs increase by $5.0 million over the Base Scenario to $80.1 million for Scenario 3. The increase in costs is the result of the more extensive piping system necessary when using flue gas. Scenario 4 uses flue gas as the carbon dioxide source but also uses the algae by-product as an electricity source instead of selling it. Total facility cost increases to $90.7 million, a $15.6 million increase over the Base Scenario. The increase in cost is the result of the power generation facilities necessary to convert algae by-product to electricity using the pyrolysis process. Scenario 5 is the same as the Base Scenario except for the higher production levels so total facility costs are unchanged at $75.1 million.

The results for the Corpus Christi Base Scenario are discouraging. Mean annual ending cash balances are negative for every year except year one, which has a 99.8% probability of a negative ending cash balance (Figure 36). Mean ending cash balances in the final year are -$128.5 million.

Table 31. Corpus Christi, Texas Scenario Assumptions.

Scenario Name	Base Scen.	Scen. 2	Scen. 3	Scen. 4	Scen. 5
Description	Base	Med. Depth	ABP Sold	ABP as Energy	High Prod.
Cost Level	Minimum	Minimum	Minimum	Minimum	Minimum
Power Source	Conv.	Conv.	Conv.	Renew.	Conv.
Ac. Ft. of Water	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00
Pond Length	700.00	700.00	700.00	700.00	700.00
Water Depth	24.00	14.00	24.00	24.00	24.00
% Recycled Water	0.0%	0.0%	0.0%	0.0%	0.0%
Source of Water	Ground	Ground	Ground	Ground	Ground
% High-Value Oil	2.5%	2.5%	2.5%	2.5%	2.5%
Raceways/Pond	10.00	10.00	10.00	10.00	10.00
Production Levels (g/L/Day)					
Min	0.10	0.60	0.60	0.60	0.60
Mid	0.20	0.80	0.80	0.80	0.80
Max	0.30	1.00	1.00	1.00	1.00
Oil Contents (%)					
Min	0.15	0.30	0.30	0.30	0.30
Mid	0.18	0.40	0.40	0.40	0.40
Max	0.20	0.50	0.50	0.50	0.50
End Use of Algae Meal	Sales	Sales	Sales	Energy	Sales
CO2 Source	Air	Air	Flue Gas	Flue Gas	Air
Total Facility Costs (Million $)	75.14	104.44	80.13	90.69	75.14
Total $ Financed (Million $)	37.57	52.22	40.07	45.35	37.57

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

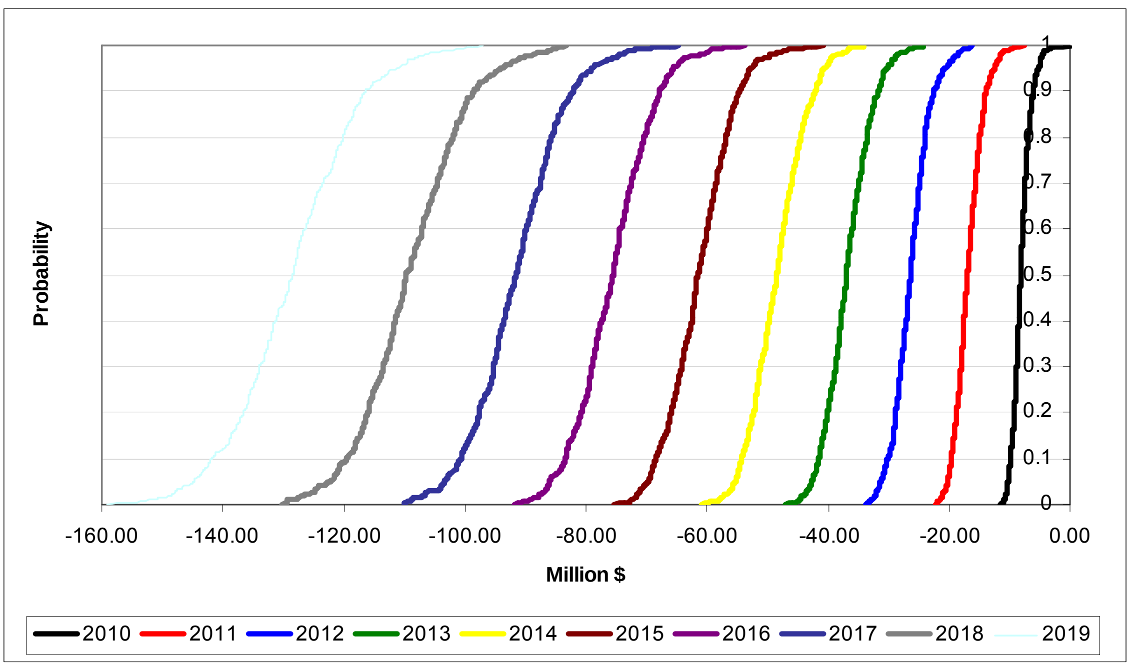

Figure 36. CDF of annual ending cash balances for Corpus Christi, Texas Base Scenario, with water depth of 24”, 1,000 acre feet of water, and low production levels.

As observed from Table 32, mean NPV is -$89.2 million with a 100.0% probability of a negative NPV. Mean ending real net worth is -$66.1 million with a 100% probability of decreasing over the ten-year horizon. Mean annual returns on investment are -18.2% in the first year and increase annually to -20.6% in the final year of the analysis. Mean debt-related expenses rapidly increase from $4.5 million in the first year to $124.1 million in the final year.

The mean cost per gallon of algae oil is $17.55 in the first year and escalates to $193.26 in the final year. The majority of that increase comes from higher mean variable costs per gallon, as this part of total cost ranges from $6.41 in the first year to $183.97 in the final year. Mean fixed costs per gallon actually decrease over the ten-year horizon, from $11.14 in year one to $9.29 in the final year as depreciation decreases. As previously stated, the cost of mounting debt servicing costs leads to these high cost estimates. Facilities would cease operations before the end of the ten-year horizon if the financial status did not improve because it would be difficult to obtain a loan to cover the cash flow deficits the facility experiences.

Table 32. Averages and Probabilities of Key Output Variables for Corpus Christi, Texas Base Scenario, with Water Depth of 24", 1,000 Acre Feet of Water, and Low Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(89.21)
ERNW (Mil. $)										(66.14)
Prob. of Dec. RNW										100.0%
Prob. of Neg. NPV										100.0%
Prob. of Neg. ECB	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Total Rev. (Mil. $)	5.24	5.43	5.50	5.59	5.72	5.83	5.86	5.91	6.02	6.09
NCI (Mil. $)	(5.46)	(6.14)	(6.84)	(7.71)	(8.79)	(9.96)	(11.25)	(12.71)	(14.25)	(16.13)
Tx. Inc. (Mil. $)	(10.63)	(11.31)	(12.02)	(12.89)	(13.97)	(15.13)	(16.42)	(17.89)	(19.43)	(21.31)
Tx. Due (Mil. $)	-	-	-	-	-	-	-	-	-	-
ECB (Mil. $)	(7.99)	(16.73)	(26.25)	(36.71)	(48.34)	(61.24)	(75.53)	(91.40)	(108.93)	(128.49)
Net Worth (Mil. $)	15.21	5.69	(4.50)	(15.52)	(27.58)	(40.78)	(55.23)	(71.11)	(88.50)	(107.74)
Net Returns (Mil. $)	(10.63)	(11.31)	(12.02)	(12.89)	(13.97)	(15.13)	(16.42)	(17.89)	(19.43)	(21.31)
ROI	-18.2%	-18.6%	-18.6%	-18.9%	-19.0%	-19.3%	-19.6%	-19.9%	-20.1%	-20.6%
Interest Exp. (Mil. $)	3.79	4.32	5.01	5.80	6.84	7.90	9.06	10.42	11.88	13.58
Debt Exp. (Mil. $)	4.45	13.04	22.54	32.92	44.51	57.30	71.46	87.23	104.68	124.06
Var. Exp. (Mil. $)	6.94	15.87	25.45	36.01	47.78	60.78	75.09	91.01	108.66	128.29
Fixed Exp. (Mil. $)	6.29	6.29	6.29	6.29	6.29	6.29	6.29	6.29	6.29	6.29
Total Exp. (Mil. $)	13.23	22.16	31.74	42.30	54.07	67.07	81.38	97.30	114.95	134.58
Nut. % VE	9.5%	5.2%	2.9%	2.0%	1.5%	1.2%	1.0%	0.8%	0.7%	0.6%
Labor % VE	25.3%	11.1%	7.0%	5.0%	3.9%	3.2%	2.6%	2.2%	1.9%	1.7%
H & E L & M % VE	1.7%	0.8%	0.5%	0.4%	0.3%	0.2%	0.2%	0.2%	0.1%	0.1%
Chem. % VE	9.2%	4.3%	2.8%	2.0%	1.5%	1.2%	1.0%	0.9%	0.7%	0.6%
H & E NG % VE	38.6%	17.8%	11.5%	8.4%	6.5%	5.3%	4.3%	3.7%	3.2%	2.8%
Elec. Cons. % VE	12.6%	5.5%	3.5%	2.6%	2.0%	1.6%	1.3%	1.1%	0.9%	0.8%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	1.1%	0.7%	0.5%	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%
OI/DE % VE	0.5%	54.2%	71.1%	79.1%	83.9%	87.0%	89.3%	91.0%	92.3%	93.2%
H & E Exp. (Million $)	3.62	3.75	3.85	3.96	4.07	4.20	4.26	4.36	4.47	4.62
Var. Exp.% TE	92.2%	93.5%	94.5%	95.3%	48.0%	28.7%	20.0%	15.0%	11.7%	9.4%
Fixed Exp. % TE	48.0%	28.7%	20.0%	15.0%	11.7%	9.4%	7.8%	6.5%	5.5%	4.7%
Int. Exp. % TE	29.0%	19.7%	15.9%	13.8%	12.7%	11.8%	11.1%	10.7%	10.3%	10.1%
DLR % TE	0.0%	35.9%	52.5%	61.9%	67.8%	72.0%	75.2%	77.6%	79.5%	80.9%
Tx. Due % TE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
H & E Exp. % TE	26.7%	16.7%	12.1%	9.3%	7.5%	6.3%	5.2%	4.5%	3.9%	3.4%
$/Gal. Oil (VE)	6.41	21.69	37.47	54.35	72.41	92.86	113.25	133.73	208.31	183.97
$/Gal. Oil (FE)	11.14	10.99	10.70	10.51	10.29	10.25	9.99	9.66	12.62	9.29
$/Gal. Oil (TE)	17.55	32.68	48.17	64.85	82.70	103.12	123.24	143.39	220.93	193.26
Growth Rate (g/L/day)	0.20	0.20	0.20	0.20	0.20	0.20	0.21	0.21	0.21	0.21
Oil Content (%)	17.5%	17.6%	17.7%	17.8%	17.9%	17.9%	18.0%	18.1%	18.2%	18.3%
BM Prod. (1,000 ST)	14.71	14.92	15.04	15.21	15.35	15.52	15.64	15.76	15.92	16.04
BM Prod. (Tons/AF)	13.34	13.53	13.64	13.79	13.92	14.07	14.18	14.30	14.43	14.54
Oil Prod. (Mil. Gal.)	0.63	0.65	0.66	0.67	0.69	0.70	0.72	0.73	0.74	0.76
Oil Prod. (Gal./AF)	574	588	599	612	624	638	649	661	675	686
Meal Prod. (1,000 ST)	12.44	12.58	12.66	12.78	12.87	12.98	13.05	13.15	13.22	13.31
Meal Prod. (Tons/AF)	11.29	11.41	11.48	11.59	11.67	11.77	11.84	11.93	11.99	12.07
Water Loss (Bil. Gal.)	0.672	0.672	0.670	0.673	0.673	0.673	0.674	0.673	0.673	0.674
NG Cons. (Mil. TCF)	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41
Elec. Cons. (Mil. kWh)	12.36	12.37	12.37	12.38	12.38	12.39	12.39	12.40	12.40	12.41

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 2 examines the consequences of decreasing water depth to 14”. The results clearly show the problem of water depths. Mean annual ending cash balances for this scenario are -$1.2 million in year one and increase to -$22.5 million in the final year. The probability of a negative ending cash balance is 58.8% in the first year and those probabilities continually rise to a probability of 78.6% the last year (Figure 37). This scenario involves a large amount of downside risk of negative annual ending cash balance as indicated in Figure 37. Mean NPV is -$26.5 million and has a 91.8% probability of being negative. Mean ending real net worth is $3.9 million and has a 99.8% probability of losing real net worth.

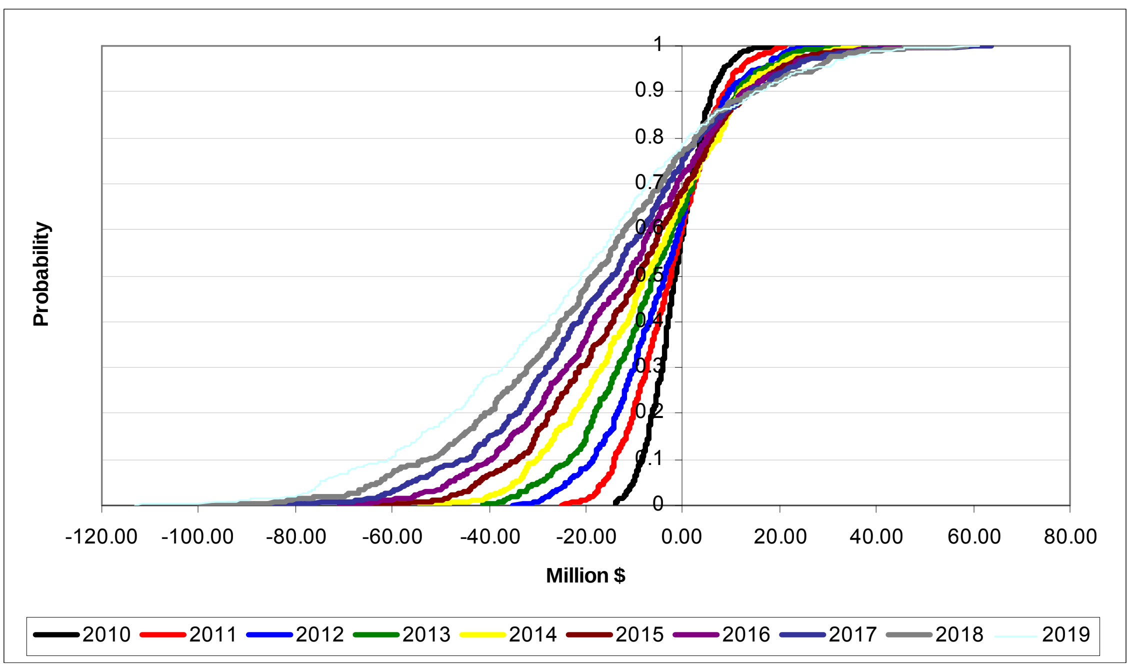

Figure 37. CDF of annual ending cash balances for Corpus Christi, Texas Scenario 2, with a water depth of 14”, 1,000 acre feet of water, and high production levels.

Total facility costs increase from $75.1 million in the Base Scenario to $104.4 million in Scenario 2, an increase of $29.3 million as the number of ponds increases to accommodate the 14” pond depth requirement. Mean annual water use increases 410 million gallons annually over the Base Scenario for a total of 4.1 billion additional gallons required over the ten-year horizon. Mean electricity usage increases by 10.4 million kWh annually over the Base Scenario for a total additional electricity consumption of 104.3 million kWh over the ten-year horizon (Table 33). This equates to an annual increase in electricity consumption of 84.2% due largely to the increased numbers of pumps, water pumping, and ponds.

The overall mean cost of producing a gallon of algae oil is $5.35, with a mean of $3.34 per gallon in the first year and a mean of $7.35 per gallon in the final year. Overall mean variable costs per gallon are $3.72, with a mean of $1.58 in the first year and a mean of $5.88 in the tenth year. The overall mean fixed cost per gallon of oil is $1.62, with a mean of $1.76 in the first year and a mean of $1.48 in the last year.

Table 33. Averages and Probabilities of Key Output Variables for Corpus Christi, Texas Scenario 2, with Water Depth of 14”, 1,000 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(26.51)
ERNW (Mil. $)										3.91
Prob. of Dec. RNW										99.8%
Prob. of Neg. NPV										91.8%
Prob. of Neg. ECB	58.8%	60.6%	62.6%	64.0%	67.0%	68.4%	72.0%	74.6%	76.8%	78.6%
Total Rev. (Mil. $)	26.14	26.94	27.36	27.72	28.31	28.91	29.12	29.51	30.00	30.43
NCI (Mil. $)	2.94	2.88	2.80	2.59	2.52	2.49	2.19	2.00	1.85	1.48
Tx. Inc. (Mil. $)	(5.00)	(5.05)	(5.14)	(5.35)	(5.41)	(5.44)	(5.75)	(5.93)	(6.08)	(6.46)
Tx. Due (Mil. $)	0.36	0.43	0.46	0.44	0.42	0.49	0.45	0.39	0.43	0.45
ECB (Mil. $)	(1.16)	(2.48)	(4.01)	(5.82)	(7.78)	(9.95)	(12.55)	(15.42)	(18.65)	(22.46)
Net Worth (Mil. $)	31.09	28.68	26.22	23.64	21.07	18.48	15.65	12.76	9.74	6.38
Net Returns (Mil. $)	(5.00)	(5.05)	(5.14)	(5.35)	(5.41)	(5.44)	(5.75)	(5.93)	(6.08)	(6.46)
ROI	0.6%	0.8%	0.8%	0.5%	0.7%	0.8%	0.4%	0.3%	0.2%	-0.2%
Interest Exp. (Mil. $)	5.32	5.46	5.55	5.62	5.77	5.85	5.94	6.06	6.17	6.36
Debt Exp. (Mil. $)	6.23	9.44	11.58	13.63	16.06	18.52	21.11	23.90	27.00	30.75
Var. Exp. (Mil. $)	17.99	21.90	24.46	27.01	29.94	32.96	35.97	39.22	42.84	47.20
Fixed Exp. (Mil. $)	9.32	9.38	9.42	9.40	9.38	9.45	9.42	9.33	9.38	9.39
Total Exp. (Mil. $)	27.30	31.28	33.88	36.41	39.32	42.41	45.39	48.55	52.22	56.60
Nut. % VE	3.6%	3.7%	3.1%	2.9%	2.6%	2.5%	2.4%	2.2%	2.0%	1.9%
Labor % VE	9.9%	8.4%	7.8%	7.5%	7.1%	6.8%	6.6%	6.4%	6.2%	5.9%
H & E L & M % VE	2.6%	2.3%	2.2%	2.1%	2.0%	1.9%	1.9%	1.8%	1.8%	1.7%
Chem. % VE	14.1%	12.5%	11.9%	11.4%	10.8%	10.2%	9.9%	9.4%	9.0%	8.5%
H & E NG % VE	57.8%	50.1%	47.4%	45.5%	43.4%	41.8%	40.1%	38.6%	37.0%	35.2%
Elec. Cons. % VE	9.1%	7.7%	7.3%	7.0%	6.6%	6.3%	6.0%	5.8%	5.5%	5.2%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.1%	2.0%	1.9%	1.8%	1.7%	1.7%	1.6%	1.5%	1.5%
OI/DE % VE	0.5%	13.1%	18.2%	21.7%	25.6%	28.7%	31.4%	34.3%	37.0%	40.0%
H & E Exp. (Million $)	13.86	14.35	14.75	15.18	15.58	16.03	16.35	16.73	17.15	17.64
Var. Exp.% TE	65.3%	69.2%	71.0%	72.6%	74.2%	75.5%	76.7%	78.0%	79.0%	80.2%
Fixed Exp. % TE	34.7%	30.8%	29.0%	27.4%	25.8%	24.5%	23.3%	22.0%	21.0%	19.8%
Int. Exp. % TE	19.9%	18.0%	16.9%	16.1%	15.3%	14.5%	13.8%	13.1%	12.4%	11.8%
DLR % TE	0.0%	8.5%	12.4%	15.3%	18.4%	21.0%	23.3%	25.8%	28.2%	30.8%
Tx. Due % TE	1.2%	1.2%	1.3%	1.1%	1.1%	1.2%	1.0%	0.8%	0.9%	0.9%
H & E Exp. % TE	49.9%	45.7%	44.1%	43.0%	41.6%	40.4%	39.4%	38.3%	37.0%	35.7%
$/Gal. Oil (VE)	1.58	2.25	2.67	3.06	3.51	3.96	4.33	4.71	5.29	5.88
$/Gal. Oil (FE)	1.76	1.74	1.71	1.67	1.63	1.61	1.58	1.53	1.51	1.48
$/Gal. Oil (TE)	3.34	3.99	4.38	4.73	5.15	5.57	5.91	6.24	6.80	7.35
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	56.35	57.05	57.57	58.17	58.73	59.36	59.88	60.38	60.98	61.49
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	5.53	5.67	5.78	5.90	6.02	6.16	6.27	6.39	6.52	6.63
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	36.24	36.39	36.51	36.66	36.80	36.91	37.03	37.17	37.20	37.35
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	1.08	1.08	1.08	1.08	1.09	1.09	1.09	1.09	1.09	1.09
NG Cons. (Mil. TCF)	1.51	1.51	1.52	1.53	1.54	1.54	1.55	1.56	1.57	1.57
Elec. Cons. (Mil. kWh)	22.72	22.74	22.76	22.78	22.80	22.82	22.84	22.86	22.88	22.91

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 3 uses flue gas as the carbon dioxide source. The probability of a negative ending cash balance is lower than the previous two scenarios at 25.8% in the first year and falls to 21.4% in the final year of the analysis. These results can be observed in Figure 38. Mean NPV is $3.0 million with a 40.8% probability of being negative. Mean ending real net worth is $24.9 million with an 84.8% probability of losing real net worth. Mean variable expenses are $17.5 million in the first year and $25.2 million in the final year (Table 34).

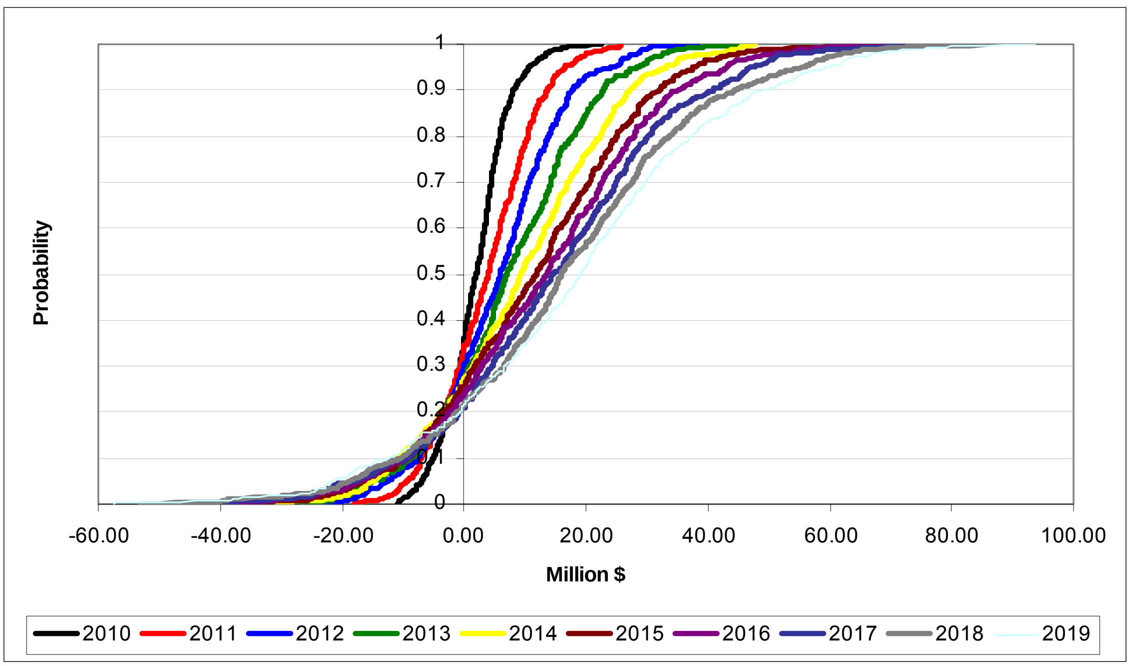

Figure 38. CDF of annual ending cash balances for Corpus Christi, Texas Scenario 3, with a water depth of 24”, 1,000 acre feet of water, a water source of food companies, a carbon dioxide source of flue gas, and high production levels.

Electricity consumption falls by an average of 16.8 million kWh annually, a decrease of 61.7% over Scenario 2 (Table 34). The majority of this decrease can be attributed to the circulation systems. Because flue gas is used to circulate and provide carbon dioxide instead of air, the model assumes blowers are no longer necessary, meaning there will not be large amounts of energy consumed. It is also assumed that the flue gas is obtained from the local power plant at no cost to the facility. Mean annual returns on investment are 10.8% over the ten-year horizon.

The overall mean cost of producing a gallon of algae oil is \$3.19, with a range over the ten year horizon of \$2.76 to \$3.37 per gallon. Overall mean variable costs per gallon are \$1.87, with variable costs starting at \$1.34 per gallon and increasing every year to \$2.16 in the final year of analysis. Overall mean fixed costs per gallon are \$1.32, with fixed costs beginning at \$1.42 per gallon and falling annually to a cost of \$1.22 per gallon in the tenth year.

Table 34. Averages and Probabilities of Key Output Variables for Corpus Christi, Texas Scenario 3, with Water Depth of 24", 1,000 Acre Feet of Water, a Water Source of Food Companies, a Carbon Dioxide Source of Flue Gas, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										2.95
ERNW (Mil. $)										24.92
Prob. of Dec. RNW										84.8%
Prob. of Neg. NPV										40.8%
Prob. of Neg. ECB	35.8%	34.0%	29.6%	27.0%	27.0%	25.6%	23.8%	20.8%	21.6%	21.4%
Total Rev. (Mil. $)	27.31	28.14	28.58	28.96	29.57	30.20	30.42	30.83	31.33	31.78
NCI (Mil. $)	5.85	5.92	5.99	5.93	6.09	6.25	6.15	6.23	6.34	6.29
Tx. Inc. (Mil. $)	0.18	0.25	0.32	0.26	0.42	0.57	0.48	0.56	0.67	0.62
Tx. Due (Mil. $)	0.97	1.04	1.09	1.09	1.11	1.16	1.25	1.13	1.23	1.23
ECB (Mil. $)	1.86	3.72	5.59	7.39	9.30	11.30	13.05	14.93	16.77	18.47
Net Worth (Mil. $)	26.60	27.63	28.79	29.99	31.43	33.11	34.69	36.56	38.56	40.60
Net Returns (Mil. $)	0.18	0.25	0.32	0.26	0.42	0.57	0.48	0.56	0.67	0.62
ROI	10.7%	11.0%	11.1%	10.8%	11.1%	11.3%	10.8%	10.7%	10.7%	10.3%
Interest Exp. (Mil. $)	4.10	4.14	4.12	4.07	4.03	3.95	3.86	3.74	3.62	3.51
Debt Exp. (Mil. $)	4.80	6.22	6.67	6.96	7.26	7.51	7.61	7.62	7.63	7.88
Var. Exp. (Mil. $)	17.45	19.59	20.43	21.21	22.00	22.80	23.31	23.77	24.29	25.16
Fixed Exp. (Mil. $)	8.00	8.08	8.13	8.13	8.16	8.22	8.31	8.19	8.29	8.29
Total Exp. (Mil. $)	25.45	27.67	28.56	29.34	30.15	31.02	31.62	31.96	32.59	33.45
Nut. % VE	3.9%	4.4%	3.8%	3.7%	3.5%	3.5%	3.5%	3.3%	3.3%	3.2%
Labor % VE	10.3%	9.4%	9.2%	9.2%	9.2%	9.2%	9.3%	9.4%	9.5%	9.5%
H & E L & M % VE	2.9%	2.7%	2.7%	2.7%	2.7%	2.7%	2.8%	2.8%	2.8%	2.8%
Chem. % VE	15.2%	14.5%	14.6%	14.6%	14.4%	14.3%	14.3%	14.3%	14.3%	14.2%
H & E NG % VE	62.4%	57.9%	57.5%	57.5%	57.4%	57.1%	57.3%	57.8%	58.1%	57.9%
Elec. Cons. % VE	2.4%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.3%	2.3%	2.2%	2.2%	2.2%	2.2%	2.2%	2.3%	2.2%
OI/DE % VE	0.5%	6.6%	7.7%	7.9%	8.4%	8.7%	8.4%	8.0%	7.6%	7.9%
H & E Exp. (Million $)	14.48	14.98	15.40	15.85	16.27	16.75	17.08	17.47	17.91	18.43
Var. Exp.% TE	68.1%	70.2%	70.9%	71.5%	72.0%	72.5%	72.6%	73.3%	73.4%	73.9%
Fixed Exp. % TE	31.9%	29.8%	29.1%	28.5%	28.0%	27.5%	27.4%	26.7%	26.6%	26.1%
Int. Exp. % TE	16.6%	15.5%	14.9%	14.4%	13.9%	13.3%	12.7%	12.1%	11.5%	10.9%
DLR % TE	0.0%	4.2%	5.0%	5.2%	5.6%	5.9%	5.6%	5.4%	5.1%	5.4%
Tx. Due % TE	3.5%	3.4%	3.5%	3.4%	3.4%	3.5%	3.7%	3.3%	3.6%	3.6%
H & E Exp. % TE	56.1%	53.8%	53.9%	54.3%	54.5%	54.5%	54.9%	55.6%	56.0%	56.1%
$/Gal. Oil (VE)	1.34	1.65	1.76	1.83	1.90	1.98	2.03	2.02	2.07	2.16
$/Gal. Oil (FE)	1.42	1.40	1.38	1.35	1.33	1.31	1.30	1.26	1.25	1.22
$/Gal. Oil (TE)	2.76	3.06	3.14	3.18	3.23	3.29	3.32	3.27	3.32	3.37
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	58.86	59.59	60.13	60.76	61.35	62.01	62.55	63.07	63.70	64.23
BM Prod. (Tons/AF)	53.38	54.04	54.53	55.11	55.64	56.23	56.73	57.20	57.77	58.25
Oil Prod. (Mil. Gal.)	5.78	5.92	6.04	6.17	6.29	6.43	6.55	6.67	6.81	6.92
Oil Prod. (Gal./AF)	5,243	5,372	5,476	5,592	5,702	5,836	5,937	6,049	6,176	6,279
Meal Prod. (1,000 ST)	37.85	38.01	38.14	38.30	38.44	38.55	38.68	38.83	38.86	39.01
Meal Prod. (Tons/AF)	34.33	34.47	34.59	34.73	34.86	34.96	35.08	35.21	35.24	35.38
Water Loss (Bil. Gal.)	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
NG Cons. (Mil. TCF)	1.57	1.58	1.59	1.60	1.60	1.61	1.62	1.63	1.64	1.64
Elec. Cons. (Mil. kWh)	5.92	5.94	5.96	5.98	6.00	6.02	6.04	6.07	6.09	6.11

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Scenario 4 uses the algae by-product as a source of energy instead of selling it as a feed product. The model operates on the assumption that the pyrolysis processes that are currently being researched will be able to convert the algae by-product to energy for the facility. Mean annual excess energy production from algae by-product is 115.9 million kilowatt hours in the first year and increases to 119.7 million kilowatt hours in year ten. Mean annual excess energy sales are $7.95 million in the first year and increase to $10.1 million in the final year of the planning horizon.

Results for Scenario 4 show mean negative ending cash balances for all ten years, ranging from a high of -$0.4 million in the first year to a low of -$5.6 million in the final year of the analysis. Figure 39 exhibits similar results, with the mean probabilities of a negative ending cash balance being centered around 55%, a probability of a negative ending cash balance in year one of 55.6%, and the remaining years staying in a probability range of 53.4% to 58.6%. Mean NPV is -$14.0 million and the facility has an 83.6% probability of being negative. Mean ending real net worth is $11.9 million, with a 98.6% probability of losing real net worth.

Total revenues for Scenario 4 are less than Scenario 3, with average annual mean revenues decreasing by $2.0 million, with the largest decrease coming in year two ($2.5 million) and the smallest decrease coming in year ten ($1.4 million). Over the ten year horizon, mean total revenues decrease by $19.8 million, which equates to an average annual decrease of 6.7% over Scenario 4 (Table 35). Mean net cash incomes fall by an average of $2.4 million, a decrease of 39.0% over Scenario 3. Total mean net cash incomes decrease by $23.8 million over the ten-year horizon.

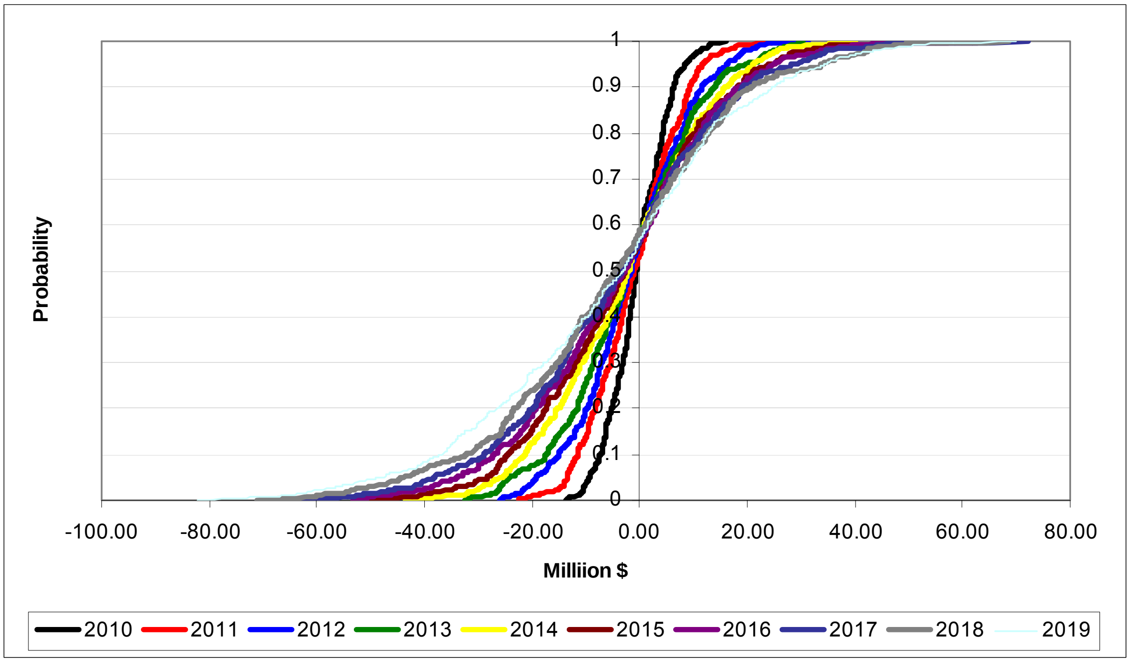

Figure 39. CDF of annual ending cash balances for Corpus Christi, Texas Scenario 4, with a water depth of 24", 1,000 acre feet of water, a water source of food companies, a carbon dioxide source of flue gas, an electricity source of algae by-product, and high production levels.

These results (and others displayed in Table 35) indicate that it is more profitable for the facility to sell the algae by-product rather using it as an energy source. The additional revenues generated from excess electricity sales and money saved by decreasing electricity variable costs does not cover the additional costs associated with constructing and operating a facility to generate electricity from algae by-products and the loss of algae by-product receipts. It should also be noted that improvements could be made in the future to make the microalgae more energy-rich and more attractive for this scenario. This scenario does not consider any government assistance or subsidies that might result from this operation.

Table 35. Averages and Probabilities of Key Output Variables for Corpus Christi, Texas Scenario 4, with Water Depth of 24”, 1,000 Acre Feet of Water, a Water Source of Food Companies, a Carbon Dioxide Source of Flue Gas, an Electricity Source of Algae By-Product, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										(14.02)
ERNW (Mil. $)										11.94
Prob. of Dec. RNW										98.6%
Prob. of Neg. NPV										83.6%
Prob. of Neg. ECB	55.6%	53.4%	56.0%	57.4%	57.4%	56.0%	56.2%	56.6%	58.6%	56.6%
Total Rev. (Mil. $)	25.01	25.62	26.32	26.79	27.37	28.12	28.54	29.30	29.79	30.42
NCI (Mil. $)	3.43	3.29	3.51	3.48	3.57	3.79	3.71	4.10	4.13	4.30
Tx. Inc. (Mil. $)	(2.77)	(2.91)	(2.69)	(2.72)	(2.63)	(2.42)	(2.49)	(2.10)	(2.07)	(1.90)
Tx. Due (Mil. $)	0.54	0.51	0.59	0.57	0.59	0.61	0.68	0.73	0.74	0.83
ECB (Mil. $)	(0.39)	(0.91)	(1.38)	(1.92)	(2.48)	(2.93)	(3.66)	(4.22)	(4.86)	(5.60)
Net Worth (Mil. $)	27.61	26.14	24.86	23.66	22.57	21.76	20.83	20.26	19.79	19.45
Net Returns (Mil. $)	(2.77)	(2.91)	(2.69)	(2.72)	(2.63)	(2.42)	(2.49)	(2.10)	(2.07)	(1.90)
ROI	4.1%	4.0%	4.6%	4.6%	4.9%	5.4%	5.1%	6.0%	5.9%	6.3%
Interest Exp. (Mil. $)	4.63	4.74	4.79	4.80	4.86	4.85	4.83	4.81	4.76	4.75
Debt Exp. (Mil. $)	5.42	7.97	9.54	10.75	12.01	13.26	14.37	15.49	16.51	17.93
Var. Exp. (Mil. $)	17.05	20.24	22.23	23.93	25.63	27.41	29.05	30.55	32.07	33.97
Fixed Exp. (Mil. $)	8.35	8.32	8.42	8.39	8.42	8.44	8.53	8.59	8.61	8.71
Total Exp. (Mil. $)	25.40	28.56	30.66	32.32	34.06	35.85	37.58	39.15	40.68	42.68
Nut. % VE	4.0%	4.2%	3.6%	3.3%	3.2%	3.1%	3.0%	2.8%	2.7%	2.6%
Labor % VE	10.6%	9.1%	8.7%	8.4%	8.2%	8.0%	8.0%	7.9%	7.9%	7.8%
H & E L & M % VE	2.9%	2.6%	2.5%	2.5%	2.4%	2.4%	2.4%	2.3%	2.4%	2.3%
Chem. % VE	15.6%	14.2%	13.7%	13.3%	12.9%	12.5%	12.3%	12.1%	11.9%	11.7%
H & E NG % VE	63.9%	56.4%	54.1%	52.7%	51.4%	50.5%	49.7%	49.3%	48.7%	47.9%
Elec. Cons. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.2%	2.1%	2.0%	2.0%	1.9%	1.9%	1.9%	1.8%	1.8%
OI/DE % VE	0.5%	11.3%	15.3%	17.9%	19.9%	21.6%	22.7%	23.8%	24.6%	25.7%
H & E Exp. (Million $)	14.50	14.93	15.40	15.86	16.24	16.70	17.15	17.51	17.94	18.34
Var. Exp.% TE	66.4%	70.0%	71.3%	72.6%	73.6%	74.5%	75.1%	75.7%	76.3%	76.8%
Fixed Exp. % TE	33.6%	30.0%	28.7%	27.4%	26.4%	25.5%	24.9%	24.3%	23.7%	23.2%
Int. Exp. % TE	18.7%	17.1%	16.2%	15.5%	14.8%	14.1%	13.5%	12.9%	12.2%	11.6%
DLR % TE	0.0%	7.3%	10.4%	12.4%	14.1%	15.6%	16.5%	17.4%	18.2%	19.2%
Tx. Due % TE	1.9%	1.7%	1.9%	1.7%	1.8%	1.8%	1.9%	1.9%	1.9%	2.1%
H & E Exp. % TE	56.1%	52.1%	50.7%	50.1%	49.3%	48.7%	48.3%	48.0%	47.8%	47.2%
$/Gal. Oil (VE)	3.10	3.61	3.88	4.10	4.32	4.51	4.68	4.79	5.00	5.19
$/Gal. Oil (FE)	0.10	0.06	0.03	(0.02)	(0.05)	(0.08)	(0.11)	(0.12)	(0.15)	(0.18)
$/Gal. Oil (TE)	3.20	3.67	3.90	4.08	4.27	4.43	4.57	4.66	4.84	5.02
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	58.87	59.54	60.20	60.70	61.26	61.93	62.50	63.09	63.70	64.33
BM Prod. (Tons/AF)	53.39	54.00	54.59	55.05	55.56	56.17	56.68	57.22	57.77	58.34
Oil Prod. (Mil. Gal.)	5.80	5.92	6.04	6.16	6.28	6.42	6.53	6.70	6.82	6.93
Oil Prod. (Gal./AF)	5,258	5,367	5,475	5,590	5,695	5,821	5,920	6,078	6,181	6,289
Meal Prod. (1,000 ST)	37.78	37.96	38.19	38.26	38.39	38.53	38.72	38.72	38.84	39.05
Meal Prod. (Tons/AF)	34.26	34.43	34.64	34.70	34.82	34.95	35.11	35.11	35.23	35.41
Water Loss (Bil. Gal.)	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
NG Cons. (Mil. TCF)	1.57	1.58	1.59	1.60	1.60	1.61	1.62	1.63	1.64	1.64
Elec. Cons. (Mil. kWh)	5.92	5.94	5.96	5.98	6.00	6.02	6.04	6.07	6.09	6.11

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

The overall mean cost of producing a gallon of algae oil is $4.26, with a cost per gallon of $3.20 in the first year and increasing to a cost of $5.02 in the final year of the analysis. Overall mean variable costs are $4.32 per gallon, with a minimum cost of $3.10 in the first year and continually increasing to $5.19 in the last year. Overall mean fixed costs are negative at -$0.05 per gallon, with a cost of $0.10 per gallon in the first year and falling to -$0.18 per gallon in the final year. Revenues from surplus energy sales were subtracted from annual fixed costs, so it is possible for mean fixed costs to be negative.

Scenario 5 simulates a facility with 1,000 acre feet of water and 24” of water depth, with ground water as the water source, air as the source of carbon dioxide, and sales for the end-use algae by-product. The probability of a negative ending cash balance is 40.6% in year one and decreases to 26.6% in the final year of analysis. As Figure 40 shows, there is much more upside potential for having positive ending cash balances than downside. The probability of losing real net worth is 86.6%, with a mean ending real net worth of $21.7 million. Mean NPV is $1.1 million, with a 46.8% probability of a negative NPV.

Mean annual net cash income for the facility is between $5.4 to $5.7 million for the ten-year horizon, while returns on investment average 10.9% across the ten-year horizon. As Table 36 exhibits, mean water use is significantly decreased for the Corpus Christi location when comparing to the same scenario at the other locations, primarily the result of lower evaporation rates and higher precipitation than the other locations. Mean annual water use is 670 million gallons, a decrease of 790 million

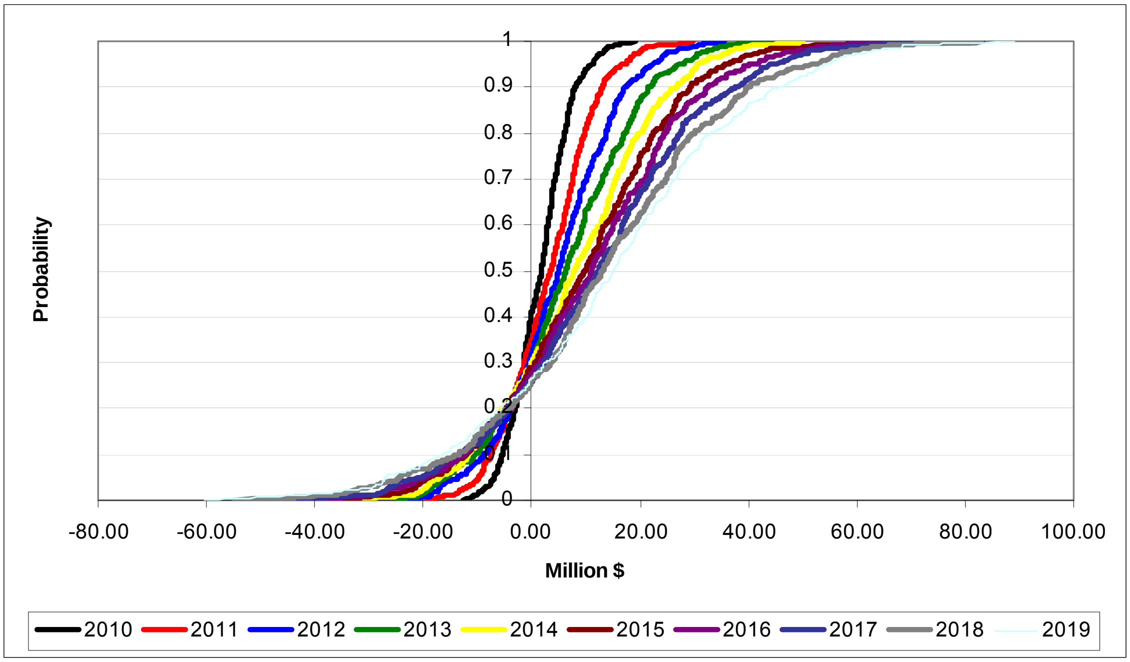

Figure 40. CDF of annual ending cash balances for Corpus Christi, Texas Scenario 5, with water depth of 24”, 1,000 acre feet of water, and high production levels.

gallons (54.0%) from the Pecos, Texas Scenario 6, and a decrease of 860 million gallons (56.2%) from the New Mexico Scenario 6. When comparing Corpus Christi Scenario 5 and Scenario 2, with the differences only being water depth, decreasing water depth from 24” (Scenario 5) to 14” (Scenario 2) causes electricity consumption to increase 7.2 million kWh annually while water use increases 410 million gallons annually. These estimates represent an annual increase of 67.2% in water consumption and an annual increase of 46.0% in electricity consumption, signifying that increasing water depth is critical to increasing economic viability.

Table 36. Averages and Probabilities of Key Output Variables for Corpus Christi, Texas Scenario 5, with Water Depth of 24”, 1,000 Acre Feet of Water, and High Production Levels.

	Year									
Variable Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NPV (Mil. $)										1.07
ERNW (Mil. $)										21.68
Prob. of Dec. RNW										86.6%
Prob. of Neg. NPV										46.8%
Prob. of Neg. ECB	40.6%	34.8%	31.8%	29.6%	30.0%	29.0%	27.6%	25.8%	26.2%	26.6%
Total Rev. (Mil. $)	27.36	28.09	28.60	28.99	29.49	30.07	30.33	30.92	31.29	31.73
NCI (Mil. $)	5.45	5.48	5.53	5.45	5.50	5.59	5.38	5.65	5.58	5.62
Tx. Inc. (Mil. $)	0.28	0.30	0.36	0.27	0.32	0.41	0.21	0.48	0.40	0.44
Tx. Due (Mil. $)	1.02	1.05	1.11	1.09	1.09	1.12	1.16	1.15	1.18	1.23
ECB (Mil. $)	1.60	3.19	4.76	6.26	7.78	9.35	10.61	12.06	13.36	14.56
Net Worth (Mil. $)	24.79	25.61	26.50	27.45	28.54	29.81	30.90	32.34	33.79	35.31
Net Returns (Mil. $)	0.28	0.30	0.36	0.27	0.32	0.41	0.21	0.48	0.40	0.44
ROI	11.0%	11.2%	11.3%	11.0%	11.1%	11.1%	10.4%	10.8%	10.4%	10.3%
Interest Exp. (Mil. $)	3.86	3.91	3.90	3.86	3.84	3.78	3.69	3.60	3.50	3.41
Debt Exp. (Mil. $)	4.51	6.11	6.65	6.97	7.39	7.70	7.88	8.03	8.17	8.59
Var. Exp. (Mil. $)	18.14	20.39	21.40	22.25	23.12	23.99	24.73	25.29	25.96	26.88
Fixed Exp. (Mil. $)	7.62	7.65	7.72	7.69	7.70	7.73	7.77	7.77	7.80	7.85
Total Exp. (Mil. $)	25.76	28.05	29.13	29.93	30.82	31.72	32.50	33.06	33.76	34.73
Nut. % VE	3.7%	4.2%	3.7%	3.5%	3.4%	3.3%	3.3%	3.1%	3.1%	3.0%
Labor % VE	9.9%	8.9%	8.8%	8.8%	8.7%	8.7%	8.8%	8.9%	8.9%	8.9%
H & E L & M % VE	2.7%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.7%	2.7%
Chem. % VE	14.6%	13.9%	13.9%	13.9%	13.7%	13.6%	13.5%	13.5%	13.5%	13.4%
H & E NG % VE	60.0%	55.4%	54.9%	54.9%	54.6%	54.4%	54.5%	54.7%	54.8%	54.7%
Elec. Cons. % VE	6.2%	5.6%	5.6%	5.6%	5.5%	5.5%	5.5%	5.5%	5.4%	5.4%
Water. Recyl. % VE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E & C % VE	2.4%	2.3%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%
OI/DE % VE	0.5%	7.2%	8.4%	8.6%	9.3%	9.7%	9.6%	9.5%	9.4%	9.7%
H & E Exp. (Million $)	14.50	14.93	15.40	15.86	16.24	16.70	17.15	17.51	17.94	18.34
Var. Exp.% TE	70.0%	72.3%	72.9%	73.5%	74.1%	74.6%	74.9%	75.4%	75.7%	76.1%
Fixed Exp. % TE	30.0%	27.7%	27.1%	26.5%	25.9%	25.4%	25.1%	24.6%	24.3%	23.9%
Int. Exp. % TE	15.4%	14.4%	13.8%	13.4%	12.9%	12.4%	11.8%	11.3%	10.7%	10.1%
DLR % TE	0.0%	4.7%	5.6%	5.9%	6.4%	6.8%	6.6%	6.7%	6.6%	6.9%
Tx. Due % TE	3.6%	3.4%	3.5%	3.3%	3.4%	3.3%	3.4%	3.3%	3.4%	3.5%
H & E Exp. % TE	55.5%	53.0%	53.0%	53.3%	53.3%	53.4%	53.7%	54.2%	54.4%	54.5%
$/Gal. Oil (VE)	1.47	1.81	1.92	2.00	2.09	2.18	2.24	2.26	2.35	2.43
$/Gal. Oil (FE)	1.35	1.32	1.31	1.28	1.26	1.24	1.21	1.19	1.17	1.15
$/Gal. Oil (TE)	2.82	3.13	3.23	3.28	3.35	3.42	3.45	3.45	3.52	3.58
Growth Rate (g/L/day)	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83	0.84
Oil Content (%)	40.0%	40.2%	40.4%	40.6%	40.8%	41.0%	41.2%	41.4%	41.6%	41.8%
BM Prod. (1,000 ST)	58.87	59.54	60.20	60.70	61.26	61.93	62.50	63.09	63.70	64.33
BM Prod. (Tons/AF)	53.39	54.00	54.59	55.05	55.56	56.17	56.68	57.22	57.77	58.34
Oil Prod. (Mil. Gal.)	5.80	5.92	6.04	6.16	6.28	6.42	6.53	6.70	6.82	6.93
Oil Prod. (Gal./AF)	5,258	5,367	5,475	5,590	5,695	5,821	5,920	6,078	6,181	6,289
Meal Prod. (1,000 ST)	37.78	37.96	38.19	38.26	38.39	38.53	38.72	38.72	38.84	39.05
Meal Prod. (Tons/AF)	34.26	34.43	34.64	34.70	34.82	34.95	35.11	35.11	35.23	35.41
Water Loss (Bil. Gal.)	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
NG Cons. (Mil. TCF)	1.57	1.58	1.59	1.60	1.60	1.61	1.62	1.63	1.64	1.64
Elec. Cons. (Mil. kWh)	15.52	15.54	15.56	15.58	15.61	15.63	15.65	15.67	15.69	15.71

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

6.3.3.1. Comparison Across Corpus Christi, Texas Scenarios

As Table 37 shows, the mean cost of producing a gallon of oil is $3.32 for Scenario 5. Mean variable costs per gallon are $2.08 and mean fixed costs are $1.25 per gallon. The variable and fixed costs do not sum to the total cost because of rounding. Scenario 3 shows a lower cost per gallon than Scenario 5 because it uses flue gas as the carbon dioxide source, which does not include the use of blowers.

Table 37. Summary Statistics for Selected Key Output Variables for Five Corpus Christi, Texas Scenarios.

	Base Scen.	Scen. 2	Scen. 3	Scen. 4	Scen. 5
Ac. Ft. of Water	1,000	1,000	1,000	1,000	1,000
Water Depth (Inches)	24.0	14.0	24.0	24.0	24.0
Electricity Source	Conv.	Conv.	Conv.	Renew.	Conv.
CO2 Source	Air	Air	Flue Gas	Flue Gas	Air
NPV (Million $)	(89.21)	(26.51)	2.95	(14.02)	1.07
ERNW (Million $)	(66.14)	3.91	24.92	11.94	21.68
Probability of Losing RNW	100.0%	99.8%	84.8%	98.6%	86.6%
Probability of Neg. NPV	100.0%	91.8%	40.8%	83.6%	46.8%
End. Cash Bal. (Million $)					
Mean	(60.16)	(10.03)	10.24	(2.84)	8.35
Min	(74.20)	(61.02)	(35.76)	(46.40)	(36.31)
Max	(42.03)	43.84	59.16	47.73	58.20
Total Exp. ($/Gal. Oil)					
Mean	102.99	5.35	3.19	4.26	3.32
Min	33.95	1.33	1.09	1.44	1.13
Max	3,129.74	16.57	10.28	13.29	10.68
Var. Exp. ($/Gal. Oil)					
Mean	92.44	3.72	1.87	4.32	2.08
Min	29.70	(0.39)	(0.74)	1.41	(0.72)
Max	2,920.80	13.95	8.68	13.13	9.08
Fixed Exp. ($/Gal. Oil)					
Mean	10.54	1.62	1.32	(0.05)	1.25
Min	3.97	0.89	0.76	(1.17)	0.68
Max	209.40	3.33	2.45	1.04	2.40

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

SERF analysis of NPV distributions shows that Scenario 3 is preferred to the other four scenarios for risk neutral to normal risk averse decision makers (Figure 41). Scenario 5 would be the second most preferred scenario for a risk averse decision maker. It should be noted that Scenario 3 and Scenario 5 are the only two scenarios that would be considered by a rational investor because they have positive certainty equivalents over a range of ARACs. A rational investor would not invest in the Base Scenario, Scenario 2, or Scenario 4 because the certainty equivalents are negative across all levels of risk aversion.

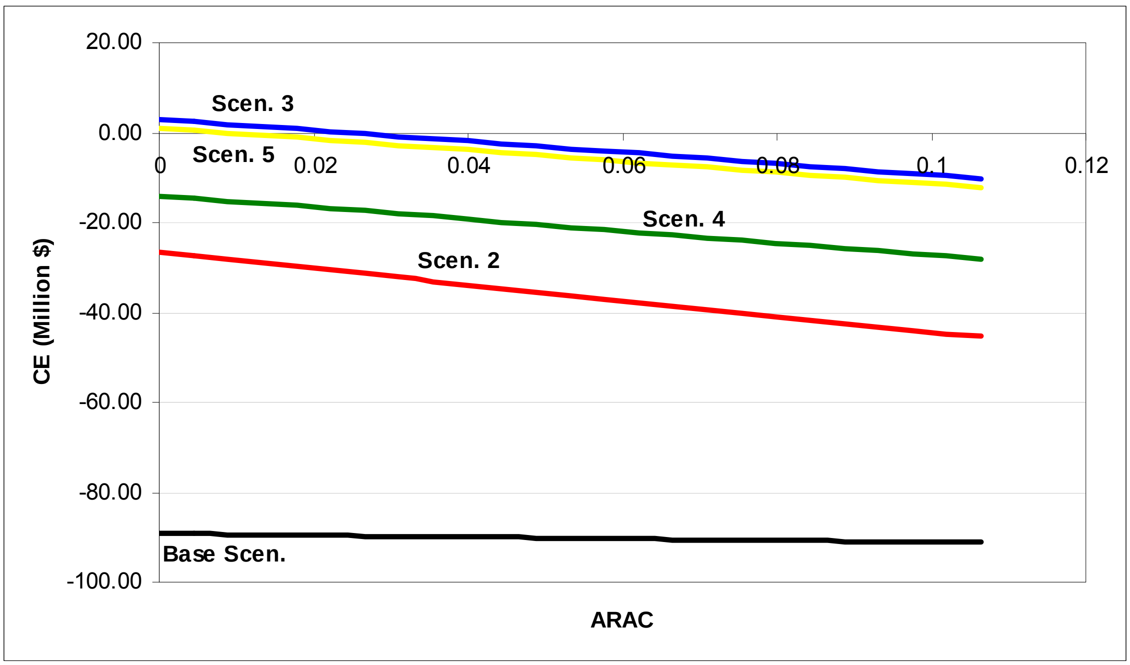

Figure 41. Stochastic efficiency with respect to a function (SERF) under a negative exponential utility function for NPV across five Corpus Christi, Texas Scenarios.

The PDF graph of NPV (Figure 42) shows the risk associated with NPV. Scenario 3 is the most preferred scenario of the five, with the highest mean and highest upper quantile and the greatest potential outcome. Scenarios 3 and 5 have very similar shapes, indicating that they share similar risk and are the only two scenarios with positive means. Scenario 4 exhibits a shape similar to the previous two scenarios, but with a negative mean and more negative results. Scenario 2 is the most risky of the scenarios, indicated by the widest distribution. It also exhibits results that are primarily negative. The Base Scenario, although the narrowest distribution of the five, will be the least preferred because of its negative results. A scenario with zero return will be preferred to the Base Scenario because of the negative NPV.

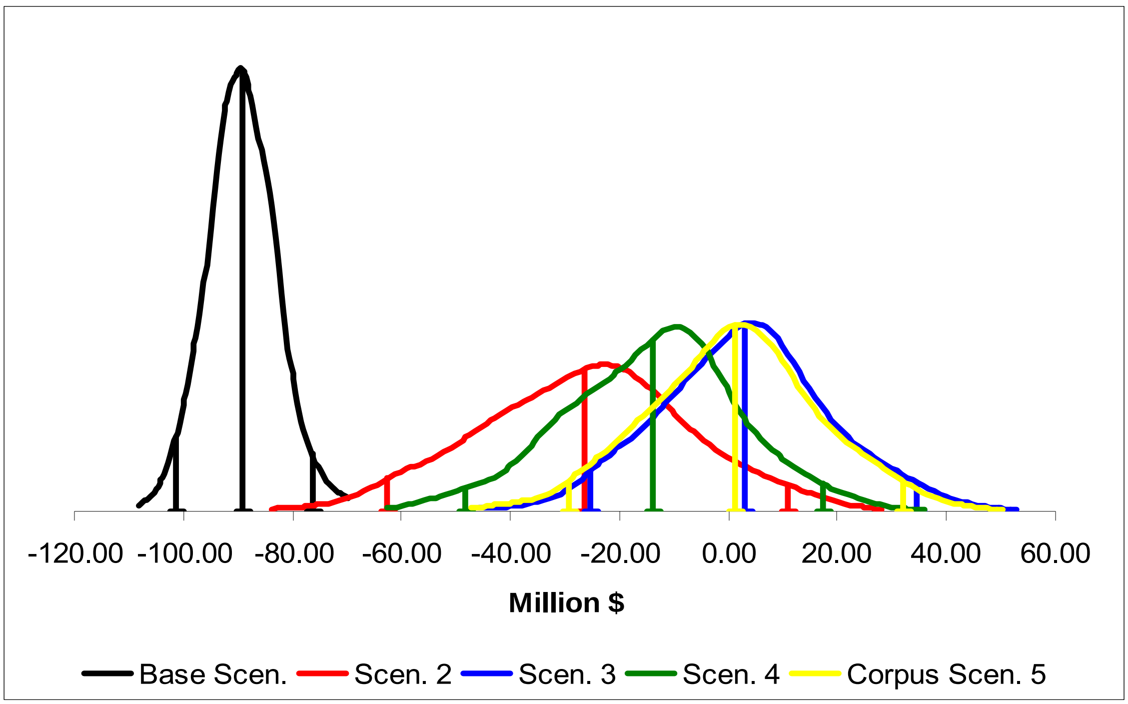

Figure 42. PDF approximations of NPV for five Corpus Christi, Texas Scenarios.

6.3.4. Comparison of Similar Scenarios Across Three Locations

A comparison of New Mexico Scenario 6, Pecos, Texas Scenario 6, and Corpus Christi Scenario 5 yields slight differences in the results with logical explanations. It should be noted that all of the input assumptions remain the same across the three locations, including production levels, pond and system designs, water sources, carbon dioxide sources, electricity source, facility size (in acre feet of water), and water depth. The only differences between the scenarios are land prices, electricity prices, and evaporation and precipitation.

Based on the NPV cumulative distribution functions, a decision maker would be indifferent between the three locations because the results are very similar (Figure 43). Because all three locations show very similar results, the CDFs of NPV overlap, making it difficult to observe differences between the scenarios. Corpus Christi exhibits much higher land costs than the other two locations and the electricity rate is considerably higher than New Mexico and slightly lower than Pecos, Texas. However, Corpus Christi water use (and the resulting electricity consumption from water pumping) is less because that area has higher rainfall and lower evaporation rates.

When comparing the mean cost of production per gallon of oil, the differences between the three scenarios are less than $0.01. All three locations have an average cost of production $3.32 per gallon (Table 38). Slight differences exist due to rounding.

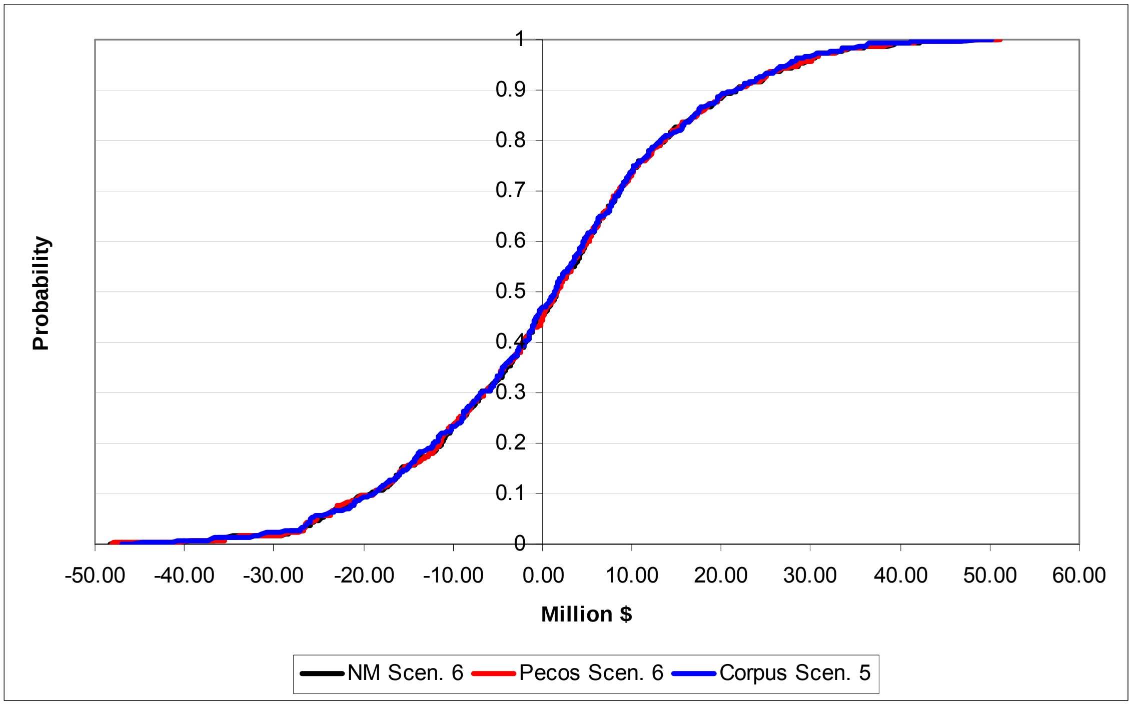

Figure 43. CDF of NPV for selected scenarios for three facility locations.

The probability of increasing real net worth is very low for three locations, meaning that all three have high probabilities of losing real net worth over the planning horizon. The Pecos, Texas location has a 13.8% probability of increasing real net worth, while the New Mexico location has a 14.0% probability of increasing real net worth. The Corpus Christi, Texas location has the lowest probability of increasing real net worth at 13.4%.

The Pecos, Texas location offers the lowest probability of a negative NPV, i.e., the highest probability of economic success and it is still not adequate to attract investors. The mean ending cash balance, mean ending real net worth, and mean NPV are slightly higher for the New Mexico location, but the means are not statistically different across the three locations. The only real difference among the locations is the much lower water requirements for Corpus Christi (0.67 billion gallons vs. more than 1.46 billion gallons for the other two scenarios).

Table 38. Averages and Probabilities of Selected Key Output Variables for Selected Scenarios for Three Locations.

Variable	NM Scen. 6	Pecos Scen. 6 Million $	Corpus Scen. 5
Mean NPV	1.30	1.27	1.07
Mean ERNW	21.76	21.73	21.68
Mean End. Cash Balance	14.83	14.78	14.56
Mean Water Use (Billion Gallons)	1.54	1.46	0.67
Mean Electricity Use (Million kWh)	15.73	15.72	15.62
Mean ROI (%)	10.9%	10.9%	10.9%
Probability of Dec. RNW	86.0%	86.2%	86.6%
Probability of Neg. NPV	45.8%	44.6%	46.8%
Total Exp. ($/Gal. Oil)			
Avg. Mean	3.32	3.32	3.32
Avg. Min	1.12	1.12	1.13
Avg. Max	10.66	10.70	10.68
Var. Exp. ($/Gal. Oil)			
Avg. Mean	2.08	2.08	2.08
Avg. Min	(0.60)	(0.64)	(0.72)
Avg. Max	9.73	9.21	9.08
Fixed Exp. ($/Gal. Oil)			
Avg. Mean	1.24	1.24	1.25
Avg. Min	0.71	0.71	0.68
Avg. Max	2.32	2.31	2.40

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

CHAPTER VII

SUMMARY AND CONCLUSIONS

7.1. Summary of Microalgae Model and Results

The economic model for the design and operation of a microalgae facility is a starting point to help determine the financial viability of algae farm. It was designed to provide a probabilistic projection of the profitability and viability of a microalgae facility in the southwestern United States. It addressed both the fixed and variable costs component of the facility for a ten-year horizon, including the inflation of variable costs and an annual improvement in facility production in the form of a stochastic learning curve. Using simulation, the model is able to forecast both profitability and production for a ten-year horizon over multiple scenarios in three locations. The differences between the scenarios were designed to analyze potential variations in cultivation systems and operational aspects of a facility.

The results for the three locations (New Mexico; Pecos, Texas; and Corpus Christi, Texas) show that for microalgae to have a modest probability of being profitable, mean production levels of 0.8 g/L/day must be attained and those levels must be able to be achieved in water depths of 24". The probability that NPV will be positive for the three scenarios that reflect these inputs (New Mexico Scenario 6, Pecos, Texas Scenario 6, and Corpus Christi, Texas Scenario 5) ranges from 53.2% to 55.4%, with Corpus Christi being the worst and Pecos, Texas being the best. All three scenarios face a high probability of losing real net worth, with Corpus Christi being the highest of the three at a probability of 86.6%. The probability of losing real net worth for the New

Mexico scenario was 86.0% and for Pecos, Texas, scenario, the probability was 86.2%. All of these probabilities for losing real net worth are considerably higher than levels acceptable to investors or lenders.

The cost of production per gallon of algae oil is high as well but that is typical for an immature industry like microalgae. As the technology and production levels improve, so too will the unit cost of production for microalgae oil. The mean cost per gallon for the Pecos, Texas Scenario 6 is $3.32, with $2.08 coming from variable costs and $1.24 coming from fixed costs. The mean cost per gallon for New Mexico Scenario 6 is $3.32, with fixed costs accounting for $1.24 and variable costs accounting for the remaining $2.08. The mean cost per gallon is slightly higher (by less than $0.01) in Corpus Christi, Texas Scenario 5, with the mean total cost per gallon being $3.32. Variable costs per gallon are $2.08 and fixed costs per gallon are $1.25.

7.2. Conclusions

Microalgae offers an alternative source of fuel for the future. However, as is clear from this research, improvements in production and cultivation must be made to make microalgae a viable renewable energy source, both physically and financially. Continued research and funding in microalgae will help improve both of those aspects. The keys to improving microalgae profitability are to improve growth rates and oil contents. These improvements will be a major factor in improving the financial viability of the industry. Much of the literature on microalgae research suggest theoretical maximums in production factors that simply are not financially viable in today's market. Researchers must be willing to think outside the current paradigm to make the necessary magnitude of improvements in production levels. Three major areas must be focused on in research to improve production levels: water (both source and depth), nutrients (both source and quantities), and carbon dioxide.

Water depths and sources are currently an area of contention throughout the industry. As has been stressed throughout this thesis, microalgae must be able to be produced at deeper water depths while maintaining the same production levels. Much concern exists regarding shading and settling of the microalgae in deeper ponds. Alternative circulation systems should be considered in which the circulation occurs at both the surface (paddlewheels) and on the bottoms of the pond (air delivery systems). The sheer volume of water lost through evaporation is of a major concern for making microalgae profitable. Increasing water depths while maintaining microalgae growth will be important in reducing the volume of water lost to evaporation. Because some of the areas being considered for microalgae production are in dry, hot climates, where water use will become a major issue due to competition for local water resources. Improving production at increased water depths is also important to minimizing facility construction costs. Because microalgae operate on a volume measurement rather than an area measurement, increasing water depths while maintaining production levels will decrease the number of ponds and all of the facilities and systems needed to keep the ponds operational.

Nutrients in the medium is the major secret among those currently working in the microalgae industry. Finding a reliable, productive, and cost effective nutrient combination is vital to improving the production capabilities of the microalgae and therefore the profitability of the industry. This is a major area of current research and one that will likely lead to improvements in production. It is accepted that nitrogen and phosphorus are two important nutrients for microalgae production. Unfortunately, this will create competition between agriculture and microalgae because nitrogen and phosphorus are also major inputs in crop agriculture production systems. Not only are prices relatively high for both of those inputs at this time, they are very volatile, as has been evidenced in their rapid price movements in the last two years. Nutrient price volatility is another source of risk that an already risky microalgae operation must manage. It will also be key to test the quantities of the nutrients necessary for algae by testing the nutrient loading of the water after the microalgae have been harvested. Nutrients remaining in the water indicate the algae is being fed too much or not being fed the correct nutrients, meaning the ration needs to be changed or reduced, either of which could help the profitability of the industry. Continued research and experimentation will help improve nutrient management in microalgae production.

Carbon dioxide is the biggest question regarding microalgae production. Much attention in recent years has been focused on carbon dioxide and global climate change. Microalgae must be carbon neutral at a minimum, meaning that the amount of carbon dioxide that enters the system is the same amount that is released as a result of the system. The source of carbon dioxide for the microalgae will be important in determining the net carbon balance. Using pure carbon dioxide not only creates additional costs because it must be purchased and stored, but it also releases unused carbon dioxide into the atmosphere. Not all carbon dioxide introduced into the production system is consumed by the microalgae, meaning that some of it will escape into the atmosphere, also known as outgassing. Releasing additional carbon dioxide into the atmosphere will not be popular with the government or environmentalists. A cheap or free carbon dioxide source, such as flue gas or atmospheric air, will not only help the facility improve its profitability but will also help capture carbon dioxide that would be released into the atmosphere or is already in the atmosphere. More research into these potential carbon sources is necessary before it can be proven that they are sufficient sources of carbon dioxide and their use will not have detrimental effects on the microalgae production. Although the microalgae will not be able to capture all of the carbon dioxide, microalgae could help mitigate carbon pollution if used properly.

Other improvements in microalgae production, both in growth rates and in oil contents, could come from genetic engineering. Genetic engineering, although controversial at times, has shown improved yields within agriculture. Creating microalgae strains, of which there are already thousands, tailored specifically for oil production will only help improve production levels. It is clear from the results of this model that water depths must be at least 24”, growth rates need to be at least 0.8 g/L/day, and oil contents need to be at least 40%. Such goals may seem lofty but it does set targets so algae researchers know what must be achieved to make microalgae production profitable with the current market conditions.

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APPENDIX A

DEFINITIONS TABLE

Appendix A Table 1. Definitions for Abbreviated Variables.

Abbreviation	Refers To:	Abbreviation	Refers To:
ABP	Algae by-product	L	Liter
Ac.	Acre	L & M	Labor and maintenance
AF	Acre feet	Max	Maximum
Avg.	Average	Med.	Medium
Bal.	Balance	Mil.	Million
Bil.	Billion	Min	Minimum
BM	Biomass	Nat.	Natural
Chem.	Chemicals	NCI	Net cash income
Cons.	Consumption	NG	Natural Gas
Contin.	Contingency	Neg.	Negative
Conv.	Conventional	NPV	Net present value
d	Day	Nut.	Nutrient
DE	Deficit Expenses	OI	Operating Interest
Dec.	Decreasing	Op.	Operating
Def.	Deficit	Prob.	Probability
DLR	Deficit Loan Repayment	Prod.	Production
E & C	Engineering and Contingency	Recyl.	Recycling
ECB	Ending cash balance	Renew.	Renewable
Elec.	Electricity	Repay.	Repayment
End.	Ending	Rev.	Revenue
Eng.	Engineering	RNW	Real net worth
ERNW	Ending real net worth	ROI	Return on investment
Exp.	Expense	Sel.	Selected
Ft.	Feet	ST	Short tons
g	Gram	TCF	Thousand cubic feet
Gal.	Gallon	TE	Total expenses
H & E	Harvesting and extraction	Tx.	Tax
Inc.	Income	Var.	Variable
Int.	Interest	VE	Variable expenses
kWh	Kilowatt hours		

APPENDIX B

MICROALGAE MODEL TABLES

Appendix B Table 1. Summary Statistics for Selected Key Output Variables for New Mexico Base Scenario.

	Year									
Sel. Var.	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Rev.	Million $									
Mean	5.24	5.43	5.50	5.59	5.72	5.83	5.86	5.91	6.02	6.09
Minimum	1.27	1.08	1.50	0.87	1.15	0.42	0.44	1.23	0.03	1.57
Maximum	15.11	16.42	13.77	17.81	16.84	15.70	14.66	16.32	16.43	14.09
NCI	Million $									
Mean	(5.49)	(6.18)	(6.88)	(7.76)	(8.84)	(10.01)	(11.31)	(12.78)	(14.33)	(16.22)
Minimum	(8.86)	(9.86)	(11.50)	(13.50)	(13.38)	(14.96)	(18.50)	(21.54)	(22.50)	(26.31)
Maximum	3.65	0.72	0.25	3.34	0.35	1.29	(0.83)	(2.00)	(3.78)	(7.86)
ECB	Million $									
Mean	(8.01)	(16.77)	(26.31)	(36.80)	(48.46)	(61.40)	(75.73)	(91.65)	(109.25)	(128.88)
Minimum	(11.38)	(22.35)	(33.79)	(47.32)	(61.10)	(75.68)	(92.29)	(111.65)	(131.15)	(160.16)
Maximum	0.95	(7.49)	(16.33)	(24.07)	(33.99)	(41.19)	(52.94)	(65.17)	(81.66)	(95.25)
Net Worth	Million $									
Mean	15.05	5.51	(4.70)	(15.74)	(27.83)	(41.06)	(55.56)	(71.49)	(88.95)	(108.26)
Minimum	11.68	(0.07)	(12.18)	(26.26)	(40.47)	(55.35)	(72.11)	(91.49)	(110.85)	(139.54)
Maximum	24.01	14.79	5.28	(3.01)	(13.36)	(20.86)	(32.76)	(45.01)	(61.35)	(74.63)
NPV	Million $									
Mean										(89.38)
Minimum										(108.59)
Maximum										(68.74)
End. RNW	Million $									
Mean										(66.46)
Minimum										(85.66)
Maximum										(45.82)
Oil Prod.	Million Gallons									
Mean	0.63	0.65	0.66	0.67	0.69	0.70	0.72	0.73	0.74	0.76
Minimum	0.11	0.12	0.18	0.14	0.14	0.06	0.08	0.13	0.00	0.20
Maximum	1.38	1.53	1.47	1.51	1.60	1.65	1.60	1.94	1.81	1.60
Water Use	Billion Gallons									
Mean	1.54	1.54	1.53	1.54	1.53	1.54	1.54	1.54	1.54	1.54
Minimum	1.04	1.04	1.05	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Maximum	1.95	1.96	1.93	1.95	1.91	1.94	1.95	1.94	1.95	1.95
Elec. Use	Million kWh									
Mean	12.47	12.48	12.48	12.49	12.49	12.50	12.50	12.51	12.51	12.52
Minimum	11.65	11.65	11.63	11.68	11.64	11.47	11.53	11.57	11.44	11.58
Maximum	13.32	13.26	13.35	13.26	13.30	13.31	13.34	13.49	13.50	13.33
% Neg. ECB										
Probability	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
% Dec. RNW										
Probability										100.0%
% Neg. NPV										
Probability										100.0%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 1. Summary Statistics for Selected Key Output Variables for New Mexico Scenario 2.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue					Million $					
Mean	26.14	26.94	27.36	27.72	28.31	28.91	29.12	29.51	30.00	30.43
Minimum	11.95	12.02	12.49	10.78	10.70	8.08	11.88	15.24	11.49	14.15
Maximum	57.75	61.47	63.06	85.52	83.71	70.14	65.60	68.10	73.79	65.85
NCI					Million $					
Mean	3.01	2.95	2.88	2.67	2.62	2.60	2.29	2.12	1.98	1.62
Minimum	(10.38)	(13.19)	(16.78)	(18.76)	(14.26)	(14.46)	(15.34)	(19.53)	(17.94)	(19.70)
Maximum	34.52	38.43	43.61	56.45	51.76	42.94	41.41	42.75	38.46	36.64
ECB					Million $					
Mean	(1.07)	(2.31)	(3.73)	(5.43)	(7.28)	(9.33)	(11.80)	(14.53)	(17.60)	(21.24)
Minimum	(13.87)	(24.65)	(34.82)	(40.86)	(53.56)	(65.19)	(69.42)	(88.55)	(97.84)	(112.13)
Maximum	19.99	21.11	31.59	38.24	36.68	53.17	56.66	64.29	59.13	61.86
Net Worth					Million $					
Mean	30.94	28.63	26.28	23.81	21.37	18.90	16.21	13.46	10.60	7.40
Minimum	18.14	6.29	(4.81)	(11.62)	(24.91)	(36.96)	(41.42)	(60.56)	(69.64)	(83.50)
Maximum	52.01	52.04	61.60	67.48	65.33	81.41	84.67	92.28	87.32	90.49
NPV					Million $					
Mean										(25.63)
Minimum										(83.01)
Maximum										28.70
End. RNW					Million $					
Mean										4.54
Minimum										(51.26)
Maximum										55.55
Oil Production					Million Gallons					
Mean	5.53	5.67	5.78	5.90	6.02	6.16	6.27	6.39	6.52	6.63
Minimum	2.31	2.39	2.59	2.58	2.80	2.23	2.74	2.90	2.81	3.18
Maximum	11.57	11.16	10.84	12.17	12.77	12.87	13.87	16.28	14.90	13.76
Water Use					Billion Gallons					
Mean	2.49	2.49	2.49	2.49	2.49	2.49	2.49	2.50	2.49	2.49
Minimum	1.68	1.69	1.70	1.68	1.68	1.68	1.68	1.68	1.68	1.69
Maximum	3.16	3.17	3.14	3.16	3.09	3.16	3.16	3.15	3.16	3.17
Electricity Use					Million kWh					
Mean	22.90	22.92	22.94	22.96	22.98	23.00	23.02	23.04	23.06	23.08
Minimum	21.33	21.33	21.35	21.42	21.34	21.04	21.13	21.29	20.91	21.26
Maximum	24.53	24.40	24.58	24.43	24.49	24.57	24.61	24.89	24.96	24.66
% Neg. ECB										
Probability	58.6%	59.6%	61.2%	63.6%	65.6%	67.0%	71.0%	73.0%	76.0%	77.8%
% Dec. RNW										
Probability										99.8%
% Neg. NPV										
Probability										91.2%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 3. Summary Statistics for Selected Key Output Variables for New Mexico Scenario 3.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue					Million $					
Mean	28.50	29.35	29.83	30.24	30.87	31.53	31.78	32.21	32.74	33.21
Minimum	13.70	13.80	14.38	12.60	12.53	9.79	13.79	17.25	13.43	16.29
Maximum	61.45	65.39	67.13	90.51	88.65	74.53	69.89	72.48	78.43	70.25
NCI					Million $					
Mean	5.24	5.30	5.40	5.36	5.52	5.69	5.60	5.69	5.82	5.78
Minimum	(8.76)	(11.67)	(15.07)	(16.67)	(11.99)	(11.92)	(13.15)	(15.16)	(14.61)	(14.69)
Maximum	38.15	42.40	47.94	61.49	56.33	47.26	46.68	47.58	42.84	41.15
ECB					Million $					
Mean	0.31	0.55	0.77	0.87	1.00	1.13	0.97	0.83	0.57	0.04
Minimum	(12.73)	(22.03)	(30.61)	(34.61)	(44.98)	(54.13)	(54.79)	(70.49)	(75.55)	(85.53)
Maximum	21.48	23.25	35.11	42.73	42.18	61.00	66.89	75.83	73.32	79.25
Net Worth					Million $					
Mean	36.66	35.67	34.84	34.07	33.51	33.18	32.77	32.60	32.57	32.55
Minimum	23.62	13.08	3.45	(1.41)	(12.46)	(22.08)	(23.00)	(38.72)	(43.55)	(53.02)
Maximum	57.83	58.37	69.18	75.93	74.70	93.05	98.69	107.60	105.33	111.76
NPV					Million $					
Mean										(13.69)
Minimum										(68.43)
Maximum										38.48
End. RNW					Million $					
Mean										19.98
Minimum										(32.55)
Maximum										68.61
Oil Production					Million Gallons					
Mean	5.78	5.92	6.04	6.17	6.29	6.43	6.55	6.67	6.81	6.92
Minimum	2.42	2.50	2.71	2.70	2.93	2.33	2.87	3.03	2.94	3.32
Maximum	12.08	11.66	11.33	12.71	13.34	13.45	14.49	17.00	15.57	14.37
Water Use					Billion Gallons					
Mean	1.54	1.54	1.53	1.54	1.53	1.54	1.54	1.54	1.54	1.54
Minimum	1.04	1.04	1.05	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Maximum	1.95	1.96	1.93	1.95	1.91	1.94	1.95	1.94	1.95	1.95
Electricity Use					Million kWh					
Mean	15.63	15.65	15.67	15.69	15.71	15.74	15.76	15.78	15.80	15.82
Minimum	14.00	13.99	14.05	14.09	14.01	13.71	13.78	13.98	13.54	13.93
Maximum	17.34	17.18	17.36	17.23	17.27	17.40	17.41	17.70	17.78	17.47
% Neg. ECB										
Probability	49.6%	47.4%	45.8%	48.6%	47.2%	46.4%	47.0%	47.6%	48.4%	47.8%
% Dec. RNW										
Probability										99.2%
% Neg. NPV										
Probability										79.6%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 4. Summary Statistics for Selected Key Output Variables for New Mexico Scenario 4.

Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
					Year					
Total Revenue					Million $					
Mean	3.34	3.45	3.50	3.55	3.62	3.70	3.72	3.77	3.84	3.89
Minimum	1.53	1.54	1.60	1.38	1.37	1.03	1.52	1.95	1.47	1.81
Maximum	7.39	7.86	8.07	10.94	10.71	8.97	8.39	8.71	9.44	8.42
NCI					Million $					
Mean	0.54	0.54	0.54	0.52	0.53	0.53	0.51	0.50	0.50	0.47
Minimum	(1.21)	(1.52)	(1.96)	(2.19)	(1.54)	(1.62)	(1.80)	(2.07)	(2.00)	(2.09)
Maximum	4.59	5.07	5.78	7.40	6.82	5.66	5.58	5.63	5.05	4.76
ECB					Million $					
Mean	0.10	0.20	0.28	0.34	0.41	0.47	0.49	0.50	0.50	0.46
Minimum	(1.51)	(2.53)	(3.50)	(4.05)	(5.29)	(6.39)	(6.25)	(7.77)	(8.25)	(10.30)
Maximum	2.70	2.97	4.35	5.29	5.36	7.89	8.77	9.80	9.59	10.42
Net Worth					Million $					
Mean	2.86	2.86	2.87	2.86	2.88	2.90	2.90	2.92	2.93	2.93
Minimum	1.25	0.14	(0.91)	(1.53)	(2.82)	(3.96)	(3.84)	(5.36)	(5.82)	(7.83)
Maximum	5.46	5.64	6.94	7.81	7.82	10.33	11.18	12.21	12.02	12.89
NPV					Million $					
Mean										(0.69)
Minimum										(7.53)
Maximum										5.86
End. RNW					Million $					
Mean										1.80
Minimum										(4.81)
Maximum										7.91
Oil Production					Million Gallons					
Mean	0.71	0.73	0.74	0.76	0.77	0.79	0.80	0.82	0.83	0.85
Minimum	0.30	0.31	0.33	0.33	0.36	0.29	0.35	0.37	0.36	0.41
Maximum	1.48	1.43	1.39	1.56	1.63	1.65	1.77	2.08	1.91	1.76
Water Use					Billion Gallons					
Mean	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Minimum	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Maximum	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Electricity Use					Million kWh					
Mean	1.91	1.92	1.92	1.92	1.92	1.93	1.93	1.93	1.93	1.94
Minimum	1.71	1.71	1.72	1.72	1.72	1.68	1.69	1.71	1.66	1.71
Maximum	2.12	2.10	2.13	2.11	2.12	2.13	2.13	2.17	2.18	2.14
% Neg. ECB										
Probability	44.4%	41.6%	41.0%	40.6%	41.6%	40.2%	42.2%	41.2%	42.0%	41.8%
% Dec. RNW										
Probability										91.0%
% Neg. NPV										
Probability										62.0%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 5. Summary Statistics for Selected Key Output Variables for New Mexico Scenario 5.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue	Million $									
Mean	13.93	14.36	14.58	14.77	15.09	15.41	15.52	15.73	15.99	16.22
Minimum	6.37	6.41	6.66	5.74	5.70	4.31	6.33	8.12	6.12	7.54
Maximum	30.78	32.76	33.61	45.58	44.61	37.38	34.96	36.29	39.33	35.09
NCI	Million $									
Mean	2.44	2.45	2.46	2.39	2.43	2.48	2.39	2.38	2.40	2.33
Minimum	(4.65)	(6.17)	(7.90)	(8.87)	(6.32)	(6.44)	(7.29)	(8.03)	(7.88)	(8.27)
Maximum	19.23	21.39	24.19	31.11	28.39	23.67	23.41	23.61	21.28	20.21
ECB	Million $									
Mean	0.53	1.03	1.50	1.90	2.31	2.74	2.99	3.26	3.46	3.53
Minimum	(5.97)	(10.30)	(14.09)	(15.60)	(20.35)	(24.46)	(24.60)	(31.91)	(33.79)	(38.57)
Maximum	11.20	12.34	18.67	22.78	22.30	32.73	36.36	40.66	39.76	43.20
Net Worth	Million $									
Mean	12.69	12.78	12.90	13.01	13.19	13.46	13.63	13.89	14.17	14.41
Minimum	6.19	1.45	(2.70)	(4.50)	(9.47)	(13.74)	(13.96)	(21.28)	(23.08)	(27.69)
Maximum	23.36	24.09	30.07	33.89	33.18	43.45	47.00	51.29	50.47	54.08
NPV	Million $									
Mean										(2.10)
Minimum										(28.99)
Maximum										24.03
End. RNW	Million $									
Mean										8.84
Minimum										(17.00)
Maximum										33.20
Oil Production	Million Gallons									
Mean	2.95	3.02	3.08	3.15	3.21	3.28	3.34	3.40	3.47	3.53
Minimum	1.23	1.27	1.38	1.38	1.49	1.19	1.46	1.55	1.50	1.69
Maximum	6.17	5.95	5.78	6.49	6.81	6.86	7.39	8.68	7.94	7.33
Water Use	Billion Gallons									
Mean	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.79	0.78	0.78
Minimum	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Maximum	12.36	12.67	13.01	12.83	13.12	12.54	12.77	12.44	13.18	12.76
Electricity Use	Million kWh									
Mean	7.98	7.99	8.00	8.01	8.02	8.03	8.04	8.05	8.06	8.07
Minimum	7.14	7.14	7.17	7.19	7.15	7.00	7.03	7.13	6.91	7.11
Maximum	8.85	8.76	8.86	8.79	8.81	8.88	8.88	9.03	9.07	8.91
% Neg. ECB										
Probability	43.0%	40.4%	38.6%	36.6%	37.8%	37.6%	38.4%	38.2%	36.6%	36.6%
% Dec. RNW										
Probability										91.2%
% Neg. NPV										
Probability										59.8%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 6. Summary Statistics for Selected Key Output Variables for New Mexico Scenario 6.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue					Million $					
Mean	27.31	28.14	28.58	28.96	29.57	30.20	30.42	30.83	31.33	31.78
Minimum	12.48	12.55	13.05	11.26	11.17	8.44	12.41	15.91	12.00	14.78
Maximum	60.33	64.21	65.87	89.33	87.44	73.26	68.52	71.13	77.08	68.78
NCI					Million $					
Mean	5.42	5.46	5.50	5.41	5.53	5.66	5.53	5.57	5.65	5.55
Minimum	(8.58)	(11.53)	(14.71)	(16.39)	(11.73)	(11.92)	(13.58)	(14.29)	(14.35)	(15.53)
Maximum	38.33	42.64	47.98	61.76	56.25	47.00	46.47	46.99	42.19	40.30
ECB					Million $					
Mean	1.61	3.21	4.80	6.28	7.84	9.47	10.82	12.26	13.63	14.83
Minimum	(11.09)	(18.71)	(25.29)	(27.62)	(35.91)	(42.93)	(41.64)	(54.36)	(56.34)	(62.53)
Maximum	22.29	25.25	37.72	46.26	46.19	66.70	74.81	83.22	82.42	90.08
Net Worth					Million $					
Mean	24.67	25.50	26.41	27.34	28.47	29.80	30.99	32.41	33.94	35.45
Minimum	11.96	3.57	(3.68)	(6.56)	(15.28)	(22.60)	(21.47)	(34.20)	(36.04)	(41.90)
Maximum	45.34	47.53	59.33	67.32	66.82	87.03	94.98	103.38	102.72	110.70
NPV					Million $					
Mean										1.30
Minimum										(48.33)
Maximum										50.97
End. RNW					Million $					
Mean										21.76
Minimum										(25.73)
Maximum										67.96
Oil Production					Million Gallons					
Mean	5.78	5.92	6.04	6.17	6.29	6.43	6.55	6.67	6.81	6.92
Minimum	2.42	2.50	2.71	2.70	2.93	2.33	2.87	3.03	2.94	3.32
Maximum	12.08	11.66	11.33	12.71	13.34	13.45	14.49	17.00	15.57	14.37
Water Use					Billion Gallons					
Mean	1.54	1.54	1.53	1.54	1.53	1.54	1.54	1.54	1.54	1.54
Minimum	1.04	1.04	1.05	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Maximum	1.95	1.96	1.93	1.95	1.91	1.94	1.95	1.94	1.95	1.95
Electricity Use					Million kWh					
Mean	15.63	15.65	15.67	15.69	15.71	15.74	15.76	15.78	15.80	15.82
Minimum	14.00	13.99	14.05	14.09	14.01	13.71	13.78	13.98	13.54	13.93
Maximum	17.34	17.18	17.36	17.23	17.27	17.40	17.41	17.70	17.78	17.47
% Neg. ECB										
Probability	38.4%	35.4%	32.2%	30.6%	29.8%	30.2%	27.4%	26.6%	25.8%	26.6%
% Dec. RNW										
Probability										86.0%
% Neg. NPV										
Probability										45.8%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 7. Summary Statistics for Selected Key Output Variables for Pecos, Texas Base Scenario.

	Year									
Sel. Var.	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Rev.	Million $									
Mean	5.26	5.40	5.49	5.61	5.68	5.79	5.86	5.88	6.01	6.09
Minimum	1.25	0.75	0.94	1.12	1.34	1.16	1.37	0.76	1.48	1.57
Maximum	13.35	16.49	13.30	14.46	14.27	21.04	16.96	16.07	15.85	15.09
NCI	Million $									
Mean	(5.44)	(6.16)	(6.86)	(7.71)	(8.86)	(9.98)	(11.27)	(12.74)	(14.31)	(16.12)
Minimum	(10.10)	(10.03)	(11.41)	(12.00)	(13.90)	(15.24)	(17.42)	(20.07)	(21.71)	(25.81)
Maximum	1.30	4.42	(1.44)	1.98	(1.39)	0.20	(2.28)	(4.53)	(5.56)	(6.26)
ECB	Million $									
Mean	(7.96)	(16.71)	(26.22)	(36.67)	(48.35)	(61.25)	(75.54)	(91.42)	(109.00)	(128.52)
Minimum	(12.62)	(22.11)	(34.28)	(46.02)	(60.14)	(74.73)	(90.62)	(112.53)	(133.96)	(157.57)
Maximum	(1.28)	(7.68)	(16.20)	(23.12)	(29.15)	(37.94)	(50.09)	(64.91)	(81.94)	(96.53)
Net Worth	Million $									
Mean	15.10	5.57	(4.61)	(15.61)	(27.72)	(40.92)	(55.37)	(71.27)	(88.69)	(107.90)
Minimum	10.44	0.17	(12.67)	(24.96)	(39.51)	(54.40)	(70.45)	(92.37)	(113.66)	(136.95)
Maximum	21.78	14.60	5.42	(2.06)	(8.52)	(17.61)	(29.92)	(44.76)	(61.64)	(75.91)
NPV	Million $									
Mean										(89.16)
Minimum										(107.00)
Maximum										(69.48)
End. RNW	Million $									
Mean										(66.24)
Minimum										(84.07)
Maximum										(46.60)
Oil Prod.	Million Gallons									
Mean	0.63	0.65	0.66	0.68	0.69	0.70	0.72	0.73	0.74	0.76
Minimum	0.18	0.10	0.09	0.14	0.14	0.15	0.21	0.10	0.20	0.17
Maximum	1.60	1.53	1.51	1.55	1.52	1.81	1.62	1.53	1.80	1.77
Water Use	Billion Gallons									
Mean	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46
Minimum	1.01	0.97	1.05	1.00	1.03	0.95	1.03	0.97	1.00	0.96
Maximum	1.92	1.91	1.91	1.90	1.88	1.89	1.90	1.85	1.87	1.90
Elec. Use	Million kWh									
Mean	12.46	12.47	12.47	12.48	12.48	12.49	12.49	12.50	12.50	12.51
Minimum	11.65	11.58	11.65	11.69	11.66	11.71	11.71	11.58	11.62	11.70
Maximum	13.42	13.41	13.28	13.30	13.43	13.31	13.38	13.28	13.43	13.33
% Neg. ECB										
Probability	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
% Dec. RNW										
Probability										100.0%
% Neg. NPV										
Probability										100.0%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 8. Summary Statistics for Selected Key Output Variables for Pecos, Texas Scenario 2.

	Year									
Sel. Var.	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Rev.	Million $									
Mean	25.03	25.79	26.19	26.54	27.10	27.68	27.88	28.26	28.72	29.13
Minimum	11.44	11.51	11.96	10.32	10.24	7.73	11.37	14.59	11.00	13.55
Maximum	55.29	58.85	60.38	81.88	80.15	67.15	62.81	65.20	70.65	63.05
NCI	Million $									
Mean	(3.28)	(3.82)	(4.60)	(5.62)	(6.76)	(7.88)	(9.40)	(11.03)	(12.66)	(14.78)
Minimum	(16.10)	(18.77)	(23.78)	(26.59)	(23.54)	(24.41)	(29.42)	(36.62)	(35.04)	(41.24)
Maximum	26.87	29.98	34.26	46.47	40.20	32.71	28.64	29.52	25.06	20.58
ECB	Million $									
Mean	(10.15)	(21.02)	(32.87)	(45.96)	(60.39)	(76.21)	(93.81)	(113.33)	(134.82)	(158.81)
Minimum	(22.89)	(43.49)	(64.65)	(82.82)	(107.76)	(133.33)	(154.18)	(192.99)	(223.84)	(260.49)
Maximum	15.46	8.22	9.63	7.39	(6.23)	5.72	(3.35)	(2.34)	(21.45)	(35.60)
Net Worth	Million $									
Mean	52.01	39.05	25.40	10.82	(4.77)	(21.40)	(39.43)	(58.99)	(80.09)	(103.21)
Minimum	39.27	16.58	(6.38)	(26.04)	(52.14)	(78.52)	(99.80)	(138.65)	(169.11)	(204.90)
Maximum	77.63	68.29	67.90	64.17	49.39	60.53	51.02	52.01	33.29	19.99
NPV	Million $									
Mean										(124.79)
Minimum										(187.59)
Maximum										(46.58)
End. RNW	Million $									
Mean										(63.36)
Minimum										(125.79)
Maximum										12.27
Oil Prod.	Million Gallons									
Mean	5.30	5.43	5.53	5.65	5.76	5.90	6.00	6.11	6.24	6.35
Minimum	2.21	2.29	2.48	2.47	2.68	2.14	2.63	2.78	2.69	3.04
Maximum	11.08	10.68	10.38	11.65	12.23	12.33	13.28	15.59	14.27	13.17
Water Use	Billion Gallons									
Mean	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
Minimum	3.59	3.43	3.42	3.62	3.77	3.58	3.62	3.62	3.57	3.58
Maximum	6.85	6.82	6.86	6.85	6.72	6.72	6.83	6.69	6.76	6.87
Elec. Use	Million kWh									
Mean	34.32	34.34	34.36	34.38	34.40	34.42	34.43	34.46	34.48	34.50
Minimum	32.79	32.78	32.81	32.85	32.81	32.53	32.56	32.71	32.49	32.72
Maximum	35.92	35.88	36.01	35.79	35.83	35.80	35.96	36.29	36.29	36.08
% Neg. ECB										
Probability	92.8%	97.4%	99.2%	99.6%	100.0%	99.8%	100.0%	100.0%	100.0%	100.0%
% Dec. RNW										
Probability										100.0%
% Neg. NPV										
Probability										100.0%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 9. Summary Statistics for Selected Key Output Variables for Pecos, Texas Scenario 3.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue	Million $									
Mean	24.86	25.62	26.02	26.36	26.92	27.49	27.69	28.07	28.53	28.94
Minimum	11.37	11.43	11.88	10.25	10.17	7.68	11.30	14.49	10.92	13.46
Maximum	54.92	58.46	59.97	81.33	79.61	66.70	62.39	64.76	70.18	62.63
NCI	Million $									
Mean	2.19	2.11	1.98	1.72	1.58	1.48	1.09	0.80	0.53	0.03
Minimum	(10.53)	(13.19)	(16.83)	(18.75)	(14.70)	(15.03)	(15.89)	(20.39)	(18.52)	(21.20)
Maximum	32.14	35.84	40.61	52.88	48.20	40.16	38.15	39.47	36.02	33.77
ECB	Million $									
Mean	(2.03)	(4.27)	(6.75)	(9.58)	(12.65)	(16.02)	(19.90)	(24.20)	(28.97)	(34.47)
Minimum	(14.34)	(25.87)	(36.91)	(44.00)	(57.75)	(70.55)	(76.75)	(97.44)	(108.95)	(124.34)
Maximum	18.56	19.26	27.81	33.58	32.12	47.12	48.03	55.96	49.62	50.67
Net Worth	Million $									
Mean	32.78	29.38	25.89	22.22	18.50	14.68	10.55	6.23	1.68	(3.33)
Minimum	20.48	7.77	(4.28)	(12.20)	(26.60)	(39.85)	(46.30)	(67.01)	(78.30)	(93.20)
Maximum	53.37	52.90	60.44	65.38	63.27	77.82	78.48	86.40	80.28	81.81
NPV	Million $									
Mean										(35.29)
Minimum										(91.79)
Maximum										20.16
End. RNW	Million $									
Mean										(2.05)
Minimum										(57.22)
Maximum										50.22
Oil Production	Million Gallons									
Mean	5.26	5.39	5.50	5.61	5.72	5.86	5.96	6.07	6.20	6.30
Minimum	2.20	2.27	2.46	2.46	2.66	2.12	2.61	2.76	2.67	3.02
Maximum	11.00	10.61	10.31	11.58	12.14	12.24	13.19	15.48	14.17	13.09
Water Use	Billion Gallons									
Mean	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63
Minimum	1.80	1.71	1.71	1.81	1.89	1.80	1.81	1.81	1.79	1.79
Maximum	3.42	3.41	3.43	3.42	3.36	3.36	3.41	3.35	3.38	3.44
Electricity Use	Million kWh									
Mean	18.90	18.92	18.94	18.96	18.98	19.00	19.02	19.04	19.06	19.08
Minimum	17.40	17.39	17.46	17.47	17.42	17.16	17.19	17.36	17.03	17.34
Maximum	20.47	20.36	20.52	20.36	20.39	20.44	20.52	20.81	20.85	20.62
% Neg. ECB										
Probability	66.2%	68.6%	73.0%	76.4%	76.0%	80.2%	83.6%	84.8%	87.6%	87.2%
% Dec. RNW										
Probability										100.0%
% Neg. NPV										
Probability										95.8%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 10. Summary Statistics for Selected Key Output Variables for Pecos, Texas Scenario 4.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue	Million $									
Mean	3.34	3.45	3.50	3.55	3.62	3.70	3.72	3.77	3.84	3.89
Minimum	1.53	1.54	1.60	1.38	1.37	1.03	1.52	1.95	1.47	1.81
Maximum	7.39	7.86	8.07	10.94	10.71	8.97	8.39	8.71	9.44	8.42
NCI	Million $									
Mean	0.57	0.57	0.57	0.55	0.56	0.57	0.55	0.54	0.54	0.52
Minimum	(1.16)	(1.50)	(1.92)	(2.14)	(1.52)	(1.58)	(1.78)	(1.99)	(1.96)	(2.02)
Maximum	4.61	5.11	5.79	7.44	6.85	5.68	5.60	5.66	5.07	4.81
ECB	Million $									
Mean	0.12	0.24	0.35	0.45	0.54	0.64	0.69	0.74	0.78	0.79
Minimum	(1.46)	(2.49)	(3.41)	(3.97)	(5.19)	(6.26)	(6.09)	(7.59)	(8.03)	(9.71)
Maximum	2.72	3.01	4.39	5.33	5.49	7.99	8.84	9.93	9.76	10.63
Net Worth	Million $									
Mean	2.88	2.91	2.94	2.97	3.01	3.07	3.10	3.16	3.21	3.26
Minimum	1.30	0.18	(0.82)	(1.45)	(2.72)	(3.83)	(3.68)	(5.17)	(5.60)	(7.24)
Maximum	5.47	5.67	6.97	7.85	7.95	10.43	11.26	12.34	12.19	13.10
NPV	Million $									
Mean										(0.48)
Minimum										(7.17)
Maximum										6.00
End. RNW	Million $									
Mean										2.00
Minimum										(4.45)
Maximum										8.04
Oil Production	Million Gallons									
Mean	0.71	0.73	0.74	0.76	0.77	0.79	0.80	0.82	0.83	0.85
Minimum	0.30	0.31	0.33	0.33	0.36	0.29	0.35	0.37	0.36	0.41
Maximum	1.48	1.43	1.39	1.56	1.63	1.65	1.77	2.08	1.91	1.76
Water Use	Billion Gallons									
Mean	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Minimum	0.12	0.12	0.12	0.13	0.13	0.12	0.13	0.12	0.12	0.12
Maximum	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24
Electricity Use	Million kWh									
Mean	1.91	1.92	1.92	1.92	1.92	1.93	1.93	1.93	1.93	1.94
Minimum	1.71	1.71	1.72	1.72	1.71	1.68	1.68	1.71	1.66	1.70
Maximum	2.12	2.10	2.13	2.11	2.11	2.13	2.13	2.17	2.18	2.14
% Neg. ECB										
Probability	43.2%	40.6%	38.6%	37.2%	38.4%	37.8%	39.4%	38.8%	38.0%	38.4%
% Dec. RNW										
Probability										90.0%
% Neg. NPV										
Probability										59.0%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 11. Summary Statistics for Selected Key Output Variables for Pecos, Texas Scenario 5.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue	Million $									
Mean	13.93	14.36	14.58	14.77	15.09	15.41	15.52	15.73	15.99	16.22
Minimum	6.37	6.41	6.66	5.74	5.70	4.31	6.33	8.12	6.12	7.54
Maximum	30.78	32.76	33.61	45.58	44.61	37.38	34.96	36.29	39.33	35.09
NCI	Million $									
Mean	2.43	2.44	2.45	2.38	2.42	2.47	2.38	2.37	2.39	2.32
Minimum	(4.72)	(6.18)	(7.92)	(8.84)	(6.37)	(6.42)	(7.28)	(7.96)	(7.93)	(8.32)
Maximum	19.22	21.41	24.13	31.12	28.33	23.58	23.37	23.60	21.22	20.22
ECB	Million $									
Mean	0.52	1.01	1.48	1.87	2.27	2.69	2.93	3.19	3.38	3.44
Minimum	(6.05)	(10.38)	(14.17)	(15.73)	(20.51)	(24.67)	(24.99)	(32.40)	(34.37)	(38.40)
Maximum	11.19	12.35	18.56	22.63	22.34	32.75	35.90	40.68	39.79	43.24
Net Worth	Million $									
Mean	12.68	12.76	12.88	12.98	13.15	13.41	13.57	13.82	14.09	14.32
Minimum	6.11	1.37	(2.77)	(4.62)	(9.63)	(13.95)	(14.35)	(21.77)	(23.67)	(27.53)
Maximum	23.35	24.10	29.96	33.73	33.22	43.47	46.54	51.31	50.50	54.12
NPV	Million $									
Mean										(2.16)
Minimum										(28.89)
Maximum										24.06
End. RNW	Million $									
Mean										8.79
Minimum										(16.90)
Maximum										33.22
Oil Production	Million Gallons									
Mean	2.95	3.02	3.08	3.15	3.21	3.28	3.34	3.40	3.47	3.53
Minimum	1.23	1.27	1.38	1.38	1.49	1.19	1.46	1.55	1.50	1.69
Maximum	6.17	5.95	5.78	6.49	6.81	6.86	7.39	8.68	7.94	7.33
Water Use	Billion Gallons									
Mean	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Minimum	0.51	0.49	0.49	0.52	0.54	0.51	0.52	0.52	0.51	0.51
Maximum	0.97	0.97	0.97	0.97	0.95	0.96	0.97	0.95	0.96	0.98
Electricity Use	Million kWh									
Mean	7.97	7.98	7.99	8.00	8.01	8.02	8.03	8.05	8.06	8.07
Minimum	7.14	7.12	7.18	7.17	7.14	7.00	7.02	7.13	6.91	7.10
Maximum	8.85	8.76	8.86	8.78	8.80	8.86	8.88	9.03	9.06	8.92
% Neg. ECB										
Probability	43.0%	39.8%	38.6%	37.0%	38.2%	37.0%	38.4%	38.2%	37.0%	36.8%
% Dec. RNW										
Probability										91.0%
% Neg. NPV										
Probability										60.0%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 12. Summary Statistics for Selected Key Output Variables for Pecos, Texas Scenario 6.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue					Million $					
Mean	27.31	28.14	28.58	28.96	29.57	30.20	30.42	30.83	31.33	31.78
Minimum	12.48	12.55	13.05	11.26	11.17	8.44	12.41	15.91	12.00	14.78
Maximum	60.33	64.21	65.87	89.33	87.44	73.26	68.52	71.13	77.08	68.78
NCI					Million $					
Mean	5.41	5.46	5.50	5.40	5.53	5.65	5.52	5.56	5.64	5.55
Minimum	(8.59)	(11.52)	(14.75)	(16.37)	(11.78)	(11.89)	(13.56)	(14.21)	(14.43)	(15.59)
Maximum	38.29	42.67	47.92	61.79	56.19	46.88	46.41	46.97	42.12	40.32
ECB					Million $					
Mean	1.61	3.21	4.78	6.26	7.81	9.43	10.78	12.21	13.59	14.78
Minimum	(11.11)	(18.81)	(25.40)	(27.78)	(36.14)	(43.22)	(42.23)	(55.08)	(57.20)	(62.16)
Maximum	22.26	25.30	37.61	46.11	46.33	66.77	74.23	83.32	82.54	90.23
Net Worth					Million $					
Mean	24.67	25.49	26.40	27.32	28.44	29.76	30.95	32.37	33.89	35.40
Minimum	11.95	3.47	(3.78)	(6.72)	(15.51)	(22.89)	(22.06)	(34.92)	(36.90)	(41.54)
Maximum	45.32	47.58	59.22	67.17	66.96	87.10	94.40	103.47	102.85	110.85
NPV					Million $					
Mean										1.27
Minimum										(48.10)
Maximum										51.07
End. RNW					Million $					
Mean										21.73
Minimum										(25.50)
Maximum										68.05
Oil Production					Million Gallons					
Mean	5.78	5.92	6.04	6.17	6.29	6.43	6.55	6.67	6.81	6.92
Minimum	2.42	2.50	2.71	2.70	2.93	2.33	2.87	3.03	2.94	3.32
Maximum	12.08	11.66	11.33	12.71	13.34	13.45	14.49	17.00	15.57	14.37
Water Use					Billion Gallons					
Mean	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46
Minimum	1.01	0.96	0.96	1.01	1.06	1.00	1.01	1.01	1.00	1.00
Maximum	1.90	1.89	1.91	1.90	1.87	1.87	1.90	1.86	1.88	1.92
Electricity Use					Million kWh					
Mean	15.62	15.64	15.66	15.68	15.71	15.73	15.75	15.77	15.79	15.81
Minimum	13.99	13.96	14.07	14.06	14.00	13.73	13.75	13.97	13.53	13.92
Maximum	17.34	17.18	17.36	17.22	17.25	17.37	17.40	17.70	17.76	17.48
% Neg. ECB										
Probability	38.4%	35.2%	32.4%	30.4%	30.0%	29.8%	28.8%	26.8%	26.0%	26.2%
% Dec. RNW										
Probability										86.2%
% Neg. NPV										
Probability										44.6%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 13. Summary Statistics for Selected Key Output Variables for Corpus Christi, Texas Base Scenario.

	Year									
Sel. Var.	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Rev.					Million $					
Mean	5.24	5.43	5.50	5.59	5.72	5.83	5.86	5.91	6.02	6.09
Minimum	1.27	1.08	1.50	0.87	1.15	0.42	0.44	1.23	0.03	1.57
Maximum	15.11	16.42	13.77	17.81	16.84	15.70	14.66	16.32	16.43	14.09
NCI					Million $					
Mean	(5.46)	(6.14)	(6.84)	(7.71)	(8.79)	(9.96)	(11.25)	(12.71)	(14.25)	(16.13)
Minimum	(8.95)	(9.80)	(11.49)	(13.42)	(13.49)	(14.71)	(18.25)	(21.25)	(22.01)	(25.79)
Maximum	3.66	0.78	0.22	3.42	0.33	1.38	(0.84)	(1.94)	(3.83)	(7.94)
ECB					Million $					
Mean	(7.99)	(16.73)	(26.25)	(36.71)	(48.34)	(61.24)	(75.53)	(91.40)	(108.93)	(128.49)
Minimum	(11.49)	(22.14)	(33.66)	(47.10)	(60.89)	(75.40)	(91.82)	(110.08)	(130.15)	(159.27)
Maximum	0.94	(7.50)	(16.04)	(24.17)	(34.01)	(40.84)	(53.65)	(64.64)	(83.26)	(97.11)
Net Worth					Million $					
Mean	15.21	5.69	(4.50)	(15.52)	(27.58)	(40.78)	(55.23)	(71.11)	(88.50)	(107.74)
Minimum	11.71	0.27	(11.91)	(25.91)	(40.13)	(54.94)	(71.53)	(89.80)	(109.72)	(138.52)
Maximum	24.14	14.92	5.71	(2.98)	(13.25)	(20.38)	(33.36)	(44.36)	(62.83)	(76.36)
NPV					Million $					
Mean										(89.21)
Minimum										(108.11)
Maximum										(69.95)
End. RNW					Million $					
Mean										(66.14)
Minimum										(85.04)
Maximum										(46.88)
Oil Prod.					Million Gallons					
Mean	0.63	0.65	0.66	0.67	0.69	0.70	0.72	0.73	0.74	0.76
Minimum	0.11	0.12	0.18	0.14	0.14	0.06	0.08	0.13	0.00	0.20
Maximum	1.38	1.53	1.47	1.51	1.60	1.65	1.60	1.94	1.81	1.60
Water Use					Billion Gallons					
Mean	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Minimum	0.15	0.08	0.10	0.15	0.05	0.15	0.11	0.09	0.11	0.08
Maximum	1.24	1.23	1.23	1.23	1.24	1.17	1.25	1.23	1.24	1.20
Elec. Use					Million kWh					
Mean	12.36	12.37	12.37	12.38	12.38	12.39	12.39	12.40	12.40	12.41
Minimum	11.57	11.54	11.55	11.58	11.51	11.41	11.45	11.48	11.31	11.48
Maximum	13.24	13.15	13.20	13.16	13.16	13.22	13.19	13.38	13.39	13.25
% Neg. ECB										
Probability	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
% Dec. RNW										
Probability										100.0%
% Neg. NPV										
Probability										100.0%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 14. Summary Statistics for Selected Key Output Variables for Corpus Christi, Texas Scenario 2.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue					Million $					
Mean	26.14	26.94	27.36	27.72	28.31	28.91	29.12	29.51	30.00	30.43
Minimum	11.95	12.02	12.49	10.78	10.70	8.08	11.88	15.24	11.49	14.15
Maximum	57.75	61.47	63.06	85.52	83.71	70.14	65.60	68.10	73.79	65.85
NCI					Million $					
Mean	2.94	2.88	2.80	2.59	2.52	2.49	2.19	2.00	1.85	1.48
Minimum	(10.46)	(13.25)	(16.90)	(18.82)	(14.42)	(14.68)	(15.33)	(19.52)	(18.15)	(19.83)
Maximum	34.42	38.40	43.46	56.40	51.60	42.77	41.22	42.62	38.33	36.61
ECB					Million $					
Mean	(1.16)	(2.48)	(4.01)	(5.82)	(7.78)	(9.95)	(12.55)	(15.42)	(18.65)	(22.46)
Minimum	(13.98)	(24.93)	(35.22)	(41.44)	(54.33)	(66.16)	(70.83)	(90.28)	(99.92)	(113.15)
Maximum	19.91	21.03	31.24	37.78	36.49	52.84	55.54	63.81	58.55	61.17
Net Worth					Million $					
Mean	31.09	28.68	26.22	23.64	21.07	18.48	15.65	12.76	9.74	6.38
Minimum	18.26	6.23	(5.00)	(11.98)	(25.48)	(37.73)	(42.62)	(62.09)	(71.52)	(84.31)
Maximum	52.15	52.19	61.46	67.23	65.34	81.27	83.75	92.00	86.94	90.01
NPV					Million $					
Mean										(26.51)
Minimum										(83.74)
Maximum										28.16
End. RNW					Million $					
Mean										3.91
Minimum										(51.76)
Maximum										55.26
Oil Production					Million Gallons					
Mean	5.53	5.67	5.78	5.90	6.02	6.16	6.27	6.39	6.52	6.63
Minimum	2.31	2.39	2.59	2.58	2.80	2.23	2.74	2.90	2.81	3.18
Maximum	11.57	11.16	10.84	12.17	12.77	12.87	13.87	16.28	14.90	13.76
Water Use					Billion Gallons					
Mean	1.08	1.08	1.08	1.08	1.09	1.09	1.09	1.09	1.09	1.09
Minimum	0.23	0.12	0.16	0.22	0.07	0.23	0.17	0.13	0.16	0.11
Maximum	2.00	2.00	1.99	1.99	2.01	1.90	2.02	1.99	2.02	1.94
Electricity Use					Million kWh					
Mean	22.72	22.74	22.76	22.78	22.80	22.82	22.84	22.86	22.88	22.91
Minimum	21.20	21.14	21.22	21.27	21.13	20.94	21.01	21.14	20.69	21.09
Maximum	24.39	24.24	24.34	24.27	24.26	24.43	24.36	24.71	24.79	24.53
% Neg. ECB										
Probability	58.8%	60.6%	62.6%	64.0%	67.0%	68.4%	72.0%	74.6%	76.8%	78.6%
% Dec. RNW										
Probability										99.8%
% Neg. NPV										
Probability										91.8%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 15. Summary Statistics for Selected Key Output Variables for Corpus Christi, Texas Scenario 3.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue	Million $									
Mean	27.31	28.14	28.58	28.96	29.57	30.20	30.42	30.83	31.33	31.78
Minimum	12.48	12.55	13.05	11.26	11.17	8.44	12.41	15.91	12.00	14.78
Maximum	60.33	64.21	65.87	89.33	87.44	73.26	68.52	71.13	77.08	68.78
NCI	Million $									
Mean	5.85	5.92	5.99	5.93	6.09	6.25	6.15	6.23	6.34	6.29
Minimum	(8.15)	(11.08)	(14.24)	(15.77)	(11.29)	(11.38)	(12.98)	(13.24)	(13.56)	(14.91)
Maximum	38.73	43.12	48.39	62.31	56.68	47.43	47.01	47.60	42.75	41.00
ECB	Million $									
Mean	1.86	3.72	5.59	7.39	9.30	11.30	13.05	14.93	16.77	18.47
Minimum	(10.85)	(18.27)	(24.57)	(26.60)	(34.50)	(41.11)	(39.52)	(51.71)	(53.14)	(57.36)
Maximum	22.52	25.79	38.40	47.18	47.84	68.50	76.30	85.76	85.55	93.79
Net Worth	Million $									
Mean	26.60	27.63	28.79	29.99	31.43	33.11	34.69	36.56	38.56	40.60
Minimum	13.88	5.63	(1.38)	(4.00)	(12.37)	(19.30)	(17.88)	(30.08)	(31.35)	(35.24)
Maximum	47.26	49.69	61.59	69.77	69.97	90.31	97.95	107.39	107.34	115.91
NPV	Million $									
Mean										2.95
Minimum										(45.80)
Maximum										52.69
End. RNW	Million $									
Mean										24.92
Minimum										(21.63)
Maximum										71.16
Oil Production	Million Gallons									
Mean	5.78	5.92	6.04	6.17	6.29	6.43	6.55	6.67	6.81	6.92
Minimum	2.42	2.50	2.71	2.70	2.93	2.33	2.87	3.03	2.94	3.32
Maximum	12.08	11.66	11.33	12.71	13.34	13.45	14.49	17.00	15.57	14.37
Water Use	Billion Gallons									
Mean	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Minimum	0.15	0.08	0.10	0.15	0.05	0.15	0.11	0.09	0.11	0.08
Maximum	1.24	1.23	1.23	1.23	1.24	1.17	1.25	1.23	1.24	1.20
Electricity Use	Million kWh									
Mean	5.92	5.94	5.96	5.98	6.00	6.02	6.04	6.07	6.09	6.11
Minimum	4.31	4.27	4.37	4.39	4.28	4.05	4.10	4.28	3.80	4.22
Maximum	7.65	7.48	7.61	7.52	7.53	7.71	7.66	7.98	8.07	7.79
% Neg. ECB										
Probability	35.8%	34.0%	29.6%	27.0%	27.0%	25.6%	23.8%	20.8%	21.6%	21.4%
% Dec. RNW										
Probability										84.8%
% Neg. NPV										
Probability										40.8%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 16. Summary Statistics for Selected Key Output Variables for Corpus Christi, Texas Scenario 4.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue	Million $									
Mean	25.01	25.62	26.32	26.79	27.37	28.12	28.54	29.30	29.79	30.42
Minimum	10.76	12.08	10.89	12.45	14.00	9.72	12.69	12.64	13.95	14.86
Maximum	49.80	59.95	55.64	62.78	55.44	64.54	64.33	92.99	59.88	64.08
NCI	Million $									
Mean	3.43	3.29	3.51	3.48	3.57	3.79	3.71	4.10	4.13	4.30
Minimum	(10.54)	(12.64)	(12.84)	(15.65)	(15.03)	(14.16)	(14.65)	(13.39)	(15.74)	(18.03)
Maximum	28.14	37.90	34.72	34.49	29.74	41.49	40.44	57.33	33.88	35.97
ECB	Million $									
Mean	(0.39)	(0.91)	(1.38)	(1.92)	(2.48)	(2.93)	(3.66)	(4.22)	(4.86)	(5.60)
Minimum	(13.59)	(22.48)	(26.06)	(32.41)	(43.43)	(51.92)	(53.23)	(67.57)	(70.98)	(82.29)
Maximum	16.00	26.36	31.23	30.34	40.18	58.94	63.10	72.33	68.73	70.05
Net Worth	Million $									
Mean	27.61	26.14	24.86	23.66	22.57	21.76	20.83	20.26	19.79	19.45
Minimum	14.41	4.58	0.19	(6.84)	(18.38)	(27.23)	(28.74)	(43.09)	(46.32)	(57.25)
Maximum	44.00	53.42	57.47	55.92	65.23	83.63	87.59	96.81	93.38	95.10
NPV	Million $									
Mean										(14.02)
Minimum										(62.79)
Maximum										35.87
End. RNW	Million $									
Mean										11.94
Minimum										(35.14)
Maximum										58.38
Oil Production	Million Gallons									
Mean	5.80	5.92	6.04	6.16	6.28	6.42	6.53	6.70	6.82	6.93
Minimum	2.35	2.84	2.68	2.88	3.01	2.45	3.35	3.03	3.42	3.20
Maximum	11.66	14.11	11.97	12.35	13.32	13.24	13.01	15.76	14.89	14.52
Water Use	Billion Gallons									
Mean	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Minimum	0.15	0.08	0.10	0.15	0.05	0.15	0.11	0.09	0.11	0.08
Maximum	1.24	1.23	1.23	1.23	1.24	1.17	1.25	1.23	1.24	1.20
Electricity Use	Million kWh									
Mean	5.92	5.94	5.96	5.98	6.00	6.02	6.04	6.07	6.09	6.11
Minimum	4.25	4.39	4.32	4.31	4.09	4.09	4.28	3.81	4.29	4.40
Maximum	7.38	7.54	7.50	7.69	7.71	7.59	7.95	8.04	7.78	7.94
% Neg. ECB										
Probability	55.6%	53.4%	56.0%	57.4%	57.4%	56.0%	56.2%	56.6%	58.6%	56.6%
% Dec. RNW										
Probability										98.6%
% Neg. NPV										
Probability										83.6%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 17. Summary Statistics for Selected Key Output Variables for Corpus Christi, Texas Scenario 5.

	Year									
Sel. Variables	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Revenue					Million $					
Mean	27.36	28.09	28.60	28.99	29.49	30.07	30.33	30.92	31.29	31.73
Minimum	11.64	12.45	10.88	12.45	14.10	9.24	14.63	12.10	13.27	15.20
Maximum	54.81	71.52	64.33	75.15	64.31	77.50	66.37	95.10	69.45	64.38
NCI					Million $					
Mean	5.45	5.48	5.53	5.45	5.50	5.59	5.38	5.65	5.58	5.62
Minimum	(10.21)	(11.57)	(13.06)	(15.47)	(11.94)	(14.00)	(15.96)	(13.61)	(15.60)	(16.51)
Maximum	33.36	46.21	45.85	46.22	38.22	53.84	44.22	60.69	39.88	36.85
ECB					Million $					
Mean	1.60	3.19	4.76	6.26	7.78	9.35	10.61	12.06	13.36	14.56
Minimum	(12.74)	(19.09)	(24.55)	(24.77)	(33.11)	(38.13)	(41.33)	(54.04)	(54.99)	(60.37)
Maximum	19.29	29.67	35.69	44.16	50.13	69.77	77.87	83.40	83.08	88.91
Net Worth					Million $					
Mean	24.79	25.61	26.50	27.45	28.54	29.81	30.90	32.34	33.79	35.31
Minimum	10.46	3.33	(2.80)	(3.58)	(12.35)	(17.67)	(21.03)	(33.76)	(34.56)	(39.63)
Maximum	42.49	52.09	57.43	65.35	70.89	90.23	98.16	103.68	103.51	109.66
NPV					Million $					
Mean										1.07
Minimum										(47.08)
Maximum										50.18
End. RNW					Million $					
Mean										21.68
Minimum										(24.33)
Maximum										67.32
Oil Production					Million Gallons					
Mean	5.80	5.92	6.04	6.16	6.28	6.42	6.53	6.70	6.82	6.93
Minimum	2.35	2.84	2.68	2.88	3.01	2.45	3.35	3.03	3.42	3.20
Maximum	11.66	14.11	11.97	12.35	13.32	13.24	13.01	15.76	14.89	14.52
Water Use					Billion Gallons					
Mean	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Minimum	0.15	0.08	0.10	0.15	0.05	0.15	0.11	0.09	0.11	0.08
Maximum	1.24	1.23	1.23	1.23	1.24	1.17	1.25	1.23	1.24	1.20
Electricity Use					Million kWh					
Mean	15.52	15.54	15.56	15.58	15.61	15.63	15.65	15.67	15.69	15.71
Minimum	13.86	14.00	13.92	13.92	13.70	13.69	13.88	13.42	13.89	14.00
Maximum	16.99	17.14	17.11	17.29	17.31	17.20	17.55	17.64	17.38	17.54
% Neg. ECB										
Probability	40.6%	34.8%	31.8%	29.6%	30.0%	29.0%	27.6%	25.8%	26.2%	26.6%
% Dec. RNW										
Probability										86.6%
% Neg. NPV										
Probability										46.8%

Note: Definitions for abbreviated variables can be found in Appendix A Table 1.

Appendix B Table 18A. Microalgae Model Input Parameters.

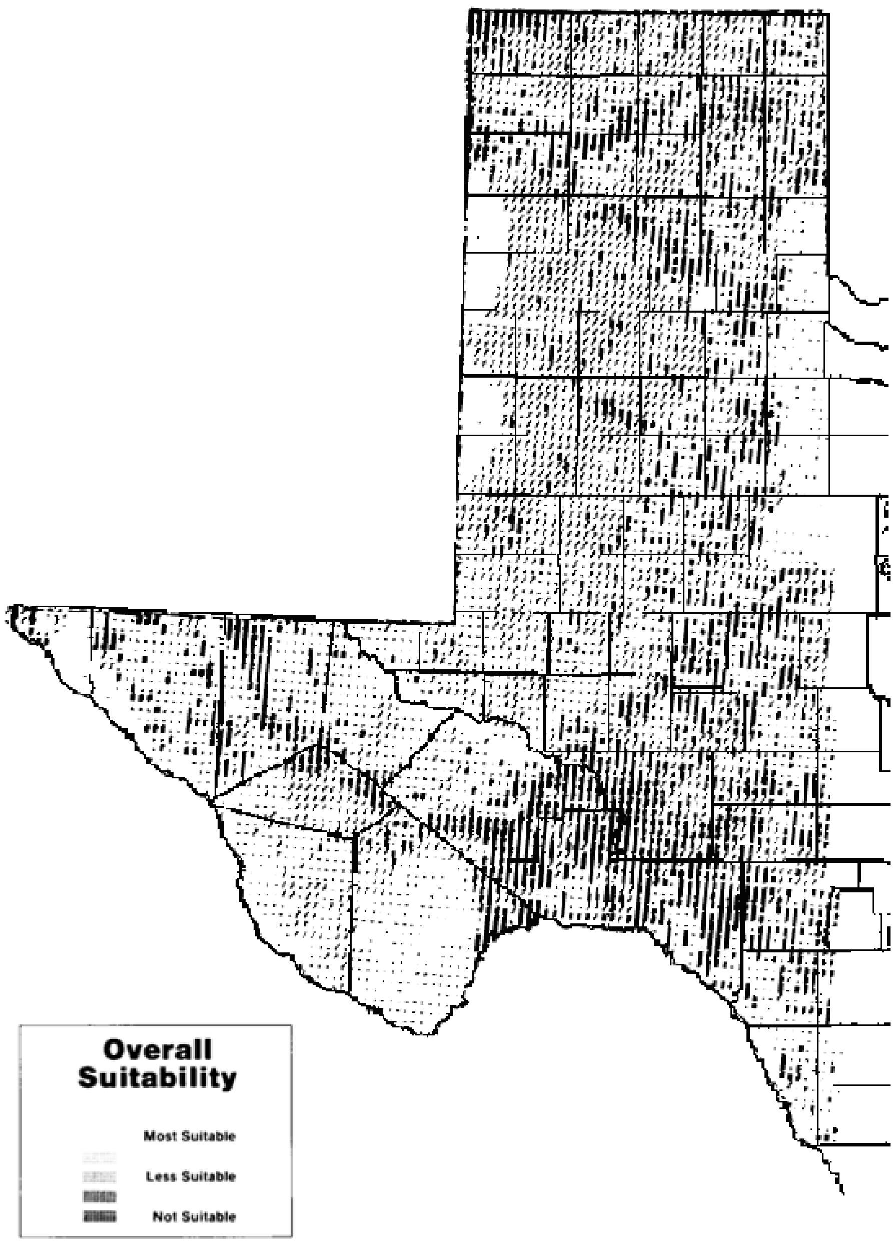
Production Inputs for GRKS	Min	Mid	Max
Microalgae Growth Rate (g/L/day)	0.60	0.80	1.00
Microalgae Oil Content (%)	30.00%	40.00%	50.00%
Stochastic Learning Curve	0.98	1.00	1.02
Number of Harvests Annually	45.00	60.00	90.00
% of Volume of Ponds Harvested Each Cycle	10.00%	12.50%	20.00%
Harvested Oil Breakdown	% BD	% HC	% HVO
Oil Composition	48.75%	48.75%	2.50%
Sum to 100%?	Yes		
Price of Hi-Value Oil (in $/gallon)	30.00	40.00	50.00
Desired Cost of Oil Production ($/gallon)	2.00		
Recycled Water for Recharge	Min	Mid	Max
Incentive for Using Recycled Water ($/barrel)	2.50	2.75	3.00
Cost of Cleaning Recycled Water ($/barrel)	0.50	0.75	1.00
% of Recycled Water Used in Water Recharge	-		
Source of Recycled Water	Oil Companies		
Facility Area Inputs			
Desired Acre Feet of Water	1,000		
# Ac. Ponds/Acre Fac.	20.00		
Pond Dimension Inputs			
Length of Pond	700		
Ratio of Length to Width of Raceway	10.00		
Depth of Pond	3.00		
Depth of Soil Removed	0.34		
Raceways per Pond (#)	10.00		
# of Sides	2.00		
# of Ends	2.00		
End Anchor	10.00		
# of Anchors	2.00		
Side Anchor	10.00		
# of Anchors	2.00		
Space Between Ponds	15.00		
Slope	3.00		
Center Wall (% Length of Raceway)	0.80		
Paddlewheel Platforms			
Width (Blocks)	4.00		
Length (Blocks)	1.00		
Angled Blocks	2.00		
Water Inputs			
Water Depth	24.00		
Center Wall Height	24.00		
Days of Operation	365.00		
Harvest Water Lost (%)	0.01		
Diameter of Replacement Culture Station Tanks (Feet)	8.00		
Number of Tanks per Replacement Culture Station	2.00		
Water Replacement Options	Daily		
Distance from Recycled Water Source to Facility (Miles)	1.00		
Carbon Dioxide Supply System			
Size of Blowers (In Cubic Feet per Minute)	800		
Size of Blower (Horsepower)	3.00		
Distance from Power Plant to Facility	0.50		
Water Wells and Pumps			
Depth of Wells (Feet)	200.00		
Capacity of Water Pump (Gallons Per Minute)	2,000		
HP of Water Pump Motor	20.00		
Power Generation/Supply Costs			
Distance from Grid to New Mexico or Pecos Location (miles)	2.00		
Distance from Grid to Corpus Christi Location (miles)	0.50		
Transmission Lines	500,000		
Distribution Lines	75,000		
Transformers	20,000		
Facility Width Needed for Each Row of Turbines (Meters)	70.00		
Turbines per Row	10.00		
BTUs per Lb. of Algae By-Product	5,500		
Annual Hours of Use for By-Product Converter	8,000		

Appendix B Table 18B. Microalgae Model Inputs. (Continued)

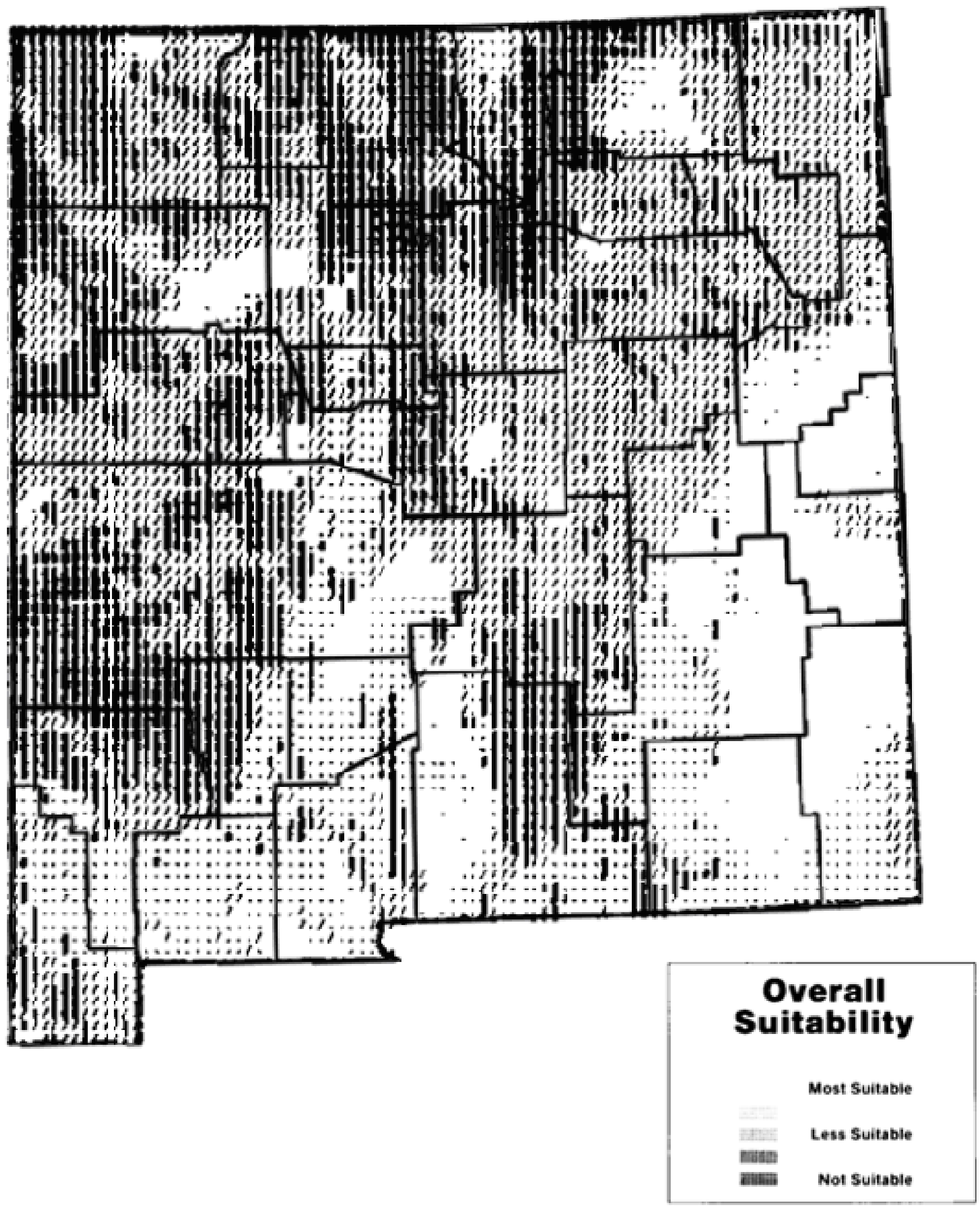
Piping Inputs			
% of Length for Water Pipe	25.0%		
% of Length for Air Supply Pipe	75.0%		
Standard Pipe Length (feet)	20.00		
Pipe Quality (Schedule 40 or 80)	40.00		
Water & Nutrients Pipe			
Length of Pipe Into Water (Feet)	2.00		
Size of Central Pipe (Inches)	8.00		
Size of Individual Raceway Supply Pipe (Inches)	6.00		
Space in Between Water Storage Tanks and Raceways (Feet)	15.00		
Carbon Dioxide Pipe			
Size of Central and Connecting Pipe	8.00		
Size of Pipe on Concrete Blocks (Inches)	6.00		
Distance Between Downspouts into Water (Feet)	5.00		
Length of Downspouts into Water (Feet)	2.00		
Harvesting Pipe			
Harvesting Pipe Length	10.00		
Harvesting Downspout Pipe Length	2.25		
Perimeter Fence Inputs			
Gauge of Fence Wire	12.00		
Height of Fence	6.00		
Concrete Block Inputs			
Concrete Block Size	Inches	Feet	Meters
Length	16.00	1.33	0.41
Width	8.00	0.67	0.20
Height	4.00	0.33	0.10
Number of Blocks Laid Per Day Per Worker	400		
Number of Workers	200		
Hourly Wage for Workers	10.00		
Paddlewheels			
Circulation Options	Continuous Air & Day Paddlewheel		
Number of Platforms per Wall	2.00		
Number of Paddlewheels Per Raceway	2.00		
Water Velocity (Units/Second)	5.91	0.49	0.15
Paddlewheel Motor RPM	900		
Paddlewheel Speed (RPMs)	10.00		
Reduction Ratio	90.00		
Storage Tanks			
Water Storage Tanks			
Depth of Soil Removed	8.00		
Depth of Water Stored	7.50		
Algal Oil			
Number of Days of Storage Needed	7.00		
Algal By-Products			
Number of Days of Storage Needed	7.00		
Square Feet Needed per ton of By-Product Stored	20.00		
Electricity Rates			
New Mexico	0.06		
Pecos	0.07		
Corpus Christi	0.07		
Harvesting & Extraction			
kWh Usage per Ton of Biomass Processed	9.63		
Natural Gas Usage per Ton of Biomass Processed	3.69		
Chemical Cost per Ton of Biomass Processed	5.83		
Labor & Maintenance Cost per Ton of Biomass Harvested	8.14		
% Lipid Recovery During Harvesting & Extraction	90.0%		
Annual Gain in Technology	0.5%		
Financial Inputs			
Engineering & Contingency Fees (% of Variable Costs)	2.5%		
Life of Loan (Years)	20.00		
Annual Interest Rate (%)	10.0%		
% Equity in Facility	50.0%		
Annual Dividend Rate (% of Equity)	5.0%		
Annual Dividend on Net Cash Income (% of NCI)	5.0%		

APPENDIX C

MICROALGAE MAPS



Appendix C Figure 1. West Texas Microalgae Suitability Map with Texas County Map Overlaid.



Appendix C Figure 2. New Mexico Microalgae Suitability Map with New Mexico County Map Overlaid.

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