ALGAL HARVESTING FOR BIODIESEL PRODUCTION: COMPARING CENTRIFUGATION AND ELECTROCOAGULATION

A Thesis

by

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ABSTRACT

Electrocoagulation was compared to centrifugation at pilot scale for harvesting *Nannochloris oculata* and *Nannochloropsis salina* for biodiesel production. The pilot scale testing is a proof of concept and no optimization was conducted. Testing used the KASELCO commercial electrocoagulation system. The KASELCO electrocoagulation system successfully coagulated microalgae in laboratory testing. Aluminum and stainless steel electrodes successfully recovered algae in laboratory testing. Electricity consumed was lowest using aluminum electrodes in laboratory testing, but inconsistently coagulated microalgae at the pilot scale. Stainless steel electrodes consistently recovered algae and were selected as the primary electrode to treat microalgae at the pilot scale. Scaling power settings to pilot testing using laboratory data was successful following KASELCO's proprietary guidelines. The KASELCO electrocoagulation system showed an electrical reduction in pilot scale operational cost for harvesting. Economic analysis using the Algae Income Simulation Model concluded that the KASELCO electrocoagulation system increase net present value of a commercial algae farm by $56,139,609 using a discount factor of 0.04. The KASELCO electrocoagulation system was calculated to use 26 kWh/ton at a commercial algae farm. However, cultivation and extraction processes are energy intensive, resulting in minimal electrical savings for the algae farm. The increase in net present value reduced production costs at the algae farm by 1%. The probability of success for the microalgae farm was zero for all scenarios analyzed. While a reduction in capital and operational costs were observed, several improvements, including harvesting using electrocoagulation, in cultivation, extraction, and conversion are necessary for economic success for biodiesel production using algae farms.

DEDICATION

To my parents, John and Marilyn Kovalcik, who instilled in me that education will give me endless possibilities.

"Whatever the mind of a man can conceive and believe, the mind of a man can achieve"

–Napoleon Hill

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I would like to thank KASELCO for the generous time in educating me to run their system and providing equipment for laboratory and pilot scale testing. The personnel was outstanding to work with and always willing to assist in any way possible. Without their help, this research project would not have been possible.

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NOMENCLATURE

$\$/ft^2$	Cost per square foot
µm	Micrometer
A	Amperes
ac-ft	Acre foot
Al	Aluminum
C	Number of clarifiers
cu. ft.	Cubic feet
d	Dosage
DC	Direct current
EC	Electrocoagulation
ft^2	Square feet
$g\ cm^{-3}$	Gram per cubic centimeter
$gal/ft^2/day$	Gallons per square foot per day
gpm	Gallons per minute
gph	Gallons per hour
gpd	Gallons per day
h	Height
ha	Hectare
hr	Hour
HVO	High valued oil

ID	Influent dosage
kW	Kilowatts
kWh	Kilowatt hour
kWh/gal	Kilowatt hours per gallon
kWh L^{-1}	Kilowatt hour per liter
kWh/ton	Kilowatt hour per ton
LANL	Los Alamos National Laboratory
LEA	Lipid extracted algae
L	Liter
L hr^{-1}	Liters per hour
lbs/day	Pounds per day
lbs/gal	Pounds per gallon
lb/m*hr	Pounds per meter every hour
M$s	Millions of dollars
m	Meter
min	Minute
mg	Milligram
mg L^{-1}	Milligram per liter
MGD	Million gallons per day
mS/cm	Microsiemens per centimeter
NPV	Net present value
Nm	Nanometer

OD	Optical density
OD_i	Initial optical density
OD_f	Final optical density
oz	Ounce
P	Power
PEAR	Post-extracted algae residue
ppm	Parts per million
r	Radius
RO	Reverse osmosis
SLR	Sludge loading rate
SS	Stainless steel
TDS	Total dissolved solids
TSS	Total suspended solids
TVS	Total volatile solids
V	Volts
V	Volume
VAC	Volts AC power
wt	Weight
Yr	Year

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CHAPTER I

INTRODUCTION

An alternative fuel source to help supplement petroleum based fuels is in high demand for the global community. A decrease in petroleum reserves has given way to developing new fuel sources. Microalgae are considered to be one promising alternative fuel source for biodiesel production. Unlike other oil crops, microalgae commonly double their biomass within 24 hours [1] and many are exceedingly rich in oil. Oil producing crops are preferred to not impede on agricultural lands used for food production. Microalgae production can solve this problem. Unlike other sources of biodiesel, the demand for a large area of land is significantly reduced when using microalgae [1,2].

Microalgae processing has four sub-processes and each sub-process is vital for biodiesel production. The four sub-processes are growth, harvest, extraction, and conversion [3]. The scope of this project will focus on the harvesting process. Harvesting or dewatering microalgae has proven to be a challenge in industry. Currently, harvesting systems for removing water from algae are energy intensive because of the diluted amount of algae in water, about 0.02-0.06% total suspended solids [4]. Harvesting techniques used to recover microalgae include centrifugation, gravity sedimentation, filtration and screening, flotation, and flocculation [2]. The standard energy input accounts for approximately 20-30% percent of the total cost associated with producing the biomass [5]. If the operational costs are greatly reduced, algae have the capability to be a competitive source for biofuel.

The technology used to harvest microalgae will benefit the renewable energy and industrial economies. The possible local impacts would be promotion of a new industry and utilization of non-competitive resources [6]. The technology will help reduce operational costs and help microalgae biodiesel become a feasible option to supplement petroleum based fuels.

KASELCO is a wastewater treatment company based in Shiner, TX. KASELCO uses electrocoagulation (EC) to remove heavy metals from wastewater. Applying a proven technology to a new problem helps reduce time needed to invent new technological advances. Electrocoagulation provides immediate treatment of mixed wastes in wastewater without the addition of chemical reagents, except under special conditions [7]. The KASELCO electrocoagulation process is most often done without the use of any chemicals, even acids or bases for pH adjustment [7]. KASELCO can process wastewater at flow rates ranging from 2.5 gpm -1200 gpm (9.5 - 4542 L min^{-1}).

Laboratory testing conducted at Texas A&M University proved that microalgae can be harvested using the bench scale KASELCO reactor. Scaling from laboratory to commercial harvesting is a major concern for the KASELCO system. The KASELCO wastewater treatment system was tested at Texas A&M's AgriLife Experimental Station in Pecos, TX in the summers of 2011 and 2012.

1.1 Objectives

The goal of this research was to demonstrate the feasibility of electrocoagulation at pilot scale (100 – 1000 L hr^{-1}) to harvest microalgae and determine if the EC system reduced operational harvesting costs compared to using centrifugation for harvesting. Pilot testing was conducted at the Texas AgriLife Research Experiment Station in Pecos, Texas. Specifically the objectives were:

1. Determine the feasibility of EC at pilot scale
2. Determine the impact of EC on commercial-scale production

Objective 1 was accomplished by a series of tasks. Tasks to complete objective 1 were:

1. Determine if EC operating parameters can be scaled from lab data
2. Determine if algae with high lipid content can be harvested by electrocoagulation
3. Evaluate stainless steel electrodes
4. Determine the effects of well water on the electrocoagulation process
5. Evaluate the Hi-Flo reactor

Objective 2 took data collected in objective 1 and modeled an algal harvesting system. Tasks used to complete objective 2 were:

1. Determine process flow for commercial operations
2. Determine economic gains using electrocoagulation in a commercial facility

CHAPTER II

LITERATURE REVIEW

In year 2008, fossil fuels accounted for 88% of the global primary energy consumption [8]. This paves the way for biofuels such as biodiesel that are both renewable and carbon neutral [2]. Biodiesel and bioethanol produced from terrestrial plants have attracted the attention of the world as potential substitutes [9]. However, due to food vs. fuel competition as well as land consumption of these biofuels, they have brought much controversy and debate on their sustainability [10]. Microalgae provide various potential advantages for biofuel production when compared with 'traditional' crops. Specifically, large-scale microalga culture need not compete for arable land, while in theory their productivity is greater [11]. Microalgae have been known to produce large quantities of oil, 58,700 L ha-1 at 30% oil (by wt) in the biomass. The next largest biodiesel producing crop is oil palm at 5950 L ha-1 [1]. However, microalgae water demand is as high as 11–13 million L ha^{-1} yr^{-1} for cultivation in open ponds [12]. Microalgae capability to grow in industrial, municipal and agricultural wastewaters and seawater not only overcomes this hurdle but also provides water treated for other uses such as cleaning water in the wastewater treatment process [9].

Harvesting or dewatering microalgae is one major issue that needs to be addressed before commercially producing microalgae biodiesel. Although studies have found that microalgae have definite advantages over conventional biofuel sources, broad commercialization of microalgae sourced biofuel has been restrained due to high costs of operation during processing [13]. The dilute concentration of microalgae in water makes current harvesting systems energy intensive. Harvesting or dewatering microalgae is one major issue that needs to be addressed before commercially producing microalgae biodiesel. Microalgae harvesting can be accomplished using two different methods: liquid constrained or particle constrained systems. Either the liquid is contained and the particles are removed from solution such as settling or the particles are trapped as the liquid is removed [4]. In past algae harvesting operations, centrifuge technology was used to mechanically separate the liquid and solids [14].

Centrifugation can harvest microalgae at a continuous rate by applying centrifugal force to separate microalgae from water with an estimated 90% recovery rate [15]. Continuous flow centrifuge systems allow sediment-bearing water to be pumped continuously through the bowl assembly, forcing particles to the wall while clarified water passes through the overflow [16]. Due to the small particle size of microalgae, 5 – 50 µm in diameter, longer retention times within the centrifuge bowl are required for algal sedimentation [17]. Energy requirements for centrifugation are estimated to be 3000 kWh/ton dry algal biomass [18]. Therefore, centrifugation may be feasible for high-value products, but is far too costly in an integrated system producing lower-value products, such as algal oils for biofuel production [19]. Thus, the unit operation of harvesting and dewatering is a major factor to be considered if a viable economics of algae-based fuels is desired [13]. The centrifuge used to compare the EC system was a disk rotor, solid wall, continuous liquid discharge, and manual solids discharge centrifuge (Figure 1).

Figure 1. The centrifuge used in Pecos, TX for pilot scale harvesting

2.1 Electrolytic coagulation

The traditional use of coagulation has been primarily for the reduction of turbidity from potable water. Applications of coagulation include: water treatment, municipal wastewater treatment, industrial waste treatment, and combined sewer overflows [20]. However, more recently, coagulation has been shown to be an effective process for the removal of many other contaminants that can be adsorbed by colloids such as metals, toxic organic matter, viruses, and radionuclides [21, 22]. Electrolytic harvesting operations may have the potential to replace the centrifugation process or work as a pre-harvesting system that will reduce the time needed to run the volume through the centrifuge. The electrolytic method being tested to possibly harvest microalgae is electrolytic coagulation. Electrocoagulation is a process that uses electricity (direct current) and metal plates to cause metal contaminants in wastewater to become destabilized and precipitate [23]. However, electrocoagulation is a relatively new harvesting method for removal of high concentrations of microalgae for biodiesel production.

Electrolytic coagulation is the process where sacrificial electrodes release insoluble oxides and hydroxides into an aqueous solution. The electrodes produce positively charged ions that induce coagulation of negatively charged microalgae. Faraday's Laws of Electrolysis give the relationship to the amount of material released from an electrode to the amount energy passed through the electrolyte [24]. The first law states the amount of ions released by current is proportional to the electricity applied at an electrode-electrolyte. The second law states that using the same electricity levels for different electrode materials will differ and is proportional to the electrode respective weights. Supplying the same power levels to different types of electrodes will result in releasing different amounts of ions into the solution being treated.

Amirtharaja and O'Melia [25] divided the coagulation process into three distinct and sequential steps:

1. Coagulant formation
2. Particle destabilization
3. Interparticle collisions

Coagulant formation is the process where particles start to form flocs in situ during treatment. Particle destabilization disrupts the surface charge of particles allowing particles to connect using ionic bonding. Creating larger sized flocs occurs with the interparticle collision process. Mixing the treated solution increases the potential for smaller flocs to connect to each other resulting in larger flocculation formations. The first two steps are usually fast and take place after chemical dispersal in a rapid mixing tank [25]. Steps 1 and 2 take place in the KASELCO reactor and de-foam tank ().The third step, interparticle collisions, is a slower process that is achieved by fluid flow and slow mixing [20]. Sweep flocculation or slow mixing may improve coagulation after leaving the reactor. Slowly stirring the effluent will increase the opportunity of microalgae metal ion interactions, increasing the efficiency of the metal ions contacting the microalgae, and may help reduce power requirements for harvesting. This is the process that causes the agglomeration of particles and it takes place in the flocculation tank [20]. After the algal slurry flows through the de-foam tank the slurry will enter the flocculation tank(s). Electrocoagulation is a proven technology in wastewater treatment and its application is a possible solution for microalgae harvesting.

2.2 KASELCO electrocoagulation description

The KASELCO system was used to determine the feasibility of EC treatment at the laboratory and pilot scales. The system is comprised of a rectifier, a reactor, a series of tanks, a clarifier, and a filter press (Figure 2). However, components required will be determined during testing as stated in section 4.7.

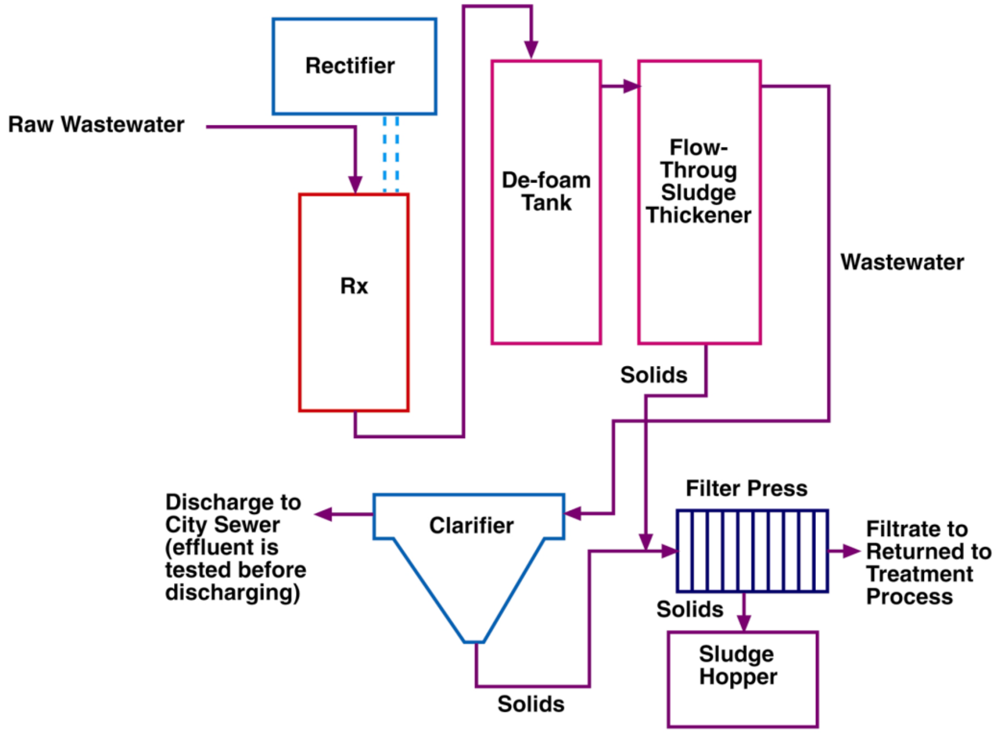

Figure 2. Diagram of the KASLECO System. Source: EPA, 2002 [30]

The unique aspect of the KASELCO system is the electrocoagulation step. KASELCO's system replaces slow and complex chemical treatment. The need for acid, caustic, ferric chloride, sulfites or many other reagents is either reduced or totally eliminated [7]. Previous flocculation studies with inorganic salts demonstrated that algal flocculation could be induced under alkaline or acidic conditions [26]. However, additional costs are incurred by introducing reagents into the algal solution. To help minimize harvesting costs this study did not include pH adjustment. Other factors effecting EC are power settings and electrode material. Different power settings dictate the amount of ions released during treatment. Higher power levels will result in greater ion dispersal whereas low power levels release fewer ions into the solution. Electrode material is selected based on the specific particles in the water being treated. Electrode material performs differently when amounts of particles are present in the wastewater. Using the wrong electrode can result in no treatment or excessive power consumption to achieve coagulation.

KASELCO’s operational and maintenance costs are low because the only parts that need replacing are the electrodes. Large EC systems are fully automated; lowering operational cost by eliminating labor required for manual EC systems. Rectifiers are designed to reverse polarity periodically during treatment. Reversing the polarity helps keep electrodes clean optimizing treatment and reducing plate cleaning time.

2.2.1 Electrode material

Metal is a commercially feasible material for donating ions, ultimately resulting in the formation of flocculants for the algae in solution [4]. Aluminum and 316 stainless steel electrodes are possibly feasible options tested under controlled variables. In a study conducted by Andrea Garzon, removal rates using aluminum chloride (AlCl¬3) reached 99% using rapid and slow mixing [26]. Immediate spontaneous reactions will take place if iron (Fe(aq)3+) or aluminum (Al(aq)3+) is used in corresponding hydroxides and/or polyhydroxides [27].

Harvesting algae using EC must consider downstream processing, because of the addition of metal (ash). Algal bi-products for livestock food quality are taken into consideration when applying electrochemical processes and choosing metallic electrodes. Four main macrominerals have been identified, calcium (Ca), phosphorus

(P), potassium (K), and sulfur (S), as being toxic to livestock if given in high volumes [28]. Metal content retained in the biomass will affect downstream processing. Aluminum and stainless steel electrodes will be required to discharge minimal amounts of ions into the algal solution for electrode feasibility. Major metals released from the tested electrodes are aluminum and iron, nickel, and chromium.

2.2.2 Power consumption

Water quality is dependent on the charge loading which is the product of time and current [29]. The ratio of current intensity (amperes) and the algal loading rate (mg m-3h^{-1}) were found to be useful operating and scale-up parameters [30]. These parameters allow the calculation of the appropriate charge dose to relate the operating current and time to release a minimum number of ions [4]. However, scale up calculations from lab data to pilot scale data is a proprietary equation for KASLECO and was not provided.

CHAPTER III

METHODOLOGY

3.1 Introduction

Electrocoagulation can effectively destabilize small colloidal particles and is cost effective [27]. The process uses current and sacrificial anodes to release positive ions in situ with the algal solution. The release of positively charged ions disrupts the charge of the negatively charged microalgae, resulting in flocculation. The principle is based on reduction of the electrical repulsion force to allow the Van der Waals force to exceed the repulsive electrical force [31]. The larger flocs will either sink (electro-coagulation) or float (electroflotation) in the solution facilitating recovery.

3.2 Laboratory procedure

Laboratory testing used the KASELCO bench top electrocoagulation system (Figure 3). The KASELCO unit has plate configurations 05, 07, and 11. The number determines the amount of intermediate plates between power plates and the electrical conductivity of the solution determines the reactor configuration. A schematic of the KASELCO bench top reactors are provided in Figure 4. Reactor configuration is chosen on the conductivity level of the solution. Conductivity was measured and KASELCO determined which reactor to use for proper treatment based off the conductivity measurement. The algae species tested were N. oculata and N. salina.

The KASELCO unit was calibrated to a flow rate of 425 mL min-1 using a peristaltic pump (Cole Parmer model No. 7553-75) and reverse osmosis (RO) treated water. Power was supplied and measured using a conventional DC power supply (TDK Lambda UP60-7). The treatment requires four passes (1A, 1B, 2A, 2B) to scale from laboratory to commercial scale. Each pass took a 100 mL sample and was placed in a 300 mL beaker and labeled 1A, 1B, 2A, and 2B. A non-treated algal solution was poured into a 2 liter PYREX beaker (beaker A) to the 2 liter mark. An additional 200 mL was added into beaker A from a 300 mL PYREX beaker for a total volume of 2.2 L per test. The initial optical density (OD) of this solution was then taken according to section 3.2. The KASECLO reactor was primed, using a non-treated algal solution, pumping 425 mL into a 2 liter PYREX beaker (beaker B). Directional flow of the algal solution was from bottom to top of the KASELCO reactor. The pump was turned off and the 425 mL algal solution was poured back into beaker A. The KASELCO reactor was now primed and ready to treat the algal solution. The power supply was turned on simultaneously with the pump. A 600 mL volume was pumped into 1L beaker and pour back into beaker A. The volume that was in the lines and reactor does not receive full treatment; this step was done to ensure the complete volume receives proper treatment. After a second 600 mL volume was pumped into beaker B a 100 mL sample (1A) was taken using a 300 mL beaker. Volts and amps were recorded after collecting the sample. The total volume was pumped through the reactor for treatment.

After beaker A was emptied into beaker B, the beakers switched positions, making beaker A beaker B and beaker B beaker A, representing the second pass (1B).

Without adding any additional algal solution or supplying power, beaker B was filled to 425 mL to flush any remaining volume out of the reactor and to prime the reactor. This step was done to ensure all of the algal solution receives full exposure to the electrical field. The 425 mL volume was pour back into beaker A. Again, the power supply was turned on simultaneously with the pump and a 600 mL volume was pumped into a 1L beaker. This volume was poured back into beaker A. Sample 1B, 100 mL, was taken when the second 600 mL of treated algal solution was pumped into beaker B. Volts and amps were recorded after sample 1B was taken.

This step was done two additional times representing passes three and four (2A and 2B). Samples settled for 1 hour before any data collection. This procedure was used for every laboratory test. Sample 1B equals one complete pass in a commercial EC unit. Sample 2B represents two complete passes and requires the volume to be treated twice on a commercial scale.

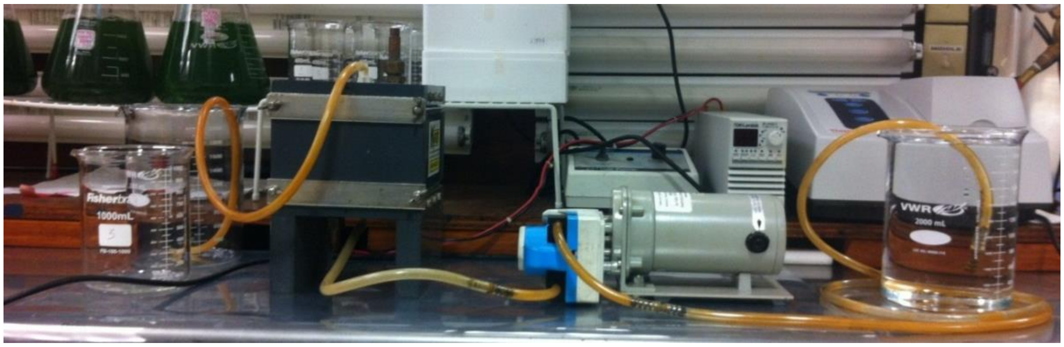

Figure 3. The KASELCO bench top electrocoagulation system used in laboratory testing

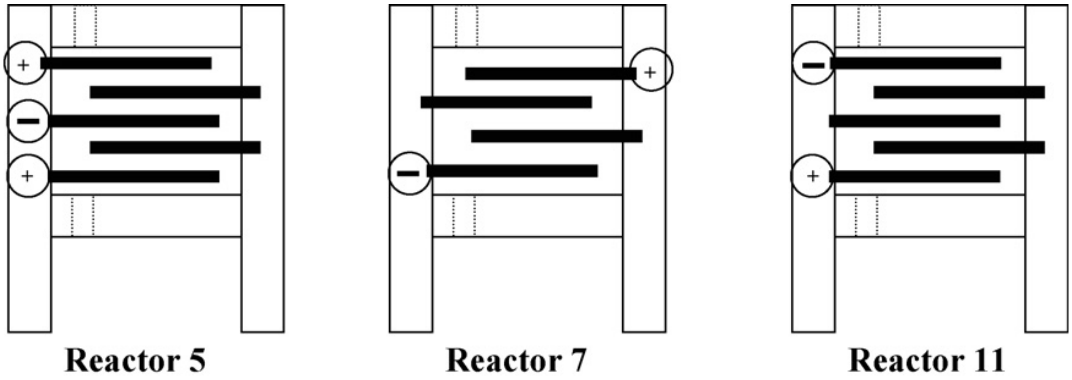

Figure 4. Schematic of the KASELCO bench top reactors [32]

3.3 Optical density procedures

Optical density was used as a measurement of recovery efficiency of algae. Optical density was calculated using a UV/Vis spectrophotometer (Thermo Fisher Scientific, Genesys 20, model: 4001/4) with a wavelength of 750 nm to determine removal efficiency. This wavelength was chosen to reflect the green chlorophyll in the samples. Individual 1mL samples were taken from samples 1A, 1B, 2A, and 2B and mixed with 9 mL of RO water. A 10x dilution is necessary to be within the linear range of the UV/Vis spectrophotometer [4]. The 1 mL samples were taken at 75 mL line of the 300 mL beakers and is the final OD. The 75 mL line was chosen because this was the middle area between settled microalgae and the clear water. The OD was used as the response of each test unless otherwise stated. Removal efficiency is calculated by subtracting the initial OD from the final OD, then dividing by the initial OD, and multiplied by 100 to give a percent reduction (Equation 1). Removal efficiency describes the amount of algae removed from the solution.

Removal efficiency was calculated as follows:

(1)

$$Removal\ Efficiency\ = \frac{(ODi - ODf)}{ODi} \times 100$$

Where
Removal Efficiency = Percentage of algae removed from water
OD_i = Initial optical density
OD_f = Final optical density

3.4 Power calculation

Power was calculated using the voltage and amperage recorded during testing and reported in kilowatts (kW). Amperage was held constant for all tests, while voltage was allowed to fluctuate. Power is calculated by multiplying voltage by amps, and then divided by 1000.

Power was calculated as follows:

(2)

$$P = \frac{V \times A}{1000}$$

Where
P = Power (kW)
V = Voltage
A = Amperes

Different power levels were selected throughout testing to determine the minimal power needed to efficiently remove algae. The power supply has a maximum output of 4 amps and a minimum of 0.01 amps.

3.5 Pilot scale Sur-Flo testing apparatus

KASELCO provided a Sur-Flo 2.5 gpm reactor test bed (Figure 5). The test bed had three separate reactors mounted: a five-plate (05) unit, a seven-plate (07) unit, and an eleven-plate (11) unit with 2.5” X 13” electrodes arranged in a horizontal orientation. The plate designation is nominal; in fact, the seven-plate reactor had 22 intermediate electrodes and 12 power electrodes, while the eleven-plate reactor had 18 intermediate electrodes and 8 power electrodes.

Figure 5. The KASELCO 2.5 gpm reactor test bed configurations. Reactors mounted are 05, 07, and 11.

The nominal flow rate was 2.5 gpm (568 L hr^{-1}) and during the 2011 tests the electrode plates were aluminum. A rectifier was used to convert 480 VAC power to DC power for the electrodes. During 2011, the standard KASELCO Sur-Flo rectifier unit was used.

KASELCO uses the following parameters to determine reactor configuration and system components:

- Residence time in the reactor
- Conductivity of solution
- Power setting
- Occurrence of sweep flocculation
- Settling time

Most of these parameters are related, giving multiple options for EC treatment systems and power settings. Conductivity levels determine the reactor configuration, i.e. a 07 or 11 reactor, and the electrical current setting.

Two weeks of testing in 2011 had a total of eleven tests. Amperage was held constant throughout all pilot scale testing to be able to scale up from laboratory data. Scaling amperage from laboratory data to commercial scale is a proprietary calculation as stated by KASELCO. Voltage was measured using a Klein Tool CL 2000 True RMS multi-meter. Power consumption was then calculated after testing was completed according to the section 3.3. Unless otherwise noted this procedure was followed in 2011 and 2012 pilot testing.

The algal solution was pumped from outdoor open raceways into a 500 gallon (1892 liter) well mixed holding tank. The 500 gallon volume was divided into smaller volumes of 150 gallons to test different power settings and flow rates. The algal solution was pumped through the reactor and into a 300 gallon (1135 liter) cone bottom tank and allowed to settle for 1 hour. Samples were then taken from the bottom of the cone bottom tank and sent off for analysis.

3.6 Pilot scale Hi-Flo testing apparatus

In addition to the Sur-Flo reactor described under section 3.4, KASELCO provided a Hi-Flo reactor for the second week of testing during 2012 (Figure 6). The KASELCO Hi-Flo 10 gpm (38 L min^{-1}) EC system included, from beginning to end of treatment: a clarifier to remove large sediment, an accumulation tank, the 09 Hi-Flo reactor, a small surge tank, and cone bottom setting tanks (located outside of building). In addition the system included an automated control panel, pumps, and prototype rectifier. Figure 6 shows the entire Hi-Flo system and a schematic of the system is provided in Figure 7 .

Figure 6. KASELCO's 10 gpm Hi-Flow reactor in the 09 configuration and rectifier system used to harvest 4550 gallons of microalgae

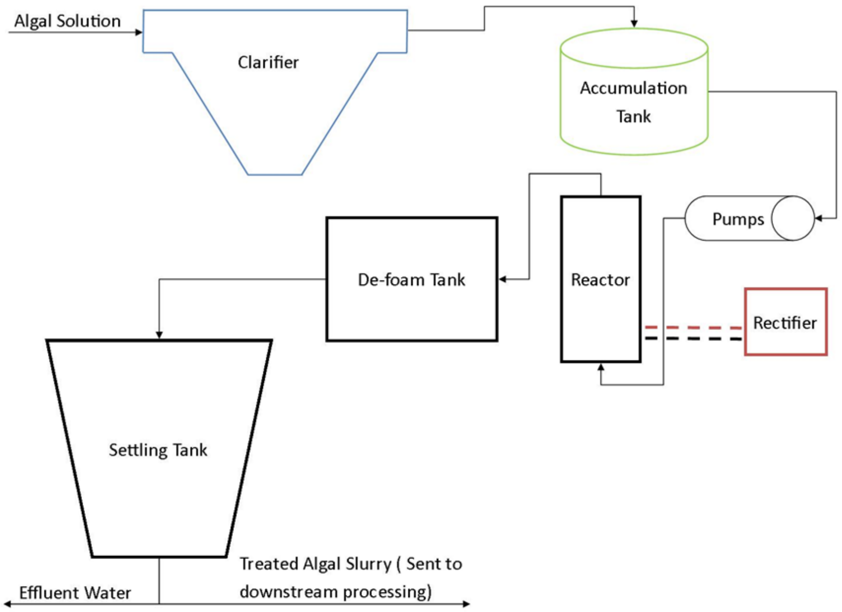

Figure 7. Schematic of the Hi-Flo reactor used for pilot scale testing

3.7 Enhancing recovery efficiency using a polymer

Laboratory testing was conducted using a KASELCO bench top reactor prior to pilot scale harvesting to calculate the power needed for harvesting. In 2011 N. oculata and N. salina were tested using aluminum electrodes in an 11-reactor configuration. Current ranged from 0.25-3 amps for testing. Five tests on N. oculata were conducted with the addition of a polymer called PolyDAD, which had a density of 1.09 g cm-3. Manufacturer and location where not provided as this was proprietary information. N. salina testing did not include the polymer, giving a better representation of EC treatment. Several tests were conducted to find optimum power requirements. The samples were allowed to settle for 1 hour before recovery rates were measured. The experimental response used to indicate polymer performance was the reduction in optical density. Optical density was used to measure recovery efficiency.

3.8 Determine if EC operating parameters can be scaled from lab data

Laboratory testing was done using a KASELCO bench top reactor prior to pilot scale harvesting and was used to calculate the power needed for harvesting. In 2011 N. oculata and N. salina were tested using aluminum electrodes in an 11-reactor configuration. Power settings from laboratory data were used to set the power requirements at pilot scale testing. The relationship between laboratory data and initial field settings is proprietary information belonging to KASELCO and is not reported here. Conductivity levels in the laboratory for N. salina ranged from 39-48 mS/cm; while pilot testing conductivity levels for N. salina ranged from 33-38 mS/cm. Aluminum electrodes were used for all tests. The appropriate reactor was chosen by KASELCO based on the conductivity level.

Eleven tests were conducted using volumes from approximately 95 to 500 gallons (360-1892 liters), a flow rate of 2.5 gpm (9.5 L min^{-1}), and aluminum electrodes. The 07 and 11 reactors were tested and flow direction along plates i.e. width vs. length of plates. The flow follows a serpentine pattern as the algal solution enters at the bottom and exits at the top. Flow along the width of the plates travel a shorter distance for each individual plate within the reactor. Directional flow across the length of the plates is also possible. An algal solution traveling the length of the plates will have a longer retention time in the reactor if flow rate and number of plates are constant. Tests were replicated once to determine if any variation is present in treatment.

Sub-samples were taken during testing using the piping system of the KASELCO system (Figure 8). The sub-samples were taken by opening a valve allowing the treated algal solution to be pumped into 12oz clear plastic cups. The sub-samples were taken to ensure proper treatment was being provided to the algal solution. Amperage was adjusted until proper treatment was established. This was allowed to determine if the KASELCO EC system could be scaled from the laboratory. The response for this experiment was watching microalgae settle in the cone bottom tank.

Figure 8. KASELCO piping system used to take sub-samples during treatment

3.9 Determine if algae with lipid content can be harvested by EC

Microalgae are stressed before harvesting starts to produce lipids for biodiesel production. During stressing nitrates are no longer added and water is no longer supplied to keep a constant water level. The decrease in water allowed for a greater ratio of salt to water volume increasing the conductivity. This test was conducted to determine how lipid production procedures will affect KASELCO's electrocoagulation process. Algae tested in the laboratory were not stressed to produce lipids and no analysis was done to determine lipid content, if any lipids were present. A 500 gallon (1892 liter) sample of N. salina containing 14% lipid was drawn from the cultivation pond and processed through the 11 reactor using aluminum electrodes at a flow rate of 2.5 gpm (9.5 L min^{-1}). Final optical density was used to measure recovery efficiency.

3.10 Evaluate stainless steel electrodes

Aluminum and stainless steel (SS) electrodes were tested in the laboratory to determine recovery efficiency on N. salina. The screening test was used to determine the drop off rate of performance of the electrodes. A recovery efficiency of 95% or higher was used as a cut off to eliminate additional testing. Six tests were run, two test with aluminum plates and four tests on stainless steel plates, to compare electrodes. Amperage for aluminum electrodes was set at 0.25 and 0.5 amps based on the polymer testing results. Stainless steel amperage on the four tests was 1, 2, 3 and 4 amps, respectively. The response that measured the performance of electrode material was optical density. Final optical density was used to measure recovery efficiency.

Six tests were run during the first week using the KASELCO Sur-Flo 2.5 gpm (9.5 L min^{-1}) reactor. Tests 1-3 had algae with high lipid content, 17.1 %, and tests 4-6 had algae with low lipid content, 6.0%. The testing volume for all 6 tests was 150 gallon (568 liter). Stainless steel (SS) and aluminum (Al) plates were tested to determine which electrode material gave greater recovery in harvesting N. salina. Reactor configurations were tested to determine the harvesting recovery (Table 1). In tests 3 and 6 the 07 and

11 reactors were configured in series with the microalgae flowing into the 11 reactor first and exiting the 07 reactor in order to increase residence time of treatment.

Table 1. Testing parameters for week 1 of 2012 tests for microalgae harvesting efficiency using electrocoagulation

Test	Reactor Configuration	Electrode Material
1	11	SS
2	11	Al
3	07/11	SS/Al
4	11	Al
5	07	SS
6	07/11	SS/Al

3.10.1 Determine viability of electro-flocculation at pilot scale

Electro-flocculation was created in the laboratory with stainless steel electrodes and low power settings conducted by Taylor Morrison in an independent study [4]. The result was an elimination of the surface charge on the algae and a self-flocculation once the opposing charges were removed. Algae have a negative surface charge and under the principle that “like repels like” remain in colloidal suspension unless the charge is removed. Chemical flocculants and the metal ions released during electrocoagulation have a positive charge, which attracts the algae resulting in a net neutral charge that flocculates and settles. The advantage of electro-flocculation is that no ions are released into the algal biomass and therefore do not contribute to the ash content. Tests 2 and 4 above were used to evaluate electro-flocculation. Aluminum electrodes were chosen because of the low power required for treatment seen in laboratory testing. Stainless steel electrodes power consumption was considered too great to achieve electro-flocculation.

3.10.2 Metal content retained in the biomass

A one factor six level analysis of variance (one-way ANOVA) was used to develop a metal content vs. power consumption curve in Design Expert. The hypothesis was at higher power levels more metal will be introduced into the biomass.

Ho = Greater metal content in the biomass at higher power settings.

Ha = The same metal content in the biomass at higher power settings.

Replicates were run at the center point and it was assumed all other points will have the same variance as the center point. The laboratory reactor used stainless steel electrodes were used while amperage was the only factor adjusted (Table 2). Chromium, iron, and nickel metal content in the biomass was measured as the response. This analysis of metal content in the biomass was conducted by SDK Laboratories in Hutchinson, KS.

Table 2. Amperage levels tested to determine metal content in harvested biomass

Run	Amps
1	1.5
2	1.25
3	1
4	0.5
5	0.25
6	1
7	0.75

3.11 Determine the effects of well water on electrocoagulation

Increased ash content in the biomass raised questions about the effect of well water on the electrocoagulation process. The water composition of the media may contain dissolved or suspended metals that coagulate and mix with the biomass after settling, increasing the ash content. A 150-gallon (568 liter) sample of well water with a conductivity level of 5.830 mS/cm, was treated using the Sur-Flo 2.5 gpm (9.5 L min^{-1}) reactor with stainless steel electrodes with amperage set at 70 and voltage was recorded. Samples were taken of well water before and after treatment to determine if total dissolved solids (TDS) were coagulating in situ with microalgae. Analysis of pretreatment samples was done at the Texas A&M Experiment Station and effluent samples were sent to SDK Laboratories.

3.12 Evaluate the Hi-Flo reactor

A Hi-Flo 09 reactor was tested using a 500-gallon (1892 liter) sample before harvesting the total volume of the harvesting pond, which was 4550 gallons (17,220 liters). This was done to determine if the Hi-Flo 09 reactor could efficiently harvest microalgae. The Hi-Flo system was used both as a complete harvesting method and a pre-harvesting step to reduce the total volume ran through the centrifuge. Stainless steel electrodes were used with amperage set at a value recommended by KASELCO while volts were measured. After pre-treatment the algae was allowed to settle overnight. The algae was then ran though the centrifuge which completed the harvest of microalgae. Samples were collected for analysis to determine the percent ash and biomass content, percent lipid content, complete lipid profile, effluent contents, and metal composition in biomass recovered.

3.13 Determine process flow for commercial operations

An ideal range of approximately 6 – 8% total volatile solids (TVS) after settling is needed to feed into a liquid-liquid extraction process to remove the lipids. However, if algae from the pilot test are less concentrated, a second stage of water removal may be needed (e.g. filter press, belt press, centrifuge). Concentrated algae samples were collected after treatment and were analyzed on site at the Texas A&M Experiment Station to determine total volatile solids.

3.14 Economic analysis

The Algae Income Simulation Model, AISIM, was designed by Dr. James Richardson and Myriah Johnson [33] at Texas A&M University to determine the probability of success of a commercial microalgae facility using a Monte Carlo firm level simulation model. The AISIM model is programmed in Microsoft® Excel using the Simetar© add-in. Required inputs are:

- Price projections
- Historical price data
- Optional farming systems
- Algae production information
- Lipid production
- Debt financing information
- Cultivation
- Land area
- Harvesting
- Extracting
- Capital costs
- Operational costs

The model computed results assuming an algae farm was built in 2012 and operating in 2013 using current data. Detailed information of the model was provided by Dr. Richardson (Appendix A) [33]. The AISIM model compared two different harvesting methods; centrifugation and electrocoagulation. Three scenarios were run to compare different feasible outcomes using EC. The baseline scenario is centrifugation, scenario 2 is EC with 8% solids, and scenario 3 is EC with 4% solids. All inputs were held constant except land area and operational costs as these two inputs depend on harvesting methods. Capital cost was held constant at $1 million to build a 1000 ac-ft pond facility. The AISIM model produced three financial statements: income statement, cash flow, and balance sheet. The income statement provided several different incomes that pertain to various algal farming scenarios. Algal oil produced, lipid extracted algae (LEA), and high valued oil (HVO) are the only values given from the selected farming scenario. Total inflows were reported in the cash flow statement. The balance sheet provided a net present value (NPV) after 10 years of operation. The NPV was the final output of the AISIM model and was used to determine the probability of success for the algae farm.

CHAPTER IV

ELECTROCOAGULATION RESULTS AND DISCUSSION

4.1 Enhancing recovery efficiency using polymer

Five tests on *N. oculata* were conducted with the addition of the PolyDAD polymer. Polymer additions interfered with the EC treatment of the five tests. It was concluded that the samples had an excess of polymer resulting in most algae flocculating and settling without the addition of electrocoagulation (Figure 9). No conclusions could be deduced to evaluate the efficiency of the KASELCO electrocoagulation unit. Polymer additions were disregarded for all subsequent laboratory tests. Note, evaluations of PolyDAD polymer were conducted by Taylor Morrison [4], and results conclude that there is no significant difference in recovery using the PolyDAD polymer.

Figure 9. Sedimentation of N. *oculata* following the addition of PolyDAD polymer

N. salina testing did not include polymer. Several tests were conducted to find optimum power requirements. Recovery rates reached 98% with power set at approximately 1 W (voltage measured at 4.5 V and current set at 0.25 on passes 2A and 2B). Algae coagulation only occurred on passes 2A and 2B (Figure 10) in laboratory testing, indicating pilot scale testing is expected to treat the algal solution twice, using the KASELCO scaling standards. The Kaselco bench top system successfully coagulated microalgae by obtaining recovery rates greater than 95%. Pilot testing plans began after this test concluded.

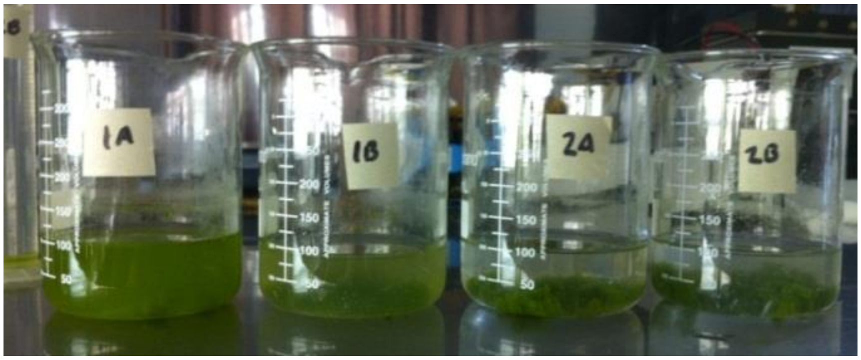

Figure 10. N. salina laboratory recovery results using aluminum electrodes

4.2 Determine if EC operating parameters can scale from lab data

The parameters measured in laboratory testing with the bench scale unit were used to determine the settings used for the 2.5 gpm system in the field test. Scaling power is a proprietary calculation and Kaselco did not provide the information. Testing started at the calculated value. Average current and voltage settings for the five tests were calculated (Table 3). No variation of treatment was observed during testing.

Table 3. Pilot scale current levels tested to confirm the KASELCO EC system can scale from laboratory data

Test	Volts	Amps	Kw
1	6.0	23.0	0.14
2	3.5	4.4	0.02
3	3.2	7.5	0.02
4	4.2	47.8	0.20
5	4.8	46.5	0.22

An 11 reactor was used in the laboratory and was successful in harvesting microalgae. A 07 reactor was used in pilot testing because of the conductivity level. The pH level varied from 7 to 8 for laboratory and pilot testing. However, the KASELCO EC system rarely adjusts pH levels for treatment as stated in section 1 and was not considered a factor. Test 1 coagulated algae; however, recovery rates did not reach the 95% threshold (Figure 11). Tests 2 and 3 had similar results with no recovery of algae (Figure 12). Tests 4 and 5 successfully coagulated algae and met the removal threshold of 95%. However, the treatment power levels for both tests allowed for electroflotation which is not desired for downstream processing (Figure 13).

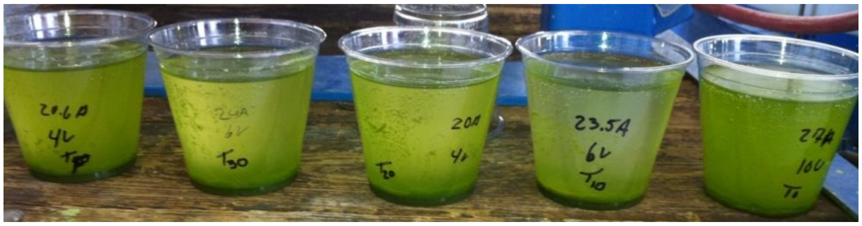

Figure 11. Test 1 partially coagulating algae but did not achieve sufficient removal rates

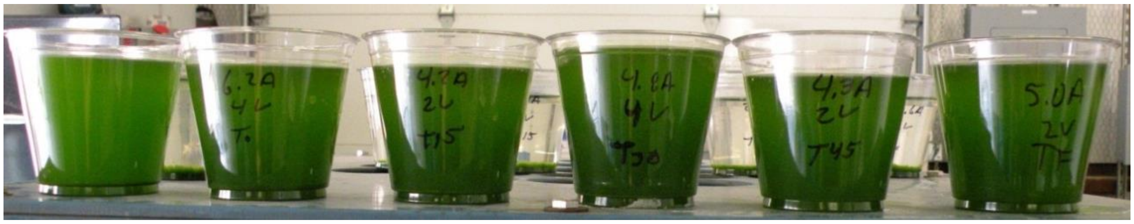

Figure 12. Test 2 and 3 unsuccessfully coagulating algae

Figure 13. Algae coagulating and floating in tests 4 and 5

Electroflotation is not desired because downstream processing will require an additional system to remove floating algae. The need for additional harvesting systems will increase capital and operational harvesting costs.

According to section 3.1, the number of passes necessary to coagulate a solution dictates the treatment time required on commercial systems. Laboratory data recommended the algal solution required treatment twice, as stated above. However, these tests only received one treatment to improve harvesting time required. The calculated current setting, test 1, shows that a second treatment would most likely coagulate the algal solution. Tests 2 and 3 are assumed to not improve settling rates if a second treatment was conducted given no coagulation occurred in the first treatment.

Successful removal was seen at current settings higher than the calculated current level. The higher current settings aloud for successful settling of algae in one treatment pass. Testing concludes that laboratory data did scale correctly to pilot scale testing. Testing also concluded that the EC system can change multiple factors to obtain desired settling as stated in section 3.4. Optimization of the EC system will need to be conducted to successfully coagulate algae using minimal power.

4.3 Determine if algae with lipid content can be harvested by EC

The Kaselco EC system successfully demonstrated the ability to harvest microalgae with 14% lipid content. The 11 reactor was use with aluminum electrodes with power averaging 0.11kW (average voltage measured at 4.3 and average amperage at 24.3). Voltage and amperage values were recorded every 15 minutes during treatment (Table 4).

Table 4. Lipid treatment test voltage and amperage settings

Lipid Harvesting Test							
Time (min)	Start up	5	15	30	45	60	Average
Amps	15	27.6	25.4	26.1	25.1	26.6	24.3
Volts	5	5	3	5	3	5	4.3

The EC system removed lipid bearing algae from water with recovery rates greater than 95% (Figure 14). However, data showed there was a reduction in the percentage of lipids from 14% to 6% after treatment. The reduction in lipid content will lower the value of the biomass for commercial production.

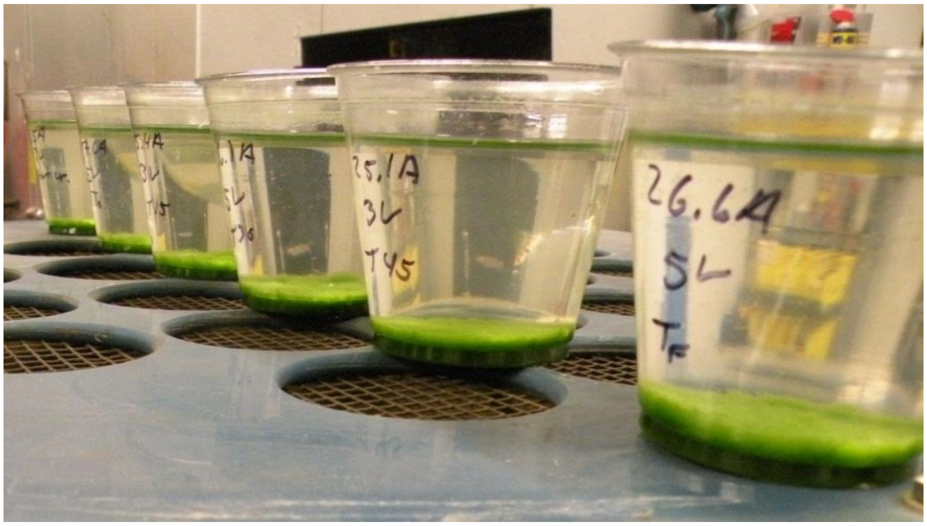

Figure 14. Recovery of high lipid bearing microalgae

Two conclusions were made after testing was completed. The first conclusion was the EC system was lysing, or breaking open, the cells allowing for lipids to escape into the effluent water. If this is true wet extraction or hydrothermal liquefaction extraction processes will need to be implemented to recover all lipids. The second conclusion was that the addition of metal ions into the algal solution is increasing the ash content. The addition of ash will reduce the lipid percentage calculation used to determine the amount of lipids in the biomass. Additional testing to determine if EC has the ability to lyse the algae cells needs to be conducted. Recovery of lipid bearing algae will help downstream processing operations by allowing lipid production to be conducted in the growth pond instead of after EC treatment. No additional time will be required to accumulate lipids after harvesting using the EC system. The algal slurry will be ready for lipid extraction processing after EC treatment.

4.4 Evaluation of stainless steel electrodes

Aluminum power levels reached 8.25 watts (voltage measured at 16.5 and amperage set at 0.5) with removal rates >95% starting at sample 1B. Stainless steel electrodes reached 25 watts (voltage measured at 12.4 and amperage set at 2) with removal rates reach a measly 7% for the 1B samples. One stainless steel test reached a removal rate of 97%, however the power level reached 63 watts (voltage measured at 15.7 and amperage set at 4). Electroflotation of microalgae was observed which in undesired for harvesting operations.

Aluminum and stainless steel electrodes successfully removed algae from water in laboratory testing. Stainless steel plates had greater power consumption than the aluminum electrodes. However, aluminum contamination in the biomass was a concern for the use of algae as a supplemental feedstock. Stainless steel electrodes were approved for pilot scale testing to help solve the contamination problem. Plans for using aluminum and stainless steel electrodes in pilot scale testing started after the conclusion of this test.

Stainless steel electrodes were expected to last longer than aluminum electrodes and thus, eliminate aluminum contamination of the bi-product. Aluminum electrodes were tested in the summer of 2012 using the 07 and 11 Sur-Flo reactors. However, consistent algal removal was not achieved during 2012. Two separate tests with the same current setting resulted in successfully and unsuccessfully removing algae (Figure 15). Power levels varied significantly when using aluminum electrodes versus using stainless steel electrodes (Table 5).

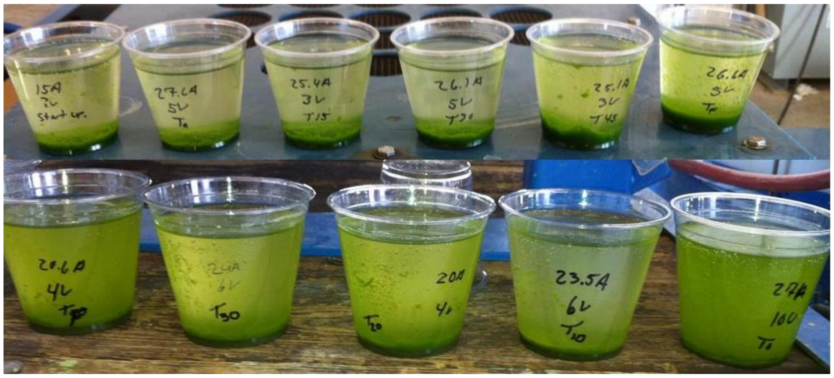

Figure 15. 2011 aluminum electrode tests successfully and unsuccessfully removing microalgae from water

Table 5. Power level differences between aluminum and stainless steel electrodes

Test	Reactor Configuration	Electrode Material	Volts	Amps	Watts
1	11	SS	17.6	67.5	1.188
2	11	Al	4.3	24.3	0.11
3	07/11	SS/Al	6	67.1	0.40
4	11	Al	10	27	0.27
5	07	SS	23.2	65	1.508
6	07/11	SS/Al	7.3	55	0.40

The tests using stainless steel consistently removed algae with recovery rates greater than 95% in tests 1 and 5. However, aluminum failed to remove algae with recovery rates greater than 95% in tests 2 and 4. Reactors ran in series increased the retention time within the reactors which was expected to lower the power required to treat the microalgae. Power was lowered however, also failed to reach recovery rates greater than 95%. Lipid content was reduced in all 6 tests showing consistency in the EC system as seen in section 4.3 (Table 6).

Table 6. Reduction in lipid content in all electrode evaluation tests

Original Lipid Content (%)	17.1
Test 1 (%)	6.5
Test 2 (%)	10.2
Test 3 (%)	13.2
Original Lipid Content (%)	6
Test 4 (%)	3
Test 5 (%)	2.3
Test 6 (%)	3.4

Ash in the biomass was analyzed during the tests. The average percent of solids and biomass of the solution was calculated (Table 7). The average percent of total solids in the sediment was consistent throughout testing.

Table 7. Percent solids concentration and percent biomass results following electrocoagulation treatment

Test	Reactor	Electrode	Average % Solids in the Sediment	% Biomass in the Solids
1	11	SS	2.82%	15.61%
2	11	Al	2.92%	19.87%
3	07/11	SS/Al	3.00%	20.36%
4	11	Al	2.39%	20.08%
5	7	SS	2.20%	18.16%
6	07/11	SS/Al	1.92%	26.02%

However, the low fraction of solids that was biomass is troubling. Samples harvested strictly with the centrifuge average 79% biomass. The hypothesis was that the electrocoagulation treatment was adding ash to the biomass and reducing the percentage of biomass recovered. The average percent of ash in solids was analyzed between the centrifuge and EC harvesting systems (Table 8). There is a significant addition of ash in the final biomass product for all samples harvested with electrocoagulation using aluminum and stainless steel electrodes.

One test using aluminum electrodes was conducted in 2012 to determine the feasibility of using aluminum electrodes at pilot scale. Microalgae were treated with current set at 65 amps, higher than 2011 and 2012 current settings, resulting in little to no coagulation at the current setting (Figure 16).

Table 8. Percent ash in the samples following electrocoagulation compared with centrifugation

Test	% Ash of Solids
Centrifuge	22.10%
1	84.39%
2	80.13%
3	79.64%
Centrifuge	18.52%
4	79.92%
5	81.84%
6	73.98%

It was concluded that failure to remove microalgae was due to the growth water. Growth water varied from 2011 to 2012 which is the only factor changed from 2011 to 2012. The change in growth water is hypothesized to have different metal contents from years 2011 to 2012. Data from 2011 was not obtainable, 2012 well water metal data is provided in Appendix B. Stainless steel electrodes removed microalgae on a consistent basis compared to aluminum electrodes. Consistent removal of microalgae during treatment using stainless steel electrodes will be further discussed in section 5.10. Metal content in growth water effects the coagulation reaction within the EC reactor. Commercial scale production of microalgae will need to know the metal content in the growth water to ensure proper removal of microalgae using EC.

Figure 16. 2012 test using aluminum electrodes failed to remove microalgae from water

4.4.1 Determine if electro-flocculation is viable at the pilot scale

Electro-flocculation for algae removal has been proven to work in lab scale testing [4]. However, electro-flocculation of algae has not been proven on a pilot scale test. Pilot scale testing using KASELCO's EC system has been concluded to be an electrocoagulation process, see section 4.6 for more detail. Achieving electro-flocculation for algal removal will need improvements in the rectifier and inert electrodes. Power supplied during testing was not precise enough to meet electro-flocculation power requirements. Improving the precision controls on the rectifier and increasing the power delivery efficiency will increase the probability of achieving electro-flocculation. Inert electrodes that are able to disrupt the electrical field of the algae cells without releasing ions into the algal solution to cause flocculation are not used by KASELCO. Improvements in manufacturing inert plates are required before becoming economically feasible. Inert electrodes theoretically will not release ions into the algal solution during treatment, meaning no replacing electrodes lowering maintenance and labor cost of using EC for algae removal, and eliminating metal in the bi-product.

4.4.2 Metal content retained in biomass

Metal content in the biomass will dictate how the post-extracted algae residue (PEAR) can be used after conversion. The feasibility of algae farming depends on a supplemental income by selling PEAR. PEAR is best suited to be used as a feed ration ingredient for livestock [28]. Ash content is a major concern for supplemental livestock feed sources. After aluminum electrodes proved to inconsistently remove algae stainless steel electrodes were chosen to be the primary electrode for pilot scale testing.

All seven tests conducted had conductivity levels that allowed for all testing to be conducted using the 11 reactor. Amperage settings were based from results in section 4.4 and were held constant (Table 9). Note the 0.5 amp test was removed because the sample analyzed was biomass recovered from the reactor and not harvested algae. The test was then changed to a 1 factor 5 level t-test with one replicate. Non-treated algae samples had nickel, chromium, and iron metal levels of 90.90, 0.44, and 6.76, respectively. Original metal in the algal solution was subtracted from data to evaluate the EC system.

Table 9. Testing parameters for determining metals retained in harvested biomass

Run	Conductivity (mS/cm)	V1	V2	V3	V4	Vavg	Amps	Watts
1	39.00	12.3	11.1	12.0	11.8	11.8	1.25	14.75
2	41.30	9.2	8.8	8.1	8.3	8.6	0.75	6.45
3	42.90	12.9	11.9	11.0	10.6	11.6	1.50	17.40
4	42.30	10.8	10.2	9.7	9.4	10.0	1.00	10.03
5	46.00	11.2	10.6	9.7	9.7	10.3	1.00	10.30
6	48.90	6.3	6.3	6.4	6.5	6.4	0.25	1.59

Table 10. ANOVA used to determine if higher power levels result in greater metal content in harvested biomass

Metal	Sum of Squares	df	Mean Square	F Value	p-value
Nickel	1686.70	4	421.67	23.43	0.1536
Chromium	7004	4	1751	875.50	0.0253
Iron	72870.33	4	18217.58	10.47	0.2273

An analysis of variance (ANOVA) was used to determine if the mode was significant. Chromium was the only factor (P value < 0.0222) to increase in metal as power increased by testing the null hypothesis. Results from the ANOVA are in

Table **10**. Biomass collected after treatment had the following nickel, chromium, and iron metal content vs. power supplied at a laboratory scale (Table 11).

There seems to be an inverse relationship between chromium content retained in the biomass and power supplied, which is counterintuitive compared to Faraday’s Law. Nickel and iron were not significant factors, but the metals follow the same pattern as chromium (Figure 17).

Table 11. Results of metal content retained in the biomass at different power levels

	Harvested Algae (ppm)		
Watts	Nickel	Chromium	Iron
1.6	25	164	18
6.5	59	213	1013
10.0	48	200	911
10.3	42	202	852
14.8	8	148	669
17.4	28	117	740

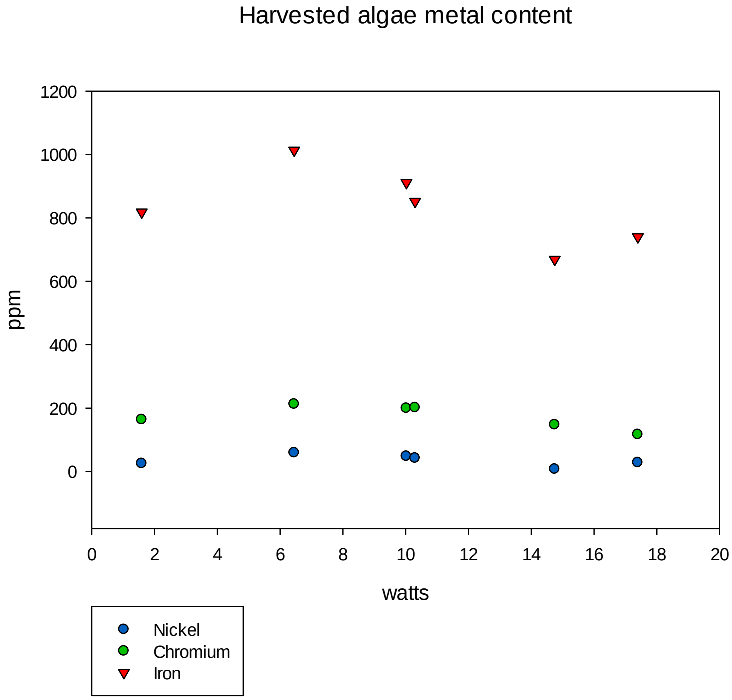

Figure 17. Metal content retained in harvested biomass at different power settings

Four additional samples were analyzed representing a saturated algal solution of metal and is hypothesized to have maximum ion bonding, meaning the algae cells have obtained the maximum amount of ions possible and can no longer acquire additional ions. These samples were collected from within the reactor after treatment was completed. Only four samples were analyzed because this was added to the experiment during the middle of the original tests (Table 12).

Table 12. Saturated algae metal content drained from the reactor after treatment

Algae Drained from Reactor (ppm)			
Watts	Nickel	Chromium	Iron
1.6	51	191	1023
4.5	58	248	1043
10.0	107	280	1253
10.3	181	493	1923

The data gives the highest values for metal content (ash) in the biomass at the different power settings. Obtaining this data is important for downstream processing systems. Knowing the maximum values for metal content will help in designing extraction and conversion systems. Increasing the efficiency of algae ion interactions for coagulation will lower these values. The metal contents are higher than the harvested algae as expected (Figure 18).

After complete ionic bonding of algal cells, excess ions in the solution have the potential to coagulate with other particles in the solution and will be captured in the biomass increasing the ash content. The amount of ions released compared to power settings possibly follows Faraday’s Law. However by using an alloy instead of a pure metal Faraday’s Law may be altered or not apply. In addition, the analysis conducted by

SDK Laboratories may only detect the biomass metal content and ignore inorganic particles. Ions released during treatment coagulating with undesired particles possibly explain the inverse relationship of metal retained in the biomass compared to power seen during testing. The amount of ions released may equal the theoretical value of Faraday's Law, but was not recorded. Additional testing is required to determine if there is an inverse relationship between metal content and increasing power settings using the KASELCO bench scale reactor or if other particles are bonding to the metal ions released during EC treatment.

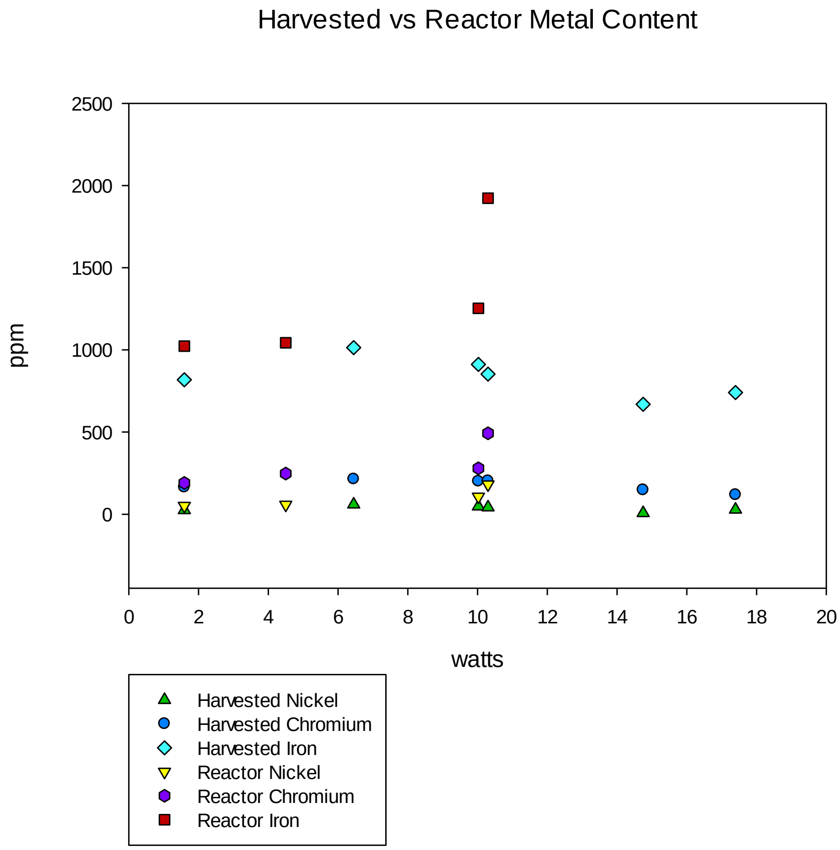

Figure 18. Metal content of saturated algae samples compared to harvested algae samples

During the metal content testing, observations on settling increased as treated microalgae were transferred to different containers. An algal biomass sample of 200mL in volume was poured into a settling cone and settled for 1 hour. Samples were transferred into 50mL centrifuge tubes. In one day the volume settled to 25mL. Finally, the algal biomass was placed in 4-13 mL centrifuge tubes and settled to the 12 mL line (Figure 19).

Figure 19. Algal biomass continuing to settle after treatment allowing for more water removal

However, 3 days were required compacting the microalgae to that volume. Gravity settling reduced 200 mL algal volume to 48 mL algal volume, reducing the algal biomass volume to less than 1/4 the original value. No statistical analysis was conducted as stated above; this was just an observation. Increasing settling time will allow decanting more water from the biomass increasing the % solids sent down stream. However, the time required to obtain this reduction may exceed the demand for biomass for downstream processing. A tradeoff between settling time and processing biomass exists and requires further testing.

4.5 Determine the effects of well water on electrocoagulation

Well water used for algal pond growth in Pecos, TX contained a significant amount of calcium (18.21 ppm), sodium (1188.29 ppm), and silica (35.57 ppm) in 2012. Complete well water data are proved in Appendix B. The metal content in the water is used as a supplement of the media recipe to help grow the microalgae, which helps reduce the chemical costs. The power setting to treat the well water was decided by KASELCO and had power at 1.54 kW (voltage measured at 22 and amperage set at 70). Analysis of effluent samples from SDK Labs shows different amounts of all metals were found (Table 13). However, there was a reduction of calcium (17.46 ppm), sodium (1059.29 ppm), and silica (26.41) from the well water.

Table 13. Metal content analysis of effluent well water treatment

Metal	Metal Content (ppm)
Calcium	0.75
Sodium	93
Chromium	1
Iron	4.18
Nickel	0.72
Silica	9.16

The EC treatment added amounts of chromium, iron, and nickel ions into the water using 316 grade stainless steel. After 24 hours of settling the metal stratified into two different layers of chromium/nickel and iron (Figure 20).

Figure 20. Metal content introduced to well water by electrocoagulation after treatment and stratified layers of metal in well water after 24 hours of settling

Water recycling is considered essential to reduce the environmental footprint for commercial production for algae. The reduction of calcium, sodium, and silica from the growth water must be added back to the growth water to ensure proper growth for microalgae. The reduction of these metals may not solely be due to the EC treatment. The microalgae use these metals for growth conditions, which will reduce the metal content. A study on how much metal is reduced by the microalgae and EC treatment will need to be conducted to determine this relationship.

The amounts of nickel, chromium and iron in the effluent are hypothesized to be due to over treating the well water as literature suggests. This will be discussed in more detail in section 4.6. Ideal treatment would use the minimal amount of power possible, but optimization of power was not of concern in this test. Metals added from EC are hypothesized to stay in the biomass which may cause problems for downstream processing.

4.6 Evaluate the Hi-Flo reactor

KASELCO's 10 gpm Hi-Flo system test is a proof of concept analysis. No optimization of the Hi-Flo EC system was conducted. All conclusions are based off of one data point and further testing needs to be conducted to confirm the results. Results are considered a baseline and are expected to improve as more testing is conducted.

Hi-Flo test 1 (NB-321), 500 gallons, provided a starting point for power 4.81 kW, 260 amps and 18.5 volts. This power setting was used in the complete harvest of one pond. This test was conducted to prove the system can harvest microalgae before harvesting a pond. The second Hi-Flo test (NB-318), 4550 gallons (17,224 L), took a total time of 5 hours to pump the complete volume through the reactor and used 59 kWh. KASELCO's 10 gpm system operated at a 15 gpm flow rate, an increase of 50% in flow rate. This observation was taken into account in the economic model and will be discussed in further detail in section 4.7.

The Hi-Flo reactor successfully coagulated algae with recovery rates approaching 98% (Figure 21). The comparison analysis between the centrifuge and EC show that the centrifuge has an average of 10.2% solids and 22.48% ash in the solids. The EC has an average of 2.8% solids and 83.8% ash in the solids. The higher ash content in the biomass is due to the addition of metal into the algal solution by using EC.

Figure 21. Test 1, 500 gallons, successfully coagulated algae using KASELCO's 10 gpm Hi-Flo reactor

Concern for successful removal of microalgae throughout the treatment was tested as mentioned in section 5.5. Samples were collected every hour during EC treatment. The KASELCO Hi-Flo reactor was consistent throughout treatment at the power setting (Figure 22).

Figure 22. Consistency of removing algae using the Hi-Flo reactor harvesting 4550 gallons

Iron precipitate can be seen in Figure 22 explaining high ash content. Biomass had 3.2% average solids with 83.8% ash in the solids using only EC. The additional iron is due to the high power setting and only one test with this volume. Optimization of

KASELCO's EC system needs to be conducted to increase the efficiency of ions released to remove algae and lower power consumption. The algal volume settled to 1000 gallons (3785 L) in a 24 hour period, reducing the algal volume to less than ¼ the original volume, consistent with results seen in section 5.8. The remaining volume was harvested using the centrifuge and took a total time of 4 hours 13 minutes, 4 gpm, and using 62 kWh. The average harvesting flow rate of the centrifuge is 13 gpm (50 L min^{-1}) at the Pecos farm. Harvesting using the centrifuge was slow because the condensed algal solution could not be pumped without losing biomass. The centrifuge was gravity fed to further condense the algal solution without losing biomass and shipped to extraction. The centrifuge did reduce the ash content in the solids by 18.14% and increase the biomass in the solids by the same percentage. Centrifuge and EC operational results are provided in Table 14.

Table 14. Comparison results of using EC and centrifugation for harvesting microalgae at pilot scale

Process Step	Power Consumed (kWh)	Process Time (hr)	Volume Processed (gal)	% Ash in the Solids	% Biomass in the Solids
Primary Dewatering: EC	59	5	4550	83.85%	16.15%
Secondary Dewatering: Centrifuge	62	4.2	1000	65.71%	34.29%
TOTAL	121	9.2	4500	65.71%	34.29%

Power consumed using EC is 0.013kWh/gal (0.003kWh L^{-1}) compared to 0.062kWh/gal (0.016kWh L^{-1}) using the centrifuge. A high power level was used to ensure the Hi-Flo EC system removed algae from water. Power consumption is expected to drop after further testing and optimizing the Hi-Flo reactor.

Results from Los Alamos National Laboratories (LANL) provided a plot of forward vs. side light scatter, which were used to determine algae population and any other debris or bacteria in the algal solution. Dilution factors for non-treated, effluent, and harvested were 1:100, 1:1000, and 1:10, respectively. Results from well water were used as the control for analyzing subsequent tests (Figure 23). Triplicates were run on all samples.

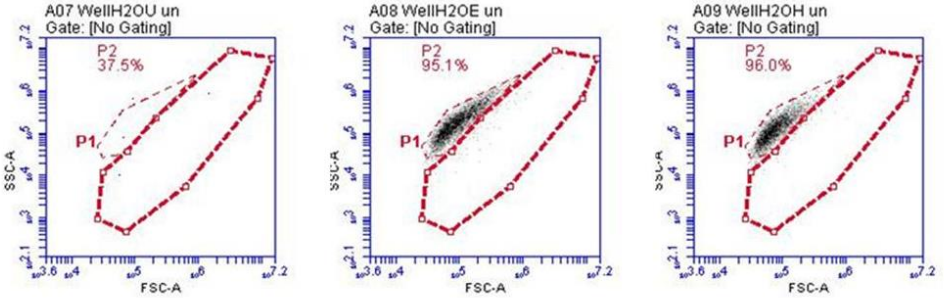

Figure 23. LANL forward vs. side light scatter analysis of the control, well water. Plot order is non-treated, effluent, and harvested samples

The plot on the left shows non-treated well water has no precipitates (small circle). Effluent and harvested plots show that an addition of precipitate comes from the EC treatment and confirms metal ions are the precipitate introduced into the algal solution. Analysis was conducted on both test 1 and 2 using the Hi-Flo reactor and have similar results, Figure 24 and Figure 25, respectively.

Non-treated samples, left plot, show no extra precipitate in the algal solution. The samples also show that the volume treated is pure healthy culture of algae. Effluent samples, middle, show a population of algae suggesting low removal rates. The dilution level used makes the plot appear to have a high concentration of cells, however there is little to no algae in the effluent in reality. Harvested samples, right, show both algae and precipitate in the sample.

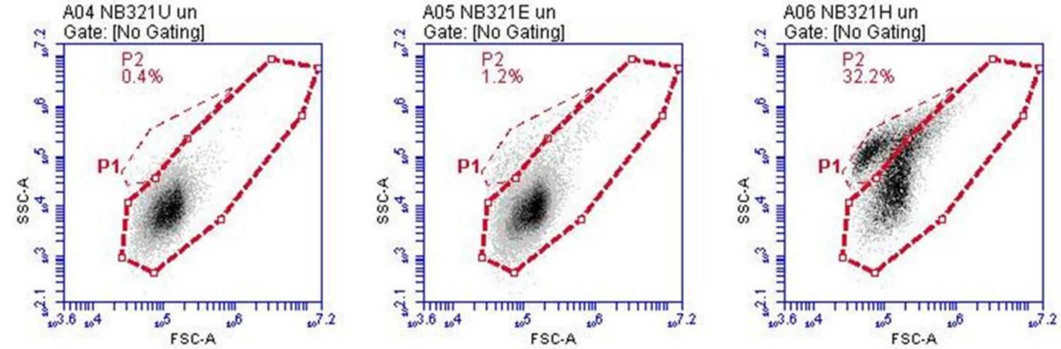

Figure 24. Hi-flo test 1 forward vs. side light scatter plot. Plot order is non-treated, effluent, and harvested samples

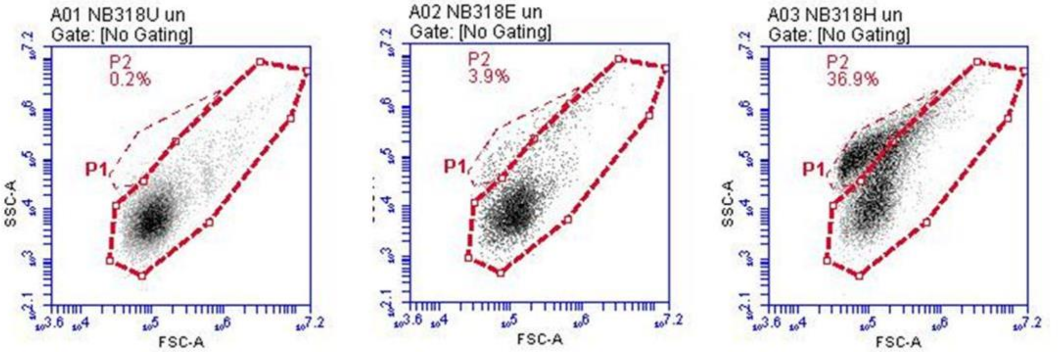

Figure 25. Hi-flo test 2 forward vs. side light scatter plot. Plot order is non-treated, effluent, and harvested samples

The analysis confirms that EC treatment introduces metal ions into the algal solution and stay with the biomass. Excess chromium, iron, and nickel in the effluent represent a “charge overdose” caused by providing excess power to coagulate the microalgae, as suggested by literature.

Concentration of algae cells, calculated on a cell only bases, from non-treated to harvested algae was increased by 5.5x using only EC. Results show test 1 effluent sample had 20% algae in the effluent compared to the non-treated algae. Test 2 had only 3% algae cells in the effluent compared to the non-treated sample. A removal efficiency of 97% was obtained in test 2 (Figure 26). The difference in removal efficiencies is hypothesized to depend on the settling time. Test 1 was a preliminary test to prove the Hi-Flo system worked and settled for 1 hour, whereas test 2 settled for 24 hours after treatment. Analysis excludes water debris and represents algae only. Note triplicates were run and error bars are standard deviations of the mean.

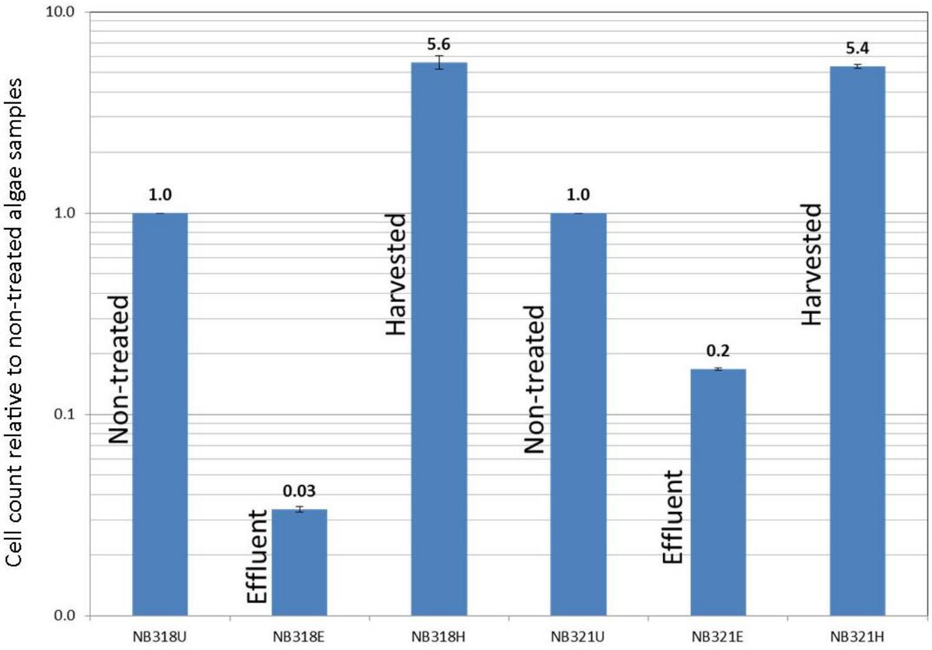

Figure 26. Concentration of algae cells using EC only and excluding water debris

Tentative results from LANL (Figure 27) showed that EC may concentrate lipids in harvested and effluent samples. Concentrating these cells may suggest that EC can harvest lipid cells only and leave non-lipid bearing cells in the effluent to inoculate a new pond.

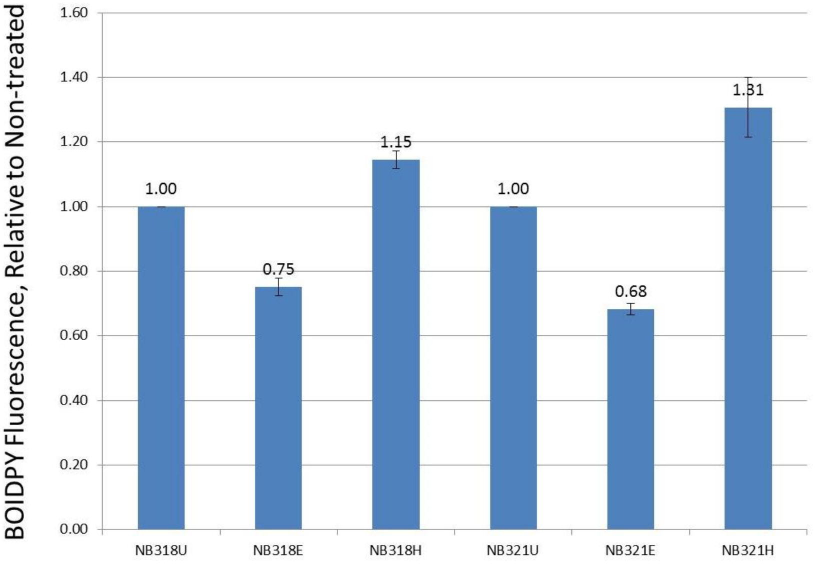

Figure 27. Preliminary lipid concentration levels of non-treated, effluent, and harvested samples excluding water debris

Analyses done on site show that lipid content was reduced using EC compared to centrifugation. Test 1 had a lipid content of 3% using only EC treatment. Harvesting the remaining algal solution using just a centrifuge had 18% lipid content. In test 2 final lipids content was 3.1% using EC and the centrifuge was 3.2%. Lipid content is calculated on a percentage basis and with the addition of more ash into the algal solution the percentage decreased. Lipid content may remain the same, but the addition of ash reduces the percentage calculation. Lipid content would need to be calculated using a lipid per volume basis to determine if any cell lysing occurred during by using EC.

After algae have been sent through lipid extraction the bi-product must be sold to supplement the income of the algae farm. Electrocoagulation treatment will affect cell viability of the bi-product, determining the usefulness of the bi-product. Preliminary results using fluorescein diacetate, of cell viability were inconclusive as to how electrocoagulation affected cell viability. Tests 1 and 2 used the same power settings; however, in test 1 the effluent algae appear to have significant damage to the cells whereas test 2 cells receive less damage (Figure 28). Cell lysing may have occurred because of the damage to the cells, but has not been proven. Lipids in the effluent can enhance or hinder extraction processes depending on the extraction system. Additional testing needs to be conducted to determine if cells are being lysed by the EC process and assumes power is the factor causing the cell damage. Note triplicates were run and error bars are standard deviations of the mean.

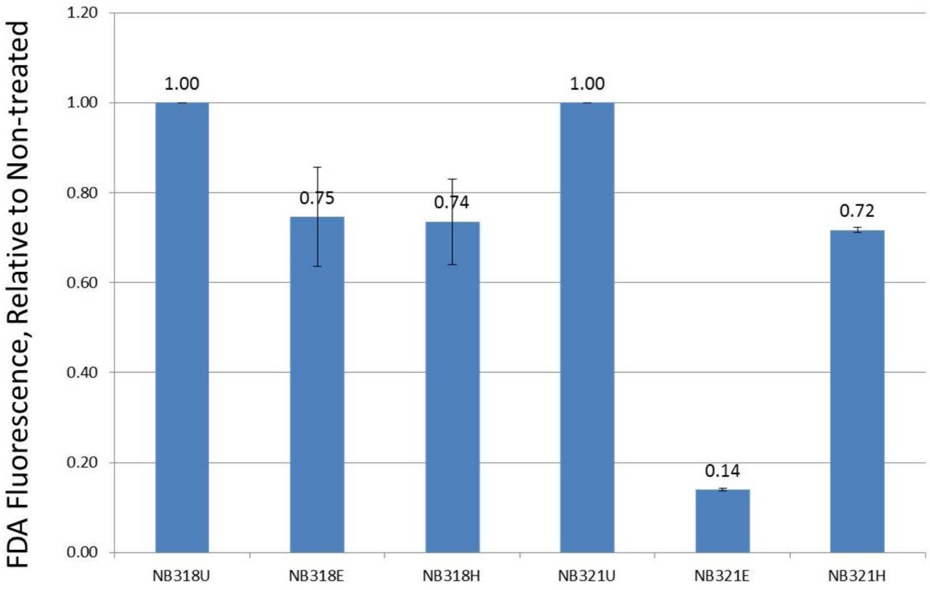

Figure 28. Preliminary cell viability results of non-treated, effluent, and harvested samples excluding water debris

KASELCO's Hi-Flo reactors successfully coagulated algae for removal. The system used less power than the centrifuge and has the capabilities to operate at 50%

above suggested flow rates. Labor required by KASELCO's EC system is significantly lower compared to the centrifuge. The fully automated system provides an easily operated system that can be managed from a control room. Workers running a centrifuge will have to constantly adjust and monitor the flow rate and recovery of algae, unless upgraded to a fully automated system. However, there are many questions left to fully understand the potential of using EC as a harvesting system as results from LANL show. Cell lysing, lipid concentrations in harvested biomass/effluent, and cell viability for bi-product supplies need additional testing to confirm or reject the preliminary results provided by LANL.

4.7 Determine process flow for commercial operations

A 1,000 acre farm with 60 harvesting ponds was assumed as the commercial scenario. A model of the growing system is shown in Figure 29 [34]. Growth assumptions state that nominally two days of growth are needed to inoculate the 5000 series growth ponds. The 5000 series ponds are the final stage of algae growth before inoculating harvesting ponds. Six days of growth is recommended before inoculating the 6000 series harvesting ponds. This step is implemented to reduce the probability of the 6000 series harvest ponds from becoming contaminated and crashing. The risk of a harvest pond crashing is reduced by ensuring the algae have enough cells to fight off competitors for nutrients. After inoculating the 6000 series harvest ponds 6 days of stressing are needed to enhance lipid production before harvesting. Harvesting systems will need to be able to process the volume within 2 days to meet inoculation rates.

Breaking the 60 harvesting ponds into three 20 pond sections allows inoculation and harvesting schedules to operate at maximum efficiency. These operating parameters allows for 300 ponds inoculated per month and 300 ponds harvested per month, 5 complete harvests of all 60 ponds, leaving no excess algal volume left in the harvesting ponds each month.

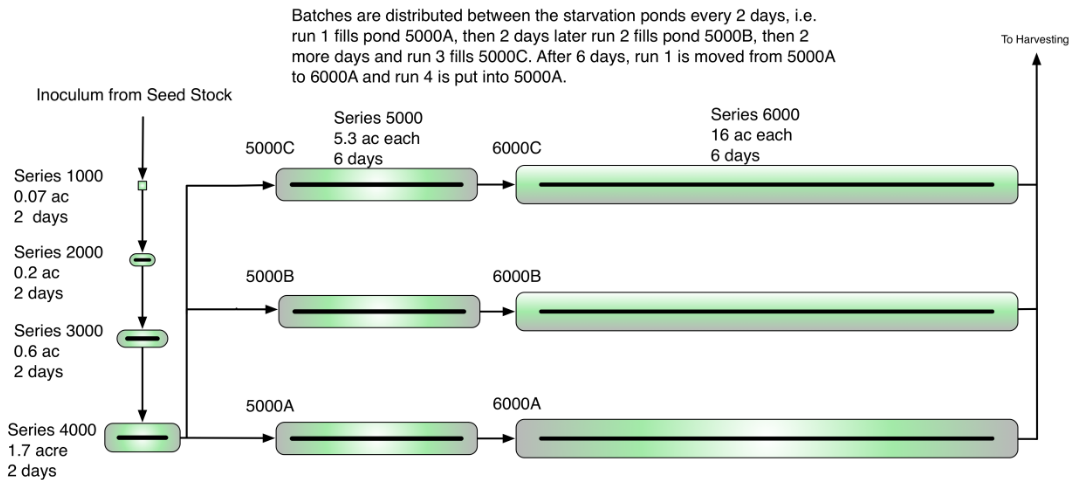

Figure 29. Schematic of one 50 ac-ft module of algae cultivation raceway ponds for commercial scale production [34]

KASELCO's Hi-Flo EC system will process 54,987,356 gallons (208,127,143 Liters), 20-6000 series ponds, using 15-1200 gpm reactors operating at 1800 gpm, as stated in section 4.6. Operations will be running 23 hours a day, 1 hour for maintenance, giving a processing capacity of 1,620,000 gph (141,029,100 L hr^{-1}). The harvesting volume will be processed in 1.5 days meeting 2 day inoculation growth conditions. During pilot testing 2500 gallon settling tanks where used for removal of algae. Given the volumes on a commercial farm, the harvesting operations will need 21,995 settling tanks priced at $1,405.95 [35] totaling $30,900,000 which is not economically feasible. The harvesting process will need to incorporate circular clarifiers from wastewater treatment to handle the volume.

Wastewater treatment facilities process vast amounts of water daily and accumulate sludge using clarifiers. This model used wastewater treatment as a benchmark for algae recovery after EC treatment. Designing a system to handle the algal solution took into account bottlenecks and estimated installation cost. The EC treatment takes 1.5 days to process the volume, but the volumes were divided into 1 full day (37,260,000 gpd) of processing and the remaining ½ day (18,630,000 gpd). Two design scenarios were taken into consideration; design 1, building two clarifier-thickeners and design 2, multiple clarifier-thickeners. Detention time is assumed to be 24 hours based on pilot scale data, based on section 4.6 settling time. Table 15 and Table 16 list the design parameters for 1 day and ½ day operations, respectively.

Table 15. Clarifier design parameters for 1 day of operation

Design Parameters	
EC Processing flow rate (gph)	1,620,000
EC Processing flow rate (gpm)	27,000
Detention (hrs)	24
Volume Process (gpd)	37,260,000

Table 16. Clarifier design parameters for 1/2 day of operation

Design Parameters	
EC Processing flow rate (gph)	1,620,000
EC Processing flow rate (gpm)	27,000
Detention (hrs)	24
Volume Process (gpd)	18,630,000

Clarifier-thickener volume was calculated using equation 3 where r is the radius (ft.), h is the height (ft.). The maximum radius and height for a clarifier-thickener are 100 ft. and 20 ft., respectively [36]. Height was held constant at 20 ft. for all calculations unless otherwise stated. Equation 3 was manipulated to solve for the required radius in feet, equation 4. Results for 1 and ½ day operations for the clarifier-thickener dimensions for design 1 are in Table 17 and Table 18, respectively.

The clarifier volume was calculated as follows:

(3)

$$V = \pi * r^2 * h$$

Where
V = Volume of the clarifier (cu. ft.)
π= Constant Pi
r = Radius of the clarifier (ft.)
h = height (depth) of the clarifier (ft.)

Radius for a clarifier was calculated as follows:

(4)

$$r = \sqrt{\frac{V}{\pi * h}}$$

Where
r = Radius of the clarifier (ft.)
V = Volume of the clarifier (ft.)
π= Constant Pi
h = Height (depth) of the clarifier (ft.)

Table 17. Clarifier dimensions for 1 day of operation

Circular Clarifier Volume	
Volume processed (gal/day)	37,260,000
Volume Processed (cu. ft.)	4,981,283
Radius (ft)	282
Depth (ft)	20
Weir (ft)	563

Table 18. Clarifier dimensions for 1/2 day of operation

Circular Clarifier Volume	
Volume processed (gal/day)	18,630,000
Volume Processed (cu. ft.)	2,490,642
Radius (ft)	199
Depth (ft)	20
Weir (ft)	398

Overflow rate was then calculated using the flow rate (gpd) and dividing by the area of the clarifier (ft^2). The area of the clarifier was determined by squaring the diameter and multiplying by a conversion factor of 0.785. The over flow rate was determined to be 150 gal/ft^2/day for both clarifiers. Weir length was assumed to be the diameter of the clarifier in feet. The results show that both clarifier dimensions exceed the maximum radius stated above.

Design 2 calculated the clarifier-thickener maximum volume (628,319 cu. ft.) using equation 3 with radius and height set to 100 ft. and 20 ft., respectively. Required processing volume(s) was divided by the maximum clarifier-thickener volume to determine the number of clarifiers. Clarifiers are designed for peak flow rates to calculate peak overflow rates for optimum removal of solids. Peak overflow rates for this clarifier ranges from 1000-1200 gal/ft^2/day [36]. The calculated overflow rate is 1187 gal/ft^2/day for the clarifier given the current flow rate. Operating in the peak overflow range may hinder removal rates. Eight maximum volume circular clarifier-thickeners will be needed for 1 day of processing. Four maximum volume circular clarifier-thickeners will be needed for the remaining ½ day processing.

Installed costs were calculated using cost values from the Chemical Engineers' Handbook 5th edition [37]. The cost includes installation; based on steel mechanisms, steel tank and bottom to 100 ft., and steel tanks and concrete bottoms from 100 ft. The cost is given in units of cost per square foot (\$/ft^2) and is based off of diameter size. Diameter size for the clarifier-thickeners is 200 ft. giving a cost of \$9/ft^2. The square footage of the maximum clarifier-thickener is 31,400 ft^2. Estimated installation cost summed the number clarifier-thickeners and multiplied by the square footage and by the \$9/ft^2, equation 5, where C is the total number of clarifier-thickeners.

Clarifier-thickener estimated installation cost calculated as follows:

(5)

$$\$ = C * 31{,}400 * 9$$

Where
$\$$ = Installation Cost (dollars)
C = Total number of clarifier-thickeners
$31{,}400$ = Maximum area of clarifier-thickener (ft^2)
9 = Cost per square foot ($\$/ft^2$)

The system requires a total of 12 clarifier-thickeners resulting in a cost of $3,360,662. Multiple clarifier-thickeners eliminate a bottleneck in the harvesting system. If a clarifier-thickener breaks or maintenance is required the flow can be shifted to other clarifier-thickeners. These scenarios are not optimal and improvements will be seen when more data is collected. Settling rates of the algae may allow for the majority of biomass to be captured in the first or second clarifier. The remaining clarifier-thickeners will recover algae that do not settle rapidly operating as a secondary removal. Settling rates of algae after EC treatment will determine if this is true. If this is true, a reduction in the number of clarifier-thickeners may be possible reducing costs. However, if settling rates are too fast algal sludge may clog the clarifier-thickeners reducing the total volume of the clarifier-thickeners. Algal sludge removal rates will need to be at a continuous rate. Additional designing and new data will give better results. This is a preliminary design requiring further analysis.

Mimicking wastewater treatment technologies and methods will increase the viability of microalgae farming. Circular clarifier-thickeners have the ability to process the volumes of water used in microalgae farming with the capability to increase the percent solids of the algal slurry for downstream processing. The challenge in using the clarifier-thickeners is recovering the sludge. Wastewater treatment focuses in recovering the effluent water while sludge accumulation is treated as a bi-product.

Installing a belt filter press to increase assumed 5% solid algal slurry leaving the clarifier-thickeners to 20-35% solid algal cake was used as the final harvesting component to meet extraction processing standards. A belt filter press with a 11.5 ft (3.5 m) belt width with a sludge loading rate of 1,500 lb/m*hr was used to process the algal slurry [38]. Calculating the sludge-loading rate of dry algae was used to determine the number of belt filter presses required for this system. The volume in MGD is 37.26 and 18.63 for 1 and ½ day of processing, respectively. The sludge-loading rate was calculated using equation 6 where dosage is the total suspended solids (TSS); MGD is millions of gallons per day. Dosage was calculated assuming the 5% TSS using equation 5 to be 50,000 mg L^{-1}.

Sludge-loading rate was calculated as follows:

(6)

$$SLR = \boldsymbol{d} * \boldsymbol{MGD} * \mathbf{8.34}$$

Where
SLR = Sludge-loading rate (lbs/day)
d = Dosage (mg/L)
MGD = Million gallons processed per day
8.34 = Constant for conversion (lbs/gal)

Influent dosage to the belt filter press was calculated as follows:

(7)

$$\boldsymbol{ID = TSS * 1,000,000}$$

Where
ID = Influent dosage (mg/L)
TSS = Total suspended solids (mg/L)
1,000,000 = Conversion factor

Processed dry solids for 1 and ½ day operations are 15,537,420 lbs/day and 7,768,710 lbs/day, respectively. The daily rates were then calculated into lbs/hr by dividing by the 23 hour work day giving 675,540 lbs/hr and 337,770 lbs/hr. The number of belt filter presses required was determined by calculating the belt width, dry solids divided by sludge-loading rate, and dividing by the maximum belt width of 3.5 m (equation 8).

Number of belt filter presses required was calculated as follows:

(8)

$$\boldsymbol{\#\,units = \left(\frac{Dry\ solids}{Sludge - loading\ rate}\right) \div 3.5}$$

Where
 # units = Total number of belt filter presses required
Dry Solids = Dry solids processed (lbs/hr)
SLR = Sludge-loading rate (lbs/m*hr)
3.5 = Maximum belt width

Belt width for one belt filter press is 450m and 64m for 1 day and ½ day of processing, respectively. This is not feasible for manufacturing. One day of processing would need 129 belt presses and ½ day processing would need 64 belt presses, totaling 193 belt filter presses. A capital cost of $115,000 for a 1.5 meter belt filter press was assumed [39]. It was assumed material costs are linear for increasing belt width. Price was inflated by 2.3 (3.5m/1.5m) multiplied by $115,000. The total amount of belt filter presses required is 193 units with a capital cost of $51,791,400, not including installation. A belt filter press was determined to be unfeasible because of the total number of units required giving an outstanding capital cost for harvesting systems. The additional installation and operational costs will increase the over harvesting process. Hydrothermal liquefaction or wet extraction systems are suggested for downstream processing and need to be located at the algae farm.

4.8 Economic analysis

The results from AISIM report that there was an increase in net present value (NPV) by switching from centrifugation to KASELCO's electrocoagulation system with 8% solids, but the probability of success was 0% in all scenarios. After 10 years of operation using the centrifuge for harvesting the NPV was -$4,949,826,073 while the NPV for EC was -$4,438,686,464, increasing the NPV by $56,139,609. A third scenario with 4% solids using EC resulted in NPV of -$8,646,123,466 after 10 years of operation. This scenario decreased NPV by $4,151,297,393 compared to the centrifuge. A discount factor of 0.04 was used in all scenarios. The cost per ton and cost per gallon of lipid are reduced when using the EC 8% scenario compared to the centrifuge, but the EC 4% scenario increases the product value (Table 19).

Table 19. Total cost per ton and total cost per gallon of lipid produced for the three scenarios

Scenario	Yr 5 TC ($/Ton)	Yr 5 TC ($/gal lipid)
Centrifuge	$54,483.50	$837.20
EC 8%	$49,464.02	$760.02
EC 4%	$96,575.88	$1,482.58

Note, additional conversion costs will be added to the cost per gallon of lipids. The model does not include conversion costs.

Centrifugation scenario required 54 units operating at the algal farm with a capital cost of $14,850,000. The EC scenarios require 15-1200 gpm Hi-Flo reactors operating at 1800 gpm (6813 L min^{-1}) with a capital cost of $10,750,000. Switching to EC reduces the capital cost by $ 4,100,000.

The significant operational expenses for all three scenarios for year 5 of operation are shown in Table 20. Note year 5 is assumed to be a stabilized algae farm. A learning curve has been assumed in the AISIM model. In year 1, 50% of the facility will be in production to minimize unnecessary cultivation and harvest expenses due to lack of experience. In year 2, 90% of the farm will be in production and year 3 forward the farm will be operating at max capacity. Operational costs from year 3 to year 10 have similar operational expenses.

The only difference between years is costs have been adjusted for inflation. Net present value was reported for year 10 to show no improvements are expected during farming operations.

Table 20. Harvesting major expense changes for three scenarios

Cost	Centrifuge Yr 5	EC 8% Yr 5	EC 4% Yr 5
Total Labor	$8,885,327	$3,872,132	$3,872,132
Natural Gas	$417,807,291	$417,807,291	$835,609,042
Electrical	$4,012,038	$3,982,282	$4,017,921
Maintenance	$1,662,708	$989,065	$989,065
Harvesting Chemicals	$-	$792,366	$792,366
Extraction Chemicals	$3,885,012	$3,885,012	$7,770,023
Carryover Debt Interest	150,138,673	148,571,732	289,164,714
Total Operational Costs	$586,391,049	$579,899,880	$1,142,215,263

The decrease in NPV with 4% solids is contributed by the increase of natural gas and extraction chemicals, costing $835,609,042 and $7,770,023, respectively, required for the wet extraction process. Natural gas costs ($417,807,291) and extraction chemicals costs ($3,885,012) are the same for centrifugation and EC at 8% solids. The 4% solids scenario increase operational cost by $555,824,214.

Labor requires 78 workers to operate the centrifuges with a total of 120 workers operating the algae farm, costing $8,885,327. Eleven workers are required to operate the EC system. A total of 53 workers are required to operate the algae farm costing for the algae farm $3,872,132. Employment is reduced by 67 workers when implementing the EC scenarios, reducing total labor by $5,013,195. Labor costs are significantly reduced because of the automated EC system. The fully automated system and can be controlled by one operator from a control room. The model assumes all workers are employed regardless if the farm is harvesting to perform other tasks. All labor cost include overhead, workman's comp., and unemployment tax.

Other expenses reduced when switching to the EC 8% solids scenario are maintenance and electrical cost. The maintenance costs are reduced by $673,643 in year 5 under the 8% solids scenario. The sacrificial electrodes used in EC are the only "moving" parts in the harvesting system. Centrifugation has several moving parts increasing the probability of a breakdown and more repairs. Maintenance costs are decreased because of a lower probability of downtime and repairs when using EC 8% solids scenario.

Electrical costs are not reduced significantly as seen in section 4.6. This is a result of all other electrical costs associated in the model. The electrical consumption from paddle wheels averages 13.43 M$s [40]. Extraction electrical costs are also included in the model. However, the centrifuge uses 75kWh/ton compared to 26 kWh/ton using EC.

A harvesting chemical cost of $792,366 is required when harvesting using EC whereas centrifugation has no chemical cost associated with that harvesting technique. Harvesting chemicals refer to the metal ions released into the algal solution to coagulate the algae. Even with the additional expense of harvesting chemicals EC 8% scenario still reduces operational costs. However, the EC 4% solids scenario does not reduce operational costs. Switching to EC 8% solids yields operational savings of $6,491,169. A detailed financial statement of the model is provided in Appendix C.

The results show that switching to EC 8% solids scenario improves the NPV, but is not the sole solution to making an algal farm profitable. Harvesting algae using EC may require additional drying depending on downstream processing which may require different percent solids of biomass coming into the extraction system(s). This problem will be answered when an extraction system(s) is chosen or can be modeled in the AISIM model.

In addition, EC is a proven technology that is constantly evolving and improving. Electro-flocculation systems do not use sacrificial electrodes, which will decrease the operational, and maintenance costs. By using charge neutralization the algae cells will flocculate to other algae cells forming flocs and will settle out in the algal solution. Inert plating technology is one area that may solve this issue reducing maintenance and harvesting chemical costs for EC. Increasing the efficiency of providing power to the EC reactor is another step to reducing the operational cost. Current rectifiers draw the maximum amount of power from the grid. The selected power setting is provided to the electrodes and the rest of the power is released as heat. Capturing the heat from rectifiers to further dry the recovered algae is another possible solution to help increase the percent solids.

The AISIM model shows that a significant amount of improvements in all areas of algal farming are required to make the system profitable. Another approach to reach profitability would be for the government to mandate a certain amount of biodiesel to be produced from algal farms. The Renewable Fuel Standard (RFS) created under the Energy Policy Act (EPAct) in 2005. The RFS was expanded in 2007 under the Energy Independence and Security Act (EISA) and is now abbreviated as RFS2. Under RFS2 and EISA, 36 billion gallons of renewable fuel will be required to be blended into transportation fuel by 2022 [41]. Amending RFS2 to include a set amount of gallons of biodiesel produced from algal farms will change the AISIM model outcome. Government programs and subsidies can be put in place to help reach profitability.

Fuel produced from algal farms could supply the Department of Defense (DoD). In 2012 the composite standard price for a barrel of fuel was $161.70 and the expected 2013 composite standard price is $156.66 [42]. A detailed list of prices for the DoD customer fuel prices can be found in appendix D. The DoD conducted an assessment for opportunities for the use of alternative and renewable fuels in the fiscal years of 2010-2011. Algae production is expected to start in 2016 with 10 million gallons and in 2020, 80 million gallons [43]. Appendix E provides a biodiesel and renewable and cellulosic diesel forecasts for feedstocks. Increasing the amount of algal based fuels the DoD is requiring for future operations will help the probability of success for algal farms by increasing the demand for algae base biodiesel.

CHAPTER V

SUMMARY

The KASELCO EC systems proved to successfully remove algae from water in laboratory and pilot scale testing. Laboratory testing using aluminum and stainless steel electrodes succeeded in coagulating microalgae; however aluminum consumed the least amount of power as described in section 4.4. Conductivity levels of media are a significant factor in selecting a KASELCO reactor for optimum recovery. A threshold for microalgae electrocoagulation and electroflotation was established at amperage levels of 1.5 in laboratory testing. All amperage levels greater than 1.5 amps resulted in electroflotation using aluminum and stainless steel electrodes. The threshold has determined the upper limit required to harvest microalgae using electrocoagulation. Knowing the upper limit of the KASELCO bench top reactors will allow for optimizing power levels required to recover microalgae. An inverse relationship between metal content in the biomass and power supplied was observed. Experiments to determine the amount of biomass and inorganic matter seeks further investigation to confirm or reject the findings.

The KASELCO EC system has the ability to operate on pilot scale using data collected from laboratory data. Aluminum electrodes to recover microalgae are recommended in literature and laboratory testing conducted. However, pilot scale testing proved aluminum electrodes perform inconsistently. Minerals and other dissolved solids in growth water used in open pond raceways effect the electrochemical reactions during

EC treatment. A better understanding of these electrochemical reactions will improve the efficiency of the KASELCO EC system. Electro-flocculation was not obtained during testing. Improvements in rectifier precision controls and inert electrodes are recommended to reach electro-flocculation. Preliminary results indicate cell lysing of microalgae cells occurred. However, conclusions were drawn from a single test using the Hi-Flo EC system and require further investigation. Electrical demand was reduced using EC compared to the centrifuge at pilot scale. According to the economic analysis the electrical reduction was not significant when modeling the complete microalgae farm. Net present value was increased for the microalgae farm, but several improvements in cultivation, extraction, and conversion are required to make biodiesel production using microalgae profitable.

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APPENDIX A: ALGAE INCOME SINULATION MODEL: AISIM

AISIM is a Monte Carlo firm level simulation model designed to simulate the annual activities of an algae farm. The model is designed to facilitate researchers analysis of the economic returns and costs of production for an algae farm under alternative management systems. The model can be thought of as a compilation of many techno-economic models of different phases of an algae farm. This appendix presents an overview of AISIM.

➢ Programming

AISIM is programmed in Microsoft® Excel and depends upon the Simetar© add-in. The Excel workbook model is divided up into multiple worksheets that include: Input, Model, SimData, Prices, and others.

All input for an algae farm is entered in the INPUT worksheet and most all calculations are in the MODEL worksheet. Simetar is used to simulate the model by drawing annual stochastic prices, production, and costs from known probability distributions. Simetar functions are used to estimate parameters for the probability distributions to simulate the stochastic variables. The parameters for price probability distributions are estimated from historical data provided as input by the researcher. The best fitting distribution for simulating production and input prices is the multivariate empirical distribution (MVEMP).

The AISIM model is simulated recursively for 10 years. This means that the ending cash position of the business in year 1 is the beginning cash flow position for year 2, and so on. The 10 year planning horizon is repeated 500 times (iterations) using different stochastic prices and production values for each year. By simulating the 10 year planning horizon for 500 iterations, the model is able to simulate most all combinations of the stochastic variables, (i.e., the best and worst cases and those in between) based on their respective probabilities of being observed.

➢ Input Requirements

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

➢ Price Projections

The annual average prices for soybean meal, electricity, nitrogen, phosphorous, CO_2, diesel, and other inputs are entered, as well as any discount or premium an algae co-product would have relative to these products. Annual values must be consistent with each other so it is recommended that the price projections all come from a common source, such as the FAPRI or USDA Baseline. In addition, annual rates of inflation for input costs and interest rates are required. These data are used to calculate annual increases in input costs not associated with the stochastic prices.

➢ Historical Price Data

Historical prices for the stochastic price variables must be entered as input to AISIM. The model requires 10 years of historical prices for the stochastic price variables. AISIM uses the historical price data to calculate the parameters to simulate prices as a multivariate empirical distribution. Entering new historical data causes AISIM to automatically update the MVEMP distribution’s parameters.

➢ Options for Farming System

AISIM is programmed to accommodate many different production systems. The production system options are listed at the beginning of the model. They are listed as yes/no or number options and trigger many different formulas within the model. The first option is the source of weather history data. Currently three weather history areas are available: Pecos and Corpus Christi, TX and Southeast New Mexico. These are used to calculate annual evaporation and precipitation. The second option is the source of the biomass production data; Pacific Northwest National Laboratory (PNNL) pre-loaded production data or specify your own growth rates. If the user chooses PNNL they are still be able to select a location. If the user chooses to use their own data they must specify whether those growth rates will be in annual (grams/liter), annual (grams/meter^2), monthly (grams/liter), and at what pond concentration they will harvest each time (grams/liter). There is also the option to have a batch or continuous growth and harvesting process. Additionally, there is the option to choose whether water will or will not be recycled. Water cost can be calculated using the energy cost for pumping the water from a well for example, or the user can specify a $/gal pumping cost.

The next set of options deals with the harvesting and extraction systems. The user can specify yes or no for each harvesting and extraction process depending on whether it is used. The user can also use more than one harvesting and extraction system, though they must remember to later specify what percent of the annual production is processed by the harvesting or extraction machine. The user can also specify whether the extraction will take place off-site or not. In the operating cost (OPEX) section the user specifies a $/ton of biomass extraction cost. The last set of options for the model deals with the final products. The farm can produce multiple products, but the user must be cognizant that some of the co-products cannot be in production together or sold at the same time. For example, if the farm produces diesel it cannot sell oil because the oil has been used to produce diesel. Also, in order for fertilizer to be produced LEA must first be produced.

➢ Algae Production Information

The model simulates 10 years of algae production for the 500 iterations using monthly biomass probability distributions or the monthly biomass yield distributions from the BAT model at PNNL. If the analyst opts to simulate biomass production based on monthly probability distributions, the model requires the parameters for 12 monthly GRKS distributions, one for each month. The GRKS distribution requires the parameters: the mode, the minimum (2.5% quantile) and the maximum (97.5% quantile). AISIM uses the monthly GRKS distributions to simulate monthly biomass production values based on biomass equations described in a subsequent section.

A second option is to use the 30 years of simulated biomass production from the BAT model. The researcher must indicate the region where the farm is located and then AISIM simulates biomass from the appropriate BAT file. The 30 years of monthly BAT biomass production are used to calculate parameters for a MVEMP distribution. The MVEMP is simulated for the necessary 12 months over 500 iterations and the random variables are used in the model.

➢ Lipid Production

A GRKS distribution parameterized by the user is used to simulate average annual percent lipid value. The average percent lipid is multiplied by the total biomass to calculate total lipid production.

➢ Debt Financing Information

The user must specify their financial and debt financing information. This information is used in ProForma Financial statements. Data needed are: dividends to the investor as a fraction of net cash income, dividends as a fraction of initial equity, discount rate, cash reserve for the first marketing year, fraction of the year for an operating loan, capital expenses (CAPEX) inflation rate, CAPEX loan length, the year the CAPEX loan is started, fraction of CAPEX financed, fraction of machinery replacements financed, number of years for machinery replacement loans, and the interest rate for machinery replacement loans.

➢ Cultivation

The cultivation input section of the model outlines the basis of the farm and is a key piece in the production and sizing of equipment for the model. First, the user must specify the desired acre feet of water for the algae production facility. Next, the number of blocks of ponds and number of harvested ponds per block must be specified. This option is provided for users to specify harvesting as a batch process. If the farm has a continuous harvesting process users specify their total number of ponds in the number of blocks of ponds entry, and the number of harvested ponds per block is specified as one. For a batch process the user specifies the number of blocks of ponds and the number of harvested ponds in each block. The number of blowdown ponds must also be specified. To accommodate an ARID raceway type situation (University of Arizona), the acres per pond is split into two categories: acres per pond and acres per trench. In the ARID raceway system the water flows through the pond and trench during the day, but is all put in the trench during the nighttime. With this system there are different exposed surface areas and, thus, different amounts evaporation during the daytime versus the nighttime. The acres per pond, along with the specified depth of water in the pond in inches, is used to calculate the total acre feet of ponds for the facility and thus is used as a check against what the user specified.

A pond concentration (g/L) at harvest must also be entered. This value is used to calculate the quantities of water and algae that move through the system. In conjunction with the accommodations for the ARID Raceway system the user must also specify the percent of daily evaporation that occurs during the daytime and at night. Lastly, a number of days of operation per year must be entered.

- **Land Area**

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

- **Harvesting**

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

- **Harvesting Method – Centrifuge**

The centrifuge is a piece of equipment for harvesting that has been used in many different industries. Because of its well established nature it is often used as a base scenario to compare to alternative harvesting methods. The centrifuge uses centrifugal force to cause the algae and water to separate from one another. Water from the centrifuge can be recycled. Information needed for programming, as well as data for the centrifuge harvesting method, was obtained from Dr. Ron Lacey in the Agricultural Engineering Department at Texas A&M University. Data given by Dr. Lacey was for an "at-scale" algae production facility with 1,000 acre feet of water. All data needed for the centrifuge process is common to the alternative harvesting methods and was listed above.

- **Harvesting Method – Polymer Flocculation**

The polymer flocculation method of harvesting is also a process that has been used extensively in other industries. In polymer flocculation a chemical is added to the algae media which causes the algae particles to "floc" or clump together. Once the algae has concentrated it can be separated from the water for further processing. Water from the flocculation process can be recycled. All data needed for the polymer flocculation process is common to the alternative harvesting methods and was listed above. Data for flocculation are based on trials at Pecos, Texas, and was provided by Mr. Lou Brown.

- **Harvesting Method – Electrocoagulation**

Electrocoagulation harvesting utilizes aluminum ions, which are released during electrolysis between two aluminum plates submerged in the media. The positively charged aluminum ions attract the negatively charged algae and create a floc. The floc then settles to the bottom of the media and is separated by decanting the clear media from the top, which can be recycled to the cultivation process. The algae are concentrated from approximately 1 g/L in cultivation to around 8% solids (80 g/L) in the sediment. The capacity of the electrocoagulation unit is determined by the size of the plates and the volume of the reactor chamber. Information for modeling of this process and data for the model was provided by Dr. Lacy and by KASELCO, via Dr. Lacey. All data needed for the electrocoagulation process is common to the alternative harvesting methods and was listed above.

- **Extraction**

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

- **Extraction Method – SRS**

In the SRS process, harvested algae biomass in water is pretreated with conditioning chemicals at precise pH, temperature and residence times followed by non-polar solvent addition and proprietary extracting techniques. This conditioning step hydrates and chemically solubilizes the algae cell to enable non polar solvent to remove lipids. The extracted algal mass is then phase separated and lipids are recovered from the non-polar solvent by distillation. Value added products are derived from processed biomass while solvent, water and conditioning chemicals are recycled. The oil is further processed for fuel production.

In addition to the extraction parameters previously listed above the following are also required for SRS: effective extraction (%), electricity usage (kwh/kg of biomass processed) or (kwh/ton biomass processed), chemical cost ($/ton of chemical), units of chemical/unit of biomass processed, and the efficiency of the chemicals. Similar to the harvesting processes, the percent effective extraction is used to determine the final amount of output leaving the SRS system that will be available to sell. Electricity is tracked from this process into the overall electricity consumption as a part of the operating costs. AISIM can accept electricity consumption in either kwh per kg or kwh per ton of biomass processed to offer the user some flexibility. The cost per ton entered for chemicals is inflated in the model using a stochastic inflation rate over the 10 years.

- **Extraction Method - HTL-CHG**

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

The two different parts of this process require information. The information that has been used for this process is from Genifuel. The HTL system requires that the user enter an algae slurry preparation cost ($/ton of algae). This cost is inflated over the 10 year horizon. Additionally, the user must enter a value for the HTL process, such as: electricity and natural gas as a percent of the system's crude oil output, the elemental composition of the algae, percent nitrogen and phosphorus and the phosphorus remake cost as a percent of new phosphorus cost. The last parameter needed from the user for the HTL part is the percent of the total oils extracted based upon the algae input.

The CHG process requires some of the same information as HTL, such as electricity and natural gas usage as percent of the system's methane output. A percent water loss value is needed to determine the amount of water that can be recycled to the ponds. The thermal efficiency of the electricity generator is used to determine the electricity production from methane per year. Lastly, a catalyst is used in the gasification step. As specified by the user, the catalyst has a life and must be replaced at the end of its life. Intermediately, the catalyst can be remanufactured to extend its life. The user must specify the cost of the initial catalyst load along with the cost of remanufacturing it and the probability of needing to remanufacture the catalyst in a given year.

➢ Extraction Method - Pyrolysis

Pyrolysis is an extraction process that chemically decomposes algae by heat in the absence of oxygen. In the pyrolysis process the harvested algae is dried to less than 10% moisture using heat from the combustion of syngas. Syngas is a by-product from the pyrolysis process and is recycled for the purpose of drying the algae. The pyrolyzed algae will produce syngas, char (which can be sold as a soil amendment), and bio-oil.

The bio-oil can be separated in a decanter to split the aqueous and organic fractions. These organic fractions are then further processed and upgraded to produce fuel.

The information and parameters needed for modeling pyrolysis were provided by Dr. Sergio Capareda of the Agricultural Engineering Department at Texas A&M University. Parameters for the pyrolysis processes include extraction machine operation (hours/day), bio-oil yield (gallons/dry ton of algae processed) and char yield (pounds/dry ton of algae processed). Additionally, each of the following are needed: organics as a percent of the bio-oil, aqueous solution as a percent of the bio-oil, percentage of the aqueous faction that is water, and the percentage of organics in the aqueous solution. An upgrade cost from the organic bio-oil to crude must also be provided ($/gal).

- There is also a startup cost for each pyrolysis unit. This is due to the fact that there isn't any syngas available to dry the first batch of algae. Thus, the user must specify what the startup cost ($/unit) is, as well as the number of startups per year they plan to have. Lastly, general information such as capital cost ($/unit), life of machine (years) and annual maintenance cost ($) must be given.

- **CAPEX**

Values for CAPEX must be specified by the user, except for in the case of the harvesting and extraction equipment, gators, vehicles, pumps, and land which are populated based on information entered elsewhere in the model. CAPEX categories are: dirt moving construction, raceway construction, photo bio-reactor (PBR) tubes or bags, sump construction, liner, perimeter fence, dividers between ponds, paddlewheels, CO_2

delivery system, nutrient storage and distribution, piping system, algae inoculum stations, water wells, storage buildings, anaerobic digester, power generation, electrical lines, office building, backhoes, motor graders, ponds sweepers, lab building and equipment, field expenses, diesel plant capital cost, contingency costs, and other capital costs. CAPEX costs are summed and split into the appropriate machinery replacement categories based upon useful life. These summations are used to compute the values of the machinery replacement loans and cash flow requirements for maintaining current equipment.

➢ OPEX

There are several different operating cost categories. In each, the user may either enter a lump sum annual operating cost for that category or be more specific and enter information that will be used to calculate usage and costs.

➢ CO_2

Three pieces of information are needed for the CO_2 calculations. The first is the pounds of CO_2 required per pound of biomass produced and the second is the efficiency of the CO_2 (%). These are used in determining the total amount of CO_2 that is needed for the year. The third piece is the contract cost for CO_2 ($/ton).

- **Media**

There are three options besides the annual media cost. The first is to enter a ratio of growth media to biomass and lipid media to biomass. The cost of the lipid and growth media ($/liter) must be entered. Additionally, it must be specified what percentages of nitrogen, phosphorus, and potassium are in the solution. This is so the media cost can be appropriately inflated according to stochastic prices for these ingredients.

The second option is to enter a ratio of nitrogen, phosphorus, potassium and other nutrients to biomass and the cost of these inputs on a $/ton basis. The final option requires the startup growth media and lipid media liters/batch. For this option, the number of growth media, lipid media, recycled growth media, and recycled lipid media batches per year must also be given along with the cost ($/liter) of each. The percents of nitrogen, phosphorus, and potassium in each media mix must be specified to appropriately simulate the costs.

- **Labor**

In the labor section the user must specify the number of employees by category. The labor categories are: CEO, legal/accounting/permitting, project manager, operations manager, administrative assistant, procurement, marketing, cultivation, harvesting, extraction, aquatic biology, fisheries biology, lab technicians, and maintenance. For each category a salary must be given to calculate a total labor cost. The assumed annual salaries for the categories are: CEO, $150,000, legal/accounting/permitting, $40,000, project manager, $60,000, operations manager, $100,000, administrative assistant, $42,500, procurement, $106,000, marketing, $84,000, cultivation, $46,000, harvesting, $60,000, extraction, $70,000, aquatic biology, $64,000, fisheries biology, $58,000, lab technician, $80,000, and maintenance, $43,000. The number of employees by category is also used to determine the number of vehicles needed. The vehicle costs are then linked in with the CAPEX section. The cost per vehicle is: SUV, $45,000, pickup, $30,000, and gators, $9,000.

➢ Electricity

Electricity for cultivation can be entered as a kwh/ton of biomass produced. Harvesting and extraction electricity is not entered in this section because they are included in each processes' respective sections. There is also an other electricity section where non-water, cultivation, harvesting, and extraction electricity can be entered in kwh/ton of biomass.

➢ Waste Water Disposal

Parameters for calculating the cost of blowdown ponds are listed in this section. These parameters are: pond depth (ft), acres of blowdown ponds, price of dirt removal ($/cubic foot), area of liner needed (ft^2), liner cost ($\$/ft^2$), liner installation cost ($\$/ft^2$) and the number and cost of pumps.

- **Natural Gas**

The amount of natural gas in cubic feet/ton of biomass is required.

- **Property Tax Rate**

The property tax percentage rate must be entered. The tax is calculated as a percentage of the total property value.

- **Workman’s Compensation/Unemployment Tax**

The workman’s compensation/unemployment tax percentage must be entered. The tax is calculated as a percentage of the total labor cost.

- **Non-Harvesting and Extraction Maintenance Costs and Crash Cleanup Costs**

All annual maintenance costs are entered here. The crash cleanup cost represents the cost of disposing of the contaminated algae and restarting a pond(s) if it were to crash.

- **Harvesting and Extraction Costs**

If any harvesting and extraction costs were not captured earlier in their respective sections they can be entered in this section as an annual cost. Alternatively, the cost of outsourcing extraction ($/ton of biomass) can be entered.

- **Pro Forma Financial Statements**

AISIM calculates three pro forma financial statements: income statement, cash flow, and balance sheet. These statements summarize the values described above.

- **Income Statement**

The income statement provides separate lines for each source of revenue, such as: diesel, electricity, PUFAs, LEA, whole algae, etc. Thus the analyst can see where receipts are being generated and can make changes to input data as needed. The receipts in the statement are calculated earlier in the model and are summarized in this location.

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

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

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

- **Cash Flow Statement**

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

- **Balance Sheet**

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

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

- **Key Output Variables (KOVs)**

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

Net present value (NPV) is calculated as:

NPV = - Beg Net Worth + Σ (dividends and cash withdrawals$_t$/discount factor$_t$) + Ending Net Worth/discount factor

Present value of ending net worth is calculated of PVENW = Ending Net Worth/discount factor

The discount factors above are calculated as: $1/(1 + \text{discount rate})^t$

- **Income Taxes**

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

➢ Model Output

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

Probability charts (PDFs, CDFs, Fan Graphs, and StopLight charts) can be developed from the 500 simulated values. Tables of the summary statistics for selected KOVs can be developed.

If the summary tables are developed using “cell reference” formulas relating back to the values in SimData, the tables will be updated automatically each time Simetar re-simulates the model. The charts developed using data in SimData will automatically update each time the model is re-simulated by Simetar.

APPENDIX B: 2012 GROWTH WATER METAL DATA

Well water date was obtained in 2012 to determine the amount of metals already in the water. The water was used in the ponds to go microalgae for harvest. This data helped determine how much nickel, chromium, and iron the EC system was putting into the algal solution after treatment. The data show no significant amounts of nickel, chromium, or iron is present in the growth water.

Table 21. 2012 Algae growth water metal content

	TALR-20101018-Water	TALR-20101020-Water	TALR 20101022-Water	TALR 20101025-Water	TALR 20101027-Water	TALR20101101-Water	TALR20101108-Water	Average
Aluminum	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm	-
Boron	<5 ppm	<5 ppm	<5 ppm	<5 ppm	<5 ppm	<5 ppm	<5 ppm	-
Calcium	17.3	16.2	19.2	21.2	15.4	17.6	20.6	18.21
Cadmium	<0.1 ppm	<0.1 ppm	<0.1 ppm	<0.1 ppm	<0.1 ppm	<0.1 ppm	<0.1 ppm	-
Chromium	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	-
Copper	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	-
Iron	<1.00 ppm	<1.00 ppm	<1.00 ppm	<1.00 ppm	<1.00 ppm	<1.00 ppm	<1.00 ppm	-
Potassium	<10.00 ppm	<10.00 ppm	<10.00 ppm	<10.00 ppm	<10.00 ppm	<10.00 ppm	<10.00 ppm	-
Magnesium	<5.00 ppm	<5.00 ppm	<5.00 ppm	<5.00 ppm	<5.00 ppm	<5.00 ppm	<5.00 ppm	-
Manganese	< 0.3 ppm	< 0.3 ppm	< 0.3 ppm	< 0.3 ppm	< 0.3 ppm	< 0.3 ppm	< 0.3 ppm	-
Molybdenum	< 0.5 ppm	< 0.5 ppm	< 0.5 ppm	< 0.5 ppm	< 0.5 ppm	< 0.5 ppm	< 0.5 ppm	-
Phosphorus	<0.075 ppm	<0.075 ppm	<0.075 ppm	<0.075 ppm	<0.075 ppm	<0.075 ppm	<0.075 ppm	-
Sodium	938	1100	1310	1240	1210	1200	1320	1188.29
Silica (SiO2)	36	39	35	34	36	34	35	35.57
Vanadium	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	-
Zinc	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	-

APPENDIX C: AISIM MODEL KEY OUTPUT VARIABLES

The financial statements below are the deliverables from the AISIM model. An income statement, cash flow statement, and a balance sheet are provided. Net present value was used to determine the success of an algal farm using three different scenarios. The base scenario is using the centrifuge for harvesting. Scenarios 2 and 3 use EC but yield different percent solids going to downstream processing.

Table 22. AISIM key output variables to determine cost savings using EC

Income Statement	Centrifuge Yr 5	EC 8% Yr 5	EC 4% Yr 5
Receipts			
Algae Oil	2,354,845	2,564,164	2,564,164
Subsidy	-	-	-
HVO	567,240	617,661	617,661
PUFA 1	-	-	-
PUFA 2	-	-	-
PUFA 3	-	-	-
LEA	1,013,524	1,103,615	1,103,615
Whole Algae	-	-	-
Fertilizer	-	-	-
Rubisco	-	-	-
Methane	-	-	-
Electricity	-	-	-
Bio-Char	-	-	-
Diesel	-	-	-
Naptha Credit	-	-	-
Power Credit/Sludge for Diesel Plant	-	-	-
Total	3,935,608	4,285,440	4,285,440
Expenses			
CO2 Costs	1,592,037	1,592,037	1,592,037

Table 22. Continued

Income Statement	Centrifuge Yr 5	EC 8% Yr 5	EC 4% Yr 5
Nutrient Costs	5,253,588	5,253,588	5,253,588
HTL/CHG Slurry Preparation	-	-	-
Total Labor & Overhead	8,227,155	3,585,307	3,585,307
Workman's Comp & Unemployment Tax	658,172	286,825	286,825
Chemicals or enter as Other Nutrients	-	-	-
Natural Gas	417,807,291	417,807,291	835,609,042
Water Costs	51,712	51,712	51,712
Waste Water Disposal	893,822	893,822	893,822
Utilities	-	-	-
Electricity or enter Electricity use below	4,012,038	3,982,282	4,017,921
Maintenance Costs	1,662,708	989,065	989,065
Crash Cleanup Costs	274,222	274,222	274,222
Insurance	96,050	87,518	87,518
Property Taxes	13,398	13,398	13,398
Harvesting Chemicals	-	792,366	792,366
Extraction Chemicals	3,885,012	3,885,012	7,770,023
Royalties	-	-	-
CHG Catalyst Remanufacturing	-	-	-
CHG Catalyst Replacement	-	-	-
Diesel Production Costs	-	-	-
Sum of Cash Costs to Here	444,427,206	439,494,446	861,216,847
Adjusted Cash Costs OPEX	444,427,206	439,494,446	861,216,847
Operating Interest	3,472,165	3,433,627	6,728,408
Carryover Debt Interest	150,138,673	148,571,732	289,164,714
Interest Machinery Debt	-	-	-
Interest on Initial Debt	2,240,128	2,041,133	2,041,133
Total	600,278,172	593,540,938	1,159,151,102
Interest Costs	155,850,967	154,046,492	297,934,254
Interest Costs as Fraction	0.26	0.26	0.26
Non-Interest Costs	444,427,206	439,494,446	861,216,847
Non-Interest Costs as Fraction	0.74	0.74	0.74
Net Cash Income	(596,342,564)	(589,255,498)	(1,154,865,662)

Table 22. Continued

Cash Flow Statement	**Year 10**	**Year 10**	**Year 10**
Beginning Cash	-	-	-
Net Cash Income	(596,342,564)	(589,255,498)	(1,154,865,662)
Interest Earned	-	-	-
Total Inflows	(596,342,564)	(589,255,498)	(1,154,865,662)
Principal Payments Initial Debt	1,147,510	1,045,575	1,045,575
Principal Payments Mach. Debt	-	-	-
Replace Equipment Downpayments	-	-	-
Income Taxes	-	-	-
Dividends as Fract Net Income	-	-	-
Dividends as Fract Beg Equity	648,145	595,010	595,010
Repay Deficit Loans	1,921,731,904	1,901,675,503	3,701,225,301
Other Outflows	-	-	-
Total Outflows	1,923,527,559	1,903,316,088	3,702,865,886
Ending Cash	(2,519,870,123)	(2,492,571,586)	(4,857,731,547)
Prob(End Cash > 0)	-	-	-

Balance Sheet	**Year 10**	**Year 10**	**Year 10**
Assets			
Cash on Hand	-	-	-
New Machinery Purchases	-	-	-
Algae Farm	38,975,414	35,513,152	35,513,152
Total Assets	38,975,414	35,513,152	35,513,152
Liabilities			
Debt on Hand	30,854,318	28,113,468	28,113,468
New Machinery Loans	-	-	-
Deficit Loans	2,519,870,123	2,492,571,586	4,857,731,547
Total Liabilities	2,550,724,441	2,520,685,054	4,885,845,016
Net Worth	(2,511,749,027)	(2,485,171,903)	(4,850,331,864)
Beginning Net Worth			
Cash	1,000,000	1,000,000	1,000,000
Assets	47,851,584	43,600,834	43,600,834

Table 22. Continued

Debts	35,888,688	32,700,625	32,700,625
Beg. Net Worth	12,962,896	11,900,208	11,900,208
Discount Rate	0.04	0.04	0.04
Discount Factors	0.82	0.82	0.82
PV Dividends	532,728	489,055	489,055
PV End NW	(4,487,120,211)	(4,431,612,323)	(8,639,049,325)
NPV	(4,494,826,073)	(4,438,686,464)	(8,646,123,466)

APPENDIX D: DEPARTMENT OF DEFENSE HISTORICAL AND PROJECTED FUEL PRICES FOR 2011-2013

Projected fuel prices for the Department of Defense 2013 budget based of previous years prices. This data is supporting information for the economic discussion in Section 4.8 pertaining to algal farm profitability.

Table 23. The Department of Defense Fuel Prices for years 2011-2013

(Rates in U.S. Dollars)	**FY 2011**		**FY 2012**		**FY 2013**	
Product Type	**Gallon**	**Barrel**	**Gallon**	**Barrel**	**Gallon**	**Barrel**
AVGAS (CONUS) - 130	$4.51	$189.42	$4.39	$184.38	$4.26	$178.92
AVGAS (OCONUS) - LL	$17.68	$742.56	$17.23	$723.66	$16.70	$701.40
Diesel Fuel:						
Distillates - F76	$3.94	$165.48	$3.84	$161.28	$3.72	$156.24
High Sulfur - DF1	$3.95	$165.90	$3.85	$161.70	$3.73	$156.66
Generic (High Sulfur) - DF2	$3.55	$149.10	$3.46	$145.32	$3.35	$140.70
Ultra Low Sulfur - DS1	$3.95	$165.90	$3.85	$161.70	$3.73	$156.66
Ultra Low Sulfur - DS2	$3.81	$160.02	$3.72	$156.24	$3.60	$151.20
Burner Grade - FS1	$3.86	$162.12	$3.76	$157.92	$3.64	$152.88
Burner Grade - FS2	$3.39	$142.38	$3.31	$139.02	$3.20	$134.40
Biodiesel – BDI	$3.82	$160.44	$3.72	$156.24	$3.60	$151.20
Jet Fuel:						
JP8 & JA1	$3.95	$165.90	$3.85	$161.70	$3.73	$156.66
JAA	$3.93	$165.06	$3.83	$160.86	$3.71	$155.82
JP5	$3.97	$166.74	$3.87	$162.54	$3.75	$157.50
JTS	$6.45	$270.90	$6.45	$270.90	$6.45	$270.90
Kerosene - KS1	$3.90	$163.80	$3.80	$159.60	$3.68	$154.56
Motor Gasoline:						
Regular, Unleaded - MUR	$3.86	$162.12	$3.76	$157.92	$3.64	$152.88
Midgrade, Unleaded - MUM	$4.07	$170.94	$3.97	$166.74	$3.85	$161.70
Premium, Unleaded - MUP	$4.56	$191.52	$4.44	$186.48	$4.31	$181.02

Table 23. Continued

(Rates in U.S. Dollars)	**FY 2011**			**FY 2012**			**FY 2013**	
Product Type	**Gallon**	**Barrel**		**Gallon**	**Barrel**		**Gallon**	**Barrel**
Gasohol - GUM	$4.07	$170.94		$3.97	$166.74		$3.85	$161.70
Ethanol - E85	$3.86	$162.12		$3.76	$157.92		$3.64	$152.88
Residual:								
Burner Grade - FS4	$2.50	$105.00		$2.44	$102.48		$2.36	$99.12
Residual (Burner Grade) - FS6	$1.98	$83.16		$1.93	$81.06		$1.87	$78.54
Fuel Oil, Reclaimed - FOR	$1.05	$44.10		$1.05	$44.10		$1.05	$44.10
Bunkers - Marine – MGO	$4.02	$168.84		$3.92	$164.64		$3.80	$159.60
Bunkers - Intermediate Grade - 180,380	$2.97	$124.74		$2.89	$121.38		$2.80	$117.60
Intoplane- Jet Fuel - IA1, IAA, IAB, IP8	$4.51	$189.42		$4.39	$184.38		$4.26	$178.92
Local Purchase Jet Fuel - NA1, NAA	$5.00	$210.00		$4.88	$204.96		$4.57	$191.94
Local Purchase Ground Fuel - NLS, NMU	$4.15	$174.30		$4.05	$170.10		$3.92	$164.64
Composite Standard Price	**$3.95**	**$165.90**		**$3.85**	**$161.70**		**$3.73**	**$156.66**

APPENDIX E: THE DEPARTMENT OF DEFENSE’S PROJECTED ALTERNATIVE FUEL SUPPLY CHAIN STAGES

The data below gives projected renewable fuel consumption for the Department of Defense. Fuel types included are: biodiesel and renewable and cellulosic diesel.

Table 24. Biodiesel and Renewable and Cellulosic Diesel Forecasts for Supply Chain Stages, 2009–20 (million gallons)

Stage	Type	2009[a]	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Feedstock availability	*FAME and Renewable Diesel*												
	Vegetable oils[b]	750	853	956	1,076	1,123	1,126	1,177	1,271	1,315	1,346	1,372	1,382
	Fats and greases[c]	1,205	1,205	1,205	1,205	1,205	1,205	1,205	1,205	1,205	1,205	1,205	1,205
	Total	1,955	2,058	2,161	2,281	2,328	2,331	2,382	2,476	2,520	2,551	2,577	2,587
	Second-Generation Biodiesel (Cellulosic Diesel)												
Production capacity	Cellulosed	33.0 to 99.4 Billion Gallons											
	FAME Biodiesel												
	Vegetable oils[b]	2,645	3,049	>3049	>3049	>3049	>3049	>3049	>3049	>3049	>3049	>3049	>3049
	Fats and greases[e,f]	45	51	70	88	107	131	144	167	189	211	233	256
Production capacity	Cellulosed	33.0 to 99.4 Billion Gallons											
	FAME Biodiesel												
	Algae[f]	0	0	0	0	0	0	0	10	20	40	60	80
	Total	2,690	3,100	>3,119	>3,137	>3,156	>3,180	>3,193	>3,226	>3,258	>3,300	>3,342	>3,385
	Renewable Biodiesel												
	Fats and greases[f]	0	0	44	89	89	126	167	167	167	167	167	167
	Cellulosic Biodiesel												

Table 24. Continued

Stage	Type	2009[a]	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Production capacity	Cellulose[f]	0	0	0	111	456	789	1,356	1,922	2,489	3,167	3,844	4,756
	Total	2,690	3,100	>3,163	>3,337	>3,700	>4,095	>4,716	>5,305	>5,893	>6,593	>7,293	>8,227
Projected production and retail sales	*FAME Biodiesel*												
	Vegetable oils[b]	434	598	724	846	914	914	956	1,037	1,081	1,107	1,120	1,108
	Fats and greases[b,f]	41	46	63	79	96	118	130	150	170	190	210	230
	Algae[f]	0	0	0	0	0	0	0	10	20	40	60	80
	Total	475	644	787	925	1,010	1,032	1,086	1,197	1,271	1,337	1,390	1,418
	Renewable Biodiesel												
	Fats and greases[f]	0	0	40	80	80	113	150	150	150	150	150	150
	Cellulosic Diesel												
	Cellulose[f]	0	0	0	100	410	710	1,220	1,730	2,240	2,850	3,460	4,280
	Total	475	644	827	1,105	1,500	1850	2,456	3,077	3,661	4,337	5,000	5,848