



# CESEM

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## Algae Growth for Lipid Production

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## 0. EXECUTIVE SUMMARY

This study analyzes the feasibility of using algae cultivated from wastewater effluent to produce a biodiesel feedstock. The goal was to determine if the energy produced was greater than the operational energy consumed without consideration to constructing the system as well as the emissions and economic value associated with the process. Four scenarios were created; 1) high-lipid, dry extraction, 2) high-lipid, wet extraction, 3) low-lipid, dry extraction and, 4) low-lipid, wet extraction. In all cases the system required more energy than it produced. In high lipid scenarios the energy produced is close to the energy consumed and with minor improvements in technology or accounting for coproducts a positive net energy balance may be achieved. In the low lipid scenarios the energy balance is too negative to be considered feasible. Therefore the lipid content affects the decision to implement algae cultivation. The dry extraction and the wet extraction both require some level of mechanical drying and this makes the two methods yield similar results in terms of the energy analysis. Therefore the extraction method does not dramatically affect the decision for implementing algae-based oil production from an energetic standpoint. The economic value of the oil in both high lipid scenarios results in a net profit despite the negative net energy. Emission calculations resulted in avoiding a significant amount of CO<sub>2</sub> for high lipid scenarios but not for the low lipid scenarios. The CO<sub>2</sub> avoided does not account for non-lipid biomass and so this number is an underestimation of the final CO<sub>2</sub> avoided from the end products. While the term CO<sub>2</sub> avoided has been used for this study it should be noted that this CO<sub>2</sub> would be emitted upon use as a fuel source. These emissions, however, are not “new” CO<sub>2</sub> because it has already been emitted and is being captured and recycled. Currently, literature is very divisive on the lipid content present in algae and this study shows that lipid content has a tremendous affect on energy and emissions impacts. The type of algae that can grow in wastewater effluent also should be investigated as well as the conditions that promote high lipid accumulation. The dewatering phase must be improved as it is extremely energy intensive and dominates the operational energy balance. In order to compete, wet extraction must have a much more significant effect on the drying phase and must avoid the use of the human toxicants, methanol and chloroform. Additionally, while the construction phase was beyond the scope of this project it may be a critical aspect in determining the feasibility these systems. Future research in this field should focus on lipid production, optimizing the belt dryer or finding a different method of dewatering, and allocating the coproducts.

## **1.0 INTRODUCTION**

Wastewater effluent is traditionally an end product that is disposed into the environment from municipal wastewater treatment plants. The nutrient content of this effluent is often high enough to sustain the growth of algae, creating the risk of oxygen depletion leading to dramatic disruptions in aquatic ecosystems. Conventional biological treatment does not typically remove enough of these nutrients to prevent environmental damage. There are advanced methods for removing additional nutrients including chemical treatments, aerobic/anaerobic systems, ion exchange and membranes; all of which are costly additions to wastewater treatment plants.

The demand for sustainable biofuel feedstocks has created interest in using the nutrient-rich effluent to serve as a medium for cultivating algae to create products, including lipids, which can be used for producing biofuels. Algae can be used for a number of other valuable goods including biomass for feedstock, biogas and biopolymers such as polyhydroxyalkanoates (Pienkos & Darzins, 2009; Yan et al., 2010). Open ponds have been used to cultivate algae for useful products because algae can grow naturally with few additional inputs. However, to effectively cultivate specific products it may be favorable to use controlled systems such as photobioreactors (PBR's) so specific, selected species can grow unhindered by contamination or competition. Coupling wastewater treatment with algae cultivation may provide a useful solution to developing alternative energy and producing higher quality effluent with less expensive treatment.

### **1.1 Research Statement**

In order to analyze this potential emerging technology we examined the effect of using algae for producing a biofuel feedstock from wastewater effluent. This research focused on using a PBR to cultivate algae. The key areas of interest are the lipid production from the algae and extraction technologies to remove the lipids from the biomass. These variables are debated within the literature but may prove to be pivotal in determining whether systems like these are feasible. The impacts considered in this study were CO<sub>2</sub> emissions, net energy production, and economic value created.

## 1.2 System Boundary

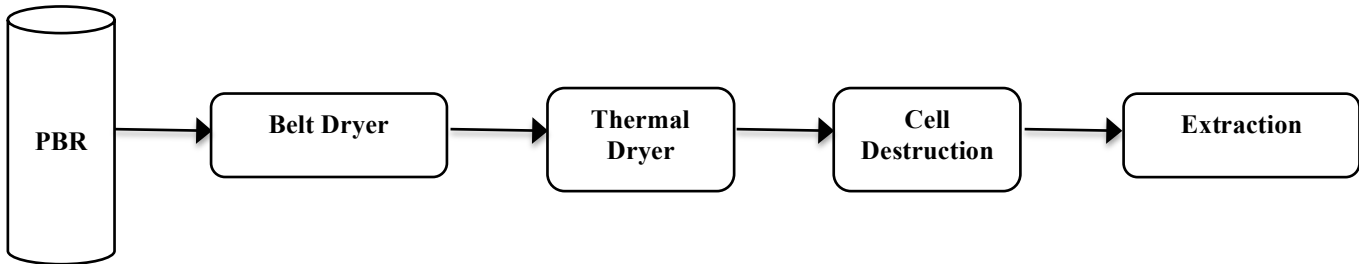
The scope of this LCA will be limited by system boundaries that are defined by the effluent coming from the wastewater treatment plant through to lipid extraction. It includes energy and chemical flows to and from the system. We have assumed that this system exists within the Phoenix metropolitan area. The study did not include the infrastructure for the systems discussed or other energy external to the immediate processes, as all the scenarios would have similar requirements in order to get finer resolution on growing and harvesting the algae. The final product streams that were considered are lipids, secondary effluent from the PBR, as well as the water and chemicals from the extraction phase. Though the benefits from improved wastewater effluent and the biomass, which is coproduced with the lipids, were not included in the data portion of the study, we have included a discussion of these products. This study also does not consider the coproducts resulting from lipid extraction. The selected system boundaries will determine the technical feasibility of using PBRs as an alternative energy production system based on several scenarios evaluating variables that have been debated within the available literature.

## 2.0 METHODOLOGY

Wastewater treatment effluent is often associated with eutrophication of natural ecosystems because the nutrient levels remain high despite treatment, causing algal and bacterial blooms, reducing the available oxygen and killing flora and fauna both locally and downstream when being dumped into waterways. Photosynthetic marine algae has long been a barrier to efficient wastewater systems, but is being reevaluated as a means to further reduce the nutrient levels in wastewater effluent, reducing eutrophication while producing 20-45% (w/w) lipid content. This oil, once separated from the algae, can be substituted for traditional feedstocks in the process to create biodiesel. The goal of this life cycle assessment (LCA) is to evaluate the net energy balance for using wastewater treatment effluent in PBR's to cultivate algae and use the oil content of the algae as a feedstock for biodiesel.

The procedure for growing, harvesting, and processing algae is described in Figure 1. It begins by introducing the wastewater treatment effluent into photo bioreactors, which allows the water to flow through a light rich environment, maximizing algae growth. Once the desired density of algae has been reached, the next task is to separate the water from the algae. This is typically achieved through settling, using flocculation, or mechanical processing, using centrifugation or belt drying. Extraction is achieved by pressing the oil out of the solid biomass

utilizing the same method used in the production of traditional, vegetable-based oils using hexane (Demirbas & Demibras, 2011).



**Figure 2.1**

The system boundaries for this LCA are relatively constrained, enabling the research to determine the feasibility of a new process. This study treats the wastewater effluent, which is currently being returned to the environment, as the primary input. The additional effluents produced by this process, which are not being evaluated, are outputs that are simply improved effluents as compared with the input effluent. The goal of this process is to create biodiesel feedstock to be used in the current production procedures for that fuel so this study is limited to the volume of oil created by this process. The biomass that is left over as a result of the extraction process has many potential uses as a co-product but is not included in the energy balance for this study. These system boundaries were selected to provide a relatively simple view for the production, harvesting, and processing of algae for oil to determine if the primary processes use less energy than can be produced, yielding a positive energy balance.

## **2.1 Required Data**

The data needed for this study are broken up based upon the five different processes that characterize this system. Regarding the PBR, the study is focusing on the initial effluent flows from a wastewater treatment plant, electrical energy inputs, the cost of operation and maintenance, and any added CO<sub>2</sub> for algae growth. Regarding separation, the focus is on the electrical energy inputs, the production and use of chemicals, the cost of operation, and the chemical and water outputs. Regarding extraction, the focus is on the mass of oil produced per unit mass of raw algal biomass produced, electrical energy inputs, the production and use of chemicals, the cost of operation, and the chemical and water outputs. With these data the study will evaluate the processes and determine the feasibility for creating oil by growing algae in wastewater treatment effluent.

## 2.2 Calculations

The study is broken out into four different scenarios to account for two variables with a relatively high degree of uncertainty, the first being the total amount of lipids accumulated within the algae and the second is the type of extraction to be done (Table 2.1).

**Table 2.1**

	<b>High lipid content</b>	<b>Low lipid content</b>
<b>Dry extraction</b>	1) High lipids/Dry	2) Low lipids/Dry
<b>Wet extraction</b>	3) High lipids/Wet	4) Low lipids/Wet

The study evaluates the net energy balance, CO<sub>2</sub> emissions, and cost balances associated with each of the four scenarios. To determine the worth of pursuing this technology, we calculated the net energy, the profit potential and the emission reduction potential as defined by equations 1-3:

$$\text{Net Energy} = \sum \text{Energy Produced} - \sum \text{Energy requirements}$$

**Equation 1**

$$\text{Economic Value} = \$\text{Oil Produce} - (\$ \text{Energy Consumption} + \$ \text{Chemical Use})$$

**Equation 2**

$$\text{Net CO}_2 = \text{kgCO}_2 \text{ avoided (PBR operation)} - \text{kgCO}_2 \text{ (Energy consumption)}$$

**Equation 3**

## 2.3 Data Sources and Assumptions

Regarding the effluent, 25 million gallons per day remains unused for recycling purposes in the phoenix area and this volume is more than sufficient for commercialization of a large scale algae cultivation system (Phoenix, 2012). The makeup of the effluent, including the nutrient content, is also being assumed based upon the typical effluent being returned to the environment (Tchobanoglous et al., 2003). Additionally, it is assumed that chemicals used in separation or extraction can be recovered and that the resulting effluents will not require additional treatment prior to being returned to the environment.

The factors that created the four scenarios discussed in Table 1, extraction method and lipid content, were chosen to evaluate upper and lower limits for variables with significant uncertainty. The lipid content of algae



depends predominantly on the species of algae. When examining the use of wastewater effluent controlling the species may not necessarily be an option and as such two sources (one arguing for, one against) the use of algae as a biofuel have been sighted for lipid content. By looking at a range for biomass growth and lipid production this study can provide results that evaluate different potential yields from a PBR based system and compare them to the energy consumption of the system (Murphy & Allen, 2011; Vijayaraghavan & Hemanathan, 2009)

GREET 1 (Argonne, 2006) was used for much of the data where more recent data was not available. Photobioreactor size and design are based on a study that attempted to determine the optimal size of the photobioreactors and a cycle length of 5 days was selected ((Kunjapur & Eldridge, 2010)). The productivity of the algae in the photobioreactor was selected based on two literature sources ((Lardon et al., 2009; Soratana & Landis, 2011) Initial analysis showed that the productivity had little effect on the photobioreactor at this size (Lardon et al., 2009; Soratana & Landis, 2011). The data for the belt dryer was taken from Lardon (2009). This study indicated that belt dryers were one of the least energy intensive methods of drying and that they were capable of drying algae to 90% solids content. The efficiency of the belt dryer may decrease over its life and this could potentially lead to placing a higher load on the thermal dryer. To determine the effect of the belt dryer efficiency on the energy balance we varied the efficiency from 90% solids content down to 80%. The uptake of nutrients was based on GREET 1, the productivity and the different constituents of the biomass and their respective chemical composition. Energy data and efficiency for the thermal dryer were taken from literature (Xu et al., 2011). Oil extraction involves cell destruction, chemical usage, evaporation of the solvent and the recovery of the oil. Dry extraction was assumed to be industrial standards and chemical requirements were taken from Xu et al. (2011). Other extraction methods were examined but have not yet reached commercial use and in some cases required toxic chemicals including methanol, MTBE, and chloroform (Sheng et al., 2011). Wet extraction data came from Xu et al. (2011).

Regarding the impacts and benefits, the study uses data for the energy mix available in Arizona from the Energy Information Administration (EIA). The CO<sub>2</sub> emission factors of each of the major source comes from Batan et al. (2010). Arizona energy produces 1,099 lbs CO<sub>2</sub>/MWh based on data from the Energy Information Administration. The cost of energy is based on Arizona's energy cost (EIA, 2012). The value of the oil produced is based on current market prices at the time of the study, February, 2012.

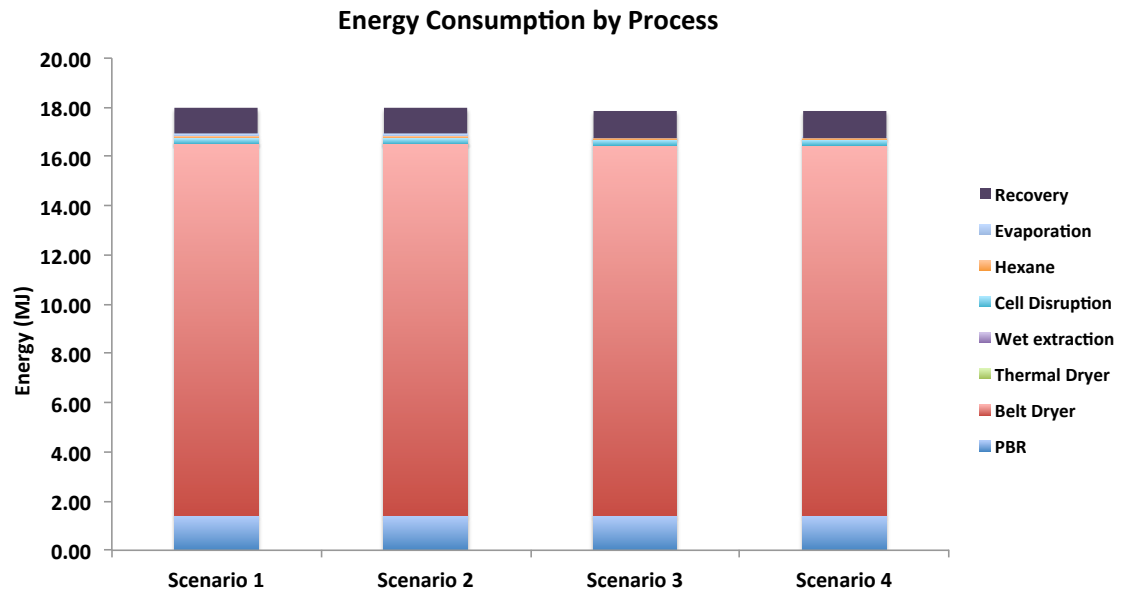
There are a number of technologies for harvesting that are acceptable at lab scale but not full scale. Centrifugation is an energy and cost intensive method that would reduce the NER to below 1 if implemented at full

scale. Lardon et al. (2009) look at the energy aspects of each step of the overall from harvesting to oil transesterification and indicate that belt drying is not as costly or energy intensive as other methods. Murphy however, indicates that belt drying will still require significant energy inputs to achieve the 90% w/w algae content needed for transesterification. As no technology has been seen as the definitive method for separating algae from water, we have selected belt drying as it is less intensive than centrifugation, and less intensive chemically and temporally than settling, which may require the addition of coagulants to aid in the flocculation process.

### **3.0 RESULTS**

The production of algal oil using photobioreactors and wastewater treatment effluent was conducted using four different scenarios. The values calculated in this study are based on the production of 1 kg of dry algae prior to lipid extraction for each scenario, which allows for a reasonable comparison of energy production. The lipid content has been shown to vary based on a number of different conditions including temperature, time of storage, and strain of algae (Chen et al., 2012). Despite the variability of oil production from different algal strains, the lipids should retain the same energy content. The energy content is 37.2 MJ/kg of lipids (Argonne, 2006). The two extraction methods being compared are wet extraction and dry extraction. Dry extraction is the conventional method but is energy intensive and many common lab-scale drying processes are not feasible for full-scale operation based on the energy input required as compared to the energy gained from producing algae. Wet extraction as an alternative to dry extraction should eliminate the most energy intensive step, however, it suffers for two reasons; wet extraction still requires a significant amount of drying for removing the majority of the water and the most effective wet extraction chemicals are chloroform and methanol (Sheng et al., 2011). Figure 3.1 shows the energy input for the four different scenarios. In all four cases the first drying stage, which cannot be avoided, dominates the energy balance (84% of the total energy in all four cases). The next most intensive processes are the recovery (3%) and operation of the photobioreactor (8%). Of these two processes the photobioreactor is more important because of the variability present in algae cultivation; cultivation can be done using photobioreactors or open ponds, carbon and nutrient sources can also be synthetic or natural and depending on which is used will significantly affect the energy and emissions

balances. Research has already shown that the drying process is the most energy intensive step; this analysis shows that the initial drying process, specifically, is the most significant step. The data on energy requirements to operate a belt dryer came from Lardon et al. (2009). Decreases in the belt dryer efficiency would increase the load on the thermal dryer, which requires much more energy per kg of water dried.



**Figure 3.1**

At 80% solids content from the belt dryer, the thermal dryer energy still contributes a negligible amount of energy to the overall energy analysis. The belt dryer is not only responsible for removing the water contained within the algae but also the water in which the algae grows. To determine how much water would have to enter the thermal dryer to make a significant difference, a goal seek analysis using Microsoft Excel shows that to increase the total input energy by 1 MJ/kg the input volume would have to be 4.83 L of water into the thermal dryer. This shows that research into lowering the required energy for the initial drying step is more critical than eliminating the energy use at the thermal dryer.

In all four scenarios, the use of the belt dryer dominates the input energy, but much more variability is present in the energy production as well as the emissions and economic analyses. Figures 3.2, 3.3 and 3.4 show the overall energy, emission and economic analysis for each scenario respectively.

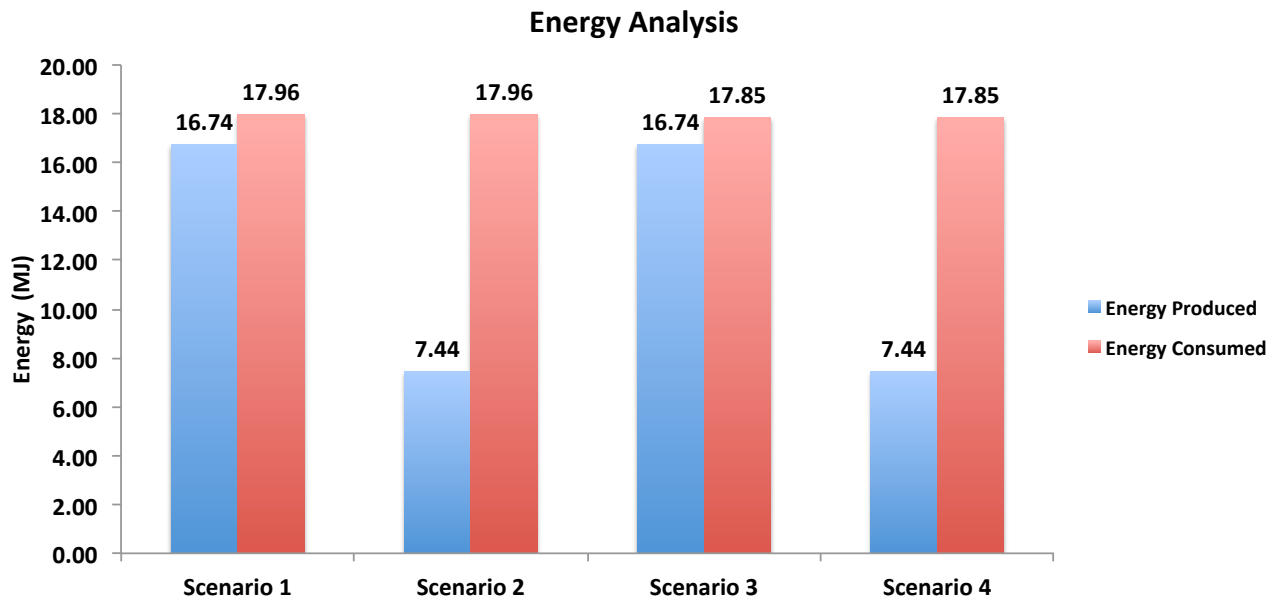


Figure 3.2

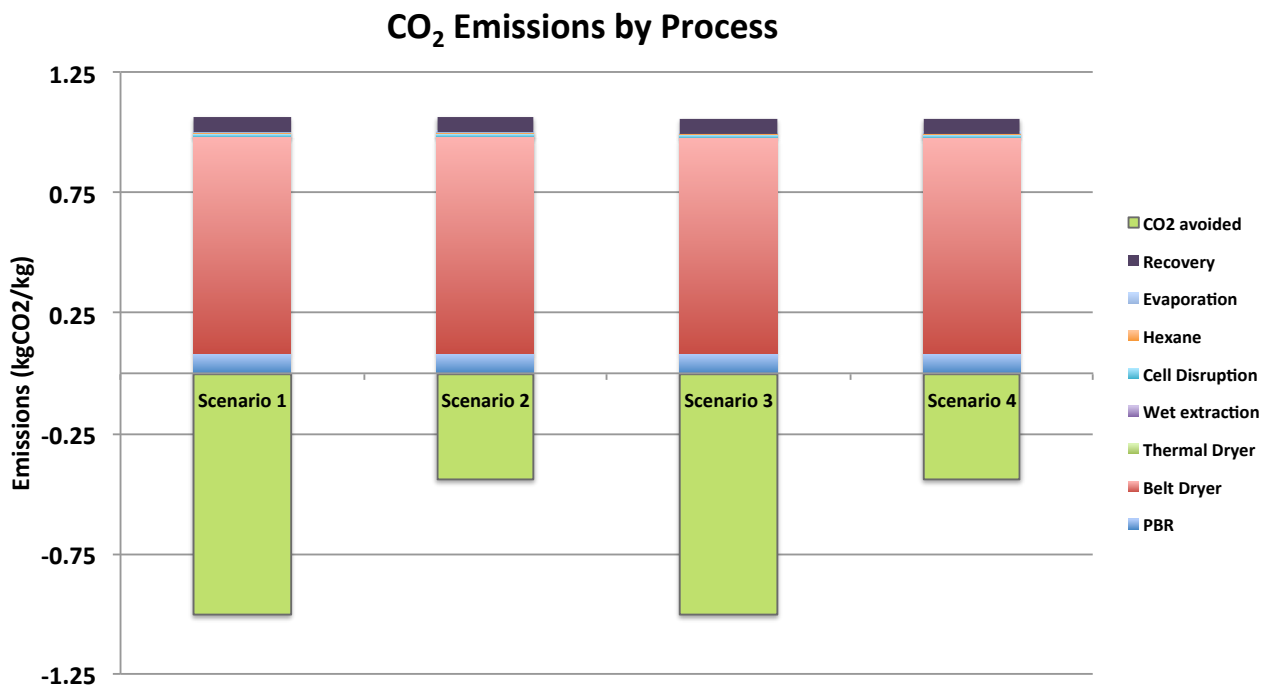
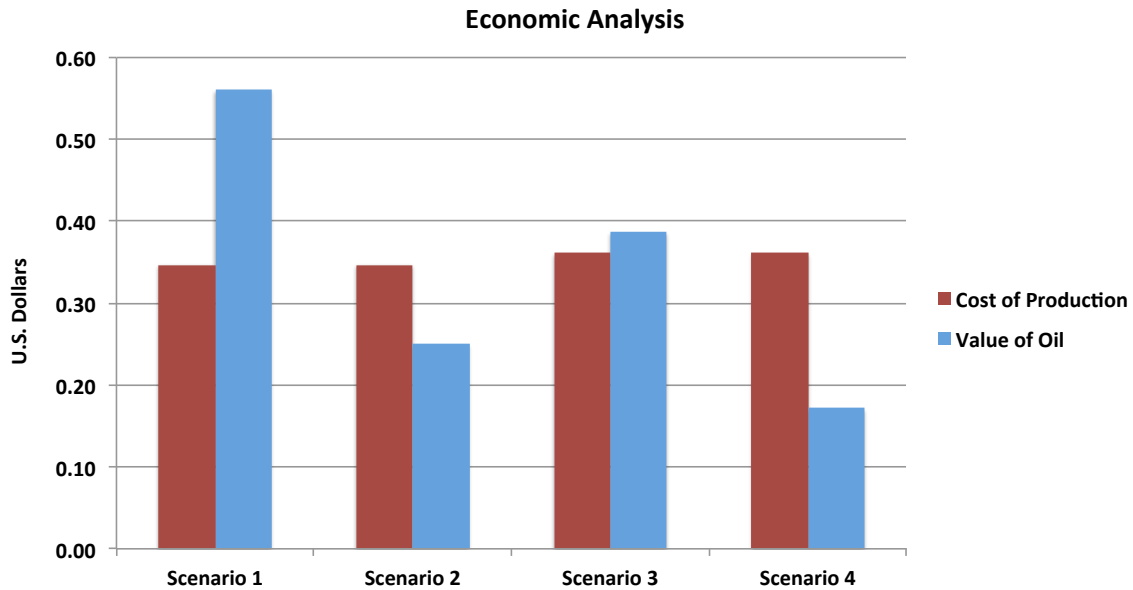


Figure 3.3



**Figure 3.4**

Scenario 1, characterized by 45% lipid content for the algae and the dry extraction process, resulted in the production of 16.74 MJ of energy embedded within the oil. This is less than 17.96 MJ/kg, which is the energy required in the production and extraction of the lipids. The cost to supply the energy for Scenario 1 is 29.34 cents/kg, while the economic value of the oil is 56 cents resulting in a net value of 27 cents per kilogram of biomass produced. The CO<sub>2</sub> emissions that result from the process, 1.07kg, are greater than the CO<sub>2</sub> that is offset by the production of algal oil for fuel, 1.00kg, resulting in a net increase in CO<sub>2</sub> of 0.07kg.

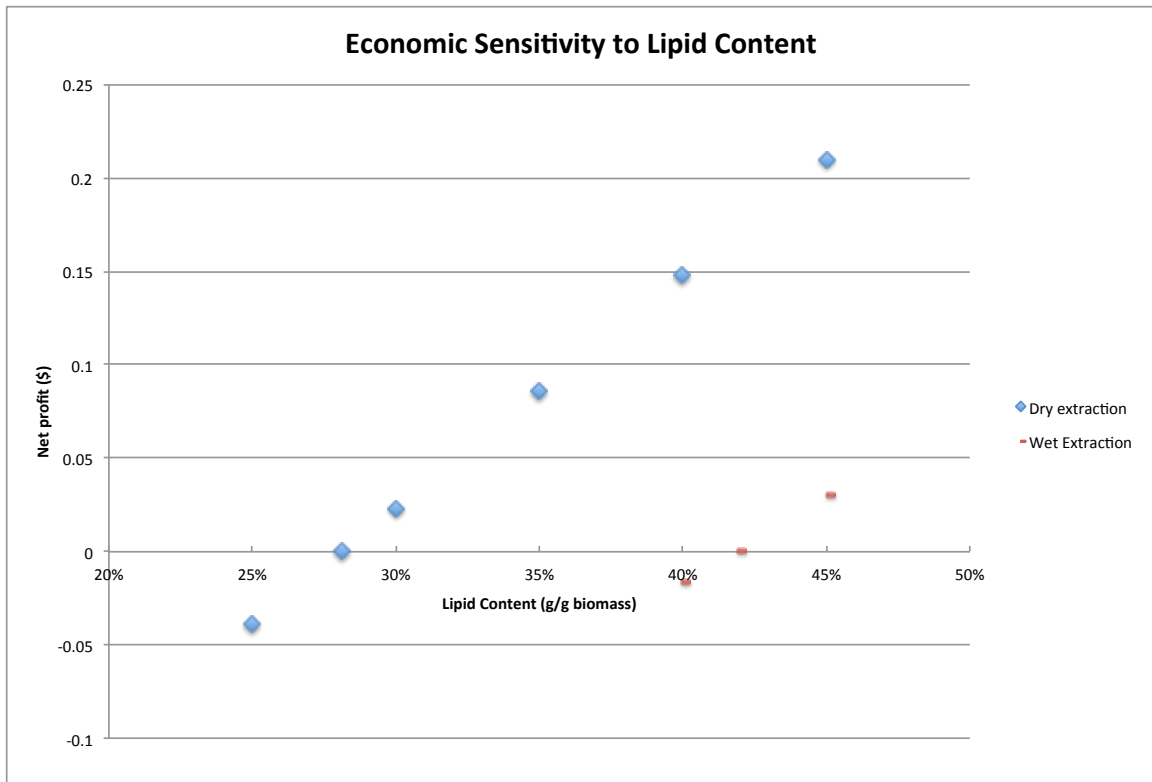
Scenario 2, characterized by 20% lipid content for the algae and the dry extraction process, resulted in the production of 7.44 MJ of energy embedded within the oil. This is less than 17.96 MJ, the energy required in the production and extraction of the lipids. The cost to supply the energy for Scenario 2 is 29.34 cents, while the economic value of the oil is 25 cents resulting in a loss of 4 cents per kilogram of biomass produced. The CO<sub>2</sub> emissions that result from the process, 1.07 kg, are greater than the CO<sub>2</sub> that is offset by the production of algal oil for fuel, 0.44 kg, resulting in a net increase in CO<sub>2</sub> of 0.63 kg.

Scenario 3, characterized by 45% lipid content for the algae and the wet extraction process, resulted in the production of 6.30 MJ of energy embedded within the oil. This is less than 17.85 MJ, the energy required in the production and extraction of the lipids. The cost to supply the energy for Scenario 3 is 29.16 cents, while the economic value of the oil is 59 cents resulting in a net value of 30 cents per kilogram of biomass produced. The CO<sub>2</sub> emissions that result from the process, 1.06kg, are greater than the CO<sub>2</sub> that is offset by the production of algal oil for fuel, 0.37kg, resulting in a net increase in CO<sub>2</sub> of 0.70 kg.

Scenario 4, characterized by 20% lipid content for the algae and the wet extraction process, resulted in the production of 2.80 MJ of energy embedded within the oil. This is less than 17.85 MJ, the energy required in the production and extraction of the lipids. The cost to supply the energy for Scenario 4 is 29.16 cents, while the economic value of the oil is 26 cents resulting in a loss of 3 cents per kilogram of biomass produced. The CO<sub>2</sub> emissions that result from the process, 1.06kg, are greater than the CO<sub>2</sub> that is offset by the production of algal oil for fuel, 0.17kg, resulting in a net increase in CO<sub>2</sub> of 0.90kg.

These scenarios do not take into account the potential energy production or the economic values from the coproducts that can be derived from the biomass remaining after lipid extraction using the dry process. Additionally, the value of the oil derived from wet extraction is uncertain, as the oil has reduced energy content.

All four scenarios show a negative energy balance but in the two high lipid scenarios it is close to breaking even energetically and results in a net profit economically. The sensitivity of the economic analysis for each type of extraction in relation to the lipid content shows the break-even lipid content from an economic standpoint. Figure 3.5 shows the sensitivity of the economic benefit of oil production as a function of the lipid content.



**Figure 3.5**

It has already been shown that both types of extraction can result in a net negative energy of algal oil. In the case of the wet extraction the break-even point is 42%, much closer to the most optimistic values of lipid content of algae. For the dry extraction the break-even point occurs at 29% showing that this method is still valuable even if the lipid content is not as high as the lipid content provided in scenario one. However, as the lipid content decreases the net energy decreases further. The economic analysis shows the potential to generate a net profit for algal cultivation but two scenarios indicate that more resources will be consumed than will be offset and more emissions will be produced as a result. The largest contributor in all cases is the initial drying technology. The drying phase going from the algae paste to powder for extraction has been shown to be of little significance in this analysis and that is the step that is replaced by wet extraction. While wet extraction initially seems promising, the use of chemicals that are hazardous to human health make it a less than ideal replacement for thermal drying in any form of commercialization. Cultivation of high lipid content algae for the production of oil is a

promising technology, but improvements in drying technology or in wet extraction are needed. The net energy of algae production has also been shown to be very close to one for high lipid content and much closer to 0.5 for low lipid content. To better understand the viability of algal oil production it is necessary to know what the lipid content of algae can be on an industrial scale.

#### **4.0 CONCLUSION**

In this study we found that algae produced from wastewater effluent may produce enough lipids to be economically viable even if it does not create a net positive energy balance. Our scenarios, which focused on the lipid production rates of algae and two possible extraction methods, demonstrated the significance of lipid content within the algae and an extraction process that is dominated by the need to remove water from the biomass. Carbon dioxide emissions were based entirely on energy use in this study and, thus, were also very closely tied to the energy used for drying the biomass. The CO<sub>2</sub> avoided by the creation of biofuels from this feedstock was, in the case of high lipid content, slightly less than the emissions created during production, resulting in close to net zero CO<sub>2</sub> emissions. We chose to only include the carbon that was directly offset by the use of the lipids as fuel but there is additional carbon embedded within the biomass as well.

Even though all four scenarios were net energy losers, there are several potential benefits that were not accounted for in the LCA. The co-product from the dry extraction process is the algal biomass. This biomass has a number of potential uses that include, but are not limited to, ethanol production, fertilizer, animal feed, and combustion (Pienkos & Darzins, 2009). The ability to use this additional material adds value to the process and would reduce the share of emissions and energy allocated to lipid production if they were included in future assessments. The wet extraction does not result in the same coproducts as dry extraction (Xu et al., 2011) and also cannot be used for applications such as feedstock for animals resulting in lower oil values in the market, which suggests the dry extraction method may be more advantageous. Additionally, all the scenarios would result in reduced nitrogen in the wastewater effluent, which will reduce the potential environmental harm caused by eutrophication. In instances of elevated nitrogen levels, an algae production system may provide a solution for environmental



compliance that has the potential to pay for itself while avoiding costly fines. Future research into algae production systems should evaluate the benefits of coproducts and the reduced environmental impacts that result from different environmental flows.

The economic feasibility of algae based lipid production depends largely on complicated global energy markets. The commodity prices for vegetable oil, which is correlated to diesel prices (Commodity Prices, 2012), determines the gross profit for these systems while the energy used by the system in our study is coming from the electrical grid. If either of these markets shift independently there could be dramatic changes in the net profit that can be obtained by producing biofuel feedstocks from algae. Additionally, with changes in the energy mix, the energy costs and CO<sub>2</sub> emissions would also change. The energy mix would be affected by changing the region where the algae is being produced or future changes in local energy production. All of these factors have deep underlying impacts for a fuel production system and can change day by day, making it very difficult to definitively state whether a given technology will be able to compete in future energy markets.

The emphasis of lipid production must be on energy efficiency throughout the process, particularly during the drying phase. The possibility of co-locating photobioreactors with industries that create CO<sub>2</sub> emissions and waste heat may provide significant benefits for the cultivation and processing of algae to create lipids and deserves further inquiry. This study assumed the use of photobioreactors, but the potential of using an open pond system may have significant benefits particularly when analyzing operation, maintenance, and construction costs for the algae production systems. The type of system and its relationship to other industries may have profound impacts on the life cycle of algae production, adding another layer of complexity when trying to determine the feasibility of algae based fuels.

The lipid content in algae varies tremendously depending on multiple conditions. Chen et. al. (2012) showed that lipid content varied by storage temperature and storage time and also included a list of the different classes of fatty acids that may be found in algae that are not necessarily useful for biodiesel production. Krohn et. al. (2011) showed that depending on the species of algae introducing environmental stresses such as nutrient limitations could increase the lipid accumulation of algae but this is not universally true and the type of lipids that

are accumulated is not clear. Furthermore the amount of total biomass that is produced decreases under these conditions. With the significant differences in the energy, economic and emissions analyses depending on lipids, it is necessary to be more certain of the lipid content to determine if algae should be used for a biofuel feedstock.

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