Spring 5-20-2016

Potential for biofuel production from algae based wastewater treatment in California: Can algal biofuels be cost-competitive with traditional petroleum based diesel?

Amanda Rupiper
Master's Student, amanda.rupiper@gmail.com

This Master's Project

Potential for biofuel production from algae based wastewater treatment in California: Can algal biofuels be cost-competitive with traditional petroleum based diesel?

by

Amanda Rupiper

is submitted in partial fulfillment of the requirements

for the degree of:

Master of Science

in

Environmental Management

at the

University of San Francisco

Submitted: Received:

....……….. ....…………

Amanda Rupiper 5/15/2016 Maggie Winslow, Ph.D. Date

Abstract:

Neither the use of algae to clean wastewater, nor the use of photosynthetic organisms to generate biodiesel, are new concepts on their own. By combining these two processes, algal-based wastewater treatment with algal biofuel production, additional benefits can be derived, among which could be a cost-savings. In California the average estimated base production cost per gallon for algal biodiesel is $5.98/gallon. Compared to the adjusted production cost of petroleum-based diesel of $1.53/gallon, biodiesel is not cost-competitive. Coupling wastewater treatment and algal cultivation reduces the net energy use of the two processes separately and, if accounted for, greatly reduces the production cost of algal biodiesel. When adjusting the production costs for some of the many co-benefits of this combined process and fuel, such as wastewater treatment cost offsets and carbon credits, the fuel becomes much more competitive with an average production cost of $0.56/gallon. As this production process develops, technological optimization, particularly improvements in algal lipid content and productivity, will further reduce the cost of algal biodiesel.

Table of Contents

List of Acronyms:

ARB – Air Resources Board

BOD – Biological Oxygen Demand

CO – Carbon Monoxide

COD – Chemical Oxygen Demand

CWA – Clean Water Act

DO – Dissolved Oxygen

EIA – Energy Information Administration

EISA – Energy Independence and Security Act

EPA – Environmental Protection Agency

GHI – Global Horizontal Irradiation

GHG – Greenhouse Gas

HRAP – High Rate Algal Pond

LCFS – Low Carbon Fuel Standard

MGD – Million Gallons Per Day

NPDES – National Pollutant Discharge Elimination System

PBR – Photobioreactor

PM – Particulate Matter

POTW – Publicly Owned Treatment Works

RFS – Renewable Fuel Standard

RPS – Renewables Portfolio Standard

SS – Suspended Solids

TAG - Triacylglycerols

TBEL – Technology Based Effluent Limits

WWT – Wastewater Treatment

Section 1: Introduction

California is an interesting state in terms of environmental challenges largely, because of its sizable population and dense city centers. Substantial numbers of people require vast amounts of energy, use significant amounts of water, and produce considerable amounts of carbon emissions. Alternative water treatment, energy generation, and carbon capture methods may be the answer to many of these challenges in this consumption driven world.

The average person in the United States uses about 100 gallons of water per day, resulting in large volumes of wastewater for a given city (USGS). Wastewater is typically high in nutrients, such as nitrogen and phosphorous, and, if left untreated, the discharge can cause ecological problems, such as toxic algae blooms and hypoxic zones from eutrophication (Arbib et al., 2014). Most developed nations require some treatment of wastewater, however that treatment traditionally requires costly chemical addition and a significant investment in energy (Abdel-Raouf et al., 2012).

California, like most of the world, depends on fossil fuels that contribute to greenhouse gas emissions and climate change, while also constituting a major cost for almost any activity. Much research is being done to lessen our dependence on nonrenewable fuel sources, but major challenges still exist that are preventing complete conversion. The issue of inadequate energy storage for developing energy sources, such as solar, is preventing a full switch to these renewable energy resources. As a result, we continue to rely on liquid fuels, which are easy to transport and store, to meet our needs. An alternative that would be both renewable and allow us to maintain our current pipeline, storage, and automotive infrastructure is biofuels. However, one of the challenges that conventional biofuels, such as from soybeans, face, is the extensive amount of land, energy, and costs required to produce them. In order for biofuels to take hold as primary fuel sources they will have to overcome these challenges and be competitive with current fossil fuel costs. Current biofuel production cannot compete, but perhaps fuel from algae can.

Algae have long been known for their rapid growth and consumption of nutrients and have been used to treat wastewater in many facilities worldwide (Mambo et al., 2014). By harvesting these algae an additional benefit can come in the form of biofuel generation, carbon mitigation, and cost-savings. Algal biodiesel production is a costly and energy intensive process on its own. However, its potential to combine with wastewater treatment may make this fuel production more attractive economically, in addition to its other benefits as a renewable fuel.

Unlike traditional single use energy streams, this coupling of water treatment, carbon capture, biomass production and biofuel synthesis, recycles both nutrients and carbon, lessening the overall ecological impact and waste. Algal biomass cultivation involves the incorporation of nutrients from the water and carbon dioxide from the air. This results in cleaned wastewater and reduced atmospheric carbon levels. The generated biomass can then be used to create biofuels and fertilizer. In a single use energy stream the fuel would be the final valuable product, and the nutrients and energy would be lost. In a closed loop energy system, the products feed back into the production. For example, burned biofuels result in carbon dioxide, which is then reincorporated via algal growth. The nutrients from fertilizer also feed back into the system as nutrients in the municipal wastewater. Since the carbon and nutrients are cycled and the added energy comes from the sun, the system is renewable and carbon neutral (Azadi et al., 2014).

As with any new technology this coupled system faces some challenges. These facilities require new infrastructure, which can be costly and require significant amounts of land. While the process has the potential to yield net energy there are still many inputs required and processing steps involved that contribute to overall production costs (Razzak et al., 2013). In order for this production of biofuel to gain support it not only needs to create a net profit, it also has to be competitive with current fuels. This paper will attempt to determine, given the current and prospective technology, if coupled algal water treatment and biofuel production could be cost-effective, particularly in California where there is great need and opportunity.

To determine if this fuel production method could be cost-competitive, the paper will break down all the different treatment options such as algal species selection, cultivation set-ups, and extraction technologies and determine their appropriateness for Northern California and their impact on cost. From there the paper will estimate the cost of fuel production in California accounting for all the energy and infrastructure inputs associated with each step. The paper will then take this cost estimation and attempt to adjust for co-benefits such as wastewater treatment replacement, renewable subsidies and carbon sequestration credits. This paper will compare the final cost estimate to current fossil fuel costs and ascertain if this method of fuel generation is either cost-effective now or could be in the future given changes in technology, a shift toward renewable fuels, and projected rising fossil fuel costs.

Section 2: Overview of Algae Use in Water Treatment

2.1 Background

Plant and algae use for water treatment is not a novel idea; in fact there are many constructed wetlands in the United States designed to improve the water quality of wastewater. Passing wastewater through constructed wetlands is a popular method for removing contaminants such as nitrogen, phosphorous, and heavy metals. Wetlands utilize plants' and algae's ability to take up and retain contaminants from wastewater. Alga is a term for a large and diverse group of photosynthetic, chlorophyll containing species that can be unicellular (microalgae), such as *Chlorella,* as seen in **Figure 1,** or multicellular (macroalgae), such as giant kelp. For the purposes of this paper discussion will focus on microalgae, the unicellular organisms, and their capacity to treat wastewater and be used as a fuel feedstock. All references to algae from here forward will refer specifically to microalgal organisms.

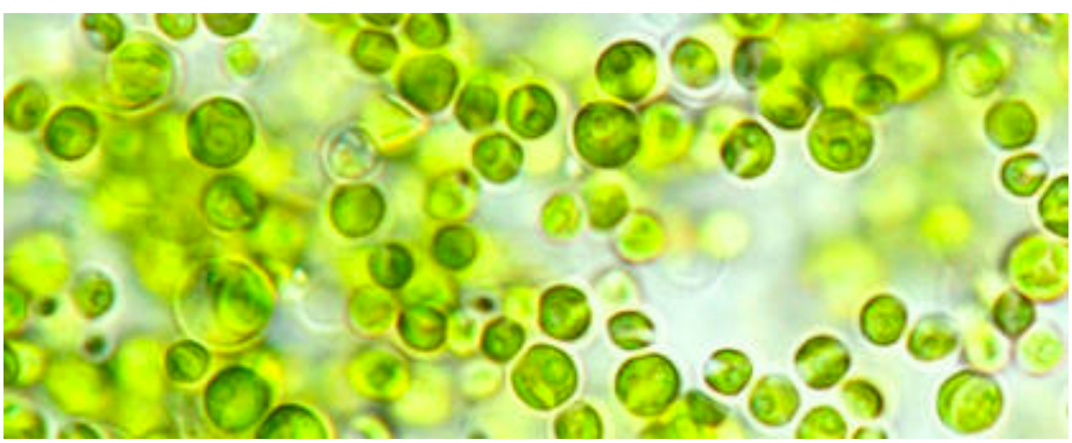

Figure 1. Chlorella Spirulina Algae cells at 400x magnification. (Photo taken from: http://www.nudisa.com)

Algae's growth involves the uptake of nutrients. These nutrients are critical to cellular formation and productivity. Algae get their necessary carbon from the air and nutrients from the water they grow in. As a result algae growth results in reduced carbon dioxide concentrations in the air and reduced nutrient concentrations in the water. The ability for algae to naturally clean wastewater, which is especially high in nutrients, can be easily exploited for modern water treatment.

Conventional wastewater treatment (WWT), not using algae, is designed to remove biochemical oxygen demand (BOD), solids, nutrients (nitrogen and phosphorus containing compounds), and bacteria prior to being discharged to a body of water (Abdel-Raouf et al., 2012). To accomplish this, a series of treatment steps are taken that focus on each contaminant's removal. First is primary treatment, which includes removing coarse solids and sedimentation of any settleable constituents (Henze et al., 2002). Secondary treatment aims to reduce the BOD using biofilms and activated sludge (Henze et al., 2002). Tertiary treatment, often the final stage or not performed, focuses on removal of organics and nutrients, which can be done either biologically or chemically, and can be very costly (Henze et al., 2002). Each step of wastewater treatment adds to the overall expense and, in general, the cost doubles for each step taken past initial primary treatment (Oswald, 1988). This means that full tertiary treatment is usually four times more costly than primary treatment, and is thus skipped by many wastewater facilities (Oswald, 1988). Quaternary treatment, the step following tertiary treatment, designed to remove organics, heavy metals, and soluble minerals, is infrequently performed due to the prohibitive costs (Oswald, 1988). Disinfection is the final treatment step for wastewater before it is released into the natural environment. Current regulations as put forth by the clean water act require that publicly owned treatment works provide at least secondary treatment and that the effluent meets certain water quality criteria for BOD and Suspended Solids (SS) as well as those set in the National Pollutant Discharge Elimination System (NPDES) permit specific to each facility.

The use of algae in place of conventional methods presents an opportunity to meet secondary, tertiary and quaternary treatment goals, while reducing the cost of treating water. Algae have been shown to remove coliform bacteria, large percentages of nitrogen and phosphorous, heavy metals, and reduce chemical oxygen demand (COD) and biological oxygen demand (BOD) (Arbib et al., 2014).

2.2 Algae as a replacement for conventional wastewater treatment.

In order for algae to be a suitable replacement for conventional secondary and tertiary wastewater treatment, it must be able to meet discharge standards and remove the same or more contaminants, while not increasing the cost of treatment.

2.2.1 Current Wastewater Standards

Publicly owned treatment works (POTWs) are required under the Clean Water Act (CWA) to treat wastewater to certain standards prior to release. At a minimum, Technology Based Effluent Limits (TBELs) including BOD, suspended solids, removal capacity, and pH are enforced. The CWA specifically requires that POTWs perform secondary treatment and obtain a permit for discharge via EPA's National Pollutant Discharge Elimination System (NPDES). NPDES permits are different for each discharger depending on the activity and the intended use of the receiving waters. The minimum parameters for a POTW, as laid out in **Table 1**, are set up for 7-day averages and 30-day averages.

Table 1. Technology based effluent limits for publicly owned treatment works as required under the Clean Water Act. (EPA 40 CFR 133.102)

Parameter	7-Day Average	30-Day Average
BOD_5	45 mg/L	30 mg/L
TSS	45 mg/L	30 mg/L
Removal	85% BOD_5 and TSS	
pH	6.0-9.0	

TSS - Total Suspended Solids

2.2.2 Contaminant Removal Capability

Since high nutrient loads from wastewater effluents can cause eutrophication, leading to hypoxic conditions in the receiving water bodies, algal wastewater treatment needs to be effective at removing nutrients prior to release (Abdel-Raouf et al., 2012). Common nutrients of concern found in wastewater are nitrogen in the form of NH_4^+ (ammonia), NO_2^- (nitrite), NO_3^- (nitrate), and phosphorous primarily as PO_4^{3+} (orthophosphate)(Razzak et al., 2012 and Mohammed et al., 2014). Arbib *et al*. (2013) compared, in a lab setting, three species of microalgae in their ability to remove nutrients. For all species and trials, the algae were found to have removed greater than 90% of the nitrogen and 98% of the phosphorous containing species. In all cases this meant outputs that were well below acceptable discharge limits of 10mg/L for total nitrogen and 1mg/L for total phosphorous (Arbib et al. 2013). On a large scale, this removal has been demonstrated in places like South Africa with a pilot algal water treatment plant delivering an effluent with on average 5.3mg/L phosphate, 2.9mg/L ammonium, and 12.4mg/L combined nitrate/nitrite, all of which are levels that meet discharge limits (Mambo et al., 2014).

In the United States, nutrient removal is not specifically regulated by the clean water act; however, the EPA has set forth nutrient goals based on the best available technology of 3.0mg/L for total nitrogen and 0.3mg/L for total phosphorous. For comparison, the Army Corps of Engineers set their nutrient goals as 6.0mg/L for total nitrogen and 1.5mg/L for total phosphorous. Actual nutrient limits vary from system to system, are usually higher than the best available technology goals, and are set by the dischargers individual permits (Strum and Lamer, 2011)

In addition to efficient nutrient removal, algae are successful in reducing the oxygen demand. High BOD effluents can diminish the dissolved oxygen from the waters they are discharged into. Dissolved oxygen (DO) is important to organisms living in these waters, particularly fish, and when DO is reduced beyond a certain level fish cannot survive. For this reason reduction of BOD and COD in wastewater is important prior to discharge (Colak & Kaya, 1988). Banat et al. (1990) found that micro-algal ponds used for municipal wastewater treatment showed an average removal of 65% BOD and 60% COD in facultative ponds and up to 95% BOD and 85% COD in the high rate algal ponds (HRAP). **Table 2** lays out the observed reduction in BOD, COD, and Nitrogen as ammonia and total between raw wastewater and high rate algal ponds (HRAP).

Table 2. Modified from Banat et al., 1990, shows measured values (ppm) for various parameters of wastewater prior to treatment and after HRAP treatment. HRAP treatment consists of 0.45m depth and 5-day residence time.

	Raw Wastewater	Post HRAP	Regulatory Limit
BOD	300-500	13	30**
Ammonia (N)	70	5	***
Total N	76	34	***

***all values in ppm**

**** Based on 30 day average of wastewater sample measurements**

*****Clean water act require through secondary treatment, nutrient removal not specified.**

Disinfection of wastewater is an important aspect of its final treatment and needs to be a part of algal WWT. Banat et al. (1990) found that WWT using algal ponds, both facultative and high rate were able to remove greater than 99% of indicator pathogens. Similarly, Cooke et al. (1978) noted that algae treatment was able to reduce a similar percentage of coliform and Salmonella. **Table 3**, shows the pathogen removal capability observed by Banat et al. (1990) in their study comparing raw sewage bacterial counts to HRAP and conventional treatment methods.

Table 3. Bacterial counts/mL and percentage removal of pathogens given raw wastewater under various treatment types. (Modified from Banat et al., 1990)

	Total Coliforms		**Fecal Coliforms**		**Fecal streptococci**		**Total Bacteria**	
	Bacterial Count/mL	Percentage Removed*	Bacterial Count/mL	Percentage Removed*	Bacterial Count/mL	Percentage Removed*	Bacterial Count/mL	Percentage Removed*
Raw Wastewater	8 x 10^4	0	3 x 10^3	0	1.65 x 10^3	0	10 x 10^5	0
HRAP 1**	35	99.9	6	99.8	10	99.7	7 x 10^2	99.9
HRAP 2**	5	99.9	5	99.9	10	99.4	1.8 x 10^3	99.8
Conventional secondary treatment	6 x 10^2	99.2	5 x 10^2	84.0	1.5 x 10^2	91.0	NM	NM
Conventional tertiary treatment	1	100	none	100	none	100	NM	NM

* Percent removal assuming raw wastewater 100%
** HRAP =0.45m depth and 5 day residence time
NM = not measured

Heavy metals are not often a worry in municipal wastewater; however, industrial and mixed wastewater can have high enough metal levels to be of concern. Typically municipal

WWT does not aim to remove metals, but could if algae were used. Algae are efficient at removing heavy metals from wastewater by accumulating them within their cells during growth (Yee et al., 2004). Trace metals such as Co, Mo, Ca, Mg, Cu, Zn, Cr, Pb, and Se have been found to accumulate in algae since they sequester these metals out of their environment (Yee et al., 2004). Wright and Weber (1991) also found that algae can be effective at removing toxic compounds such as organochlorides and tributyltin tin.

One of the larger challenges with using algae for WWT is that complete removal of the algal biomass can be difficult, leading to effluent with high levels of suspended solids. As part of the Clean Water Act, suspended solids are regulated such that, a 30 day average for a discharger should be at most 30mg/L, see **Table 1**.

2.2.3 Common Algal Treatment Designs

There are several widely accepted ways for setting up an algal wastewater system. Typically the set up depends on the constraints and needs of the water treatment plant. The two most popular constructions are open algal raceway ponds and closed photobioreactors (PBRs). Each has unique benefits and costs that must be weighed by each facility.

2.2.3.1 High Rate Algal Pond

High rate algal ponds (HRAPs) are typically set up as long open raceway ponds. They are shallow, usually between 15-40cm deep, and use a paddlewheel to mix and optimize the algae's biological processes for water treatment and productivity (Craggs et al., 1999). The paddles circulate the wastewater to prevent settling of algal cells while maximizing contact with the water and exposure to the sun (Craggs et al., 1999). Raceway ponds can be made up of single or multiple channels, require sizeable areas of flat land, and can yield algal productivities in the range of 60-100mg dry weight/L d (Tredici et al., 2004). **Figure 2** shows the general construction of an open raceway HRAP.

Figure 2. Basic open raceway high rate algal pond including paddlewheel and central baffle to circulate and mix the wastewater and algae. (Photo taken from: http://articles.extension.org/pages/26600/algae-for-biofuel-production)

This set up uses energy from the sun to treat the wastewater via algal growth, resulting in low energy WWT. In general, open pond algal WWT has a lower operating cost than conventional WWT for large cities (Muga and Mibelcic, 2008). Craggs et al. (2013) estimates that the use of HRAPs for WWT could save 50% of the energy typical mechanical systems use.

Raceway ponds are most limited by their variability in algal productivity due to several factors. Specifically raceways ponds are limited by light access due to settling and depth, water loss to evaporation, carbon dioxide uptake from ambient air since exchange only happens at the surface, temperature fluctuation, and sizable land requirements (Mehrabadi et al, 2014). Addressing some of these limitations can most easily be accomplished by adding a cover and regulating heat or injecting carbon dioxide. Adding a cover adds to capital costs of the system and required maintenance and can be impractical given their size and added expense (Razzak et al., 2013).

2.2.3.2 Photobioreactors

Photobioreactors (PBRs) come in all shapes, sizes, and designs, but generally are closed systems in which algae grow. The most common type is the tubular PBR that is made up of clear tubes of either glass or PVC with diameters ranging from 24cm to 24mm, in which algae are circulated (Abdel-Raouf et al., 2012). To these tubes carbon dioxide can be added, while oxygen is removed. Temperature can be highly regulated to maximize productivity, and the thinness of the tubes along with the circulation allows maximization of light exposure. **Figure 3** shows the most popular PBR design of horizontal tubes through which the wastewater is moved.

These systems require a good deal of infrastructure and as such can be expensive. However, PBRs offer greater control of parameters such as temperature, gases, light, and selection of algal strains without contamination (Pruvost et al., 2015). The productivity of these systems can vary greatly depending on the designs and parameters controlled for.

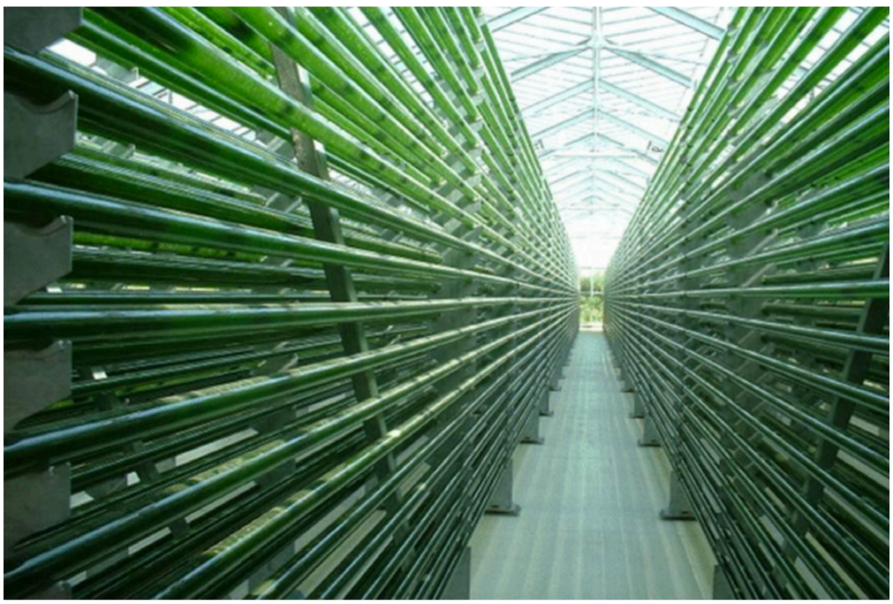

Figure3. Tubular photobioreactor set up in a horizontal design pattern within a greenhouse type outer enclosure. (Photo taken from: http://www.et.byu.edu)

2.3 Benefits of algal water treatment over conventional methods

Current conventional chemical and physical treatment methods do not significantly remove nitrate and are often more costly than biological tertiary treatment methods (Abdel-Raouf et al., 2012). While constructed wetlands have been a popular alternative to conventional treatment, microalgae are preferred over plants for nutrient removal because of their increased efficiency and rate of nutrient uptake. Microalgae are approximately 10% nitrogen and phosphorous by weight, which is several times greater than that of plants (Razzak et al., 2012).

Algae WWT offers several benefits that conventional WWT does not. Algal WWT removes many contaminants such as nitrogen and phosphorous at the same time instead of requiring multiple treatment stages. Upon finishing treatment the treated effluent has not only been stripped of its BOD/COD, but it has also been oxygenated from the algal photosynthesis (Arbib et al., 2014). Algal WWT converts nutrients in the water into valuable biomass instead of waste. This generated biomass can then be used for nutritive supplements, animal feed, cosmetics, pharmaceutical applications, and biofuels (Pruvost et al., 2015). An additional benefit that algal WWT has that conventional treatment does not, is carbon dioxide mitigation. Algae's growth rate is much greater than land plants and can convert carbon dioxide 10-50 times more efficiently, making them a large carbon sink (Li et al., 2008).

Another benefit of replacing traditional WWT with algae is the energy savings. Goldstein and Smith (2002) estimated the energy inputs at each stage in conventional WWT. They found for secondary treatment alone, 192.32J/L were required for thickening of solids, 161.69J/L for heat in the digester, 48.32J/L for pumping solids to digester, 43.47J/L for dewatering of sludge, and 2.38J/L for gravity thickening. In total this comes to 448.18J/L (1696MJ/10^6gal) of treated wastewater for secondary treatment alone. By utilizing algae instead and combining two processes into one, most of the energy for treatment can be saved, which amounts to not only an energy and cost savings, but also a green house gas savings from not consuming as much energy.

In summary, algal WWT can yield water that meets current water quality standards, and in some aspects exceeds them by removing contaminants that are traditionally not treated for. It generates biomass that can be sold instead of creating sludge waste. It saves on energy costs and inputs by replacing conventional WWT practices. Lastly, the process sequesters carbon as the algae take up carbon dioxide to grow.

Section 3: Overview of algae as biofuel

Biofuels are renewable fuels created from animal fats or plant oils. They are cleaner than petroleum based diesel, non-toxic, and biodegradable (EPA). Biodiesel can be used in place of or mixed with traditional diesel with little to no modification required (EPA). The U.S. Energy

Information Administration (EIA), in their monthly biodiesel production report, estimated that in November 2015 the U.S. produced 106 million gallons of biodiesel. Currently, California has six producers of biodiesel that combined generate 63 million gallons per year (EIA).

Oswald and Golueke first proposed algae as a feedstock for biofuel generation in 1960 (Oswald & Golueke, 1960). In the past decade algae have gotten more attention as an alternative to traditional biofuel feed-crops since it can produce more fuel per acre, has a high productivity rate, and does not require profitable farmland.

3.1 How biofuel is generated from algae

In general, biofuel is derived from algae following a four-step process: cultivation, harvesting, extraction, and processing (Scott et al., 2014). **Figure 4** lays out the order of these processes and outlines the general inputs required at each step as well as the outputs and byproducts.

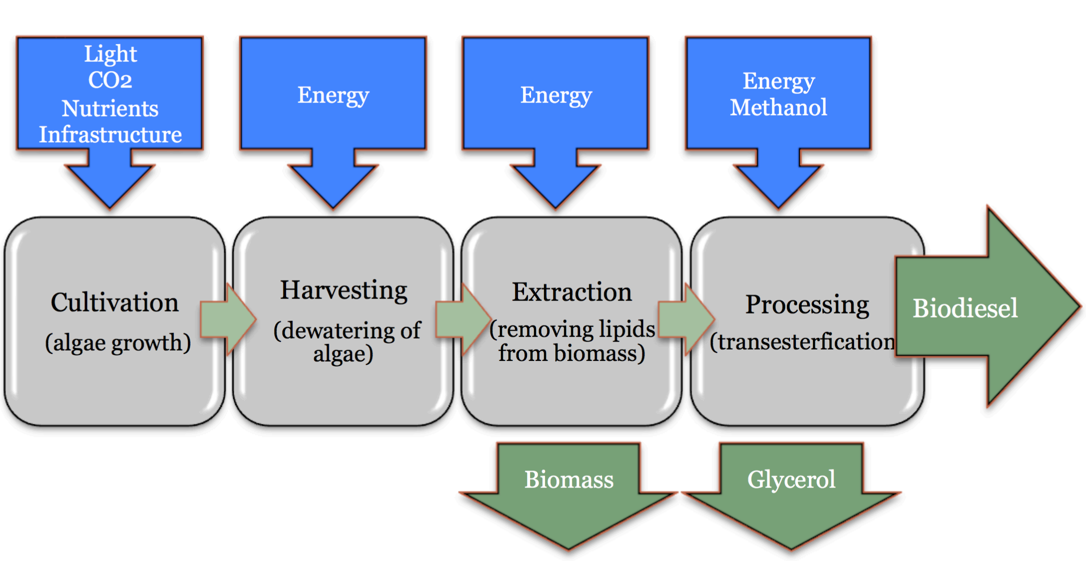

Figure 4. Grey boxes represent the four step process for biofuel generation from algae, including inputs in blue and outputs in green. Figure based on Scott et al., 2010 findings.

3.1.1 Cultivation

The cultivation of algae can be done in various ways depending on algal species selection and the structure used to grow the organisms. In all cases, the algae's cultivation involves exposure to light and access to nutrients and carbon dioxide. Algal growth is impacted by factors such as sun exposure, temperature, and pH (Razzak et al., 2013). Each alga, using the inputs and adjusting for given conditions, creates lipids to store captured energy. Most algae store their energy by synthesizing specific lipids known as Triacylglycerols (TAGs) or triglycerides (Maity et al., 2014). TAGs are made up of a glycerol backbone to which three fatty acids are attached. **Figure 5** shows the structure of a TAG. These TAGs are concentrated stores of chemical energy and are the reason algae make good fuel sources.

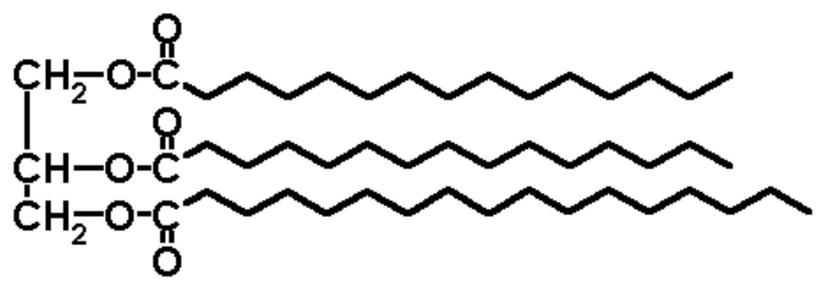

Figure 5. Structure of a triacylglycerol, made up of three fatty acids attached to a glycerol backbone. (Taken from Campbell, G, 2002)

3.1.2 Harvesting

Harvesting of the algae involves dewatering or removal from the treated wastewater and drying. This step can require great amounts of energy and has a great potential for optimization. Currently the most common ways of harvesting algae are via flocculation, filtration, and centrifugation (Razzak et al., 2013). Section 4.3.1 further discusses different harvesting techniques and their energy requirements.

3.1.3 Lipid Extraction

The lipid content of algae can vary between 15-80% depending on the species (Maity et al., 2014). The aim of biofuel production is to convert these lipids into biodiesel, which requires that the lipids be extracted or separated from the rest of the algal biomass. This is yet another step in the fuel generation process that has many options for how it can be done. Section 4.3.2 outlines different processes in more detail.

3.1.4 Processing

Once the lipids are removed from the algae they must undergo a conversion process. This can be done chemically, biochemically, and thermochemically (Mehrabadi et al., 2015). The most common of these is chemical conversion via transesterification, which converts the TAGs into methyl esters, which can be directly used as biodiesel (Chisti et al., 2007). **Figure 6** shows the chemical equation for transesterification. In this reaction triglycerides combined with methanol undergo conversion via a lye catalyst to produce glycerol and biodiesel. Biochemical conversion, a different conversion process, involves fermentation of the carbohydrates to bioethanol and digestion of the biomass to produce biogas. Thermochemical conversion involves using heat to decompose the organic components to liquid or gaseous fuels (Mehrabadi et al., 2015). The selection of which processing step to use depends on characterization of the generated biomass and the desired fuel output.

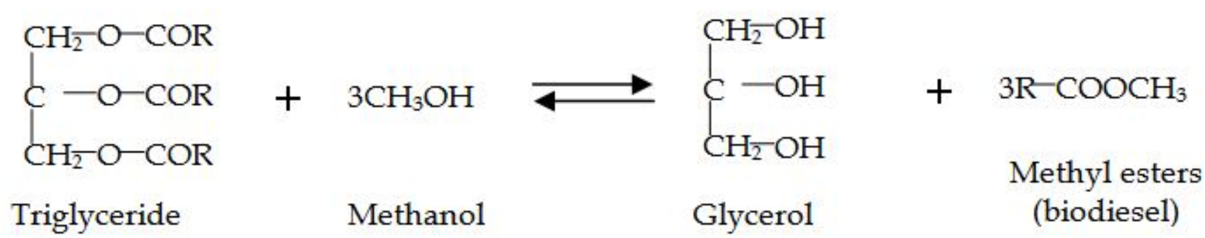

Figure 6. Chemical schematic of transesterification: algal lipids are converted to methyl esters, which can be used as biodiesel via this process. (Taken from Chisti et al., 2007)

3.2 Benefits of biofuel from algae

The use of algae to generate biodiesel has many advantages over traditional fossil fuels, as well as other biofuel feedstocks. Algal biodiesel is a clean carbon neutral fuel and its cultivation takes up large volumes of carbon dioxide. Algae do not require fertile farmland and can be grown on traditionally undesired land. In addition, in comparison to other popular biofuel feedstocks, algae are many times more productive and efficient per area and per kilogram biomass at generating fuel (Li et al., 2008).

3.2.1 Green House Gas Emissions

Azadi et al. (2014) conducted a life cycle analysis, tracking greenhouse gas (GHG) emissions throughout the entire production process of algal biodiesel, accounting for all energy inputs. They found that, assuming moderate values, depending on how the biodiesel is processed that the net GHG emissions per biodiesel energy to be -75.29 CO_2e/MJ, if you account for carbon sequestration in the algal biomass (Azadi et al., 2014 and Batan et al., 2010). Compare this to the average 17.24g CO_2/MJ for conventional petro-diesel (Batan et al., 2010). This is not accounting for the emissions saved by not having to conduct conventional WWT, which would make the difference in GHG emissions greater.

3.2.2 Less emissions than traditional diesel

Biodiesel, either by replacing petro-diesel or by being added as a blend, reduces emissions from combustion (EPA). In the EPA report, A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emission put out in 2002, they measured a reduction in several primary air pollutants when petro-diesel was supplemented or replaced with biodiesel. The specific reductions, as outlined in **table 4**, were a decrease in sulfates, particulate matter (PM) and carbon monoxide (CO). These contaminants were more greatly reduced the higher the percentage of biodiesel used (EPA).

Table 4. Percentage of air contaminant emission from biodiesel fuels, assuming unblended petro-diesel represents 100% emissions (Modified from EPA Report EPA420-P-02-001)

	20% Biodiesel Blend	100% Biodiesel
Sulfates (SOx)	80%	0%
Particulate Matter (PM)	90%	50%
Carbon Monoxide (CO)	90%	50%

*Percentage values represent percentage of emission remaining as compared to 100% petro-diesel

3.2.3 Noncompetitive land use

Since algae do not have roots or require soil for growth, they do not necessitate fertile land that could be used for food production. Currently, all other biological feedstocks require arable land for cultivation leading to a competition between food and fuel. In 2005, when the first renewable fuel standard mandate came out requiring certain levels of fuels to come from renewable sources, the market price of corn was $1.96. By 2011 it rose to $6.01, tripling the 2005 price (CBO, 2010). Since algae can be grown anywhere that has an appropriate climate and some flat land, they do not contend with agriculture or food commodity prices. They could be grown in arid regions, reclaimed land, and poor soils, all areas where growing crops could be challenging.

3.2.4 Compared to other biofuel sources

Among the primary benefits of obtaining fuel from biological sources is that they are renewable unlike fuel mined from the ground. There are many options when it comes to selecting an appropriate feedstock for fuel production and it is important to compare them to determine which yields the best results for the smallest input.

When the average person thinks of biofuels, ethanol from corn is likely the first thing that comes to mind because of its publicity and the governmental push for ethanol blended gasoline. When it comes to biodiesel, currently, the most popular feedstock in the United States is soybeans. Other feedstocks for second-generation fuel production include wheat, barley, corn, potato, and sugarcane. For biodiesel, those feedstocks are rapeseed, sunflower, palm, coconut, animal fats, jatropha, cassava, wood, straw, and grass (California Energy Commission, 2012). These crops require large areas of land for growth, can often only be grown seasonally, and do not have a high rate of production when it comes to fuel generation. Algae can be considered a third generation fuel source because its production rate of biodiesel per area is many times greater than any other biological feedstock (California Energy Commission, 2012). Algae have the capability of producing up to 5,000 gallons of biofuel per acre per year. Palm oil comes in second, at a rate of 500 gallons per acre per year (California Energy Commission, 2012). **Figure 7** shows the productivities of other popular crops used for biodiesel production.

Productivity per land area is important, but the net energy ratio and GHG emissions of each also say a lot about the fuels desirability. The net energy ratio (NER) is a ratio of the energy produced in the form of fuel over the energy consumed to produce it (Luo et al., 2010). A high NER means a high rate of return and a low NER means there is less energy produced per unit consumed. Petroleum-Diesel has been, and is, a popular fuel choice because of its large NER. The fuel is very energy dense and takes relatively little energy to produce and refine it. Renewable fuels, on the other hand, are slightly less energy dense and require large amounts of energy for processing, which lowers their NER. **Table 5** shows the NER's and GHG emissions for petroleum-diesel and popular alternative renewable liquid fuels.

Algal diesel falls in a similar range as other biofuels, if you do not consider coupled WWT, it has an average NER of 0.93 (Luo et al., 2010). Given that algal biodiesel, on its own, has a NER of below one, indicates that it requires more energy to produce than is obtained as a fuel. A net input of energy is neither desirable nor sustainable, which is why the coupling of the two processes, WWT and algal fuel production, is important to make current algal fuel energy-positive. This NER assumes base estimates for algae biodiesel. An increase in the energy rate of return could be achieved given increases in the lipid content of the algae and greater productivity rates. If algal oil content, for example, could be doubled from the base estimate of 25% to 50%, the NER would be 1.56 since little increase in energy input would be required, but twice the energy would be produced (Passell et al., 2013). A NER of 1.56 represents a net energy production and makes this fuel more desirable. Given this, it should be kept in mind that the profitability and desirability of algal fuel depends on improved technology and growth techniques and its ability to replace much of WWT.

Table 5 also compares the GHG emissions per MJ of energy produced and shows that renewable fuels have a net negative emissions rate since their production requires sequestering carbon to form biomass (Batan et al., 2010). Acknowledging the reality of climate change and the importance of reducing carbon emissions, this aspect of biofuels may become ever more important in the future.

The future of biofuels depends on their benefits over petro-diesel. These advantages make algae as a feedstock for biodiesel worth exploring. It is a renewable carbon neutral fuel source that does not compete with food sources for arable land. Its production requires less GHG emissions than diesel production and the emissions it gives off when burned are generally cleaner. It requires quite a bit more energy to produce than petroleum-based diesel, but that will decrease over time. Lastly, its productivity far surpasses that of any other biological feedstocks that are currently looked to for biofuel generation.

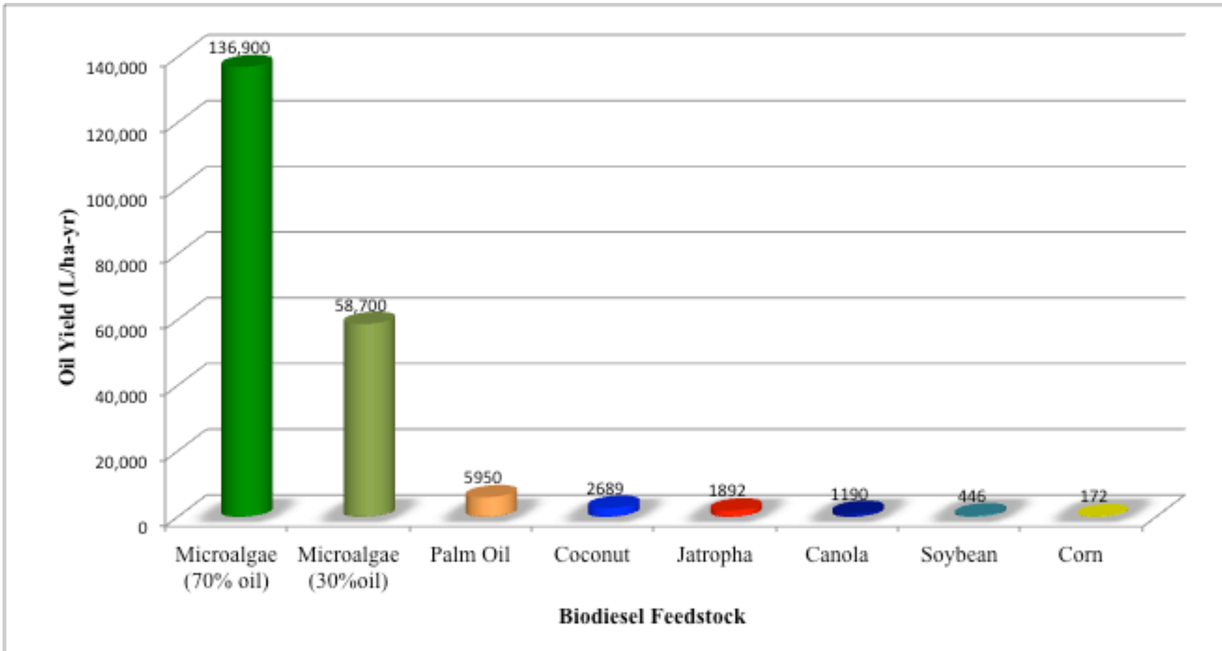

Figure 7. Productivity of various biological feedstocks for biofuel generation measured as L/ha-yr. (Data taken from Chisti et al., 2007)

Table 5. Net Energy Ratio and Greenhouse Gas emissions for several popular alternative fuel types compared to conventional petroleum-based diesel. (Data taken from Batan et al., 2010 and Luo et al., 2010).

Fuel Type	Net Energy Ratio (MJ Produced/MJ Consumed)	Greenhouse Gas Emissions (gC02e/MJ)
Petroleum-Diesel	8-9	17.24
Corn Ethanol	0.20-1.67	12.3-29.8**
Soybean Diesel	0.81-3.67	-71.73**
Algal Diesel	0.93*	-75.29**

* (Luo et al., 2010) In combined WWT/Algal Biofuel case the energy ratio represents energy consumed by biofuel production and does not account for the energy not used to treat wastewater.

**Negative values reflect CO2 sequestered in biomass, sequestration is not reflected in the ethanol GHG value here.

Section 4: Costs and Challenges associated with coupled treatment and generation

In spite of the benefits of algal WWT paired with fuel generation, it has not yet taken off as the new standard for how we treat our wastewater. The main reason for this is that this process has many challenges and costs associated with it that can make it unprofitable for many companies or regions.

4.1 Land footprint

In most cases, starting up an algal wastewater and biofuel production treatment facility requires a parcel of available land. Ideally, this land will be located adjacent to the current water treatment and power generation facility. For obvious reasons WWT plants are located near cities to minimize expensive transportation, resulting in the desired land costing more than if built somewhere more rural.

In addition to specific locations, algal WWT treatment facilities require a good amount of space. Raceway ponds, the most popular cultivation set-up, require about 5x the volume that photobioreactors do to produce equivalent masses of algae (Pruvost et al., 2015). For example, on average it would take a PBR system about $20m^3$ of volume to produce one ton of biomass while it would take $105m^3$ to produce the same biomass in a raceway pond (Pruvost et al., 2015). Photobioreactors also have the benefit of taking on different configurations, meaning they can be built to be stacked high so as to reduce land footprint. In expensive cities it may not be practical to turn a valuable plot of land into a large pond and so PBRs may make sense. The median WWT facility in the United States treats about 3 million gallons of wastewater per day (MGD). If most raceway ponds are about 0.5m deep, then the ponds would need an area of 22710 m^2 or 5.6 acres to hold all of the 3 million gallons. This assumes only one day holding time and that all the water would be treated with algae. In reality, the water would need to be exposed to algae for about 5 days and not all of the water would require such high levels of treatment to meet current standards (Banat et al., 2010). Regardless, ponds require a large land space, which is one of the most prohibitive aspects of algal water treatment. Overall, the cost associated with land use varies greatly depending on the location chosen and therefore its impact on total cost is variable.

4.2 Infrastructure Costs

Depending on whether opting for a PBR or open raceway system also has a large impact on cost. Light cannot penetrate into a dense solution of algal cells for more than a few centimeters, meaning that surface area plays a large role in scaling up infrastructure (Scott et al., 2010). This fact favors PBR systems, in terms of light penetration, over Ponds whose depth can cause shading and whose surface area depends on land space. PBR's also have the benefit in that one can control more factors. PBR systems allow control of contamination, temperature, and light, things that are difficult to do with an open pond system (Scott et al., 2010).

PBR's require less land space, but much more initial infrastructure and maintenance than HRAPs. Davis *et al*. in 2011 estimated, for an un-optimized base case, that in order to achieve a 10% profit, biodiesel from open ponds would have to be sold for $9.84/gal and $20.53/gal for closed PBRs. Davis et al. (2011) assumed a higher productivity and algal density in the PRB system and still the estimated cost was over $10 greater given this method. **Figure 8** breaks down the capital cost into individual components as found by Davis et al. in 2011. The graph shows the infrastructure costs in blue. For PBR systems over three fourths of the capital costs are claimed by the tubular system itself as opposed to the open pond system in which the pond infrastructure commands less than one sixth of the total cost. This not only makes PBR systems more expensive, but also limited in terms of their optimization capacity in the future. Improving harvesting would have a large impact on the cost for fuel from ponds, but at most, only a small impact on PBR fuel production. This presents a steep challenge, and in most cases removes PBRs as an option. In spite of this estimate being a few years old, it gives an idea of how much infrastructure can play a role in final costs.

Infrastructure cost and land use aside there may be other metrics to consider for cultivation decisions. **Table 6** lays out major metrics of concern and compares them for both HRAP and PBR systems. For example, if algal strain selection is of key importance than PBR systems are the most effective. If strain selection is not important, but capital investment cost is, then a pond type system may make the most sense. This further highlights that the choice between the two may depend on the desired outcome and product.

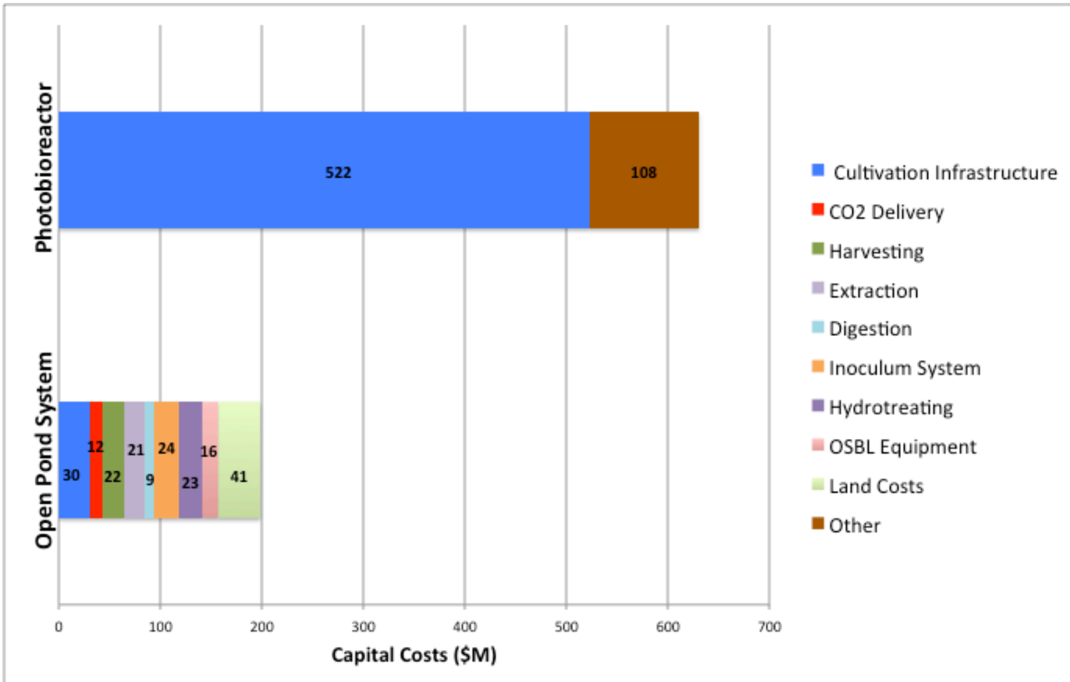

Figure 8. Estimates taken from Davis et al., 2011 study on capital costs by component in million dollars for PBR and open pond systems. The majority of capital costs for PBR system rest in the cultivation infrastructure whereas for Pond systems the costs are more spread out over various components.

Table 6. Comparision of photobioreactors (PBR) and high rate algal ponds (HRAP) using several metrics of interest. (Modified from Davis et al., 2011)

PBR	Metric	HRAP
High	**Capital Cost**	Low
Variable	**Scale-up ability**	Good
No large scale demonstrations	**Technology**	Many large scale ponds in operation
Low (dense culture)	**Post Cultivation Processing Costs**	High (dilute culture)
High (closed system)	**Strain Selection (Purity)**	Low (open to invasives)
Low	**Water Use**	High (evaporation)

4.3 Energy Inputs and Efficiency

The efficiency of the system and the required energy inputs are the challenges that are receiving the most focus and research right now. This is largely because they have one of the biggest effects on overall cost, and because they have the greatest room for optimization. **Figure 9** breaks down the direct electrical input required to generate biodiesel from algae. It takes approximately 19.0 kWh of direct electrical input to produce one gallon of biodiesel (Frank et al., 2011). Of the 19.0 kWh required, 14.3 can be recovered on-site via biogas and biomass burning (Frank et al., 2011). **Figure 9** shows that the largest energy consumers of the process are the dewatering stages and lipid extraction. Production of biodiesel requires 2.6 times the energy required for petroleum diesel production (Frank et al., 2011). In spite of this, the overall energy consumption of biodiesel from algae is 45% that of petro-diesel due to WWT savings (Frank et al., 2011).

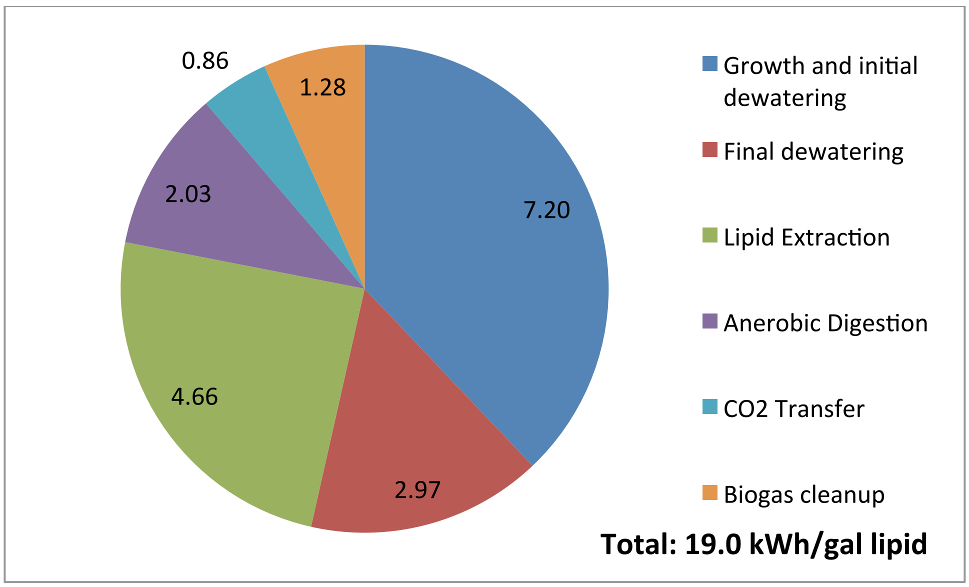

Figure 9. Direct electrical energy consumed at various stages of biodiesel processing from algae in units of kWh/gal of lipid produced. (Data taken and converted from Frank et al., 2011).

4.3.1 Harvesting and Dewatering

Harvesting is one of the most energy intensive steps of biofuel generation from algae. Current practices for doing this include centrifugation, evaporation, filtration, and precipitation via flocculation (Saeid & Chojnacka, 2015). Flocculation and physical precipitation is a relatively low energy process, however, it can only concentrate the algal solution to 10% algae by mass since algae density is similar to that of water and thus hard to separate (Azadi et al., 2014). Centrifugation can increase this to 20% by mass, but that requires an additional energy input (Azadi et al., 2014). For a wet extraction process the precipitate from centrifugation can be used directly and the oil extracted in an organic phase leaving behind the algal biomass and aqueous phase. For the more common dry method the algae need to be further dried. The final dewatering and drying, no matter how it is done, proves to be an energy sink given current technology. Solar drying requires the least energy inputs, but requires valuable time and space and still requires oven drying at the end. Complete oven drying is much faster and space efficient, however, large ovens require large amounts of energy to operate. Sturm and Lamer (2011), calculated the energy inputs required for the most commonly used dewatering methods and found that filtration via belt presses were the least energy intensive, followed by centrifugation and then lastly oven evaporation as the most energy costly. **Figure 10** compares their findings. The figure shows the energy consumption of two thickening methods, gravity sedimentation and dissolved air flotation (DAF) in conjunction with three dewatering methods, belt press, centrifugation, and evaporation. It compares the energy expended in each case to the energy gained from the biofuel produced. Evaporation, the most energy intensive, uses up over half of the energy produced greatly reducing the net energy yield of the entire process.

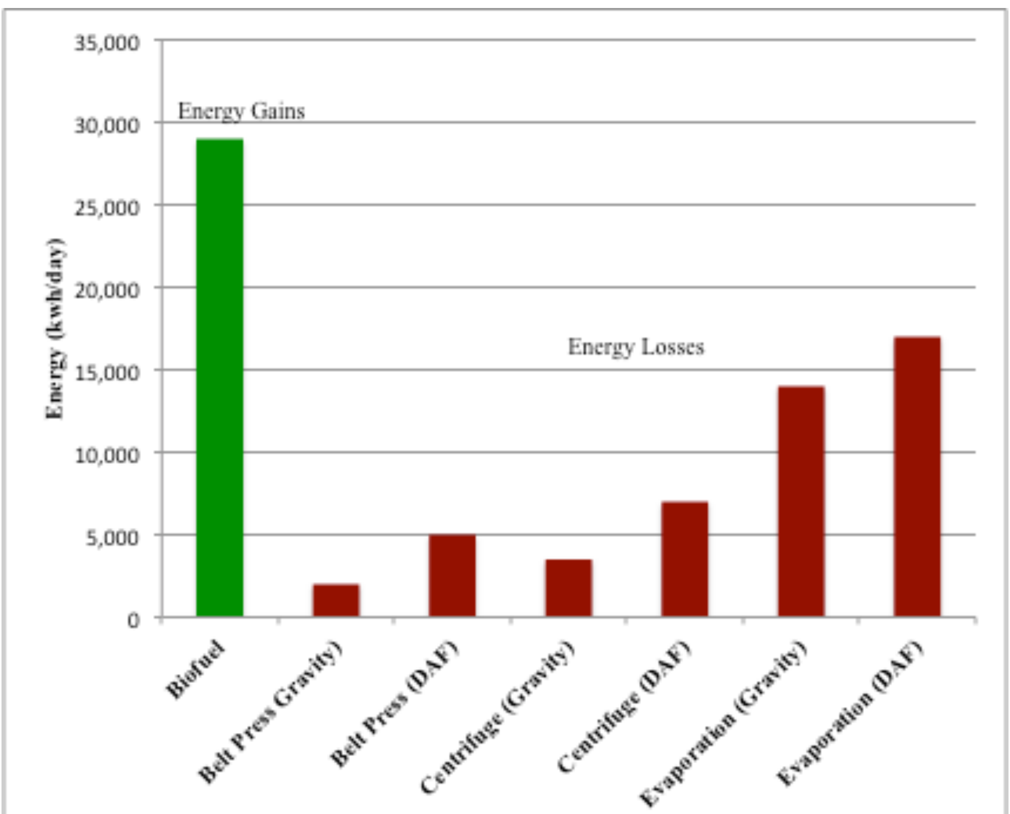

Figure 10. The graph depicts the energy gain from overall biofuel production and losses depending on dewatering methods (modified from Strum and Lamer, 2011)

4.3.2 Lipid Extraction

Another aspect of biofuel production that can affect the efficiency is the lipid extraction from the algal cells. Typical lipid extraction involves two aspects, cell disruption and lipid extraction. There are multiple ways of breaking open the cells, Potter-Elvehjelm homogenization, microwaves, ultrasonication, liquid nitrogen grinding, autoclaving, bead-beating, and 10% NaCl solutions are a few of them (Axelsson and Gentili, 2014, Lee et al., 2010). Axelsson and Gentili (2014) found that none of the investigated cell disruption techniques produced statistically different yields with the exception of microwave and homogenization whose yields were approximately 24% more than the control and popular sonication method for some microalga species. Lee et al. (2010) also found that the microwave method was the most simple and effective method for lipid extraction. Additionally, heating from microwaves cost two thirds less than conventional heating resulting in an energy and cost savings (Drira et al., 2016). This could be utilized more fully in the future, however this is not a popular approach at present and has not been demonstrated on a large scale. Homogenization may also be effective at cell disruption, however it is the most time consuming and energetic process involving manual breaking of the cell well via blenders or other mechanical means. Overall, for the majority of species the cell disruption technique selected did not have an impact on the final lipid yield post extraction as most of the neutral lipids can be extracted across the cell well of the microalgae and only the remaining lipids requiring cell disruption (Lee et al., 2010, Axelsson and Gentili, 2014).

Without treatment or coupled with one of the cell disruption techniques described above the most common extraction method is done via a solvent extraction using a 2:1 or 1:1 by volume chloroform-methanol mixture (Axelsson and Gentili, 2014, Lee et al., 2010). Another extraction method that is emerging is the use of supercritical fluid extraction primarily using CO2. The benefit of this new method is that it results in a crude oil product free of solvents thus minimizing its environmental impact (Drira et al., 2016). More research needs to be done on this front, but the current results make this a promising technique moving forward.

Commercially many different extraction techniques exist and are being developed to meet individual needs. Origin Oil™, a commercial algal oil producer has developed a "Single

Step Oil Extraction" which uses electromagnetism and pH adjustment to rupture cell walls and then let the lipids rise to the surface for skimming (Origin Oil 2009). **Figure 11** shows a schematic of the lipid extraction procedure as an example. The figure shows the algae slurry passing through an electromagnetic field and undergoing a pH adjustment to promote cell well rupture. Post extraction the top layer is sent for settling in a gravity clarifier where the lipid layer is allowed to rise to the top for collection while the water can be recycled and the biomass can be collected (Origin Oil™, 2009).

As this can be an energetically demanding process, the selection and optimization of lipid extraction could have a significant impact on cost per gallon of biodiesel. While many different processes exist the data on energy and cost impact to the overall process is lacking. However, this information should be considered as much as possible when conducting a final production cost calculation.

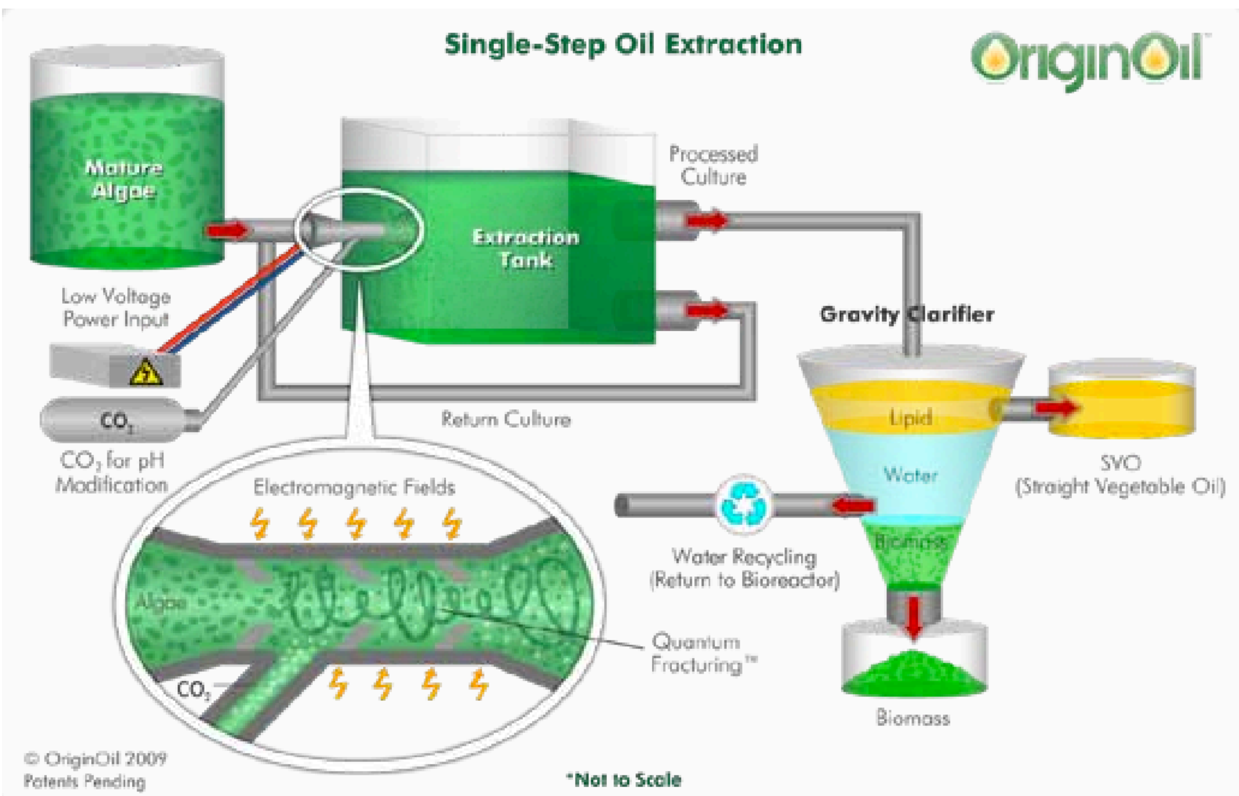

Figure 11. Origin Oil (TM) single step oil extraction procedure using electromagnetic fields and pH adjustment for cell disruption while using gravity clarifiers to separate the phases, oil, water, and biomass (Taken from Origin Oil (TM), 2009).

4.4 Species Selection

It is estimated that there are about 300,000 species of algae leading to many options when selecting which to use for WWT and biofuel generation. Ideally the strain chosen would have a high productivity, high lipid content, and ability to grow under varying conditions. Common algal groups used for biofuel production include several species of Green Algae and Diatoms. These are chosen because of their oil production capability. **Table 7** shows the lipid productivity and content found in several species of microalgae. Most algae in this table are of the green algae type. For the Chlorella and Nannochloropsis Genera there are several commonly used species whose range can vary greatly (Scott et al., 2010). These species have been identified as a result of different screening programs and initial studies in the 1980's with the Government sponsored Aquatic Species Program that pioneered much of this field of biofuels.

Table 6. Popular algal species for biofuel generation by lipid content and productivity (Adapted from Maity et al., 2014 and Scott et al., 2010).

Species	Type	Lipid Content (% of dry wt.)	Lipid Productivity (mg/L/day)
Botryococcus braunii	Green	25.0-75.0	_
Chlorella (various)	Green	11.0-58.0	10.3-1214
Danaliella salina	Green	16.0-44.0	46
Nannochloropsis (various)	Green	12.0-68.0	30.0-142
Phaeodactylum tricornutum	Diatoms	18.0-75.0	44.8
Thalassiorsire pseudonana	Diatoms	20.6	17.4

4.5 Carbon Dioxide Acquisition

Algal biomass depends on the uptake of carbon dioxide (CO2). When CO2 is limited productivity decreases which results in less WWT and lipid production capability (Park and Craggs, 2011). To obtain maximum WWT and lipid generation the addition of CO2 is critical. The CO2 can come from biogas produced on site by digestion of wastewater solids or from flue gas from combustion of that same biogas. According to Park and Craggs (2011), algal biomass productivity in HRAP for WWT increased by 30% when CO2 was applied. Typical C:N ratios in wastewater are 2.4-4:1, adding CO2 to bring that ratio to 6:1 increases productivity since it more closely resembles the composition of biomass (Park et al., 2013). CO2 addition has also been shown to increase fatty acid production. An increase of CO_2 from 2% to 12% resulted in an increased algal energy content of greater than 30% (Muradyan et al., 2004)

If biogas is not generated on site it can also be purchased and brought in, which adds a large expense to the overall operating costs. Slade and Bauen (2013) estimated the cost impact of purchasing CO_2 as being over 50% of the total cost per gallon for HRAP systems. This furthers the idea that in order for algal biofuel production from wastewater in HRAPs to be cost-effective they need to either be located next to a power generation facility from which to get inexpensive CO_2 or they need to generate their own power on-site using biogas and recycle their CO_2 byproduct into the algae.

Section 5: Feasibility in Northern California

5.1 Land Use and Location

Building large raceway ponds or PBR facilities take up space. In California's bay area where population is dense and a lot of wastewater is generated, algal water treatment has a lot of potential, but land costs and space issues prohibit this type of water treatment and biofuel production from being successful. Currently, NASA's OMEGA project (Offshore Membrane Enclosures for Growing Algae) is looking at implementing an algal based water treatment/fuel production set up using a floating bag system, essentially a membrane PBR, within the bay itself (Trent, J., 2012). The program sees the great potential that the area has, but needed a way to sidestep the issue of a large footprint so they moved off land entirely. The project is undergoing feasibility studies now.

Inland northern California does not have quite the same issue with land space as the Bay Area, but space can still be costly and the goal of any water treatment facility is to stay as small as possible. To be successful the coupled treatment plant would need to be located near a significantly sized city with a population of 200,000-800,000 and ideally located next to a wastewater treatment facility and operating power plant that will allow capitalizing on carbon dioxide emissions (Speranza et al., 2015). Major cities in northern California that may meet these requirements include Sacramento, Stockton, Modesto, and Oakland. All of these cities have a good population density and size.

Given that algal treatment takes up large land areas to treat high volumes of water the possible alternative may be to maintain current treatment infrastructure and divert only a portion of the wastewater received for algal treatment thus lessening the land footprint of the system while still receiving some of the benefits of combined treatment and fuel production. A second alternative may be to increase pond depth, which would decrease productivity, but also land area.

5.2 Infrastructure

Given that algal growth for fuel generation does not necessitate strict purity of algal strains and that wastewater is abundant, there can be less worry about contamination and evaporation. In this examination, cost is the overall issue of importance and it makes sense that for California and for this type of algal cultivation that HRAPs are the most appropriate cultivation set-up. The use of ponds means low infrastructure capital investment as well as low energy inputs for paddlewheel operation. California receives high levels of solar radiation and experiences less extreme temperatures as compared to the rest of the nation. Freezing is not an issue, also making the ponds more feasible. The use of HRAPs over PBRs means greater processing costs as the algal cultures are less dense in HRAPs; however, in most cases the greater processing costs do not outweigh the infrastructure costs of PBR systems (Davis et al., 2011). Assuming HRAPs would be the preferred method of cultivation, from here forward the paper will consider how they would function here in California, specifically considering the impact of climate.

5.3 Climate

Pond systems are exposed to the elements and productivity is largely uncontrolled. Factors that need to be considered when looking at installing this cultivation set-up in California are temperature, evaporation rates, and solar radiation. These considerations are interrelated, and all have an impact on overall productivity of the system.

Nagarajan et al. (2013), found that with California having a global horizontal irradiation (GHI) of 5.25 kWh/m2/day biomass photosynthetic efficiency is 15.4% and 7.5% for biodiesel photosynthetic efficiency. Other irradiation values are shown in **Table 8**, which highlights that greater irradiation does not necessarily result in greater photosynthetic efficiency, due to light saturation's impact on photosynthesis (Nagarajan et al., 2013).

Bouterfasl et al., 2002 examined the impact of both irradiance and temperature on algal growth rates and found that once a certain level of irradiation is met it no longer increases productivity and can even inhibit it. They also examined temperature ranges from 15°C to 35°C and found that as temperature increased so did productivity (Bouterfasl et al. 2002). The growth rate at 35°C was twice that of at 15°C for select algal species (Bouterfasl et al., 2002). Since inland Northern California experiences a range of temperatures this is important to consider. The Sacramento region, for example, experiences an average temperature of 16 °C and has an average range of 10-23°C (US Climate Data, 2016). Other areas may experience higher temperatures, which could impact growth and productivity.

Table 7. Global Horizontal Irradiation (GHI) and Biomass Photosynthetic efficiency for different regions. (Based on Nagarajan et al., 2013)

Region	Avg. GHI (KWh/m2/day)	Biomass Photosynthetic efficiency (%)*
Central Africa, Western South America	6.75	12
North and Central Africa, Mexico	6.25	12.9
Central Australia, Southern North America	5.75	14
India, South Australia, South America, **California**	5.25	15.4
Central North America, Parts of Asia	4.75	17
East Asia, Parts of Central North America	4.25	19

*Efficiency calculation based on 50% lipid, 30g/m2/day biomass productivity, CO2 addition, and GHI data.

5.3 Policy and Laws in California and Nationally

California has adopted several regulations that are advantageous to algal biofuel production. Given these standards and the direction the country and the rest of the world is attempting to head with renewable fuels, the feasibility of algal biofuels becomes more and more likely. Two such standards that are specific to California are the Low Carbon Fuel Standard and Renewable Portfolio standard.

5.3.1 Low Carbon Fuel Standard

California readopted a Low Carbon Fuel Standard (LCFS) Program in 2015, which requires a minimum of 10% reduction in carbon emissions from transportation fuels supplied and sold in California by 2020. California Environmental Protection Agency's Air Resources Board (ARB) explains that the required 10% reduction is measured in terms of carbon intensities, which are calculated as the totaled greenhouse gas emissions from each stage of the fuel cycle divided by the energy content of the fuel. It is expressed as grams of carbon dioxide equivalent per megajoule of energy (gCO2e/MJ). A life-cycle assessment of algal fuels as compared to petroleum based gasoline shows that algal fuels yield 50% less greenhouse gas emissions as part of their production and use (Soratana et al., 2012). This carbon intensity reduction makes algal biofuel a good candidate for credit under this system.

As part of the carbon intensity calculation, to make comparisons between traditional fossil fuels and biofuels more accurate, indirect land use is also considered. When land for crop-based biofuels is obtained the conversion of this land into agriculture releases stored carbon from the soil and present vegetation. These emissions are considered indirect land use change and are used when calculating the carbon intensity of crop based biofuels. Different crops have different impacts. **Table 9**, shows that biodiesel from palm has the greatest Carbon Intensity impact due to its indirect land use change while sugarcane has the least. Since algal biodiesel is not a crop-based fuel it would therefore not have an indirect land use change impact on its carbon intensity calculation, making it more desirable as a fuel and yielding more credits to the producer while also giving it an advantage over other renewable competitors.

Table 8. Indirect land use change by biofuel type (CA EPA Air Resources Board 2014)

Biofuel Type	Indirect Land Use Change (gCO2/MJ)
Sugarcane ethanol	11.8
Canola biodiesel	14.5
Sorghum ethanol	19.4
Corn ethanol	19.8
Soy biodiesel	14.5
Palm biodiesel	71.4

The LCFS system is based on credits. Credits can be gained by producing fuel with lower carbon intensity than the standard requirement and sold or bought to make up for any deficits. Credits can be banked for future needs or to be sold to fuel producers who have not achieved the required reduction levels by the end of each year. Since algal biofuel burns cleaner and has no indirect land use change, algal biofuel production could potentially bank a lot of LCFS credits which could be sold to offset production cost and lower fuel prices (Soratana et al., 2012). Depending on the going rate for LCFS credits in the coming years the Air Resources Board predicts that they could have a noticeable impact on cost per gallon of fuel. **Table 10** lays out the cost impacts from 2016-2020 on a single gallon of fuel for three different credit price possibilities. Assuming these predictions are accurate, by 2020 in California algal biodiesel could be generating an extra $0.035-0.139 per gallon produced in LCFS credits.

Table 9. Low Carbon Fuel System credit prices projected impact on fuel cost (Data from CA Air Resources Board, 2015)

Price of Credit	Fuel Type	2016	2018	2020
$25	Gasoline	$0.009	$0.017	$0.030
	Diesel	$0.007	$0.017	$0.035
$57	Gasoline	$0.021	$0.039	$0.068
	Diesel	$0.016	$0.039	$0.079
$100	Gasoline	$0.036	$0.069	$0.120
	Diesel	$0.028	$0.069	$0.139

5.3.2 Renewables Portfolio Standard in California

In 2002 Senate Bill 1078 created the Renewables Portfolio Standard (RPS) which required 20% of retail energy sales to come from renewable sources by 2017. The Senate Bill 107 shortened the time frame to 2010 and Governor Schwarzenegger issued Executive Order S-14-08 and 09 which mandated 33% renewables by 2020 and gave the California ARB authority to develop regulations that would support this goal, such as the LCFS credit system. This push toward renewables strengthens the future of algal biofuel production as it offers an opportunity that other renewables cannot, storage. Most renewable electrical generation right now comes from solar and wind energy (CA Energy Commission, 2015). The issue with requiring larger and larger portions of the state's energy to come from renewable sources is that these are inconsistent and not easily stored. Algal biofuel from wastewater provides a steady source and as a liquid fuel can be stored until it is needed such as at night when solar production has stopped or when wind energy production is low. There is no easy way to quantify this value, but as the state and country moves forward looking for alternative cleaner energy sources algal biofuel will present an attractive option.

5.3.3 The Energy Independence and Security Act and Renewable Fuel Standard

From a national standpoint, the Energy Independence and Security Act (EISA) set requirements for advanced biofuels and developed the Renewable Fuel Standard (RFS) in 2007. The RFS required 15.2 billion gallons of alternative fuels to be domestically produced by 2012 and 24 billion by 2017 of which 9 billion needed to be advanced biofuels and no more than 15 billion of the total gallons could be corn ethanol (CBO, 2014). Advanced biofuels emit 50% less greenhouse gases during their life cycle than petroleum based fuels. Biodiesel from algae would be one example of an advanced biofuel (Maity et al., 2014). Of those 9 billion gallons of advanced biofuels at least 2 billion need to come from biomass based biodiesel, meaning they need to come from vegetable or animal oils that have been processed via transesterification, again algae qualifies (CBO, 2014). To further promote these fuel types under EISA for the purpose of compliance1 gallon of biomass based diesel is worth 1.5 gallons of other renewable fuel types including ethanol from corn. Corn ethanol is being capped at 15 billion gallons and by 2022 the projected requirement for renewable fuels under the RFS will be 40 billion gallons (COB, 2014). To meet that goal will require more focus on advanced biofuels, which means that even if they are not quite cost-competitive with petroleum based diesel there will be an impetus to work to make them less costly to produce as the government forwards their position.

Section 6: Co-benefits and their value

Generation of biodiesel from algae using wastewater has many quantifiable costs as well as some less easy to quantify benefits that should be considered. In addition to the LCFS discussed in section 5.3.1 the coupled treatment/generation offers the advantage of replacing much of the cost of wastewater treatment, improving the quality of wastewater effluent, recycling and capturing carbon, and qualifying for governmental subsidies. In order for these benefits to show up in the production cost estimate they first need to be discussed and quantified.

6.1 Replacing Wastewater Treatment

The ability for the generation of algal fuel to replace much of the required costs and energy consumption of wastewater treatment is perhaps the largest benefit of the coupled production process. Utilizing algae fuelstock to treat wastewater yields both a substantial financial and ecological benefit worth discussing and quantifying.

6.1.1 Financial Benefit

A report, entitled *Energy-Water Nexus: The Water Sector's Energy Use,* by the Congressional Research Service states that for municipal wastewater facilities, energy is the second largest expense, second to labor costs (2014). The energy budget for WWT plants goes primarily toward aeration, pumping, and solids processing (Congressional Research Service, 2014). In northern California approximately 4,000kWh of electricity are required for every million gallons delivered and treated and total water processing and delivery accounts for 19% of the states overall electricity consumption (California Energy Commission, 2005).

Not all of this energy is used for treatment; a large portion is used for pumping from the users to the WWT facility. Filtration systems use 955 kWh/million gallons treated and advanced treatment with nitrification, which yields a product with similar attributes to algal treatment, uses about 1,911 kWh/million gallons treated (National Institute of Standards and Technology, 2010). According to the U.S. Energy Information Administration in January 2016 the average cost of a kWh for the commercial sector was $0.1373. This means that conventional advanced WWT, not including filtration because algal treatment does not replace pretreatment and initial filtration, uses approximately $262.4 of electricity for every million gallons of treated water. If conventional methods are replaced with algal production those costs are almost entirely saved as algae can entirely replace advanced treatment and nitrification. Accounting not just for the energy and money spent on algal production, but taking into consideration the energy and money not spent on WWT greatly impacts cost calculations and makes them more representative of the overall process cost. By combining two processes and only using the energy required of one, a substantial energy savings can be had and should be accounted for.

According to Maity et al. (2014), the average biomass productivity of *spirulina,* a popular algae genus, in an open pond system is 1.21g/gal/day. Regional San, a wastewater treatment facility in Sacramento, treats between 10 and 260 million gallons per day (MGD) depending on wet weather. Assuming the least amount of water, 10MGD, a conservative lipid content of 30% and a fatty acid methyl ester (FAME) density of 0.88Kg/L, the biodiesel output of that facility would be 1090 gallons/day. If it cost $262.4/million gallons for electricity then the plant treating 10MGD would spend about $2624/day. To truly represent the savings this expenditure should be subtracted from the cost/gallon of algal biodiesel produced. This would yield a deduction of

\$2.41/gallon of biofuel, which significantly impacts the overall cost. The calculations are laid out in **Figure 12.**

For comparison purposes, Strum and Lamer (2011) also estimated the energy savings of replacing wastewater, by averaging the findings of several other studies, to be approximately 5,500kWh saved for every 4,500kWh of energy produced as biodiesel,. Given that 1gallon of biodiesel has an energy content of about 35kWh, then 5,500kWh of energy are being saved for every 130 gallons of biodiesel produced. Using the average electricity price of \$0.1373/kWh this equates to \$5.80 saved per gallon of fuel produced.

Given the high-energy use of wastewater treatment plants, the replacement of conventional methods with algae should be reflected in the cost per gallon of algal biofuel production. A decrease of between \$2.41 to \$5.80/gal may make biofuels much more attractive and cost-competitive when compared to petro-diesel.

Figure 12. Wastewater treatment cost and savings calculations for 10MGD WWT facility assuming energy use for treatment of 1911kWh/million gallons (NIST 2010), energy cost of \$0.1373/kWh, lipid content of 30%, and lipid density of .88kg/L.

Wastewater Treatment Cost and Savings Calculations for 10MGD WWT Facility:

Energy Cost for Conventional WWT of 10MGD:

$$\frac{1911kWh}{1x10^6 gal\ treated} * \frac{10 * 10^6 gallons}{day} * \frac{\$0.1373}{kWh} = \frac{\$\mathbf{2624}}{\boldsymbol{day}}$$

Biodiesel Produced from WWT of 10 MGD:

$$10x10^6\ gal\ WasteWater * \frac{1.21\ g\ biomass}{gal\ Wastewater * day} * \frac{0.3\ g\ lipids}{1\ g\ biomass} * \frac{1\ kg\ lipids}{1000\ g\ lipids} * \frac{1\ L\ biodiesel}{0.88\ Kg\ lipids} * \frac{1\ gal\ biodiesel}{3.785\ L\ biodiesel} = \mathbf{1089.8}\ \boldsymbol{gallons\ biofuel}$$

Energy Cost Savings Per Gallon of Biodiesel Produced:

$$\frac{\$2624\ saved\ on\ energy/day}{1089.8\ gallons\ biofuel\ produced/day} = \frac{\$\mathbf{2.41}\ \boldsymbol{saved}}{\boldsymbol{gallon\ produced}}$$

It is important to note that given a storm event the inflows to the WWT system would be too great for an algal system to handle since the water must sit with the algae in open ponds. In this situation conventional WWT could occur on the surplus water. Storm events bring in water that often requires less treatment then typical wastewater and missing out on advanced treatment is less of a concern during these events. Given this, the calculation for the co-benefit of replacing WWT considers only the water that could be treated by algae and the benefits it would derive. In a separate sewer system, as in older cities, where storm flow is not treated, the plant capacity would not fluctuate as greatly.

6.1.2 Ecological Benefit

Current WWT effluent from Regional San in Sacramento has been causing severe ecological problems, which caused increased requirements to be instated in their NPDES permit. To meet these new requirements the plant will have to add tertiary treatment. The WWT facility is calling this new addition the EchoWater Project, an approximately two billion dollar construction project that will allow the current treatment plant to provide tertiary treatment and remove nutrients from the wastewater. Ecological benefits are often difficult to quantify, but in this case to preserve the environment the WWT facility is having to spend billions of dollars, money that could have potentially been saved if using algal treatment.

While ecological benefits often do not directly impact the cost per gallon they do have indirect financial value. Clean up and restoration of damaged ecosystems due to high nutrient loads can be very costly. Eutrophication leading to depleted oxygen in a system results in low productivity and can affect commercial fishing and other wildlife. Aeration systems may solve the DO issues, but they also require energy and maintenance, which has a cost.

6.2 Carbon Capture

In addition to algal fuels' reduced carbon emissions and 50% less life cycle production of greenhouse gases, their growth also requires the uptake of CO2 from the air or flue gas (Maity et al., 2014). Li et al. (2008) found that algae can sequester carbon dioxide 10-50 times more efficiently than land plants. Different algal species have varying CO2 fixation rates and can range from 0.8 g/m3/h for Chlorogleopsis species to 148 g/m3/h for Chlorella vulgaris(Maity et al., 2014). Since algae uptake carbon dioxide they could generate carbon credits, which could offset production costs.

In 2006 California passed the California Global Warming Solutions Act, Assembly Bill 32 (ARB, 2014). The Act included different policies and programs aiming to reduce greenhouse gas emissions to 1990 levels by 2020 (ARB, 2014). One such program is the Cap and Trade Program, which limits or caps the emissions in California and allows organizations to sell and trade their permitted allowances. Each tradable credit or allowance is equal to the equivalent of one metric ton of carbon dioxide (ARB, 2016). In 2015 Gov. Jerry Brown put forth a new reductions target of 40% below 1990 levels by 2030 (ARB, 2016).

The California Carbon Dashboard (2016) estimated that in April, 2016 one carbon credit (for one ton of carbon dioxide), is worth $12.61. Given a median range of carbon fixation rates for algae of 75g/m3/h approximately 28 carbon credits could be generated each day by a 10MGD WWT facility. **Figure 13**, lays out this calculation assuming, algae are photosynthetically active for 10 hours/day, the volume required for 10 million gallons of wastewater is 37850m3, and that a 10MGD facility produces 1090gal/biodiesel/day as per **Figure 12**. Given the calculation from 6.1.1 that a 10MGD could produce 1090gal biodiesel /day the cost savings per gallon due to carbon credits would equate to about $0.32/gal.

Figure 13. Per gallon cost savings due to algae carbon credit generation. Calculations assume 10MGD of wastewater being treated, a photosynthetic activity of 10h/day for the algae, a carbon credit cost of $12.61 (CCD 2016), and a carbon uptake rate of 75g/m3*hr. (Maity et al., 2014).

<u>**Carbon Credits Generated by 10MGD Facility and Biodiesel Cost Impact:**</u>

Carbon Sequestered by 10MGD Facility:

$$37850m3 * \frac{75g\ CO2}{m3 * hr} * \frac{10hr}{1\ day} * \frac{1kg}{1000g} = 28{,}388\frac{kg\ CO2}{day} \approx \mathbf{28\ metric\ tons\ CO2/day}$$

Carbon Credit Value:

$$\frac{28\ metric\ tons\ CO2}{day} * \frac{\$12.61}{ton\ CO2} = \frac{\mathbf{\$353}}{\mathbf{day}}$$

Cost Per Gallon Impact:

$$\frac{\$353}{day} * \frac{day}{1090\ gal\ biodiesel} = \frac{\mathbf{\$0.324}}{\mathbf{gal\ biodiesel}}$$

6.3 Federal Government Incentives

One reason why biofuel blends such as E85 with ethanol were able to become so widespread was because there was a lot of government support for them in terms of regulations and subsidies. Without the support, corn ethanol blends could not have competed with 100% petroleum based gasoline especially when ethanol delivers approximately 30% less energy than gasoline (Congressional Budget Office, 2010).

As the focus moves away from corn and onto other biofuel feedstocks, new governmental incentives have been issued to promote their development and production. Such incentives include the Biomass Crop Assistance Program, Biodiesel Mixture Tax Credit, Biodiesel Income Tax Credit, Second Generation Biofuel Producer Tax Credits, and Biofuel Production Grants (DOE, 2016).

6.3.1 Tax Credits

Several tax credits that could apply to algal biodiesel have most recently been extended through December 31, 2016. These tax credits have been extended multiple times and would greatly impact the final cost/gallon of algal biodiesel if considered. The Biodiesel Mixture Excise Tax Credit is one of the incentives in place. It provides a tax credit to blenders of $1.00/gallon for pure biodiesel mixed with petroleum based fuel such that the mixture is at least 0.1% petro-diesel (DOE, 2016). The tax credits can be used to lower the blender's tax liability. Any credits beyond the liability would then be paid directly from the IRS (DOE, 2016). The Biodiesel Income Tax Credit functions the same way as the previously discussed credit as $1.00/gallon for unblended biodiesel specifically for vehicle consumption (DOE, 2016).

6.3.2 Grants

In addition to tax credits the government is offering an Advanced Biofuel Production Grant and Loan Guarantee, under the Biorefinery Assistance Program, to promote renewable biofuel generation. The loans can be used for construction, development, and retrofitting of refineries that produce advanced biofuels, excluding those derived from corn (DOE, 2016). Up to $250 million is being offered in loans and grant funding up to 50% of project cost (DOE, 2016)

These programs are often re-extended each year, but not knowing when they will cease to exist can make investors in this process less confident. Additionally, $1.00/gallon tax credit does impact final cost/gallon, but if the cost beforehand was several dollars greater than competitors, it still might not make sense for refineries to focus on biofuels. For this reason, in order for these incentives to really impact the energy sector and liquid fuel production the entire process needs to be made more efficient and cost-effective. When that happens these incentives will quickly accelerate their growth.

The government incentives do not eliminate the challenges that biofuels face, but they do give them an extra edge that could help advance their development and production. The available grants could subsidize much of the cost of buildup for coupled treatment facilities and help get this process started. The tax credits can help make the fuels competitive and keep research focused on optimization so that by the time these incentives are terminated algal biofuels may not need them to be competitive in the global market.

Section 7: Cost Estimates for Algal Biofuel From Wastewater

Having discussed different parameters that affect cost, final estimates can be made. Background information shows this process as feasible, a focus on California brought to light certain challenges this process faces in this region, and various co-benefits and factors that could affect cost have been discussed and quantified. To bring all of these factors together this section will first estimate a base cost per gallon for this process by pulling various existing cost estimates from the literature. From there, knowing what makes the most sense and is most feasible in California, the costs that reflect this situation will be narrowed in on to serve as a base cost range for this process. Once a base cost is established an adjusted cost to account for the benefits of this fuel type will be determined. Lastly, a projected cost will be estimated using the predicted impact of emerging technologies on the base cost. Once these three values, base, adjusted for co-benefits, and projected for emerging technology have been calculated then a cost-comparison will be done looking at petroleum-based diesel's historical, current, and projected costs.

7.1 Literature Cost Estimates and California Base Case

7.1.1 General Cost Estimates from Literature for all Processing Types

Many studies have been done that have estimated the cost of producing algal biofuel commercially. Compiling all of these estimates will give a better picture of where the process is at and the range of cost estimates that exist. **Table 11** puts several cost estimates from various studies together for comparison with all estimates adjusted for inflation to $\$_{2016}$ using an inflation calculator from the U.S. Department of Labor. The cost/gallon ranges from $1.64 to $20.68. The average cost/gallon estimate is $6.15. This calculation includes production using both open pond and PBR types, as well as a range of lipid contents and productivities.

Table 11. Table o f various price estimates from literature sources adjusted to 2016 $. The table lays out the assumptions of each study and classifies the case as appropriate for a Base CA estimate with a single asterisk, appropriate for an optimized estimate with two asterisks, and not appropriate for CA at this point in time with no asterisk.

Source	Price ($2016/gal)	Cultivation Type	Lipid %	Productivity (g/m2/day)	Carbon Source	Case
Benemann & Oswald, 1996	2.78	Open Pond	40	30	Flue Gas	**
Benemann & Oswald, 1996	3.33	Open Pond	40	30	CO2 ($40/MT)	**
Benemann & Oswald, 1996	2.08	Open Pond	40	60	Flue Gas	**
Benemann & Oswald, 1996	2.27	Open Pond	40	60	CO2 ($40/MT)	**
Chisti et al., 2007	2.28	PBR	30	NA	NA	
Chisti et al., 2007	2.93	Open Pond	30	NA	NA	*
Davis et al., 2011	9.49	Open Pond	25	25	Flue Gas	*
Davis et al., 2011	4.69	Open Pond	50	40	Flue Gas	**
Davis et al., 2011	3.72	Open Pond	60	60	Flue Gas	**
Davis et al., 2011	20.58	PBR	25	1250	Flue Gas	
Davis et al., 2011	7.72	PBR	50	2000	Flue Gas	
Davis et al., 2011	5.49	PBR	60	3000	Flue Gas	
Delrue et al., 2012	6.57	Open Pond	NA	NA	NA	*
Delrue et al., 2012	10.94	PBR	NA	NA	NA	
Nagarajan et al., 2013	2.78	Open Pond	50	30	Flue Gas	**
Nagarajan et al., 2013	1.64	Open Pond	50	60	Flue Gas	**
Nagarajan et al., 2013	3.79	Open Pond	50	30	CO2 ($40/MT)	**
Nagarajan et al., 2013	2.19	Open Pond	50	60	CO2 ($40/MT)	**
Richardson et al., 2012	12.09	PBR	NA	NA	NA	
Richardson et al., 2012	4.94	Pond	NA	NA	NA	*
Taylor et al., 2013	14.01	PBR	NA	NA	NA	
Taylor et al., 2013	8.95	PBR	NA	NA	NA	

All prices have been adjusted to 2016 values.
*CA Base Case
**CA Optimized Case

7.1.2 Base Cost of Algal fuel in Northern California

Given the discussion in Section 5, there are certain set-ups that make the most sense for California in terms of the most efficient and cost-effective. By identifying the processes that would be most efficient, the cost/gallon estimate can be more accurate. Given the infrastructure expense and limited scale up of PBR systems, HRAP systems are the likely choice for California at this time. Current technology has HRAP systems showing a moderate productivity of about 25g/m2/day and a lipid content around 25-30% (Davis et al., 2011)

Selecting only the estimates from **Table 11** that represent HRAP conditions and current technology, denoted in the figure with a single asterisk, we are left with a range of $2.69 to $9.49 with an average of $5.98/gallon. This will serve as the base estimate for California for comparison with petro-diesel and for adjustment in the following sections.

7.2 Co-Benefits Cost Savings Estimates

In order to determine cost-effectiveness of algal biodiesel as compared to petro-diesel the two fuels need to be examined side by side. They are both liquid fuels that are easy to store and transport, but beyond that they have major differences that should be addressed in order to even begin comparing them to each other. Diesel derived from algae has a slew of co-benefits that petro-diesel does not, so in order to accurately compare the two, algal biodiesel's cost needs to be adjusted to include these added benefits.

Not all of the co-benefits laid out in this paper are easily quantifiable and so not all will be reflected in the cost adjustment. Some co-benefits, such as being a renewable fuel, having less pollutant emissions than gasoline, and generating wastewater that has had nutrients removed, do not have a discreet numerical value and so in spite of them not being accounted for in the following calculation they should be kept in mind when comparing the two fuels holistically.

Section 6 explored a few of the co-benefits of combining algae WWT and biofuel production and quantified the value of each. While not a comprehensive view, section 6.1.1 estimated the cost savings from an energy standpoint of replacing much of WWT with algae. From the two estimates using values found in the literature and current energy costs, WWT replacement could equate to an approximately $2.40-$5.80 savings per gallon of biodiesel produced. Section 6.3.1 discussed the generated fuels potential for tax credits and revealed that algal biodiesel qualifies for $1.00 tax credit per gallon through the end of 2016 and is likely to be renewed beyond that date. Section 6.3 examined the impact of carbon capture and roughly estimated that each gallon of biodiesel could earn approximately $0.32/gal. Lastly, California's LCFS system could have this fuel type earning LCFS credits up to $0.14/gal by 2020.

To represent these co-benefits their cost savings should be subtracted from the California base case of $5.98/gallon as found in section 7.1.2. Since these numbers are only approximate ranges a high, low, and average adjustment will be done. LCFS credits will not be included for this calculation as it is meant to represent current costs and LCFS credits would not substantially impact cost for several years.

Base Case Adjusted for Co-benefits, Low/Conservative Estimate:

$5.98/gal - $2.40/gal (WWT) – $1.00/gal (Tax Credit) – 0.32/gal(Carbon Credit) = **$2.26/gallon**

Base Case Adjusted for Co-Benefits, Average Estimate:

$5.98/gal - $4.10/gal(WWT) – $1.00/gal(Tax Credit) - $0.32/gal(Carbon Credit)= **$0.56/gallon**

Base Case Adjusted for Co-benefits, High/Aggressive Estimate:

$5.98/gal - $5.80/gal(WWT) - $1.00/gal(Tax Credit) -$0.32/gal(Carbon Credit) = **- $1.14/gallon**

For comparison purposes we can look at the high, average, and low co-benefit adjustment combined with the high and low ends of the cost estimate range in addition to the base case from section 7.1.2. **Table 12** lays out the different combinations to see where biodiesel stands depending on the assumptions made. The negative cost per gallon values indicate that given these assumptions WWT is less expensive when using algae in place of conventional methods, even if biofuel is not generated for sale. In this situation the biofuel price would be pure profit as opposed to the price representing production costs. These are only rough estimates and not to be taken as final adjustments, but it gives an idea of where biodiesel's cost per gallon could fall when co-benefits are accounted for.

Table 10. Co-Benefit adjusted estimates using low, base, and high literature estimates combined with low, average, and high WWT adjustments.

		Unadjusted Cost/Gallon Biodiesel		
		Low Estimate ($2.69/gallon)	**Base Estimate** ($5.98/gallon)	**High Estimate** ($9.49/gallon)
Co-Benefit Adjustment: WWT (Low Avg, High), Tax Credit(-$1.00), & Carbon Credit (-$0.32)	**Low WWT**	$-1.03/gallon	$2.26/gallon	$5.77/gallon
	Average WWT	$-2.73/gallon	$0.56/gallon	$4.07/gallon
	High WWT	$-4.43/gallon	$-1.14/gallon	$2.37/gallon

7.3 Cost Estimates Assuming Optimized Technology

Table 11 includes cost estimates for higher lipid contents and productivity as well as the base case. The reason being, that many new lab studies and some large scale pilot operations have demonstrated that these levels are achievable (Nagarajan et al., 2013). Since this is a developing field, biodiesel production is continually becoming more efficient and this will have an impact on the final cost/gallon. To determine how implementing this new technology and achievements will affect cost, an adjustment can be made given each development. For example lipid content has the largest impact on biofuel production efficiency and therefore cost (Davis et al., 2011). Lipid content is impacted by species selection and growth conditions. Doubling lipid content means twice as much biofuel yield for the same processes cost and as such could roughly cut cost/gallon in half.

Harvesting or dewatering of the algae is one of the more difficult processes and highly energy intensive. Section 4.3.1 discussed different harvesting techniques that are being implemented and researched. Strum and Lamer (2011), calculated the energy consumption of different harvesting methods, which can be used to estimate potential cost savings due to improved technology and harvesting processes. Given all the methods examined, the average energy use of harvesting is 8.75kWh/gal fuel produced (Strum and Lamer, 2011), given the average national commercial energy rate of $0.1373/kWh, it equates to a cost of $1.20/gal. The lowest energy achieving technology, the Gravity Belt Press, was able to reduce the energy required/gallon produced to about 2.75kWh/gal or about $0.378/gal (Strum and Lamer, 2011).

The worst examined technology from an energy standpoint was evaporation, requiring 21.5kWh/gal or \$2.95/gal (Strum and Lamer, 2011). This means that optimization of just this step of production could reduce the energy cost/gal by as much as \$2.57/gal or more realistically \$0.82/gal. This technology is developing and not all harvesting techniques have been shown to be effective for large-scale growth and production; however, it further sheds light on the potential future of combined treatment and biofuel production. Conducting an analysis for all treatment steps and areas of optimization would allow a more complete picture of the production cost reductions that could be achievable in the future.

Consideration of different cost contributors and how their development impacts production costs is important, but the sensitivity of each factor may be even more worth examining. Brownbridge et al. (2014) found that the four most sensitive factors when it comes to production cost are; algae oil content, productivity, facility capacity and carbon price. **Figure 14**. shows a similar list to Brownbridge et al., the five largest cost contributors to algal biodiesel production as found by Davis et al. (2011). The graph presents three scenarios, a pessimist, base, and optimist case for each factor and how each would impact overall cost/gal. For example, if lipid content could be increased from a base of 25% to 50% it would decrease cost/gal by approximately \$4.00. Given a base cost of \$8.50/gal that would bring the cost down to \$4.50/gal and much more competitive than before. **Figure 14** shows that lipid content and growth rate of algae have the most significant impact on overall cost and therefore have the greatest potential to reduce it (Davis et al., 2011). Improving CO2 costs may lessen the price per gallon, but not near as much as increasing the lipid content would. This sensitivity analysis shows where a small change could make a big difference and where research and optimization efforts should be focused in order to reduce production costs. Using Davis et al.'s (2011) findings, and assuming that all optimization targets could be reached, would roughly result in a biodiesel fuel cost per gallon of:

\$8.50 (Base) - \$4.00 (50% lipid) - \$2.00 (50g/m2/day) – \$1.00 (365 Operation) - \$0.50 (Nutrient Recycle) – \$0.25 (CO2) = \$0.75/gallon biodiesel

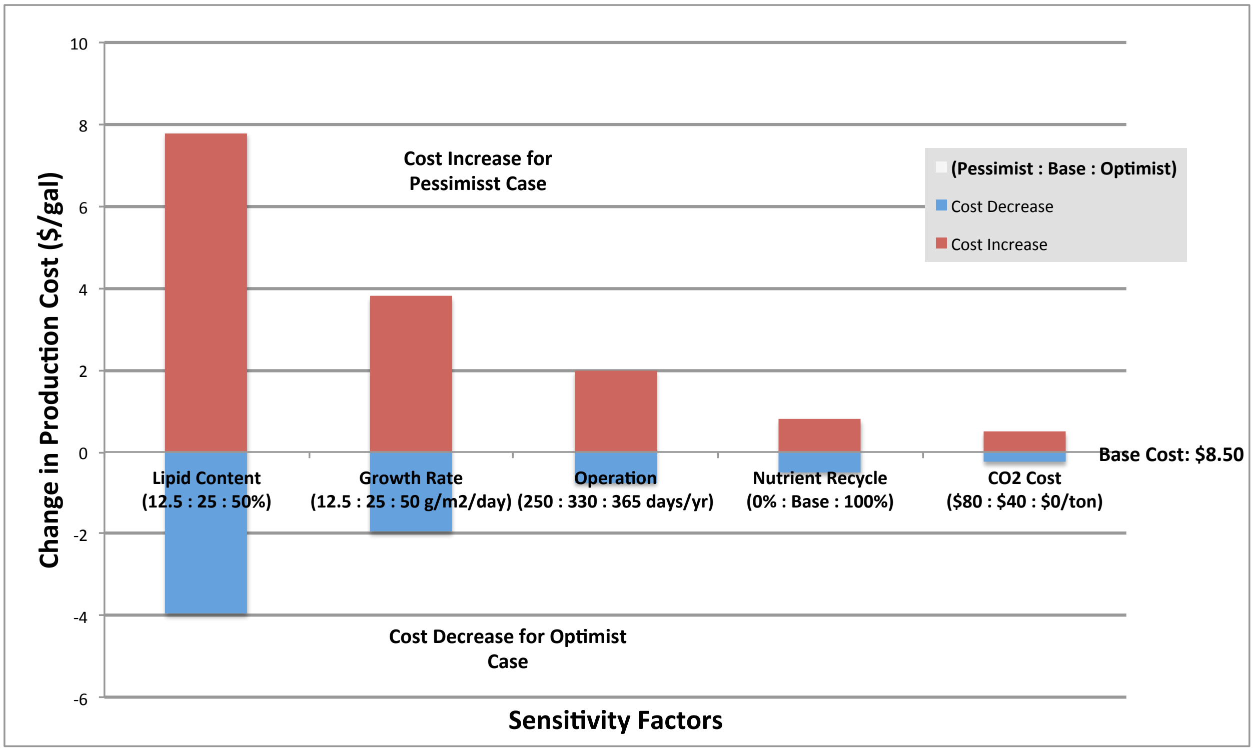

Figure 14. Shows the top five most sensitive cost parameters for combined algal WWT and biofuel production. Assuming a base cost of $8.50/gallon the figure shows how a pessimist case, in red, would increase cost and how an optimist case, in blue, would decrease cost for each parameter. (Data taken from Davis et al., 2011).

Using **Table 11** as a guide, an estimate can be made for algal biodiesel cost/gallon using literature estimates represented in the table by two asterisks. These estimates assume higher lipid contents and productivity rates than are currently found by large-scale facilities, but have been demonstrated in the lab and smaller pilot plants. The average cost/gallon of these studies is $2.93/gal with a range from $1.64-4.69/gal. This estimate represents optimization of the process, but does not consider the co-benefits of this fuel.

An actual hard estimate of algal fuel that incorporates future development and optimization is difficult given the nature of research and advancements that are constantly being made. A lab scale finding may not easily translate to full plant scale and so incorporating it into a cost adjustment might not make sense. The cost impact due to the energy consumption of different harvesting techniques as researched by Strum and Lamer (2011), and Davis et al.'s (2011) sensitivity analyses give a general overview of how greatly production costs could change given improved technology. When comparing current costs to petro-diesel this should be considered since the production of petroleum products in many ways do not have the same optimization opportunities or cost variability due to improved technology that is evidenced above for algal biodiesel.

Section 8: Petro-Diesel Cost-Comparison

To determine cost-effectiveness of algal biodiesel from WWT requires comparing the fuel to conventional petroleum-based diesel. This paper has attempted to estimate the cost/gallon of producing biodiesel from algae using wastewater treatment, but since these fuels have many differences it does not make sense to simply compare them on a straight gallon to gallon basis. Prior to comparing the fuels an adjustment for their varied energy contents will be done, and an acknowledgement of their differences will be made.

8.1 Petroleum Diesel Cost Per Gallon Adjustments

The current price of petro-diesel has been fluctuating given global issues with overproduction. The U.S. Energy Information Administration estimated the cost/gal at the pump of petroleum based diesel on April 11, 2016 to be $2.13. The breakdown of that cost is as follows: Crude Oil 34%, Refining 17%, Distribution and Marketing 23%, Taxes 26% (EIA, 2016). Assuming distribution and marketing would be the same for all fuel types a subtraction of 23% will be done to compare fuel costs only since the algal fuel estimates in section 7 do not account for distribution costs. Additionally, assuming tax breaks on renewable fuels, the tax portion will be included for comparison since this is a point of difference. This results in an adjusted diesel price of $1.64/gal.

From an energy and fuel economy standpoint, one gallon of petro-diesel and biodiesel are not equivalent. They both have a greater energy yield than gasoline, but biodiesel's energy content is roughly 93% of pure petroleum-diesel (AFDC, 2014). To adjust for this the cost of diesel should be represented as only 93% of its estimated cost per gallon. In this way the petro-diesel cost only represents 93% of its energy capacity and can be directly comparable to biodiesel from an energy perspective. Adjusting the $1.64/gal from above for energy differences the equivalent cost/gal of petro-diesel is approximately $1.53/gal.

8.2 Biodiesel and Petro-Diesel Cost Comparisons

The adjusted fuel costs can now begin to be compared. **Figure 15** displays the cost estimates from Section 7, including the high and low range, alongside the adjusted petro-diesel cost/gal from section 8.1. Looking at the graph, none of the California base case and optimized base case estimates is more cost-effective than petroleum-diesel; the low and average co-benefits estimates are more cost-effective than petro-diesel by as much as $2.67/gallon.

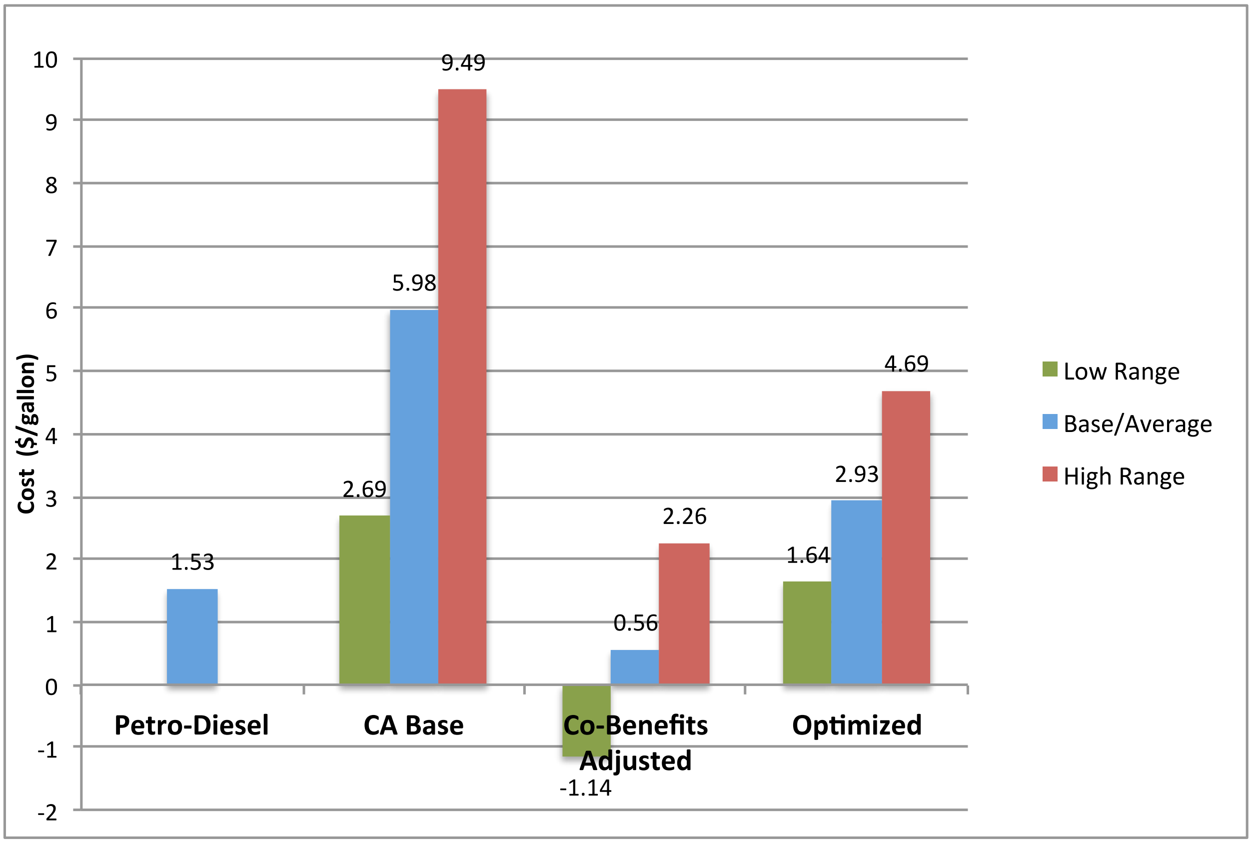

Figure 15. Comparison of the cost estimates of petroleum-based diesel to three situations, a base California case, a co-benefit adjusted case, and an optimized case. For each case the figure displays the low, average, and high range.

8.3 Un-priced Benefits and Costs

Cost is the parameter of interest for this paper, but it is not the only thing to consider when juxtaposing these two fuels. The two fuels have very different ecological impacts, carbon lifecycles, emissions, scale-up ability, and capacity. The co-benefits adjusted cost attempts to reflect some of these differences, such as carbon lifecycle in the form of WWT energy savings, and carbon credits, but it does not fully capture these differences. **Table 13** highlights some of the major differences between these two fuels that cannot be ignored or completely represented in a side by side cost analysis.

Table 13. Some differences between algal biodiesel and petro-diesel that are not directly accounted for in the side-by-side cost comparison. (Data taken from Luo et al., 2010, Batan et al., 2010, Davis et al., 2011, & EPA, 2002)

Algal Biodiesel	Parameter	Petro-diesel
-75.29	GHG Lifecycle (gCO2e/MJ)	17.24
0.93*	Net Energy Ratio (MJ Produced/MJ Consumed)	8-9
Not difficult, but large land requirement	Scale-Up Ability	Easy, but limited to source
Wastewater, renewable	Future Source	Limited, diminishing
50%	Particulate Matter Emissions**	100%
0%	Sulfate Emissions**	100%

* Ratio not account for energy savings from WWT
**Percentage based on average petro-diesel emissions

One of the most difficult things to represent in a cost-analysis is the fact that this is a renewable fuel, versus petro-diesel, which has a limited and diminishing supply. As time and use progress, petro-diesel's cost will eventually rise due to limited supply, whereas algal fuel from wastewater will not face that prospect. Tax credits are given to try an represent this benefit, but it is hard to say exactly how much this is worth. This difference will show up in a cost comparison in the future as petroleum prices rise, but is not easy to represent at present.

Another difference between the two fuel types, which is not perfectly represented in this strict cost comparison, is the emissions. From a lifecycle perspective, algal biodiesel sequesters carbon and petro-diesel releases it. Carbon credits can somewhat represent this difference, but do not fully account for the ecological and economic cost of putting GHGs into the atmosphere. Climate change has sweeping, expensive, global effects. It is challenging to say that $12.61 per ton of carbon dioxide equivalent really covers the cost of climate change. Furthermore, the pollutant emissions of each fuel differ and are not represented at all in this cost comparison. Algal fuels have reduced particulate matter, sulfate, and carbon monoxide emissions (EPA, 2002). These pollutants contribute to health problems such as asthma, cancer, and many others still being identified. Calculating the cost of health care as a result of emissions is an arduous task that is worth examining, but difficult to reduce to a cost per gallon of fuel basis.

Lastly, the opportunities for these two fuels in the future are not represented in the co-benefit adjustment, but are significantly different between the two fuels. Algal fuels, particularly as new fuels, have lots of room for optimization. Petro-diesel, an established fuel, does not have the opportunities to the same degree. The more money put towards biofuels will make them more efficient and less costly to produce. New techniques in petroleum fuels, such as fracking, do not make the process more efficient or less costly, they simply extend the supply. This future payoff for investing in algal biofuels from WWT now is not easy thing to represent in current fuel costs, but is not something that should be ignored when comparing fossil and algal fuels.

This is not an exhaustive list of the co-benefits of algal based biodiesel from WWT, but it highlights some of the major differences between it and petroleum based diesel. The findings of this paper show that when adjusting for just three co-benefits algal biodiesel is more cost-effective than petro-diesel. If these other benefits from **table 13** were represented here as well, the cost difference between the fuels would be even greater. Future analyses should attempt to account, as much as possible, for these benefits to most accurately represent this fuel.

Section 9: Conclusions

In conclusion, biodiesel produced from combined WWT in California is not currently cost-competitive with petroleum based diesel when viewed on a strict gallon to gallon generation cost basis, but is cost-effective when the co-benefits of this fuel production type are considered. The prices continue to drop, but the current base estimates have a way to go before they fall below petro-diesel's market price of $1.53/gal. Even the low range estimate, taken from the literature, of $2.69/gal is still over $1.00 more expensive, and the average base cost of $5.98/gal is almost four times more expensive. That being said, petro-diesel and algal biodiesel from

WWT have many differences that should not be ignored and, if even partially adjusted for, make biodiesel much more competitive in the context of cost.

Taking into account some co-benefits of this process makes the fuel much more attractive and either on par with, or more financially beneficial than current petro-diesel prices. The major benefit of combining WWT with biodiesel production is the energy and cost savings. Other considerations include the fact that biodiesel is a renewable fuel and has a lower carbon impact, which can be represented by subtracting tax credits and carbon credits from production costs. Adjusting the cost/gal for just these three benefits brings the production cost/gal below petro-diesel's market price. Using the average base case for California and adjusting for co-benefits brings the cost down to $0.56/gal, a third of the cost of petro-diesel, and using the low base case estimate brings the cost to a -$1.14/gal, representing an energy savings from combining WWT and biofuel production that is greater than the production cost of biofuel.

Likewise if the projected future cost of algal biodiesel and that of gasoline is considered, the outcome looks promising for algal biofuels. Much research is being done in this field and many labs have demonstrated the capability of reaching increased productivity and lipid contents among other developments that will drastically improve production efficiency and reduce cost. As these developments become widespread and usable on a large scale, algal fuels will become more cost competitive. The findings of this paper show that algal fuel prices could be reduced by optimization, but optimization alone will likely not be enough to make the fuel competitive with petro-diesel. The estimated optimization cost in Section 7 is based on the California base cost and does not consider the co-benefits. If the co-benefit estimate was adjusted to also represent future optimization the estimates would be even lower and very competitive in the current market.

While fuel cost does offer a great way to compare two very different fuels, it does not encapsulate all the impacts or opportunities that either has to offer. There are some considerations regarding these fuels that should be kept in mind when evaluating future investments and fuel development. Among these considerations are the renewable nature of biodiesel, which makes it a more reliable fuel, its lower emissions and air pollution rates, and its ability to produce water that can exceed standards for several unregulated parameters. Though difficult to quantify, they are not insignificant and even if algal biodiesel is not directly cost-competitive from a production standpoint these other attributes should be considered.

In spite of algal biodiesel showing promise as a replacement or supplement to petro-based fuels from a cost perspective, it is still likely to face many challenges. The scale-up necessary to provide large volumes of fuel would require significant areas of land, which are not always easy to come by. Other challenges include initial investment obstacles, and public perception and knowledge about algal biofuels. The recommendations in section 10 offer suggestions to help combat these challenges.

Section 10: Recommendations

Algal fuel costs will only improve and decrease as new technology and developments allow further optimization of the system. Petro-gasoline will do the exact opposite, as the limited supply gets depleted and new sources need to be exploited, the prices will steadily rise. Intuitively it makes sense to invest in the fuel that is renewable and will become more cost-effective over the fuel that will eventually runout and become more expensive both in purchase cost and ecological consequences. Based on the findings of this paper I propose several recommendations to government agencies, the general public, and scientific community as the next steps for combined WWT and algal biodiesel production.

- Continue research on the leading cost-factors of this process to further the profitability and future of this fuel.

- Focus on public outreach, when people think renewable fuels they only think of ethanol and E85 gasoline. Education on the fuels energy capacity and air pollution reductions will help promote the use of this fuel. Success for biodiesel will come with popular acceptance.

- Subsidize adjusted infrastructure, such as diesel engines, and modified WWT facilities. Currently biodiesel can only be used in diesel burning engines. A push toward more diesel engines could reduce this limiting factor and further algal biodiesels use. New WWT facilities or retrofitting of existing ones, are a major hurtle for this combined process. Grants, subsidies, and tax breaks for these facilities could promote their construction and aid in the transition between reliance on petroleum to utilizing new renewable fuels.

- Begin planning and building a pilot plant facility in California. Several countries have begun planning combined WWT and biofuel plants and a handful of small scale facilities are operational here in the United States. The feasibility of this process has been demonstrated and with California's focus on renewable energy sources a great opportunity exists here.

Acknowledgements:

I would like to thank and recognize all of the faculty at USF who inspired this project and motivated me to pursue more knowledge and education in this field. It is because of them that I will be attending UC Davis in the fall to pursue a PhD in Environmental Engineering with a focus of water treatment. A special acknowledgement, also, to my husband Juan and my family who have supported me with the day to day struggles and made my Masters degree and this project possible.

Bibliography:

Abdel-Raouf, N., Al-Homaidan, A. A., & Ibraheem, I. B. M. (2012). Microalgae and wastewater treatment. *Saudi Journal of Biological Sciences*, *19*(3), 257–75. http://doi.org/10.1016/j.sjbs.2012.04.005

Alternative Fuels Data Center - Fuel Properties Comparision. (2014, October 24). Retrieved April 5, 2016, from http://www.afdc.energy.gov/

Arbib, Z., Ruiz, J., Álvarez-Díaz, P., Garrido-Pérez, C., & Perales, J. A. (2014). Capability of different microalgae species for phytoremediation processes: wastewater tertiary treatment, CO2 bio-fixation and low cost biofuels production. *Water Research*, *49*, 465–74. http://doi.org/10.1016/j.watres.2013.10.036

Assembly Bill No.32, CA Health and Safety Code §§ Chapter 488-38500-38599 (2006).

Axelsson, M., & Gentili, F. (2014). A Single-Step Method for Rapid Extraction of Total Lipids from Green Microalgae. *PLoS ONE*, *9*(2), e89643. http://doi.org/10.1371/journal.pone.0089643

Azadi, P., Brownbridge, G., Mosbach, S., Smallbone, A., Bhave, A., Inderwildi, O., & Kraft, M. (2014). The carbon footprint and non-renewable energy demand of algae-derived biodiesel. *Applied Energy*, *113*, 1632–1644. http://doi.org/10.1016/j.apenergy.2013.09.027

Banat, I., Puskas, K., Esen, I., & Al-Daher, R. (1990). Wastewater treatment and algal productivity in an integrated ponding system. *Biological Wastes*, *32*(4), 265–275. http://doi.org/10.1016/0269-7483(90)90058-Z

Batan, L., Quinn, J., Willson, B., & Bradley, T. (2010). Net Energy and Greenhouse Gas Emission Evaluation of Biodiesel Derived from Microalgae. *Environmental Science & Technology*, *44*(20), 7975–7980. http://doi.org/10.1021/es102052y

Benemann, J.R., & Oswald, W.J. (1996). Systems and economic analysis of microalgae ponds for conversion of CO{sub 2} to biomass. *Final report*. United States. doi:10.2172/493389

Bouterfasl, R., Belkoura, M., & Dauta, A. (2002). Light and temperature effects on the growth rate of three freshwater algae isolated from a eutrophic lake. *Hydrobiologica*, 489, 207-217.

Brownbridge, G., Azadi, P., Smallbone, A., Bhave, A., Taylor, B., & Kraft, M. (2014). The future viability of algae-derived biodiesel under economic and technical uncertainties. *Bioresource Technology*, *151*, 166–73. http://doi.org/10.1016/j.biortech.2013.10.062

Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances*, *25*(3), 294–306. http://doi.org/10.1016/j.biotechadv.2007.02.001

Colak, O., Kaya, Z. (1988). A study on the possibilities of biological wastewater treatment using algae. *Doga Biyolji Serisi* 12 (1), 18–29.

Cooke, M.B., Thackston, E.L., Malaney, G.W. (1978). Reduction of coliform and Salmonella bacteria during anaerobic digestion. *Water Sew Works*, pg 50-54

Copeland, C. (2014, January 3). *Energy Water Nexus: The Water Sector's Energy Use* (United States, Congressional Research Service). Retrieved from https://www.fas.org/sgp/crs/misc/R43200.pdf

Craggs, R.J., Green, F.B., Oswald, W.J. (1999). Economic and energy requirement of advanced integrated wastewater pond systems. *NZWWA Annual Conference*. 1-7

Davis, R., Aden, A., & Pienkos, P. T. (2011). Techno-economic analysis of autotrophic microalgae for fuel production. *Applied Energy*, *88*(10), 3524–3531. http://doi.org/10.1016/j.apenergy.2011.04.018

Drira, N., Piras, A., Rosa, A., Porcedda, S., & Dhaouadi, H. (2016). Microalgae from domestic wastewater facility's high rate algal pond: Lipids extraction, characterization and biodiesel production. *Bioresource Technology*, *206*, 239–244. http://doi.org/10.1016/j.biortech.2016.01.082

Delrue, F., Setier, P. A., Sahut, C., Cournac, L., Roubaud, A., Peltier, G., & Froment, A. K. (2012). An economic, sustainability, and energetic model of biodiesel production from microalgae. *Bioresource Technology*, 111, 191-200.

EchoWater Project. (n.d.). Retrieved April 4, 2016, from http://www.regionalsan.com/echowater-project

Frank, E.D., Han, J., Palou-Rivera, I., Elgowainy, A., & Want, M.Q. (2011) Life-cyle analysis of algal lipid fuels with the GREET model. Argonne National Laboratory.

Gallagher, B. J. (2011). The economics of producing biodiesel from algae. *Renewable Energy*, *36*(1), 158–162. http://doi.org/10.1016/j.renene.2010.06.016

Goldstein R., Smith W., (2002). Water & Sustainability: U.S. Electricity Consumption for Water Supply & Treatment. Palo Alto.

Henze, M., Harremoes, P., Arvin, E., & Jansen, J. (2002). *Wastewater Treatment: Biological and Chemical Processes* (3rd ed.). Germany: Springer.

Lee, J.-Y., Yoo, C., Jun, S.-Y., Ahn, C.-Y., & Oh, H.-M. (2010). Comparison of several methods for effective lipid extraction from microalgae. *Bioresource Technology*, *101 Suppl* (1), S75–7. http://doi.org/10.1016/j.biortech.2009.03.058

Li, Y., Horsman, M., Wu, N., Lan, C.Q., Dubois-Calero, N. (2008). Biofuels from microalgae. *Biotechnology Program*. 24, 815-820.

Luo, D., Hu, Z., Choi, D.G., Thomas, V.M., Realff, M.J., Chance, R.R. (2010). Life cycle energy and greenhouse gas emissions for an ethanol production process based on blue-green algae. *Environ Sci Technol 44*(22): 8670-8677.

Maity, J. P., Bundschuh, J., Chen, C.-Y., & Bhattacharya, P. (2014). Microalgae for third generation biofuel production, mitigation of greenhouse gas emissions and wastewater treatment: Present and future perspectives – A mini review. *Energy*, *78*, 104–113. http://doi.org/10.1016/j.energy.2014.04.003

Mambo, P., Westensee, D., Zuma, B., & Cowan, A. (2014). The Belmont Valley integrated algae pond system in retrospect. *Water SA*, *40*(2), 385. http://doi.org/10.4314/wsa.v40i2.21

Mehrabadi, A., Craggs, R., & Farid, M. M. (2015). Wastewater treatment high rate algal ponds (WWT HRAP) for low-cost biofuel production. *Bioresource Technology*, *184*, 202–14. http://doi.org/10.1016/j.biortech.2014.11.004

Mohammed, K., Ahammad, S. Z., Sallis, P. J., & Mota, C. R. (2014). Energy-efficient stirred-tank photobioreactors for simultaneous carbon capture and municipal wastewater treatment. *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, *69*(10), 2106–12. http://doi.org/10.2166/wst.2014.123

Muga, H. E., & Mihelcic, J. R. (2008). Sustainability of wastewater treatment technologies. *Journal of Environmental Management*, 88(3), 437–47. http://doi.org/10.1016/j.jenvman.2007.03.008

Muradyan, E.A., Klyachko-Gurivch, G.L., Tsoglin, L.N., Sergeyenko, T.V., & Pronina, N.A. (2004) Changes in lipid metabolism during adaptation of the *Dunaliella salina* photosynthetic apparatus to high CO2 concentration. *Russ Journal of Plant Physiology*. 51:53-62.

Nagarajan, S., Chou, S. K., Cao, S., Wu, C., & Zhou, Z. (2013). An updated comprehensive techno-economic analysis of algae biodiesel. *Bioresource Technology*, *145*, 150–6. http://doi.org/10.1016/j.biortech.2012.11.108

Origin Oil. A Breakthrough Technology to Transform Algae to Oil (Rep.). (2010). Retrieved http://www.originclear.com/pdf/OOIL_World_Biofuels_Markets_100316.pdf

Oswald, W.J. (1988) The role of microalgae in liquid waste treatment and reclamation. in *Algae and human affairs*. Editors Lembi, C.A., & Waaland, J.R. Cambridge University. P.255-281.

Oswald, W.J., Golueke, C.G. (1960). Biological transformation of solar energy. *Advanced Applied Microbiology*. 2, 223-262

Park, J.B.K., Craggs, R.J., Shilton, A.N. (2011). Wastewater treatment high rate algal ponds for biofuel production. *Bioresource Technology,* 102 (1), 35–42.

Park, J. B. K., Craggs, R. J., & Shilton, A. N. (2013). Enhancing biomass energy yield from pilot-scale high rate algal ponds with recycling. *Water Research*, 47(13), 4422–32. http://doi.org/10.1016/j.watres.2013.04.001

Passel, H., Dhaliwal, H., Reno, M., Wu, B., Amotz, A., Ivry, E., Gay, M., Czartoski, T., Laurin, L., & Ayer, N. (2013) Algal biodiesel life cyle assessment using current commercial data. *Journal of Environmental Management*. 15 (129), 103-111. doi: 10.1016/j.jenvman.2013.06.055

Pruvost, J., Le Gouic, B., Lepine, O., Legrand, J., & Le Borgne, F. (2015). Microalgae culture in building-integrated photobioreactors: biomass production modelling and energetic analysis. *Chemical Engineering Journal*, *284*, 850–861. http://doi.org/10.1016/j.cej.2015.08.118

Razzak, S. A., Hossain, M. M., Lucky, R. A., Bassi, A. S., & de Lasa, H. (2013). Integrated CO2 capture, wastewater treatment and biofuel production by microalgae culturing—A review. *Renewable and Sustainable Energy Reviews*, *27*, 622–653. http://doi.org/10.1016/j.rser.2013.05.063

Richardson, J.W., Johnson, M.D., Outlaw, J.L. (2012). Economic comparison of open pond raceways to photo bio-reactors for profitable production of algae for transportation fuels in the Southwest. *Algal Research* 1 (1), 93–100.

Saeid, A., & Chojnacka, K. (2015). Toward production of microalgae in photobioreactors under temperate climate. *Chemical Engineering Research and Design*, *93*, 377–391. http://doi.org/10.1016/j.cherd.2014.06.008

Scott, S. A., Davey, M. P., Dennis, J. S., Horst, I., Howe, C. J., Lea-Smith, D. J., & Smith, A. G. (2010). Biodiesel from algae: challenges and prospects. *Current Opinion in Biotechnology*, *21*(3), 277–86. http://doi.org/10.1016/j.copbio.2010.03.005

Slade, R., & Bauen, A. (2013). Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. *Biomass and Bioenergy*, *53*, 29–38. http://doi.org/10.1016/j.biombioe.2012.12.019

Soratana, K., Harper Jr., W. F., & Landis, A. E. (2012). Microalgal biodiesel and the Renewable Fuel Standard's greenhouse gas requirement. *Energy Policy*, *46*, 498–510. http://doi.org/10.1016/j.enpol.2012.04.016

Speranza, L. G., Ingram, A., & Leeke, G. A. (2015). Assessment of algae biodiesel viability based on the area requirement in the European Union, United States and Brazil. *Renewable Energy*, *78*, 406–417. http://doi.org/10.1016/j.renene.2014.12.059

Sturm, B. S. M., & Lamer, S. L. (2011). An energy evaluation of coupling nutrient removal from wastewater with algal biomass production. *Applied Energy*, *88*(10), 3499–3506. http://doi.org/10.1016/j.apenergy.2010.12.056

Tredici, M. R. (2004). Mass production of microalgae: Photobioreactors (A. Richmond, Ed.). Oxford: Blackwell.

Trent, Jonathan. (NASA Ames Research Center). 2012. OMEGA (Offshore Membrane Enclosures for Growing Algae) - A Feasibility Study for Wastewater to Biofuels**.** California Energy Commission. Publication number: CEC-500-2013-143.

United States, Air Force Center for Engineering and the Environment. (n.d.). *Net Energy Ratio of Biofuels*. Retrieved from http://www.afcec.af.mil/shared/media/document/AFD-100122-080.pdf

United States, California Environmental Protection Agency, Air Resources Board. (2014, December). *Proposed Re-adoption of the Low Carbon Fuel Standard*. Retrieved from http://www.arb.ca.gov/regact/2015/lcfs2015/lcfs15isor.pdf

United States, Department of Energy, Energy and Information Administration. (2016, March). *Monthly Biodiesel Production Report with Data for January 2016*. Retrieved from http://www.eia.gov/biofuels/biodiesel/production/biodiesel.pdf

United States, Environmental Protection Agency, Transportation and Air Quality. (2002, October). *A Comprehensive Analysis of Biodiesel Impacts and Exhaust Emissions*. Retrieved from https://www3.epa.gov/otaq/models/analysis/biodsl/p02001.pdf

United States, Environmental Protection Agency. (1993, September). *Constructed Wetlands for Wastewater Treatment and Wildlife Habitat*. Retrieved from http://www.epa.gov/sites/production/files/2015-10/documents/2004_10_25_wetlands_introduction.pdf

United States, US Congress, Congressional Budget Office. (2014, June). *The Renewable Fuel Standard: Issues for 2014 and Beyond*. Retrieved from https://www.cbo.gov/sites/default/files/113th-congress-2013-2014/reports/45477-Biofuels2.pdf

United States, US Energy Informatin Administration. (2016, April 11). *Gasoline and Diesel Fuel Update*. Retrieved April 15, 2016, from https://www.eia.gov/petroleum/gasdiesel/

Wright, P.J. & Weber, J.H. (1991). Biosorption of inorganic tin and methyltin compounds by estuarine macroalgae. Environmental Science and Technology, 25: 287-294.

Yee, N., Benning, L.G., Phoenix, V.R., & Ferris, F.G. (2004). Characterization of metal-cyanobacteria sorption reactions: A combined macroscopic and infrared spectroscopic investigation. *Environmental Science and Technology*, 38: 775-782.