

DISSERTATION

LIFE CYCLE AND TECHNOECONOMIC ANALYSIS OF MICROALGAE-BASED  
BIOFUELS

Submitted by

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## ABSTRACT

# LIFE CYCLE AND TECHNOECONOMIC ANALYSIS OF MICROALGAE-BASED BIOFUELS

Microalgae are an appealing feedstock for production of biofuels due to their high productivity compared to terrestrial plant-based feedstocks, and their relative tolerance of low quality land and water. Despite these potential benefits, there are technological, environmental and economic challenges that must be overcome to enable commercialization of any microalgae-to-biofuels process. Due to the relative immaturity of the field, assessments of the environmental performance, scalability and economic performance of microalgae-based biofuels are highly uncertain, data poor, and incomparable across technologies. This dissertation seeks to study these aspects of microalgae-based biofuels so as to provide models of increased utility for technical design, investment planning, and achieving policy-level objectives.

This work is divided in three primary research efforts. First, this research develops an integrated life cycle assessment of the microalgae to biofuels process using a detailed engineering model derived from a pilot-scale photobioreactor system. The life cycle assessment quantifies and compares energy consumption, greenhouse gas emissions, and scalability of the biofuel life cycle. Second, this work defines the water footprint for a photobioreactor-based biofuel production system with geographical and temporal resolution. The water footprint (WF) of microalgae biofuel is comprehensively assessed using a combined process and economic input-output lifecycle analysis method, using blue, green and lifecycle WF metrics, four different fuel conversion pathways, and 10 continental US locations with high productivity yields.

Finally, a technoeconomic analysis of the baseline enclosed photobioreactor microalgae to biofuels system is performed with stochastic economic risk assessment. This section provides a range of probabilities of economic success based on the sensitivity of the microalgae-to-biofuel process to the variable economic variables and scenarios.

Based on the results of these integrated assessments of microalgae biofuels, this study communicates an improved understanding of the economic and environmental performance of microalgae biofuels and their characteristics compared to petroleum and biofeedstock-based biofuels.

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## **Chapter 1. Introduction**

### **1.1 Research Motivation**

Due to instability in oil prices and strong global concerns about climate change, terrestrial-based biofuels have been identified as potential alternative energy sources because of potential reduction of fossil fuel dependence, lower CO<sub>2</sub> emissions, incentives to agriculture and economies (Posten and Schaub 2009; Tao and Aden 2009). However, the combined oil corps, waste cooking oils and fats cannot meet the world's need for transportation fuels, not even meet the diesel demand of 44 billion gallons per year by the United States (Pienkos and Darzins 2009). Conventional terrestrial plants are relatively inefficient in capturing light, converting only less than 0.5% of the solar energy. Other concerns are the strong impacts on global food supplies, either by converting foods into biofuels or switching agricultural production from food to non-food crops. Some key features make microalgae a superior feedstock for biofuel production. Microalgae exhibit rapid growth rates, can thrive in water of wide range of salinities and chemical compositions. Microalgae synthesize neutral lipids and oils and other harvestable biochemical products that can offset the costs of production. There are also a variety of potential coupling uses of microalgae, such as nutrient and contaminant removal of wastewater sources, as sequester of CO<sub>2</sub> gas produced in power plants. However, due to the incipient maturity of this technology, the merits of microalgae-to-biofuel pathway are still debatable.

### **1.2. Background**

Algae are presented as an alternative renewable fuel feedstock that could enable a more sustainable and economic source of biofuel (Pienkos and Darzins 2009; Mata, Martins et al. 2010). Compared to first-generation biofuel feedstocks, microalgae are characterized by higher

solar energy yield, year-round cultivation and unlike other land-based crops, algae can be grown in low quality or marginal lands, desert land that are not utilized to grow food (Brown and Zeiler 1993; Dismukes, Carrieri et al. 2008; Li, Horsman et al. 2008; Raja, Hemaiswarya et al. 2008; Posten and Schaub 2009). Some algal strains can also thrive in saline water, thus avoiding further use of freshwater. Algae feedstock cultivation can also be coupled with combustion power plants to sequester CO<sub>2</sub> through biofixation and be integrated into wastewater treatments and output processes (Li, Horsman et al. 2008).

Microalgae environmental and economic impact analysis has been challenged by the lack of real-world cultivation data available. For instance, studies have also asserted that the high yield of microalgae will make it so that so only 1 to 3% of the US total crop area would be used to produce approximately 50% of US transportation fuel needs (Chisti 2007). Similarly, the theoretical maximum production of oil from algae has been calculated at 354,000 L·ha<sup>-1</sup>·a<sup>-1</sup> (Weyer, Bush et al. 2010). In opposition to these theoretical data sources, pilot plant facilities and scalable experimental data sources have shown a near-term realizable production potential of 58,700 liters·ha<sup>-1</sup>·a<sup>-1</sup> of biodiesel from microalgae, compared to 3,217 liters·ha<sup>-1</sup>·a<sup>-1</sup> of ethanol from corn or 540 liters·ha<sup>-1</sup>·a<sup>-1</sup> of biodiesel from soybeans (Pimentel and Patzek 2005; Chisti 2007; Pradhan, Shrestha et al. 2008).

Debates over microalgae biofuel exist about sustainability and economic feasibility of commercial algae productions (Chisti 2007; Liu, Clarens et al. 2012). Numerous studies have been published on the topic, and despite most approaches have modeled facilities that include an algae growing facility, extracted lipids being converted into biodiesel and residual biomass being applied to marketable use, results seem to be divergent. Disparities are mainly attributed to inconsistency in system boundaries, scope, methodologies of allocation of coproducts,

preventing on clear agreement on environmental performance of microalgae biofuels (Benemann 1996; Kadam 2002; Lardon, Helias et al. 2009; Sialve, Bernet et al. 2009; Clarens, Resurreccion et al. 2010; Luo, Hu et al. 2010; Sander and Murthy 2010; Stephenson, Kazamia et al. 2010; Campbell, Beer et al. 2011). Economic analyses on photosynthetic microalgae based biofuels were also being conducted in many studies (Carriquiry, Du et al. 2011; Sun, Davis et al. 2011). Due to early stage of development of this segment, cost of producing algal oil remains a challenge. Existing cost studies present widely diverging results (Benemann 1996; Molina Grima, Belarbi et al. 2003; Schenk, Thomas-Hall et al. 2008). These differences are mainly attributed to ranges of oil yields that can vary from conservative to aggressively high yields affecting strongly the cost estimates. Capital costs, several coupled plants with CO<sub>2</sub> sequestration, or wastewater application as cost lowering components and a scenario-by-scenario basis per studies do not allow direct cross-comparisons (Tapie and Bernard 1988; Benemann 1996; Campbell, Beer et al. 2011; Davis, Aden et al. 2011; Norsker, Barbosa et al. 2011). These results show a continued lack of agreement on production costs and economic studies on microalgae based biofuels.

### **1.3. State of the Field**

Based on the results of the studies of microalgae biofuels performed to date, the primary challenges for sustainability and feasibility of microalgae-to-biofuels are described in the following sections:

#### **1.3.1. Life Cycle Assessment Modeling**

Life cycle assessment (LCA) has been the fundamental tool to evaluate the sustainability of biofuels. Although LCA is a well-recognized method, published standards are incomplete and

are not widely adhered to (Delucchi 2004). LCAs of the microalgae-based biodiesel process exist in the literature but consensus on the inputs and methods appropriate for microalgae-based biofuels is lacking.

The LCA literature makes use of the metrics of net energy ratio (NER), defined here as the ratio of energy consumed to fuel energy produced and GHG emissions per unit of energy produced as the functional units for comparison purposes. As previous studies have shown, results from LCA are highly sensitive to definitions of system boundaries, life cycle inventories, process efficiencies, and functional units (Delucchi 2004; Farrell 2006; Hill, Nelson et al. 2006). LCA studies often include various NER definitions, key parameter values, sources of fossil energy, and coproduct allocation and displacement methods, complicating comparisons among studies and policy synthesis (Kim and Dale 2005). Some authors focused on ethanol as primary biofuel (Luo, Hu et al. 2010).

Hirano (1998) considered the production of algae-derived methanol and derived a NER of 1.1 (Hirano, Hon-Nami et al. 1998). Minowa and Sawayama (1999) perform a net energy analysis of algae gasification with nitrogen recovery which increases the NER ( $>1$ ) but do not incorporate a detailed process model (Minowa and Sawayama 1999). Campbell et al. (2011) perform a net energy analysis based on review of previous studies, but the combination of data from different microalgae strains presents a problem of consistency (Campbell, Beer et al. 2011). Lardon et al. (2009) provides a thorough life cycle assessment of an open raceway pond system for the production of algae biodiesel. Lardon et al. extrapolates laboratory-scale results to assign the energy burdens due to cultivation and allocates energy consumption to coproducts without using coproduct displacements (Lardon, Helias et al. 2009). Clarens et al. (2010) does not incorporate energy and materials for conversion of algae oil to fuel, but does include energy for

the procurement of CO<sub>2</sub> (Clarens, Resurreccion et al. 2010). Jorquera et al. (2009) perform a very detailed life cycle analysis for both raceway ponds and closed photobioreactors, however exclude energy use for some cultivation stages, oil extraction and fuel conversion in the analysis (Jorquera, Kiperstok et al. 2010). A recent study from Argonne National Laboratory (ANL) has reconciled microalgae biofuels LCA to preexisting LCAs of soy and other feedstock-based biodiesel to allow for direct, consistent comparison among these technologies. ANL expanded the GREET model for algal lipid fuels, where algae's C, N and P contents were stoichiometrically used as approach to determined fertilizer consumption; water and transport costs are quite well estimated, but strict mass and energy balances were not attempted since the analysis is not based on detailed engineering process modeling, yet data were collected from published literature, inventories, benchmarking, extrapolating and theoretical data (Frank, Han et al. 2011a).

To date, the LCA of algae biofuels has proceeded without detailed experimental data and engineering process models of each production stage, without a standard and consistent set of conditions and boundaries by which results can be compared to conventional fuels and biofuels, and without detailed consideration of PBR-specific productivity, and energy and material consumption.

### **1.3.2. Evaluation of Water Footprint**

The water resource is highly linked to energy and food production. Renewable energy and fuel production targets are predicted to increase dramatically the water intensity and consumption for transportation and energy sectors. Previous evaluations of the water consumption of microalgae biofuels have not developed a lifecycle methodology comparable to

other biofuels studies in literature, and have concentrated on open-pond cultivation systems as opposed to photobioreactor (PBR) microalgae cultivation systems (Clarens, Resurreccion et al. 2010; Harto, Meyers et al. 2010; Wigmosta, Coleman et al. 2011; Yang, Xu et al. 2011).

Among other resources and material consumption by the microalgae-to-biofuel process, water resource has been identified as a key resource limitation (EISA 2007). Clarens et al. (2009) analyzed WF for direct and upstream process, but only for cultivation of biomass, excluding steps of fuel conversion, transportation and distribution. Yang et al. (2010) studied the WF from microalgae biodiesel derived from open-pond cultivation systems, but only accounted for the actual water consumed in process, excluding the water requirements associated with energy and consumable materials. Wigmosta et al. (2011) constructed a detailed geographically-resolved water consumption analysis of microalgae feedstock production and fuel conversion, but distribution, transportation and coproduct allocations were not included as would be required for a complete lifecycle accounting. Harto et al. (2010) performed a comparison of the lifecycle water footprint of open pond and tubular horizontal PBR cultivation systems, but incorporated higher productivities than has been reported in studies of near-term, industrially-realizable cultivation systems (Quinn, de Winter et al. 2011; Quinn, Catton et al. 2012).

In general, the water consumption analysis studies lack on comparable basis, system boundary conditions and diverse process-specific assumptions of the many modeled conversion processes. In addition to these factors, different scopes, lack of standard and system metrics enhance difficulties to compare the water intensity of microalgae biofuels to water intensity of other fuels and bio-based fuels and to evaluate effects of geographical and climatic variability in the water intensity.

### **1.3.3. Technoeconomic Modeling**

Most technoeconomic studies present a traditional cost and capital investment calculation, but few consider more informative way of assessing and presenting the risk in microalgae-to-biofuel investment (Hertz 1964; Hertz 1979). No study has presented a measurement of the risks involved as a way to inform decisions on key technological or capital investments, (Damodaran 2007).

A number of technoeconomic studies over the years have informed a current conventional wisdom for algae biofuels production. In this conventional wisdom, algae biofuels are a capital cost-intensive, but high productivity source of biofuels. Open ponds are commonly viewed as the most economical and near-term feasible technology for realizing algae biofuel production at scale (Amer, Adhikari et al. 2011; Davis, Aden et al. 2011; Sun, Davis et al. 2011). For examples, Benemann et al. study provided complete explanations of costs estimates, but focused only on open pond production systems and did not analyze risks (Benemann 1996). Tapie and Bernard conducted a review of the algae literature, describing data and costs for large-scale algae production facilities and reporting total production costs of non-processed biomass ranging from \$0.15 to \$4.00/kg (Tapie and Bernard 1988). Huntley and Redalje estimate oil production costs at \$84/bbl (2004 dollars), assuming no improvements in current technology, but because of the private nature a detailed list of costs is not presented (Huntley and Redalje 2007). Chisti evaluated the technical feasibility of microalgae for biodiesel production. In reviewing production practices, Chisti finds that the current technology in microalgal production, estimating the cost per gallon of production to be \$2.95 and \$3.80 for PBRs and open ponds, respectively (2006 dollars), but there are no details for how the author arrived at these cost estimates (Chisti 2007). Shen et al. reviewed the performance, special features, and technical

and/or economic barriers of various microalgae mass production methods, including open ponds and PBRs, but the analyzed plant was not for biofuel production, adding difficult to any reliable conclusion about the use of open ponds for algae production for biofuels. Plus, the open pond and PBR systems are for different locations and producing different amounts of biomass, further complicating an accurate comparison (Shen, Yuan et al. 2009). Norsker et al. calculated production costs under Dutch climatic conditions for three different microalgal production systems: open ponds, horizontal tubular PBRs and flat panel PBRs. They evaluate the economics for a commercial size 100 hectare facility and calculate the capital and operating costs for a one hectare facility, showing the economies of scale that exist between the two different size facilities and conducting a sensitivity analysis on the effects of reducing mixing costs and nutrient costs, and improving irradiation and photosynthetic efficiency, which is significant for algal production (Norsker, Barbosa et al. 2011). Davis et al. is one of the most recent and comprehensive techno economic studies evaluating the economics of open pond and PBR systems, where both systems use an anaerobic digestion system as a coupled system with microalgae cultivation (Davis, Aden et al. 2011). Richardson et al. analyzes probability of success for both open pond and PBR systems, based on Davis et al. models, evaluating CAPEX and OPEX reductions from 100 to 10% in several scenarios as to achieve probability of success of 95% or higher, but does not discuss what major changes would allow those reductions (Richardson, Johnson et al. 2012).

In general, technoeconomic analyses (TEAs) are more focused on open pond technologies, and the existing few analyses on enclosed PBR are not based on large-scale commercial scale model. Hence more, previous studies focused on determining microalgae biofuel costs, breakeven costs and prices only comparable to the analyzed period of the study and

based on fixed costs for energy and other supplies, not considering the dynamic changes of fossil fuel prices and materials, and their influence on microalgae biofuel costs.

#### **1.4. Research Questions**

Several studies have claimed microalgae biofuels as a potential fossil fuel replacement due to microalgae high growth rate and high lipid content, among other properties, over land-based agricultural feedstocks for biofuels. However the advantages of this potential biofuel are still controversial and unclear among researchers.

Based on these challenges, a primary research question can be posed:

##### **1.4.1. Primary research question:**

*What is the environmental and economic performance of microalgae biofuels in system-scale metrics and life cycle perspective?*

To answer this question, this research effort will combine a system of models to be developed and individually validated. The system comprises of a systemic fuel life cycle model adjusted at a level appropriate for boundaries and framework of the analyzed process. The systemic life cycle model will then be integrated with the baseline engineering model to derive system-level performance with focus on environmental impacts and sustainability.

The primary research question can be further broken down into research questions of smaller scope and, afterward, works that are required to answer each research question are broken down into tasks. Each task provides outputs to accomplish the dissertation goals and contribute to answer the primary research question.

#### **1.4.1.1. Research Question 1**

*What are the energy efficiency, GHG emission reduction and scalability of the microalgae-to-biofuel process?*

##### **1.4.1.1.2. Hypothesis 1**

The combination of a fuel LCA model with a robust and detailed engineering model of a microalgae-to-biofuel process can enable a system-level evaluation of the environmental performance of microalgae biofuel.

##### ***Task 1.1 – Integrate LCA Model with a Detailed Engineering Model***

The LCA model uses specifically Argonne National Laboratory GREET model integrated into process specifics of the detailed engineering model. Appropriate and consistent boundary is clearly defined as inputs of material consumption and energy use in the microalgae-to-biofuel process are provided by the detailed engineering model.

##### ***Task 1.2 – Evaluate Environmental Performance through Life Cycle Assessment***

This baseline life cycle assessment model will be used to compare and contrast the net energy and GHGs of microalgae to that of conventional petroleum-based diesel and soy-based biodiesel. For clarity and comparability, these comparisons are made using the same assumptions and LCA boundaries as GREET 1.8c. This baseline model is integrated with a robust and detailed engineering model of the microalgae growth, harvest and extraction phases as to describe types and amounts of energy use, material inputs, material outputs for the microalgae feedstock processing stage. After feedstock processing for oil

extraction, the conversion stage consists of chemical and industrial process to convert the extracted algae lipids into biodiesel through transesterification. Microalgae fatty acid composition suggests some advantages in conversion treatment and fuel properties of microalgae oil over vegetable oils, but there is a lack of quantifying the WF of industrial-scale lipid to biofuel conversion data using microalgae-derived lipids. Instead, the data for the conversion process considered in this study are based on soybean oil conversions.

The GREET 1.8c model will be used to simulate the material consumption, net energy use, and GHG emissions for the life cycle of the microalgae-to-biofuel process. The boundaries of the life-cycle considered for this study start with the growth stage of the microalgae and end at the point of distribution of biodiesel to consumer pumping stations. This LCA boundary is called “strain-to-pump” and is analogous to the “well-to-pump” boundary for conventional crude oil. GREET 1.8c was modified to represent the microalgae-to-biodiesel process, with no changes in methodology inherent in the original model. To allow a direct comparison of these results to previous GREET LCAs on soy-based and conventional petroleum fuels, this study applies the same life cycle boundaries as does GREET.

#### **1.4.1.2. Research Question 2**

***What is the water resource impact of a large commercial scale of microalgae-to-biofuel production?***

#### ***1.4.1.2.1. Hypothesis 2***

The dependency of microalgae-to-biofuel on geography and climate is significant and shown in several studies (Wigmosta, Coleman et al. 2011; Quinn, Catton et al. 2012). As microalgae cultivation is a process that demand reasonable capital investment and costs, a sample of locations with high productivity of lipid are to be studied as evaluation of stressing of water resource in baseline engineering model plants. A model of water footprint with consistent boundaries at several system levels can enable assessment of water intensity of microalgae biofuels at local and economic-wide scale.

#### ***Task 2.1. Develop Model for Water Footprint Evaluation***

Ten relevant locations with high productivity of lipid will be selected. The selection will be based on local lipid yields or land availability with moderate lipid yields that can actually achieve high productivities.

While exists an uncountable amount of water, only a small percent of freshwater exists. The water footprint is primarily the evaluation of freshwater resource stressing due to microalgae-to-biofuel process. To address the variety of study scopes, system boundaries and metrics, this research effort proposes to analyze water footprint in three main metrics: blue, green and life cycle water footprint for four conversion pathways.

The water footprint analyses require different approaches: (1) a process approach, for direct process water use, and (b) an economic input-output life cycle assessment approach, for upstream water use estimations

### ***Subtask 2.1.1. Develop Process WF Assessment***

Develop a process WF model, with the quantitative measurements of water, energy and material inputs are performed for each process, based on the detailed engineering model of the Solix Biosystem Generation3 Photobioreactor cultivation system. The four fuel conversion pathways, transportation and distribution systems are based on the Argonne National Laboratory GREET model. The process WF model will enable the estimation of blue water footprint.

### ***Subtask 2.1.2. Develop Geographic and Climate Resolution Model***

Develop a matrix to estimate: (1) cultivation length, specific to each analyzed locations, in order to define biomass and lipid yield and, (2) evaporation and precipitation rates, linked to the cultivation period of each analyzed locations, in order to complement the loss of water through evaporation of microalgae-to-biofuel process and the water gain through precipitation water captured by microalgae cultivation systems.

### ***Subtask 2.1.3. Build Economic Input-Output Life Cycle Assessment***

Build the economic input-output approach to estimate water use for fertilizers and material inputs to the microalgae-to-biofuel process. The economic input-output lifecycle assessment (EIO LCA) approach uses value from the Carnegie Mellon University EIO LCA tool (Institute 2008).

***Task 2.2. Evaluate the water footprint of algae biofuels at a variety of scales and metrics***

Integrate process WF assessment with geographic and climate resolution model in order to estimate blue and green water footprint of microalgae biofuels.

Integrate critically process WF and economic input-output life cycle assessments, with geographic and climate resolution model in order to estimate life cycle water footprint of microalgae biofuels. In the boundaries of LCA, upstream and downstream water consumptions are considered. Upstream water consumption is estimated through EIOLCA approach for all energy and materials and downstream water consumption is estimated through coproduct allocation.

***Subtask 2.2.1. Estimate Coproduct Water Credits***

Estimate water credits for the coproducts generated in the four conversion pathways, for two coproduct allocation methods:

(1) The displacement method will analyze water credits related to the replacement of algae for fish and shrimp feed by algal extract, or Lipid Extracted Algae (LEA); the coproducts of other fuel conversion pathways - heavies, fuel gas, propane fuel mix, light-cycle oils (LCO) and clarified slurry oil (CSO) - can replace fossil fuels, such as natural gas, residual fuel oil and diesel. The coproduct glycerin can replace petroleum-based glycerin, but since glycerin is mostly impure and with low economic value, no water credits will be assigned to it.

(2) The energy allocation method will analyze water credits related to the use of coproducts to generate energy. The water credits are assessed with use of LEA as co-firing product for bioelectricity generation. The coproducts – heavies, fuel gas, propane fuel mix, LCO and CSO – will replace fossil fuels with water credits based on the ratio of their low heating values (LHV) and diesel LHV. No water credit is assigned to glycerin, as it is assumed as process waste.

Evaluate water intensity of microalgae-to-biofuel process, in terms of local and regional demands for large-scale productions and to the water intensity of fossil fuel and other biofeedstock-based biofuels. The blue, green and lifecycle water footprints of microalgae biofuels will allow assessment of water resource demands and constraints at both local and economy-wide lifecycle scales.

### **1.4.1.3. Research Question 3**

*What is the economic potential of microalgae to biofuel process?*

#### ***1.4.1.3.1. Hypotheses 3***

Probability of economic success of microalgae-to-biofuel is dependent on a variety of economic and technical details of the production environment including: fossil fuel prices, market size and growth, selling prices and revenue projections of microalgae biofuels.

A dynamic analysis model with multifactorial inputs, such as projections of fossil fuel prices or historical data range when in case of lack of price projections, analogies for market size and growth, and ranges of selling prices can estimate economic performance and success probability of microalgae biofuels.

### ***Task 3.1. Develop a Baseline Technoeconomic Model***

LCA and TEA must go together to evaluate if microalgae biofuel process is an environmentally sustainable and economically acceptable process. The sustainability of biofuel process requires not only positive environmental performance (as detailed in Section 1), but also requires the feedstock-to-process to be economically viable in terms of costs and benefit analysis.

The baseline technoeconomic model is based on an enclosed suspended PBR system for production capacities from 3,000 to 6,500 ton of lipid per year. The baseline model will use NREL economic detailing as starting point and Solix Biosystem design.

### ***Task 3.2. Evaluate Cost and Capital Investment Risks***

The economic success of microalgae biofuels is highly dependent on fossil fuel prices. Due to energy use and material consumption of microalgae-to-biofuel process, the prices of natural gas and coal are direct variables to electricity prices and, consequently, to microalgae biofuel prices. The prices of petroleum also affects directly to chemicals, such as plastic and fertilizers, which affects capital and operational expenditures of microalgae biofuel process. In the other hand, the increase of fossil fuel prices presents as a potential market demand and growth for renewable biofuels, thus higher prices and higher revenue.

The risk factors that are evaluated with higher impacts on microalgae biofuels are energy and material input prices, market size, microalgae biofuel production costs, capital investment, operating expenses and others (Hertz 1979; Razgaitis 1999).

***Subtask 3.2.1. Estimate the Range of Values for Each of Risk Factors***

For fossil fuel prices, price projections will define the value ranges. Capital investment, operating expenses and fixed costs will be based on the technoeconomic model, within the range of production capacities.

***Subtask 3.2.2. Define the Risk Factor Distributions***

Due to the uncertainty nature, a sensitivity analysis will be performed with all inputs into the baseline technoeconomic model.

All inputs will be tested within a variation of -30% and +30% from their baseline values, to evaluate. This sensitivity analysis will provide the variables that will have higher or significant effects in the distribution of production costs on the baseline model.

***Subtask 3.2.3. Generate Probability Curves of Production Cost***

With these variables, Monte Carlo simulations will be performed with low, high and reference projections to evaluate and generate probability-weighted average of production costs.

## **1.5. Research Plan**

A three-phase research plan is proposed to address the proposed problems. The three phases, while independent, are ordered to construct a cohesive research effort and all add to a collective knowledge.

Phase 1 involves the development of life cycle assessment model to enable evaluation of net energy efficiency and GHG emissions of microalgae-to-biofuel process.

Phase 2 focuses on estimation of water footprint in different metrics to enable understanding local and regional water demands and credits.

Phase 3 involves the development of the technoeconomic baseline model for estimation of production costs of microalgal diesel and the evaluation of risks and probability of return of investments of microalgae-to-biofuel process.

## **Chapter 2. Life Cycle Analysis on the Net Energy and Greenhouse Gas Emissions of Biodiesel Derived from Microalgae**

### **2.1. Chapter Summary**

Biofuels derived from microalgae have the potential to replace petroleum fuels and first-generation biofuels, but the efficacy with which sustainability goals can be achieved is dependent on the lifecycle impacts of the microalgae-to-biofuel process. This study proposes a detailed, industrial-scale engineering model for the species *Nannochloropsis* using a photobioreactor architecture. This process level model is integrated with a lifecycle energy and greenhouse gas emissions analysis based on the methods and boundaries of the Argonne National Laboratory GREET model. Results are used to evaluate the net energy ratio (NER) and net greenhouse gas emissions (GHGs) of microalgae biodiesel in comparison to petroleum diesel and soybean-based biodiesel with a boundary equivalent to “well-to-pump”. The NER of the microalgae biodiesel process is 0.93 MJ of energy consumed per MJ of energy produced. In terms of net GHGs, microalgae-based biofuels avoids 75 g of CO<sub>2</sub>-equivalent per MJ of energy produced. The scalability of the consumables and products of the proposed microalgae-to-biofuels processes are assessed in the context of 150 billion liters (40 billion gallons) of annual production.

### **2.2. Introduction**

The next generation of biofuel feedstocks must be critically analyzed to determine their energetic and greenhouse gas (GHG) emissions impact while considering scalability to a significant level of production. Compared to first-generation biofuel feedstocks, microalgae are characterized by higher solar energy yield, year-round cultivation, the use of lower quality or brackish water, and the use of less- and lower-quality land (Brown and Zeiler 1993; Dismukes,

Carrieri et al. 2008; Li, Horsman et al. 2008; Raja, Hemaiswarya et al. 2008; Posten and Schaub 2009; Williams, Inman et al. 2009). Researchers have shown that algae feedstock cultivation can be coupled with combustion power plants or other CO<sub>2</sub> sources to sequester GHG emissions and has the potential to utilize nutrients from wastewater treatment plants (Li, Horsman et al. 2008). The theoretical maximum production of oil from algae has been calculated at 354,000 L·ha<sup>-1</sup>·a<sup>-1</sup> (38,000 gal·acre<sup>-1</sup>·a<sup>-1</sup>) (Weyer, Bush et al. 2009), but pilot plant facilities and scalable experimental data have shown a near term realizable production of 46,000 liters·hectare<sup>-1</sup>·a<sup>-1</sup> (5000 gal·acre<sup>-1</sup>·a<sup>-1</sup>), compared to 2,533 liters·hectare<sup>-1</sup>·a<sup>-1</sup> (271 gal·acre<sup>-1</sup>·a<sup>-1</sup>) of ethanol from corn or 584 liters·hectare<sup>-1</sup>·a<sup>-1</sup> (62.5 gal·acre<sup>-1</sup>·a<sup>-1</sup>) of biodiesel from soybeans (Ahmed, Decker et al. 1994; Pimentel and Patzek 2005; Chisti 2007; Pradhan, Shrestha et al. 2008; Yeang 2008).

Life cycle assessment (LCA) has been the fundamental tool to evaluate the sustainability of biofuels. Although LCA is a well-recognized method, published standards are incomplete and are not widely adhered to (Delucchi 2004). The LCA literature makes use of the metrics of net energy ratio (NER, defined here as the ratio of energy consumed to fuel energy produced) and GHG emissions per unit of energy produced as the functional units for comparison purposes. The results from LCA are highly sensitive to definitions of system boundaries, life-cycle inventories, process efficiencies, and functional units (Pimentel and Patzek 2005; Farrell 2006; Hill, Nelson et al. 2006). Biofuels LCA studies often include various NER definitions, key parameter values, sources of fossil energy, and coproduct allocation and displacement methods, complicating comparisons among studies and policy synthesis (Sheehan, Camobreco et al. 1998; Kim and Dale 2002; Pimentel and Patzek 2005; Farrell 2006; Hill, Nelson et al. 2006; Davis, Anderson-Teixeira et al. 2009).

LCAs of the microalgae-based biodiesel process exist in the literature but consensus on the inputs and methods appropriate for microalgae-based biofuels is lacking. Hirano (1998) considered the production of algae-derived methanol and derived a NER of 1.1 (Hirano, Hon-Nami et al. 1998). Minowa and Sawayama (1999) perform a net energy analysis of algae gasification with nitrogen recovery which increases the NER ( $>1$ ) but do not incorporate a detailed process model (Minowa and Sawayama 1999; Chisti 2008). Campbell et al. (2008) perform a net energy analysis based on review of previous studies, but the combination of data from different microalgae strains presents a problem of consistency (Campbell, Beer et al. 2011). Lardon et al. (2009) provides a thorough life cycle assessment of an open raceway pond system for the production of algae biodiesel. Lardon et al. extrapolates laboratory-scale results to assign the energy burdens due to cultivation and allocates energy consumption to coproducts without using coproduct displacements (Lardon, Helias et al. 2009). Clarens et al. 2010 does not incorporate energy and materials for conversion of algae oil to fuel, but does include energy for the procurement of CO<sub>2</sub> (Clarens, Resurreccion et al. 2010). Performing a coherent LCA of the microalgae to biodiesel process requires detailed models of each of the feedstock processing stages (growth, dewater, extraction, conversion, and distribution) combined with a standard and consistent set of LCA boundary conditions.

Based on the state of the field, there exists a need to quantify the sustainability effects of the microalgae-to-biofuel process. This study builds on academic literature, industrial consultation, and pilot plant experience of algae feedstock processing to generate a model of net energy and GHG emissions of the microalgae-to-biofuel process. This baseline LCA will be used to compare and contrast the net energy and GHGs of microalgae to that of conventional petroleum-based diesel and soy-based biodiesel. For clarity and comparability, these

comparisons are made using the same assumptions and LCA boundaries as GREET 1.8c (Wang, Wu et al. 2005).

### **2.3. Methods**

In order to describe the net energy and GHG impacts of microalgae biodiesel, we must develop a valid, extensible, and internally consistent model of the materials inputs, energy use, and products for the process. The three primary components of this model are: a detailed engineering process simulation of microalgae from growth through extraction, a more generalized model of microalgae from conversion to end use, and an integrated calculation of net energy and GHG emissions due to impacts from the inputs, outputs, processes, and coproduct allocation for the microalgae biodiesel production. The simulation architecture is shown in Figure 1.

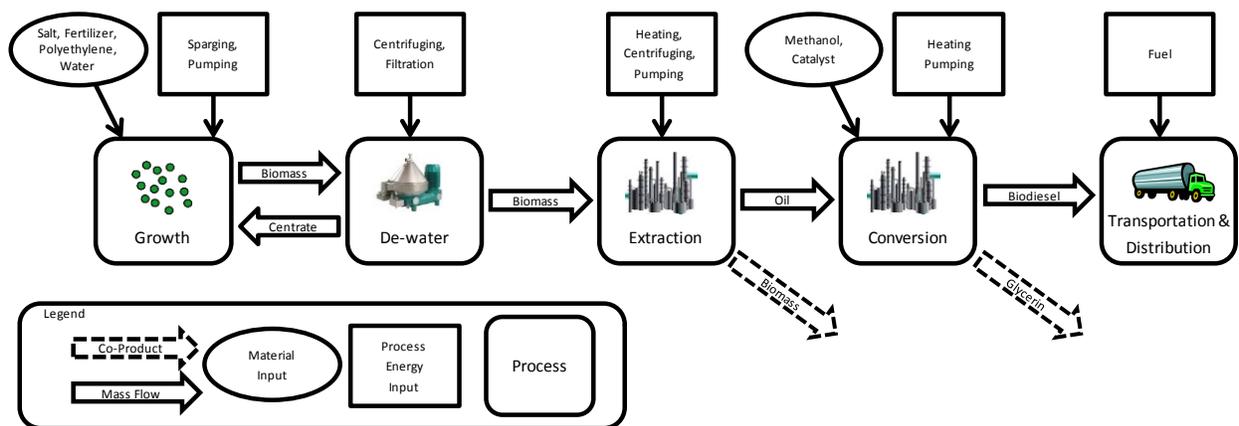


Figure 1. Microalgae Biodiesel Processing and Lifecycle Analysis Model Overview

## 2.4. Detailed Engineering Process Model

The purpose of the detailed engineering process model of the microalgae growth, harvest, and extraction phases is to describe the material inputs, material outputs, and types and amounts of energy consumed in the microalgae feedstock processing stages. The baseline model of microalgae to biodiesel process is based on a 315 hectares (776 acres) facility, which includes photosynthetically active and built areas. The temporal unit for evaluation of the process is 1 year. The model incorporates the recycling of growth media but does not recover nitrogen from extracted biomass (Chisti 2008). Additional material recycling will affect the results of the LCA, but a lack of data regarding the energy and material costs preclude its inclusion in this study.

### 2.4.1. Growth Model

Two primary architectures for mass-culture of microalgae have been proposed: open ponds (ORP) and photobioreactors (PBR). PBR cultivation has advantages over ORP in they can achieve higher algae densities, higher productivity, and mitigate contamination. The algae strain *Nannochloropsis salina* was selected and modeled because of its high lipid content and high growth rate. Under the conditions of the Colorado State University pilot plant scale reactor system, *Nannochloropsis salina* can achieve a lipid content of 50% by weight (Suen, Hubbard et al. 1987; Emdadi and Berland 1989; Fábregas, Maseda et al. 2004), and an average annual growth rate of  $25 \text{ g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$  (Boussiba, Vonshak et al. 1987; Suen, Hubbard et al. 1987; Gudin and Chaumont 1991). The nitrogen and phosphate content of the algae are defined as 15% and 2% by mass according to biological growth requirements and lipid productivity research (Redfield 1958; Arrigo 2005; Rodolfi, Zittelli et al. 2009). The salinity of the system is set at  $20 \text{ g}\cdot\text{L}^{-1}$  (Abu-Rezq, Al-Musallam et al. 1999).  $\text{CO}_2$  enriched air (2%  $\text{CO}_2$ ) is sparged through the bioreactor to provide carbon and active mixing of the culture. The energy required for sparge is

based on an experimentally validated specific power requirement of  $0.4 \text{ W}\cdot\text{m}^{-2}$  (Weissman, Goebel et al. 1988). Mixing by sparge is performed during periods of photosynthetically active growth and when bio-available nitrogen is present in the media. The facility is assumed to be located in a temperate region of the US where the amount of energy required for thermal regulation is assumed negligible due to the availability of very low power thermal regulation resources (including ground and pond loop heat exchangers). The difference between precipitation and evaporation results in water losses of  $2.5 \text{ cm}\cdot\text{day}^{-1}$  ( $1 \text{ in}\cdot\text{day}^{-1}$ ) from the water bath that supports the reactors (Smith, Lof et al. 1994). The polyethylene PBR bags are replaced at 5 year intervals.

Electricity is used to power pumping and sparging. Diesel is used to fuel transportation on the facility for maintenance and inspection. The microalgae facility is assumed to be located next to a pure  $\text{CO}_2$  source, such as a natural gas amine plant, which implies no transportation costs, preprocessing costs, or energy requirements to deliver  $\text{CO}_2$ . The material inputs, material outputs, and energetic inputs for the growth model are detailed in Table 1..

#### **2.4.2. Dewater Model**

The removal of free water from the harvested algae is required and can be achieved through flocculation, centrifugation, vacuum belt dryers, or solar driers. Centrifugation is modeled for this study because it is currently commercially used and represents a mature technology (Grima 2003).

The energy consumption for transport of the algae medium from the PBR to a centralized processing unit is based on losses from pumping through a 13 cm (5 in) PVC pipe over a distance of 500 m with a pump efficiency of 70% (White 1999; Glover 2000). The energy consumption required for centrifugation is modeled based on the performance of a continuous

clarifier that consumes 45 kW steady state with a throughput of 45,000 liters·hour<sup>-1</sup> (based on the particle size of *Nannochloropsis*) (Yanovsky 2009). The centrate (free water) from the clarifier is recycled with a 0.1 micron polypropylene filtration system (Keystone\_Division 2002). The algae paste is then conveyed from the clarifier output to the extraction stage requiring 0.00137 J·kg<sup>-1</sup> (Herum 1960).

Energy consumption for these processes is derived entirely from electricity as summarized in Table 1.

### **2.4.3. Extraction Model**

The lipid extraction and recovery model is designed from literature to represent a scalable and near-term realizable and commercially viable extraction process. The process is based off of the process for recovery of lipids from soybeans due to the lack of large scale oil recovery systems for microalgae. The process incorporates a shear mixer, centrifuge, decant tank, solvent recovery, and two distillation units for the recovery of solvents.

The extraction system uses a hexane to ethanol solvent mixture of 9:1, at a solvent to oil ratio of 22:1, which recovers 90% of the lipids present in the algae. The parameters of this process are assumed to be identical to the extraction process used for other oil crops (Conkerton, Wan et al. 1995; Dominguez, Nunez et al. 1995; Gandhi, Joshi et al. 2003; Zhang and Liu 2005). Counter flow heat exchangers with an effectiveness of 0.90 are used to recover process heat (Shah 2003). Evaporator-condenser systems with 80% energy recovery are used for solvent recovery and oil separation. The energy required to move and centrifuge is modeled based on 500 m length, 13 cm (5 in) diameter PVC transfer pipe with a pump efficiency of 70% and a centrifugal separator respectively (Glover 2000; Yanovsky 2009).

Energy consumption for these processes is derived from electricity for pumping, shear mixing, and centrifugation and natural gas for heating, with all solvents being recycled as summarized in Table 1.

#### **2.4.4. Conversion Model**

The conversion stage consists of the chemical and industrial processes required to convert the extracted algae lipids into biodiesel through transesterification. The process requires the reaction of lipids (triacylglycerols) with methanol in the presence of a catalyst, producing fatty acid methyl esters (biodiesel) and glycerin. Microalgae lipids and soybean lipids are composed of similar triacylglycerols but at slightly different composition percentages (Reske, Siebrecht et al. 1997; Tonon, Harvey et al. 2002). For this study, the types and quantities of energy and material inputs to the conversion processes are assumed identical and are derived from the GREET 1.8c soy conversion model.

Natural gas is used for process heating at a rate of  $2.10 \text{ MJ}\cdot\text{kg}^{-1}$  of algae biodiesel and electricity is used for mixing and transport at a rate of  $0.03 \text{ KWh}\cdot\text{kg}^{-1}$  of biodiesel. The methanol, catalyst (sodium methoxide), and neutralizer (hydrochloric acid) are consumed in proportion to the quantity of biodiesel produced, as summarized in Table 1.

#### **2.5. Transportation and Distribution Model**

The microalgae production facility modeled includes facilities for growth, dewater, extraction, and conversion stages, enabling the transportation of the feedstock to the processing plant to be performed by conveyor. The distances and means of transportation and distribution (barge, rail, and truck) are assumed to be the same as soy biofuel. Energy consumption for the transportation and distribution stage is summarized in Table 1.

## **2.6. Lifecycle Assessment Model**

The GREET 1.8c model was used to simulate the material consumption, net energy use, and GHG emissions for the life cycle of the microalgae-to-biofuel process. The boundaries of the life-cycle considered for this study start with the growth stage of the microalgae and end at the point of distribution of biodiesel to consumer pumping stations. This LCA boundary is called “strain-to-pump” and is analogous to the “well-to-pump” boundary for conventional crude oil. GREET 1.8c was modified to represent the microalgae-to-biodiesel process, with no changes in methodology inherent in the original model. To allow a direct comparison of these results to previous GREET LCAs on soy-based and conventional petroleum fuels, this study applies the same lifecycle boundaries as does GREET. For example, GREET 1.8c excludes the energy required to construct agricultural facilities, processing facilities and refineries. Similarly, this study excludes the energy required to construct the micro-algae bioreactors and significant modifications were made to the GREET1.8c LCA for N<sub>2</sub>O emissions.

### **2.6.1. Microalgae growth facility**

The modeled photosynthetic facility is composed of a number of 36 meter (120 ft) long and 5 millimeter thick clear polyethylene bags supported in a thermal bath. The reactors incorporate an air sparge system designed to provide CO<sub>2</sub> and turbulent mixing. The reactors are assumed to have a lifetime of 5 years. The bags are subdivided into three different reactor sets: incubation reactors, growth/stress reactor set 1, and growth/stress reactor set 2.

The growth process as modeled is a batch system comprised as of one set of incubation reactors and 2 sets of growth/stressing reactors. The incubation reactors are used to provide microalgae inoculum for the growth/stress reactor systems. The growth/stress reactors are used

to used to grow and stress the culture in a procedure to maximize lipid yield, while minimizing energy consumption.

The growth process begins with the inoculation of algae into nutrient-rich medium in the incubator reactors. All bioavailable nutrients are absorbed in the first 2 days of growth. The culture is then cultivated until it transitions from linear growth stage (nutrient-rich growth) to a stationary growth stage (nutrient-deprived) after approximately 5 days. The stationary growth stage represents a growth stage with lower biomass productivity rate (approximately  $15 \text{ g m}^{-2} \text{ day}^{-1}$ ), but with increased lipid production. On the 5<sup>th</sup> day, all of the culture in the incubation reactors is harvested, and mixed with nutrient-rich media. Part of the culture is injected into the incubation reactors, the remainder is injected into the growth/stress reactors. This incubation, growth, and inoculation process is repeated every 5 days within the incubation reactors.

In the growth/stress reactors, the inoculum from the incubation reactors will grow for 5 days and will then transition from the linear growth phase into the stationary growth phase. For the next 5 days, the culture is cultivated under nutrient-deprived stationary growth conditions. Lipid content increases to 50% of cell weight during the stationary stress growth (Emdadi and Berland 1989). At the end of a 10 day growth cycle, the culture is harvested and the reactors are re-inoculated with culture from the incubation reactors. This inoculation, linear growth, stationary growth, harvest cycle is repeated every 10 days with each set of growth/stress reactors. Two sets of growth/stress reactors with their 10 day cycle time are required to match the 5 day cycle of the incubation reactors. The facility is assumed to operate year round and does not require annual repopulation.

## **2.7. Lifecycle Energy Model**

The modified GREET model is used to calculate both direct and upstream energy consumption throughout the microalgae-to-biofuel process and to calculate energy credits due to coproducts. The total energy consumption can be represented as a NER with units of MJ of energy consumed per MJ of energy produced.

Funded by the U.S. department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), the Center for Transportation Research at Argonne National Labs undertook a project to develop a full life cycle model for the evaluation of various fuel and vehicle combinations. The model generated entitled GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) fully evaluates energy and material consumption and the corresponding emissions of a full fuel-cycle. GREET incorporates more than 100 fuel production pathways with the general fuel pathways illustrated in Figure 2. The LCA boundary of GREET can be defined by either "well-to-pump" or "well-to-wheel" as illustrated in Figure 3.

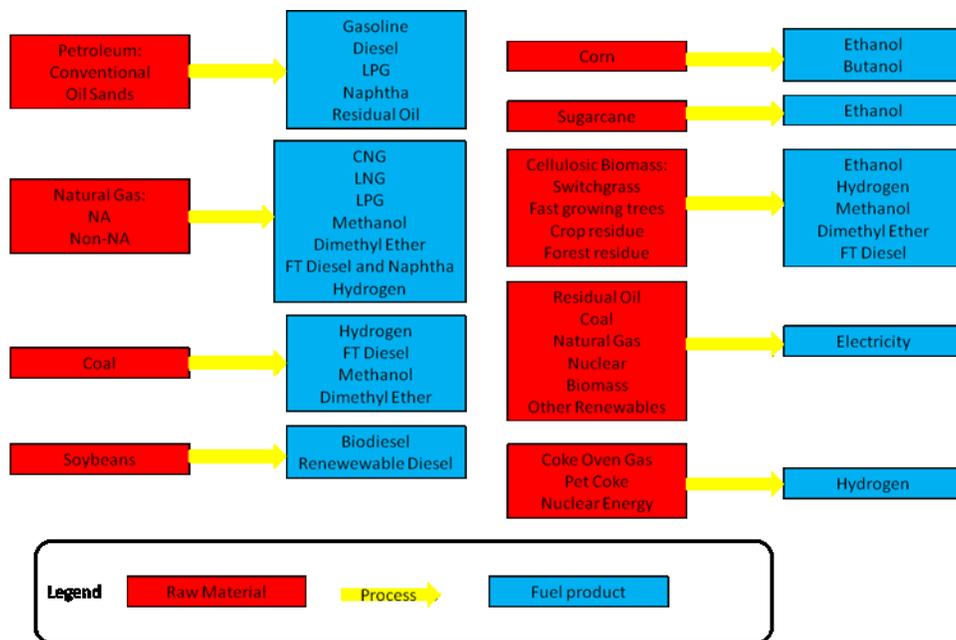


Figure 2. General fuel production pathways (Wang 2005)

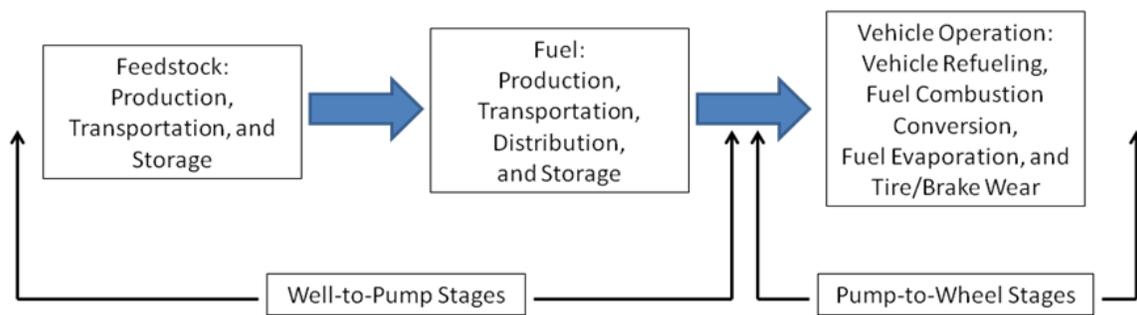


Figure 3. Illustration of “Well-to-Pump” and “Well-to-wheel” boundaries (Wang 2005)

GREET separates the energy use by type (petroleum, coal, natural gas, nuclear, etc) to more accurately evaluate environmental impacts. GREET evaluates the type of energy consumed to calculate upstream energy and GHG emissions implicit in materials and energy flows. GREET draws on open literature, engineering analysis, and stakeholder inputs to generate an accurate data base of energy and material requirements for specific processes. The major assumptions in GREET on “well-to-pump” study are the energy efficiencies of the fuel production activities, GHG emissions of the fuel production activities and the emission factors of fuel combustion technologies. In this study, the GREET model was utilized to evaluate the microalgae life cycle with a boundary defined as “strain-to-pump” (cultivation stage of microalgae, dewatering algae, algae oil extraction, algae oil conversion and algae biodiesel transportation and distribution) which is analogous to “well-to-pump” for conventional diesel. The system boundaries for the analysis performed are presented in Figure 4.

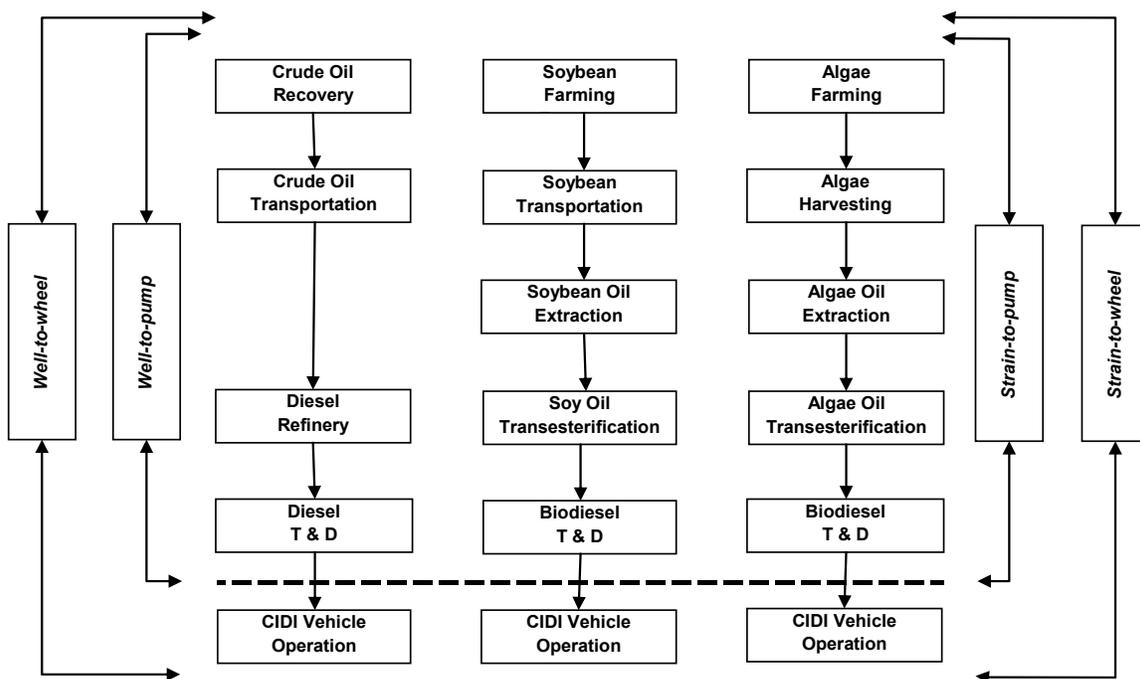


Figure 4. System Boundaries for Life cycle Analysis of Petroleum Diesel, Soybean Biodiesel and Algae Biodiesel (Wang 2005)

The GREET model utilizes data from Energy Information Administration (EIA) and US Department of Agriculture (USDA) for all energy and material inputs to the process of recovery and refinery of petroleum based diesel, and the production and process of soybean based biodiesel, including the stages of agricultural farming, harvesting, transportation of feedstock, soybean oil extraction, conversion and biodiesel transportation and distribution to the pump stations.

The NER is calculated in units of MJ of energy consumed per MJ of energy produced. The modifications required to the GREET model for the evaluation of microalgae based biofuel were the inclusion of life cycle energy and emissions of salt (NaCl) and high density polyethylene (HDPE) bags (material for construction of the photobioreactors) to the database.

## **2.8. GHG Emission Model**

GREET is used for the evaluation of the lifecycle GHG emissions associated with the microalgae-to-biofuel process. GREET accounts for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions originated from specific sources of energy and materials consumed and their respective upstream emissions. IPCC global warming potentials are applied to CH<sub>4</sub> and N<sub>2</sub>O emissions to calculate the CO<sub>2</sub> equivalent (CO<sub>2</sub>-eq) emissions of the microalgae-to-biofuel process. GREET also accounts the avoidance of CO<sub>2</sub> emissions due to allocation of coproducts, i.e. replacement of conventional products by microalgae-to-biofuel coproducts.

The GHG emissions model totals the CO<sub>2</sub> captured during microalgae growth with the CO<sub>2</sub> credits due to coproducts and combines the CO<sub>2</sub> and CO<sub>2</sub>-eq emissions due to the energy and materials consumed for a final result.

The total GHG emissions are calculated in units of grams of CO<sub>2</sub>-eq per MJ of energy produced. Gases such as methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are converted to a CO<sub>2</sub>-eq basis using IPCC global warming potential standards (IPCC 2006). GREET also calculates the emissions of six criteria air pollutants non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), particulate matter with a diameter of 10 micrometers or less (PM<sub>10</sub>) and 2.5 micrometers or less (PM<sub>2.5</sub>), and sulfur oxides (SO<sub>x</sub>). Both this study and GREET assign an indirect GHG emissions equivalency to NMVOC and CO emissions. This indirect GHG emissions equivalency considers that NMVOC and CO emissions are converted into CO<sub>2</sub> in the atmosphere (Seinfeld and Pandis 1998). Molecular weight ratios are used to convert NMVOC and CO emissions to CO<sub>2</sub>-eq emission. This method for assessing environmental burden from CO and NMVOC has been the subject of debate and revision at IPCC. Although IPCC methods do not define a global warming potential associated with CO or NMVOC emissions, IPCC assessment reports do quantify an indirect global warming potential for NMVOCs (Forster 2007). Inclusion of indirect emissions is methodologically defensible (Gillenwater 2008) and has been used in many peer-reviewed publications including (Huo, Wang et al. 2009). Inclusion of the indirect emissions of CO and NMVOCs in this study allows for direct comparison to GREET's conventional and biofuel models. GREET contains a database of the GHG emissions for many types of energy sources, fertilizers, and other relevant materials used in this assessment. Only the upstream GHG emissions and energy consumption due to the production of NaCl (required for replacing salt lost in media recycling) had to be added to the GREET inventory.

In addition to the “strain-to-pump” analysis, this study has also run simulations using the “strain-to-wheel” LCA boundary, which includes all stages of “strain-to-pump” as well as the

combustion of fuel in transportation vehicles. GREET assumes that soybean-derived and algae-based diesel fuels are used in 100% pure form in compression-ignition, direct-injection (CIDI) engine vehicles. Due to the lack of emissions data from the combustion of microalgae based biofuel, it was assumed that the fuel economy and emissions from soy- and microalgae-based biofuels in CIDI vehicles are the same. These simulations result in 93.08 g CO<sub>2</sub>-eq/MJ for petroleum-based diesel, 5.01 g CO<sub>2</sub>-eq/MJ for soy-based biodiesel, and the avoidance of 1.31 g CO<sub>2</sub>-eq/MJ for microalgae-based biodiesel.

### **2.8.1. N<sub>2</sub>O Emissions Details**

Due to their high global warming potential value, N<sub>2</sub>O emissions can have a significant impact in the total GHG emissions. For terrestrial crops, N<sub>2</sub>O emissions are produced in 3 distinct ways:

- From upstream N<sub>2</sub>O emissions during manufacture of nitrogen-based fertilizer.
- From direct emissions from the fertilizer applied to the field.
- From residual biomass left in the field after harvesting.

For microalgae biofuels, these upstream, direct, and residual biomass sources of N<sub>2</sub>O emissions must be considered.

For the upstream emissions, the default GREET 1.8c N<sub>2</sub>O emissions from the manufacturing of nitrogen-based (urea) fertilizer are used.

For the direct and residual biomass sources of N<sub>2</sub>O, the microalgae growth system is fundamentally different than a traditional terrestrial crop system. This study proposes that the direct and residual biomass N<sub>2</sub>O emissions for the microalgae-to-biofuel are negligible due to the processes and controls used to cultivate microalgae. In terrestrial

crop N<sub>2</sub>O emissions, the guideline for calculating the emissions is assuming that 1% of the total nitrogen applied is converted to N<sub>2</sub>O (IPCC 2006). This percentage includes:

- fertilizer converted into N<sub>2</sub>O by denitrifying bacteria in the soil,
- biomass left in the field which is afterward converted into N<sub>2</sub>O,
- fertilizer carried away by runoff and then converted into N<sub>2</sub>O in the watershed.

The mechanism for the generation of N<sub>2</sub>O in terrestrial crop fields is the anaerobic denitrification of nitrogen based fertilizer by bacteria found in the soil (Delwiche 1981; Golterman 1985; Bothe 2007). Despite the presence of bio-available nitrogen within microalgae reactors, denitrification (and direct N<sub>2</sub>O emissions) will not occur within the reactors because the system is a closed system where denitrifying bacteria is not present, and because the reactors are an aerobic environment. In the microalgae growth stage, nitrogen is supplied in the form of dissolved fertilizer at the beginning of the batch growth process. The uptake rate of the nitrogen by the microalgae is a light-dependent process and the bio-available nitrogen is depleted in 36 hours (Flynn, Davidson et al. 1993; Yamaberi, Takagi et al. 1998; Takagi, Watanabe et al. 2000). During photosynthetically active periods, the algae produce oxygen and therefore are growing in an aerobic environment (Skerman and Macrae 1957; Jannasch 1960). At night, an oxygen level of 8 ppm can be achieved by sparging air through the culture. Maintaining an oxygen level greater than 0.2 ppm will inhibit the reduction of nitrogen by denitrifying bacteria (Skerman and Macrae 1957). The growth of denitrifying bacteria in a high oxygen environment will restrict the synthesis of the nitrogen-reducing enzyme, inhibiting the potential for N<sub>2</sub>O emission (Sacks and Barker 1949). For this study, the

system is sparged 24 hours per day during periods of bio-available nitrogen to generate an aerobic environment, eliminating denitrification and direct N<sub>2</sub>O emissions.

For this study, the microalgae reactor is a self-contained closed photobioreactor (PBR) and thus does not have any loss of fertilizer through runoff.

## **2.9. Coproduct Allocation Methods**

In evaluating the life cycle energy consumption of the microalgae-to-biofuel process, the biomass that is not converted to fuel can be considered as a coproduct. For this study, the microalgae coproduct credits are allocated using the displacement method. The displacement method assumes that the coproduct displaces a preexisting conventional product. The displacement coproduct credits represent the lifecycle energy and GHG emissions that would be required to produce the displaced product. Coproduct credits are subtracted from the overall energy and GHG emissions of the microalgae-to-biofuel process.

The two primary coproducts of the microalgae to biofuels process are extracted algae biomass (generated from the extraction stage) and glycerin (generated from the conversion stage). For the displacement method, the extracted microalgae biomass is used to displace conventional microalgae biomass, which is an ingredient in aquaculture fish feed. The displaced algae biomass is cultivated using conventional, industrial-scale processes (Renaud, Parry et al. 1991; Markovits, Conejeros et al. 1992; Sukenik, Zmora et al. 1993; Reboloso-Fuentes, Navarro-Perez et al. 2001; Carraretto, Macor et al. 2004). The microalgae extract mass to microalgae mass displacement ratio is 1.3:1 due to the higher content of protein in microalgae extract. Microalgae-derived glycerin is assumed to directly displace petroleum-derived glycerin (Wang 2005).

## **2.10. Results**

The process parameters presented above and the displacement coproduct allocation method define the baseline scenario designed to represent a near-term realizable, industrially relevant microalgae-to-biofuel production process based on a PBR configuration.

### **2.10.1. Materials and Energy Consumption of the Microalgae-to-Biofuel Process**

The first results of the microalgae-to-biofuel process model are a tabulation of the consumables and energy consumption of each process stage, presented in Table 1..

The quantities and types of these direct consumables are the inputs to the NER and GHG calculation models which translate these consumptions into lifecycle energy consumption and GHG emission rates.

There are a few steps of the microalgae-to-biofuel process that make up a large proportion of the primary energy consumption. 99% of the electrical energy consumed in the growth phase is consumed to compress air for sparge. 76% of the energy consumed during extraction is required for solvent recovery. Some other steps of the process are energetically negligible (moving the algae and recycling media consume less than 1% of the total electrical energy).

Table 1. Summary material and energy inputs and outputs for the baseline microalgae to biofuel process for a period of 1 year

<b>STAGE/Inputs</b>	<b>VALUE</b>	<b>UNITS</b>
<b>GROWTH STAGE</b>		
Photosynthetic area per facility area	0.80	ha·ha <sup>-1</sup>
Salt consumption	134	g·(kg dry algae) <sup>-1</sup>
Nitrogen fertilizer consumption	147	g·(kg dry algae) <sup>-1</sup>
Phosphorus fertilizer consumption	20	g·(kg dry algae) <sup>-1</sup>
Polyethylene consumption	1.17	m <sup>3</sup> ·ha <sup>-1</sup>
Diesel fuel consumption	10	L·ha <sup>-1</sup>
Electricity consumption	41,404	kWh·ha <sup>-1</sup>
Algae biomass yield	91,000	kg·ha <sup>-1</sup>
<b>DEWATER STAGE</b>		
Electricity use	30,788	kWh·ha <sup>-1</sup>
<b>EXTRACTION STAGE</b>		
Natural gas consumption	141,994	MJ·ha <sup>-1</sup>
Electricity consumption	12,706	kWh·ha <sup>-1</sup>
Extracted oil yield	43,009	L·ha <sup>-1</sup>
<b>CONVERSION STAGE</b>		
Natural Gas consumption	2.10	MJ·(kg biodiesel) <sup>-1</sup>
Electricity consumption	0.03	kWh·(kg biodiesel) <sup>-1</sup>
Methanol consumption	0.10	g·(kg biodiesel) <sup>-1</sup>
Sodium hydroxide consumption	0.005	g·(kg biodiesel) <sup>-1</sup>
Sodium methoxide consumption	0.0125	g·(kg biodiesel) <sup>-1</sup>
Hydrochloric acid consumption	0.0071	g·(kg biodiesel) <sup>-1</sup>
<b>TRANSPORTATION &amp; DISTRIBUTION</b>		
Diesel consumption	0.0094	L·(kg biodiesel) <sup>-1</sup>

### **2.10.2. Net Energy Results**

The second result of this analyses is a comparison of the net energy of the microalgae-to-biofuel process to the soy-to-biofuel process and to a conventional petroleum-to-diesel process (both obtained from U.S. average data of GREET 1.8c), illustrated in Table 2. It is notable that both soy-based biodiesel and microalgae-biodiesel take advantage of coproduct credits to reduce the net energy consumed. Since refineries produce multiple products, the energy use and emission of petroleum-based fuel are calculated by allocating total refinery energy use into individual refinery products at the aggregate refinery level (Wang **2008**). The microalgae biofuel has 30% less input energy per unit of product (before coproduct allocation) than conventional soy-based biofuel.

Table 2. Net Energy Ratio (NER) in MJ/MJ of Conventional Diesel, Soybean Biodiesel and Microalgae Biodiesel Processes with the Energy Consumption for Each Feedstock Processing Stage

Stage	Conventional Diesel	Soybean Biodiesel	Microalgae Biodiesel
Crude oil recovery*	0.053	-	-
Growth*	-	0.32	0.73
Dewater*	-	-	0.17
Oil extraction*	-	0.46	0.21
Fuel conversion*	0.13	0.17	0.17
Feedstock input*	-	1.50	0.43
Transportation & Distribution*	1.8E-7	0.01	0.01
<b>Coproduct credits*</b>	-	<b>(0.83)</b>	<b>(0.79)</b>
<b>Total NER**</b>	<b>0.19</b>	<b>1.64</b>	<b>0.93</b>

\*Stage MJ consumed·(MJ produced)<sup>-1</sup>

\*\*Total MJ consumed·(MJ produced)<sup>-1</sup>

Table 2 shows that the energy required to support the growth stage during microalgae cultivation is 2.1 times higher than the energy required to support the growth stage for soy cultivation. Microalgae oil extraction uses less energy than soy oil extraction, however, the algae requires an energy intense dewatering stage that is not present in the soy-to-biofuels process. The primary energetic advantage of the algae process, relative to soy, is related to the energy embedded in the feedstock. Soybeans contain 18% lipid by dry weight, whereas *Nannochloropsis salina* contains 50%. This means that less algae is required to produce 1 unit of biofuel energy than is required of soy. GREET quantifies this relationship as a conversion ratio, defined as the ratio of the lower heating value (LHV) of biodiesel to the LHV of the feedstock. For soybeans, the ratio of the energy of the feedstock to the energy of the fuel output is 40% compared to 70% for microalgae. A higher conversion ratio means that a lower fraction of the LHV of the algae input to the conversion process is lost to coproducts. In summary, although algae cultivation is more energy intensive, as has been asserted in previous studies (Nash and Frankel 1986; Hirano, Hon-Nami et al. 1998; Sawayama, Minowa et al. 1999; Sawayama, Minowa et al. 1999; Richmond 2004; Spolaore, Joannis-Cassan et al. 2006; Reijnders 2008; Posten 2009), lifecycle analysis shows that the microalgae-to-biofuels process is less energy intensive per unit of energy output.

### **2.10.3. GHG Emissions Results**

Total GHGs can provide a more holistic comparison of the environmental impact of the production of these fuels. Table 3 presents the comparison of the GHG components and net emissions for production of petroleum diesel, biodiesel from soybean and microalgae feedstocks.

Table 3. Net GHG Emissions of Conventional Diesel, Soybean Biodiesel and Microalgae Biodiesel Processes with the Contribution of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O gases per unit of MJ of energy produced.

	<b>Conventional Diesel</b>	<b>Soybean Biodiesel</b>	<b>Microalgae Biodiesel</b>
<b>CO<sub>2</sub> (g·MJ<sup>-1</sup>)</b>	14.69	-72.73	-59.49
<b>CH<sub>4</sub> (g·MJ<sup>-1</sup>)</b>	2.48	0.42	0.74
<b>N<sub>2</sub>O (g·MJ<sup>-1</sup>)</b>	0.07	0.58	-16.54
<b>Net “strain to pump” GHG (gCO<sub>2</sub>-eq·MJ<sup>-1</sup>)</b>	17.24	-71.73	-75.29

These results show that soybean and microalgae based biofuels processes can realize GHG reductions relative to a petroleum diesel baseline. Both biofuels result in a net negative CO<sub>2</sub> output due to CO<sub>2</sub> capture intrinsic in the production of biomass during photosynthesis, the displacement of petroleum, and the displacement of coproducts. The microalgae biodiesel process has a 5% better performance in terms of net GHGs compared to soy-based biodiesel in the boundary “strain-to-pump”. A notable component of the microalgae GHG emissions reduction is the net avoidance of N<sub>2</sub>O that is achieved. Although the microalgae growth stage uses a higher mass of N-fertilizer than the soy growth stage, the aerobic conditions of algae cultures suppress the direct emission of N<sub>2</sub>O. For microalgae, no biomass is left in the field where it can be subject to denitrification and the closed PBRs do not experience loss of fertilizer through runoff (Sacks and Barker 1949; Skerman and Macrae 1957; Jannasch 1960; Golterman 1985; Flynn, Davidson et al. 1993; Bothe 2007). Coproduct displacement provides additional net-negative N<sub>2</sub>O emissions. The net N<sub>2</sub>O emission avoidance that can be realized through the microalgae-to-biofuels process represents a significant difference between the GHG emissions profiles of microalgae compared to other agricultural bioenergy processes, which often have N<sub>2</sub>O emissions as the largest source of positive GHG emissions (Adler, Del Grosso et al. 2007).

#### **2.10.4. Sensitivity to Allocation Method**

The production of microalgae-based biofuel has not been performed at industrial scale, the uses and values of the algae coproducts are highly uncertain. To test the sensitivity of the results of this study to coproduct end-uses, allocations of coproduct credits are considered in three different ways: displacement, energy-value allocation, and market-value allocation.

With the displacement method, it is assumed that a conventional product is displaced by a coproduct generated in the biofuel process. The life cycle energy that would have been used and

the emissions that would have been generated during production of the displaced product are counted as credits for the coproduct generated by the biofuel pathway. These credits are subtracted from the total energy use and emissions associated with the fuel pathway under evaluation. The allocation method allocates the feedstock use, energy use, and emissions between the primary product and coproducts on the basis of mass, energy content, or economic revenue. In this study, glycerin and extracted biomass are produced as coproducts during the production of algae-based fuel.

The displacement method bases the replacement of algae used as fish and rotifer feed in aquaculture by the algal extract produced in the algae-to-fuel process. As alga used in aquaculture does not require harvesting, this allocation accounts for the energy used for algae cultivation only. It was used an averaged value of algae cultivation of 3,250 Btu/lb of dry algae (Kadam, 2002; Aresta, 2005). For GHG emissions, the energy used in the algae cultivation was assumed as primarily electricity from coal and natural gas powered plants.

The energy-value allocation method bases the value of the coproduct credits on the heating value of the coproduct. This study assumes that the extracted biomass can be used as co-firing material with a heating value of 14.2 MJ/Kg for the baseline scenario (Kadam 2002). Glycerin is allocated at its lower heating value.

The market value method bases the value of the coproduct credits on the economic revenue potential of the coproduct. The value of extracted biomass as an economic commodity has not been fully investigated due to the immaturity of the technology. At present, a large-scale use of microalgae biomass is as a component of the feed used for the cultivation of fish fry in aquaculture. The current commercial (Kost 2010) market value of fish feed for aquaculture, is US \$2.65 kg<sup>-1</sup>. This feed is composed of a minimum of 50% protein and of 20% oil content.

The extracted biomass can be used to construct a feed of similar composition. The extracted biomass is 36.7% protein and 5% oil on a dry weight basis. Canola oil at \$0.93 kg<sup>-1</sup> (20) is added to the extracted biomass to produce a product with the same ratio of protein to oil. To create an equivalency between the algae-canola feed and the conventional feed, a mass displacement of 1.5 is applied, where 1.5 lb of algae-canola feed can replace 1 lb of fish feed (De Pauw, Morales et al. 1984; Lubzens, Gibson et al. 1995; Metting 1996; Pulz and Gross 2004; Richmond 2004). A market value for the original algae extract (before oil addition) is then estimated is \$1.87 kg<sup>-1</sup>. Costs relating to oil mixing and transportation are not included. The market value of glycerin applied in the simulation is \$0.81 kg<sup>-1</sup>, which is the average of the range of \$0.62-\$0.99 kg<sup>-1</sup> (21)

The NER obtained using the displacement method is 0.93 MJ of energy consumed per MJ of fuel energy produced, which is lower than the NER of 1.29 MJ MJ<sup>-1</sup> and 0.83 MJ MJ<sup>-1</sup>, obtained by energy- and market-value methods, respectively. In terms of NER, the displacement and market-value methods find that the proposed microalgae-to-biofuels process realizes more energy than it consumes. The CO<sub>2</sub> equivalent discounts as calculated using the displacement method are higher than those calculated using the energy-value or the market-value method. For the metric of net GHG emissions, the sustainability benefits of the proposed process are shown to be sensitive to these three methods of coproduct allocation as presented in Table 4.

Table 4. Comparison of the net GHG Emissions of the microalgae to biodiesel process as a function of method of coproduct allocation

<b>Microalgae Biodiesel Emissions</b>	<b>Displacement Method</b>	<b>Energy-Value Method</b>	<b>Market-value Method</b>
CO <sub>2</sub> (g/MJ)	-59.49	-29.80	-55.92
CH <sub>4</sub> (g/MJ)	0.74	2.22	0.98
N <sub>2</sub> O (g/MJ)	-16.54	0.21	0.09
Net “strain to pump” GHG (gCO <sub>2</sub> - eq/MJ)	-75.29	-27.37	-54.85
Net “strain to wheel” GHG (gCO <sub>2</sub> - eq/MJ)	-1.44	49.35	21.88

### **2.10.5. Sensitivity to Electricity Sources**

A major component of the energy used in the microalgae to biofuels process is electricity, as shown in Table 1. As such, the composition of the electricity will have an effect on the process NER and GHG emissions. Average US electricity mix, the Northeast electricity mix, and the California electricity mix are compared to understand the sensitivity of this analysis to electricity sources.

The average US electricity mix is composed of 50.4% coal, 20% Nuclear power, 18.3% natural gas, and 11.3% biomass, residual oil and others. Northeast (NE) mix is composed of 33.9% nuclear, 29.9% coal, 21.7% natural gas, 14.5% biomass, residual oil and others. The California mix is composed of 36.6% natural gas, 28.3% variety of renewable sources, 20.5% nuclear, 13.3% coal and 1.3% biomass (Wang 2005). The NER and GHG emissions for the different power sources are presented in Table 5 and Table 6, respectively.

The small variation in NER and GHG emissions shown in Table 5 and Table 6 are due to the different efficiencies and sources for electricity generation. The California mix as electricity source presents the best net GHG emission and NER compared to Northeast and US average mix.

This analysis shows that the NER and GHG performance of the proposed microalgae-to-biofuels process is robust to assumptions regarding electricity sources.

Table 5. Net Energy Ratio per Electricity Source and Mix with a LCA boundary of “strain-to-pump” for the baseline scenario

<b>Electricity Source</b>	<b>NER</b>
US Average Mix	0.93 MJ MJ <sup>-1</sup>
North-east Mix	0.86 MJ MJ <sup>-1</sup>
California Mix	0.82 MJ MJ <sup>-1</sup>

Table 6. Analysis of Net GHG per source of Electricity with a LCA boundary of “strain-to-pump” for the baseline scenario

	<b>Conventional Diesel</b>	<b>Soybean Biodiesel</b>	<b>Microalgae Biodiesel</b>		
	<b>U.S. Electricity Mix</b>	<b>U.S. Electricity Mix</b>	<b>California State Electricity Mix</b>	<b>Northeast Electricity Mix</b>	<b>U.S. Electricity Mix</b>
CO <sub>2</sub> (g/MJ)	14.69	-72.73	-80.36	-72.34	-59.49
CH <sub>4</sub> (g/MJ)	2.48	0.42	0.45	0.45	0.74
N <sub>2</sub> O (g/MJ)	0.07	0.58	-16.56	-16.54	-16.54
Net GHG (g CO <sub>2</sub> -eq/MJ)	17.24	-71.73	-96.47	-88.43	-75.29

### **2.10.6. Scalability**

The Energy Policy Act of 1992 directed the US Department of Energy to evaluate the goal of replacing 30% (~150 billion liters) of the transportation fuel consumed in the US by 2010 with replacement fuels. In March of 2007 this goal was deemed unreachable and the deadline for fuel replacement was changed to 2030 (Department of Energy 2007). Algae-based biofuels are purported to be the most scalable of the biofuel processes currently available (Chisti 2007). In order to understand the scalability of the proposed processes, material inputs and material outputs, the baseline engineering process model was scaled so as to produce 150 billion liters per year with the corresponding consumables and products presented in Table 7.

Table 7. Scalability metrics derived from the baseline micro-algae to biofuels process model scaled to a production of 40 billion gallons per year of algae biodiesel

Scalability Metric	Value	Notes
Land Required	4.41x10 <sup>6</sup> hectares (1.09x10 <sup>7</sup> acres)	16% of Colorado Land Area (0.45% of US Land Area) (U.S. Census Bureau 2009)
CO <sub>2</sub> Consumption	8.17 x10 <sup>11</sup> kg·a <sup>-1</sup>	32% of CO <sub>2</sub> from US power generation (Energy Information Administration 2007)
Natural Gas Consumption	1.39 x10 <sup>11</sup> kWh·a <sup>-1</sup>	2% of US production (Energy Information Administration 2009)
Electricity Consumption	2.77 x10 <sup>11</sup> kWh·a <sup>-1</sup>	7% of US production (Energy Information Administration 2007)
Water Consumption	5.07 x10 <sup>12</sup> L·a <sup>-1</sup> (1.34 x10 <sup>12</sup> gal·a <sup>-1</sup> )	27% of Colorado river annual flow (Reisner 1993)
Nitrogen Consumption	4.71 x10 <sup>10</sup> kg·a <sup>-1</sup>	1900% of US urea production (U.S. Census Bureau 2009)
Algae Biodiesel Production	150 x10 <sup>9</sup> L·a <sup>-1</sup> (40 x10 <sup>9</sup> gal·a <sup>-1</sup> )	18% of US Transportation Energy Sector (Energy Information Administration 2009)
Glycerin Coproduct Production	2.1 x10 <sup>10</sup> kg·a <sup>-1</sup>	7500% of North American production (Energy Information Administration 2007)
Algae Extract Coproduct Production	6.3x10 <sup>8</sup> kg·a <sup>-1</sup>	11% of protein required for NOAA US Aquaculture Production Outlook for 2025 (Kim and Kaushik 1992; U. S. Department of Commerce 2009)

Limits on water availability, nitrogen availability, and the constraints of the glycerin coproduct market will limit the scale to which this type of microalgae biofuels production model can be extrapolated. Alternative sources of nitrogen and water, including perhaps from wastewater (Yun, Lee et al. 1997) or anaerobic digestion for nitrogen recovery from the extracted biomass (Chisti 2008), and other uses for the glycerin coproduct (Yazdani and Gonzalez 2007) must be considered to achieve long-term process scalability.

## **2.11. Chapter Conclusions**

The purpose of this chapter has been to answer Research Question 1 which is repeated for reference below:

***What are the energy efficiency, GHG emission reduction and scalability of the microalgae-to-biofuel process?***

The NER of the microalgae biodiesel process is 0.89 MJ of energy consumed per MJ of energy produced. In terms of net GHGs, microalgae-based biofuels avoids 75.3 g of CO<sub>2</sub>-equivalent per MJ of energy produced. The results of these models are used to evaluate the NER and net GHG emissions of microalgae biodiesel in comparison to petroleum diesel and soybean-based biodiesel as presented in Figure 5 and Figure 6.

The microalgae-to-biofuel process has a positive NER, in which it produces 7% more energy than it consumes and has 5.4 times larger GHG emission reduction compared to petroleum-based diesel and around 5% more GHG emission reduction compared to soybean-based biodiesel. In the scalability analysis to produce 150 billion liters per year, availability of water and nitrogen sources can limit the scale of microalgae biofuel production and the input of large amount of coproducts (glycerin) can affect biofuel market.

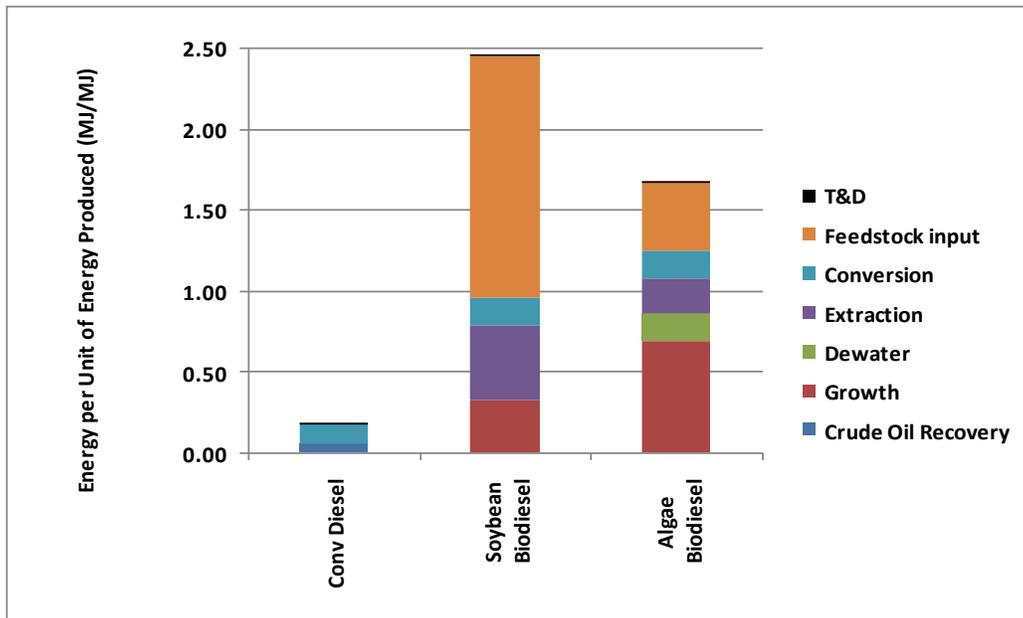


Figure 5. Comparison of Energy Consumption for each feedstock processing stage of conventional diesel from GREET 1.8c, baseline soybean biodiesel from GREET 1.8c, and the baseline microalgae to biofuels process from this study.

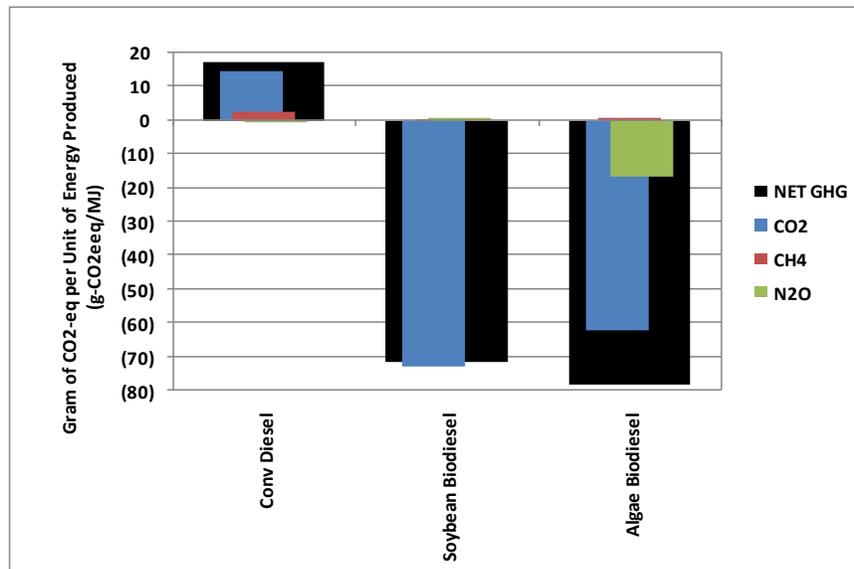


Figure 6 . Comparison of Net GHG Emissions for conventional diesel from GREET 1.8c, baseline soybean biodiesel from GREET 1.8c, and the baseline microalgae to biofuels process from this study

The integration and robustness of a fuel LCA when combined with a detailed engineering model, which boundaries were aligned and consistent in terms of processes and in systemic level in order to provide a comparable basis of microalgae-to-biofuel process to other fuels and biofuels. These results provide data for critical analysis of potential improvements and performance bottlenecks for the whole system level of a microalgae-to-biofuel process and also provide evidence to support Hypothesis 1.

This study is novel in which it has defined the first cross-fuel comparison of algae biofuels to other near-term bio and petroleum-based diesel fuels. To develop this comparison, this work had to develop the means to place algae biofuels into the LCA framework of GREET1.8. This involved the construction of a suite of coproduct allocation methods and scenarios to make valid comparisons to these other fuels.

## **Chapter 3. Analysis of Water Footprint from Blue, Green and Lifecycle Perspectives**

### **3.1. Chapter Summary**

Microalgae are currently being investigated as a feedstock for commercial production of transportation fuels, due to their potential scalability and sustainability advantages over conventional feedstocks. The water consumption of microalgae has been postulated to be a resource barrier for large-scale production. This study presents an assessment of the water footprint (WF) of a closed photobioreactor-based biofuel production system, where microalgae cultivation is simulated with geographical and temporal resolution. The assessment focuses on WF as modeled for four different fuel conversion pathways, and in 10 continental US locations with high productivity yields. WF is comprehensively assessed using a combined process and economic input-output lifecycle analysis method, using three metrics: blue, green and lifecycle WF. Results show that the blue WF of microalgae biofuels varies between 23 and 85  $\text{m}^3 \cdot \text{GJ}^{-1}$ . The green WF can reduce the required water withdrawal. Water credits from the coproducts vary highly with allocation methods and end uses, from credits of less than 4 up to 334  $\text{m}^3 \cdot \text{GJ}^{-1}$ . Net lifecycle WF with coproduct credits varies between 80 and -291  $\text{m}^3 \cdot \text{GJ}^{-1}$ . Discussion focuses on the sensitivity of microalgae biofuels WF and highlights potential local and national strain of water resources relative to other fuels and biofuels.

### **3.2. Introduction**

Water is a stressed resource in many regions of the US, and future increases in biofuels production are predicted to dramatically increase the water intensity and consumption of the transportation and energy sectors (Postel 2000; Blackhurst, Hendrickson et al. 2010). In general, current biofuels production has been found to be less greenhouse gas (GHG) intensive and more

water intensive than conventional petroleum fuels production (King and Webber 2008; Chiu, Walseth et al. 2009; Mekonnen and Hoekstra 2011), although there exists a great deal of uncertainty regarding the water requirements for next-generation biofuels.

Microalgae-based biofuels are one of the most promising biofuels in terms of GHG emissions reduction potential (Pienkos and Darzins 2009; Batan, Quinn et al. 2010; Brennan and Owende 2010; Campbell, Beer et al. 2011; Vasudevan, Stratton et al. 2012). However, divergent results in LCA do not offer conclusive understandings of microalgae as potential feedstock for low carbon biofuels ; yet its environmental benefits are still widely debated, for instance, the water consumption in large-scale microalgae-to-biofuel systems being a potential key limitation (Lardon, Helias et al. 2009; Clarens, Resurreccion et al. 2010; Frank, Han et al. 2011a; Frank, Han et al. 2011b; Davis, Fishman et al. 2012; Liu, Clarens et al. 2012; Vasudevan, Stratton et al. 2012). Previous evaluations of the water consumption of microalgae biofuels have not developed a lifecycle methodology comparable to other biofuels studies in literature, and have concentrated on open-pond cultivation systems as opposed to photobioreactor (PBR) microalgae cultivation systems (Clarens, Resurreccion et al. 2010; Harto, Meyers et al. 2010; Wigmosta, Coleman et al. 2011; Yang, Xu et al. 2011). Clarens et al. (2009) analyzed microalgae biofuels WF including direct water consumption and water consumption associated with processes upstream of cultivation, but excluding consumption in the stages of fuel conversion, transportation and distribution. Yang et al. (2010) studied the WF from microalgae biodiesel derived from open-pond cultivation systems, but only accounted for the actual water consumed in process, excluding the water requirements associated with energy and consumable materials. Vasudevan et al. (2012) performed a very thorough LCA with focus on freshwater consumption of microalgal biofuels from dry and wet extraction technology routes, excluding upstream water use

related to energy and material inputs. Wigmosta et al. (2011) constructed a detailed geographically-resolved water consumption analysis of microalgae feedstock production and fuel conversion, but distribution, transportation and coproduct allocations were not included as would be required for a conventional lifecycle accounting. Harto et al. (2010) performed a comparison of the lifecycle water footprint of open pond and tubular PBR cultivation systems, but incorporated higher productivities than has been reported in studies of near-term, industrially-realizable cultivation systems (Quinn, de Winter et al. 2011; Lammers, Quinn et al. 2012; Quinn, Catton et al. 2012). In general, the synthesis of the results of water consumption analyses among studies is complicated by the many modeled conversion processes, by geographical and climactic variability, and by differences in study scopes, system boundaries, and metrics.

To address these challenges, this article describes a detailed analysis of the water footprint (WF) of microalgae-based biofuels. This WF assessment includes detailed models of industrial feedstock cultivation, de-water, extraction, conversion, transportation and delivery to derive a geographically- and temporally-resolved model of the water requirements for four different fuel production pathways. These four pathways represent the production pathways for biodiesel, green diesel type 1, green diesel type 2 and renewable gasoline (Huo, Wang et al. 2009). The study focuses on 10 locations in the continental US that have been identified with high productivity potential based on lipid yields and land availability. Climatic variation in WF is modeled using precipitation and pan evaporation rate data and a biomass productivity and lipid accumulation model based on 15 years of historical, hourly meteorological data. To facilitate comparison to the fractured literature, three WF metrics are analyzed for microalgae-based biofuels: green, blue and lifecycle WF (Mekonnen and Hoekstra 2011; Yeh, Berndes et al. 2011). Discussion focuses on a comparison of these results to the water consumption of other

petroleum-based fuels and biofuels, and presents the sensitivity of the analyses to geography and climate.

### **3.3. Methods**

#### **3.3.1. Water Footprint Functional Unit, Boundaries, and Metrics**

Water consumption is defined as the total water that is not returned to a water body or source for reuse (King and Webber 2008). WF is the freshwater consumption of a process or product per functional unit (Hoekstra and Chapagain 2007; Gerbens-Leenes, Hoekstra et al. 2009; Mekonnen and Hoekstra 2011). The functional energy unit for this study is a unit of biofuel based on its lower heating value (LHV). The WF is therefore quantified as cubic meters of water per unit of energy of biofuel produced ( $\text{m}^3 \cdot \text{GJ}^{-1}$ ). The LHV of biodiesel, green diesel type 1, green diesel type 2 and renewable gasoline are assumed to be  $37.6 \text{ MJ} \cdot \text{Kg}^{-1}$ ,  $43.6 \text{ MJ} \cdot \text{Kg}^{-1}$ ,  $44.0 \text{ MJ} \cdot \text{Kg}^{-1}$  and  $43.4 \text{ MJ} \cdot \text{Kg}^{-1}$ , respectively (Huo, Wang et al. 2009).

The temporal unit for this study is 1 calendar year, with the number of cultivation days varying for each cultivation facility due to regional climatic conditions. The cultivation season is approximated using a thermal model of the cultivation system (Quinn, Catton et al. 2012). This study assumes that the growth facility is active after the first full thaw of the cultivation system, and is dormant for the remainder of the year after ice first forms on the surface of the growth system.

Three different metrics of WF are analyzed in this study: blue WF, green WF and lifecycle WF (Mekonnen and Hoekstra 2011; Yeh, Berndes et al. 2011). The blue WF is a metric of the direct water withdrawal of a process, for either consumptive or non-consumptive use (see Equation 1-4). The green water footprint is a metric representing the difference between

the water lost through soil moisture evaporation, feedstock evapotranspiration, and the water gained through precipitation (see Equation 5). The total WF is defined as the sum of blue and green WFs. The lifecycle WF metric is the most comprehensive metric, accounting for the direct water consumption in the process, the upstream water consumed in materials and energy production, and the water credits that are returned to the accounting due to the displacement of marketable products by the coproducts generated in the biofuel production process (see Equation 6-8).

A model of water inputs to the microalgae-to-biofuels process is used to apply these WF metrics to microalgae-based biofuels. The process boundary for this study is the fuel cycle or “strain-to-pump”. The stages studied within this boundary include cultivation, harvesting, dewatering, oil extraction, fuel conversion and fuel transportation and distribution (Batan, Quinn et al. 2010). Energy and materials to manufacture infrastructure, vehicles, and facilities are not included in this analysis. For the modeled microalgae-to-biofuel processes, the direct water withdrawal represents the water that is consumed by each stage in the microalgae-to-biofuel process including, for instance, water for microalgae cultivation, water required to make up for pond evaporation, water lost from the process during filtration, and water reacted during fuel conversion. Internal water recycling of the microalgae-to-biofuel process (for example, centrate recycling) displaces direct water consumption. For this microalgae-to-biofuels process, green water footprint only accounts for precipitation as basin evaporation is directly accounted for through makeup water, and disturbances to soil quality or moisture content are assumed negligible. The lifecycle boundary includes upstream water use, which is defined as the water consumed to produce materials and energy inputs to the microalgae-to-biofuel process, such as

electricity, fertilizers and photobioreactor material. Coproduct water allocations represent the water consumption that is avoided because of the availability of microalgae-based coproducts.

For the blue and green WF calculations, this study uses a process approach, wherein the water consumption is modeled or measured at each stage of the microalgae-to-biofuels process. For the lifecycle WF calculations, this study uses a hybrid method combining process and economic input-output approaches to estimate the water inventory for each process stage. Under this hybrid method, the process approach is applied to the process water consumption and water consumption associated with energy inputs, while the economic input-output approach is applied to estimate the upstream water consumption associated with all materials inputs including fertilizers and other consumables. The WFs of conventional energy inputs, such as electricity, gasoline, and diesel are based on process WFs as calculated in the lifecycle assessment literature (Webber 2007; King and Webber 2008; King, Webber et al. 2010).

The blue WF estimation is the direct computation of any water use or consumption per stage of the modeled system. The blue WF is mainly divided in direct process water use (loss), make-up water to replace evaporated water in the open basin, water retained in open basin. Our input data are water use and algal lipid. To obtain WF in terms of the defined functional unit (e.g. 1 unit of energy of produced fuel), all water inputs are divided by the respective low heating value (LHV) of the modeled fuel and lipid-to-fuel conversion efficiency ( $\epsilon$ ), per each fuel conversion pathway:

$$W_{blue} = W_{process} + W_{make-up} + W_{retained} \quad \text{in } \frac{m^3}{GJ} \quad (\text{Equation 1})$$

$$W_{process,f} = \frac{\sum w_i}{L_s \cdot \epsilon_f \cdot \rho \cdot \gamma \cdot LHV_f} \quad (\text{Equation 2})$$

$$W_{make-up,f,s} = \frac{\sum^{n \rightarrow m} pan_s}{L_s \cdot \epsilon_f \cdot \rho \cdot \gamma \cdot LHV_f} \quad (\text{Equation 3})$$

$$W_{retained,f} = \frac{V \cdot Area}{L_s \cdot \varepsilon_f \cdot \rho \cdot \gamma \cdot LHV_f} \quad (\text{Equation 4})$$

$$W_{green} = \frac{\sum^{n \rightarrow m} p_s}{L_s \cdot \varepsilon_f \cdot \rho \cdot \gamma \cdot LHV_f} \quad \text{in } \frac{m^3}{GJ} \quad (\text{Equation 5})$$

$$W_{lc} = W_{blue} + W_{green} + W_{inputs} + W_{cr} \quad \text{in } \frac{m^3}{GJ} \quad (\text{Equation 6})$$

$$W_{inputs} = \frac{\sum_f e_i \cdot wf_c + \sum_f m_i \cdot wf_c}{L_s \cdot \varepsilon_f \cdot \rho \cdot \gamma \cdot LHV_f} \quad (\text{Equation 7})$$

$$W_{cr} = \frac{\sum_f c_f \cdot wf_c}{L_s \cdot \varepsilon_f \cdot \rho \cdot \gamma \cdot LHV_f} \quad (\text{Equation 8})$$

### Legends:

$W$ : Water footprint (in  $m^3/GJ$ )

$w$ : water use (in  $m^3 H_2O \cdot ha^{-1} \cdot yr^{-1}$ )

$L_s$ : lipid yield per site (in  $m^3$  algal oil  $\cdot ha^{-1} \cdot yr^{-1}$ )

$\varepsilon_f$ : conversion efficiency (kg fuel  $\cdot kg$  algal oil $^{-1}$ )

$\rho$ : density of algal oil (kg  $\cdot m^{-3}$ )

$\gamma$ : conversion factor from MJ to GJ or from MJ to KWh

$LHV_f$ : low heating value of specific fuel, per fuel pathway (MJ  $\cdot kg^{-1}$ )

$f$ : fuel pathway

$s$ : site or location

$pan_s$ : pan evaporation per site ( $m^3 H_2O \cdot ha^{-1} \cdot yr^{-1}$ )

$p_s$ : precipitation per site ( $m^3 H_2O \cdot ha^{-1} \cdot yr^{-1}$ )

$e_i$ : energy input (MJ  $\cdot ha^{-1} \cdot yr^{-1}$ , KWh  $\cdot ha^{-1} \cdot yr^{-1}$ )

$m_i$ : material input (kg  $\cdot ha^{-1} \cdot yr^{-1}$ )

$wf_i$ : water footprint or credit ( $m^3 H_2O \cdot m^{-3}$  natural gas,  $m^3 H_2O \cdot MJ^{-1}$ , others)

$c_f$ : coproduct yield, per fuel pathway (kg  $\cdot ha^{-1} \cdot yr^{-1}$ )

### **3.3.2. Process WF Assessment Details**

The process approach to microalgae WF requires the quantitative measurement of the direct water input into each process of biofuels production. For this study, quantitative measurements of water, energy and material inputs for each process is based on a detailed engineering model of the Solix Biosystems Generation 3 photobioreactor (PBR) cultivation system, a centrifugal de-watering system, and conventional hexane/ethanol based lipid extraction systems (Batan, Quinn et al. 2010; Quinn, de Winter et al. 2011). The WF associated with the four fuel pathways' conversion, transportation, and distribution systems are based on the ANL GREET model (Huo, Wang et al. 2009). This study assumes that there is no energy associated with the transport of microalgae feedstock to a co-sited extraction and conversion facility, but does consider the energy required for transport and distribution of fuel to pump stations, and for transport of coproducts.

### **3.3.3. Economic Input-Output Lifecycle Assessment Details**

For some materials, a process lifecycle approach to WF estimation has not been performed, or does not appear in open literature. In these cases, the Economic Input-Output lifecycle assessment (EIO-LCA) approach is used to estimate the lifecycle water footprint of the material. The EIO-LCA approach uses an economic model that comprehensively maps the interrelationships among the main sectors of the US economy and enables identification of direct economic inputs, indirect economic inputs, products and service supply chains. Economic data are combined with resource consumption, environmental emissions, and waste data to map connections between economic expenditures and corresponding resource consumptions (Institute). For this study, the EIO-LCA approach is applied to estimate the WF of fertilizers, and polyethylene for PBRs and liners used in the microalgae cultivations system (for more details,

see Appendix). The EIO-LCA model data are based on the US economy as measured in 2002, thus 2011 prices are used to adjust the EIO-LCA data (Borruso 2011; Glauser 2011; Linak, Janshekar et al. 2011; USDA 2011).

#### **3.3.4. Microalgae-to-Biofuel Process Model**

This study analyses an industrial-scale PBR microalgae-to-biofuels production plant cultivating *Nannochloropsis salina*. The PBR are vertically oriented polyethylene panels with thermal and structural support provided by a water basin (Lammers, Quinn et al. 2012). The PBR cultivation facility has a footprint of 315 hectares that includes growing and processing facilities (Batan, Quinn et al. 2010). De-watering is accomplished through the use of a centrifuge with centrate recycling. The microalgae oil is extracted through an ethanol/hexane solvent extraction process (Batan, Quinn et al. 2010).

Microalgae fatty acid composition suggests some advantages in conversion, treatment and fuel properties of microalgae oil over vegetable oils, but there is no public data quantifying the WF of industrial-scale lipid-to-biofuel conversion using microalgae-derived lipids. The fatty acid composition of *Nannochloropsis* is composed, in average values, of 30.96% of saturated lipids and 59.2% of unsaturated lipids. Microalgae oil has a non-detectable amount of linolenic acid (C18:3) and the polyunsaturated lipids range between 2 - 22% (Sukenic, Zmora et al. 1993; Gouveia and Oliveira 2009; Fischer, Marchese et al. 2010). Instead, the data for the four conversion processes considered in this study are based on four models of soybean oil-to-biofuels conversion: (i) biodiesel (BD), (ii) green diesel type 1 (GD1), (iii) green diesel type 2 (GD2) and (iv) renewable gasoline (RG). BD is the biofuel obtained with simple transesterification of crude oil. GD1 is the biofuel obtained through hydrocracking, hydrotreating and hydrogenation of lipids using the *Supercetane* process (NRC 2003). GD2 is the biofuel

obtained through dehydroxygenation and decarboxilation of lipids, using the *Ecorefining* process (UOP 2006). RG is gasoline obtained from catalytic cracking of lipids. Refining data are drawn from the ANL GREET 1.8d model and its associated process inventories (Huo, Wang et al. 2009).

Fifteen years of hourly meteorological data is input to the microalgae growth model. Microalgae biomass and lipid production is modeled as a function of time, temperature, photosynthetically active radiation, nutrient levels, culture density and a variety of other biological variables (Quinn, de Winter et al. 2011). Water for producing growth media and for filling the water basin is assumed to be freshwater. Wastewater produced by the growth system is nitrogen-depleted and is assumed to require no treatment before discharging.

Coproduct credits play a key role in lifecycle WF assessment, as each coproduct incorporates water credits that must be accounted for. Coproducts from the microalgae-to-biofuels process vary with the fuel pathway considered but can include lipid-extracted microalgae biomass, glycerin, and various hydrocarbon coproducts from the refining process. Both energy and displacement allocation methods are analyzed in turn for this study. The energy allocation method uses the energy embedded in the coproducts to calculate water credits. In this allocation method, the algal extract and glycerin are used as co-firing material to generate bioelectricity, therefore, water credits are based on the WF of the produced electricity (Kadam 2002; King and Webber 2008). The displacement allocation method assumes that the microalgae biofuel coproducts will substitute for conventional products in the market. Using displacement allocation, lipid-extracted algal biomass substitutes for microalgae as an aquaculture fish or shrimp feed. The water credit assigned to microalgae biomass is equal to the water needed to produce microalgae conventionally cultivated in an open-pond system. The other coproducts

displace the equivalent types of gas, heavies and other energy fuel carriers, and their water credit is based on the water footprint of the conventional energy fuel carriers that they replace. Market saturation due to coproducts generated by microalgae-to-biofuel process is not analyzed in this study.

Average national distances, fuel transportation means and capacities from ANL GREET 1.8d are adopted for this study (Huo, Wang et al. 2009); where the diesel consumed to operate trucks is converted into an equivalent water footprint (King and Webber 2008).

### **3.3.5. Geographical and Climatic Resolution**

Land availability limits the regions of the US where large scale microalgae-based biofuels can be cultivated. To model the potential siting of microalgae biofuel cultivation facilities, this study defines a set of geographical locations in the US where land is available for microalgae cultivation. The baseline scenario includes production barren land, shrubland, grassland, and herbaceous covered land, and excludes production on agricultural land, urban areas, wetlands, open water, and forested land. Other exclusions are wilderness areas, federal research areas, national parks, forests, recreation areas, and high-slope areas. Large-scale microalgae cultivation requires a slope of 2% or less for economic reasons related to the cost of construction of photobioreactors and water basins (Benemann, Goebel et al. 1982; Lansford, Hernandez et al. 1990; Muhs, Viamajala et al. 2009).

For each geographic location, solar radiation, dry-bulb temperature, dew-point temperature, wind speed, wind direction, cloud cover and atmospheric pressure are used to model the radiative, conductive and convective heat balance and temperature of the water basin. Large-scale cultivation is assumed to preclude artificial heating and cultivation is assumed to shut down

when the water basin freezes. Therefore, the length of the cultivation season is a function of the weather at each geographic location, and varies from year to year.

Analysis of WF requires the modeling of both evaporation and precipitation. Evaporation is a significant component of the water consumption in the modeled PBR system because the water basin is an open pool, where water evaporation can occur from the basin's free surface. To maintain the function of the water basin, water must be added to make up for water evaporation. As recommended in Farnsworth (1982a), water evaporation rate is assumed to be 75% of the measured pan evaporation rate, with mean monthly pan evaporation rate modeled as the average of a 15 year database of Class A pan evaporation data (Farnsworth, Thompson et al. 1982a; Farnsworth and Thompson 1982b). The open basin collects water from precipitation during the cultivation period, thus avoids additional water withdrawal to supply evaporated water (more details see Appendix). Mean monthly precipitation data is estimated from a 20-year average database (NOAA).

Extreme weather conditions and smaller-scale meteorological variations, such as drought, flood, monsoons and hurricanes are not representable using these methods.

To characterize the WF of microalgae biofuels for this baseline scenario, ten locations (listed in Table 1) were chosen in states with the highest algae biofuels production. Some of the chosen locations do not have a high area-specific productivity, but have high land availability, and therefore high production (Quinn, Catton et al. 2012).

### **3.3.6. Example calculation of WF for green diesel type 1, at Tempe, AZ**

The blue, green and lifecycle WF calculations are demonstrated as follows, with inputs from Table 8 and Table 9.

Table 8. Materials and energy inputs

<b>STAGE/Inputs</b>	<b>VALUE</b>	<b>UNITS</b>
<b>GROWTH STAGE</b>		
Nitrogen fertilizer consumption	147	$\text{g} \cdot (\text{kg dry algae})^{-1}$
Phosphorus fertilizer consumption	20	$\text{g} \cdot (\text{kg dry algae})^{-1}$
Polyethylene consumption	1.17	$\text{m}^3 \cdot \text{ha}^{-1}$
Diesel fuel consumption	10	$\text{L} \cdot \text{ha}^{-1}$
Water loss	0.023	$\text{m}^3 \cdot (\text{kg dry algae})^{-1}$
Electricity consumption	41,404	$\text{kWh} \cdot \text{ha}^{-1}$
<b>DEWATER STAGE</b>		
Electricity use	30,788	$\text{kWh} \cdot \text{ha}^{-1}$
<b>EXTRACTION STAGE</b>		
Natural gas consumption	141,994	$\text{MJ} \cdot \text{ha}^{-1}$
Electricity consumption	12,706	$\text{kWh} \cdot \text{ha}^{-1}$
<b>CONVERSION STAGE</b>		
Electricity consumption	0.087	$\text{kWh} \cdot (\text{kg green diesel})^{-1}$
Hydrogen consumption	0.03	$\text{kg} \cdot (\text{kg green diesel})^{-1}$
Cooling water	65.06	$\text{kg} \cdot (\text{kg green diesel})^{-1}$
<b>TRANSPORTATION &amp; DISTRIBUTION</b>		
Diesel consumption	0.0094	$\text{L} \cdot (\text{kg green diesel})^{-1}$

Table 9. Price and water data for non-irrigation agricultural inputs

<b>Input</b>	<b>Water use (Gal H<sub>2</sub>O/\$)<sup>a</sup></b>	<b>Price (\$/ton) (2007)</b>	<b>W (m<sup>3</sup> H<sub>2</sub>O/kg)</b>	<b>Notes</b>
Ammonium nitrate	24.01	398 <sup>b</sup>	0.0362	
P fertilizers	24.01	1,103 <sup>b</sup>	0.1003	
Polyethylene	16.74	2,008 <sup>c</sup>	0.1272	
Hydrogen	--	--	0.22e	Average of 27 gallons water/kg Hydrogen (5%) and 4.6 gall water/kg Hydrogen (95% of market production method)
Hexane	20.25	1,000 – 3,000 <sup>d</sup>	0.23	Highest price have been used
Ethanol	44.37	689 – 1,115 <sup>c</sup>	0.1873	Highest price have been used
Sodium hydroxide & methoxide	15.17	600- 3,000 <sup>d</sup>	0.1722	Highest price have been used

<sup>a</sup> CMUGDI 2008 (Institute 2008); <sup>b</sup> USDA (USDA 2011); <sup>c</sup> CEH Marketing Reports (Borruso 2011), <sup>d</sup>Retail selling prices ([www.businesswire.com](http://www.businesswire.com)), <sup>e</sup> Webber 2007 (Webber 2007)

$$W_{\text{blue}} = W_{\text{process, growth}} + W_{\text{make-up}} + W_{\text{retained water}} + W_{\text{process, conversion}} = [5 (\text{m}^3 \text{ water loss/ha/yr}) + 14,360 (\text{m}^3 \text{ evap water/ha/yr}) + 4,349 (\text{m}^3 \text{ retained water/ha/yr})] * 1.51 (\text{kg algal oil/kg green diesel}) / [23.7 (\text{m}^3 \text{ algal oil/ha/yr}) * 923 (\text{kg/m}^3 \text{ algal oil}) * 43.6 (\text{MJ/kg green diesel}) * 10^{-3} (\text{GJ/MJ})] + [0.065 (\text{m}^3 \text{ water/kg green diesel})] = 29.63 + 1.49 = \mathbf{31.13 \text{ m}^3 \text{ water/GJ}}$$

$$W_{\text{green}} = 2,042 (\text{m}^3 \text{ rainwater/ha/yr}) * 1.51 (\text{kg algal oil/kg green diesel}) / [23.7 (\text{m}^3 \text{ algal oil/ha/yr}) * 923 (\text{kg/m}^3 \text{ algal oil}) * 43.6 (\text{MJ/kg green diesel}) * 10^{-3} (\text{GJ/MJ})] = \mathbf{3.23 \text{ m}^3 \text{ water/GJ}}$$

$$W_{\text{lifecycle}} = W_{\text{blue}} + W_{\text{upstream inputs}} - W_{\text{retained water}} - W_{\text{green}} - W_{\text{credits}}$$

$$W_{\text{upstream inputs}} = W_{\text{energy inputs}} + W_{\text{material inputs}}$$

$$W_{\text{energy inputs}} = (\text{Energy 1 input} * \text{Energy 1 water footprint} * \text{Conversion of Algal oil to fuel} / (\text{Algal lipid yield} * \text{Algal oil density} * \text{LHV fuel} * \text{Conversion of MJ to GJ}) + (\text{Energy 2 input} * \text{Energy 2 water footprint} / \text{LHV fuel} * \text{Conversion of MJ to GJ}) = [(41,404 + 30,788 + 12,706) (\text{KWh/ha/yr}) * 0.008 (\text{m}^3 \text{ H}_2\text{O/KWh}) + 13,957 (\text{m}^3/\text{ha/yr natural gas}) * 0.0007 (\text{m}^3 \text{ H}_2\text{O/m}^3 \text{ natural gas}) + 0.01 (\text{m}^3 \text{ diesel/ha/yr}) * 2.95 (\text{m}^3 \text{ H}_2\text{O/m}^3 \text{ diesel}) * 1.51 (\text{kg algal oil/kg green diesel}) / [23.7 (\text{m}^3 \text{ algal oil/ha/yr}) * 923 (\text{kg/m}^3 \text{ algal oil}) * 43.6 (\text{MJ/kg green diesel}) * 10^{-3} (\text{GJ/MJ})] + 0.0867 (\text{KWh/kg green diesel}) * 0.008 (\text{m}^3 \text{ H}_2\text{O/KWh}) / 43.6 (\text{MJ/kg green diesel}) * 10^{-3} (\text{GJ/MJ})] = 1.08 + 0.015 = \mathbf{1.09 \text{ m}^3 \text{ water/GJ}}$$

$$W_{\text{material inputs}} = (\text{Material input 1} * \text{Material water footprint} * \text{Conversion of Algal oil to fuel} / \text{Algal lipid yield} * \text{Algal oil density} * \text{LHV fuel} * \text{Conversion of MJ to GJ}) + (\text{Material input 2} * \text{Material water footprint} / \text{LHV fuel} * \text{Conversion of MJ to GJ}) = [(1,100 + 32,712) (\text{kg HDPE/ha/yr}) * 0.1272 (\text{m}^3 \text{ H}_2\text{O/kg HDPE}) + [7,783 (\text{kg N/ha/yr}) * 0.0362 (\text{m}^3 \text{ H}_2\text{O/kg N}) + 1,059 (\text{kg P/ha/yr}) * 0.1003 (\text{m}^3 \text{ H}_2\text{O/kg P}) + 102,17 (\text{kg hexane/ha/yr}) * 0.23 (\text{m}^3 \text{ H}_2\text{O/kg hexane}) + 12.15 (\text{kg ethanol/ha/yr}) * 0.1873 (\text{m}^3 \text{ H}_2\text{O/kg ethanol})] * 1.51 (\text{kg algal oil/kg green diesel}) / [23.7 (\text{m}^3 \text{ algal oil/ha/yr}) * 923 (\text{kg/m}^3 \text{ algal oil}) * 43.6 (\text{MJ/kg green diesel}) * 10^{-3} (\text{GJ/MJ})] + 0.03 (\text{kg H}_2/\text{kg}$$

$$\text{green diesel}) * 0.022 \text{ (m}^3 \text{ H}_2\text{O/kg H}_2\text{)} / 43.6 \text{ (MJ/kg green diesel)} * 10^{-7} \text{ (GJ/MJ)} = 7.46 + 0.01 =$$

**7.47 m<sup>3</sup> water/GJ**

$$W_{\text{upstream inputs}} = \mathbf{8.52 \text{ m}^3 \text{ water/GJ}}$$

### 3.3.7. Example calculation of coproduct water credits

In the displacement allocation method, the coproduct credits were calculated based on data from Harto et al (2010). Since Harto et al data are presented in gallon of water use per gallon of fuel. To obtain the water use per unit of mass of microalgae, we assumed an efficiency of fuel conversion and lipid extraction of 96% and 85%, respectively. As for lipid content, we kept the assumptions of low and high case scenarios from Harto and authors.

$$WF_{\text{microalgae biomass}} = \frac{WF_{\text{Harto}}}{f_1 \text{fuel conversion} \times f_2 \text{lipid extraction} \times f_3 \text{lipid content}} \quad \text{in } \frac{\text{m}^3}{\text{kg of algae}}$$

$$W_{\text{algal biomass (lowest case)}} = 67.3 \text{ (gallon of water/gallon of fuel)} * 0.96 \text{ (gallon of fuel/gallon of algal lipid)} * 0.85 \text{ (algal lipid extraction efficiency)} * 0.35 \text{ (kg algal lipid/kg of algal biomass)} / 264 \text{ (m}^3\text{/gallon)} = \mathbf{0.127 \text{ m}^3 \text{ water/kg biomass}}$$

$$W_{\text{algal biomass (highest case)}} = 659.7 \text{ (gallon of water/gallon of fuel)} * 0.96 \text{ (gallon of fuel/gallon of algal lipid)} * 0.85 \text{ (algal lipid extraction efficiency)} * 0.35 \text{ (kg algal lipid/kg of algal biomass)} / 264 \text{ (m}^3\text{/gallon)} = \mathbf{3.675 \text{ m}^3 \text{ water/kg biomass}}$$

	Units	OPEN SYSTEM		ENCLOSED SYSTEM	
		Low case	High case	Low case	High case
<b>Lipid content</b>	%	50%	35%	35%	25%
<b>Total WF</b>	m <sup>3</sup> H <sub>2</sub> O/m <sup>3</sup> of fuel	67.30	32.04	33.19	659.70
<b>before fuel conversion</b>	m <sup>3</sup> /kg of algae lipid	0.080	0.038	0.039	0.781
<b>after lipid extraction</b>	m <sup>3</sup> /kg of algae lipid	0.094	0.045	0.046	0.919
<b>Water credits</b>					
<b>before lipid extraction</b>	m <sup>3</sup> /kg of algae	<b>0.187</b>	<b>0.127</b>	<b>0.132</b>	<b>3.675</b>

Therefore, the water credits from lipid extracted algae (LEA) from the process in the 10 locations were estimated with the lowest and highest scenario values, 0.13 and 3.68 m<sup>3</sup>/Kg of algae, respectively.

### 3.3.8. Example calculation of of coproduct water credits using displacement allocation

W displacement alloc = (Coproduct 1 yield \*Coproduct 1 water footprint + Coproduct 2 yield \*Coproduct 2 water footprint)/LHV fuel\*Conversion of MJ to GJ + (Algal biomass yield\* Algal biomass water footprint\* Conversion of MJ to KWh\*Displacement ratio \* Conversion of Algal oil to fuel/ Algal lipid yield\* Algal oil density\*LHV fuel\*Conversion of MJ to GJ)

W displacement alloc min = [0.253 (kg fuel gas/kg green diesel)\*0.008 (m<sup>3</sup> water/kg fuel gas) + 0.175 (kg heavies/kg green diesel) \* 0.004 (m<sup>3</sup> water/kg heavies)]/43.6 (MJ/kg green diesel)\*10<sup>-3</sup>(GJ/MJ) + 52924 (kg biomass/ha/yr) \* 0.55 (oil extraction)\*1.3 (displacement ratio)\* 0.127 (m<sup>3</sup> water/kg biomass) \*1.51 (Kg algal oil/Kg green diesel)/[23.7 (m<sup>3</sup> algal oil/ha/yr)\*923 (kg/m<sup>3</sup> algal oil)\*43.6 (MJ/kg green diesel)\*10<sup>-3</sup> (GJ/MJ)] = **7.6 m<sup>3</sup> water/GJ**

W displacement alloc max = [0.253 (kg fuel gas/kg green diesel)\*0.008 (m<sup>3</sup> water/kg fuel gas) + 0.175 (kg heavies/kg green diesel) \* 0.004 (m<sup>3</sup> water/kg heavies)]/43.6 (MJ/kg green diesel)\*10<sup>-3</sup>(GJ/MJ) + 52924 (kg biomass/ha/yr) \* 0.55 (oil extraction)\*1.3 (displacement ratio)\* 3.675 (m<sup>3</sup> water/kg biomass) \*1.51 ( kg algal oil/ kg green diesel)/[23.7 (m<sup>3</sup> algal oil/ha/yr)\*923 (kg/m<sup>3</sup> algal oil)\*43.6 (MJ/kg green diesel)\*10<sup>-3</sup> (GJ/MJ)] = **220 m<sup>3</sup> water/GJ**

**W displacement = 7.6 to 220 m<sup>3</sup> water/GJ**

### 3.3.9. Example calculation of of coproduct water credits using energy allocation

W energy alloc = [Coproduct 1 yield \*Coproduct 1 water footprint + Coproduct 2 yield\*Coproduct 2 water footprint)/LHV fuel\* Conversion of MJ to GJ] + (Algal biomass yield\* LHV algal biomass for bioelectricity\* Electricity water footprint\* Conversion of MJ to KWh\*Conversion of Algal oil to fuel/ Algal lipid yield\* Algal oil density\*LHV fuel\*Conversion of MJ to GJ)

$$\begin{aligned}
 \text{W energy alloc} = & [0.253 \text{ (kg fuel gas/kg green diesel)} * 0.122 \text{ (m}^3 \text{ water/kg fuel gas)} + 0.175 \text{ (kg} \\
 & \text{ heavies/kg green diesel)} * 0.09 \text{ (m}^3 \text{ water/kg heavies)}] / 43.6 \text{ (MJ/kg green diesel)} * 10^{-3} \text{ (GJ/MJ)} + \\
 & 529474 \text{ (kg biomass/ha/yr)} * 0.55 \text{ (oil extraction)} * 14 \text{ (MJ/kg biomass)} * 0.008 \text{ (m}^3 \text{ water/KWh)} \\
 & * 1.51 \text{ (Kg algal oil/ kg green diesel)} / [3.6 \text{ (KWh/MJ)} * 23.7 \text{ (m}^3 \text{ algal oil/ha/yr)} * 923 \text{ (kg/m}^3 \text{ algal} \\
 & \text{ oil)} * 43.6 \text{ (MJ/kg green diesel)} * 10^{-3} \text{ (GJ/MJ)}] = 1.36 + 1.06 = \mathbf{2.42 \text{ m}^3 \text{ water/GJ}}
 \end{aligned}$$

### 3.4. Results and Discussion

#### 3.4.1. Biomass and Oil Yield

The biofuel WF is sensitive to the temporal and areal productivity of biofuel, because WF is defined as water consumption per unit of biofuel energy. This section presents and discusses the biomass and oil yield results as modeled in this study.

Across the 10 locations modeled in this study, yearly averaged biomass yields range from 29.5 to 53  $\text{ton} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ , and microalgae oil yields range from 13 to 23.7  $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ . The results are compatible with productivity as measured under large-scale production (USDOE 2010; Quinn, de Winter et al. 2011; Lammers, Quinn et al. 2012). The average productivity among the 10 sites is 40.9  $\text{ton} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$  of biomass yield and 18.3  $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$  of lipid yield. As shown in Table 10, the Arizona and California locations present the longest cultivation seasons, corresponding to the highest oil productivities. Montana and Wyoming are the least productive locations with as few as 66% of days available for cultivation.

Table 10. Location and corresponding production characteristics for the 10 US locations evaluated

STATE	LOCATION	LOCATION		GROWING	BIOMASS YIELD	OIL YIELD
	NAME	Latitude	Longitude	days	kg·ha <sup>-1</sup> ·year <sup>-1</sup>	m <sup>3</sup> ·ha <sup>-1</sup> ·year <sup>-1</sup>
<b>ARIZONA</b>	TEMPE	33.5°N	-111.9°W	365	52,947	23.70
<b>CALIFORNIA</b>	HAYFIELD PUMP PLANT	33.6°N	-114.7°W	365	52,616	23.51
<b>COLORADO</b>	JOHN MARTIN	37.9°N	-100.7°W	274	36,400	16.29
<b>MONTANA</b>	YELLOWTAIL	45.5°N	-100.4°W	236	29,481	12.97
<b>NEBRASKA</b>	NORTH PLATTE	40.7°N	-99.0°W	254	33,736	15.11
<b>NEVADA</b>	BOULDER CITY	36.0°N	-112.1°W	280	38,285	17.26
<b>NEW MEXICO</b>	STATE UNIVERSITY	32.3°N	-104.2°W	355	46,795	20.52
<b>TEXAS</b>	GRAND FALLS	31.8°N	-103.2°W	355	47,460	20.91
<b>UTAH</b>	FISH SPRINGS	40.2°N	-111.7°W	277	38,520	17.47
<b>WYOMING</b>	FARSON	42.8°N	-108.7°W	241	32,921	14.85

### 3.4.2. Blue and Green Water Footprint

For microalgae-based biofuels, the blue WF is the sum of the water directly used to supply cultivation and process needs, the water retained in the open basins, and the water used to make up for evaporated water. The blue WF represents the local water requirements for the microalgae-to-biofuels process. The average blue WF of microalgae biofuel among all locations and conversion pathways is  $42 \text{ m}^3 \cdot \text{GJ}^{-1}$ . Blue WF varies as a function of fuel conversion pathway and location between 23 and  $85 \text{ m}^3 \cdot \text{GJ}^{-1}$ , as shown in Table 11. Averaged among the locations and conversion pathways, the process water use for feedstock cultivation, harvesting and extraction accounts for 97.6% of the blue WF, the fuel conversion accounts for 2.4% of the blue WF and transportation and distribution for 0.002% of the blue WF.

For microalgae-based biofuels the green WF is negative, representing a water gain in the water basin due to precipitation. The green WF is therefore a ratio of the precipitation that each geographic location receives and the energetic productivity of the location. The green WFs for biodiesel and GD2 are the lowest among the four fuel conversion pathways, varying among the geographies between 1.3 and  $8.9 \text{ m}^3 \cdot \text{GJ}^{-1}$ . The green WFs for GD1 and RG are higher, varying among the geographies between 1.7 and  $17 \text{ m}^3 \cdot \text{GJ}^{-1}$ .

The total WF is the sum of blue and green WFs and varies among the geographies and processes considered between 18 and  $82 \text{ m}^3 \cdot \text{GJ}^{-1}$ . Figure 7a shows the allocation of the total WF to each component of the microalgae-to-biofuels process for the four conversion pathways considered, and averaged among locations.

Table 11. Blue, green and total WF for the 10 US sites evaluated. All values are presented in  $\text{m}^3 \cdot \text{GJ}^{-1}$ , averaged across all 4 conversion pathways. Negative values appear in parenthesis.

LOCATION NAME	Blue WF		Green WF	Total WF
	Process water	Fuel conversion		
TEMPE	23 – 44	0 – 1.5	(2) – (5)	20 – 40
HAYFIELD PUMP PLANT	39 – 76	0 – 1.5	(1) – (2)	38 – 74
JOHN MARTIN	32 – 62	0 – 1.5	(6) – (12)	26 – 52
YELLOWTAIL	30 – 59	0 – 1.5	(9) – (17)	22 – 43
NORTH PLATTE	27 – 51	0 – 1.5	(9) – (17)	18 – 35
BOULDER CITY	43 – 84	0 – 1.5	(2) – (3)	42 – 82
STATE UNIVERSITY	31 – 61	0 – 1.5	(3) – (6)	28 – 55
GRAND FALLS	34 – 66	0 – 1.5	(7) – (13)	27 – 53
FISH SPRINGS	28 – 53	0 – 1.5	(3) – (5)	25 – 49
FARSON	25 – 48	0 – 1.5	(3) – (6)	22 – 44

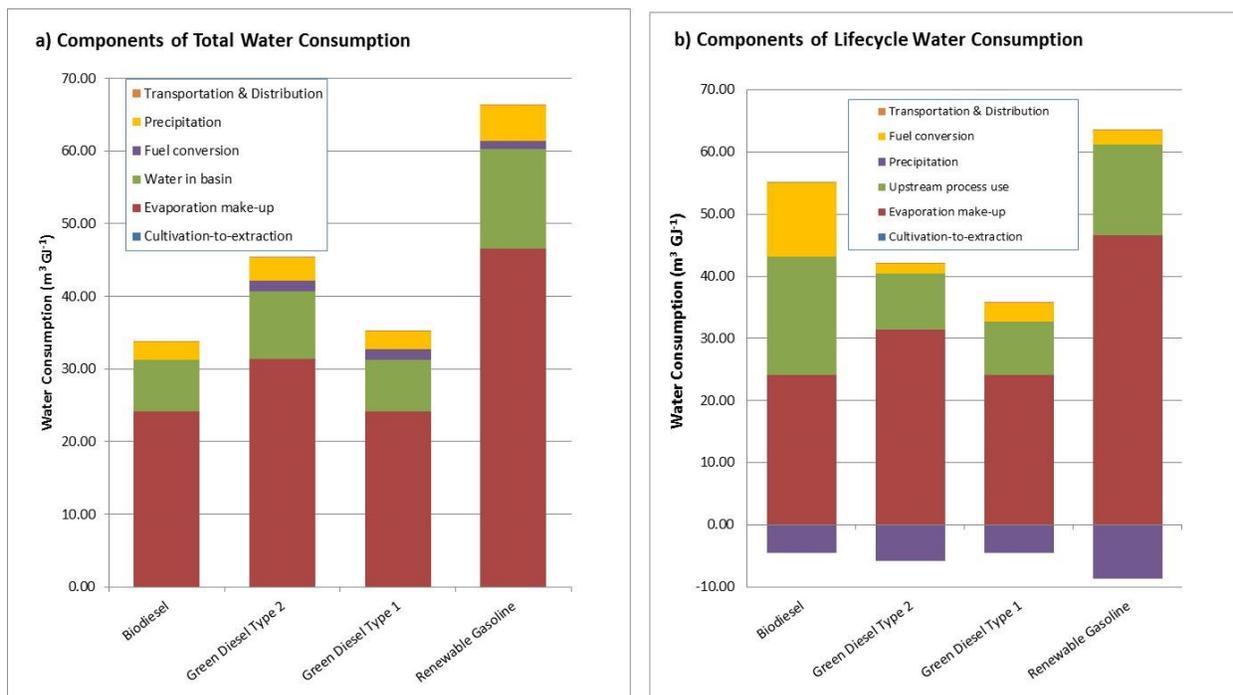


Figure 7. Geographically averaged water footprint for each conversion pathway. Total water footprint (1a) and lifecycle water footprint without coproduct allocation (1b) are presented in

$$\text{m}^3 \cdot \text{GJ}^{-1}$$

### 3.4.3. Lifecycle Water Footprint

Whereas the blue, green and total WFs provide metrics of local water use or withdrawal, the lifecycle WF provides a system-level metric of net water consumption for the process of producing microalgae-based biofuels. The lifecycle WF includes the inventories of the process water consumed, the upstream water consumption associated with energetic and material inputs for each stage of the fuel cycle, and the water credits associated with the coproducts. Because of this lifecycle perspective, lifecycle WF excludes the water retained in the water basin, as this water is presumed to be returned to original source after cultivation, and is considered not consumed in this perspective.

Before considering coproduct credits, the microalgae lifecycle WFs vary among geographies and fuel conversion pathways between 21 and 83  $\text{m}^3 \cdot \text{GJ}^{-1}$ . This variation is primarily due to the effects of the fuel conversion pathways. The GD1 pathway is the least water-consumptive, with lifecycle WF varying between 21 and 46  $\text{m}^3 \cdot \text{GJ}^{-1}$ . The RG pathway has the highest water-consumptive pathway with lifecycle WF varying from between 35 and 83  $\text{m}^3 \cdot \text{GJ}^{-1}$ . BD and GD2 have intermediate conversion efficiencies and water consumptions, as shown in Table 12.

The set of available coproducts from the four production pathways are lipid extracted algae (LEA), and petroleum coproducts including product gas, light cycle oil and clarified slurry oil. In this analysis, glycerin is treated as a waste product and is allocated none of the WF<sup>1</sup>. The water credits allocated to coproducts varies depending on the allocation method. The two methods considered in this study are the energy allocation and the displacement allocation methods.

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<sup>1</sup> Although not negligible, byproduct glycerin after transesterification is impure and of low value.

Under the energy allocation method, water consumption is allocated to coproducts according to their LHVs. LEA is used as co-firing material to generate electricity. The water credit allocated to co-firing of LEA is  $0.03 \text{ m}^3$  of water per kilogram of LEA, based on the lifecycle WF of the displaced electricity (King and Webber 2008; Batan, Quinn et al. 2010). For other coproducts, water credits are allocated based on the ratio of their LHV to the LHV of petroleum-based diesel, based on a WF of petroleum-based diesel at  $0.08 \text{ m}^3$  water per GJ (King and Webber 2008).

Under the displacement allocation method, LEA partially displaces conventionally cultivated microalgae as a fish and shrimp feed. After lipid extraction, the LEA has higher protein content per unit mass than conventional microalgae, for which 1 kg of LEA can substitute 1.3 kg of microalgae aquaculture feed. LEA water credits are based on the water consumption required to cultivate the displaced microalgae biomass using open-ponds. Harto et al. (2010) is used for estimating LEA water credits. An efficiency of fuel conversion and lipid extraction of 96% and 85%, respectively, were assumed to obtain the lifecycle WF for 1 unit of displaced LEA (Harto, Meyers et al. 2010; Yang, Xu et al. 2011). The water credits for LEA are  $0.13$  and  $3.67 \text{ m}^3 \text{ kg}^{-1}$  of LEA, based on the Harto et al. low and high cases, respectively; all other coproducts are assumed to displace products on a mass basis. A summary of coproduct displacement and energy allocations is shown in Table 13

Table 12 also presents the lifecycle WF of the microalgae-to-biofuels production process for all locations and coproduct displacement methods. The ranges represent the range of WFs associated with the four conversion pathways. The lifecycle WF for the microalgae-to-biofuels process can vary between a maximum WF of  $80 \text{ m}^3 \cdot \text{GJ}^{-1}$  to a minimum WF of  $-291 \text{ m}^3 \cdot \text{GJ}^{-1}$ , representing  $291 \text{ m}^3 \cdot \text{GJ}^{-1}$  of water consumption avoidance. The variation among lifecycle WFs

is also due to geographic and climactic variability among the locations. Those locations with shorter winters and warmer temperatures have a longer cultivation season, longer cultivation days, higher productivity, and consequentially higher energy and material consumptions. Averaged among all the fuel conversion pathways and locations, the upstream water accounts for 29.3% of lifecycle WF, the evaporation and process use accounts for 74.2%, while fuel conversion and precipitation water gain account for 10.3% and -13.9%, respectively. Transportation and distribution account for less than 0.002% of the lifecycle WF, as shown in Figure 7b (for more details, see Appendix).

Table 12. Lifecycle water footprint, coproduct credits and net lifecycle water footprint for the 10 US sites evaluated for four fuel pathways. All values are presented in  $\text{m}^3 \cdot \text{GJ}^{-1}$ . Negative values appear between parentheses.

Locations	Lifecycle Water Footprint	Coproduct credits				Lifecycle Water Footprint
	Without coproduct credits	Energy allocation		Displacement allocation		With coproduct credits
		Min.	Max.	Min.	Max.	
TEMPE	26 – 46	1.0	3.7	5.9	327	(282) – 44
HAYFIELD PUMP PLANT	44 – 79	1.0	3.7	5.9	328	(249) – 75
JOHN MARTIN	30 – 53	1.0	3.7	5.9	327	(274) – 49
YELLOWTAIL	24 – 44	1.0	3.7	5.9	333	(291) – 43
NORTH PLATTE	21 – 41	1.0	3.7	5.9	327	(291) – 40
BOULDER CITY	46 – 83	1.0	3.7	5.8	325	(241) – 80
STATE UNIVERSITY	34 – 60	1.0	3.7	6.0	333	(274) – 56
GRAND FALLS	33 – 58	1.0	3.7	6.0	332	(274) – 54
FISH SPRINGS	29 – 50	1.0	3.6	5.8	322	(272) – 47
FARSON	25 – 44	1.0	3.6	5.8	324	(282) – 43

Table 13. Coproduct water credits.

<b>Microalgae Biofuel Pathway</b>	<b>Co products</b>	<b>Water credits</b>	
		<b>Energy allocation (m<sup>3</sup>·Kg<sup>-1</sup>)</b>	<b>Displacement allocation (m<sup>3</sup>·Kg<sup>-1</sup>)</b>
Green diesel type 1	Fuel gas	0.122	0.008
	Heavies	0.090	0.004
Green diesel type 2	Propane fuel mix	0.081	0.003
Renewable gasoline	Product gas	0.080	0.003
	Light-cycle oil	0.084	0.004
	Clarified slurry oil	0.081	0.004
All fuel pathways	Lipid Extracted Algae (LEA)	0.03	0.13 – 3.67

#### 3.4.4. Comparison with Fossil Fuel and Other Feedstock Fuels

To place these results in context, this section compares the results of this study to the literature on WF of various biofuels and petroleum-based fuels. As discussed in the introduction, the comparison of microalgae biofuels' WF to those WFs present in the literature must be made using the same WF metrics, although no additional harmonization is performed in this study. These comparisons are detailed in Table 14.

Using the same total WF (blue WF plus green WF) metric that is used in the most cited petroleum fuel WF studies, the WF of microalgae based biofuels is found to be higher than that of conventional petroleum-based fuels. The WFs of petroleum-based diesel and gasoline are between 0.04 and 0.2 m<sup>3</sup>·GJ<sup>-1</sup>, where the range of values are due to various scenarios of water use including the use of desalinated seawater, the use of water recycling, or the re-injection of produced water for oil recovery (King and Webber 2008; Wu, Wang et al. 2009). This can be compared to the findings of this study where the total WF of microalgae based biofuels is between 18 and 82 m<sup>3</sup>·GJ<sup>-1</sup>, depending on the geographical location and conversion pathway.

Using the same WF metrics that are used in the most cited biofuel WF studies, the WF of microalgae-based biofuels is found to be roughly comparable to that of other starched-based biofuels. Dominguez-Faus et al. (2009) calculated the soybean biodiesel total WF as 287 m<sup>3</sup>·GJ<sup>-1</sup>, including evapotranspiration. Mekonnen et al. (2011) calculated soybean biodiesel total WF as 337 m<sup>3</sup>·GJ<sup>-1</sup>, using global weighed averages and including water from precipitation. Studies that show a lower WF for soy-based biodiesel do not adhere to any of the WF definitions presented above, in that partial irrigation is assumed and evapotranspiration is not included in the WF accounting (King and Webber 2008; Harto, Meyers et al. 2010). Biodiesel from oil palm, rapeseed and other oilseeds are shown to have higher total WFs than microalgae biofuels, from

150  $\text{m}^3 \cdot \text{GJ}^{-1}$  and up (Dominguez-Faus, Powers et al. 2009; Gerbens-Leenes, Hoekstra et al. 2009).

Comparison of this study's findings to those of previous microalgae biofuel WF studies is more complicated, as no studies adhere to these WF metrics or boundaries. Clarens et al. (2010) estimated microalgae biofuel for an open-pond cultivation system at between 303 and 454  $\text{m}^3 \cdot \text{GJ}^{-1}$ , but does not apply the same lifecycle boundaries as this study. Instead, the boundary for Clarens is cradle-to-gate for cultivation of feedstock, and does not include lipid extraction, fuel conversion and distribution. Yang et al. (2011) estimated a WF for microalgae biofuel of between 14 and 87  $\text{m}^3 \cdot \text{GJ}^{-1}$ , although their lifecycle analysis did not include upstream water use from energy and materials. Harto et al. (2010) calculated the microalgae biofuel WF from open-ponds (ORP) as between 1 and 20  $\text{m}^3 \cdot \text{GJ}^{-1}$  and a microalgae WF from enclosed photobioreactors as between 1 and 2  $\text{m}^3 \cdot \text{GJ}^{-1}$ . The latter study used boundaries and metrics comparable to those of this study, but the modeled microalgae productivity is between 72 and 130  $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ , which is 3 to 10 times higher than is feasible with modern open ponds and photobioreactor systems (Lammers, Quinn et al. 2012).

Table 14. Comparison of microalgae biofuels blue (B), green (G) and lifecycle (LC) WF with petroleum-based diesel and other biodiesel feedstocks.

TYPE OF FUEL	TYPE OF WF	WF ( $\text{m}^3 \cdot \text{GJ}^{-1}$ )*	REFERENCE	MAJOR DIFFERENCE AND ASSUMPTIONS
Petroleum-based diesel	B	0.04 – 0.08	(King and Webber 2008)	
Petroleum based-gasoline	B	0.08 – 0.20	(Wu, Wang et al. 2009)	King & Webber included extraction, prospection and oil refining.
	B	0.04 – 0.09	(King and Webber 2008)	Wu et al. accounted for U.S. national production, Saudi crude oil and Canadian sand oils
Bioethanol from				
- Sugar beet	B+G	41	(Mekonnen and Hoekstra 2011)	Mekonnen et al. estimated blue and green WF,
	B+G	89	(Dominguez-Faus, Powers et al. 2009)	includes rain-fed and irrigated crops.
- Sugar cane	B+G	85	(Mekonnen and Hoekstra 2011)	Excludes though water burden from refining process and transportation
	B+G	139	(Dominguez-Faus, Powers et al. 2009)	and distribution burdens.
- Potatoes	B+G	73	(Mekonnen and Hoekstra 2011)	
	B+G	86	(Dominguez-Faus, Powers et al. 2009)	

- Maize	B	4.5	(Wu, Wang et al. 2009)	Dominguez-Faus et al. Estimated WF, that includes actual process
	B+G	86	(Dominguez-Faus, Powers et al. 2009)	water use and evapotranspiration
	B+G	102	(Mekonnen and Hoekstra 2011)	per type of crop.
- Cassava	B+G	106	(Mekonnen and Hoekstra 2011)	
- Rice, paddy	B+G	147	(Mekonnen and Hoekstra 2011)	Wu et al. estimated production-weighted average for ethanol WF.
- Barley	B+G	127	(Mekonnen and Hoekstra 2011)	
- Wheat	B+G	160	(Mekonnen and Hoekstra 2011)	
- Rye	B+G	142	(Mekonnen and Hoekstra 2011)	
- Sorghum	B+G	95	(Dominguez-Faus, Powers et al. 2009)	
	B+G	291	(Mekonnen and Hoekstra 2011)	
- Switchgrass	B	0.1- 0.5	(Wu, Wang et al. 2009)	
	B+G	66	(Dominguez-Faus, Powers et al. 2009)	

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Biodiesel from

- Coconuts	B+G	4723	(Mekonnen and Hoekstra 2011)
- Groundnuts	B+G	188	(Mekonnen and Hoekstra 2011)
- Oil palm	B+G	150	(Mekonnen and Hoekstra 2011)
- Rapeseed	B+G	165	(Mekonnen and Hoekstra 2011)
- Seed cotton	B+G	487	(Mekonnen and Hoekstra 2011)
- Soybeans	B+G	287	(Dominguez-Faus, Powers et al. 2009)
		337	(Mekonnen and Hoekstra 2011)
- Sunflower	B+G	449	(Mekonnen and Hoekstra 2011)

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Biodiesel from

- Microalgae (open system)	B+G	14 – 87	(Yang, Xu et al. 2011)
	LC	1 – 20	(Harto, Meyers et al. 2010)

Yang et al. estimated all lifecycle stages, but did not include upstream water.

	LC	30	(Vasudevan, Stratton et al. 2012)	Clarens et al. calculated actual process water and upstream water for algae WF from cradle-to-gate.
	LC	43	(Wigmosta, Coleman et al. 2011)	
	LC	303 - 454	(Clarens, Resurreccion et al. 2010)	Harto et al. assumed high fuel yields: 72 to 130 m <sup>3</sup> fuel per year per hectare.
- Microalgae (closed system)	LC	1 – 2	(Harto, Meyers et al. 2010)	

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\* Some references units were converted into m<sup>3</sup> water per GJ, for comparison reasons.

### **3.4.5. Geographic and Climactic Sensitivity of Microalgae Biofuels WFs**

Whereas, most of the studies cited above present national average WFs, the resource intensity of microalgae-based biofuels production makes it so that microalgae WFs may be particularly affected by geographical and climatic factors. Qualitatively, regions of the US with warm temperatures and larger cultivation seasons result in higher evaporation rates and more process water use, but also result in higher biomass and oil yields. Whether the tradeoff between these effects makes a particular location beneficial for low-WF microalgae biofuels production depends on the WF metric of interest.

On average among locations and fuel pathways, the blue WF of the microalgae-based biofuels is composed of 75.3% make-up water due to evaporation from the open basin, 22.3% water retained in open basin, 0.02% direct water use for algal cultivation, harvesting and extraction processes, and 2.4% fuel conversion water consumption. Evaporation is the major component of WF, causing blue WF to be strongly linked to local evaporation rate and precipitation. Therefore, sites located in California, Nevada, Texas and New Mexico, have high blue WFs despite their high biomass and oil yields.

Lifecycle WF is shown to be most sensitive to its energy and material inputs. Averaging the results for the four fuel pathways, the lifecycle WF of microalgae-based biofuels is composed of less than 0.05% direct process water use, 10.4 % fuel conversion water consumption, 74.2% make-up water due to evaporation, 29.3% upstream water consumption, and 14% water gain through precipitation. Because of the significance of upstream water consumption, lifecycle WF is very sensitive to the coproduct allocation method. Energy allocation methods result in lower water credits compared to displacement allocation methods, and various coproduct displacement scenarios result in a wide range of lifecycle WFs. These variations among these values of WF

are primarily due to variation in the water credits available for LEA, the effect of geographic and climatic differences on biomass yields, and the differences among fuel conversion pathways.

### **3.4.6. Scalability of Production**

Microalgae have been proposed as an oil feedstock with the potential to meet future alternative fuel goals (Chisti 2007). Based on the results of this study, if microalgae biofuel production relies only on freshwater to meet the EISA 2022 target of 136 million m<sup>3</sup> of biofuel, it would require between 91 and 420 billion m<sup>3</sup> of water (using the total WF metric), for the best and worst scenarios, respectively. These values are equivalent to an additional direct water consumption of 0.7 to 3 times the amount of water currently used directly for US grain farming (Blackhurst, Hendrickson et al. 2010).

In the lifecycle perspective, the WF of microalgae biofuel production could range from a water consumption avoidance of 1.5 trillion m<sup>3</sup>, to a water consumption of 410 billion m<sup>3</sup>, for the best and worst scenarios, respectively. The lowest water consumption scenario corresponds to the use of LEA to displace conventional microalgae already cultivated for fish or shrimp feed. The highest water consumption scenario corresponds to the use of LEA as a co-firing material for bioelectricity generation.

## **3.5. Chapter Conclusions**

The purpose of this chapter has been to answer Research Question 2 which is repeated for reference below:

***What is the water resource impact of a large commercial scale of microalgae-to-biofuel production?***

This study has comprehensively accounted for the water consumption of microalgae-based biofuels allows for three different WF metrics comparison among fuel pathways, among geographic locations, and against other biofuel feedstocks.

The total WFs vary between 18 and 82  $\text{m}^3 \cdot \text{GJ}^{-1}$ . And the lifecycle WFs vary between 21 and 83  $\text{m}^3 \cdot \text{GJ}^{-1}$ , before accounting for coproduct credits. The total WFs and lifecycle WFs before allocating coproduct credits are very close. These results are consistent, as they represent the actual water consumption of the microalgae-to-biofuel process and the differences are due to upstream water use that is considered in lifecycle WFs. With coproduct allocation, the lifecycle WFs vary between 80  $\text{m}^3 \cdot \text{GJ}^{-1}$  to water avoidance of 291  $\text{m}^3 \cdot \text{GJ}^{-1}$ . The large range of lifecycle WF is due to the end-uses that the coproducts are allocated to.

The strong dependence of WFs on geography and climate is denoted by the need of water make-up due to water evaporation, which accounts for 74-75% of blue WF and lifecycle WF. This high water evaporation rate is also related to the design of open water basin of Solix Biosystem PBR cultivation system. These results provide support to the Hypothesis 2, as water intensity of microalgae biofuels is very dependent on the type of investment (microalgae-to-biofuel model), the site location and climate.

Overall, the production of microalgae biofuels is more water intensive than petroleum-based fuels, is comparable to that of bioethanol from most types of land-based feedstock, and is less water intensive than that of oilseed-based biodiesel. And although various microalgae biofuels scenarios can be constructed with low WF (see Figure 8), the results of this study show that under a variety of metrics, both local water consumption and lifecycle water consumption will be still a significant resource constraint for large-scale microalgae biofuels production.

This study is also novel in water intensity analysis in terms of redefining water footprints that is conventionally applied to land-based biomass. The major WF concept differences are for evapotranspiration, which is normally categorized as green WF, but due to the nature of microalgae cultivation, the evapotranspiration is accounted and measured as blue WF; another difference is the precipitation, while for conventional land-based biomass, precipitation is accounted as water use, supply by rainfalls, in microalgae biofuel, precipitation is water gain, as it is collected (and further use or discharge) in the Solix Biosystem PBR open water basin design.

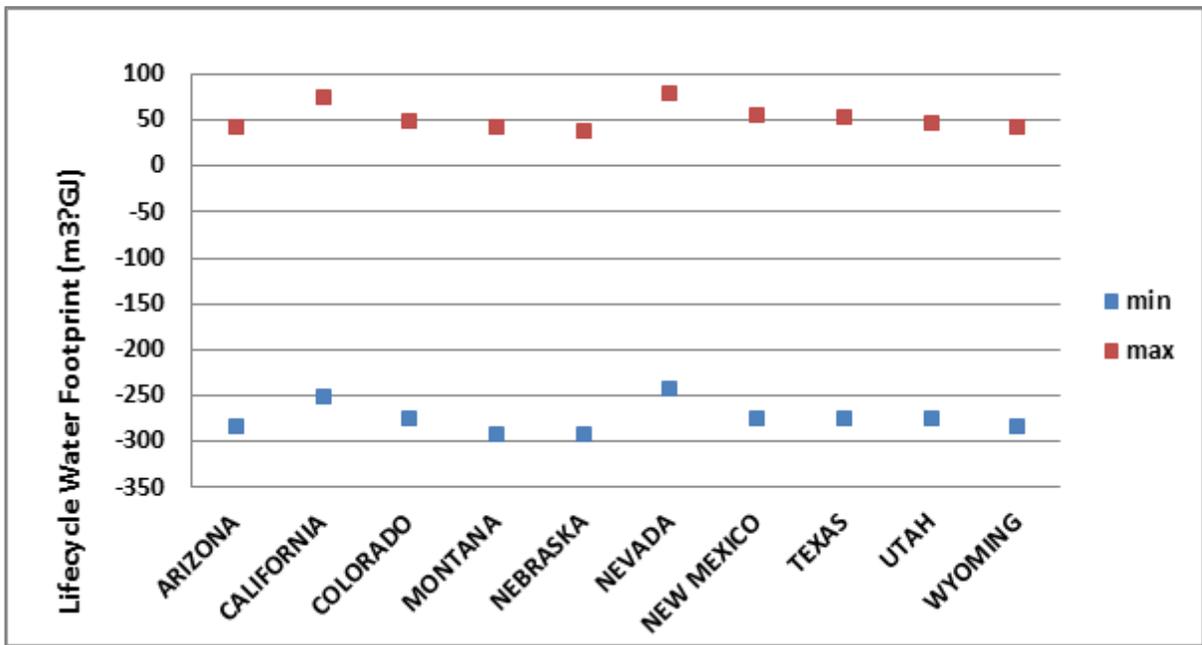


Figure 8. Lifecycle Water Footprints with low and high scenarios, per site location.

## **Chapter 4. Technoeconomic Analysis and Monte Carlo Probability Analysis of Microalgae Production System**

### **4.1. Chapter Summary**

Microalgae are considered a potentially valuable production system due to their high growth rate, no requirement for quality cropland and ability to use a wide range of water quality. Microalgae products include algae oils as a potential replacement for fossil fuels, algae biomass with desirable nutritional profile for livestock and aquaculture feed, as well as other high-value but small volume specialty compounds useful as food ingredients, cosmetics and pharmaceuticals. At present, intensive research on approaches and technologies seeks to overcome commercial and economic challenges. This section of the dissertation seeks to identify the technical and economic challenges to microalgae biofuels through analysis of an enclosed photobioreactor system of microalgae cultivation capable of producing biofuels with production capacity of 10 million of gallons per year. The uncertainties associated with inputs and scenario variables are addressed through Monte Carlo simulation. Estimated probability density functions are generated for the total cost of microalgae-derived biofuels under various scenarios. The effect of co-product allocations and valuations is analyzed. The baseline technoeconomic model shows average total costs of production of raw algal oil and algal diesel of \$13.10 and \$14.11 per gallon, respectively. The economic feasibility analysis shows that this microalgae biofuel production system can recover the capital investment costs and operating costs if the algal biodiesel is sold at the minimum price of \$13.95 per gallon, with the revenue credits of naphtha and lipid-extracted algae, as gasoline and co-firing biomass, respectively. The feasibility analysis also shows that the revenue credits from lipid-extracted algae as fish feed replacement and, naphtha as gasoline, generate profits enough to drop the minimum selling price

of algal biodiesel to \$-1.78 per gallon. The probability of financial success of the microalgae cultivation facility is also evaluated based on projections of future prices and costs of significant variables of microalgae-to-biofuel systems. Monte Carlo simulation results show that in the long term, the average minimum selling prices of refined diesel varies from \$17.16 to \$-2.58 per gallon, depending on the co-product revenues.

## **4.2. Introduction**

Debates over the future of microalgae biofuels exist have focused on the quantification of the sustainability benefits and economic feasibility of commercial-scale algae production (Chisti 2007; Liu, Clarens et al. 2012). Numerous studies have been published on the topic, but results are quite divergent. Disparities among these studies are mainly attributed to inconsistency in system boundaries, scope, cultivation system architectures, and degrees of waste and co-product integration, all of which prevent agreement on environmental performance of microalgae biofuels (Benemann 1996; Kadam 2002; Lardon, Helias et al. 2009; Sialve, Bernet et al. 2009; Clarens, Resurreccion et al. 2010; Luo, Hu et al. 2010; Sander and Murthy 2010; Stephenson, Kazamia et al. 2010; Campbell, Beer et al. 2011). Economic analyses of photosynthetic microalgae-based biofuels are also conducted in many of these studies (Carriquiry, Du et al. 2011; Sun, Davis et al. 2011), but due to the early stage of development of this segment, estimating the cost of producing algal oil remains a challenge. Existing cost studies present widely diverging results (Benemann 1996; Molina Grima, Belarbi et al. 2003; Schenk, Thomas-Hall et al. 2008). These differences are attributed to ranges of oil yields that can vary from conservative to aggressively high yields affecting strongly the cost estimates. Capital costs, several coupled plants with CO<sub>2</sub> sequestration, or wastewater application as cost lowering

components and a scenario-by-scenario basis per studies do not allow direct cross-comparisons (Tapie and Bernard 1988; Benemann 1996; Campbell, Beer et al. 2011; Davis, Aden et al. 2011; Norsker, Barbosa et al. 2011). These results show a continued lack of agreement on production costs and economic viability of microalgae based production systems.

Most studies present a traditional accounting of cost and capital investment, but few consider a more informative way of assessing and presenting the risk in microalgae-to-biofuel investment (Hertz 1964; Hertz 1979). No microalgae economic viability studies have presented a quantification of the risks and uncertainty associated with a project (Damodaran 2007) .

A number of studies over the years have supported the development of the modern concept of algae biofuels production. Benemann et al. provide complete explanations of costs estimates, but focus only on open pond production systems and do not analyze risks (Benemann 1996). Tapie and Bernard conduct a review of the algae literature, describing data and costs for large-scale algae production facilities and reporting total production costs of non-processed biomass ranging from \$0.15 to \$4.00/kg (Tapie and Bernard 1988). Huntley and Redalje estimate oil production costs at \$84/bbl (2004 dollars), assuming no improvements in current technology, but because of the proprietary nature of the study, a detailed list of costs is not presented (Huntley and Redalje 2007). Chisti evaluates the technical feasibility of microalgae for biodiesel production. In reviewing production practices Chisti finds that the current technology in microalgal production results in a cost per gallon of production of \$2.95 and \$3.80 for PBRs and open ponds, respectively (2006 dollars), but there are no details for how the author arrived at these cost estimates (Chisti 2007). Shen et al. reviewed the performance, special features, and technical and/or economic barriers to various microalgae mass production methods, including open ponds and PBRs, but the analyzed plant was not for biofuel production. In addition, the

open pond and PBR systems studied are for different locations and producing different amounts of biomass, further complicating comparison (Shen, Yuan et al. 2009). Norsker et al. calculated production costs under Dutch climatic conditions for three different microalgal production systems: open ponds, horizontal tubular PBRs and flat panel PBRs. They evaluate the economics for a commercial 100 hectare facility and calculate the capital and operating costs for a one hectare facility. Their study shows the economies of scale that exist between the two different size facilities of the sensitivity of production costs to reducing mixing costs and nutrient costs, and the effect of improving irradiation and photosynthetic efficiency, which is significant for algal production (Norsker, Barbosa et al. 2011). Richardson et al. analyzes probability of success for both open pond and PBR systems, based on Davis et al. models, evaluating CAPEX and OPEX reductions from 100 to 10% in several scenarios as to achieve probability of success of 95% or higher, but does not discuss what major changes would allow those reductions (Richardson, Johnson et al. 2012).

Davis et al. is one of the most recent and comprehensive economic viability studies evaluating the product costs of microalgae-derived biofuel from open pond and airlift PBR systems, where both systems use an anaerobic digestion system as a coupled system with microalgae cultivation. The model was constructed with open, clear, accurate and detailed engineering data and referencing, for every part of the process (Davis, Aden et al. 2011).

Based on our understanding of the literature, we can generate two primary requirements of a study that can contribute to the current debate. First, microalgae analyses have been more focused on open pond technologies and the existing few analyses on enclosed photobioreactors are not based on commercial scale models and system operation data. Second, TEAs provide production costs of microalgae products for a base case with just one or few market scenarios,

not assessing the investment risks of microalgae biofuels from various outcomes and the probabilities that may impact forecasted profits.

The objective of this effort is to develop a baseline model of the Solix Biosystem Generation3 Photobioreactor cultivation model to assess the values of microalgae-derived biodiesel and co-products. As the biofuels industry continues to commercialize, it is critical to determine the value of microalgae-derived products and co-products for investors to maximize the return of their investment and to identify constraints of this microalgae-to-biofuel system (i.e. initial capital investment, operational costs or concerns, location and land costs, etc). The first part of this TEA will provide the baseline of cost and capital investments for this microalgae-to-biofuel design, based on the detailed engineering model, following by estimation of the product and co-product values. The second part presents a risk analysis that quantifies the investment risks involved in the microalgae-to-biofuel process using Monte Carlo simulation to analyze set of variable factors that affect the economic feasibility of microalgae production of biofuel and co-products.

#### **4.3. Methods**

This study presents a dynamic accounting analysis model including multiple inputs, capital investment inputs, operating and maintenance costs, and technical details on microalgae production rate, which allows us to model the range of economic performance and success probability of microalgae biofuels. The first stage of this analysis is to determine the baseline technoeconomic model for a suspended PBR microalgae cultivation system, based on the Solix Biosystem Generation 3 Photobioreactor.

The economic model developed by Davis et al. is used as reference basis, due to its adherence to a consistent framework that has been used in various biofuel techno-economic reports published by National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL) and Argonne National Laboratory (ANL), that enable studies of different systems to be comparable (Davis et al., 2013; Roberts et al., 2012; Swanson et al., 2010; Jones et al., 2009). The use of Davis' model is due to the meticulous construction, with clear, open, reliable and detailed engineering data and reference. Its construction allows flexible introduction or exclusion of specific engineering process or type of equipment or working load of equipments, which was important for its choice as model basis and to adapt the Solix model in its framework. The Solix Biosystem engineering model is combined with the accounting model developed by Davis et al. (Davis, Aden et al. 2011) as shown in Figure 9.

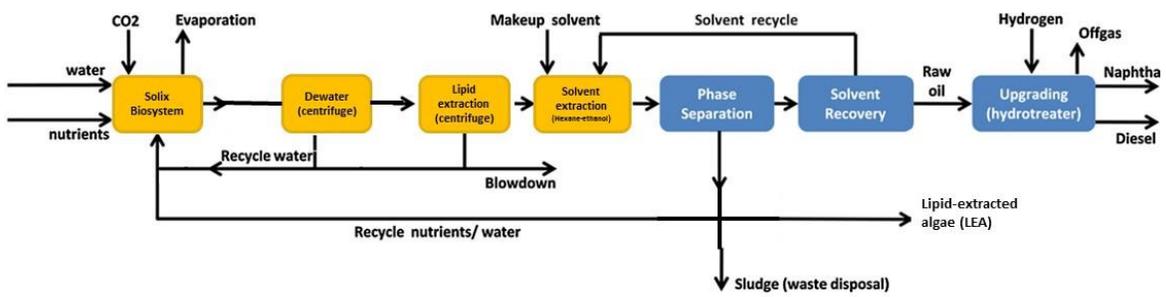


Figure 9. Flow diagram of Solix Biosystem baseline model

Capital costs, land costs, site development costs and CO<sub>2</sub> delivery system costs are based on the prior literature and standard engineering cost estimates. It also model the capital costs for pumping systems for water, nutrient and electrical supply, general machinery, office buildings, warehouses, field expenses, contingency costs, salaries and overhead, maintenance, taxes and insurance costs. The analysis aims to evaluate the production costs for cultivating and converting microalgae into refined diesel as well as producing and selling co-products. The Davis et al. accounts and allocates the selling prices of co-products as credits in the operating costs of the overall algae production system. The variables analyzed in this study are the minimum fuel selling price (MFSP) and production costs. Production costs are the costs to produce refined diesel. The MFSP is an accounting concept, which will be explained in greater detail in section 4.4.2, that aims to evaluate at what price the fuel must be sold to make the net present value of the algae production facility equal to zero, with a specific discounted cash flow rate of return, over a defined economic lifespan of the plant.

Analysis of Solix Biosystem Generation 3 Photobioreactor system provides a breakdown of the capital and operating costs to evaluate strength and constrains of this microalgae-to-biofuel system, in a comparable basis to other alternative systems. While there are many economic feasibility studies in the field, many of these studies gather the best of state-of-art of each processing technology, but do not necessarily represent a realistic system that can use all of the available state-of-art.

In the second part, this study will analyze the probabilities of financial success for the microalgae cultivation facility by varying key inputs to the analysis in a Monte Carlo framework. Projections of crude oil prices, natural gas, fertilizer, electricity and solvents prices and feed prices in the aquaculture market up to 2020 will compose the set of variables that can impact

significantly the outcome of the TEA of Solix Biosystem Generation3 Photobioreactor model. Due to the uncertainties involved in the projections, distributions of in costs and output revenues will be applied to the Monte Carlo simulations (See Figure 10).

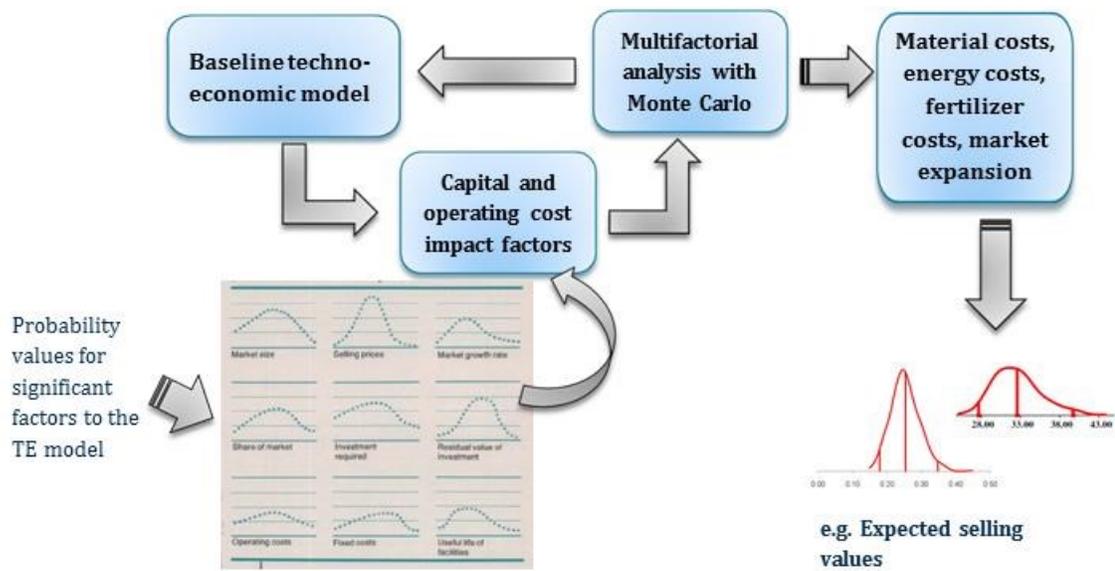


Figure 10. Technoeconomic and risk analysis approach diagram

#### **4.3.1. Develop a Baseline Technoeconomic Model**

The baseline engineering model will be based on the Solix Biosystem Generation 3 Photobioreactor cultivation system, an enclosed suspended PBR system. The existing Solix system is scaled to represent a facility with production capacity of 10 million of gallons of raw algal oil per year (Batan, Quinn et al. 2010; Davis, Aden et al. 2011).

#### **4.3.2. Technical Modeling Description**

##### **4.3.2.1. Cultivation system**

The modeled baseline PBR system is a photosynthetic facility composed of a number of 36 meters long and 0.127 mm (5 mil) thick clear polyethylene bags, supported in a thermal water bath, as shown in Figure 11. The Solix Biosystem Generation 3 Photobioreactor growth rates are based on the microalgae strain *Nannochloropsis salina*. The growth rate and lipid content are assumed as  $0.15 \text{ kg}\cdot\text{m}^{-3}\cdot\text{day}$  and 30%, according to the latest update from Solix Biosystem (Quinn, Yates et al. 2012). The microalgae are fed with fresh nutrient. The reactors incorporate an air sparge system designed to provide CO<sub>2</sub> and turbulent mixing. A sparging combination of 0.6 VVM of air flow and 25% duty is adopted for the system (Lammers, Quinn et al. 2012). The reactors are assumed to have a lifetime of 5 years and thus the annual costs of reactor replacement are assumed to be 1/5 of total reactors. The percentage of land used for PBR system is 80% and the percentage of harvesting is 67% of total reactor throughput per day. The microalgae are fed with fresh nutrient. Due to the presence of the water bath, a sprinkler system for cooling is excluded.

##### **4.3.2.2. Harvesting System**

The microalgae medium is transported from the PBR to a centralized processing unit, then harvest is accomplished through a centrifugal system. The centrate (free water) from the

clarifier is recycled with filtration system and the algae paste is then conveyed from the clarifier output to the extraction stage.

#### **4.3.2.3. Oil Extraction System**

The oil extraction separating the algae oil from the aqueous cellular environment is performed by high pressure centrifuges, followed by solvent extraction with hexane and ethanol, both tested by Solix Biosystem. The extraction process incorporates a shear mixer, centrifuge, decant tank, solvent recovery, and two distillation units for the recovery of solvents. The extraction system uses a hexane to ethanol solvent mixture of 9:1, at a solvent to oil ratio of 22:1, which recovers 90% of the lipids present in the algae. Counter flow heat exchangers with an effectiveness of 0.90 are used to recover process heat. Evaporator-condenser systems with 80% energy recovery are used for solvent recovery and oil separation (Batan, Quinn et al. 2010). The operating data are summarized in the Table 15.

#### **4.3.2.4. Algal Oil to Biodiesel Conversion System**

The extracted microalgal oil is converted to refined biodiesel via hydrotreating to remove oxygen and saturate double bonds present in the fatty acid chains of the triglyceride components, and crack large molecules into smaller components. This hydrotreating process is based on a UOP study for hydrotreating of vegetable oils and brown grease (Marker 2005; Davis, Aden et al. 2011 {Marker, 2005 #746). The model is set up to target biodiesel production, where biodiesel yield is kept high, compared to naphtha yield. The resulting conversion produces a small amount of naphtha-range material is also produced from the hydrotreater with 80% fuel yield, distributed in 78% of diesel and 2% of naphtha. The remaining co-products are offgas (mostly propane), CO<sub>2</sub>, CO and water (Davis, Aden et al. 2011).

#### **4.3.2.5.Possibilities for Utilization of Co-products**

The Solix production system generates a set of co-products: lipid-extracted algae (LEA), biodiesel and naphtha. The naphtha is sold as a component blended in gasoline. The LEA, however, can have several applications, such as fish feed for aquaculture, as co-firing biomass for bioelectricity generation, as food ingredients, cosmetics or pharmaceutical specialties. The Solix Biosystem cultivation and microalgal oil extraction system is qualified as *feed grade* (i.e. not suitable for human consumption), therefore, the uses of LEA as food ingredients, cosmetics and pharmaceuticals are excluded in this study.

##### **4.3.2.5.1. Feed**

Conventional fish and rotifer feed is composed of a minimum of 50% protein and of 20% oil content. The lipid extracted algae can be used to construct a feed of similar composition. The use of LEA to replace a conventional market product is also called the “displacement allocation” of co-products in this study, following the terminology of Huo et al. (Huo, Wang et al. 2009).

##### **4.3.2.5.2. Energy**

Renewable portfolio standards (RPS), also referred to as renewable electricity standards (RES), are policies designed to increase generation of electricity from renewable resources. These policies require or encourage electricity producers to supply a certain minimum share of their electricity from designated renewable resources that can include wind, solar, geothermal, biomass, landfill gas, municipal solid waste, and others. There is not a RPS program in place at a National level, and RPS or other mandate renewable policies varies from State to State. A combination of Federal incentives, State

programs and market conditions encourage the increase of the amount of electricity generated from eligible renewable resources.

Microalgae have potential use as co-firing biomass with coal in power plants to generate electricity (Kadam 2002). The use of LEA as an electricity generator, based on its energy content is called the “energy allocation” of co-products in this study, again following the terminology of (Huo, Wang et al. 2009).

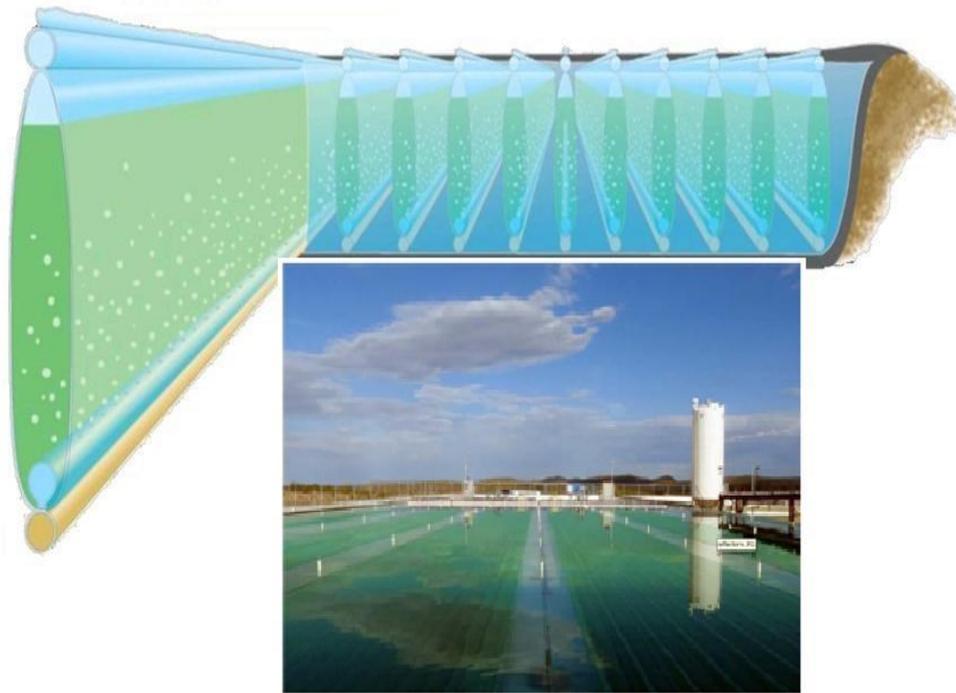


Figure 11. Illustration and photograph of the pilot facility modeled for this study.

Table 15. Microalgae cultivation system operating data

<b>Operating Variable</b>	<b>Value</b>	<b>Note</b>
Average growth rate	0.15 kg·m <sup>-3</sup> ·day <sup>-1</sup>	(Quinn, Yates et al. 2012)
Annual average lipid production	13 m <sup>3</sup> ·ha <sup>-1</sup> ·year <sup>-1</sup>	(Quinn, Yates et al. 2012)
Algae lipid content	30%	(Batan, Quinn et al. 2010; Quinn, Yates et al. 2012)
Harvest cell density	3 g/L	(Quinn, Yates et al. 2012)
Water recycling	98%	(Quinn, Yates et al. 2012)
Water losses		
- Dewatering	1%	(Batan, Quinn et al. 2010)
- Harvesting and extraction	10%	
Extraction losses	10%	
- TAG	10%	
- Ethanol	2%	(Batan, Quinn et al. 2010)
- Hexane	2%	
Nutrient requirements:		
- Nitrogen (dry weight %)	6.3%	(Sturm and Lamer 2011)
- Phosphorus (dry weight %)	0.873%	
CO <sub>2</sub> demand	2 kg/kg of algae biomass	(Batan, Quinn et al. 2010)

### 4.3.3. Financial Feasibility Economic Model Description

The outputs of the engineering model are used to evaluate all capital and operating costs in order to establish a baseline of production costs for this microalgae production of biofuels and co-products. Many capital and operating costs were based on the model of Davis et al. (Davis, Aden et al. 2011), but the following significant changes were made to the microalgae to biofuels system model:

- modelling of Solix-type enclosed PBRs;
- 80% of photosynthetic area is assumed for land use;
- ethanol-hexane extraction system;
- exclusion of sprinkler cooling system;
- exclusion of ground-lining;
- exclusion of anaerobic digestion and nitrogen recycling and,
- exclusion of on-site power generation.

The general economic assumptions for this study were based on the model of Davis et al. with few changes and are summarized in the Table 16 with few changes:

- inclusion of allocation methods for co-product LEA and,
- number of area per operator.

Table 16. Economic assumptions and inputs for the baseline model (Davis, Aden et al. 2011)

<b>Economic variable/input</b>	<b>Value</b>
Tax rate	35%
Analyzed period	20 years
Facility depreciation period	15 years
Learning curve to full production	0.25 years
Discount rate for NPV	10%
Loss in Capital Equipment Value per year	5%
Indirect costs	
- Warehouse	1.5% of Total Installed Capital (TIC)
- Site development	9% of process-related capital
- Home office and construction	25% of TIC
- Contingency	30% of TIC
- Prorateable costs	10% of TIC
- Field expenses	10% of TIC
Insurance and taxes	1.5% of TIC
Maintenance	2% of equipment costs
Overhead	60% of labor costs

#### **4.4. Results**

The results and discussion are presented in three sections. The first presents the baseline results, where the baseline is defined using the default values of each technical and economic input so as to model the 2013 operation of the Solix Biosystems PBR and biofuels process. The second result presents a sensitivity analysis to determine those technical and economic inputs that have the largest impact on microalgae biodiesel minimum selling price. The third results section presents a probabilistic analysis of the minimum fuel selling price inclusive of realistic levels of technical and economic uncertainty.

##### **4.4.1. Baseline Results**

The resulting production costs for the microalgal raw crude oil of \$13.10 per gallon and refined diesel of \$14.11 per gallon. The breakdown of microalgae costs is shown in Figure 12. The operating costs represent the largest contribution (63%) to total production cost, the capital investment costs represent almost 30%, and land purchasing costs are only 7% of the production costs.

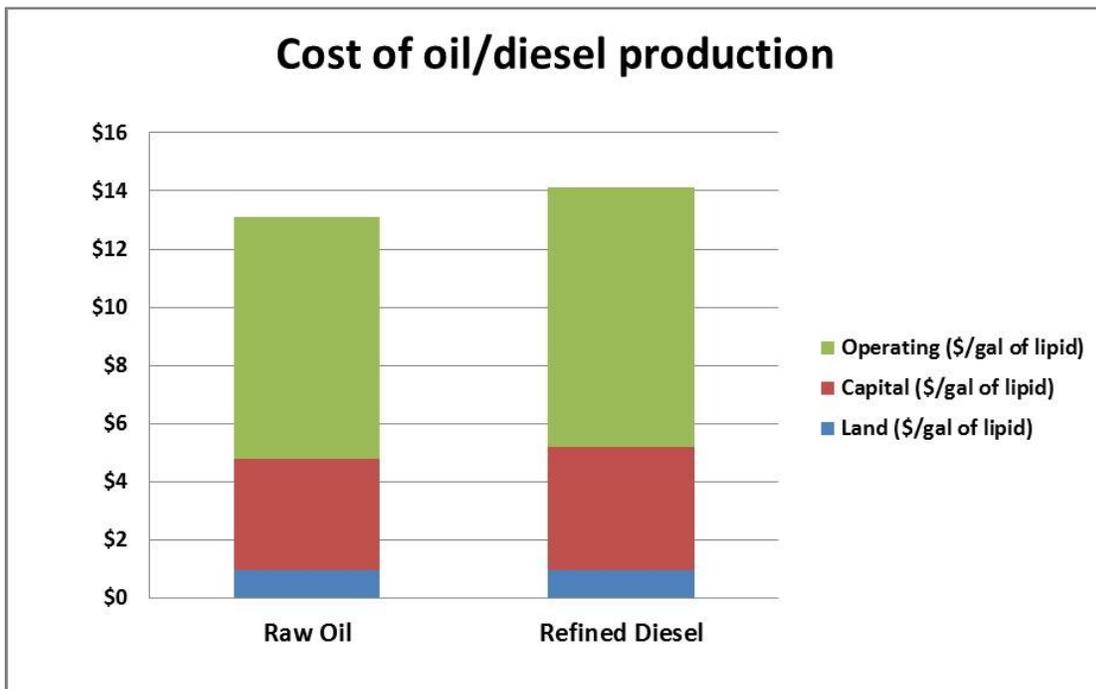


Figure 12. Breakdown of microalgae crude oil and biodiesel production costs.

The components of capital investments and operating costs are demonstrated in Table 17. The results show that dewatering and lipid extraction are the areas for improvements or further researches. The harvesting of microalgae (dewatering) and lipid extraction centrifuges are 23% and 24% of the total direct installed capital costs. The operating costs also demonstrate that the solvent consumption in the lipid extraction is the major component (28%) of total operating costs.

The PBR capital costs represent almost 16% of total direct installed capital and, with 5-year-lifetime, its annual replacement costs is only 8% of total operating costs. Following after solvent consumption, the nutrient costs and power supply costs are the other major costs, with contribution of 22% and 16% of total operating costs.

Table 17. Technoeconomic baseline model results for refined biodiesel. Values are in millions of US dollars.

<b>CAPITAL AND EQUIPMENT INVESTMENT COSTS</b>	<b>In MM \$Dollars</b>
<b>Microalgae lipid production</b>	
PBR tube system	\$35.43
CO2 distribution	\$0.65
Primary harvesting (settling)	\$4.19
Cell rupturing (homogenizer)	\$49.00
Extraction Centrifuge + Stripper	\$51.61
Water/Nutrient/Waste/Electrical Supply	\$7.54
General machinery	\$3.88
Initial Water Charge	\$0.88
<b>Diesel hydrotreating plant</b>	
Diesel hydrotreating plant	\$8.37
<b>Non-Depreciable Capital</b>	
Land Costs	\$52.57
<b>Total Direct Installed Capital</b>	<b>\$214.12</b>

<b>INDIRECT INSTALLED COSTS</b>	
Site Development (2)	\$4.61
Warehouse	\$0.72
Prorateable Costs	\$5.31
Field Expenses	\$5.31
Home Office and Construction	\$13.28

Contingency (1)	\$50.06
Other Costs	\$12.71
Working capital (25% of Operating Costs)	\$21.63
<b>Total Indirect Installed Costs</b>	<b>\$113.63</b>
<b>TOTAL DIRECT AND INDIRECT INSTALLED COSTS</b>	<b>\$327.74</b>

<b>OPERATING COSTS</b>	
<b>Microalgae lipid production</b>	
Power	\$13.46
Nutrients (N,P,Fe) + wastewater nutrients	\$18.96
CO2	\$5.92
Solvent extraction	\$24.03
PBR 5-year replacement	\$7.09
Waste Disposal	\$1.36
Utilities (cooling water, steam)	\$2.92
Labor and Overhead	\$3.82
Maint., tax, ins	\$5.43
<b>Diesel hydrotreating plant</b>	
Hydrogen	\$1.68
Steam	\$0.01
Labor and Overhead	\$0.76
Maint., tax, ins	\$1.09
<b>TOTAL OPERATING COSTS (\$/YR)</b>	<b>\$86.52</b>

#### 4.4.2. Minimum Fuel Selling Price

The economic feasibility analysis consist of first estimating the total capital investment (TCI), computed from the total equipment cost and land costs. Following, it is estimated variable and fixed operating costs. These costs are used with a discounted cash flow analysis and a modified accelerated cost recovery system (MACRS) to calculate the minimum fuel selling price (MFSP), required to obtain a zero net present value (NPV) with the specified internal rate of return. The MFSP is calculated by following equations:

**MFSP**

$$= \frac{(\text{Operating Costs}_{Net}) + (TCI_{Depreciable} \cdot FCR_{Depreciable}) + (TCI_{Non-depreciable} \cdot FCR_{non-depreciable})}{Yield_{Biodiesel}}$$

Where:

Operating Costs<sub>Net</sub> = Total Operating Costs – Coproduct Credits (revenue)

TCI = Total Capital Investment

FCR = Fixed charge rate

Yield = Annual biodiesel yield (gallons per year)

$$FCR_{Degradable} = \frac{\frac{ROI \cdot (1 + ROI) \cdot j}{[(ROI + 1)^j - 1]} \cdot (1 - i) \cdot NPV}{(1 - i)}$$

$$FCR_{Non-degradable} = \frac{\frac{ROI \cdot (1 + ROI) \cdot j}{[(ROI + 1)^j - 1]}}{(1 - i)}$$

Where:

ROI = Desired rate on investment

$j$  = Analysis period

NPV = Net Present Value factor (for depreciation charges)

$i$  = Tax rate

The set of economic assumptions is shown in Table 16.

The Solix production system generates a set of co-products: lipid-extracted algae (LEA), biodiesel and naphtha. This study focuses on the production of biodiesel, therefore, the revenue of co-products LEA and naphtha is treated as credits.

The co-product revenue can be accounted for in two different ways:

#### **4.4.2.1. Displacement allocation**

The naphtha produced is sold as gasoline replacement. Its revenue is based on the gasoline retail price of \$3.58 (annual average in 2013, reported by EIA), which accounts for credits of \$0.13 per gallon of biodiesel produced.

The current market requires a fish feed with a minimum of 50% protein and 20% of oil with a selling price of \$1.53 per kg. The LEA feed has 36.7% protein and 5% oil on a dry weight basis. In order to create an equivalency between the LEA feed and the conventional fish feed, there are two adjustments that are regarded: (1) protein and oil ratio, and (2) percentage of protein. To achieve the requirement of protein and oil ratio, a 9.7% on dry weight basis of canola oil at \$0.97 kg<sup>-1</sup> (20) is added to the extracted biomass to produce a product with the same ratio of mass weight of protein to oil (5:2). The cost of canola oil is added to variable operating costs. To meet the minimum of 50% protein of fish feed, the amount of 1.3 kg of LEA-canola should be used to replace 1 kg of fish feed, and it is reflected in the revenue credits as 1.3 kg of LEA-canola feed is sell

for \$1.53 (De Pauw, Morales et al. 1984; Lubzens, Gibson et al. 1995; Metting 1996; Pulz and Gross 2004; Richmond 2004; Huo, Wang et al. 2009).

The current commercial market value of fish feed for aquaculture is US \$1.53 kg<sup>-1</sup>. Costs relating to oil mixing and transportation are not included in this study as further investigation is still required for accurate estimation of costs. The microalgae system produces a 99.8 metric tonnes of LEA per year and its revenue as fish feed provides equivalent credits of \$15.76 per gallon of microalgae biodiesel produced.

The final MFSP of algal diesel, with the revenue credits of LEA and naphtha is \$-1.78 per gallon. Again, the MFSP variable is an accounting concept, not a real price. A negative value of the MFSP simply means that even if the biodiesel is sold at a loss the algae production facility would still be economically feasible, in this case due to the high value of the LEA co-product being sold as fish feed.

#### **4.4.2.1. Energy Allocation**

The naphtha produced has equivalent energy value of gasoline. Its revenue is based on the gasoline retail price of \$3.58 per gallon, which accounts for credits of \$0.13 per gallon of biodiesel produced.

After the algal oil extraction, the LEA has a heating value of 14.2 MJ/Kg for the baseline scenario. The biomass price for electricity generation is \$2 per million BTU of heating value capacity (Brown and Baek 2010). The sale of co-product LEA as biomass co-firing material accounts for a credit of \$ 0.03 per gallon of biodiesel produced.

The final MFSP of algal biodiesel, with the revenue credits of LEA and naphtha, is \$13.95 per gallon.

#### **4.4.1. Sensitivity Analysis of Minimum Fuel Selling Prices**

A sensitivity analysis was undertaken to identify which components of the microalgae-to-biofuel system design contribute most directly to the final feasible selling price of algal biodiesel, allowing an algae photobioreactor production system to be economically viable.

The results of this sensitivity analysis are presented as a tornado plot, in Figure 13. The magnitude of each bar indicates the difference in average output (e.g. production cost) associated with a 30% change of that single input from its average value, with all other inputs are held constant. Changes in output associated with an increase of input values are indicated on each side of the centerline (baseline case) using blue shading; while decrease of input values are indicated with red shading.

The sensitivity analysis shows that a change in the selling prices of the co-product LEA as fish feed have the greatest influence on the minimum selling price that is feasible for algal biodiesel produced by this system. A 30 percent change in the selling price of the co-product causes a 270 percent change in the minimum selling price for biodiesel. Changes in the most significant input costs, including the price of hexane, HDPE, electricity and nitrogen fertilizer increase the algal MFSP in the range of 20– to 34 percent. A 30 percent change in any of the other input cost variables results in a less than 17 percent change in the MFSP of algal biodiesel.

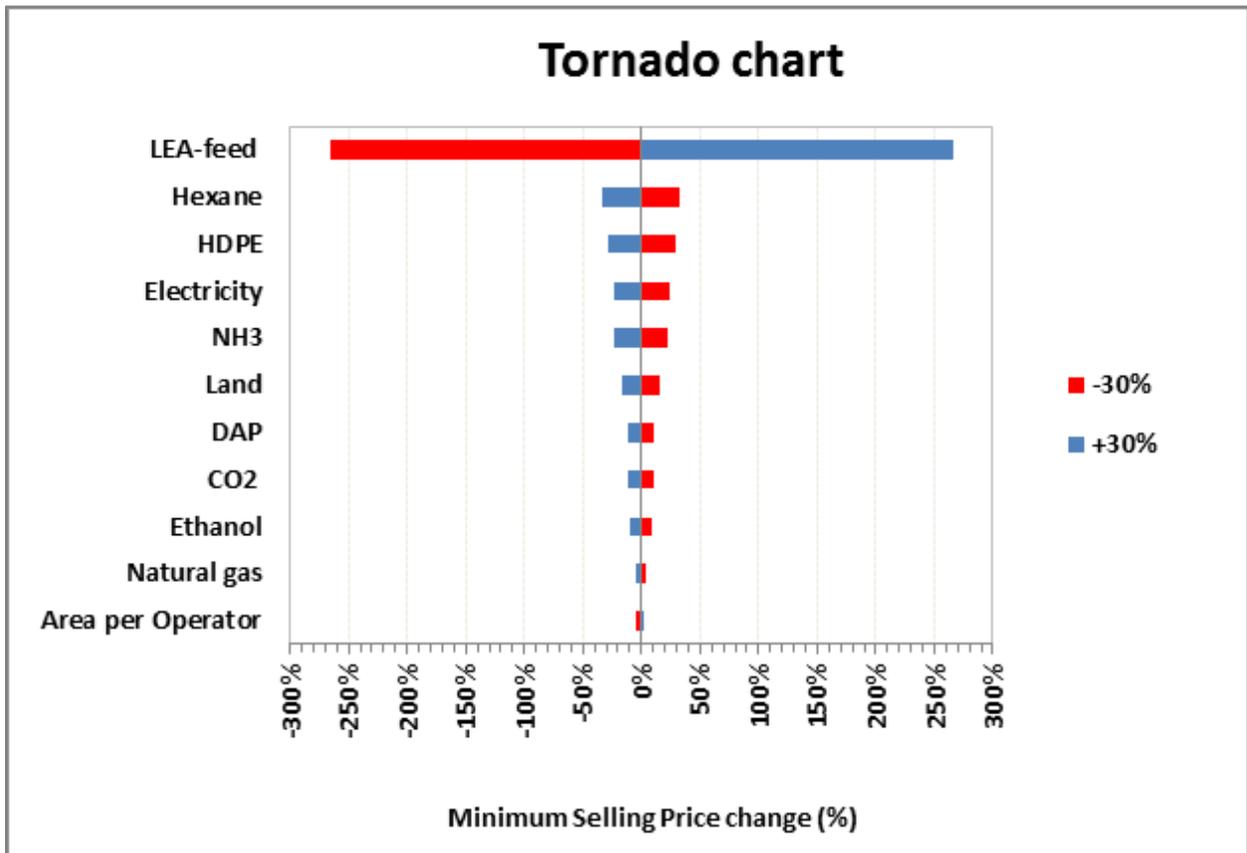


Figure 13. Tornado plot demonstrated the extent to which raw algal oil MSP (production cost) changes with  $\pm 30\%$  of input parameters. The center line represents the baseline case. The blue and red shading bar represents the direct and reverse relationships.

#### 4.4.2. Probability Curves of Minimum Fuel Selling Price using Monte Carlo

In the final results set, this analysis aims to evaluate the distribution of MFSP of microalgal biodiesel so as to provide decision-makers or investors with a range of possible outcomes to the development of a microalgae biofuel system. The Monte Carlo method is a stochastic simulation technique that iteratively evaluates a deterministic model (i.e. baseline case), using a random variables as inputs. The combination of input variables encompasses the set of scenarios and risks to which the investment could be exposed. A Monte Carlo simulation runs a high number of trials randomly drawing input values from this set to generate probability distributions of the outcomes. In the field of capital investment analysis, Monte Carlo techniques are used to value an investment proposition and to better understand and manage risks (Hertz 1979; Razgaitis 1999; Jèackel 2002).

The inputs to the Monte Carlo simulations performed in this study are the 5 variables to which MFSP is most sensitive: *LEA selling price, polyethylene, hexane, electricity, and nitrogen fertilizer costs*. Probability density functions for these inputs were constructed on the basis of projections of future prices. We adopted triangular probability distributions, where lower bound is related to lower or worst scenario, the upper bound is related to higher or best scenario, and the median is approximated by a reference scenario (Tan, Culaba et al. 2002; Damodaran 2007). The derivation and data sources for these probability distribution functions are presented below.

Under displacement allocation, LEA is considered for sale as a fish feed replacement. A common condition for all scenarios and future-cast of aquaculture expansion is that human population growth will continue and the demand for more fish and seafood will also increase. Over the period of 1980 to 2010, aquaculture has expanded in an annual average of 8.8% globally, but has stagnated in the United States (FAO 2012). Aquaculture experts predict

improvements in aquaculture production and products over next 5 to 25 years (from baseline year of 2011), which include expanding knowledge of nutrient availability and value of new nutrients, genetically modified species that can better utilize plant based nutrients and increasing share of plant-derived proteins and oils into aquaculture feedstuffs (also known as “aquafeed” or fish feed). For the latter, the scale of biofuel industry can have a major impact on feed composition (Rust, Barrows et al. 2011). The biofuel industry generates a large quantity of co-products such as dried distiller grains with solubles (DDGS), which due to its low and competitive price and protein content, will likely be incorporated as part of aquafeeds. DDGS have some disadvantages as aquafeed due to nutritional contents. Co-product LEA has some advantages in this market, with a high fraction of proteins required in aquafeeds. To date, however, the high cost of production has been limiting the utilization of LEA in aquaculture (Rust, Barrows et al. 2011; Walker and Berlinsky 2011).

For probability analysis, the LEA selling price is modeled based on aquaculture production scenarios and projected fishmeal prices. The reference aquaculture scenario incorporates an annual rate of increase of 1.5% of global food fish production (Delgado, Wada et al. 2003), resulting in a modeled 18% increase in LEA price, between 2013-2020. The higher case scenario assumes a faster aquaculture expansion scenario as would be associated with a decrease in food fish price and an increase of fishmeal price (FAO 2012), resulting in a modeled 59% increase in LEA price between 2013-2020. The lower bound or the slower aquaculture expansion scenario is based on a scenario projecting price increase for all food fish (Delgado, Wada et al. 2003), resulting in a modeled 0% increase in LEA price.

Under the energy allocation of co-product, LEA is analyzed as co-firing biomass to generate electricity in power plants. The LEA selling price as co-firing biomass is projected

using the baseline data for 2013 and the same yearly percentage increase in price as is projected for industrial electricity (EIA 2013).

The input costs for high density polyethylene (HDPE), hexane and nitrogen fertilizer costs are projected using the baseline data for 2013 and the projected yearly percentage increase in price for crude oil. Both materials reference the U.S. Energy Information Agency (EIA) reference scenario, lower case scenario, and higher case scenario (USDA 2011; EIA 2013). These projections are summarized in Table 18.

The Monte Carlo simulations were performed in the Phoenix Integration Model Center v.10.1 software, with 3,000 runs (determined through a convergence study) for each co-product allocation. The Monte Carlo simulations resulted in an average production cost for a gallon of refined diesel of  $\$17.32 \pm 0.87$  per gallon, without accounting for co-product credits.

Under the displacement allocation of co-products, the revenues of co-products, LEA and naphtha reduces the average minimum selling price to  $-\$2.58 \pm 2.11$  per gallon of refined diesel. The resulting distribution of MFSPs under displacement allocation of co-products is a widespread curve with large deviation. This result is very consistent with the sensitivity analysis performed for the MFSP of microalgal biodiesel (in section 4.4.1), where it was demonstrated the significant influence of the revenue of LEA as fish feed in the MFSP of algal biofuel. The large deviation of the resulting curve also is a direct influence of the widespread projection of selling price of LEA as fish feed, which varies from 0% to 59% from the 2013 baseline value (see Table 19).

Under the energy allocation method, the revenues of co-products slightly reduce the average minimum selling price to  $\$17.16 \pm 0.88$  per gallon of refined diesel. The resulting distribution of MFSPs under energy allocation of co-products is very narrow curve with small

deviation, which is expected according to the sensitivity analysis. The revenue of LEA as co-firing biomass accounts for dramatically smaller credits compared to displacement allocation and also the projection of selling prices for LEA as co-firing biomass is narrower, varying from 15 to 19% from the 2013 baseline value, as can be seen in Table 19.

The distributions of MFSP for each of these co-product allocation methods are shown in Figure 14.

Table 18. Summary of reference, low and high scenario projection for Monte Carlo simulations

<i>Variable</i>	<i>Projections Scenarios 2020</i>			
	<b>Reference Costs (2013)</b>	<b>Lower</b>	<b>Reference</b>	<b>Higher</b>
<b>LEA as co-firing biomass sell price</b>	\$2.7/MMBTU	\$3.11	\$3.15	\$3.23
<b>LEA as fish feed sell price</b>	\$ 1.53 per Kg	\$1.53	\$1.81	\$2.43
<b>Hexane price</b>	\$0.91 per Kg	\$0.63	\$0.88	\$1.39
<b>Nitrogen Fertilizer price</b>	\$863 per metric ton	\$600.12	\$845.38	\$1,329.32
<b>Electricity price</b>	\$0.067 per KWh	\$0.077	\$0.078	\$0.080
<b>HDPE price</b>	\$2 per Kg	\$1.39	\$1.96	\$3.08
<b>Naphtha sell price</b>	\$3.58	\$2.55	\$3.08	\$4.16
<b>Diesel sell price</b>	\$3.58	\$2.96	\$3.67	\$4.99

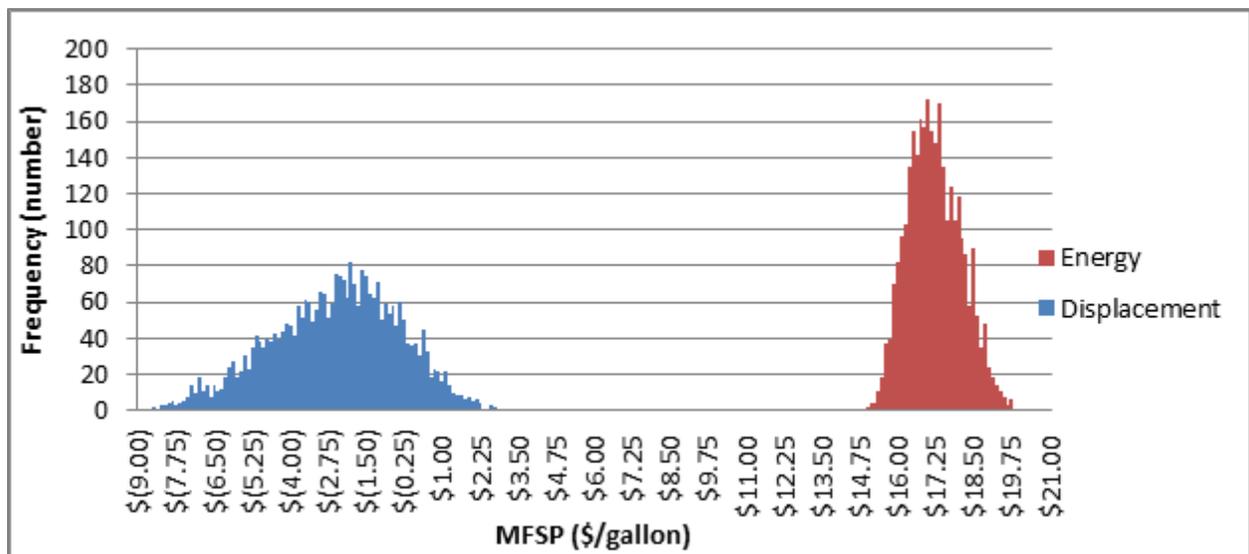


Figure 14. Microalgal diesel average MFSP, simulated with replacement allocation, where LEA is sold as fish meal replacement, is \$-2.58 per gallon (in blue). Microalgal diesel average MFSP, simulated with the energy allocation, where LEA is sold as co-firing supply, is \$17.16 (in red).

#### 4.5. Chapter Discussion and Conclusions

The purpose of this chapter has been to answer Research Question 3 which is repeated for reference below:

***What is the economic potential of microalgae to biofuel process?***

This study has developed a baseline model for the Solix Biosystem of PBR microalgae cultivation system to produce biofuels, with the production cost of \$14.11 per gallon of microalgal diesel. The co-product LEA and naphtha generate different revenue depending on the allocation method. Displacement allocation of co-products can add profit to drop the minimum selling price of algal biodiesel to \$-1.78 per gallon, while the energy allocation of co-products can add credits to drop the minimum selling price to \$13.95 per gallon of algal biodiesel

The microalgal diesel production cost is very high compared to soybean-based biodiesel costs, ranging from \$2.15 to \$2.55 per gallon (Tao and Aden 2009) and other diesel from alternative feedstocks and technologies, such as diesel from wood by hydrolysis with minimum selling price of \$1.60 per gallon (Roberts, Marker et al. 2012); Fischer-Tropsch biofuels from corn stover with production cost range of \$4.26 to \$4.83 per gallon (Swanson, Satrio et al. 2010); diesel from wood chips through fast pyrolysis with production cost of \$2.20 per gallon (Jones, Valkenburg et al. 2009).

The microalgae biodiesel derived from Solix model may have competitive production costs over some models of microalgae biorefineries, i.e. Richardson et al. (2014)'s study includes single solvent extraction for algal lipid and estimated average production costs of \$109 and \$77 per gallon of algal crude oil, respectively for open and PBR system (Richardson, Johnson et al. 2014); Brownbridge et al. (2014) assessed microalgae biodiesel derived from Fischer-Tropsch process and with production costs between £0.8–1.6 per kg of biodiesel (Brownbridge, Azadi et

al. 2014), and Davis et al. (2014) assessed microalgae biodiesel from hydrothermal liquefaction (HTL) process with MFSP of \$10 per gallon of biodiesel (Davis, Fishman et al. 2014).

The results of sensitivity analysis show the significant impact of co-product end-use values in the net operating costs and MFSP, followed by solvent hexane costs, HDPE costs, electricity costs and nitrogen fertilizer costs.

The Monte Carlo simulations have demonstrated that microalgae biofuel have to sell algal biodiesel at minimum price of \$17.16 per gallon, when allocating co-product LEA as co-firing biomass and naphtha as gasoline. When co-product LEA is allocated as fish feed replacement and naphtha as gasoline, the revenue generates enough profit to recover capital and operating costs to produce algal biodiesel, thus the minimum selling price of algal biodiesel can be dropped to \$-2.58 per gallon. This demonstrates that the economic performance of the microalgae to biofuels process is dependent on access to co-product markets. Microalgae facilities that only produce fuels and electricity will be forgoing value that is available through sales of co-product.

These results provide evidence to support to Hypothesis 3 in that a dynamic analysis model with multifactorial inputs, including projections of input prices, analogies for market size and growth, and ranges of selling prices have been able to estimate the economic performance and probability of success of microalgae biofuels.

## **Chapter 5. Contributions of the Research and Future Work**

### **5.1. Conclusions**

System level assessments of microalgae-based biofuels have generally been complicated by the lack of data for these developing cultivation systems, the presence of novel coproducts and energy pathways for these new systems, the capital cost-intensity (and energy intensity) of microalgae cultivation systems, and the lack of a common framework with which to compare algae based biofuels to more conventional petro-, or bio-fuels. This dissertation has defined and completed a series of tasks to address the primary research challenges associated with the system-level assessment of the state of the art microalgae-to biofuels processes.

This dissertation has demonstrated the integration of a detailed engineering model of microalgae-to-biofuels process into an integrated LCA Model. This model was then used to evaluate and assess the environmental performance of an industrially demonstrated microalgae cultivation, processing and conversion system. Results show demonstrated that industrial-scale microalgae-based biofuels can realize benefits in terms of the metrics of net energy consumption and GHG emissions under certain allocation scenarios, but will face large scalability challenges to be able to meet current biofuels development goals. This work was one of the first and is one of the most cited studies of microalgae biofuels LCA.

This dissertation has developed a framework for evaluating the water consumption and footprint of the microalgae-to-biofuels process using the metrics of blue, green and lifecycle water footprint. These metrics are then evaluated for microalgae biofuels at a variety of scales, metrics, geographic locations and climates. The results show that the WF of microalgae biofuels are sensitive to the uses of their coproducts but under a default scenario microalgae biofuels will

have intermediate WF when compared to more conventional biofuels. This study is the first to evaluate the lifecycle WF of microalgae biofuels.

This dissertation has developed a techno-economic model of microalgae biofuels production that includes the capability to model and evaluate parametric, and scenario uncertainty and to evaluate investment risk. This study shows that microalgae biofuels are more costly than presently available biofuels and that the economic viability of microalgae biofuels is sensitive to the uses of microalgae cultivation coproducts. These methods are novel in that they are applied to PBR-type cultivation systems and in that they present stochastic simulation results.

## **5.2. Research Contributions of This Dissertation**

To complete the research tasks associated with these complications, this work has developed several new contributions to the field of assessment of microalgae based biofuels.

First, detailed engineering models of the technical characteristics of the microalgae cultivation, harvesting, conversion, transportation, and coproducts have been integrated into parametric assessments of net-energy, greenhouse gas emissions, scalability, water consumption, and economics. To inform this effort, detailed data on energy and materials consumptions and emissions associated with microalgae cultivation, processing, and conversion were obtained through referencing new data gathered at Solix Biofuels and Colorado State University's Engines and Energy Conversion Laboratory. These detailed data were incorporated into engineering and technical models that inform the system level assessment with a level of detail and fidelity that has not been performed before. This work enabled the development of detailed tradeoffs among the technical performance of the cultivation system with the objective of maximizing system-level performance metrics.

For each of these system level metrics, the comparability of these results to previous work was enabled through the development of common frameworks of comparison. For the net energy and GHG comparisons, this work developed a microalgae LCA under an ANL GREET-type framework, which enabled comparison to the suite of LCA results available from ANL GREET's long duration effort in transportation energy assessment. For the water footprint comparisons, this work has developed a definition of lifecycle, blue, and green WF that is applicable to microalgae-based biofuels. Again, this allows for a direct comparison to the growing body of literature that uses these WF metrics for water impacts assessment. For the economic assessments, this work has developed a parametric, stochastic simulation that allows direct comparison to the NREL body of work on TEA of microalgae and more conventional biofuels. In each case, these works are the first studies proposing a suite of microalgae biofuels system-level metrics that are directly comparable to similar metrics for other petro- or bio-fuels.

The research contributions of this dissertation can be summarized as:

- This research effort has developed a novel combined LCA, WF and economic analysis for a closed PBR system for microalgae biofuel production.
- As contribution, the results of the LCA research have:
  - Modeled the energy and material inputs and outputs of a closed PBR system,
  - Identified coproduct allocation as a key factor in assessment of the resulting energy and GHG metrics,
  - Performed rigorous and detailed comparison of the environmental performance of microalgae biofuels to more conventional petro- and bio-fuels.
- Results of the WF research have:

- Defined water footprint metrics relevant to the characteristics of current algae biofuel systems,
  - Quantified the biomass and lipid yield dependency of WF,
  - Quantified the sensitivity of WF to geographical and climatic conditions,
  - Developed comprehensive boundaries and standardized metrics, to provide clear and direct information on the sustainability of microalgae biofuels compared to more conventional petro- and bio-fuels.
- Results of the TEA research have:
    - demonstrated that microalgae biofuels from suspended polyethylene bags are economically challenged when compared to biofuels from alternative feedstocks and technologies,
    - Quantified the sensitivity of microalgae biofuels to coproduct allocation,
    - Derived risk-based scenarios that characterize microalgae biofuels success and failure. Quantified the economic risks associated with fossil fuel-derived inputs and costs (hexane, fertilizer, polyethylene for bags, electricity price). Quantified the economic risks associated with uncertainties surrounding coproduct markets.

### **5.3. Future Work**

This dissertation develops the framework of life cycle analysis for fuel pathways and a deeper understanding of the technoeconomic and capital investment risks for the microalgae biofuels from the design of submerged PBRs of Solix Biosystem cultivation system.

Although the detailed engineering plant models are specific to this design, the LCA and technoeconomic models developed for this research effort can be applicable to future efforts of analysis and comparison of biofuels.

There are also other applications that would benefit from the framework and models developed in this research. This work has concentrated on the development of consistent and comprehensive boundaries for novel biofuels technologies which may help new technologies (including waste-to-fuel, cyanobacteria, and bio-butanol) analysis identify design and economic bottlenecks, and areas of key investment.

Within the field of algae-biofuels, a Pareto analysis on the economic results shows that the next investigations should focus on characterization of alternative materials and geometric design of the PBRs for the cultivation of microalgae. These studies should seek to develop (1) a low price or affordable transparent material that can replace polyethylene, its costs and petroleum dependency, and (2) lower water use in the geometric shape of PBRs and water basin to lower WF impacts. Then conceptual design studies will compare the performance of the entire life cycle of microalgae-to-biofuel against its economic performance and risks.

Finally, these studies have identified the coproduct markets as key areas of uncertainty regarding the viability of algae-biofuels. Future investigations should focus on the viability of LEA as animal feed, in terms of its nutritional and economic value for fish and terrestrial animals. The energy use and GHG emissions required should be also evaluated for transportation and distribution of co-products.

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## Appendix

There are many products that do not have established or measured WF data. In this study, it was used the EIOLCA to evaluate WFs from their respective water consumptions and their respective market price. The calculated WFs for fertilizers and chemicals used in the analyzed processes are shown in Table A-1.

Table A- 1. : Price and water data for non-irrigation agricultural inputs

<b>Input</b>	<b>Water use (Gal H<sub>2</sub>O/\$)<sup>a</sup></b>	<b>Price (\$/ton) (2007)</b>	<b>W (m3 H<sub>2</sub>O/Kg)</b>	<b>Notes</b>
Ammonium nitrate	24.01	398 <sup>b</sup>	0.0362	
P fertilizers	24.01	1,103 <sup>b</sup>	0.1003	
Polyethylene	16.74	2,008 <sup>c</sup>	0.1272	
Hydrogen	--	--	0.22e	Average of 27 gallons water/kg Hydrogen (5%) and 4.6 gall water/Kg Hydrogen (95% of market production method)
Hexane	20.25	1,000 – 3,000 <sup>d</sup>	0.23	Highest price have been used
Ethanol	44.37	689 – 1,115 <sup>c</sup>	0.1873	Highest price have been used
Sodium hydroxide & methoxide	15.17	600- 3,000 <sup>d</sup>	0.1722	Highest price have been used

<sup>a</sup> (Institute 2008); <sup>b</sup> (USDA 2011); <sup>c</sup> (Borruso 2011)CEH Marketing Reports, <sup>d</sup>Retail selling prices ([www.businesswire.com](http://www.businesswire.com)), <sup>e</sup> (Webber 2007)

The respective WF of transportation and distribution were calculated based on the use of fuels for logistics. Logistic data were obtained for each fuel pathway from Luo et al. (2005) and the T&D WF results are shown in Table A-2.

Table A- 2. Transportation and distribution energy use, in GJ fuel produced

<b>T&amp;D</b>	<b>Biodiesel</b>	<b>Green diesel, types 1 &amp; 2</b>	<b>Renewable gasoline</b>
<b>Coal</b>	1.5E-06	1.3E-06	3.3E-06
<b>NG</b>	3.2E-04	2.7E-04	4.4E-04
<b>Petroleum</b>	6.4E-04	5.5E-04	5.1E-04
<b>Total</b>	<b>9.6E-04</b>	<b>8.2E-04</b>	<b>9.5E-04</b>

In the Table A-3 are shown data for precipitation, per month for each location analyzed in this study. These data are then coupled with each location freezing and melting temperatures (which establish the cultivation period for each location) to calculate green WF.

Table A- 3. Precipitation data (in meters of water) (NOAA)

<b>Location</b>	<b>JAN</b>	<b>FEB</b>	<b>MAR</b>	<b>APR</b>	<b>MAY</b>	<b>JUN</b>	<b>JUL</b>	<b>AUG</b>	<b>SEP</b>	<b>OCT</b>	<b>NOV</b>	<b>DEC</b>	<b>Total Precipitation per Cultivation Period</b>
<b>TEMPE</b>	0.020	0.020	0.023	0.009	0.005	0.003	0.020	0.030	0.021	0.015	0.013	0.026	0.204
<b>HAYFIELD PUMP PLANT</b>	0.018	0.013	0.011	0.003	0.002	0.000	0.007	0.013	0.011	0.007	0.006	0.014	0.105
<b>JOHN MARTIN</b>	0.008	0.008	0.020	0.028	0.052	0.052	0.066	0.055	0.034	0.025	0.012	0.008	0.343
<b>YELLOWTAIL</b>	0.022	0.019	0.033	0.053	0.073	0.066	0.033	0.025	0.045	0.043	0.023	0.019	0.388
<b>NORTH PLATTE</b>	0.010	0.013	0.029	0.052	0.085	0.090	0.078	0.055	0.039	0.030	0.015	0.011	0.464
<b>BOULDER CITY</b>	0.017	0.016	0.017	0.009	0.005	0.002	0.012	0.018	0.013	0.008	0.011	0.013	0.100
<b>STATE UNIVERSITY</b>	0.012	0.010	0.006	0.006	0.008	0.018	0.040	0.053	0.034	0.022	0.012	0.018	0.236
<b>GRAND FALLS</b>	0.015	0.014	0.011	0.017	0.043	0.071	0.097	0.095	0.071	0.043	0.015	0.016	0.508
<b>FISH</b>	0.010	0.013	0.018	0.027	0.027	0.018	0.013	0.014	0.017	0.021	0.013	0.011	0.172
<b>FARSON</b>	0.010	0.009	0.011	0.018	0.027	0.025	0.017	0.017	0.019	0.017	0.009	0.008	0.151