INTERDEPENDENCE OF FINANCING PARAMETERS AND PROCESSING IMPROVEMENTS IN THE DESIGN OF ECONOMICALLY COMPETITIVE ALGAL BIOFUEL PRODUCTION PATHWAYS

Adam McCutchan Hise

A thesis submitted to the faculty at the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Department of Environmental Sciences and Engineering.

Chapel Hill
2015

Approved by:

Gregory W. Characklis

Michael D. Aitken

Robin Gerlach

Sridhar Viamajala

ABSTRACT

Adam McCutchan Hise: Interdependence of Financing Parameters and Processing Improvements
in the Design of Economically Competitive Algal Biofuel Production Pathways
(Under the direction of Gregory W. Characklis)

Financing parameters have often been considered exogenous variables in techno-economic analyses of algal biofuels production systems; these parameters reflect investment risk, a function of the processing techniques used and uncertain regulatory support, and are therefore linked to biorefinery design and current policy. Variations in financing parameters, representing regulatory policies (e.g. tax credits, loan guarantees, accelerated depreciation methods) and a range of investment risk are modeled to evaluate the impact of each on the economic competitiveness of novel algal biofuel processing techniques. The benefits from financing improvements are found to increase with the percent of the annual production cost from capital expenses, effectively incentivizing the development of processes which increase the ratio of annual capital to operating expenses. The availability of incentives and feasibility of investment risk reduction therefore impacts the choice of sub-process alternatives in the design of algal biofuel production systems for maximal cost competitiveness with conventional fuels.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
CER	Cumulative Energy Ratio
CHG	Catalytic Hydrothermal Gasification
CoC	Cost of Capital
DAF	Dissolved Air Flotation
DAP	Diammonium Phosphate
g CO2-eq	Equivalent warming potential as grams of CO2
gge	Gallon Gasoline Equivalent
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Transportation
HTL	Hydrothermal Liquefaction
LCA	Life Cycle Analysis
LEA	Lipid Extracted Algae
LHV	Lower Heating Value
MACRS	Modified Accelerated Cost Recovery System
MFSP	Minimum Fuel Selling Price
NEB	Net Energy Balance

ORP	Open Raceway Pond
PBR	Photobioreactor
PTC	Production Tax Credit
RFS2	Renewable Fuel Standard
TEA	Techno-Economic Analysis

CHAPTER 1: INTRODUCTION

Greater urgency surrounding the environmental degradation associated with fossil fuel energy sources has prompted substantial research and investment in renewable energy platforms (National Research Council, 2012). While the electricity sector has seen marked increases in clean energy production (e.g. wind, solar), the transportation sector, which accounts for 28% of US demand, remains 95% reliant on petroleum (U.S. Energy Information Administration, 2014). Considering automotive fleet turnover cycles of 10 to 15 years (Samaras & Meisterling, 2008), as well as the infrastructural hurdles facing large scale adoption of electric or fuel cell vehicles, increased use of advanced biofuels provides the most feasible means of short-term transportation emissions reductions (Richard, 2010). Diverted food crops (e.g. corn, sugar cane, soybeans; “1st generation") and cellulosic non-food crops (e.g. switchgrass, miscanthus; “2nd generation”) have been of primary interest as biofuels feedstocks to date (Ho et al., 2014), though both have faced significant challenges related to such issues as competition for arable land and resources (e.g. food/forest vs. fuel) (Fargione, 2008) and unclear advantages in terms of environmental benefits over the product life cycle (Decicco, 2014). Producing biofuels from microalgae offers the potential to mitigate many of the challenges faced by crop-based biofuel production, thanks to several advantages conferred by efficient microbial processes and an increasingly closed-loop production system.

Microalgae are capable of photosynthetic efficiencies up to 10 times greater than land-based crops (Brennan & Owende, 2010), allowing for biomass productivity rates 50 times greater than switchgrass, currently the fastest growing terrestrial biofuel crop (Li et al., 2014). Oleaginous algae store energy in the form of lipids, which can comprise over 70% of cell biomass in certain strains and are readily converted into methyl esters (i.e. “biodiesel”) using established chemical processes (Chisti, 2007). These traits allow microalgae to produce 30 to 100 times more energy per hectare than terrestrial biofuel feedstocks (Kirrolia et al., 2013); cultivation can also occur on land ill-suited for agriculture, greatly reducing the competition for arable land posed by conventional biofuel crops (Clarens et al., 2010).

Furthermore, meeting the Energy Independence and Security Act (*EISA*, 2007) mandate of 1 billion gallons of biodiesel with algae would consume freshwater, nitrogen, and phosphate constituting 86%, 17%, and 104% of current national consumption (respectively), demands likely to be disruptive to other economic sectors (Yang et al., 2011). However, engineered systems for algal cultivation and biofuel production, while requiring significant capital investments, do allow for efficient recycling of resources, a key aspect in the design of commercially-feasible algal "biorefineries" (Rawat et al., 2013). Biomass not converted into liquid fuels (i.e. "residual biomass") retains significant portions of initial intracellular nutrients; further processing allows for biogas production (Frank et al., 2013; Nagarajan et al., 2013) and up to 65% of nitrogen and phosphorus to be recycled (Chowdhury et al., 2012) to increase economic competitiveness, improve the energetic balance, and limit resource demands.

Optimal algal growth in open cultivation ponds requires dilute cultures as well as shallow depths to maintain efficient light transfer (Van Wagenen et al., 2012), with the resulting high surface area-to-volume ratio leading to high evaporative loss rates (Delrue et al., 2012) and a large water footprint for growth (Batan et al., 2013). Efficient biorefinery design can reduce biofuel water demands by up to 90% via recycling (Vasudevan et al., 2012), a necessary step towards sustaining algae production in many regions with optimal temperature (warm) and insolation (sunny), features that correlate with constrained water availability (Venteris et al., 2013).

While the recycling enabled by biorefineries is necessary for sustainable algal biofuel production, financing these capital intensive commercial-scale facilities (i.e. relative to agriculturally-derived biofuel feedstocks) has been impeded by the novelty of processing techniques and the commensurate uncertainty in cost estimates (Kirrolia et al., 2013). Systems analysis methods, especially techno-economic analysis (TEA) and life cycle analysis (LCA), provide a more accurate assessment of future economic and environmental potential (Quinn & Davis, 2014), better describing the operational risk faced by investors and thereby reducing barriers to investment. LCA uses energy and resource demands to quantify the life cycle environmental impacts associated with each stage in a product's life, from material extraction to disposal (Klöpffer, 1997). TEA utilizes energy and material inputs, facility costs, and financing assumptions to determine the economic potential of a considered pathway, measured in terms of a \$ gal^{-1} selling price (Zhu et al., 2013).

These methods have been widely utilized to evaluate the performance improvements achievable through development of novel techniques for algal cultivation, harvesting/dewatering, extraction/conversion, and recycling processes (Collet et al., 2013; Quinn & Davis, 2014). Alternative sub-processes exhibit tradeoffs related to product yields, capital and operating expenses, and environmental impacts; using TEA/LCA models, sub-processes can be integrated into economically competitive, energetically beneficial, and environmentally sustainable production pathways (Wijffels & Barbosa, 2010). However, few TEAs (Resurreccion et al., 2012; Richardson et al., 2012; Rogers et al., 2014; Stephens et al., 2010) of algal biofuels have addressed uncertainty in financial factors embedded in economic models. Rather than being exogenous to production pathway design, these factors reflect perceived risk of reliance on processes untested at commercial scale and uncertain regulatory support (Resurreccion et al., 2012), and are therefore linked to biorefinery design and plant performance.

This work seeks to address several gaps in the literature by integrating technical process improvements and variable financing parameters into the performance evaluation of novel production sub-processes. A TEA/LCA model has been developed to evaluate commercially available unit operations, quantify the environmental impacts and production costs, and identify the best performing baseline pathway from which to determine relative process improvements. This baseline pathway is then used to determine the benefits of two novel operations: a bicarbonate-induced lipid productivity boost developed by collaborators at Montana State University, and a dewatering process utilizing temperature sensitive “hydrogels” developed by collaborators at the University of Toledo. These operations are evaluated across a range of starting lipid contents and achievable growth rates, and in pathways using both transesterification and hydrothermal liquefaction (HTL) conversion techniques, in order to determine how up-and downstream factors influence relative benefits.

Financing parameters embedded in the economic model are varied to represent accelerated depreciation methods, tax credits, guaranteed loans, and risk management strategies. The impact of these financing variations on economic competitiveness is compared with the improvements achievable through processing advances alone; financing and processing improvements are then combined to investigate the impact of financing parameters on pathways using novel techniques. Finally, the interdependence of the value of regulatory support and managerial strategies, reflected in the varied financing parameters, and the capital to operating expense ratio of a given pathway is investigated. This framework for performance evaluation provides a means for identifing the conditions, both physical (e.g. influencing achievable lipid productivities) and financial (e.g. availability of incentives, feasibility of risk management strategies) in which proposed production pathways are most economically competitive.

CHAPTER 2: MATERIALS AND METHODS

Simultaneous evaluation of environmental, economic, and energetic metrics for algal biofuel production pathways composed of alternative sub-processes allows systems designers to select pathways that increase aggregate life cycle benefits (Delrue et al., 2012). Rigorous analysis of existing and emerging processing techniques identifies promising technologies for use in commercial scale facilities, thereby helping reduce, at a minimum, the operational risk of the significant capital investment required to scale up techniques (DOE, 2010). The methodology for performing life cycle analysis (LCA) is well established (ISO 14040, 1997) and provides a useful framework for an integrated techno-economic and environmental analysis.

2.1 Life Cycle and Techno-Economic Framework

The life cycle analysis process consists of four stages: (1) definition of goals and scope of analysis, including specification of system boundaries; (2) inventory of all inputs and outputs associated with the production of a functional unit of the product; (3) translation of inventory into environmental impacts; and (4) interpretation of analysis results (ISO 14040, 1997). Techno-economic analyses build off this methodology by simultaneously performing technical and cost analyses of product systems. Technical performance is evaluated using systems engineering models to evaluate energy demands and process efficiencies (Zhu et al., 2013). Economic competitiveness of the resulting product is determined based on the capital and operating expenses of the pathway considered, as well as the financing assumptions used for the analysis (Davis et al., 2011).

Inventories are developed for LCA which catalog the resource demands and environmental emissions associated with process inputs and use of products (Klöpffer, 1997). Similarly, TEA inventories compile process yields, material and energy demands, and capital and operating expenses for the unit operations composing the production pathway (Quinn & Davis, 2014). The LCA inventory is translated into environmental impacts using an environmental impact assessment methodology, which assigns an impact factor to each flow emitted to the environment from the system (ISO 14040, 1997). Inventory items for TEA are used to calculate energetic balances (e.g. input energy divided by fuel output energy) as well as the production costs for a production pathway (Zhu et al., 2013). Finally, interpretation identifies uncertainty in the data utilized and assumptions embedded in the analysis which affect modeled results.

2.2 Integrated LCA/TEA Methodology

2.2.1 Goal and Scope of Analysis

A systems process model has been developed to examine the performance of an algal biorefinery producing a "functional unit" of 10 million gallons of biofuel (either biodiesel or renewable diesel) annually. This unit is chosen to enhance comparability with a recent, comprehensive TEA performed by Davis et al. (2011). The modular TEA/LCA model developed facilitates the comparison of alternative sub-processes for the cultivation, dewatering, conversion and recovery stages (Figure 1). The system boundary is defined as the biorefinery gate, in order to facilitate comparisons of fuel production pathways by focusing on the systems-

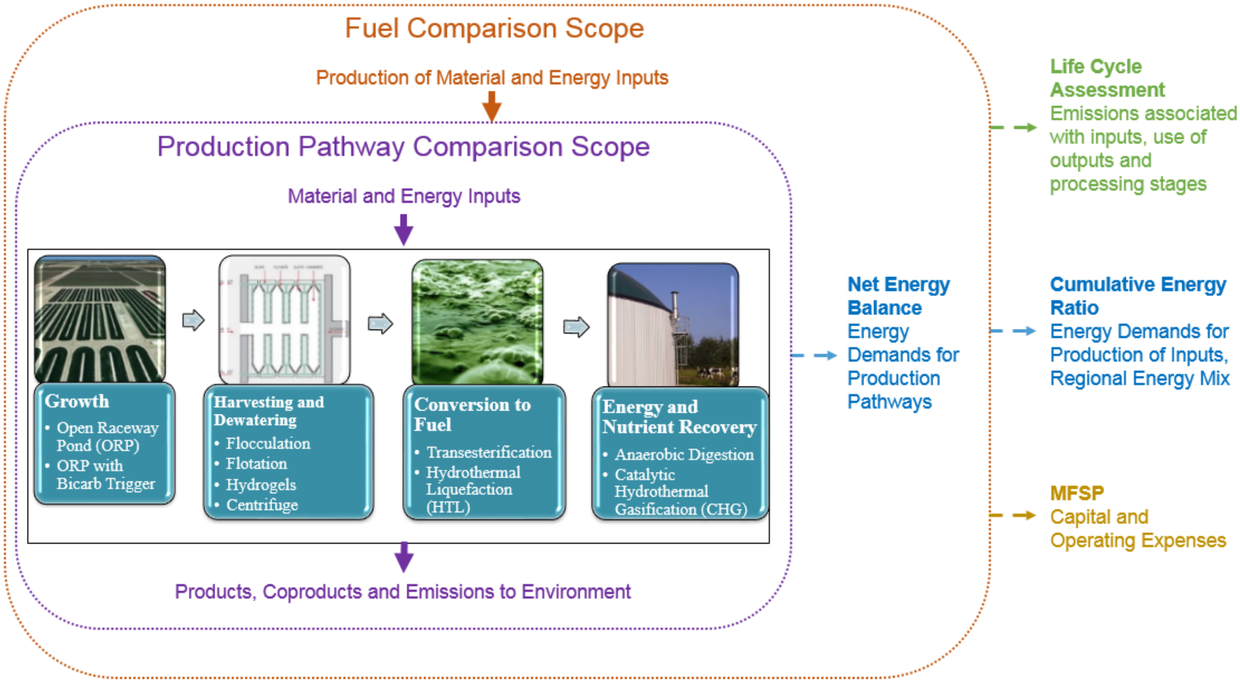

Figure 1. Integrated LCA/TEA Methodology

level tradeoffs resulting from production process-level decisions (Decicco, 2014).

Environmental impact analysis has, similar to some previous analyses (Batan et al., 2010; Bennion et al., 2015; Liu et al., 2013), focused on the characterization of biorefinery global warming potential (GWP) and energetic balance. As per previous analyses, the energy and emissions associated with system construction are excluded as these are assumed to be similar for all the considered pathways and relatively small when evaluated over the facility lifetime (Batan et al., 2010; Frank et al., 2011). The benefits of an increasingly closed-loop production system (e.g. efficient recycling of input materials and energy, reduced emissions to the environment) are therefore weighed against the increased capital expense required to achieve this state.

2.2.2. Inventory

The net energy balance (NEB) is commonly used to compare the energy demands of similar processing pathways, calculated as the sum of energy demands for each unit operation divided by the energy embodied in the produced fuel (Slade & Bauen, 2013). The cumulative energy ratio (CER) includes in the numerator of the energy balance the indirect energy demands, including those required to produce the energy and material inputs to the process; this metric allows for comparability with other fuel production systems by accounting for upstream impacts of process inputs and energy (Huijbregts et al., 2010).

Using the methodology of Hill et al. (2006), biofuels produced are assumed to displace fossil fuels based on their net energy balance, resulting in a credit for avoided emissions that is subtracted from emissions from biofuel production. Pathway NEB is multiplied by lifecycle (i.e. production and combustion) emissions from diesel fuel and added to the pathway emissions; summed offset and pathway emissions are then divided by diesel emissions to calculate total pathway emissions as a percent of those from diesel fuel (Equation 1). Since the CO_2 released from algal biofuels is sourced from industrial flue gas (at significant energy expense), biofuel combustion is “carbon neutral” as CO_2 emitted was recovered from an atmospheric waste stream (Liu et al., 2013).

$$GHG\ [\%\ of\ Diesel] = \frac{Diesel\ Emissions\left[\frac{g\ CO_2eq}{MJ}\right] \times \left(1 - \frac{Energy\ Outputs}{Energy\ Inputs}\right) + Pathway\ Emissions\left[\frac{g\ CO_2eq}{MJ}\right]}{Diesel\ Emissions\left[\frac{g\ CO_2eq}{MJ}\right]} \quad [1]$$

2.2.3. Impact Assessment

Global Warming Potential (GWP) is calculated by multiplying emissions (CO_2, N_2O, and CH_4) from energy and material production by impact factors from the International Panel on Climate Change (2007), as utilized by the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (GREET, 2011) to transform emissions into grams of CO_2 equivalents (g CO_2-eq). The emissions and energy associated with process inputs are obtained from GREET, other analyses, and industrial sources (see Appendix C for details). Unlike the biogenic CO_2 recovered from flue gas, sodium bicarbonate represents a source of sequestered carbon, and thus combustion of biofuel from algae grown with this inorganic carbon addition incurs a GHG penalty equaling the g CO_2-eq of sodium bicarbonate uptake.

The minimum fuel selling price (MFSP) for each pathway is calculated by summing manufacturing and financing costs over the plant's lifetime and dividing by the volume of biofuel produced over this timeframe. To compare fuels of different energy contents, the calculated MFSP in dollars per gallon is converted to dollars per gallon gasoline (energy) equivalent ($\$ \text{ gge}^{-1}$) by multiplying by the ratio of gasoline energy content over the produced fuel's energy content. The MFSP represents the breakeven selling price of each gallon of biofuel produced, such that the net present value of the project equals zero (i.e. Present Value of Costs = Present Value of Revenues). As shown in the stylized production pathway overview in Figure 1, NEB is used for direct comparison of considered algal biofuel production pathways, while MFSP, CER, and GWP comparisons with other fuel systems requires consideration of process inputs (Table 1).

Table 1. Overview of Performance Metrics and Inventory Items

Metric	Inventory Required for Calculation
Minimum Fuel Selling Price *(MFSP)* $[\$\ gal^{-1}]$	Capital and Operating Expenses Non-Equipment Production Costs Financial Parameters
Net Energy Balance (NEB) $\dfrac{[\text{Direct Energy Inputs}]}{\text{Fuel Energy}}$	Direct Energy Inputs to Unit Operations Fuel Energy (Lower Heating Value*)
Cumulative Energy Ratio (CER) $\dfrac{[\text{Direct + Upstream Energy Inputs}]}{\text{Fuel Energy}}$	Direct Energy Inputs to Unit Operations Energy Required to Produce Inputs Fuel Energy (Lower Heating Value*)
GHG Emissions	Emissions from Energy Production and Use Emissions from Input Production and Use Emissions from Unit Operations

*Lower Heating Value (LHV) represents the energy released from fuel combustion (i.e. the Higher Heating Value (HHV)) *minus* the energy of vaporized water; fuels combusted in vehicle or turbine engines are not able to condense and thus capture energy in vaporized water, making the LHV appropriate (Collet et al., 2013)

2.3 Biorefinery Processes and Sub-Process Alternatives

The algal biomass-to-biofuel pathway consists of four general stages: algae cultivation, harvesting and dewatering, conversion to fuels, and recycling of nutrients and energy (Figure 1). While technical developments are numerous and ongoing for the sub-processes making up each of these stages, our goal is to identify commercially viable operations to develop a baseline pathway from which to evaluate performance benefits from incorporation of novel techniques. These processes, potential alternatives and justification for the sub-processes included in this analysis (listed below each process in Figure 1) are discussed in detail below.

2.3.1 Algae Cultivation

Life cycle environmental and economic comparisons of algal cultivation alternatives, particularly open raceway ponds (ORPs) and enclosed photobioreactors (PBRs), have been a significant topic of research. Ponds have been used at commercial scale algal biofuel facilities due to their low capital and operating expenses (Rawat et al., 2013), though they suffer from high evaporative losses (Brennan & Owende, 2010), are at high risk for contamination from other microbes (Benemann & Oswald, 1996), and have low harvest densities as a result of suboptimal solar exposure due to poor culture mixing (Chisti, 2007). Enclosed PBRs have significantly greater capital expense, but allow for reduced contamination, increased photosynthetic growth rates due to increased solar exposure, and temperature and pH control for maintenance of ideal growth conditions, which can reduce lifetime operating expenses (Molina Grima et al., 2003; Resurreccion et al., 2012). As capital expenses for PBRs have been often found prohibitively high for the production of low-value biofuels (Davis et al., 2011; Jorquera et al., 2010; Kirrolia et al., 2013), and high-value chemical production is outside the scope of this investigation, ORPs are the sole cultivation infrastructure considered in this analysis.

Nutrients are supplied to ORPs based on the algal stoichiometric coefficients from Williams & Laurens (2010), as described by the GREET model. Previous analyses have assumed a variety of nutrient sources, ranging from various chemical fertilizers (Collet et al., 2013) to utilization of waste streams (Chen et al., 2015; Orfield et al., 2014; Pittman et al., 2011). This analysis considers the use of diammonium phosphate (DAP) to meet all phosphorus demand (and some nitrogen demand) and ammonia added to meet residual nitrogen demand, with nutrients recycled from recovery processes reducing the net external demand of these fertilizers. Carbon dioxide is supplied to maintain the 55% of cellular mass from carbon (Williams &

Laurens, 2010) based on an 82% efficiency of uptake (Frank et al., 2011), and is assumed harvested from the flue-gas of a nearby power plant as per Davis et al. (2011).

2.3.1.1 Growth Scenarios

Achievable algal growth rates and lipid contents are widely disparate in the literature, and known to critically impact economic analyses (Collet et al., 2013; Quinn & Davis, 2014). Algal strain characteristics and growth rates have been shown to affect the relative performance of sub-process alternatives, impacting the choice of optimal growth reactor (Richardson et al., 2014) and conversion method (Clarens et al., 2011). The relative performance of bicarbonate-induced lipid productivity increases and hydrogel dewatering in all production pathways is therefore evaluated under two growth scenarios. The Department of Energy's Biomass Program developed a baseline growth framework by harmonizing results from national resource assessment (Wigmosta et al., 2011), techno-economic (Davis et al., 2011) and life cycle (Frank et al., 2011) models of algal biofuels production pathways (Davis et al., 2012). The national average areal productivity for open pond systems was calculated as 13.2 grams algae m^{-2} day^{-1}, and an extractable lipid content of 25% of dry algae by weight (henceforth referred to as wt%) was established; these characteristics are used to define the “Harmonized Growth” scenario for this analysis.

In regions with higher annual insolation and less temperature variations, areal productivity can be significantly greater, with various analyses showing growth rates, or “productivities,” up to 40.6 g m^{-2} d^{-1} (Clarens et al., 2010). Additionally, strain selection for biofuels production has shown that certain algal strains are capable of producing lipid contents as high as 50 wt% (Collet et al., 2013). To examine the impact of higher lipid productivity on the relative benefits of process improvements, an “Optimal Growth and Strain” scenario is developed with an areal productivity of 32 g m^{-2} d^{-1} and a lipid content of 45%. To reflect the increased insolation and reduced temperature variability, the average ambient temperature in this scenario is increased from 23°C (assumed for the "Harmonized Growth" scenario) to 28°C (reflective of regions of the US Gulf Coast, Central America, the Middle East, and Southeast Asia).

2.3.1.2 Bicarbonate-Induced Lipid Productivity Boost

Efforts to boost oil production from algae have largely focused on nutrient stressing, as nitrogen depletion halts cell growth and induces the cell to store energy in the form of accumulated lipids (Brennan & Owende, 2010; Lardon et al., 2009; Sheehan et al., 1998). However, boosting lipid content at the expense of growth rate can actually decrease the total lipid productivity (grams lipid produced m^{-2} d^{-1}) and thereby the biofuel production potential, making this tradeoff between biomass productivity and lipid content undesirable (Brennan & Owende, 2010; Quinn & Davis, 2014).

Alternatively, recent work has shown that gains in total lipid productivity can be achieved through the addition of sodium bicarbonate (Gardner et al., 2013). The methodology (Appendix B) which is considered in this analysis begins with addition of low-grade sodium bicarbonate at low concentrations during growth, increasing the alkalinity of the growth medium and the driving force for gaseous CO_2 dissolution into the aqueous phase, resulting in greater dissolved inorganic carbon uptake rates by biomass (Markou et al., 2014). This initial addition has been shown to increase the specific growth rate by 69%, leading to an overall increase of 27% in biomass productivity (Lohman et al., 2015). A second, higher concentration addition of sodium bicarbonate occurs as nitrogen is depleted, halting cell growth and inducing further lipid accumulation. This second bicarbonate addition increases the achievable biodiesel content by

8%; together with the increased biomass productivity, an increase of lipid productivity of over 37% is achievable. This two phase sub-process has been included in selected pathways in the cultivation process, with the first addition occurring during open pond cultivation, followed by nitrogen depletion and the second bicarbonate addition in a separate lipid accumulation tank.

2.3.2 Dewatering and Drying

Conventional dewatering methods examined include settling via autoflocculation (to 1 wt% solids content), dissolved air flotation (DAF, to 6 wt%), filter pressing (to 20 wt%), and centrifugation (to 25 wt%); such mechanical methods are most efficiently utilized in series to dewater the harvested algal slurry prior to extraction and conversion (Xu et al., 2011). These processes have been incorporated into this model based on the unit operations defined in the Algae Process Description developed for the GREET model (Frank et al., 2011) and from industrial sources (see Appendix A). If downstream sub-processes require more algal slurries with less than 75% water content for efficient biofuel conversion, natural gas drum drying is used. Water removed from mechanical dewatering operations in the modeled system is returned to cultivation to reduce external water demands.

2.3.2.1 Hydrogel Dewatering

A novel dewatering procedure developed by collaborators at the University of Toledo (Zhao, 2015) has been incorporated as a sub-process alternative in this analysis. Gels with high absorption capacities have been synthesized which respond to temperature changes by rapidly absorbing or releasing water, with lab scale tests concentrating algal slurries from 0.1 wt% up to 10 wt% with less than 1% biomass loss (Vadlamani, 2014). The dilute algal slurry flows to a tank containing the “hydrogels” where swelling occurs at room temperature; this mixture is then passed through a sieve, where swollen gels are trapped and sent to a deswelling tank where a

10°C temperature increase causes the gels to shrink (Figure 2). Given that this temperature shift can occur between 32°C and 35°C, it is anticipated that waste heat might be employed to reduce de-swelling energy demands (Zhao, 2015). Testing has shown minimal degradation of hydrogel performance over 100 swelling/de-swelling cycles, and commercial scale costs and efficiencies have been extrapolated using this material lifetime (Vadlamani, 2014). As with the mechanical dewatering processes, water recovered from the hydrogels after de-swelling is collected and recycled to cultivation ponds to reduce net water demands.

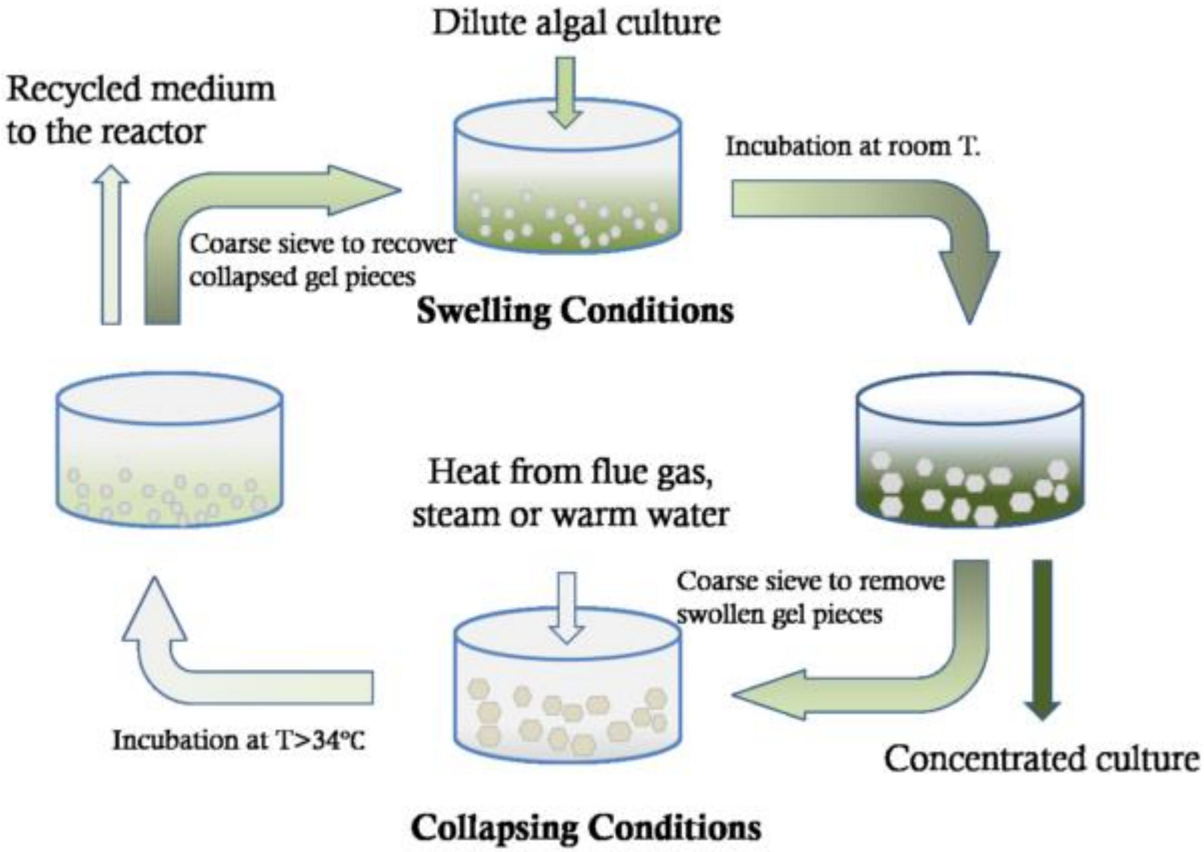

Figure 2. Hydrogel Dewatering (Zhao, 2015)

2.3.3 Extraction and Conversion

Transesterification has been considered the most viable pathway to produce environmentally beneficial biofuels from vegetable oils (Kirrolia et al., 2013), and is used commercially for conversion of soy, canola, palm and waste oils into biodiesel. In conventional transesterification processes, lipids are extracted from algal cells and reacted with an alcohol (e.g. methanol) to form fatty acid methyl esters, or "biodiesel" (Rawat et al., 2013). The small size of algal cells makes mechanical extraction (used to remove oils from vegetable feedstocks) of accumulated oils challenging; most analyses have assumed the use of an organic solvent to remove oils for conversion (Collet et al., 2013). Efficient extraction of cellular lipids requires biomass inputs with less than 15 wt% water, or 850 grams dry biomass L^{-1} (Xu et al., 2011). Thermal drying is required to evaporate intracellular water and reach concentrations greater than 400 grams biomass L^{-1}, a step that can account for 75% of the direct energy input to the production process (Vasudevan et al., 2012). Numerous studies have examined oil-extraction methods that limit the thermal drying requirement, including "wet" solvent extractions (e.g. capable of using slurries with less than 40 wt% solids content) (Brennan & Owende, 2010; Delrue et al., 2012; Kirrolia et al., 2013; Lardon et al., 2009; Quinn et al., 2014; Ríos et al., 2013; Torres et al., 2013; Vasudevan et al., 2012; Zaimes & Khanna, 2013) as well as one step direct transesterification of "wet" algal slurries into biodiesel (Delrue et al., 2013; Nagarajan et al., 2013; Patil et al., 2011; Ríos et al., 2013; Torres et al., 2013).

2.3.3.1 Thermochemical Conversion

As an alternate means of reducing the energy demands for extraction, thermochemical conversion techniques have been developed which use heat and pressure to convert whole algal cells, not just the cell lipids, into useable oils, gases, and char (Khoo et al., 2013). Several hydrothermal conversion methods can utilize a slurry with roughly 20 wt% solids content, greatly reducing or eliminating the thermal drying requirement (Frank et al., 2013). Of these, hydrothermal liquefaction (HTL) has shown the most promise for liquid biofuel production (López Barreiro et al., 2013a). Pilot scale HTL tests show conversions of over 60% of cell biomass into useable fuels (Liu et al., 2013), with fuel yields consistently greater than cellular lipid content (Duan et al., 2015) suggesting that maximizing biomass productivity (rather than lipid productivity) in the cultivation stage might be more appropriate when utilizing HTL (Elliott et al., 2013). Broader acknowledgement of the impact of conversion method on the choice of optimal cultivation techniques (Liu et al., 2013; López Barreiro et al., 2013b; Torres et al., 2013) and implications for dewatering techniques (Ríos et al., 2013), make it worthwhile to model the incorporation of novel growth and dewatering techniques into pathways using different conversion methods.

An HTL pathway has been included in this analysis, with modeling based upon published data scaled to the functional unit of this analysis (Appendix A) (Bennion et al., 2015; Frank et al., 2011; Jones et al., 2014). This technique is then used in an examination of the benefits of incorporating the bicarbonate-induced lipid productivity boost and hydrogel dewatering into pathways based around this conversion method. HTL-based pathways have been shown to increase capital expenses while decreasing annual operating expenses relative to transesterification-based pathways (Zhu et al., 2013); modeling such a pathway is further useful for examining the impact of techniques of improving project financing (i.e. tax incentives, accelerated depreciation, loan guarantees, risk management strategies) on pathways with similar annual production costs but different capital to operating expense ratios.

2.3.4 Nutrient and Energy Recycling

Anaerobic digestion (AD) has been proven effective for nutrient and energy recovery from lipid-extracted algae (LEA) (Davis et al., 2011), and thus has been modeled as a means of producing biogas from the residual biomass in transesterification pathways. The aqueous phase from AD reactors has high levels of nitrogen and phosphorus which have been shown to support algal growth when returned to ORPs (Bohutskyi et al., 2015). Aqueous phase recycle from AD is examined to determine cost savings from net fertilizer and water demand reductions.

The hydrothermal degradation of intracellular protein results in carbon to nitrogen ratios in HTL aqueous phase which render it unsuitable for anaerobic digestion (Frank et al., 2013). Researchers have examined alternative methods for recycling of nutrients and carbon within the production system; among these, catalytic hydrothermal gasification (CHG) has proven an efficient method for recycling of HTL inputs (Elliott et al., 2013), and recovery via this technique is considered in this analysis. Frank et al. (2013) note that comparison of HTL and transesterification processes must consider the quality of the produced biofuel, as the higher nitrogen and oxygen content in HTL bio-oil renders it unsuitable for direct use in engines. The engineering system model used for this TEA therefore includes a hydrotreating process to reduce nitrogen and oxygen content in the produced bio-oil, such that the end product is a renewable diesel chemically identical to petroleum diesel (Jones et al., 2014).

2.4 Baseline Pathway Development

The TEA model was used to identify the best performing pathway for producing 10M gallons of biofuel through conventional means. This was then used as the baseline pathway into which novel operations would be incorporated, and from which relative performance benefits would be determined. The major processing pathways are:

- Baseline Pathway: auto-flocculation, dissolved air flotation (DAF) and Evodos™ centrifuges for dewatering, transesterification and anaerobic digestion of lipid-extracted algae to recover nutrients and energy (Figure 3a)
- Bicarbonate-Induced Lipid Productivity Boost: Two-phase addition of sodium bicarbonate, in the growth reactor to boost biomass productivity and in a lipid accumulation tank following harvesting (Figure 3b)
- Hydrogel Dewatering: hydrogels are considered to replace DAF, and are capable of concentrating the slurry to 10 wt% (100 g L^{-1}) instead of the 6 wt% capable via DAF (Figure 3c)
- Hydrothermal Liquefaction (HTL): high pressure HTL reactors replace the transesterification reactor, followed by phase separation to isolate the oil phase for upgrading in a hydrotreating reaction. The aqueous phase is sent to a catalytic hydrothermal gasification process, where ammonia, biogas and water are collected and recycled onsite (Figure 3d).

The Baseline and HTL pathways are each evaluated with the bicarbonate-induced lipid productivity boost, hydrogel dewatering, and both novel techniques under both the Harmonized Growth and Optimal Growth and Strain scenarios (for a total of 16 considered production pathways).

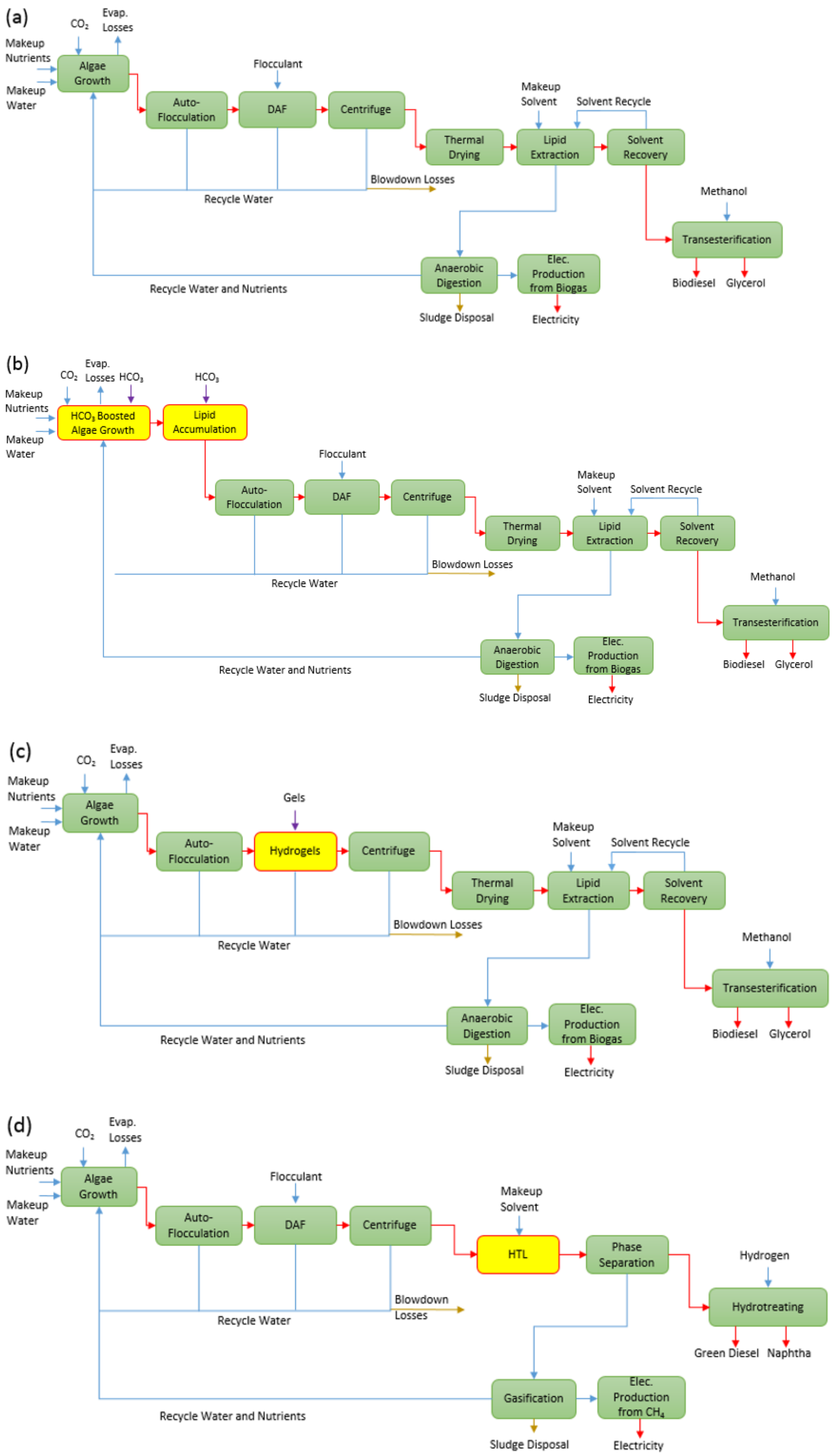

Figure 3. Processing Schematics for (a) Baseline Transesterification Pathway, (b) Transesterification with Bicarbonate-Induced Lipid Productivity Boost, (c) Transesterification with Hydrogels and (d) HTL Pathways

2.5 Economic Analysis

2.5.1 Financial Factor Uncertainty

Financial assumptions embedded in economic analyses represent a significant source of uncertainty for feasibility analyses (Quinn & Davis, 2014), as these factors are subject to change due to federal or state policies as well as managerial decisions. The cost of capital (CoC), or interest rate on debt, is the rate charged on capital used to finance the biorefinery. This rate increases with the perceived risk of the project; managerial strategies to mitigate exposure to market, technology, and operational risks can decrease the CoC and therefore decrease the cost of manufacturing (Michelez et al., 2011). Additionally, federal programs such as the DOE's Loan Guarantee sponsorship allow advanced biofuel producers to borrow capital at rates below what might otherwise be possible given the perceived operational risk (Yacobucci, 2011). Managerial steps taken to mitigate upstream (e.g. variable input costs), operational, and downstream risks (e.g. uncertain value and volume demanded of outputs) can also reduce the project cost of capital (Lamers et al., 2015). Assuming the facility is financed 100% with debt (as opposed to a mix of debt and equity), biorefinery MFSP has been calculated under three CoC scenarios:

1. CoC of 8%, representing a typical financing scenario (the baseline financing assumption);
2. CoC of 6%, representing a scenario wherein steps have been taken to mitigate operational or market risk exposure; and
3. CoC of 4%, representing a case in which the investment qualifies for a DOE Loan Guarantee or measures to significantly diminish project risk have been taken.

The depreciation method used for the MFSP calculations is also impacted by regulatory policies designed to support renewable fuels. Used to account for the loss in the value of capital assets over time, the depreciation charge is a percent of total capital expenses that is deducted from the taxable income of a company (IRS, 2015). Straight line depreciation, used for the baseline financial analysis, is calculated by dividing the total depreciable capital expenses by the asset lifetime, such that an equal charge is applied annually until the end of its useful life, at which point it is considered valueless. Accelerated depreciation methods are allowed as a means of incentivizing the purchase of certain types of assets (US PREF, 2014). A simple illustration of the depreciation of a hypothetical $300M asset via an accelerated method is presented in Figure 4. As opposed to straight line depreciation (green columns), accelerated depreciation methods instead allow larger depreciation charges (blue columns) early in the asset life, leading to full asset depreciation before the end of the asset's useful life. The difference in the taxable income deduction (i.e. "depreciation charge", black line) between operations with an accelerated

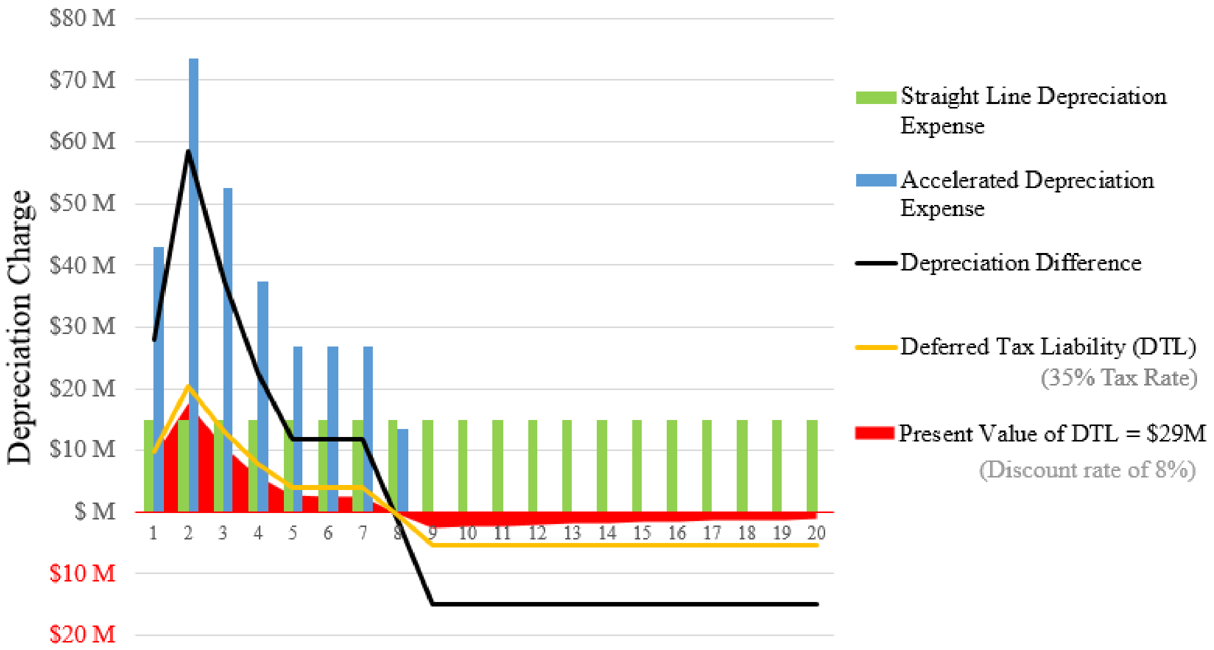

Figure 4. Mechanism of Tax Savings from Accelerated Depreciation

and straight line depreciation allowances is positive for the span of the accelerated period, then becomes negative as straight line charges remain constant and accelerated charges drop to zero.

In undiscounted terms, lifetime depreciation charges are equal under both depreciation methods; however, accounting for the time value of money with a discount rate, near term tax savings become worth more than long-term tax liabilities, and the net discounted value of these savings (red area) increases project value (US PREF, 2014). 7-yr Modified Accelerated Cost Recovery System (MACRS) depreciation and Bonus depreciation (Appendix D) methods have been substituted for the straight line method to evaluate the impact on MFSP calculations for all production pathways and growth scenarios.

The updated *(EISA, 2007)* Renewable Fuel Standard (RFS2) sets minimum volumes of biofuels which must be blended by refineries, supporting both the volume demanded and market value of biofuels (Yacobucci, 2011) and thereby helping producers mitigate offtake risk and secure financing (Miller et al., 2013). Additionally, this policy established a \$1.01 gal^{-1} production tax credit (PTC) for biomass-based diesel fuel with life cycle GHG emissions less than 50% those of petroleum diesel (enacted in 2007 and sporadically extended since (RFS2, 42 U.S. Code 7545(o)). The impact of this tax credit on the calculated MFSP of production pathways that meet the required emissions reductions has been evaluated; the relative benefits of these biorefinery financing improvements (e.g. risk management strategies, accelerated depreciation methods, loan guarantees and the PTC) to the proposed production pathways under both growth scenarios are then compared.

2.5.2 Economic Assumptions

Equipment costs have been calculated using the CapCost™ software (Turton et al., 2008) or scaled from published analyses; Appendix A contains sources of technical operation details, capital and operating expenses for production pathway equipment. Recent design reports have developed economically competitive HTL production pathways to produce renewable drop-in fuels from either whole-cell (Jones et al., 2014) or lipid extracted algae (Davis et al., 2014); these reports have been used to calculate scaled capital costs for the HTL pathway. The methodology of Delrue et al. (2012) was utilized to calculate initial and non-equipment operating expenses; these factors, as well as the baseline parameters used for the MFSP calculation are outlined in Table 2.

Table 2. Overview of Economic and Base Financial Analysis Factors (Delrue et al., 2012)

Initial Expenses	
Maintenance Costs	35% of Capital Expenses
Engineering Costs	15% of Capital Expenses
Spare Parts	15% of Capital Expenses
License Fees	\$650,000
Initial Expenses	2% of Capital Expenses
Start Up Costs	25% of Operating Expenses
Depreciable Capital	Initial Expenses + Capital Expenses
Non-Operating Annual Expenses	
Labor Cost	$10000000*(\text{Capital Expenses}/(10000000*500)^{0.2}$
Other Costs	0.9% of Capital Expenses
Maintenance Costs	4% of Capital Expenses
Business Expenses	1% of Capital Expenses
Base Financial Parameters	
Discount Rate	8%
Lifetime	20 Years
Tax Rate	35% of Operating Income
Depreciation Method	Straight Line
Cost of Capital (CoC)	8%
Annual Capital Factor	$(\text{CoC} *(1 + \text{CoC})^{\text{Lifetime}})/((1 + \text{CoC})^{\text{Lifetime}} - 1)$
Annual Debt Payment	Annual Capital Factor * Depreciable Capital

2.6 Interpretation

2.6.1 Distribution of Impacts

Significant uncertainty exists in the literature regarding the proper method for distributing impacts of production systems between multiple outputs (Quinn & Davis, 2014). Allocation spreads the burdens between all of the outputs, based on the mass, economic, or energetic value of each (Collet et al., 2013). The international LCA standard (ISO 14040, 1997) suggests avoiding the uncertainty involved in burden distribution, advocating instead that the system boundary be expanded to include the life cycle of other systems affected. The system, including the production of all outputs, substitutes for traditional coproduct production systems; this "substitution" method then assigns a credit to the system representative of the energy, costs, or emissions (depending on the scope) associated with the avoided traditional coproduct production process (Finnveden et al., 2009).

The transesterification pathways produce biodiesel, lipid extracted algae (LEA), and glycerol in proportions based on the cellular composition of the algae. LEA is utilized onsite for energy and nutrient recovery through anaerobic digestion (AD), thereby reducing net energy and fertilizer demands for the pathway. Catalytic hydrothermal gasification (CHG) of the nutrient-rich aqueous phase from HTL reactions reduces nitrogen to ammonia while producing biogas for energy recovery (Liu et al., 2013). Recovered ammonia and biogas from the CHG reactor are recycled within the biorefinery to reduce external energy and fertilizer demands. Reduced resource demands make these pathways favorable (e.g. economically, energetically, and environmentally) when compared with fuel cycles not recycling inputs; assigning a credit to the recycled resources, based on the inputs avoided, would double-count the recycling benefits when comparing alternative pathways and has therefore been avoided.

Onsite recycling has been proposed for glycerol, for enhanced biofuel production via fermentation (Akiyama et al., 2003), boosting algal productivity via mixotrophic growth (Cabanelas et al., 2013), or as a co-firing material to generate bioelectricity on-site (Batan et al. , 2013). Rather than considering the uncertainties surrounding such on-site uses, glycerol has been regarded as a substitute for biomass co-fired for bioelectricity offsite, generating a credit based on its LHV (Koutinas et al., 2014; Ponnusamy et al., 2014).

2.6.2 Limitations

The nascent stage of the cultivation and conversion technology often necessitates the use of data extrapolated from the bench scale to commercial scale feasibility assessments, reducing certainty in modeled performance estimates (Collet et al., 2013). The National Algal Biofuels Technology Roadmap (DOE, 2010) notes that extrapolated data should be treated with caution, but points out that qualitative trends emerging from modeling efforts can be highly useful for guiding technical, economic and policy decisions. HTL modeling has been developed using processing parameters from Frank et al. (Frank et al., 2011), with hydrotreating parameters as well as capital and operating expenses scaled from Jones et al. (2014) to match the functional unit of this analysis. Inclusion of this conversion method is intended not to develop high resolution results for MFSP, CER, or GHG emissions, but rather to examine the potential differences in the impact of incorporating novel sub-processes into pathways based around different conversion methods.

Relative to agriculturally-based 1st and 2nd generation biofuels production systems, cultivation of algal biomass is intensive with respect to materials and capital (Collet et al., 2013). Exclusion of construction energy and emissions should be noted when drawing comparisons with other energy production pathways, as this omission may make algal biofuels appear to have artificially low impact (Clarens et al., 2010). The limited scope of environmental impact assessment, while appropriate for the goals of this analysis, may skew comparisons with other fuel cycles. To observe environmental benefits relative to terrestrial biofuel production systems, which have considerable land use change, water demands, and eutrophication impacts (Clarens et al., 2011), a full life cycle analysis including these factors would be required, which is beyond the scope of this project.

2.7 Analysis Overview

An overview of the growth scenarios, processing advances, and the variable financing parameters that are modeled in the described methodology is provided in Table 3. Processing pathways evaluated each novel technique alone as well as in series with other novel techniques, under both growth scenarios, and with stand-alone as well as cumulative changes to the financing parameters.

Table 3. Production Pathway Growth Scenarios, Processing Advances, and Financing Parameters

Growth Scenarios	Harmonized Growth Scenario	13.2 g m^{-2} d^{-1} Areal Productivity, 25% Lipid Content
	Optimal Growth and Strain	32 g m^{-2} d^{-1} Areal Productivity, 45% Lipid Content
Processing Advances (Figure 2)	Baseline	Open raceway pond, autoflocculation, dissolved air flotation, natural gas drum drying, hexane extraction, transesterification, anaerobic digestion of lipid extracted algae
	Hydrogels	Dissolved air flotation is replaced by temperature sensitive hydrogels
	Bicarbonate-Induced Lipid Productivity Boost	Two-phase addition of sodium bicarbonate to boost lipid productivity
	HTL	Hydrothermal liquefaction replaces transesterification; no natural gas drum dryers are required; hydrotreating is required to produce renewable diesel from biocrude

Variable Financing Parameters	MACRS Depreciation	7-year MACRS depreciation schedule replaces straight line depreciation for calculation of income tax; deferred tax assets increase economic potential of project
	Bonus Depreciation	50% of depreciable capital is deductible in the first year of operations, followed by 7-year MACRS for remainder of depreciable capital
	Production Tax Credit (PTC)	Pathways with life cycle GHG emissions < 50% of conventional diesel receive a \$1.01 gal^{-1} tax credit, which directly reduces the tax liability; deferred tax assets accrue if credits are greater than current liabilities
	6% / 4% Cost of Capital (CoC)	Cost of capital reduction to 6% from 8%, represents actions taken to mitigate project risks; reduction to 4% represents guarantee of project loans (e.g. DOE Loan Guarantee)

CHAPTER 3: RESULTS

3.1 Processing Improvements

3.1.1 Economic and Energetic Performance

The calculated minimum fuel selling price (MFSP) and cumulative energy ratio (CER) for the four processing pathways for both conversion methods (e.g. transesterification and HTL) under the “Harmonized Growth” and “Optimal Growth and Strain” scenarios are displayed in Figure 5. Incorporation of hydrogel dewatering results in minor relative reductions (from the given growth scenario and conversion method) from the baseline MFSP for both transesterification scenarios (3.7% and 5.4% for Harmonized and Optimal, respectively) and both HTL scenarios (2.8% and 3.8%). CER reductions from hydrogel use are in the same range, at 4.4%, 6.3%, 3.4%, and 5.3% for the Harmonized transesterification, Optimal Transesterification, Harmonized HTL, and Optimal HTL, respectively. Dewatering energy constitutes a larger fraction of overall energy demand in transesterification pathways and in higher lipid productivity growth scenarios, contributing 14% and 19% of total energy input in Harmonized and Optimal Growth transesterification pathways (respectively) versus less than 9% in all HTL pathways. Reducing dewatering energy demands with hydrogel incorporation therefore has a greater impact in these scenarios.

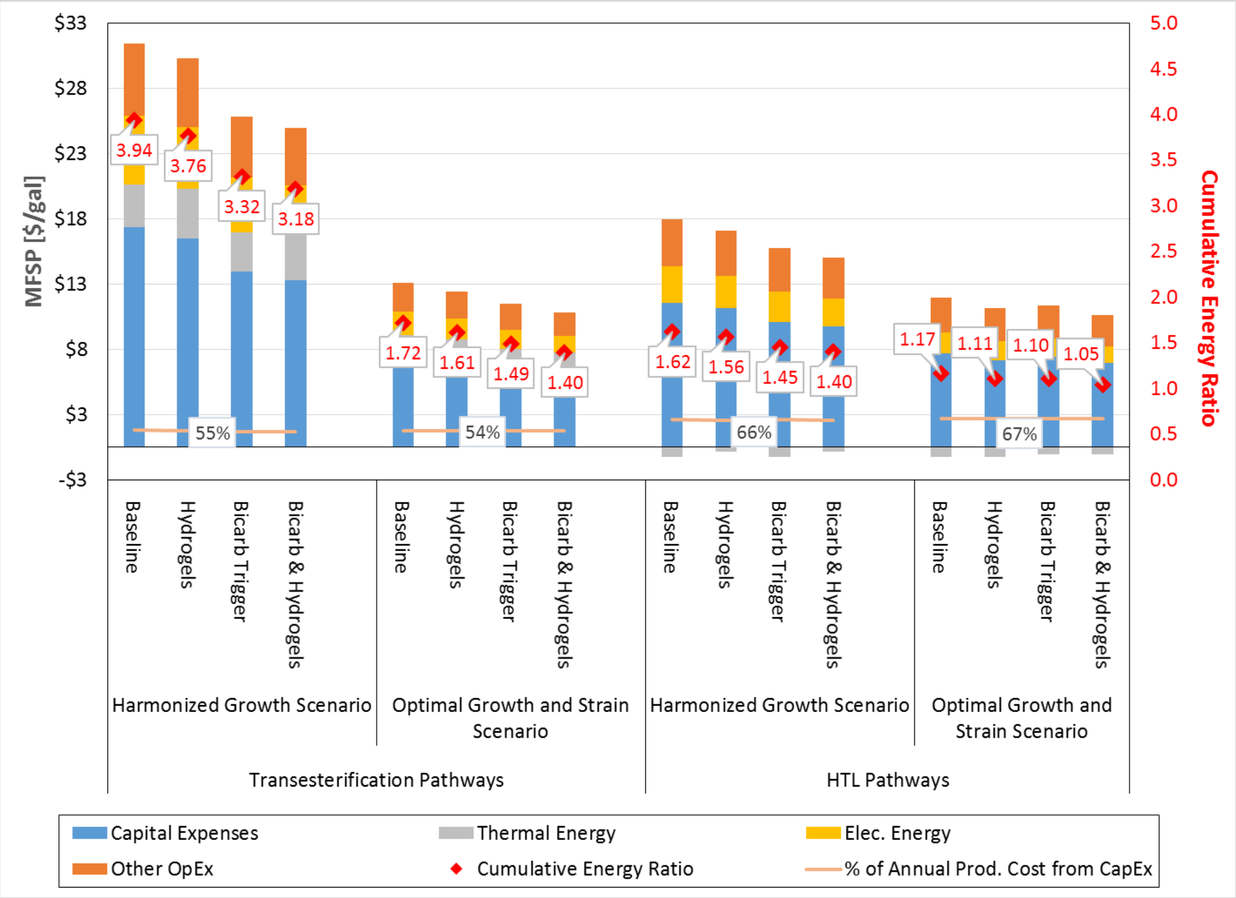

Figure 5. MFSP and CER for Transesterification and HTL Pathways

Bicarbonate-induced lipid productivity boosts have greater relative energy and monetary savings for the transesterification based pathways, with CER reductions of 15.6% and 13.5% and MFSP reductions of 18.5% and 12.9% for Harmonized and Optimal Growth scenarios, respectively. The bicarbonate addition to HTL based processes results in energy savings of 10.6% and 5.4% and MFSP reductions of 13.3% and 7.3% for the Harmonized and Optimal growth scenarios. Since HTL conversion yield is modeled as independent of intracellular lipid content, the same amount of biomass is produced and processed with or without the bicarbonate addition, with the increased production rate allowing annual production requirements to be met with reduced pond acreage, reducing capital and operating expenses. For all considered pathways in both scenarios, combining the bicarbonate addition with substitution of hydrogels for conventional dewatering results in further economic and energetic improvements, though none of the production pathways are able to reach energy parity (e.g. energy inputs + embodied energy = energy in outputs; CER = 1) (Figure 5).

The catalytic hydrothermal gasification (CHG) of HTL aqueous phase produces more biogas than is required to produce thermal energy for the pathway; substitution offsite for this net thermal energy production generates energetic (CER offset equaling 17% of renewable diesel energy content) and monetary credits (MFSP offset of 4% shown by the negative MFSP contribution in Figure 5) for these systems. Conversion via HTL reduces the overall energy inputs and cost of production, while the percent of the production cost coming from capital expenses (i.e. “debt service”) slightly increases, as shown by the orange lines in Figure 5.

Biorefineries using transesterification to produce biofuels generate glycerol, as a byproduct of the conversion reaction, and biogas from anaerobic digestion of the lipid-extracted algae biomass. The energy content of the glycerol and biogas represents only 2% and 7% of the energy content of the produced biodiesel (Figure 6). For all transesterification pathways, the energy content of inputs exceeds the combined energy content of outputs, resulting in CER values greater than 1. Under the Harmonized Growth scenario, the direct energy inputs (e.g. growth, dewatering and drying, and conversion energy) together outweigh the output energy for all pathways, with dewatering energy alone contributing between 57% and 70% of the energy in the produced biodiesel. Using the Optimal Growth and Strain conditions, direct energy inputs are less than the output energy, however the significant energy embodied in the material and energy inputs to the pathway increase the CER above 1 for all pathways.

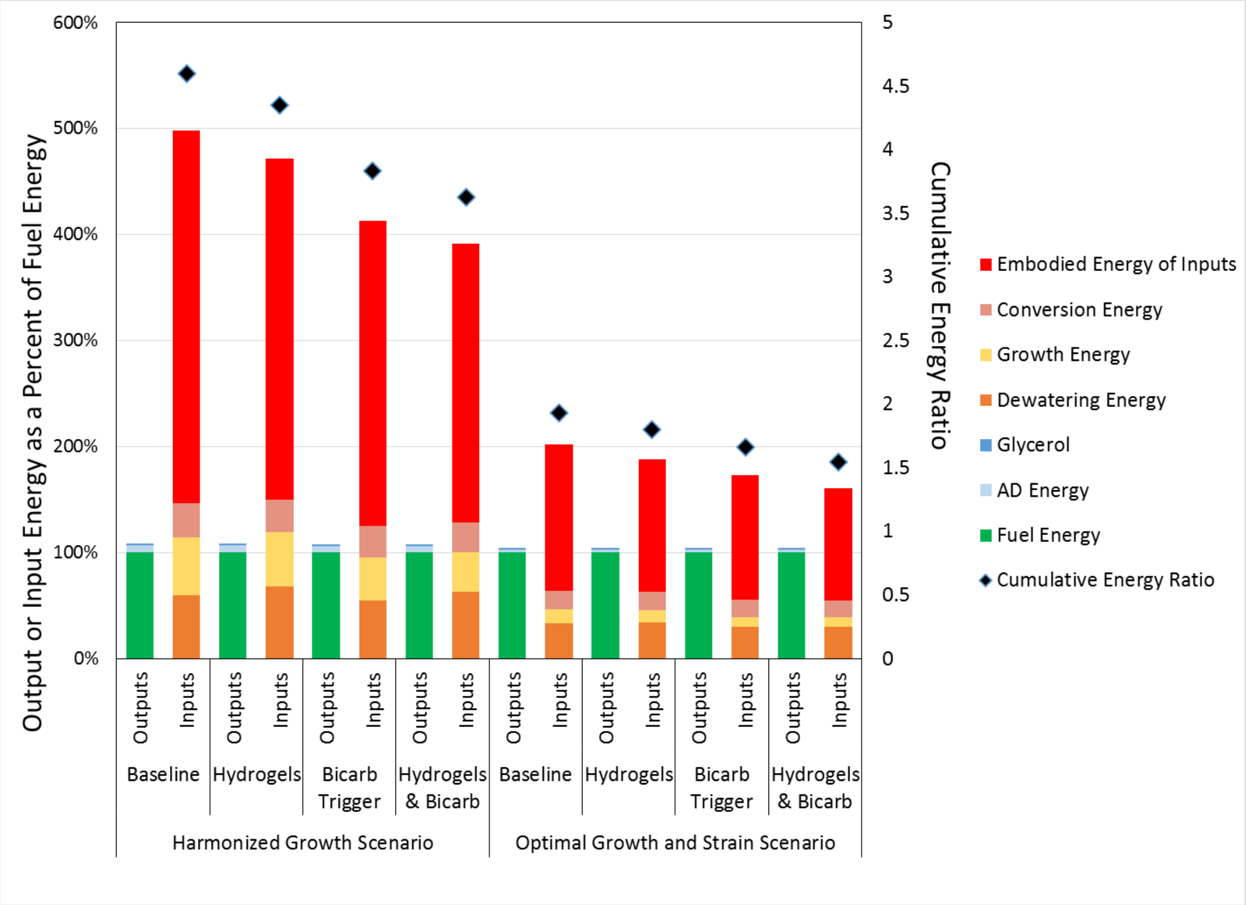

Figure 6. Cumulative Energy Ratio Breakdown for Transesterification Pathways

The itemized contributions to the embodied energy for transesterification pathways (Figure 7) show that the embodied energy of electricity generation represents the largest contribution to upstream energy, with the energy required to capture and transport industrial effluent CO_2 the second largest contributor in all pathways for both growth scenarios. This significant electricity embodied energy factor represents the 43% efficiency of the national average electricity generation mix (GREET, 2011) and the significant electricity demand for mixing of the open ponds (representing between 48% and 78% of pathway electricity).

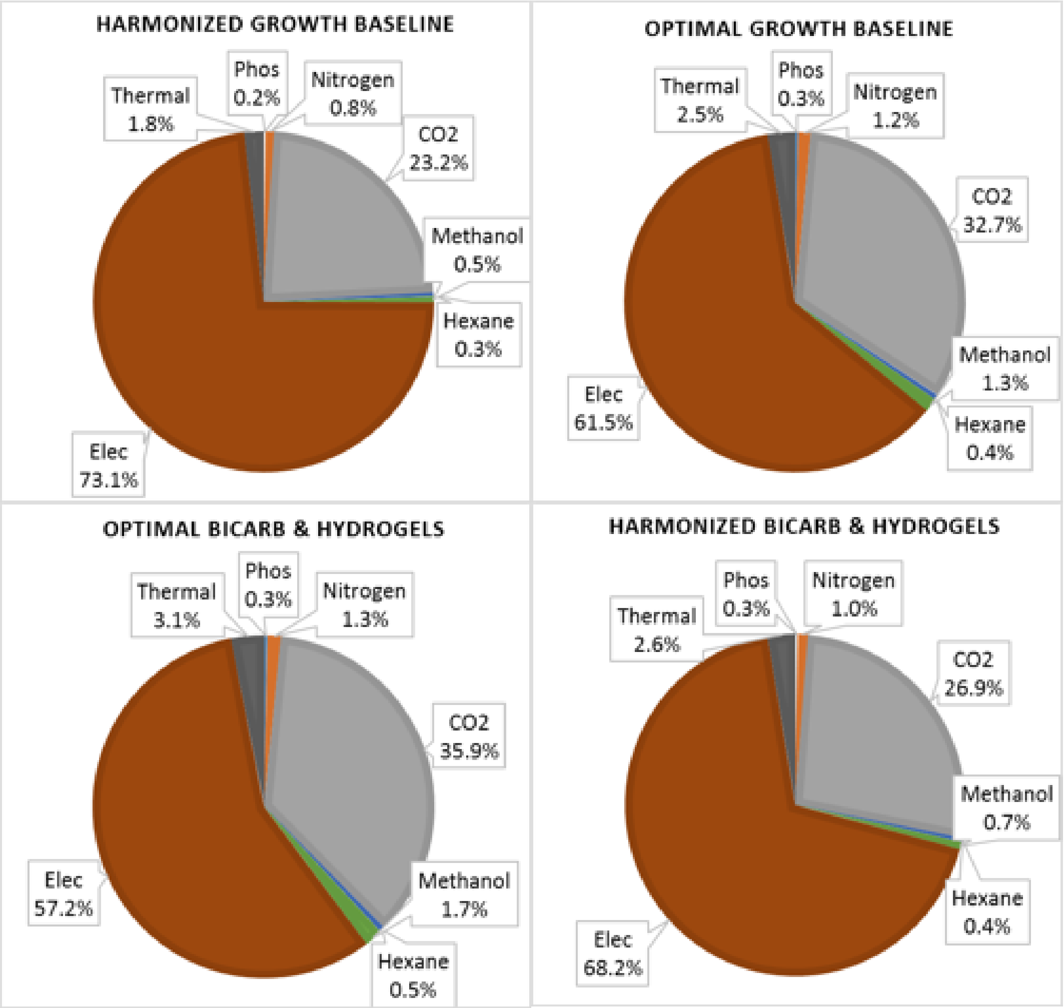

Figure 7. Embodied Energy Contributions for Transesterification Pathways

Combined with catalytic hydrothermal gasification (CHG) of the aqueous phase, HTL pathways produce renewable diesel (after hydrotreating the biocrude output from the conversion reaction) and biogas. For all HTL pathways in both growth scenarios, the energy in these outputs is greater than the direct energy inputs to the biorefinery, giving favorable net energy balances (NEB < 1) (Figure 8). However, the embodied energy of inputs is substantial for these pathways (representing between 76% - 83% of input energy, as opposed to only 61% - 63% of inputs to transesterification pathways), resulting in unfavorable cumulative energy ratios (i.e. CER > 1) for all HTL pathways.

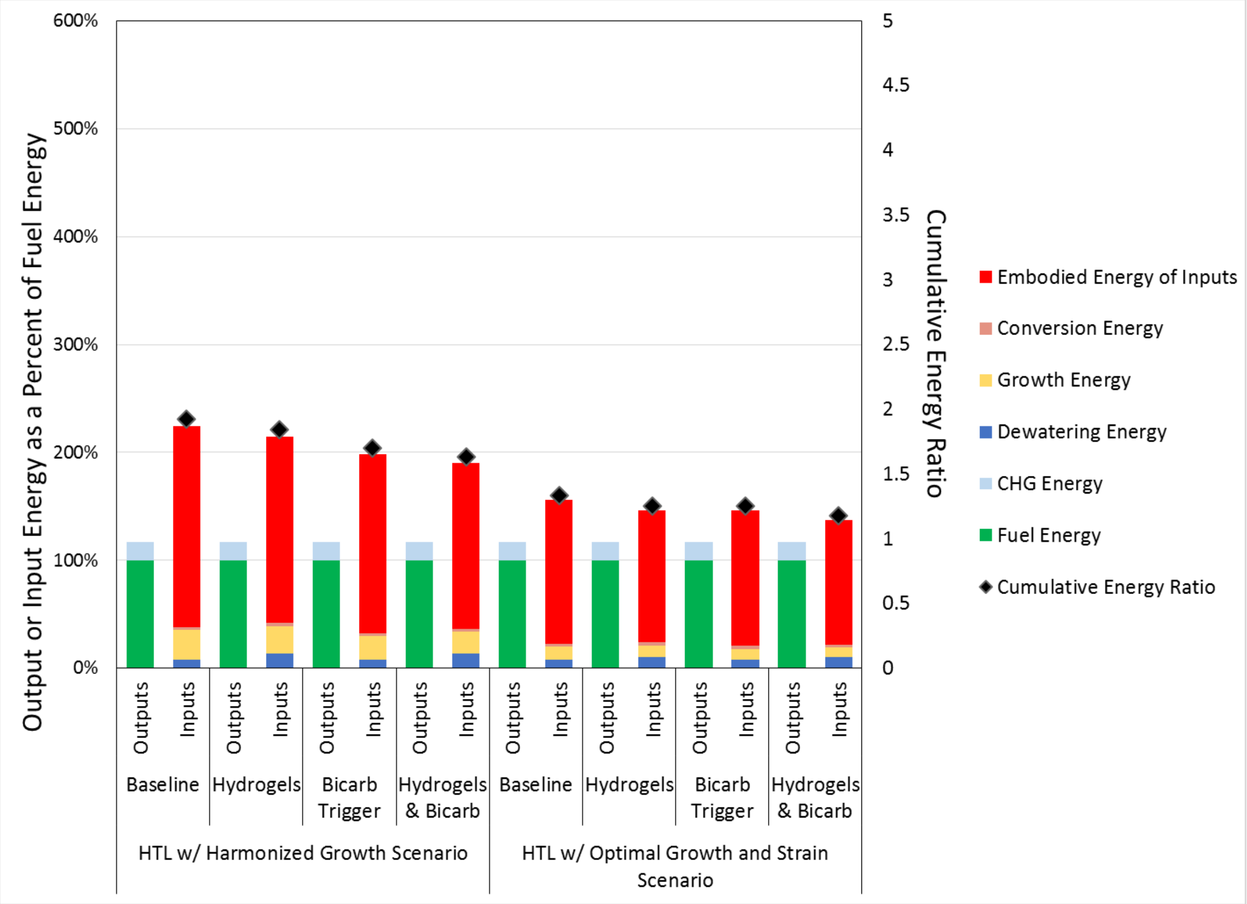

Figure 8. Cumulative Energy Ratio Breakdown for HTL Pathways

As with the transesterification pathways, the energy required to produce electricity represents the greatest contribution to the embodied energy for all HTL pathways in both growth scenarios, followed by the embodied energy of capturing and transporting industrial-effluent CO_2 (Figure 9). However, hydrogen production (from natural gas reforming) has a significant upstream energy demand as does the increased nitrogen fertilizer demand resulting from high nitrogen loss to the oil phase in the HTL reaction. Given that embodied energy represents the majority of energy inputs to HTL pathways, these results provide clear indication that low-value (in terms of embodied energy and cost) replacements should be sought.

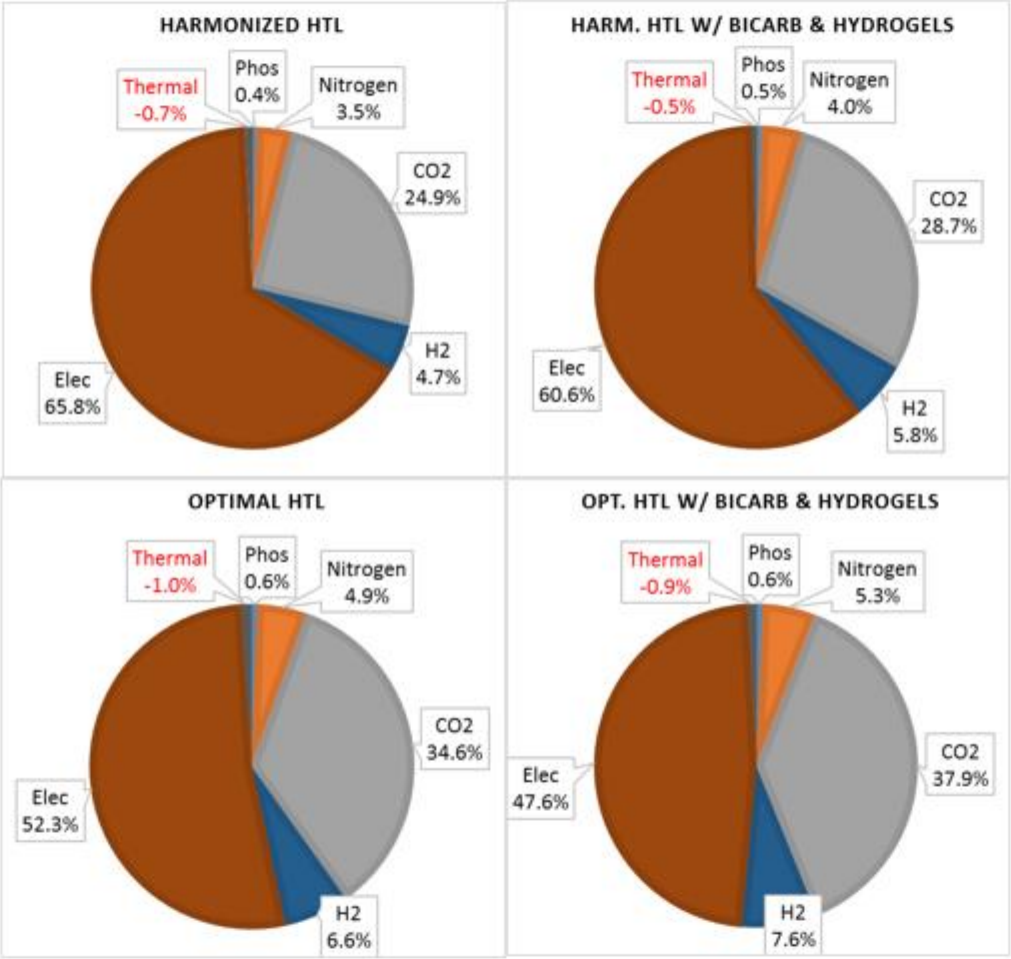

Figure 9. Embodied Energy Contributions for HTL Pathways

3.1.2 Environmental Performance

Global warming potential (GWP) relative to the life cycle GWP of conventional diesel has been calculated based on the net energetic gains, material and energy inputs for each production pathway and growth scenario (see Appendix C). Based on the US national average electricity generation mix (GREET, 2011), emissions from the electricity usage represent the largest contribution to global warming potential (Figure 10). The thermal energy demands for transesterification-based pathways (66% and 73% from dewatering for the Baseline and Hydrogels pathways, respectively) represent the second largest contribution to GHG emissions in

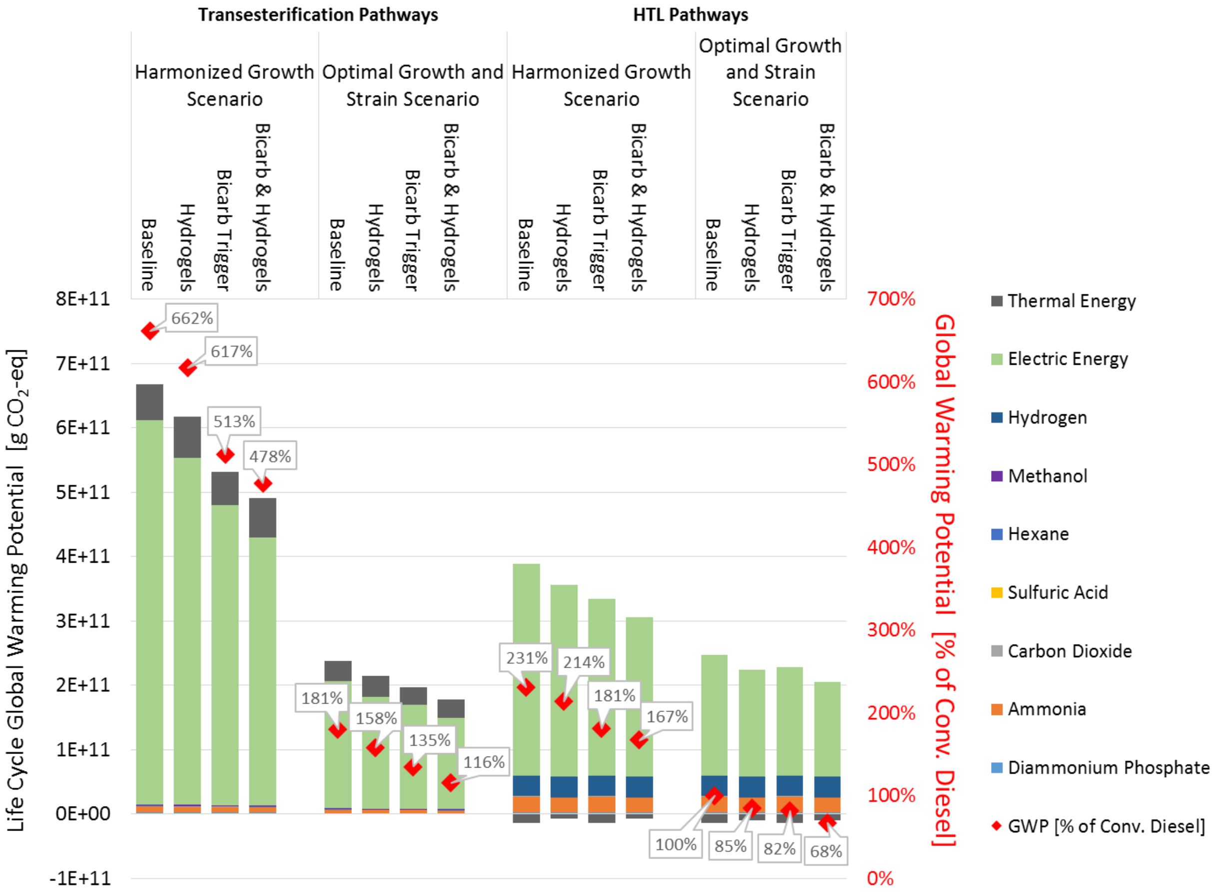

Figure 10. Global Warming Potential for Transesterification and HTL Process Pathways

pathways using this conversion method, with nitrogen fertilizer the second largest addition under both growth scenarios. While the Baseline pathway has GWP 6x greater than that of petroleum diesel, improvements from incorporation of novel operations are visible.

The increased thermal energy demand resulting from replacing DAF with hydrogels is muted by the increased cell retention efficiency of hydrogels (relative to DAF) which reduces the total biomass throughput (and therefore material and energy inputs) required for production of 10 million gallons of biodiesel; hydrogel incorporation results in an 8% decrease in GWP compared to the Baseline. Use of the bicarbonate-induced lipid productivity boost results in a 20% reduction in GWP from the Baseline pathway. In the Optimal Growth and Strain scenario, the improved energetic balances result in greater fossil fuel offsets which, along with the reduced thermal energy for the transesterification pathways in this scenario, result in GWP reductions ranging from 64% to 73% of the Baseline pathway. These reductions are greater than those achieved by using HTL under the Harmonized Growth scenario (44% reduction from Baseline).

As HTL pathways are more energetically beneficial (i.e. smaller CER) than transesterification pathways, they displace higher levels of fossil fuels; this greater displacement explains how the Harmonized Growth HTL pathways, which have greater pathway GHG emissions than the Optimal Growth and Strain transesterification pathways, actually realize greater GWP reductions. These findings corroborate the findings of the embodied energy calculations (Figure 9) in emphasizing the negative impacts of virgin hydrogen gas and ammonia use in HTL pathways, though warming potential is dominated by electricity use. The Optimal Growth and Strain HTL pathway with bicarbonate addition and hydrogels for dewatering is the most environmentally beneficial, reducing GWP by 32% relative to petroleum diesel, though this still fails to meet the 50% reduction required to qualify for the \$1.01 gal^{-1} production tax credit under the Renewable Fuel Standard (Yacobucci, 2011)

3.2 Financing Improvements

The economic potential of each production pathway, under both growth scenarios, was reevaluated (from the base analysis using straight line depreciation and an 8% cost of capital) with financing scenarios reflecting both:

1. Policy incentives impacting production costs, including:
    - MACRS and Bonus Depreciation methods
    - a \$1.01 gal^{-1} Production Tax Credit (PTC), made available through the Renewable Fuel Standard

- Federally-backed loan guarantees ensuring a 4% cost of capital (CoC); and

2. Risk mitigation techniques allowing a CoC reduction to 6%

As the pathways considered failed to meet the 50% GHG emissions reduction required to qualify for the PTC, this policy has no impact on the economic competiveness of any pathway (Figure 10). MACRS and Bonus depreciation methods generate MFSP reductions in transesterification pathways of 11% and 13% (respectively) versus MFSP reductions of 15% and 18% (respectively) for HTL-based pathways (Figure 11). Reducing the CoC to 6% (from the assumed 8%) allows the MFSP to be reduced 8% for transesterification pathways and 10% for HTL pathways. Further cost of capital reduction to 4% results in MFSP reductions of 14% for transesterification pathways and 20% for HTL pathways.

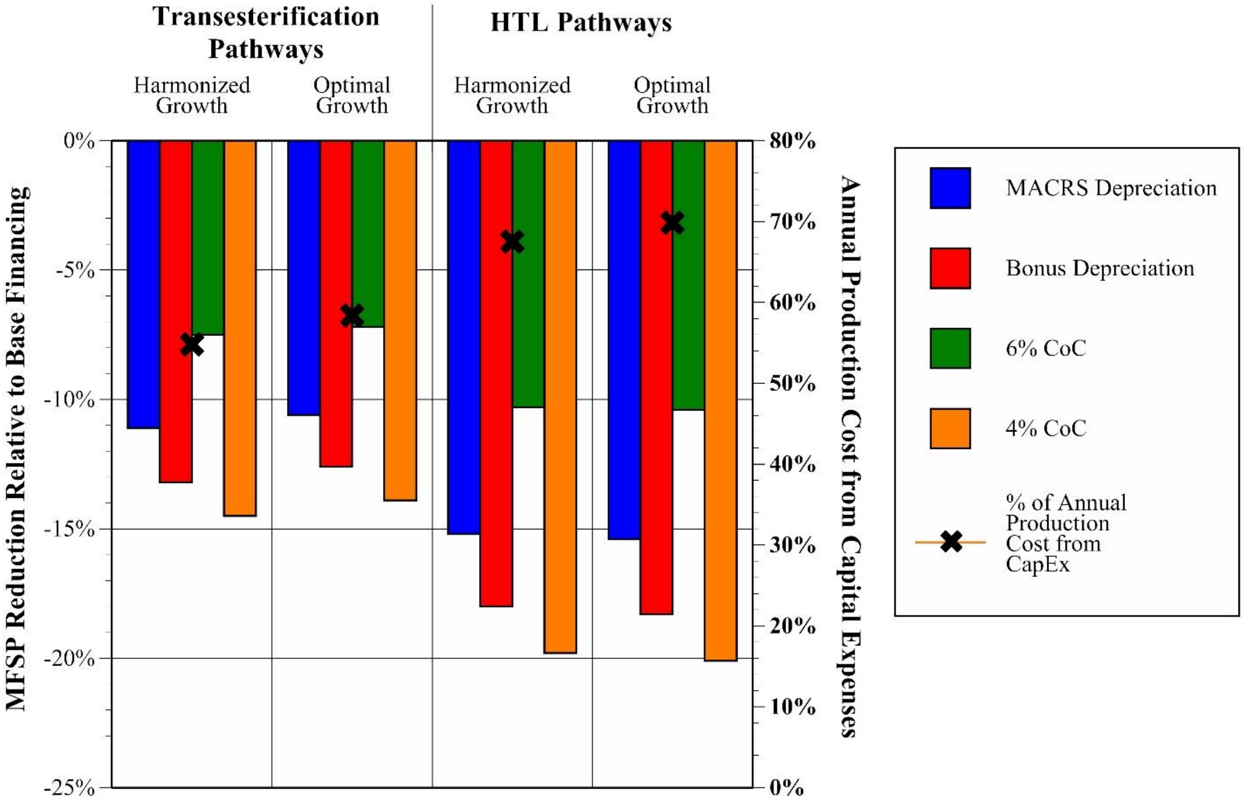

Figure 11. MFSP Reductions from Stand-Alone Financing Improvements

Calculated MFSP reductions from accelerated depreciation methods and reduced cost of capital exhibit high correlations ($r^2 > .91$) with the percent of the annual production cost that comes from capital expenses (i.e. payments made on the capital borrowed to construct the facility ("debt service")). Deferred tax assets (see Appendix D), which increase the lifetime value of facilities using accelerated depreciation methods, are calculated on the basis of the asset's depreciable capital; savings increase linearly with this capital expense. Likewise, the cost of capital is used to calculate the annual payment required on borrowed capital, therefore the savings from lowering this rate increase with greater amounts of borrowed capital. Therefore, when sub-process alternatives offer a tradeoff between capital and operating expenses, it follows that pathways with a higher annual capital expense to operating expense ratio receive greater benefits from accelerated depreciation methods and reduced cost of capital.

3.3 Relative Impact of Technical Optimization and Financing Improvements

While the calculated Baseline MFSP is clearly not competitive with conventional fuels, optimizing production pathway efficiencies and improving financing parameters both have potential to significantly increase their economic competitiveness. MFSP reductions achieved from changing a single parameter from the Baseline analysis, either implementing a novel technique or varying a financial parameter, are compared in Figure 12. Replacing DAF with hydrogels results in an MFSP reduction of 3.7%, roughly half the reduction achieved from reducing the cost of capital from 8% to 6% (7.3%). The bicarbonate-induced lipid productivity boost achieves an MFSP reduction of 18%, slightly above the reductions from a 4% cost of capital (15% reduction), Bonus (13%) or MACRS (11%) depreciation. The cost reductions from switching to an HTL-based conversion process (46%) are eclipsed only by those achieved by

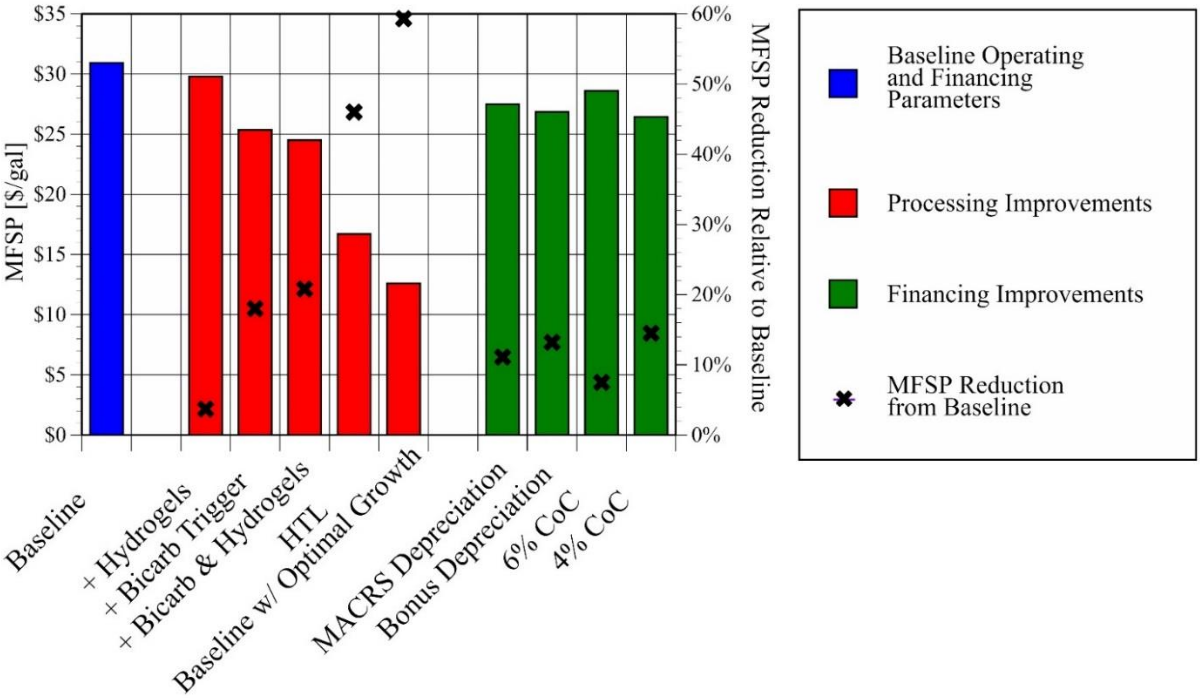

Figure 12. MFSP Impacts from Stand-Alone Processing and Financing Improvements to Baseline Pathway

operating the Baseline pathway where the Optimal Growth characteristics are achievable with a high lipid-producing algal strain (MFSP reduction of 60%).

3.4 Combining Processing and Financing Improvements

Noting that technical and financing improvements have distinct impacts on the economic competitiveness of biofuels which vary based on the production pathway, it is worth considering these improvements in tandem to identify specific scenarios where pathways are dominant (Figure 13). Incorporating bicarbonate additions and hydrogel dewatering in transesterification pathways under the Optimal Growth and Strain scenario reduces MFSP, CER and GWP by 67%, 56%, and 73%, respectively. Financing improvements, with the cost of capital reduced from 8% to 4% and Bonus depreciation methods available, further reduce the MFSP to 75% of the MFSP calculated under baseline financial conditions. Bicarbonate additions to an HTL pathway using

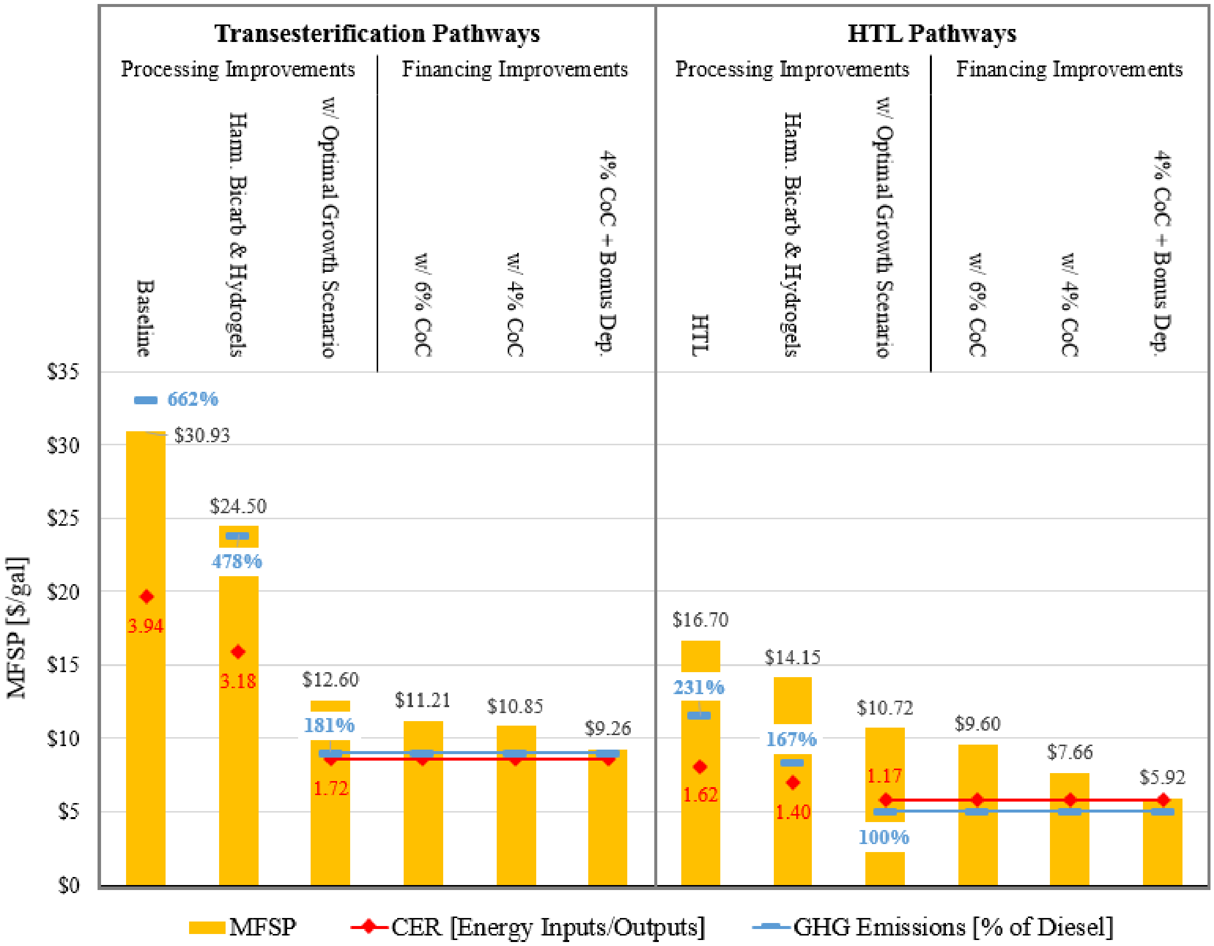

Figure 13. Combining Benefits of Technical and Financing Improvements

hydrogels in the Optimal Growth and Strain scenario result in MFSP, CER, and GWP reductions of 36%, 27%, and 57%, respectively. Reducing the CoC to 4% and using Bonus depreciation results in a MFSP reduction of 66% from the Harmonized Growth HTL pathway with baseline financial assumptions. These cumulative processing and financing improvements to processing pathways highlight that production pathways utilizing transesterification can be competitive with HTL-based pathways under certain circumstances.

3.5 Sensitivity Analysis

This analysis has specifically addressed uncertainty in the achievable lipid productivity, up-and downstream operations, and financing parameters which impact the performance evaluation of novel processing techniques. As mentioned in Section 2.7.2, there is potential for uncertainty in the inputs embedded in the model, especially the capital and operating expenses as well as resource demands of processes untested at commercial scale, to impact modeled performance. The impact of single parameters embedded in the TEA/LCA model was analyzed by varying factors above and below the assumed value and examining the impact on performance metrics. Seven factors were identified as having significant impacts on process economics (Figure 14); these impacts were found to be similar between pathways of differing composition.

While uncertainty in these factors may slightly skew model results, the MFSP shows less than 5% sensitivity to any single change in input value. The model was most sensitive to annual operating days, which will be impacted by the temperature and insolation of the biorefinery site. The discount rate impacts all pathways using accelerated depreciation methods, with higher discount rates (e.g. future cash flows are discounted more heavily and therefore worth less) improving pathway economic competitiveness. Varying the cost of the most capitally intensive

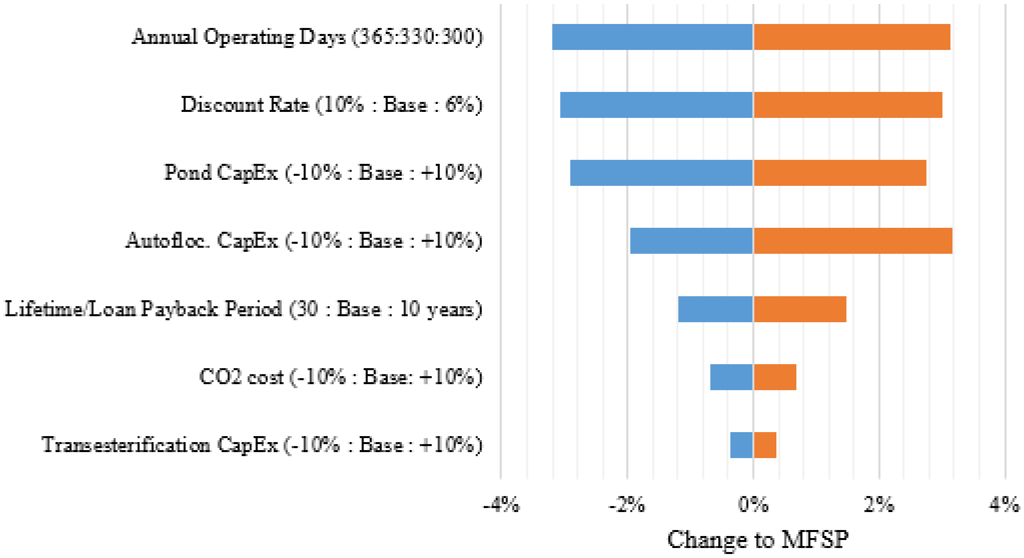

Figure 14. MFSP Sensitivity of Transesterification Pathways

equipment (i.e. open raceway ponds, autoflocculation tank, and conversion reactor) and the cost of CO_2 (the largest contributor to material operating expenses) resulted in only slight impacts on pathway MFSP.

Noting that the electricity demand represented the largest contribution to the life cycle GWP and embodied energy inputs for the modeled pathways, the relationship of these impacts on the regional electricity generation mix was evaluated. California and Montana were chosen to illustrate generation mixes varying from the national average (Table 4); while Montana's energy mix slightly increases the GWP of both transesterification and HTL pathways, the embodied energy is similar to that of the national average mixture, and shows no discernable impact on pathway CER. However, sourcing electricity from California decreases the transesterification global warming potential over 100% compared to the national average electricity mix, and reduces the CER by 4%.

Table 4. Sources of Electricity Generation

	Oil	NG	Coal	Nuclear	Others*	Embodied Energy [kWh input/ kWh output]	GHG Emissions [g CO2-eq/kWh]
Montana[1]	6%	2%	54%	0%	38%	3.1	1063.4
U.S. Ave.[2]	1%	23%	46%	20%	10%	2.3	608.3
CA[2]	1%	48%	8%	17%	28%	1.9	326.1

* Includes hydroelectric, geothermal, wind, solar, biogas

[1] EIA, 2013

[2] GREET, 2011

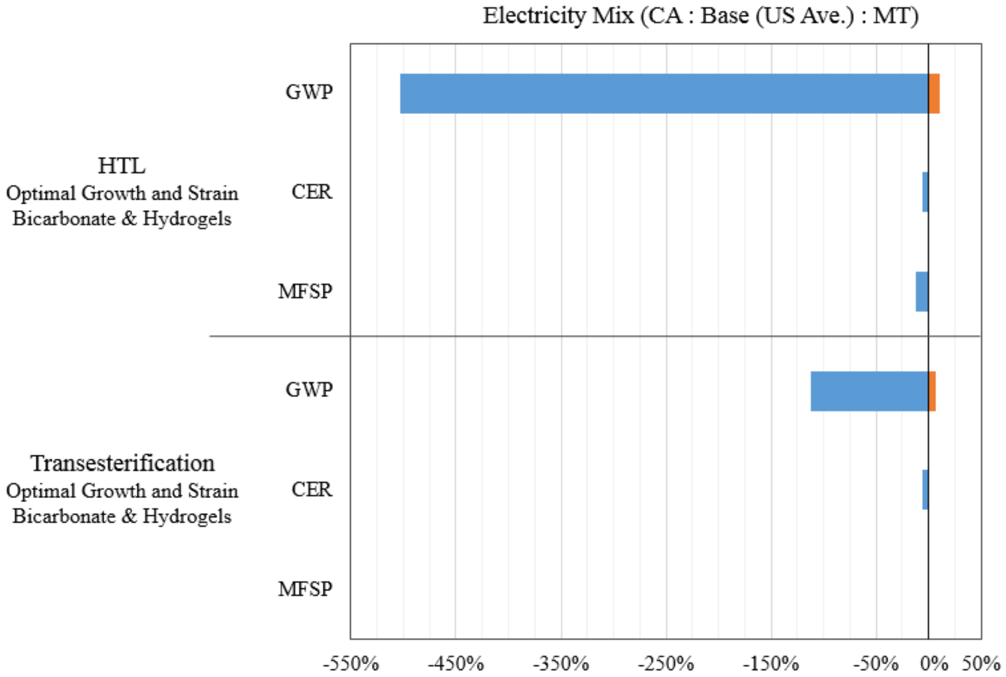

Figure 15. Sensitivity of Transesterification and HTL Pathways to Electricity Generation Mix

The reduced emissions from the California electricity mix allow the HTL pathway with bicarbonate-induced lipid productivity boost and hydrogel dewatering to reduce GWP 503% compared to the US average mix, reducing this pathway GWP to 11% that of petroleum diesel. In doing so, this pathway qualifies for the \$1.01 gal^{-1} PTC; Figure 16 shows the simultaneous economic, energetic, and environmental benefits of sourcing electricity generation from a cleaner, more efficient mixture. The CA generation mix allows the Optimal growth HTL pathway with bicarbonate addition and hydrogel dewatering to reach energy parity (CER = .98), while the PTC results in MFSP reductions of 49% relative to the economic competitiveness calculated with base financing parameters. The combination of PTC with Bonus depreciation and 4% CoC allows this (technically) improved HTL pathway to produce renewable diesel with a MFSP of \$5.61, a 66% reduction from that of the base HTL economic analysis.

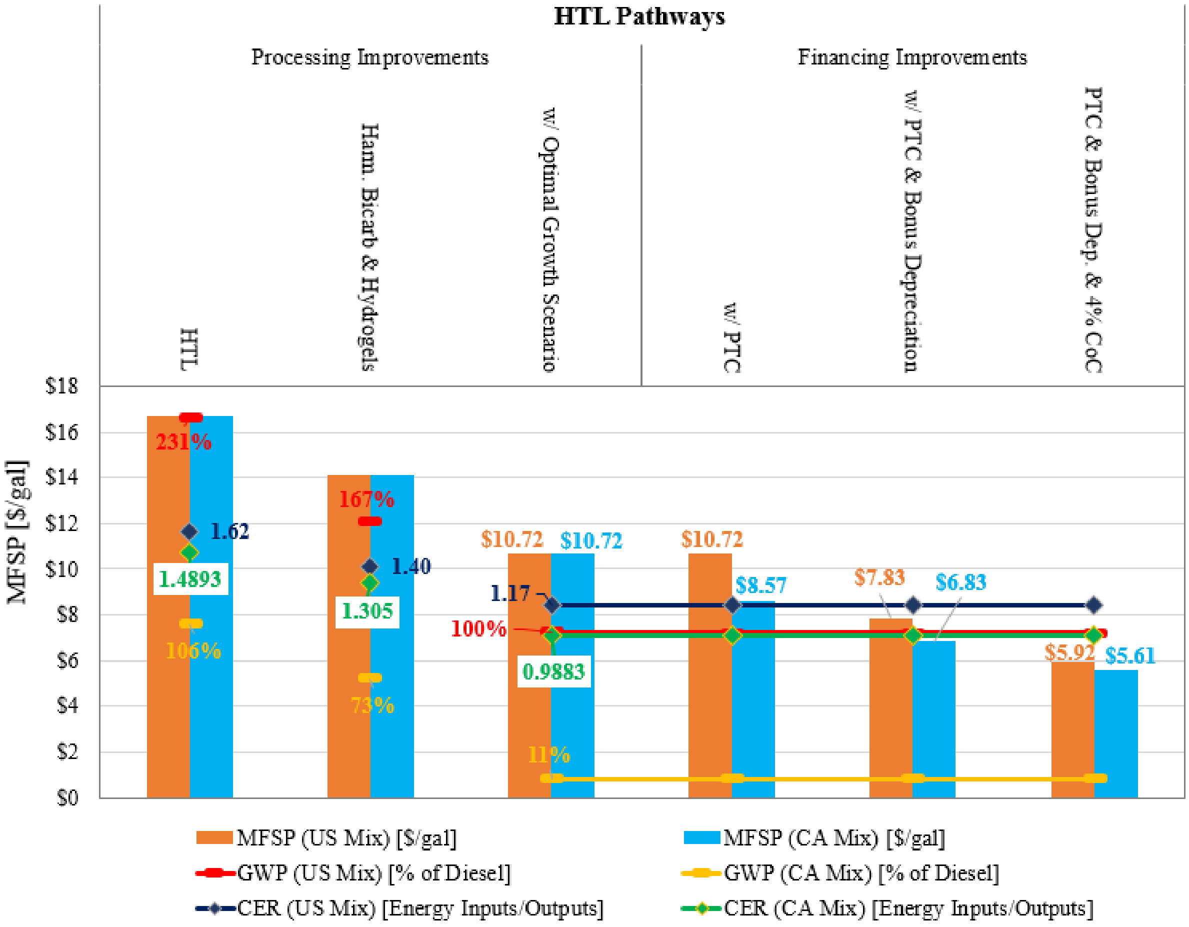

Figure 16. Technical and Financial Improvements with US Ave. and CA Elec. Generation Mix

CHAPTER 4: DISCUSSION

4.1 Considering Sub-Process Decisions within Financing Environment

The simultaneous gains achievable through cumulative improvements to production pathway efficiency and financing show the potential for algal biofuels to approach economic competitiveness with fossil alternatives, achieve substantial (even net negative) reductions in GHG emissions, and minimize fossil energy inputs required to generate renewable transportation fuels. Given the demonstrated interconnectedness of the physical environment and strain characteristics (i.e. site-specific temperature and insolation impacting achievable lipid productivity), downstream operations and financing parameters on the relative performance of processing advances, potential advances in sub-processing efficiency should be evaluated within a much larger context than has traditionally been performed. This framework should include the geographic constraints of the proposed site (e.g. average temperature, annual insolation), prevailing financing parameters (e.g. use of accelerated depreciation methods, availability of tax credits and loan guarantees, risk perception of private investors), and efficacy with alternative up-and-downstream unit operations (e.g. different cultivation techniques, conversion methods). Additionally, sensitivity of system performance to the electricity generation mix dictates that this parameter be of special consideration when evaluating potential biorefinery sites.

Achieving the potential of algal biofuels to compete at commercial scale requires designing pathways that take advantage of the environment, both physical and financial, in which operations will occur. The dependence on the physical environment, as well as the variety and uncertainty of policies impacting biorefinery financing suggest that there will be no “cookie-cutter” designs which optimize economic, energetic and environmental performance in all circumstances, but instead strategic designs tailored to the proposed biorefinery.

4.1.1 Risk Mitigation Perspective

A significant hindrance to investment in algal biorefineries is the operational risk associated with processes unproven at commercial scale (UNEP, 2004). Biodiesel production via transesterification is a well-established process; a biorefinery using this conversion technique may well be able to reduce the cost of capital below that available for financing a commercially-untested thermochemical process (e.g. HTL). From a biorefinery developer’s perspective, results of this analysis indicate that HTL pathways outperform transesterification pathways in all performance metrics under the Harmonized Growth scenario (Figure 13). If two sites were under consideration for biorefinery development, transesterification-based systems with bicarbonate addition and hydrogels operating where the Optimal Growth and Strain scenario is achievable exhibit comparable energetics, 22% lower GWP, and a MFSP 35% less than that of the Harmonized Growth HTL pathways. Moreover, in evaluating pathways for a site where the Optimal Growth and Strain scenario is achievable, if the cost of capital reflects the lowered perceived operational risk and is therefore lower for a transesterification-based facility than one utilizing HTL, transesterification-based biorefineries can achieve MFSPs competitive with HTL-based operations.

Operations at pilot scale are below the scale required to reach economic viability, with the capital required to expand likely to become more accessible when production pathways are proven to be economically competitive at commercial scale (Stephens et al., 2010). Adoption of financial and techno-economic analyses throughout the development and testing of sub-processes can both identify potential life cycle challenges as well as provide estimates of scaled performance to reduce perceived operational risk. Thus, while financing parameters have been widely regarded as exogenous variables in previous techno-economic analyses, these factors critically impact the calculated economic viability in such studies. It is also important to note that failing to link financing parameters to the risks associated with biorefinery operations and available incentives is likely to generate erroneous results.

Algal biorefineries face a unique set of risks relative to those posed by conventional refineries; while petroleum refineries face market risk with volatile input prices (i.e. crude) and output (e.g. gasoline, diesel) prices, biorefineries are likely to face less exposure to volatile input prices, and therefore reduced susceptibility to market risk (Michelez et al., 2011). Policies such as the RFS2 and state-level mandates requiring refineries to blend biofuels into gasoline and diesel ensure a market for biorefinery products, effectively mitigating output market risk providing both offtake certainty (i.e. obligating refiners to purchase biofuels ensures customers) and price support (producers are able to sell biofuel above the price that customers would normally be willing to pay) (Miller et al., 2013). Mitigation of output market risk via such policies, along with the reduced susceptibility to input price risk, could allow biorefineries to secure long-term margins with input contracts (setting the price of inputs) and offtake agreements (setting the volume and selling price of products) that are viewed as critical to securing low cost financing (Einowski et al., 2006).

4.2 Improving CER by Reducing Embodied Energy of Inputs

Highly attractive pathway energy balances were found to be significantly diminished when upstream energy burdens of production inputs were considered. While recycling of nutrients and carbon via recycling processes provides cost, energy and emissions benefits, the energy from production and use of chemical fertilizers, hydrogen, and energy inputs substantially reduce the performance of process pathways. Electricity production, based on the US national average generation mix (GREET, 2011) represented the largest single contribution to pathway embodied energy and global warming potential for all pathways. Reducing these impacts could be achieved, as was illustrated by pathway evaluation using the CA generation mix, through switching to more efficient, cleaner sources (e.g. replace coal generation with natural gas combined cycle) or through the use of renewable energy. Renewable sources tend to have higher embodied energy (GREET, 2011) than conventional energy sources, negatively impacting the cumulative energy ratio; the fossil energy ratio (i.e. fossil fuel input energy/biofuel output energy) has proven useful for evaluating fuel cycles using renewably-sourced energy (Davis et al., 2013).

Colocation with, and utilization of, waste streams for meeting carbon (e.g. from flue gas) and nutrient (e.g. agricultural or industrial wastewater streams) demands should be a primary consideration in the siting of commercial scale algal biorefineries. Algal cultivation systems have been shown to both effectively treat wastewater while prosperously nurturing algal cultures (Cabanelas et al., 2013), thereby decreasing the cost, embodied energy and emissions related to production of virgin nitrogen and phosphorus sources as well as facility water footprint (Yang et al., 2011). Optimal use of all cellular components, a foundational principle in biorefinery design, must be considered when selecting recovery methods and determining the fate of coproducts. Development of biorefinery pathways which generate hydrogen instead of methane from residual biomass, if proven viable, may be of greater life cycle economic, energetic and environmental value given the upstream burdens of hydrogen required for biocrude upgrading (Jones & Mayfield, 2012).

4.3 HTL Upgrading Energy

The hydrothermal liquefaction model used for this analysis recognized no energetic impact due to changing feedstock lipid content, and only modest impacts on process economics due to nutrient recycling efficiency impacts. While this coincides with previous findings emphasizing the focus on increased biomass productivities over lipid content for thermochemical conversion methods (Elliott et al., 2013), the impact of cellular composition on HTL oil quality has recently been the topic of increased research (López Barreiro, Zamalloa, et al., 2013). Incorporation of cellular nitrogen into HTL oil causes the oil phase to require upgrading prior to use as a transportation fuel (Frank et al., 2013). Algae with low lipid content have higher protein and carbohydrate contents; strains with especially high protein content have been shown to produce higher levels of nitrogen in the HTL aqueous products (Li et al., 2014), and therefore may require greater energy and cost to upgrade. Further investigation of the life cycle impacts of low-lipid containing algae is required to determine how cellular composition is linked to energy required to produce a useable fuel.

4.4 Future Work

The transesterification – HTL comparison used in this analysis provides a useful paradigm for analyzing the impact of financing parameters on engineering design decisions for optimizing economic competitiveness, as the two conversion methods produce clear tradeoffs between capital and operating expenses. This framework could be readily applied to the analysis of open raceway ponds and photobioreactors (PBRs) for algal cultivation. Financial analysis of production systems has demonstrated that the increased capital expenses of PBRs relative to ORPs is offset by decreased operating expenses (due to higher cell concentration and lipid content, increased number of operational days) increased reliability of yields (due to decreased contamination of culture), such that PBRs are more financially viable than ORPs (Richardson et al., 2014). The decreased financial risk from higher reliability biomass yields and increased performance relative to ORPs in periods of sub-optimal growth conditions are therefore likely to make PBRs economically competitive in certain physical and financial environments.

Additionally, the significant impact that the electricity generation mix has on the GWP and embodied energy suggest that incorporation of this parameter into biorefinery planning and development will have energetic, environmental, and (when a PTC or other mechanism incentivizes GWP reductions) economic benefits. As novel operations continue to be developed for algal biofuels production, this methodology could be useful in examining the environmental and financial conditions in which proposed processes are most economically competitive.

CHAPTER 5: CONCLUSIONS

This research develops an integrated techno-economic and life-cycle analysis model to examine the economic, energetic and environmental performance of algal biofuel production pathways. Novel sub-process alternatives for algae cultivation (bicarbonate-induced lipid accumulation) and dewatering (temperature-sensitive hydrogels) were integrated into production pathways under different growth scenarios, with different biomass-to-fuel conversion methods, and with a variety of improvements to biorefinery financing available to highlight relative pathway performance improvements in each case. While often considered extrinsic variables in economic analyses of algal biofuels, the financing parameters reflect perceived operational risk and uncertain regulatory support for renewable energy production systems. Thus, it is important that they be fully integrated, as the impact of accelerated depreciation methods and reduced financing costs (representing risk management strategies as well as guaranteed loans) on the cost of produced fuel is observed to be dependent on the sub-process operations which make up a proposed production pathway.

Biorefinery design to maximize lifetime economic potential must then consider the relevant financing environment, including perceived risk of operations and regulatory policies, when evaluating sub-process alternatives. Modeling of proposed alternatives in production pathways composed of various operations (e.g. for growth, dewatering, extraction and conversion, energy and nutrient recovery) and sited in diverse geophysical environments provides a more accurate representation of the exact conditions in which sub-processes dominate alternatives. Elucidation of the links between the environment (i.e. physical and financial) in which a biorefinery operates and the processes chosen will promote the development of site-specific, economically competitive, energetically positive and environmentally beneficial algal biofuels production pathways.

APPENDIX A: MODEL INPUTS AND REFERENCES

Parameter	**Value**	**Units**	**Reference**
Algae Cultivation			
Land Cost	3000	$/acre	Davis et al., 2011
Pumping water to pond	1.20E-04	kWh/L	GREET
Pumping culture to pond	2.50E-05	kWh/L	GREET
Paddlewheel Circulation	48	kWh/ha*d	GREET
CO2 Demand	1.83	g / g dry algae	GREET
CO2 Loss	18%		GREET
Productivity	13.20	g/m2/d	Davis et al., 2012
Operational Days	330.00	Days/year	Davis et al., 2012
Lipid Content	25%		Davis et al., 2012
Pond Outlet Conc	0.5	g DW /L	GREET
Pond CapEx	50600	$/ha	Nagarajan et al., 2012
	8 - 50	$/m3	Lundquist et al. (2010) ; Stephens et al. (2009); Davis et al. (2011); Benemann and Oswald (1996); Campbell et al. (2011); Weissmann and Goebel (1987); Putt (2007)
Water Cost	0.05	$/1000 gal	Davis et al., 2011
Nitrogen Demand	0.077	g N/g algae	GREET
Ammonia Cost	407	$/ ton NH3	Davis et al., 2011
Phosphorus Demand	0.0081	g P/g algae	GREET
DAP Cost	442	$/ ton DAP	Davis et al., 2011
CO2 Cost	40	$/kg	Davis et al., 2011
Bicarb Trigger			
HCO3 Demand	55	mM	Gardner et al., 2013
HCO3 Cost	0.55	$/kg	Industrial Quote
Dewatering			
AF Tank Cost	71.15	$/m3	Delrue et al., 2012
AF Outlet Conc.	10	g DW/L	GREET
DAF Elec Demand	2.48	kWh/g algae	GREET
Chitosan Demand	0.004	g/g algae	GREET
DAF CapEx	5.14e6	$	CapCost
DAF Outlet Conc	60	g DW/L	GREET
DAF Retention	90%		GREET

Hydrogels			
Temp Change	10	Deg C	Vadlamani, 2014
Retention Efficiency	98%		Vadlamani, 2014
CapEx (.1 g/L Input)	2.06E+07	$	CapCost
OpEx (.1 g/L Input)	5.67E+04	$	CapCost
Capex (1 g/L Input)	2.30E+06	$	CapCost
OpEx (1 g/L Input)	4.61E+03	$	CapCost
Evodos Centrifuge			
Energy Demand	1.2	kWh/m^3	Evodos
Retention	95%		Evodos
Yield	240	g BM/L	Evodos
Thermal Drying			
CapEx	45-129	$/ton water evaporated	Chauvel et al., 2001
Dry Hexane Extraction			
Elec Demand	5.40E-04	kWh/g oil	GREET
	.00024-.00045	kWh/kg DW biomass	Delrue et al., 2012
Thermal Demand	1.38E-03	kWh/g oil	GREET
	.87 - 1.74	kWh/kg DW biomass	Delrue et al., 2012
Hexane Demand	5.00E-03	g/g oil	GREET
Hexane Cost	4.70E-01	$/kg	http://www.icis.com
Retention Efficiency	95%		GREET
CapEx	51 - 155	$/ton DW biomass	Chauvel et al., 2001
Transesterification			
Methanol	1.00E-01	g/g biodiesel produced	Orfield 2013
Methanol Cost	4.90E-01	$/kg methanol	http://www.icis.com
Retention Efficiency	80%		Orfield 2013
Electricity Demand	.00019-.00057	kWh/kg CL	Delrue et al., 2012
	0.36	MJ/kg oil	Xu et al., 2013
Thermal Demand	.34 - 1.01	kWh/kg CL	Delrue et al., 2012
	1.75	MJ/kg oil	Xu et al., 2013
CapEx	219.9 - 659.7	$/ton CL/yr	Chauvel et al., 2001
Glycerol yield	0.111	kg glycerol/kg BD	Chowdhury et al., 2012

HTL			
Catalyst -NaCO3	0.0039	kg/kg BM	Bennion et al., 2015
Reactor	6.51	MJ/kg Algae	Bennion et al., 2015
Cooling	0.0018	MJ/kg Algae	Bennion et al., 2016
Centrifuge	0.001	MJ/kg Algae	Bennion et al., 2017
Energy Recovery - Burning Gaseous	0.28	MJ/kg Algae	Bennion et al., 2018
Energy Recovery - heat exchanger	0.33	MJ/kg Algae	Bennion et al., 2019
Heat Transfer Efficiency	85	%	Bennion et al., 2020
Bio-oil yield	0.37	kg/kg Algae	Bennion et al., 2021
Solids Yield	0.16	kg/kg Algae	Bennion et al., 2022
Aqueous phase yield	0.17	kg/kg Algae	Bennion et al., 2023
Gaseous yield	0.30	kg/kg Algae	Bennion et al., 2024
Bio-oil HHV	34	MJ/kg	Bennion et al., 2025
Gaseous HHV	1.11	MJ/kg	Bennion et al., 2026
Hydrotreating H_2 Demand	0.043	kg H2/kg oil treated	Jones et al., 2014
Hydrocracking H_2 Demand	0.02	kg H2/kg oil treated	Jones et al., 2014
Anaerobic Digestion			
Elec Demand	.05-.2	kWh/kg residue	Couturier et al., 2001
	2.20E-04	kWh/g residue	GREET
Thermal Demand	.1-.3	kWh/kg residue	Couturier et al., 2001
	8.50E-05	kWh/g residue	GREET
Gas Production	0.28	L CH4/g solids	Chowdhury et al., 2012
	.262-.8	m3 CH4/kg dry matter	Collet et al., 2013
	.33	L methane/g solids	Quinn et al., 2013
	.2-.4	m3 CH4/kg solids	Delrue et al., 2012
Elec Yield	5.40E-01	kWh/g digested	Quinn et al., 2013
Thermal Yield	1.40E-01	kWh/g digested	Quinn et al., 2013
	2.1-4.2	kwh/kg digested	Delrue et al., 2012
CapEx	84 - 245.7	$/ton residue/yr	Davis et al. (2011) ; Couturier et al. (2001)

APPENDIX B: BICARBONATE-INDUCED LIPID PRODUCTIVITY BOOST

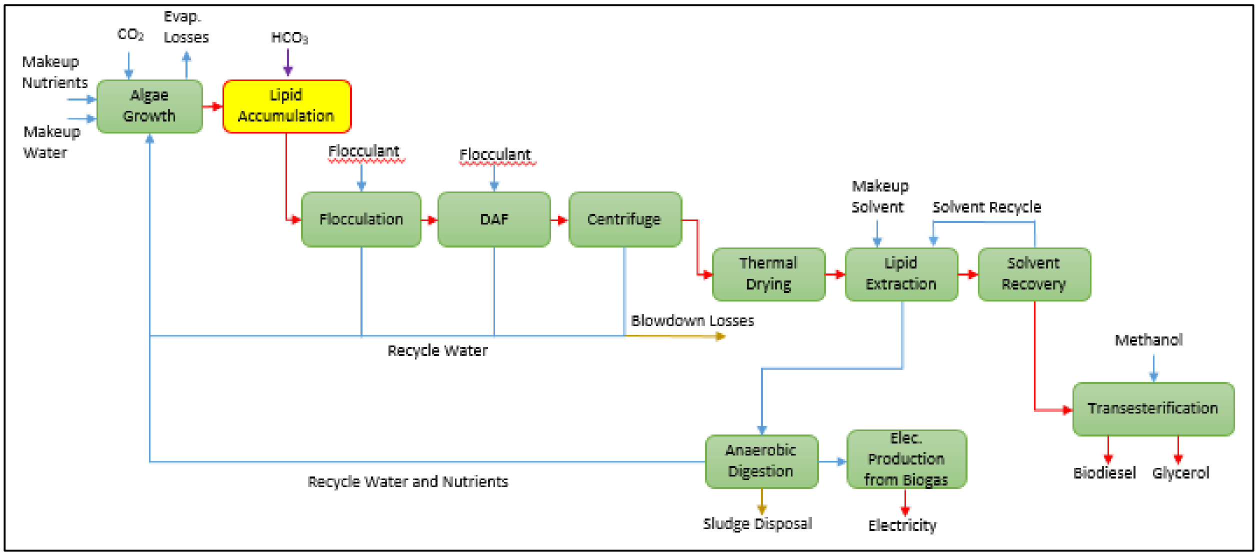

Figure B1. Schematic for Baseline + Bicarb Trigger Pathway

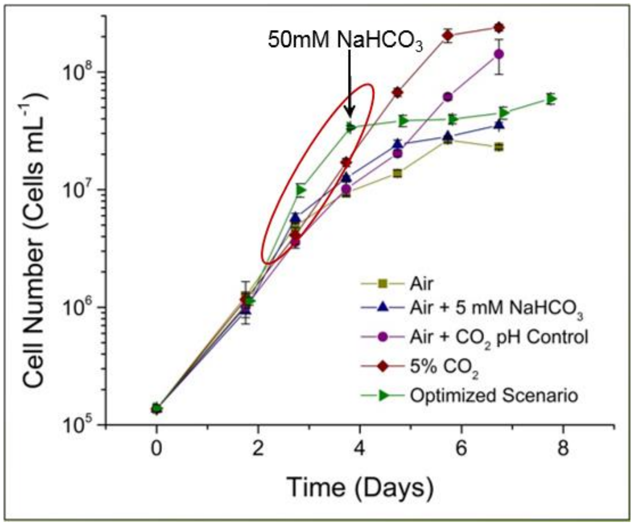

Figure B2a. Phase 1 Bicarb Trigger[1]

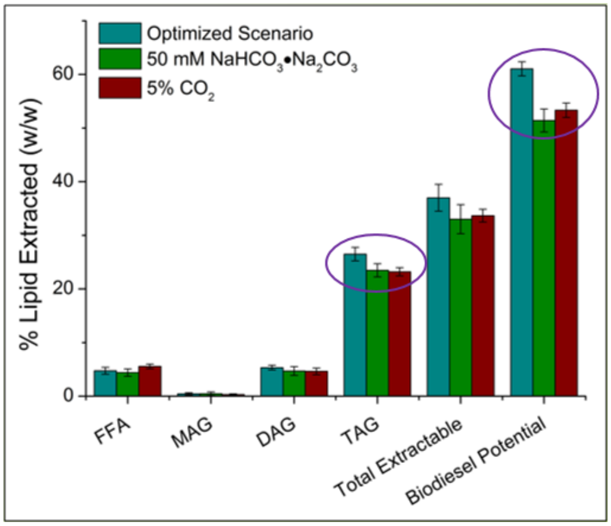

Figure B2b. Phase 2 Bicarb Trigger[1]

[1](Lohman et al., 2015)

Photosynthetic organisms generally use inorganic CO_2 as a carbon source; microalgae rely on CO_2 dissolved in their aquatic environment, where it forms a weak acid-base buffer system with water (Markou et al., 2014). The equilibrium of inorganic carbon species (e.g. carbonic acid, bicarbonate and carbonate) is dependent on the pH of the medium; between pH of 6.3 and 10.3 (where most algae thrive) bicarbonate is the dominant form, though CO_2 uptake increases the pH and increases the concentration of the unusable carbonate form (Markou et al., 2014). Addition of bicarbonate to the growth medium increases the alkalinity, forcing OH^- ions to react with CO_2 and form bicarbonate, thereby increasing available dissolved inorganic carbon (DIC) (Gardner et al., 2013). The increased media pH additionally increases the mass transfer rate of gaseous CO_2 into the media, since dissolution via the CO_2 – OH^- chemical reaction occurs more quickly than the hydration of CO_2 to H_2CO_3 (Markou et al., 2014), further increasing available DIC.

The two phase “bicarbonate trigger” for enhanced lipid productivity (henceforth referred to as the “Bicarb Trigger”) begins with addition of low-grade sodium bicarbonate at low concentrations during growth, increasing the alkalinity of the growth medium. At higher pH, the driving force for gaseous CO_2 dissolution into the aqueous phase increases, resulting in greater dissolved inorganic carbon uptake rates by biomass. Phase 1 was shown to increase the specific growth rate by 69%, leading to an overall increase in biomass productivity of 27%. Phase 2 consists of a higher concentration addition of sodium bicarbonate as nitrogen is depleted, halting the cell cycle and inducing lipid accumulation. Results of Phase 2 trials show increases in the achievable biodiesel content of 8%; together with the increased biomass productivity, an increase of lipid productivity of over 37% is achievable. This two phase Bicarb Trigger has been included as a cultivation phase sub-process, with Phase 1 occurring during open pond cultivation, followed by Phase 2 in a separate lipid accumulation tank.

APPENDIX C: LIFE CYCLE GWP AND EMBODIED ENERGY OF INPUTS

Methanol			
Energy	6.78	kWh/kg	GREET
GWP	505.11	g CO2-eq/kg	
Hexane			
Energy	14.95	kWh/kg	GREET
GWP	851.14	g CO2-eq/kg	
Ammonia Fertilizer			
Energy	10.48	kWh/kg	GREET
GWP	2577.64	g CO2-eq/kg	
DAP Fertilizer			
Energy	3.18	kWh/kg	GREET
GWP	800.55	g CO2-eq/kg	
NG			
Energy	0.10	kWh/kWh	GREET
GWP	65.56	g CO2-eq/kWh	
Elec Production			
Energy	2.33	kWh/kWh	GREET
GWP	605.33	g CO2-eq/kWh	
Industrial CO2			
Energy	2.31	kWh/kg	Liu et al., 2014
GWP	0.82	g CO2-eq/kg	
H2			
Energy	59.62	kWh/kg	GREET
GWP	14480.05	g CO2-eq/kg	
H2SO4			
Energy	0.00	kWh/kg	GREET
GWP	50.16	g CO2-eq/kg	
HCO3			
Energy	0.30	kWh/kg	Church and Dwight
GWP	31.76	g CO2-eq/kg	

APPENDIX D. ACCELERATED DEPRECIATION TAX BENEFITS

A visualization (Figure 4) of straight line (SL) and accelerated (MACRS 7-year) depreciation schedules for the Baseline production pathway show the generation of deferred tax liabilities (DTLs) for pathways using accelerated depreciation methods for income tax calculations. Financial reporting accounts for the loss of asset value using straight line depreciation, where the annual charge is equal to the asset value divided by the lifetime of asset, represented by the orange columns. Use of an accelerated depreciation method accrues larger losses in asset value early in the asset's life, as shown by the blue columns; over the asset lifetime, these charges are equal to those from the straight line asset depreciation. However, depreciation charges are deductible from income taxes, and larger charges therefore result in larger deductions and reduced tax liability. The difference between the accelerated depreciation expense and the SL depreciation expense (grey line), when multiplied by the effective income tax rate (assumed to be 35%), gives the deferred tax expense in each year (yellow line). This represents the value of the tax savings in each year resulting from reduced income taxes from the accelerated depreciation deductions.

Early in the asset life, when accelerated depreciation deductions are ongoing, a positive depreciation difference results in the accrual of a large DTL; once the accelerated schedule ends, the depreciation difference goes negative, representing future increased tax liabilities. However, when taking into account the time value of money (with an assumed discount rate of 8%), the present value of the DTL is calculated (red line) and we observe that future liabilities are of far less consequence than the significant near-term deferred expenses.

Bonus depreciation further allows for 50% of the total depreciable capital to be deducted in the first year of operation, followed by a standard MACRS schedule.

REFERENCES

Akiyama, M., Tsuge, T., & Doi, Y. (2003). Environmental life cycle comparison of polyhydroxyalkanoates produced from renewable carbon resources by bacterial fermentation. *Polymer Degradation and Stability*, *80*(1), 183–194. doi:10.1016/S0141-3910(02)00400-7

Batan, L., Quinn, J. C., & Bradley, T. H. (2013). Analysis of water footprint of a photobioreactor microalgae biofuel production system from blue, green and lifecycle perspectives. *Algal Research*, *2*, 196–203. doi:10.1016/j.algal.2013.02.003

Batan, L., Quinn, J., Willson, B., & Bradley, T. (2010). Net energy and greenhouse gas emission evaluation of biodiesel derived from microalgae. *Environmental Science & Technology*, *44*(20), 7975–80. doi:10.1021/es102052y

Benemann, J. R., & Oswald, W. J. (1996). *Systems and Economic Analysis of Microalgae Ponds for Conversion of CO2 to Biomass*.

Bennion, E. P., Ginosar, D. M., Moses, J., Agblevor, F., & Quinn, J. C. (2015). Lifecycle assessment of microalgae to biofuel : Comparison of thermochemical processing pathways q. *Applied Energy*, 1–10. doi:10.1016/j.apenergy.2014.12.009

Bohutskyi, P., Ketter, B., Chow, S., Adams, K., Betenbaugh, M. J., Thomas Allnutt, F. C., & Bouwer, E. J. (2015). Anaerobic digestion of lipid-extracted Auxenochlorella protothecoides biomass for methane generation and nutrient recovery. *Bioresource Technology*, *183*, 229–239. doi:10.1016/j.biortech.2015.02.012

Brennan, L., & Owende, P. (2010). Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews*, *14*(2), 557–577. doi:10.1016/j.rser.2009.10.009

Cabanelas, I. T. D., Arbib, Z., Chinalia, F. a., Souza, C. O., Perales, J. a., Almeida, P. F., … Nascimento, I. A. (2013). From waste to energy: Microalgae production in wastewater and glycerol. *Applied Energy*, *109*, 283–290. doi:10.1016/j.apenergy.2013.04.023

Chen, G., Zhao, L., & Qi, Y. (2015). Enhancing the productivity of microalgae cultivated in wastewater toward biofuel production: A critical review. *Applied Energy*, *137*, 282–291. doi:10.1016/j.apenergy.2014.10.032

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

Chowdhury, R., Viamajala, S., & Gerlach, R. (2012). Reduction of environmental and energy footprint of microalgal biodiesel production through material and energy integration. *Bioresource Technology*, *108*, 102–11. doi:10.1016/j.biortech.2011.12.099

Clarens, A. F., Nassau, H., Resurreccion, E. P., White, M. A., & Colosi, L. M. (2011). Environmental impacts of algae-derived biodiesel and bioelectricity for transportation. *Environmental Science and Technology*, *45*(17), 7554–7560. doi:10.1021/es200760n

Clarens, A. F., Resurreccion, E. P., White, M. a., & Colosi, L. M. (2010). Environmental life cycle comparison of algae to other bioenergy feedstocks. *Environmental Science and Technology*, *44*(5), 1813–1819. doi:10.1021/es902838n

Collet, P., Spinelli, D., Lardon, L., Hélias, A., Steyer, J.-P., & Bernard, O. (2013). Life-Cycle Assessment of Microalgal-Based Biofuels. *Biofuels from Algae*, 287–312. Retrieved from http://hal.inria.fr/hal-00854438

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

Davis, R., Fishman, D., Frank, E., & Wigmosta, M. (2012). *Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model*. Retrieved from http://www.nrel.gov/docs/fy12osti/55431.pdf

Davis, R., Kinchin, C., Markham, J., Tan, E., Laurens, L., Sexton, D., … Lukas, J. (2014). *Process Design and Economics for the Conversion of Algal Biomass to Biofuels : Algal Biomass Fractionation to Lipid- Products*.

Davis, R., Tao, L., Tan, E. C. D., Biddy, M. J., Beckham, G. T., Scarlata, C., … Schoen, P. (2013). Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons : Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons Process Design and Economics for the Conversion, (October 2013), 147. doi:10.2172/1107470

Decicco, J. M. (2014). The liquid carbon challenge: Evolving views on transportation fuels and climate. *Wiley Interdisciplinary Reviews: Energy and Environment*, *4*(February). doi:10.1002/wene.133

Delrue, F., Li-Beisson, Y., Setier, P., Sahut, C., Roubaud, a, Froment, a-K., & Peltier, G. (2013). Comparison of various microalgae liquid biofuel production pathways based on energetic, economic and environmental criteria. *Bioresource Technology*, *136*, 205–12. doi:10.1016/j.biortech.2013.02.091

Delrue, F., Setier, P.-A., Sahut, C., Cournac, L., Roubaud, A., Peltier, G., & Froment, A.-K. (2012). An economic, sustainability, and energetic model of biodiesel production from microalgae. *Bioresource Technology*, *111*, 191–200. doi:10.1016/j.biortech.2012.02.020

DOE. (2010). *National Algal Biofuels Technology Roadmap*.

Duan, P., Wang, B., & Xu, Y. (2015). Catalytic hydrothermal upgrading of crude bio-oils produced from different thermo-chemical conversion routes of microalgae. *Bioresource Technology*, *186*, 58–66. doi:10.1016/j.biortech.2015.03.050

Einowski, E. D., Hanni, C. M., Smith, L. N., & Doll, K. J. (2006). *The Law of Biofuels - A Guide to Business and Legal Issues*.

EISA, Pub. L. No. PublicLaw110-140, 2007 (2007). Retrieved from http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi? dbname)110_cong_public_laws&docid)f: publ140.110.pdf.

Elliott, D. C., Hart, T. R., Schmidt, A. J., Neuenschwander, G. G., Rotness, L. J., Olarte, M. V., … Holladay, J. E. (2013). Process development for hydrothermal liquefaction of algae feedstocks in a continuous-flow reactor. *Algal Research*, *2*, 445–454. doi:10.1016/j.algal.2013.08.005

Fargione, J. (2008). Land Clearing and the Biofuel Carbon Debt. *Science (New York, N.Y.)*, *319*(February), 1235–1239.

Fields, M. W., Hise, A., Lohman, E. J., Bell, T., Gardner, R. D., Corredor, L., … Gerlach, R. (2014). Sources and resources: importance of nutrients, resource allocation, and ecology in microalgal cultivation for lipid accumulation. *Applied Microbiology and Biotechnology*, *98*(11), 4805–16. doi:10.1007/s00253-014-5694-7

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., … Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91*(1), 1–21. doi:10.1016/j.jenvman.2009.06.018

Frank, E. D., Elgowainy, A., Han, J., & Wang, Z. (2013). Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae. *Mitigation and Adaptation Strategies for Global Change*, *18*(1), 137–158. doi:10.1007/s11027-012-9395-1

Frank, E., Han, J., Palou-Rivera, I., Elgowainy, A., & Wang, M. Q. (2011). *Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model*. *Center for Transportation …*. doi:ANL/ESD/11-5

Gardner, R. D., Lohman, E., Gerlach, R., Cooksey, K. E., & Peyton, B. M. (2013). Comparison of CO(2) and bicarbonate as inorganic carbon sources for triacylglycerol and starch accumulation in Chlamydomonas reinhardtii. *Biotechnology and Bioengineering*, *110*(1), 87–96. doi:10.1002/bit.24592

GREET. (2011). GREET (The Greehhouse Gases, Regulated Emissions, and Energy Use in Transportation Model). ANL. Retrieved from http://greet.es.anl.gov/

Hill, J., Nelson, E., Tilman, D., Polasky, S., & Tiffany, D. (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National*

Academy of Sciences of the United States of America, *103*(30), 11206–10. doi:10.1073/pnas.0604600103

Ho, D. P., Ngo, H. H., & Guo, W. (2014). A mini review on renewable sources for biofuel. *Bioresource Technology*. doi:10.1016/j.biortech.2014.07.022

Huijbregts, M. a J., Hellweg, S., Frischknecht, R., Hendriks, H. W. M., Hungehbühler, K., & Hendriks, a. J. (2010). Cumulative energy demand as predictor for the environmental burden of commodity production. *Environmental Science and Technology*, *44*(6), 2189–2196. doi:10.1021/es902870s

IRS. (2015). A Brief Overview of Depreciation. Retrieved March 5, 2015, from http://www.irs.gov/Businesses/Small-Businesses-&-Self-Employed/A-Brief-Overview-of-Depreciation

ISO 14040. (1997). *Environmental management - Life Cycle Assessment - Principles and Framework* (Vol. Geneva: In). Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Environmental+management+-+Life+Cycle+assessment+-+Principles+and+framework#0

Jones, C. S., & Mayfield, S. P. (2012). Algae biofuels: versatility for the future of bioenergy. *Current Opinion in Biotechnology*, *23*(3), 346–51. doi:10.1016/j.copbio.2011.10.013

Jones, S. B., Zhu, Y., Anderson, D., Elliott, D. C., Schmidt, A. J., Albrecht, K. O., … Kinchin, C. (2014). *Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons : Whole Algae Hydrothermal Liquefaction and Upgrading*.

Jorquera, O., Kiperstok, A., Sales, E. A., Embiruçu, M., & Ghirardi, M. L. (2010). Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. *Bioresource Technology*, *101*(4), 1406–1413. doi:10.1016/j.biortech.2009.09.038

Khoo, H. H., Koh, C. Y., Shaik, M. S., & Sharratt, P. N. (2013). Bioenergy co-products derived from microalgae biomass via thermochemical conversion - Life cycle energy balances and CO2 emissions. *Bioresource Technology*, *143*, 298–307. doi:10.1016/j.biortech.2013.06.004

Kirrolia, A., Bishnoi, N. R., & Singh, R. (2013). Microalgae as a boon for sustainable energy production and its future research & development aspects. *Renewable and Sustainable Energy Reviews*, *20*, 642–656. doi:10.1016/j.rser.2012.12.003

Klöpffer, W. (1997). Life cycle assessment: From the beginning to the current state. *Environmental Science and Pollution Research International*, *4*(4), 223–228. doi:10.1007/BF02986351

Koutinas, A. a., Chatzifragkou, A., Kopsahelis, N., Papanikolaou, S., & Kookos, I. K. (2014). Design and techno-economic evaluation of microbial oil production as a renewable resource for biodiesel and oleochemical production. *Fuel*, *116*, 566–577. doi:10.1016/j.fuel.2013.08.045

Lamers, P., Roni, M. S., Tumuluru, J. S., Jacobson, J. J., Cafferty, K., Hansen, J. K., … Bals, B. (2015). Techno-economic analysis of decentralized biomass processing depots. *Bioresource Technology*. doi:10.1016/j.biortech.2015.07.009

Lardon, L., Hélias, A., & Sialve, B. (2009). Life-cycle assessment of biodiesel production from microalgae. *... Science & Technology*, 6475–6481. Retrieved from http://pubs.acs.org/doi/full/10.1021/es900705j

Li, H., Liu, Z., Zhang, Y., Li, B., Lu, H., Duan, N., … Si, B. (2014). Conversion efficiency and oil quality of low-lipid high-protein and high-lipid low-protein microalgae via hydrothermal liquefaction. *Bioresource Technology*, *154*, 322–329. doi:10.1016/j.biortech.2013.12.074

Liu, X., Saydah, B., Eranki, P., Colosi, L. M., Greg Mitchell, B., Rhodes, J., & Clarens, A. F. (2013). Pilot-scale data provide enhanced estimates of the life cycle energy and emissions profile of algae biofuels produced via hydrothermal liquefaction. *Bioresource Technology*, *148*, 163–171. doi:10.1016/j.biortech.2013.08.112

Lohman, E. J., Gardner, R. D., Pederson, T., Peyton, B. M., Cooksey, K. E., & Gerlach, R. (2015). Optimized Inorganic Carbon Regime for Enhanced Growth and Lipid Accumulation in Chlorella vulgaris. *Biotechnology for Biofuels*, *8*(82), 1–13. doi:10.1186/s13068-015-0265-4

López Barreiro, D., Prins, W., Ronsse, F., & Brilman, W. (2013a). Hydrothermal liquefaction (HTL) of microalgae for biofuel production: State of the art review and future prospects. *Biomass and Bioenergy*, *53*, 113–127. doi:10.1016/j.biombioe.2012.12.029

López Barreiro, D., Prins, W., Ronsse, F., & Brilman, W. (2013b). Hydrothermal liquefaction (HTL) of microalgae for biofuel production: State of the art review and future prospects. *Biomass and Bioenergy*, *53*(0), 113–127. doi:10.1016/j.biombioe.2012.12.029

López Barreiro, D., Zamalloa, C., Boon, N., Vyverman, W., Ronsse, F., Brilman, W., & Prins, W. (2013). Influence of strain-specific parameters on hydrothermal liquefaction of microalgae. *Bioresource Technology*, *146*, 463–71. doi:10.1016/j.biortech.2013.07.123

Markou, G., Vandamme, D., & Muylaert, K. (2014). Microalgal and cyanobacterial cultivation : The supply of nutrients. *Water Research*, *65*, 186–202. doi:10.1016/j.watres.2014.07.025

Michelez, J., Rossi, N., Martin, J. M., Mera, E., Christensen, D., Peineke, C., … Stevens, G. (2011). *Risk Quantification and Risk Management in Renewable Energy Projects Risk Quantification and Risk Management in Renewable Energy Projects*.

Miller, N., Christensen, A., Park, J. E., Barel, A., & Seearle, S. (2013). Measuring and Addressing Investment Risk in the Second- Generation Biofuels Industry.

Molina Grima, E., Belarbi, E.-H., Acién Fernández, F. ., Robles Medina, A., & Chisti, Y. (2003). Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnology Advances*, *20*(7-8), 491–515. doi:10.1016/S0734-9750(02)00050-2

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

National Research Council. (2012). *Sustainable Development of Algal Biofuels in the United States*.

Orfield, N. D., Keoleian, G. a., & Love, N. G. (2014). A GIS based national assessment of algal bio-oil production potential through flue gas and wastewater co-utilization. *Biomass and Bioenergy*, *63*, 76–85. doi:10.1016/j.biombioe.2014.01.047

Patil, P. D., Gude, V. G., Mannarswamy, A., Deng, S., Cooke, P., Munson-McGee, S., … Nirmalakhandan, N. (2011). Optimization of direct conversion of wet algae to biodiesel under supercritical methanol conditions. *Bioresource Technology*, *102*(1), 118–22. doi:10.1016/j.biortech.2010.06.031

Pittman, J. K., Dean, A. P., & Osundeko, O. (2011). The potential of sustainable algal biofuel production using wastewater resources. *Bioresource Technology*, *102*(1), 17–25. doi:10.1016/j.biortech.2010.06.035

Ponnusamy, S., Kumar Reddy, H., Muppaneni, T., Meghan Downes, C., & Shuguang Deng, and. (2014). Life cycle assessment of biodiesel production from algal bio-crude oils extracted under subcritical water conditions. *Bioresource Technology*. doi:10.1016/j.biortech.2014.07.072

Quinn, J. C., & Davis, R. (2014). The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling. *Bioresource Technology*. doi:10.1016/j.biortech.2014.10.075

Quinn, J. C., Smith, T. G., Downes, C. M., & Quinn, C. (2014). Microalgae to biofuels lifecycle assessment — Multiple pathway evaluation. *Algal Research*, *4*, 116–122. doi:10.1016/j.algal.2013.11.002

Rawat, I., Ranjith Kumar, R., Mutanda, T., & Bux, F. (2013). Biodiesel from microalgae: A critical evaluation from laboratory to large scale production. *Applied Energy*, *103*, 444–467. doi:10.1016/j.apenergy.2012.10.004

Resurreccion, E. P., Colosi, L. M., White, M. A., & Clarens, A. F. (2012). Comparison of algae cultivation methods for bioenergy production using a combined life cycle assessment and life cycle costing approach. In *Bioresource Technology* (Vol. 126, pp. 298–306). doi:10.1016/j.biortech.2012.09.038

Richard, T. L. (2010). Challenges in scaling up biofuels infrastructure. *Science (New York, N.Y.), 329*(5993), 793–6. doi:10.1126/science.1189139

Richardson, J. W., Johnson, M. D., & Outlaw, J. L. (2012). Economic comparison of open pond raceways to photo bio-reactors for profitable production of algae for transportation fuels in the Southwest. *Algal Research, 1*(1), 93–100. doi:10.1016/j.algal.2012.04.001

Richardson, J. W., Johnson, M. D., Zhang, X., Zemke, P., Chen, W., & Hu, Q. (2014). A financial assessment of two alternative cultivation systems and their contributions to algae biofuel economic viability. *Algal Research, 4*, 96–104. doi:10.1016/j.algal.2013.12.003

Ríos, S. D., Torres, C. M., Torras, C., Salvadó, J., Mateo-Sanz, J. M., & Jiménez, L. (2013). Microalgae-based biodiesel: economic analysis of downstream process realistic scenarios. *Bioresource Technology, 136*, 617–25. doi:10.1016/j.biortech.2013.03.046

Rogers, J. N., Rosenberg, J. N., Guzman, B. J., Oh, V. H., Mimbela, L. E., Ghassemi, A., … Donohue, M. D. (2014). A critical analysis of paddlewheel-driven raceway ponds for algal biofuel production at commercial scales. *Algal Research, 4*, 76–88. doi:10.1016/j.algal.2013.11.007

Samaras, C., & Meisterling, K. (2008). Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy. *Environmental Science & Technology, 42*(9), 3170–3176. doi:10.1021/es702178s

Sheehan, J., Dunahay, T., Benemann, J., & Roessler, P. (1998). Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae; Close-Out Report. doi:10.2172/15003040

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

Stephens, E., Ross, I. L., King, Z., Mussgnug, J. H., Kruse, O., Posten, C., … Hankamer, B. (2010). An economic and technical evaluation of microalgal biofuels. *Nature Biotechnology, 28*(2), 126–8. doi:10.1038/nbt0210-126

Torres, C. M., Ríos, S. D., Torras, C., Salvadó, J., Mateo-Sanz, J. M., & Jiménez, L. (2013). Microalgae-based biodiesel: a multicriteria analysis of the production process using realistic scenarios. *Bioresource Technology, 147*, 7–16. doi:10.1016/j.biortech.2013.07.145

Turton, R., Bailie, R. C., Whiting, W. B., & Shaeiwitz, J. A. (2008). *Analysis, synthesis and design of chemical processes*. Pearson Education.

U.S. Energy Information Administration. (2014). *Annual Energy Outlook 2014 (AEO2014).*

UNEP. (2004). *Financial Risk Instruments for Renewable Energy*.

US PREF. (2014). *MACRS Depreciation and Renewable Energy Finance*.

Vadlamani, A. (2014). Assessment of Temperature- and pH- Sensitive Hydrogels for Dewatering Dilute Algal Suspensions. In *AIChE Annual Meeting*. Atlanta, GA.

Vasudevan, V., Stratton, R. W., Pearlson, M. N., Jersey, G. R., Beyene, A. G., Weissman, J. C., … Hileman, J. I. (2012). Environmental performance of algal biofuel technology options. *Environmental Science & Technology*, *46*(4), 2451–9. doi:10.1021/es2026399

Wigmosta, M. S., Coleman, A. M., Skaggs, R. J., Huesemann, M. H., & Lane, L. J. (2011). National microalgae biofuel production potential and resource demand. *Water Resources Research*, *47*(3), n/a–n/a. doi:10.1029/2010WR009966

Wijffels, R. H., & Barbosa, M. J. (2010). An Outlook on Microalgal Biofuels. *Science*, *329*.

Williams, P. J. le B., & Laurens, L. M. L. (2010). Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics. *Energy & Environmental Science*. doi:10.1039/b924978h

Xu, L., Wim Brilman, D. W. F., Withag, J. a M., Brem, G., & Kersten, S. (2011). Assessment of a dry and a wet route for the production of biofuels from microalgae: energy balance analysis. *Bioresource Technology*, *102*(8), 5113–22. doi:10.1016/j.biortech.2011.01.066

Yacobucci, B. D. (2011). Biofuels Incentives: A Summary of Federal Programs. *Order Code RL33572 Washington, DC: US Congressional Research Service*.

Yang, J., Xu, M., Zhang, X., Hu, Q., Sommerfeld, M., & Chen, Y. (2011). Life-cycle analysis on biodiesel production from microalgae: water footprint and nutrients balance. *Bioresource Technology*, *102*(1), 159–65. doi:10.1016/j.biortech.2010.07.017

Zaimes, G. G., & Khanna, V. (2013). Microalgal biomass production pathways: evaluation of life cycle environmental impacts. *Biotechnology for Biofuels*, *6*, 88. doi:10.1186/1754-6834-6-88

Zhao, X. (2015). *Harvesting Microalgae-Development of a Short Residence Time Method Using Rapid- response Temperature-sensitive Semi-IPN Hydrogels*. University of Toledo.

Zhu, Y., Albrecht, K. O., Elliott, D. C., Hallen, R. T., & Jones, S. B. (2013). Development of hydrothermal liquefaction and upgrading technologies for lipid-extracted algae conversion to liquid fuels. *Algal Research*, *2*(4), 455–464. doi:10.1016/j.algal.2013.07.003