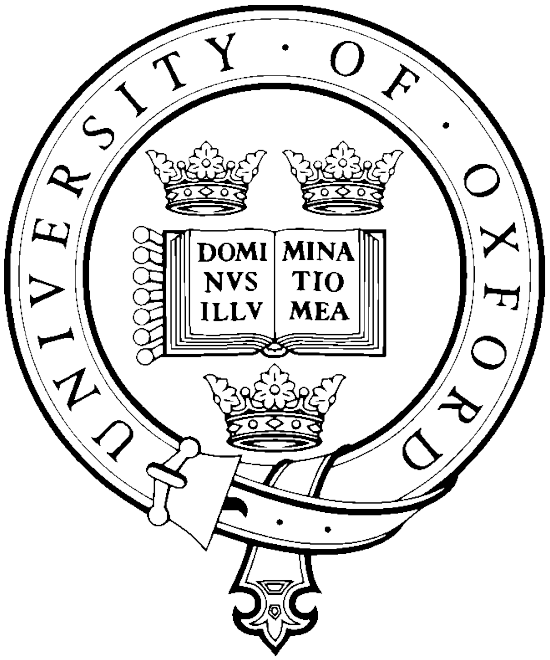
THE ROLE OF CATALYSTS AND ALGAE IN FORMING A SUSTAINABLE SOLUTION FOR A GLOBAL FOOD AND FUEL CRISIS



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Abstract

This thesis undertakes three separate lifecycle analyses to determine the emissions and fossil energy demand required to process algae biomass into renewable fuel and animal feed. A complete well-to-wheel fuel-cycle analysis is conducted for the production of biodiesel and jet biofuel from algae biomass. The environmental impacts of algae-based fuels for the road transportation and aviation industry are benchmarked against analogue conventional fossil fuels. This thesis demonstrates that algae biofuel production can only realize its inherent environmental advantage of reduced GHG emissions, once every step of the production chain is fully optimized and decarbonized. This includes smart co-product utilization, offsetting fertilizers through wastewater recycling, reusing exhaust gases as additional CO_2 source and using decarbonized electricity, heat and indirect energy.

The definition of a Catalyst Sensitivity Index (CSI) demonstrates how catalytic efficiency increases can impact the fossil energy consumption and the greenhouse gas emissions balance of catalyst-dependent processes. The CSI will allow the industry to highlight ‘best practice catalysts’ and draw conclusions for what efficiency gains one could anticipate with higher performance catalysts.

For countries where a decarbonized electricity and heat grid is not available to guarantee low-carbon algae fuel production and the looming resource scarcity around marine feed production has become more pressing, the alternative use of algae for aquafeed production is recommended. This thesis analyses major routes towards the future cost-competitive production of microbial biomass as sustainable fish meal and oil source to meet a global demand for depleting fish feed supplies. A comprehensive economic cost analysis and lifecycle assessment demonstrates the feasibility of replacing global fish meal and fish oil supplies with low-carbon and affordable algae feed by the year 2030. This research reveals how algae feed production has the potential to transform a pressing resource tipping point into a turning point.

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List of Publications

From this thesis the following papers I-VI have been published, submitted or are in preparation. The papers are ordered from most recent to last.

I	**T.Shirvani**, J.Sheehan, T.Searchinger and D.A. King, *Harvesting the algal bloom to meet a global fish feed crisis,* Nature, 2012	(In Progress)
II	**T. Shirvani**, X. Yan, P. P. Edwards and D. A. King, *Algae Jet Biofuel: A Flight Path for Sustainable Aviation Fuels*, Environmental Science and Technology, 2012	(Submitted)
III	**T. Shirvani** *Energy Security in an Emission-Constrained World: The Potential for Fuels,* Chapter 5 in 'Energy, Transport & the Environment' Book series, O.R. Inderwildi, D.A. King, Springer London 2012, VIII	(Published)
IV	**T. Shirvani,** *Environmental Feasibility of Algae Biodiesel Production,* Applied Petrochemical Research, Springer KACST Forum, 2012, DOI 10.1007/s13203-012-0015-5	(Published)
V	**T. Shirvani**, X. Yan, O. R. Inderwildi, P. P. Edwards and D. A. King, *Life Cycle Energy and Greenhouse Gas Analysis for Algae-Derived Biodiesel*, Energy and Environmental Science, Energy and Environmental Science, 2011, vol. 4, 3773-3779	(Published)
VI	**T. Shirvani** and O. R. Inderwildi, *A futuristic View of Gas-to-Liquid Technology,* Oxford Energy Forum, 2011, vol.86, 25-27	(Published)

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List of Abbreviations and acronyms

AD	Anaerobic Digestion
APR	Aqueous phase reforming
ARA	Arachidonic Acid
ASTM	American Society for Testing and Materials
BTL	Biomass-to-Liquid
C*	Catalyst
CCS	Carbon Capture and Storage
CH_4	Methane
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSI	Catalyst Sensitivity Index
CTL	Coal-to-Liquid
DCL	Direct Coal Liquefaction
DHA	Docosahexaenoic Acid
E-Factor	Environmental Factor
EBR	Energy Balance Ratio
EIA	Energy Information Administration
EPA	Eicosapentaenoic Acid
EU	European Union
EU ETS	European Union Emissions Trading System

FAME	Fatty Acid Methyl Esters
FAO	Food and Agriculture Organization of the United Nations
FCR	Feed Conversion Ratio
FeSO4	Ferrous Sulfate
FFV	Flexible-Fuel Vehicles
FIFO	Fish-In-Fish-Out Ratio
FT	Fischer Tropsch
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global Warming Potential
GTL	Gas-to-Liquid
H_2	Hydrogen
H_2O	Hydrogen Oxide
HUFA	Highly Unsaturated Fatty Acids
ICEV	Internal Combustion Engine Vehicle
ICL	Indirect Coal Liquefaction
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
K_2O	Potassium Oxide
KOH	Potassium Hydroxide
LCA	Lifecycle Analysis
LCI	Lifecycle Inventory
LCIA	Lifecycle Impact Assessment
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
MSW	Municipal Solid Waste
N	Nitrogen
N_2O	Nitrous Oxide
Na_2CO_2	Sodium Carbonite
$NaHCO_3$	Sodium bicarbonate
NH3	Ammonia

OECD	Organization for Economic Co-operation and Development
OPEC	Organization of Petroleum Exporting Countries
P	Phosphorous
P_2O_5	Phosphorus Pentoxide
PBR	Photobioreactor
PUFA	Polyunsaturated Fatty Acids
PVC	Polyvinyl chloride
SCO	Single-Cell Oil
SCWG	Supercritical Water Gasification
SPF	Specific Pathogen Free
SR	Steam Reforming
TTW	Tank-to-Wheel
WTT	Well-to-Tank
WTW	Well-to-Wheel
UNFCCC	United Nations Framework Convention on Climate Change

List of Units

bbl	Barrel of crude oil
bbl/d	Barrel of crude oil per day
boe	Barrel of oil equivalent
bn	Billion
BTU	British Thermal Unit
EJ	Exajoule
d	Day
g	Grams
gal	Gallon (US)
gCO_2	Grams of CO_2 emissions
g/l	Grams per liter
GJ	Gigajoule
ha	Hectare

kJ	Kilojoules
kg	Kilogram
km	Kilometer
km^2	Square kilometer
l	Liter
m	Meter
m^2	Square meter
m^3	Cubic meter
mb/d	Million barrels a day
Mha	Million hectares
MJ	Megajoule
mm^2/s	Square millimeter/second
Mt	Million ton
p.a	Per annum
ppm	Parts per million
ppmv	Parts per million by volume
t	Ton (metric)
wt	Weight
wt %	Weight percentage

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Extended Abstract

In an era of increasing concerns around the global water-food-energy nexus, coupled with the issue of marginal land availability, this thesis provides a systematic lifecycle assessment on how best to use abandoned or degraded land to address, through the use of microalgae, the issue of global food and fuel demand. The research contained here represents a comprehensive analysis of the emissions and corresponding energy balances of processing algae biomass for the production of renewable fuel and animal feed. Through a lifecycle analysis approach detailed in Chapter 2, an accurate and complete assessment of the vehicle fuel-cycle, i.e. the Well-to-Wheel chain, is given for the production of algae biodiesel and algae jet biofuel. All stages of the algae-to-biofuel production cycle are examined and potential avenues for lowering technical bottlenecks are highlighted. The environmental impacts of algae-based fuels, for the road transportation and aviation industry, are benchmarked against analogue conventional fossil fuel products. In Chapter 3, I discuss the impact of alternative fuels from all types of biomass feedstock in regards to issues of energy security and Greenhouse Gas (GHG) emissions reduction policies, by combining both socio-economic and technological aspects. This chapter constitutes a critical review of the current literature specific to the transport fuel dilemma and does not contain new results.

In Chapter 4, I evaluate whether algae biodiesel production can be a viable fuel source once the energy and carbon intensity of the various processes are managed accordingly. Currently, algae biodiesel production is 2.5 times as energy intensive as conventional diesel and nearly equivalent to the high fuel-cycle energy use of oil-shale diesel. Biodiesel from advanced biomass, such as

algae, can realize its inherent environmental advantages of GHG emissions reduction once every step of the production chain is fully optimized and decarbonised. This includes smart co-product utilization, decarbonisation of the electricity and heat grids as well as indirect energy requirements for fertilizer, transport and building material. Only if all these factors are taken into account is the cost of heat and electricity reduced, and GHG emissions fully mitigated.

In Chapter 5, I illustrate, through a lifecycle approach, how the production of jet biofuel from algae biomass can operate on an improved fossil energy balance which is around 30-80% lower than that of analogue Jet A-1 fuels produced from crude oil. Algae jet biofuel can become a viable low-carbon fuel through the larger uptake of fossil-free heat and electricity, the offset of fertilizers through wastewater recycling and the reuse of exhaust gases from co-product utilization as additional sources of CO_2 for algae farming. Here I also highlight that the critical break-even lipid content, which meets the life-cycle fossil energy use of kerosene from crude oil, has already been reached at 30% algae oil. The engineering of higher oil yields becomes in this case irrelevant, as additional increases in algae lipid rates will only result in a marginal improvement of the jet biofuel lifecycle energy demand and the resulting GHG balance. Moreover, compared to biodiesel from algae feedstock, large-scale jet biofuel production requires 60% less marginal landmass to substitute global fossil fuel demand by 2050. At today's oil prices around $100/barrel, the production of algae biodiesel at a cost of $252/barrel is expected to be more viable in the mid-term future, than jet biofuel production ($714/barrel).

In Chapter 6, I present a preliminary discussion and definition of a Catalyst Sensitivity Index (CSI) which illustrates how catalytic efficiency increases can impact upon the fossil energy consumption and GHG emissions balance of catalyst-

dependent processes. Through the analysis of several catalyst-dependent alternative fuel paths I outline the critical importance of catalytic chemistry for the development of a low-carbon fuel mix. The CSI index will allow industry to highlight ‘best practice catalysts’ and draw conclusions as to what efficiency gains one could theoretically anticipate with higher performance catalysts. This new CSI concept has certain similarities to the industry-wide used E-factor and should go in the future hand-in-hand with environmentally-conscious industry decisions on sustainable practices and environmental efficiency gains.

In Chapter 7, I demonstrate an alternative use for algae biomass as a large-scale feed replacement in aquaculture farming systems. I present the analysis of major routes towards the future cost-competitive production of microbial biomass as sustainable fish meal and fish oil source to meet an ever-growing demand for depleting sources. This thesis shows quantitatively how microbial feed production can act as a sustainable future food source producible at affordable prices and as part of a resource-efficient and low carbon farming process that maintains essential ecosystems. From a cost analysis, as well as a comprehensive lifecycle assessment, I conclude that there is a potential by the year 2030 for the large-scale replacement of fish meal and fish oil sources with cost-competitive and low-carbon algae feed production. My analysis demonstrates how by the year 2030 algae feed production will result in 18-29% lower production costs and become cost-competitive against rising prices for fish meal and oil. I show how the cultivation of marine shrimp in Chinese intensive farming systems, on various nutritionally compatible algae diets, will result in 14-28% lower lifecycle fossil energy use and 8-21% GHG emissions savings compared to the use of standard shrimp feed.

In Chapter 8, I recapitulate the aims, nature and conclusions of this research, map out areas of future research, and draw out implications for emerging energy and environmental policies. I stress that for countries where a decarbonized electricity and heat grid is not available to guarantee low-carbon algae fuel production, and the looming scarcity around marine feed production has become more pressing, the alternative use of algae for feed instead of fuel production has the potential to transform a pressing resource tipping point into a turning point.

1. Introduction

1.1 Background

The world's supplies of food, energy and water are in greater demand than at any other time in human history – yet these vital natural resources are finite. Meeting future demand in an environmentally responsible manner will be an enormous challenge given the rise in anthropogenic greenhouse gases[1].

Food security is nearing the top of the global political agenda, with a projected 2050 population of 9-10 billion (bn) – including many more global middle class consumers seeking a protein-rich diet. Since global middle class consumers are anticipated to rise from 1.8bn today to 4.8bn by 2030, to meet a global food demand production must increase by between 70% and 100 %[2]. However, world supplies of wild pelagic fish are estimated to decline from 20 to 15 million ton (Mt) from 2006 to 2020 which is potentially a serious risk for the future availability of fish meal and fish oil supplies [3]. Nowhere is the supply of pelagic fish, in the form of fish meal and oil, more critical than in Asia which accounts for 90% of global aquaculture. Skyrocketing global fish meal and fish oil prices linked to the depletion of wild fisheries and rising demand

from China have left the aquaculture industry facing a global tipping point of finite fish feed sources. In fact, the rising demand from China alone has the potential to consume 70% of total global fish meal supplies by 2030 and cause the depletion of 40% of global fish oil by 2015. The entire world's supply could be consumed well before 2030 [4].

Similarly in the transport sector, the search for alternative fuels is relentlessly underway with 90% of liquid fuels being hydrocarbon sourced [5] and uncertainty around depletion levels of conventional oil reserves mounting. Global vehicle ownership is forecast to reach two billion [5] in the near future and climate change concerns are expected to rise [1]. The aviation sector is facing particular mounting pressure to reduce its carbon footprint with a predicted rise in the proportion of global GHG emissions from 2.6% in 2006 to 3.2% in 2020. For the road transportation sector several options are available to lower carbon emission, including electric vehicles, hybrids and compressed natural gas technologies. Yet, when mapping out ways to reduce emissions from aviation, the range of renewable alternatives is considerably smaller than for the automotive sector, with 'drop-in' replacement fuels strongly favored by the industry.

Liquid transport fuels derived from unconventional oil resources could initially solve the issue of falling conventional oil resources, but will inevitably exacerbate the problem of increased environmental pollution [6] and increased cost. Biofuels can be a viable substitute for fossil fuels, most notably when produced in a sustainable manner and from feedstock that is not in direct competition with food or animal feed production. The myriad of new green fuel technologies can collectively have a significant impact on replacing a share of the current energy demand of our global transport system. While relatively few technologies can individually make major

contributions, biofuels remain a crucial puzzle piece in the design of a low carbon fuel mix that will drive efforts to decarbonize our global economy.

Such concerns have fuelled the interest in developing advanced biofuels from inedible biomass such as agave or microalgae, as these potentially help overcome problems faced by first generation biofuels such as land use change as well as trade-offs with food security.

Algae biomass production possesses several advantages over terrestrial crop cultivation for biofuel production. Microalgae, rich in lipids and protein, can grow in waste and saltwater and are adapted to survive in naturally resource limited environments when producing superior biomass yields per hectare compared to other feedstock [7,8]. Microalgae have high growth rates which allow for a doubling of biomass productivities in relatively short time periods, and are capable of all year round production, which increases the oil productivity of the feedstock [9] [10]. Relative to the cultivation requirements of other advanced feedstock, the farming of microalgae mainly requires solar radiation, carbon dioxide, water and nutrients in the form of inorganic salts. The cultivation process does not need any form of pesticides or herbicides and can be improved through the sourcing of nutrients from wastewater sources which in turn also reduces freshwater consumption.

Compared to hydrocarbon based fuels the inherent potential advantage of biodiesel production from algae remains its lower lifecycle GHG emissions. Algae biomass converts atmospheric CO_2 through photosynthesis into bio plant material which is eventually released back into the atmosphere when used as a fuel and consequently emitted in the form of engine tail pipe emissions. In comparison, fossil fuel

combustion releases additional carbon which took millions of years to be removed from the atmosphere [11].

Given the nutrient profile of microalgae, promising fuel paths include the conversion of algae biomass to synthetic oil products, jet fuel or biodiesel. However, to be a viable substitute for fossil fuels, an alternative fuel should emit less GHGs than the fossil fuel it displaces, provide a net energy gain above the fossil energy input [12], use all residual co-products within the cycle, be producible at prices competitive with crude oil, and be available in meaningful volumes to impact on energy demand. Algae biomass, rich in protein or highly unsaturated fatty acid lipids, can also be used as feed additive for the aquaculture industry. Yet, for algae feed to be a competitive future alternative to standard fish meal and fish oil ingredients, it will have to be producible in reliable large volumes and well below current market prices.

So far the limitations to the greater use of microalgae for both fuel and feed production focus on the technical and economic problems of large-scale production. The issue remains of how to mass-produce algae cultures with desirable characteristics while avoiding a culture collapse and keeping production costs to a minimum. Similarly, while algae fuel production is more promising than first generation biofuels, it also requires a mass production breakthrough to be economically viable in the long-term.

1.2 Aims and Objectives of the Thesis

As the transport fuel industry is facing a global challenge from both depleting conventional fuel reserves and rising GHG emissions, it is critical for biofuels to contribute as well as complement our current fuel mix as part of a larger mission to diversify our global transport system within the mid-to long-term future.

This thesis examines how microbial biomass feedstock can play an important role as niche renewable fuel product as well as sustainable feed source for the animal feed industry, in particular within aquaculture. The specific first aim of this thesis is an assessment of algae-derived biofuel production for the road transportation and aviation industry. It includes a comparison of algae biodiesel and jet biofuel production with analogue hydrocarbon fuels through an analysis of lifecycle GHG emissions, fossil energy demand and marginal land use savings. This thesis also examines the alternative use of microalgae for fish feed instead of fuel production. It includes a new cost-effective method of algae feed production to replace fish oil and fish feed ingredients at affordable price levels. A lifecycle analysis highlights the improvements in fossil energy demand and GHG emissions for live shrimp production as part of intensive farming systems located in China and cultivated on different algae feeding regimes.

As I am mainly taking a lifecycle approach in this thesis, I have also made an initial analysis of what quantitative impacts advances in catalysis would have on the energy balance and GHG emissions of various fuel pathways. I emphasize the critical importance of catalytic chemistry for the development of a low-carbon fuel mix through the analysis of catalyst-dependent alternative fuel paths. This thesis includes a novel first attempt to define a Catalyst Sensitivity Index (CSI)

which highlights the impact of catalyst efficiency on the fossil energy consumption of a conversion technology and the subsequent final carbon footprint of the fuel product.

1.3 Novel Aspects of the Thesis

The novel aspects of this study in the field of lifecycle analysis, biofuel production from advanced biomass and single-cell oil production for animal feed replacement can be summarized as follows:

- Two complete well-to-wheel lifecycle analysis for the production of biodiesel and jet biofuel from algae biomass. All stages of the algae-to-biofuel production cycle are considered and potential avenues for lowering technical bottlenecks around high fertilizer inputs, fossil-fuel intensity of electricity and heat production, the engineering of superior algae oil yields and alternative optimized uses for co-products, are considered.
- Six nationally explicit life-cycle analyses are conducted which focus on the specific production of algae biodiesel in the UK, France, Brazil, China, Nigeria and Saudi Arabia. GHG emissions and energy balance ratios are compared by simulating the sourcing of primary energy and carbon intensity of the electricity and heat grids in each country.
- This thesis benchmarks the lifecycle fossil energy demand and GHG emissions of algae biodiesel and jet biofuel against the analogue conventional fossil fuel products in the market.
- A novel preliminary definition of a Catalyst Sensitivity Index (CSI) which highlights the impact increased catalyst efficiency can have on the total fossil

energy consumption of selected fuel conversion technologies and their subsequent carbon footprint.

- This thesis provides a novel economic feasibility assessment which outlines how algae feed production, as an alternative to depleting fish meal and fish oil sources, can be price competitive by the year 2030.
- This thesis also presents the first lifecycle analysis of its kind which outlines the improvements in fossil energy demand and GHG emissions for shrimp production in China cultivated on algae feed instead of standard fish feed.

1.4 Structure of the Thesis

A detailed description of the Life Cycle Analysis (LCA) methodology used in this thesis is provided in Chapter 2, along with definitions and assumptions used throughout the dissertation.

In Chapter 3, a critical review is given of the current literature specific to the transport fuel dilemma. This chapter does not contain new results but provides the background content to the main questions of this thesis. This review focuses on dwindling conventional crude oil reserves and the global rise in GHG emissions that have triggered an interest in alternative fuels from unconventional sources and renewables. This chapter suggests that microalgae feedstock can help overcome problems faced by first generation biofuels such as land use change as well as trade-offs with food security.

Chapter 4, investigates through a lifecycle approach whether algae biodiesel production can be a viable fuel source once the energy and carbon intensity of

the process is managed accordingly. Results are also presented for the energy and environmental bottlenecks which to date prohibit algae biodiesel from becoming a low carbon energy source.

In Chapter 5, I assess the environmental and economic feasibility of producing aviation fuels from microalgae in the UK. I also present results on the critical break-even lipid content, at which the life-cycle fossil energy use of kerosene meets the analogue level from crude oil production. In addition, the marginal land requirements and financial expenditures needed for a large-scale production of biodiesel and jet biofuel from algae feedstock are also assessed and compared.

In Chapter 6, I outline the preliminary work on the definition of a Catalyst Sensitivity Index (CSI), which will highlight the impact of catalyst efficiency on the fossil energy consumption of a conversion technology and the subsequent final carbon footprint of a fuel product.

In Chapter 7, I determine an alternative path for the use of algae biomass as fish feed instead of renewable feedstock for fuel production is discussed. This chapter emphasizes through a cost benefit analysis how the production of large-scale microalgae can become a cost-efficient and financially viable replacement option for fish feed production by the year 2030. A lifecycle analysis will highlight the potential improvements in GHG emissions balance and cumulative energy demand for a standard shrimp farming process which operates on algae feed.

In Chapter 8, I recapitulate the aims, nature and conclusions of this research and map out areas of future research.

2. Methodology of Life Cycle Analysis

2.1 Technique of Life Cycle Analysis

The Life Cycle Analysis (LCA) approach used here is based on a methodological framework which estimates and assesses the environmental impacts attributable to the life cycle of a product, process or an activity through identifying, and quantifying energy and materials used and wastes released into the environment [13,14]. The methodology is based on the guidelines of the International Organization for Standardization (ISO) [15] and is undertaken via the following sequential stages, each of which are described in more detail in the subsequent sections of this chapter:

- **Goal and scope definition**: This section of the LCA methodology includes a full description of the product system in terms of system boundaries and functional unit used. The functional unit is defined by providing a clear description of the product or service under assessment, from which results can be interpreted and compared. The product system is determined by defining a set of unit operations which make up the product or service, and identifying the sources and destinations of all the materials and energy inputs used.
- **Lifecycle Inventory (LCI)**: The LCI encapsulates a material and energy balance for estimating the consumption of resources and the quantities of waste flows and emissions caused by or otherwise attributable to a product's life cycle [13,14]. The quantities of different resources required and emissions released are calculated per functional unit. This stage involves substantial data collection and analysis.
- **Life Cycle Impact Assessment (LCIA)**: The result of the LCIA is an evaluation of a product life cycle on a functional basis and in terms of several impact

categories such as climate change, fossil energy use, land use, water use or stratospheric ozone depletion[15].

- **Interpretation and Reporting**: Interpretation is concerned with exploring explicit trade-offs amongst environmental impacts, particularly as a process is altered. The reporting stage is insofar important as it sets out not only the results but also the assumptions used in the analysis.

2.2 Goal and Scope Definition

As the use of algae feedstock for fuel and fish feed production will be investigated as part of this thesis, the functional unit varies with each scenario analyzed and therefore is defined in more detail as part of each chapter. In brief, in chapter 4 and 5 the functional unit is defined as 1 mega joule (MJ) of biofuel (biodiesel in chapter 4 and jet biofuel in chapter 5) produced from algae-oil and delivered to the final users who combust it in driving a typical compact-size, 5-seater car or by flying a standard aircraft machine. In Chapter 7 the functional unit is defined as 1 metric ton of live weight of shrimp produced in a cradle-to–farm-gate scenario.

As an LCA provides a systematic approach to impact analysis of a product, ideally all phases of the product's life cycle, from extraction and processing of raw materials, conversion, transportation to consumption and waste disposal should be included. A complete LCA should also evaluate the use, re-use, maintenance, recycling and final disposal. The definition of system boundaries will largely determine the outcome of an LCA.

In particular, an accurate assessment of future fuel systems requires a complete vehicle fuel-cycle analysis, commonly called a Well-to-Wheel (WTW) chain analysis,

see Figure 1. The analysis is generally broken down to a Well-to-Tank (WTT) and Tank-to-Wheel (TTW) evaluation. The WTT pathway consists of feedstock farming, harvesting, transportation, conversion and fuel distribution while the TTW stage attributes for the fuel combustion step. A full WTW fuel chain analysis has been conducted for the two fuel production pathways discussed in Chapter 4 and 5. More details on the specific assumptions made are given in the respective chapters.

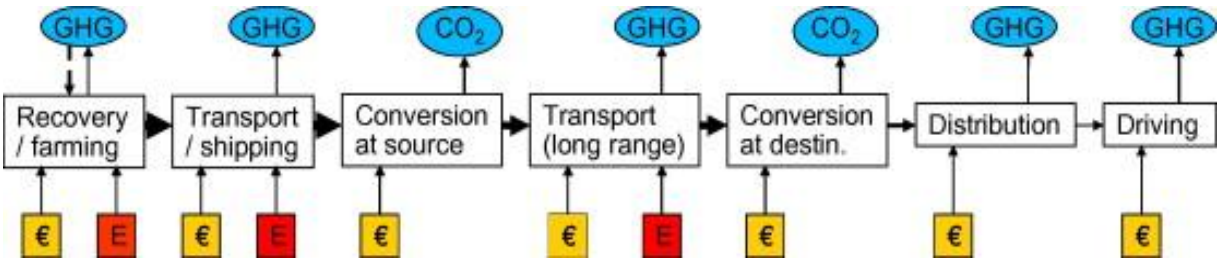

Figure 1: Well-to-Wheel analysis: chain inputs and emissions.
(E= fossil energy, €= Money) [16]

In Chapter 7, a cradle-to-farm-gate system boundary has been chosen to assess the environmental impacts of using algae feed for intensive shrimp farming systems in China, see Figure 2. The cradle-to-farm-gate system boundary accounts for feed production, production of larvae at hatcheries and the production of marketable-size shrimp at the farm level. The processing and transportation of final products to the export markets was deemed irrelevant in this study and not further considered, see methods section of Chapter 7. Process flow diagrams as part of each chapter further illustrate for each LCA the respective system boundaries, assumptions and limitations.

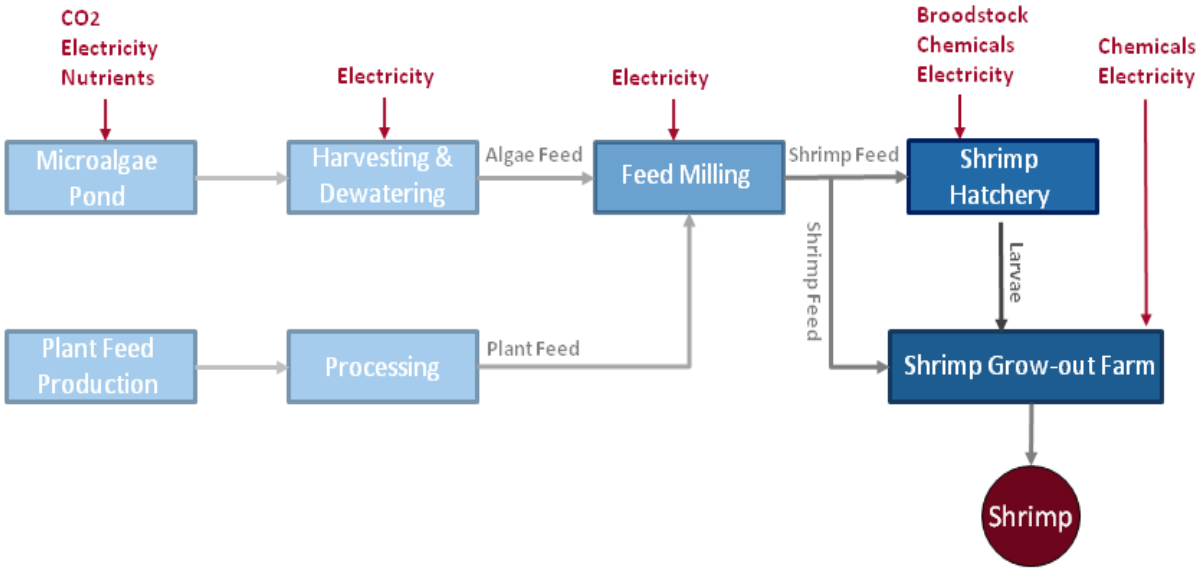

Figure 2: Cradle-to-Farm-gate system boundaries for shrimp production in China

2.3 Lifecycle Inventory Analysis

To perform quantitative mass and energy balances over each system, substantial data collection is required. Given that at present no algal-oil-extraction plant is in large-scale commercial operation, the majority of process information for algae fuel production is based on literature reviews and own analysis. Where applicable, global LCI databases and software, such as GREET, EcoInvent and Gabi 4, were used to provide data detailing the emissions and burdens associated with the production of raw materials and resources required for the respective fuel/feed production pathway. The mass and energy balances and all other environmental exchanges at relevant stages of the product's lifecycle have been compiled and tabulated to reflect the resource usage and associated emissions with the production of one functional unit (e.g. 1 MJ of biodiesel/ jet biofuel or 1 ton of live-weight shrimp). An exact outline of all LCI inventory data used is given in Appendix 10.1-10.3.

2.4 Lifecycle Impact Assessment and Interpretation

The Life Cycle Impact Assessment stage consists of classification, characterization and normalization of steps. Classification assigns the input and output data of the lifecycle inventory to different impact categories. While input and output values can be assigned to several impact categories, a specific characterization factor is assigned in order to calculate the total potential environmental burden of each impact category. The characterization factors are made available in the literature, in the form of LCA databases and support tools. As an example, CO_2 emissions would be assigned to the global warming impact category. The relative contributions of various gases to climate change are then compared in terms of carbon dioxide equivalents using Global Warming Potentials (GWPs) as characterization factor, see Table 1.

Table 1: Global Warming Potentials over lifetime of 100 years [17]

CO_2	1
CH_4	23
N_2O	296

In addition to better understand the relative scale of results from certain impact categories, figures can be further normalized against a reference value such as total resource use or emissions for a given area. As part of the corresponding Life Cycle Impact Assessment (LCIA) section this dissertation reports on the total global warming potential (gCO_2 equivalent) over a time horizon of 100 years and the total energy consumption (also referred to as cumulative energy demand or energy balance ratio) in regards to the primary energy source used.

In the final lifecycle interpretation step the goal, scope, lifecycle inventory and impact assessment stage are reviewed and evaluated in order to draw conclusions and policy recommendations for stakeholders involved.

2.5 Co-Product Allocation Methods

Our LCA methodology is further used to calculate energy credits and the level of GHG emissions avoidance through the utilization of co-products. The purpose of co-product allocation is to determine how a particular environmental burden, e.g. GWP, should be shared amongst the main product and the by-products. In this case the production of biodiesel from microalgae generates co-products such as crop residue (biomass cake) and glycerol. For the production of bio jet fuel not glycerol but propane fuel-mix is considered a by-product.

In this dissertation a so-called displacement method [18] has been employed as the main allocation method. A co-product replaces a pre-existing input product and is utilized with a corresponding co-product credit. The credit is further reflected throughout the complete lifecycle GHG emissions and energy balance, as well as the production of the displaced input factor [17,18]. Co-product credits are further subtracted from the overall LCA energy balance and carbon footprint, in order to complete the analysis. When applicable, simpler allocation methods, by economic value, calorific value or mass, have been considered. Details on all respective co-product utilization methods used in each LCA study are given in Appendix 10.1-10.3.

2.6 Dealing with Uncertainty in Lifecycle Analysis

The reliability of life cycle assessment is affected by the dependence on input parameters from various countries, unit operations and sources as well as datasets which are not always collected for LCA purposes *per se* [19-21]. Thus far, detailed uncertainty analyses is rarely performed as part of LCA studies partly due to the lack of consensus about standardized methodology, varying levels of uncertainty and practical guidance provided by handbooks such as the ISO standards. However, sensitivity and uncertainty analysis are an important part of LCA studies and can provide a better understanding of accounting models, their respective results and margins of error. Their application is highly valuable for increasing the overall credibility, reliability and robustness of LCA studies.

Sensitivity is defined as the influence one independent variable has on the value of another dependent variable, both of which can either be continuous or discrete. Sensitivity analyses are common systematic procedures for estimating the impacts on the results of a study by the chosen methods and datasets [20]. It is most often applied with either arbitrarily selected ranges of variation, or variations that represent known ranges of uncertainty. According to the ISO standards it has been recommended to assess the influence on variations in LCA assumptions, methods and data by conducting sensitivity analysis for the most significant issues [15]. One-way sensitivity analyses are commonly practiced as part of LCA studies with larger datasets to assess the amount an individual input parameter value has to change, all other parameters held constant, in order to vary the output parameter by a certain percentage [20]. Other common variations of standard sensitivity analyses are tornado diagrams, scenario analysis, factorial design and multivariate analysis (MVA), critical

error factor (CEF) and ratio sensitivity analysis [20]. Among the main weaknesses of sensitivity analysis remains the likelihood of overlooking potential synergies, the considerable effort involved in testing the robustness of each individual input parameter and the lack of consideration for relative probability[19-21].

Uncertainty analyses for LCA studies are defined as a systematic procedure to ascertain and quantify the uncertainty introduced into the results of a life cycle inventory analysis due to the cumulative effects of input uncertainty and data variability [20]. Uncertainty in input data is mathematically expressed as distribution over a certain range, which should preferably be derived by statistical analysis of multiple measurements[19-21]. This is in direct contrast to generic LCA studies where single point estimates are used as input parameters. It is widely accepted [15], that the application of uncertainty analysis to LCA studies remains uncommon and a practice still in its infancy. However, wherever possible the use of this type of analysis is highly advisable in order to better explain and support LCA outcomes. Uncertainty analysis is either undertaken by estimating the uncertainty of each parameter as a function of uncertainty distribution or by disseminating the uncertainty through models to the final output[19-21].

In the context of LCA-related uncertainty analyses, probabilistic simulation is often mentioned as a successful tool. It is applicable to any type of uncertainty distribution and operation and can be used in combination with different distributions as part of the same simulation. Among the most common stochastic simulation techniques described are Monte Carlo and Hypercube simulations[19-21]. Monte Carlo simulation determines the probability distribution for independent model inputs by taking random samples from each input probability distribution, computing random samples into the model to obtain outputs and then repeating the previous steps N-times to

generated N-samples of each output [20]. As a result, Monte Carlo simulation produces a frequency distribution of each output factor, which estimates the probability distribution, which then can be analyzed with further standard statistical techniques. The larger the sample input size, the better the accuracy and resemblance to the actual probability distribution [20]. Latin Hypercube analysis is comparable to Monte Carlo simulations but will further divide the uncertainty distribution of an input parameter into non-overlapping intervals of equal probability. As values are chosen from each segment based on the probability within the segment, this uncertainty analysis will provide more accurate random samples[19-21].

Aside from the above mentioned tools, there is a multitude of other software tools available which address, reduce or illustrate different types of uncertainty in LCA studies. While most tools have not been specifically developed for LCA applications, it is clear that given the diverse types of uncertainty, not one method alone can be enough. Additional research will be necessary to define which methods and tools one should use in different scenarios, either on its own or in combination. However, the credibility of LCA studies can easily be questioned without the provision of adequate and necessary uncertainty and sensitivity analyses[19-21]. The illustration of LCA results as mere point estimates without uncertainty distributions can lead to over-estimation of model accuracy and robustness. However, presenting incomplete methods as part of uncertainty analysis can also lead to false credibility and inaccurate decision making. Therefore it is important to find a balanced approach between offering robust and sufficient uncertainty and sensitivity analysis that will increase confidence in LCA results, while not exceeding the complexity of model results and outcomes.

In this thesis I have decided to test the robustness and reliability of my LCA studies through the application of one-way sensitivity analysis. As the main focus of my thesis is not the treatment of uncertainty in LCA studies or the modeling of probabilistic and stochastic risk factors, I have excluded the application of more detailed uncertainty and sensitivity analyses from this thesis. All LCA results presented in this thesis should be considered under the above caveat. Future research in the form of stochastic and probabilistic simulation will complement the results provided in this thesis and strengthen the credibility and robustness of datasets and LCA results.

3. The Potential for Alternative Fuels in an Emission-Constrained World

Based on T. Shirvani, '*Energy Security in an Emission-Constrained World: The Potential for Alternative Fuels',* Chapter 5, 'Energy, Transport & the Environment' Book Series, O.R. Inderwildi, D.A. King, Springer London 2012, VIII.

This chapter is a critical review of the current literature specific to the transport fuel dilemma. It does not contain new results, but provides the background content to the main research questions of this thesis.

3.1 Introduction and Global Context

Since the beginnings of the Industrial Revolution fossil fuels have become the engine of economic growth and industrial development. Once crude oil displaced coal and other early fuels from alcohols as the dominant source of energy, an era of cheap and readily available fuels emerged, that drastically redesigned the transport sector [5,22,23], see Figure 3. As mass-produced transport vehicles became omnipresent in the industrialized world, the export of affordable and reliable automotive vehicles rapidly extended to the developing world. In an economic climate which has benefitted from falling transport costs, technological progress as well as rising global trade and investment flows, the integration of industrialized economies has effectively shrunk the globe [5]. The transport revolution has not only spread to the automobile sector, but also further extended

to the aviation industry where the use of conventional liquid fuels, in the form of crude oil derived kerosene, has become commonplace. This technological proliferation has acted as a catalyst for establishing the foundations of today's globalized society: the quintessence of worldwide accessibility through reduced restrictions on international trade as well as intercontinental travel [24].

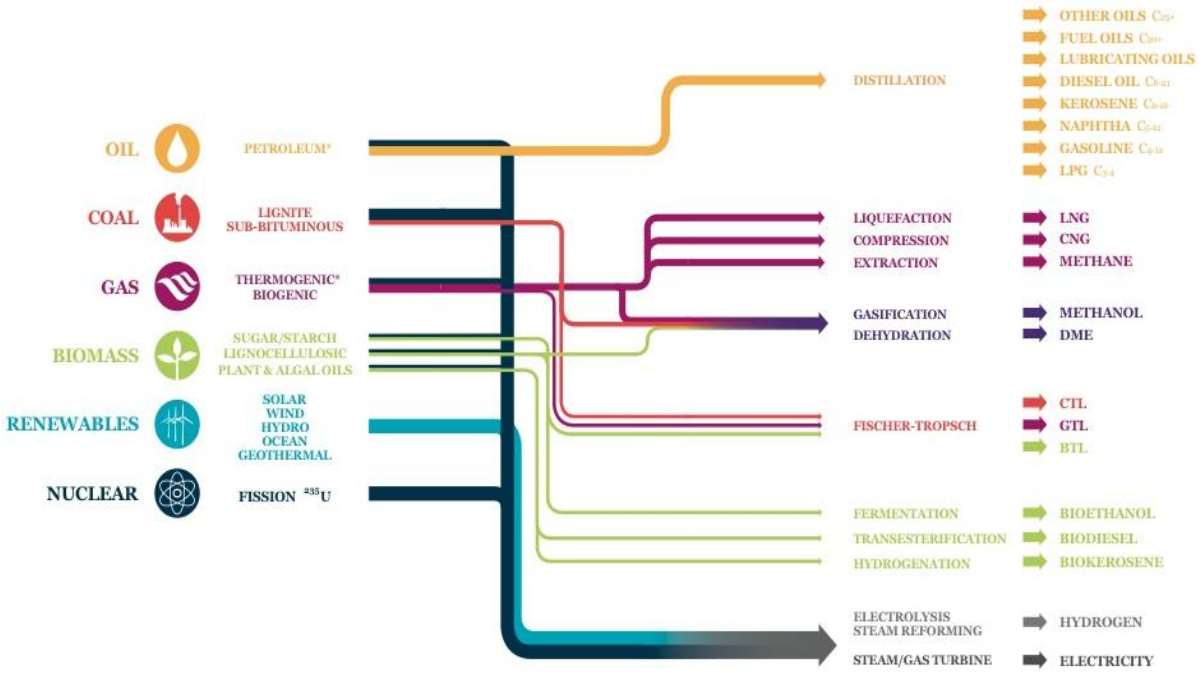

Figure 3: Commercial fuels and primary energy [11]

Whilst the transport boom of the past decades evidently improved our economic conditions and social welfare, it has inevitably left us with a severe addiction for personal vehicles and nearly limitless mobility [5,25]. Global car ownership levels surpassed the one-billion-mark and are expected to rise to two billion in the foreseeable future [5], while the rapidly advancing number of vehicle ownership in the emerging world accelerated our global thirst for crude oil . Coupled with 90% of liquid transport fuels being supplied from crude oil [5], our dependence on a single commodity has become one of our first and foremost economic

chokepoints. With global population figures expected to soar from 6.5 to approximately 9.4 billion by midcentury [26,27] , the limits to our natural resources and their unequal distribution will become more apparent and economically challenging, particularly for the world's poorest and undernourished. Currently, world oil demand is pending around 84 million barrels a day (mb/d) as global consumption volumes are expected to reach 116 b/d by 2030, of which the transport sector will hold a 60% share of rising demand [28]. Although the international economic crisis of the 21st century may have slowed down our industrial race momentarily, until mankind is not willing to transform its concept of mobility and diversify their fuel supply mix successfully, we remain to be relentlessly vulnerable to external shocks. With the transport sector ranked as the second largest emitter of GHG emissions in the developed world, see Figure 4, the question arises of how to accommodate the global desire of human mobility whilst mitigating GHG emissions [5].

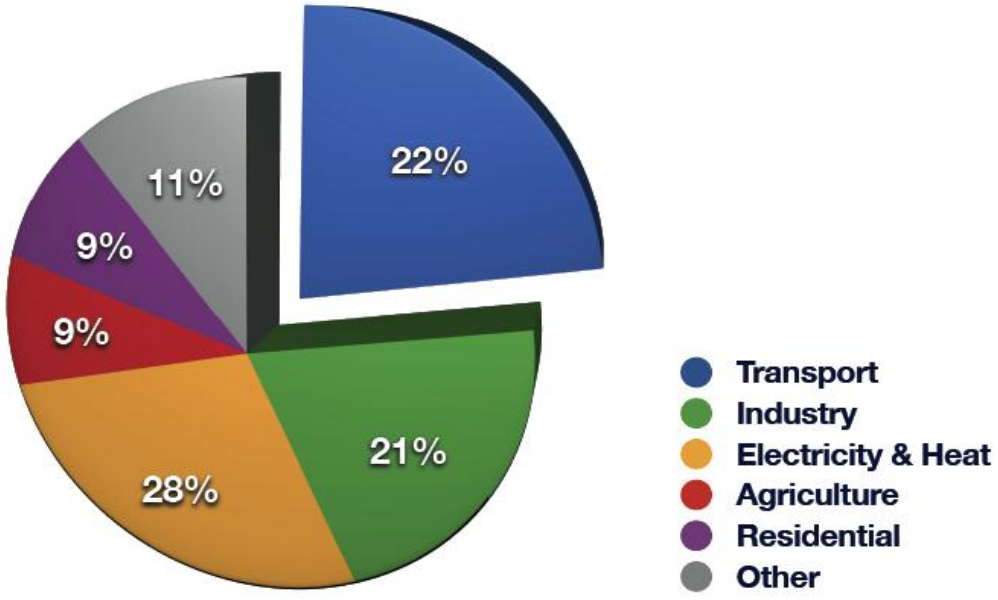

Figure 4: GHG emissions of European Union by industry.

Transport sector ranks as second largest emitter.

The current transport fuel dilemma, which centers around the input problem of dwindling conventional crude oil reserves, described in more detail in chapter 3.1.1, and the so-called output problem of increasing GHG emissions [6], see chapter 3.1.2. This has triggered an increased interest in alternative fuels from other hydrocarbon sources such as natural gas and coal as well as renewables. The increased consumption of unconventional oil resources would initially solve the input problem of falling conventional oil resources, but inevitably exacerbate the output problem of increased environmental pollution [6]. Biofuels can be a viable substitute for fossil fuels, most notably when produced in a sustainable manner and from feedstock which is not in direct competition with food or animal feed, see chapter 3.4. The transition towards advanced biofuels may contribute towards a low carbon, sustainable fuel mix, but is unlikely to become the silver bullet for substituting the current energy demand of our global transport system.

Such concerns have fuelled the interest in developing advanced biofuels from inedible biomass such as agave or microalgae, as these potentially help overcome problems faced by first generation biofuels such as land use change as well as trade-offs with food security.

3.1.1 The Input Problem of Declining Conventional Fuel Reserves

Whilst global oil supply and the health of our global economy are clearly and inextricably interlinked, issues around energy security have widespread effects on our society and economic welfare. The political nature of energy, linked to the uneven distribution of global supplies, comes to public attention at moments of crisis when volatile oil markets shoot prices up to unprecedented levels. The disruption of

oil supplies, whether that is through geopolitical tensions, rising terrorism, natural disasters or war is a critical threat to the prosperity and sustained growth of the world economy. With member countries of the Organization of Petroleum Exporting Countries (OPEC) governing 45% of global oil production [29], the political instability of several states has put major importing countries at severe unease about their increasing dependency. Famously, all 28-member countries of the International Energy Agency (IEA) hold strategic petroleum reserves equivalent to at least 90 days of net oil imports [30,31] as a preventive measure in case of a potential disruption in global oil supply. Also, in recent years it has become undeniable that financial speculators have contributed considerably to the rise in crude oil prices by trading in the commodity derivatives markets [32]. The widespread effects of the 2008 oil price spike not only damaged the global economic recovery, but also impacted other financial markets such as the currency, soft commodities and metals market. Regardless of the considerable debate around the relative balance of influence on oil prices, either from speculators or through demand and supply dynamics, the concerns over the availability of conventional oil reserves necessary to satisfy global transport fuel demand have been rising drastically [33]. To interpret the importance of accurately calculated and clearly defined conventional oil reserves within the context of rising transport fuel demand, the influx of oil entering and exiting the global conventional oil reserve inventory during the past century is illustrated in Figure 5.

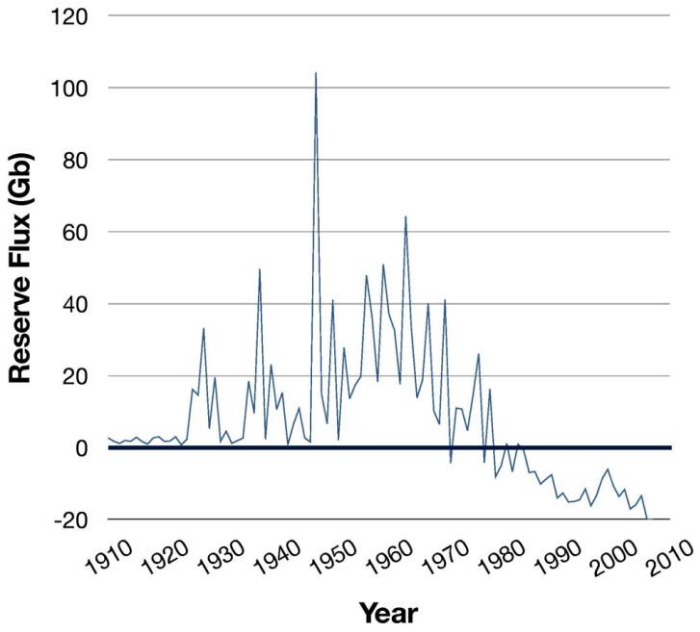

Figure 5: Oil flux entering and exiting the global conventional oil reserve [34]

Data below the zero flux axis indicates periods of net withdrawal from reserves. This first occurred in 1972 and has consistently occurred since 1980, indicating that conventional oil reserves have been in decline since then. This is in sharp contrast to figures published by reporting and information agencies that indicate oil reserves are continuously rising. However, since records show that the peak of conventional oil discovery occurred in the early 1960's [35], it is unlikely that many significant and accessible conventional oil fields remain to be found in easy extractable region. The 2010 World Energy Outlook [36] estimates that the world's producing oil fields are declining at such a rate that by 2020, only 50% of liquid fuel demand will be serviced by reserves that are in production today. Faced with declining output from onshore oilfields, the industry is sharpening its focus on explorations in the Arctic Region and the offshore South China sea basin [37].

3.1.2 The Output Problem of Rising GHG Emissions

According to the Intergovernmental Panel on Climate Change (IPCC), temperature levels on the earth's surface have risen by between 0.18 and 0.74 degree Celsius over the last 100 years [1]. A further increase of 1.1 to 6.4 degree is likely to occur in this century [1] alone, as the rate of warming has doubled over the second half of the last century [38]. Accelerated climate change is largely attributable to anthropogenic GHG emissions comprised of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO_x)[39-41]. Since the beginnings of the Industrial Revolution, CO_2 and CH_4 concentrations have effectively been rising by 36% and 148% [42]. The current level of atmospheric emissions is equivalent to 430 parts per million (ppm) of CO_{2eq}, compared to 280 ppm prior to the Industrial Revolution [41]. As the atmosphere is heated through the absorption and release of infrared radiation of GHG emissions [25,43], current concentrations have already caused the globe to warm by more than half a degree Celsius [41]. A further half degree warming is expected over the next few decades due to the climate system's inertia [41]. If GHG emission levels can be kept at current levels, atmospheric GHG concentrations will still reach 550ppm CO_{2eq} by the year 2050, which translates into double pre-industrial levels. More worryingly, if the global economy maintains their current business as usual practices, we could hit 550ppm of CO_2 by the year 2035 [41].

Given the ecosystem's inertia bound by the vast heat capacity of the oceans and the long atmospheric lifetime of carbon dioxide[44,45] the impact of changes to atmospheric pollution will not be felt immediately but in a delayed manner beyond the year 2100. For example, glacial retreats and the melting of Arctic ice caps will lead to an expected sea level rise of 0.18 to 0.59 meters by the end of the century [46]. This will

put inhabitants of coastal areas at significant risk and raise the wide-ranging and substantial costs of flooding to unprecedented highs [47]. As global temperatures increase, rainfall patterns change, extreme weather events become more common and crop yields will drop significantly in the developing world. Large areas of the Amazon and central African rainforest could be lost, and up to 40% of animal and plant species could face extinction [41]. As droughts are likely to become more frequent, up to three billion people could suffer from increased water shortage alone by the year 2080 [48,49]. In addition, with rising temperatures the volume of mountain snow will decline [38,43], while tropical diseases, like malaria, dengue fever and river blindness may expand and shift to other geographic areas [38]. The Stern Report[41] has warned that the 'cost of extreme weather alone could reach 0.5 - 1% of world Gross Domestic Product (GDP) per annum by 2050, and will keep rising if the world continues to warm'. A temperature rise of 2-3°C could lead to a 3% reduction in global economic output and a 5°C rise in a 10% decline [41].

The Kyoto Protocol was established by the United Nations Framework Convention on Climate Change (UNFCCC) to gather 37 industrialized countries and the European community and develop targets for the reduction of GHG emissions. The aim has been the reduction of GHG emissions by 5% against 1990 levels over the period of 2008 to 2012. Three carbon pricing methods have been developed: 1) carbon taxation, 2) carbon trading and 3) subsidies [50]. Carbon trading works similar to a carbon tax, as it requires polluters to purchase carbon allowances in order to continue emitting carbon into the atmosphere [51]. Since its launch in 2006, the European Emissions Trading System (EU ETS) has been the largest and most established global carbon trading scheme linked to the Kyoto Protocol. It covers

approximately 50% of the EU's carbon emissions and is increasing in scope in its 3rd Phase from 2013 to 2020 [50].

3.2 Unconventional Oil Resources

With the majority of conventional oil reserves located within the developing world and in particular under the management of OPEC, the Western Hemisphere has fortified its search for new energy resources located in regions with less geopolitical tension. Unlike conventional oil, unconventional oil resources are mainly concentrated in developed countries. More than 85% of global natural bitumen reservoirs are located in South and North America, 81% of all explored tar sands are concentrated in Canada [52] and 75% of world oil shale reservoirs are situated in the US [53]. While Saudi Arabia manages 20% of world's total conventional oil reserves, the unconventional oil industry can, based on future on-stream capacity, circumvent geopolitical issues related to oil supply.

According to the IEA's 2012 World Energy Outlook [54], the United States, which currently imports around 20% of its total energy needs, has the potential to become energy-independent by the year 2020. This is mainly due to the on-going unconventional oil and gas developments and new extraction techniques – most notably hydraulic fracturing, or fracking, and horizontal drilling [54], see Figure 6.

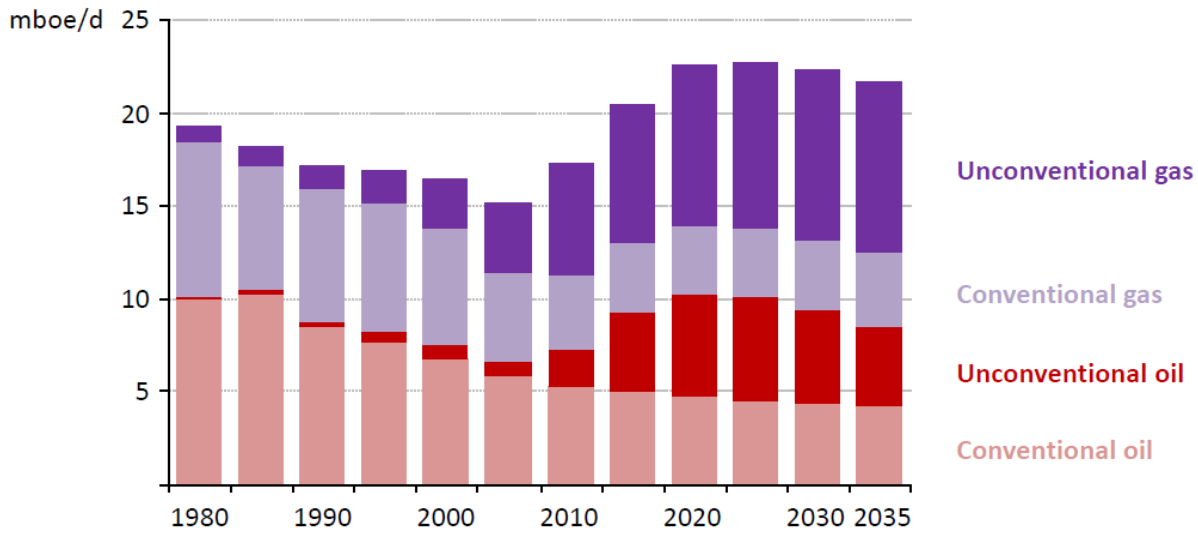

Figure 6: US oil and gas production 1980 to 2035 [43]

The report predicts that the US have the potential to overtake Saudi Arabia and Russia to become the world's largest global oil producer by the second half of this decade [54]. However, no country is an energy "island" and the interactions between different fuels, markets and prices will inevitable intensify [54]. This overall trend would likely lead to a shift in the direction of international oil trading towards Asia and put a focus on the security of strategic routes that bring Middle Eastern oil exports to Asian markets. While the US shale oil boom is still in its infancy and continued growth cannot be guaranteed, environmental concerns around extraction processes are gaining considerable public attention.

Unconventional oil products are commonly separated into natural bitumen and heavy oils which both are a precursor of crude oil. As the feedstock shares the same formation history as conventional oil, it would develop over the turn of million years, into conventional crude as the reservoirs degrade through bacteria attack and erosion under light suspension [53]. Nowadays, to produce liquid fuels from unconventional oil resources, synthetic crude is first extracted from tar sands, extra-heavy oil or oil shale before it is refined into finished products. Bitumen is extracted

from tar sands by open-pit mining or in-situ method and then distillated, catalytically converted and hydrotreated to produce synthetic crude. Oil shale is a calcareous rock containing kerogen, a precursor of crude oil. It is extracted, similarly to bitumen, by underground mining or in situ method and then heated to produce synthetic crude oil products [52,53]. As all unconventional oil resources are solid and have a high carbon-to-hydrogen ratio their conversion to liquid fuels is very energy intensive. For example, bitumen extraction in lower regions requires steam injection, whereas in deeper underground reservoirs process heat must be provided by either i) controlled underground nuclear explosions, ii) in situ combustion or iii) electric heating elements immersed into bore holes [53].

Along with the energy intensity of the extraction process, the separation step for hydrocarbon compounds from associated sands, rocks and clay residues requires a considerable amount of additional feedstock which amounts to roughly 2,000 kilograms of oil sands/oil share processed per barrel of synthetic fuel produced [53]. Also, the high viscosity of unconventional fuel stock requires expensive transport methods, which further aggravate the lifecycle energy demand. In addition to environmental degradation, the drawbacks associated with synfuel production from oil shale are production costs three times higher than conventional oil extraction; and a considerable water usage of roughly 3 barrels of water per barrel of fuel produced [55,56]. As conventional oil resources become depleted, the larger uptake of unconventional resources, here in the form of shale oil, is reflected in a higher fossil energy balance ratio of 1.65MJ/MJ_{fuel} and GHG emissions of around 182gCO_{2eq}/MJ_{fuel} [53]. Unconventional oil resources have higher volumes of nitrogen, oxygen, sulphur and heavy metal particles, which not only require special purification and separation methods, but will add to the fuel's atmospheric pollution level.

Compared to atmospheric emissions from conventional fuels, oil shale processing has 4 to 6 times higher Well-to-Tank (WtT) emissions [53]. Similarly, for liquid fuels produced from tar sands, extra-heavy oil and oil shale, life cycle GHG emissions are 5-40% [53,57,58] and 26-180% [53,58] higher than for those of conventional fuels. However definitive conclusions about GHG emissions for tar sands and oil shale cannot be drawn with existing studies as additional research is needed to better understand these technologies [57].

3.3 Synthetic Fuels - Fischer-Tropsch Synthesis

In addition to the increased interest in unconventional oil reserves, there is renewed interest in producing liquid fuels from coal and natural gas. Production from both unconventional and renewable sources has been increasing rapidly in recent years and is projected in IEA's Reference Scenario to grow to 7.4 million barrels per day by 2030, or ~10% of global conventional oil supply [36]. Geopolitically, synthetic fuel production is an important process, as it allows the conversion of alternative fossil resources such as coal or gas into liquid fuels and has therefore been used to improve energy independence [59]. Nazi Germany and later the Apartheid regime in South Africa, both oil-poor and coal-rich, used the process to circumvent oil embargoes by the production of liquid fuels from coal [60]. These fuels indeed sustained these economies by ensuring transport fuel security. In the case of South Africa, a substantial amount of liquid fuels are still produced using the Sasol Fischer-Tropsch (FT) synthesis, *vide infra* [59].

Synthesis gas is mainly produced from fossil resources such as coal and natural gas, but it can also be produced from renewable biomass. Commonly, fuels made from natural gas are referred to as gas-to-liquid (GTL) fuels and analogously fuels manufactured from biomass or from coal are referred to as biomass-to-liquid (BTL) and coal-to-liquid (CTL), respectively. Hybrid approaches that use a mixture of fossil and renewables feedstock are referred to as XTL fuels. However, at the moment the state of technology for low sulphur FT-fuel from biomass is neither mature nor economically feasible.

One of the biggest advantages of liquid fuels from unconventional fossil sources over other alternative fuels is that they are compatible with existing vehicles and fuel infrastructure [11]. Another advantage for CTL and GTL is that they can achieve higher engine efficiencies and lower regulated air pollutant emissions mainly because of their several chemical and physical characteristics, including reduced density, ultra-low sulphur levels, low aromatic content and a high cetane number [61]. Although liquid fuels from unconventional fossil sources may help to address the energy security concerns and urban air pollution problems, they are likely to result in higher GHG emissions. The life cycle GHG emissions for CTL without CCS are estimated to be more than 100% higher than those of conventional fuels [16,53,62] and even without CCS around 5-29% higher [53] . One promising option to reduce CTL GHG emissions is to combine CTL with BTL as they both produce syngas from solid feedstock through gasification [73].

One possible route to convert alternative feedstock to liquid fuels is via the gasification process: the feedstock reacts with oxygen or steam to produce a gaseous mixture of CO, CO_2, H_2, CH_4 and N_2. When gasifying the feedstock, the carbonaceous components are further broken down into a gaseous mixture of H_2

and CO which is commonly referred to as synthesis gas. The conversion process occurs under limited oxygen availability and as part of a thermal decomposition step. Syngas is currently used to generate transport fuels, by generating hydrogen via a water-gas-shift reaction [63] or hydrocarbons via the Fischer-Tropsch synthesis [64], see Figure 7. The chemists Franz Fischer and Hans Tropsch developed a chemical process that converts synthesis gas into liquid hydrocarbons that can be used as fuels [65,66]. The Fischer-Tropsch process, catalytically converts syngas into liquid hydrocarbons ranging from C1 to C50 long chains [16,64]. By varying the temperature and pressure level as well as the type of catalyst used, a distinct variety of fuel products can be generated, which in the case of biomass are of higher economic value than syngas produced from gasification.

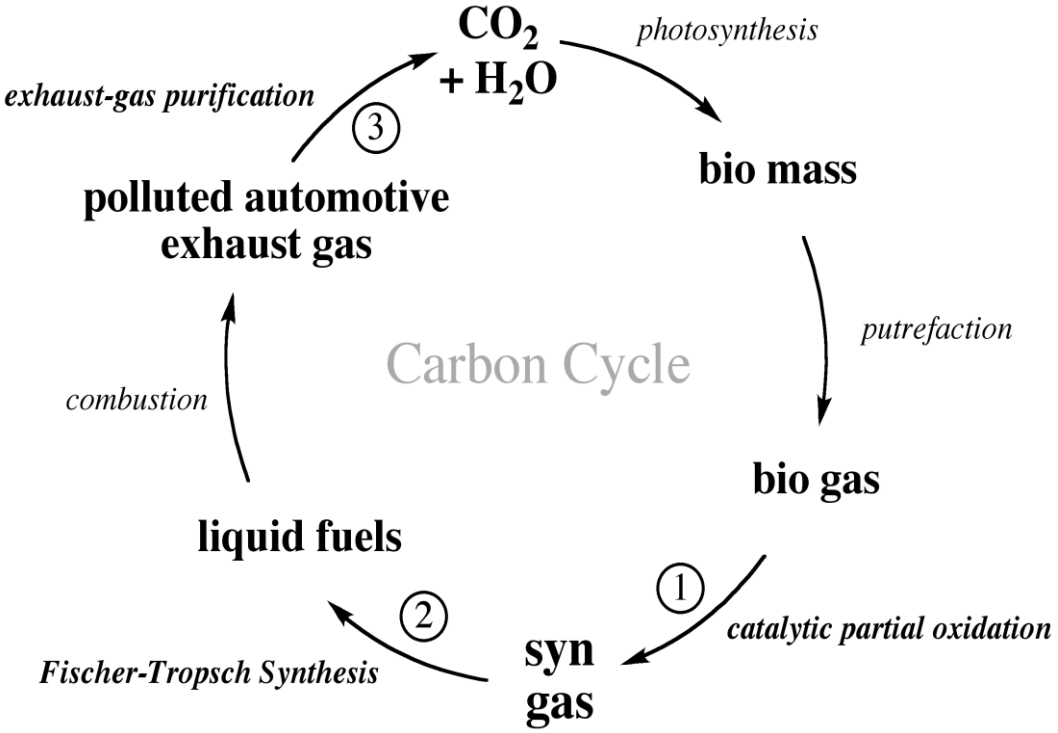

Figure 7: Fischer-Tropsch synthesis of advanced biomass [59]

Coal-to-Liquid (CTL) is a technology that was developed in the early 20th century. CTL products are generated by either: i) pyrolysis, ii) direct coal liquefaction (DCL) or iii) indirect coal liquefaction (ICL) [52,67]. ICL is considered the most promising option out of the three as pyrolysis has low liquid fuel yields; liquids produced via pyrolysis and DCL require further treatment to be used in existing vehicles; ICL allows easier implementation of Carbon Capture and Storage (CCS) technology, and has also been in commercial operation in South Africa for over 50 years [69]. Countries with large oil demands and domestic coal reserves, such as the US and China, are particularly interested in developing CTL technologies [26,68]. China's commercial CTL plants are already in the design and construction phase, with a projected annual production of 70 billion liters by 2030 based on a high oil price scenario [8].

Gas-to-Liquid (GTL) production converts syngas from natural gas into synthetic middle distillates through FT synthesis [61]. In order to convert natural gas into liquid hydrocarbons it first has to be produced, liquefied and upgraded as part of a multistep process, see Figure 8.

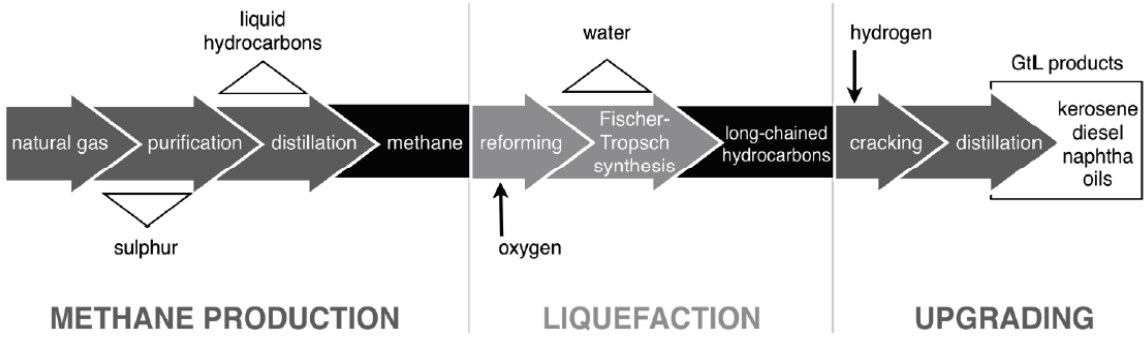

Figure 8: Gas-to-Liquid production process [69]

After producing the natural gas, impurities such as sulphur components have to be removed after which the natural gas feedstock is cooled down to separate higher hydrocarbons from methane – *i.e.* the starting material for catalytic liquefaction. Methane is further combined with oxygen for the production of synthesis gas via either catalytic partial oxidation or steam reforming, which is further used as feedstock for the production of FT-fuels. The synthetic crude is converted to yield diesel, kerosene and naphtha. Fuels manufactured from natural gas using the Fischer-Tropsch process can replace conventional fuels at any ratio (0 to 100%) as they are miscible. The GTL process generates around 75% middle distillates and 25% non-fuel chemical products. In the case of syncrude, it is assumed that a barrel yields 31 gallons of middle distillates plus chemical by-products. Due to the higher energy density of the middle distillates a barrel of syncrude yields approximately 13% more energy in the form of liquid fuels than conventional crude oil [69].

Just as with oil reserves, gas reserves are asymmetrically distributed, with three countries, Russia, Iran and Qatar in control of more than 50% of the conventional reserves [70]. The North Dome–South Pars complex located 3 km below the seabed of the Persian Gulf accounts for 23% of proven conventional gas reserves. This complex is shared by Iran and Qatar and contains more than 50 trillion cubic meters of natural gas plus vast amounts of gas condensates [36]. Currently, there are four commercial GTL plants online: PetroSA's plant in Mossel Bay (SA) which produces 35,000 bbl/d, Shell's Bintulu plant in Malaysia produces 12,500 bbl/d, in Qatar Sasol's Oryx plant produces 34,000 bbl/d and the first phase of Shell's Pearl plant which produces 70,000 bbl/d. The current global GTL capacity is 151,500 bbl/d, which is less than 0.2 % of the global demand for liquid transport fuels [69] [71], see Figure 9.

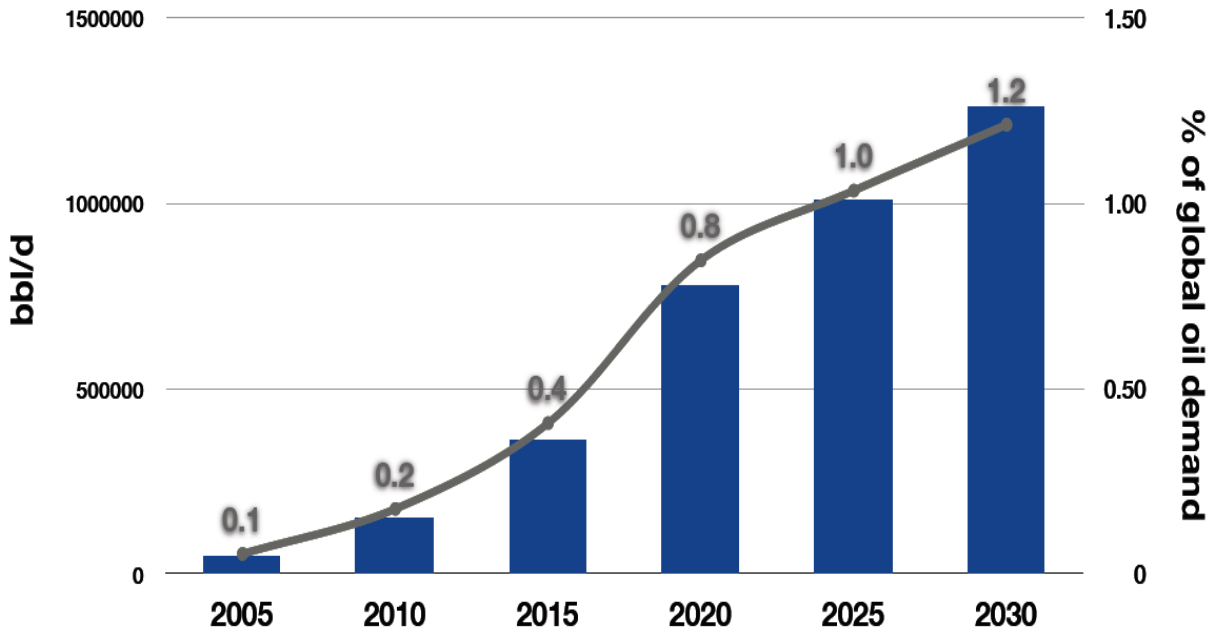

Figure 9: GTL production capacity until 2030 under a high oil price scenario [69]

In the near future, the most modern GTL plant in Qatar, Shell's Pearl will produce 140,000 barrels of GTL syncrude and 120,000 barrels of liquid petroleum gas (LPG), using 1.6 billion cubic feet (45 million m^3) of natural gas. This plant will convert 1.6 trillion British Thermal Units (BTU) of natural gas into approximately 612 billion BTU of GTL middle distillates products and 481 billion BTU LPG products plus chemicals such as naphtha and lubricants.

With current technologies the surplus in conventional gas resources could be used to produce more than one trillion barrels of GTL syncrude, more than the projected demand over next two decades as projected by both IEA and EIA. Consequently, GTL production could theoretically mitigate oil supply shocks as there is no resource constraint. However, currently there is not enough GTL capacity online to absorb oil supply shocks. Due to significant lead times for additional capacity and exorbitant upfront investment, it is unlikely that a substantial percentage of global liquid fuel demand will be available. A capacity constraint prevents GTL fuels from being

produced on a scale sufficiently significant to have a major impact on energy security and global GHG emissions [69].

GTL fuels also contribute to the reduction in local pollutants as FT fuels are of high quality and virtually free of sulphur, metals and aromatics. The high fuel quality is directly reflected in the emissions profile as CO, NO_x, hydrocarbon and particulate matter pollutants are considerably lower than for conventional diesel [72,73]. Experimental studies have furthermore shown that the thermal efficiency of a diesel engine is improved when GTL blends are used[74,75]. Still, synthetic fuels are by no means environmentally friendly as they emit, over their lifecycle, significantly more GHG emissions than fuels derived from conventional crude oil. Mitigation through GTL fuel substitution would come at a significant environmental cost as these fuels have an increased carbon footprint and hence, the growing contribution of the transport sector to GHG emissions would be exacerbated by large-scale deployment of GTL fuels. There is a consensus in the scientific community that the carbon footprint of GTL fuels is approximately 10% higher than that of conventional fuels [16,62]. GTL fuels are only environmentally friendly when their synthesis is combined with CCS technology [62]. However, this in turn might lower the efficiency of the process and reduce energy gains.

Still, in the coming decades more of these environmentally polluting resources will enter the global fuel mix. Table 2 shows the market entrance crude oil price for liquid fuels from different resources (*i.e.*, oil prices that make the corresponding resource profitable). It can be seen that with current oil prices above 100$/barrel, producing liquid fuels from unconventional fossil sources is already economically competitive. This trend has to be mitigated in order to reduce global pollution levels.

Table 2: Market entrance oil prices for liquid fuels from different resources [52]

Resources	Market entrance oil price ($/barrel)
Tar sands	38
Extra-heavy oil	30
Oil shale	70 (short run); 30 (long run)
CTL	86
GTL	70
BTL	205
Corn ethanol	40

3.4 Biofuels

Biofuels, in the form of ethanol or methanol from plants and woody biomass [59], synthetic oil products from agricultural or dedicated crops, and diesel fuel stock from vegetable oils, microalgae or animal fats [53], can act as a viable substitute for fossil fuels. Biofuels and XTL fuel products provide roughly 1% of transport fuels and 0.2%-0.3% of global energy supply, see Figure 10.

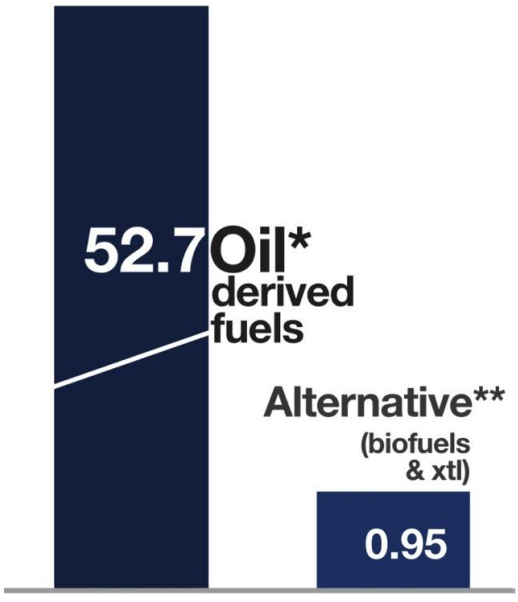

Figure 10: Fuel supply oil derived vs. alternative (million barrels a day) [76]

Currently a total of 1.5 billion hectares of arable land mass (0.55%) is in use with a potential spare capacity of 250 million hectares in South America and 180 million hectares in Africa [77]. The size of occupied cropland is expected to rise between 17 to 44% by 2020 due to growing population figures, increased biofuels demand and changing diets. An important prerequisite for biofuels to realize low lifecycle GHG emissions, is the consideration for careful land management [53].

For biofuels to provide truly sustainable transport solutions, the appropriate selection of cultivation sites and avoidance of land-use change is of paramount importance. When incorporating matters of land-use change, the environmental feasibility of biofuels from agricultural crops is considerably exacerbated and at times worse than that of conventional fossil fuels. By including the CO_2 emissions associated with the clearing of tropical forest areas or conversion of peat lands and savannas to new biomass cultivation sites [53,78], the favorable GHG emissions balance for biofuels is rapidly negated through the increase of the associated biomass and soil carbon release. In Southeast Asia where biomass feedstock is grown on carbon-rich rain forests a substantial biomass and soil carbon, *i.e.* 'carbon debt' [78], is released which would take up a payback period of 423 years [59]. Without the consideration of land-use change, the production of sugarcane-led ethanol in Brazil [77,79], soybean-derived biodiesel in the United States [12,80], rapeseed in Europe [81,82] as well as palm oil in Southeast Asia [83,84] results in considerable GHG emissions savings, see Figure 11.

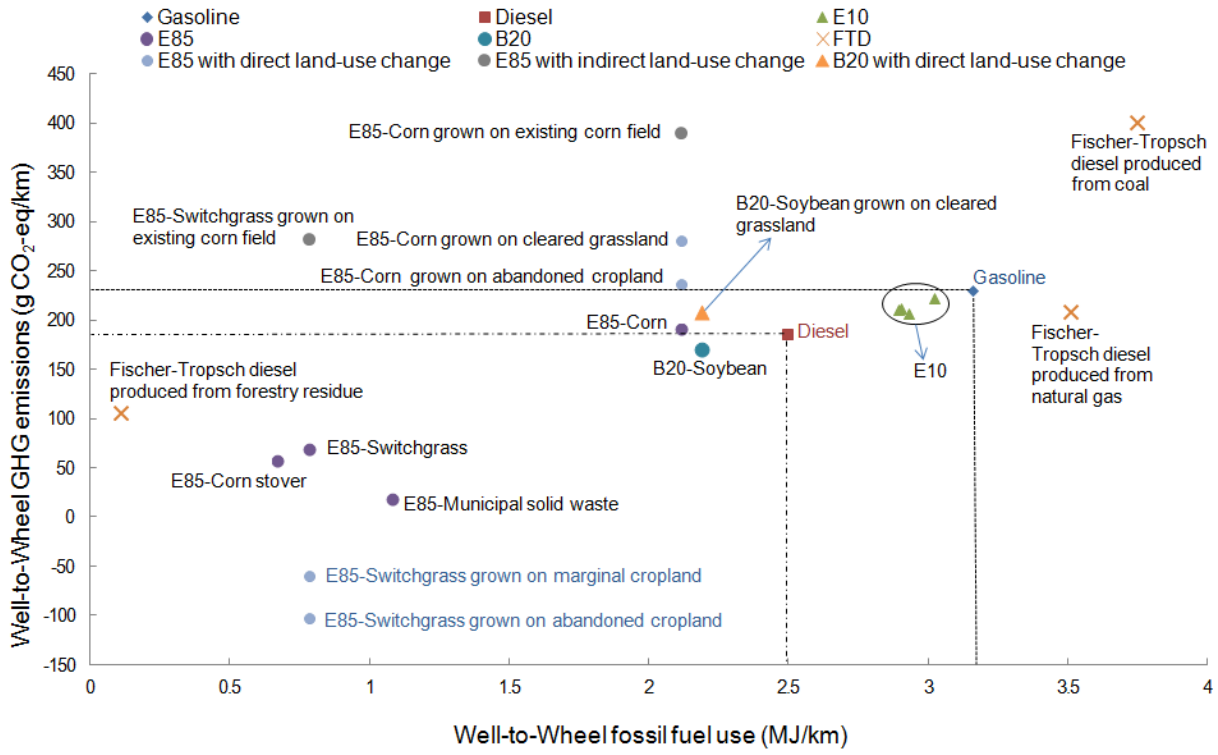

Figure 11: Lifecycle energy use and GHG emissions for biofuels and FT-fuels[6]

Other fuel lifecycles such as corn ethanol production in the United States [12,85] and China [86] yield marginal or no GHG emissions reductions when ignoring land-use change issues. The same effect may well occur indirectly (*i.e.* indirect land-use change), when existing arable land is diverted to biofuels production at the expense of reduced food or feed production [77,87]. For similar reasons, US corn-ethanol production has come under severe criticism by causing considerable soil erosion and requiring more nitrogen fertilizers, insecticides and herbicides than many other biofuel sources [88]. The high emission rates of nitrogen and phosphorus released from crop cultivation areas and drainage water systems, strongly impact nearby freshwater and marine ecosystems [89]. The application rate of artificial fertilizers must be carefully monitored and kept to a minimum to prevent emissions from nitrous oxide, a potent greenhouse gas [89] . For example, in the Gulf of Mexico US remnants

of fertilizers are swept into the ocean and have created dead zones so devoid of oxygen that most sea life cannot exist [59,90].

With first generation biofuels mainly derived from agricultural crops such as sugar, starch, vegetable oils or animal fats and grain crops [59] most major production shifts have proven to trigger a direct competition with their use for food or animal feed [59]. Parts of the developing world have already experienced the economic consequences of the 'food vs. fuel' dilemma. Particularly during the 2008 food price spike when rising energy prices and the weakening US dollar have been responsible for a 25%-30% increase in soft commodity prices, see Figure 12.

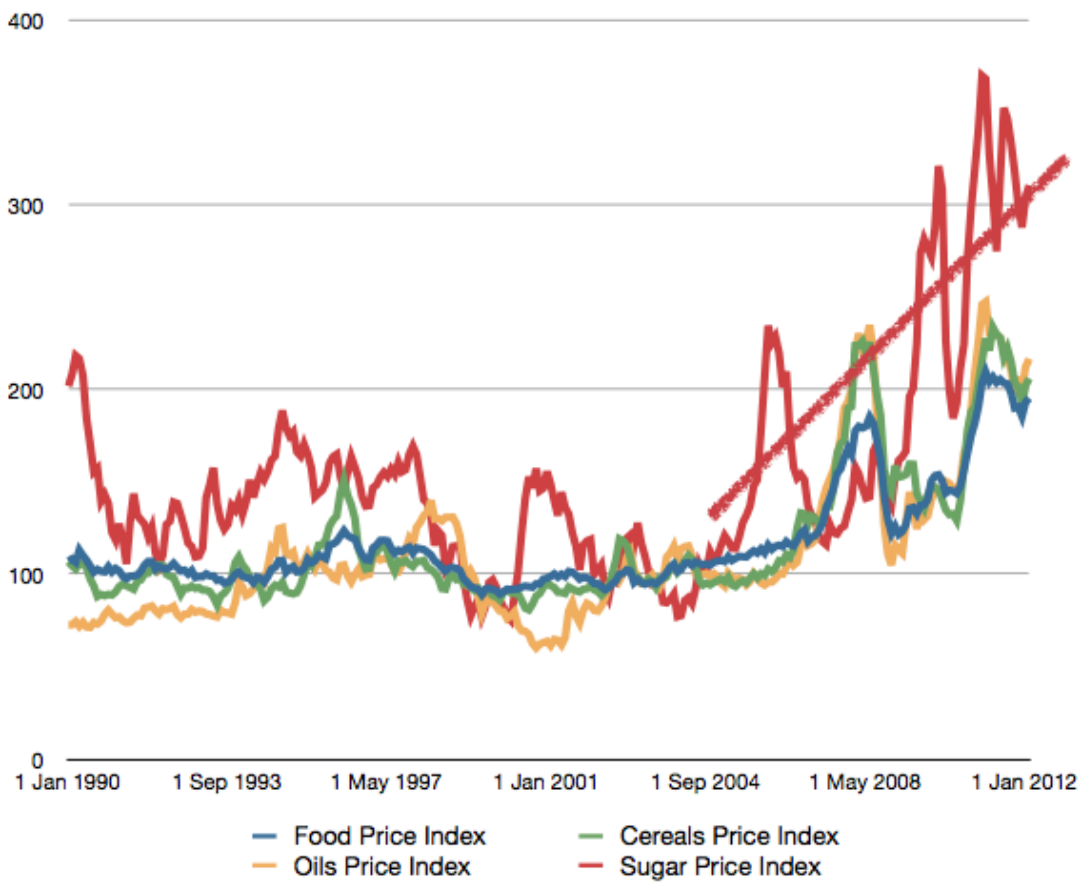

Figure 12: Food Price Index 1996-2009 [91]

The remaining 70-75% was due to the expansion of biofuel production, low grain stocks, vast land-use shift, export bans and speculative trading [91]. Triggered by the rising demand for grain, further price spikes in correlated soft commodity markets were recorded: with maize prices tripling, wheat prices rise by 127% and the price of rice increase by 170% [91]. The rapid expansion of global ethanol production from Brazilian sugarcane did not contribute to the past food price surge. The continued diversion of grain away from food to fuel production, and the incentive to set aside agricultural land for biofuel production [92] continues to put pressure on the global food market as well as global land use. With food price spikes similar to the one in 2008 likely to become more frequent, a continuation of aggravated food security problems in the developing world is inevitable.

3.4.1 Carbohydrate derived fuels: Ethanol

Currently the alternative biofuels market is dominated by ethanol and biodiesel production, given their closely resembling chemical characteristics with conventional diesel and petrol [53] and 'blending flexibility'. With the exception of synthetic fuel products, high-level blends of biofuels require changes to the vehicle's engine infrastructure as otherwise the fuel's vapor pressure levels, oxygen contents, lower volumetric energy content and hydrophilic nature increase the corrosion of the car engine.

For the case of ethanol the high octane number and oxygen level allows petrol fuel blends to operate on a higher compression ratio and is more thoroughly combusted than conventional gasoline [93,94]. Ethanol is commonly blended in low proportions of

up to 10% of volume (E10) with conventional gasoline-fuelled spark-ignition ICEV's, whereas in the United States flexible fuel vehicles (FFVs) operate on a modified engine/fuel system that is powered by higher blends of up to 85% volume (E85). Ethanol in its pure form (E100) is used in adapted vehicles in Brazil [59]. The production of ethanol through the fermentation of sugars is a mature technological process. The fermentation technology is typically defined as a metabolic process in which an organic substrate undergoes chemical changes via enzyme activity of micro-organisms [63]. As part of the successful fermentation of starch and lignocellulosic crops, the sugar content of the feedstock must be released from the plant material in an initial pre-treatment step [95]. Starch crops are hydrolyzed enzymatically to release the sugar solution after which they undergo the microbial fermentation step to generate bioethanol.

For converting lignocellulosic material into ethanol fuel the cellulosic and hemicellulosic biomass must be separated from the non-fermentable lignin content[96]. The covalent cross-links, which bind the cellulosic material together, are broken up mechanically and further undergo acid, alkali and/or steam treatment. The fermentable cellulosic and hemicellulosic biomass' component is hydrolyzed enzymatically to release the sugar content, which is fermented to generate ethanol fuel. The residual lignin material is combusted on-site to provide additional heat volumes which can be used to offset the production cycle's energy requirements [96]. In comparison to the more straightforward conversion process for pure C6 sugars of starch or saccharose, the fermentation process for broken-down hemicelluloses requires the application of certain organisms capable of converting C5 sugars such as Xylose [64]. Current research efforts focus on the development of more efficient and

robust microorganisms that are more resistant to the high pressure and temperature levels of the fermentation process.

Ethanol is mainly derived from grain and sugar crops grown on dedicated agricultural land mass, with the majority being produced from maize in the United States and sugarcane in Brazil [77]. In the future, more environmentally friendly feedstock will include cassava [97], sweet sorghum [98], cellulosic biomass from crop residues, perennial grasses and municipal solid wastes (MSW) [99]. In 2007, ethanol's global production volume of 46 billion liters replaced 4% of global petrol demand [100]. With present governmental production quotas in the United States, Europe and Asia on the verge of implementation, worldwide ethanol production is expected to reach 125 billion liters by 2020 [100]. The occupied land area used for ethanol production in 2006 stretched from 5.1 million hectares of US corn production to 2.9 million hectares of Brazilian sugarcane production [77].

By combining the synergies between the sugar market, a defossilized national heat and electricity grid and the initial assistance of a governmental subsidy program [27], Brazil has become the world's second largest producer of ethanol fuel and the world's largest exporter [101]. The country benefits from high levels of solar radiation, year-round water supply and large untapped landmass used for ethanol plantations without diverting food and farmland [27]. The land mass occupied by sugarcane production only accounts for 10% of cultivated land and 1% of total arable land mass[27,77] with plantations mainly expanded to degraded grassland situated far from the Amazonian tropical forests. Most importantly, the production of ethanol from sugarcane, which benefits from low nitrogen fertilizer rates and mature sugar fermentation technology, has been strongly promoted due to its positive net energy balance. For every 1 MJ of fossil energy consumed the production process

generates approximately 8 MJ of biofuel [27] [102]. Also, from a financial perspective, the Brazilian sugarcane production outcompetes all industry rivals by producing ethanol at US$ 30 to US$ 35 per barrel of oil equivalent (boe), mostly without the assistance of government subsidies [27,103]. In comparison, the high costs of ethanol production in Europe of around US$ 80/boe and the United States of US$ 55/boe, supports the investment case for Brazilian ethanol production. Coupled with the European Union running out of time to fulfill their target of supplying 10% of total transport fuel with biofuels by the 2020 [77] , the necessity for imports of crops and residues cultivated abroad has become inevitable. For the EU to meet its 10% biofuels directive domestically an area of between 20-30 million hectares of arable land will be required [104]. Reports by the European Commission [105] have estimated that the biofuels directive will trigger 12% of total rapeseed biodiesel production to be provided by outsourced palm oil plantation on peat lands with particularly high emission levels. However, for every liter of European rapeseed oil diverted to biodiesel, if only 2.4% of that rapeseed oil is replaced by palm oil grown on peat lands, the emissions from the oxidizing peat cancel out the benefits from biodiesel indefinitely [87]. In this case, the European Union may well increase import levels of Brazilian ethanol up to a total of 3.9 billion gallons [77] to meet the production target.

3.4.2 Lipid derived fuels: Biodiesel

Biodiesel is predominantly produced from edible oil crops such as rapeseed in Europe, palm oil in Asia and soybeans in Brazil [77,106]. The production has expanded to process future feedstock such as microalgae [7,8,18,107-112] and jatropha [113]. Globally, with a production volume of 10 billion liters in 2007 [106], the biodiesel industry is a

growing market expected to take up a larger share of the fuel matrix in the future. In comparison to ethanol fuelled vehicles, biodiesel blends can be used with compression-ignition ICEVs running on conventional diesel without altering the existing engine design and infrastructure. Similar to ethanol, biodiesel is able to achieve higher thermal efficiencies due to the combustion-enhancing oxygen level in the fuel, and results in lower criteria pollutant emissions, e.g. no sulphur oxides and particulates [77], without affecting the engine performance [6]. Biodiesel has proven to have a more favorable fuel efficiency profile than conventional diesel, as it achieves a higher thermal efficiency (MJ/km) and considerably lower pollutant emissions (except NO_x) [6,93,114].

Biodiesel is a mixture of fatty acid alkyl esters (FAME) produced by the transesterification (ester exchange reaction) of a triglyceride (vegetable oil or animal fat) with methanol or ethanol in the presence of a base catalyst (usually sodium hydroxide or other advanced catalysts [7]), see Figure 13. Transesterification is generally classified into three groups based on the catalyst used: 1) chemical catalytic transesterification, 2) non-catalytic transesterification and 3) enzymatic transesterification[115].

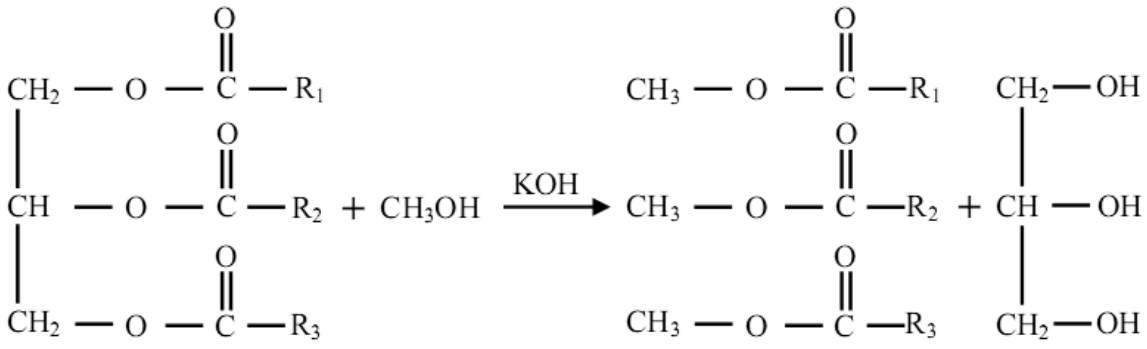

Figure 13: Transesterification of vegetable oils [115]

Lipid feedstock are composed of 90 to 98% w/w of triglycerides, small amounts of mono- and diglycerides, free fatty acids (1 to 5%), residual amounts of phospholipids, phosphatides, carotenes, tocopherols, sulphur compounds, and water traces [7]. The transesterification process is a multiple step reaction involving three reversible reactions, whereby triglyceride molecules are converted into diglycerides which then are converted to monoglycerides and then completely cleaved into esters (biodiesel) and glycerol (co-product). Each step consumes one mole of alcohol and forms one mole of ester [116]. Thus, between 0.2 and 0.25 liters of methanol are required per liter of oil, which equates to 4.8-6 moles of methanol per mole of oil [7,116]. It is considered advisable to use methanol as the alcohol of choice, since the glycerol and ester products are almost immiscible and form two separate layers, thus simplifying the initial separation [116]. A homogenous or heterogeneous acid or basic catalyst is required to ensure a high transesterification reaction rate at moderate conditions of 60°C and atmospheric pressure. Two of the most commonly used catalysts include sodium hydroxide and potassium hydroxide [117].

3.4.3 Advanced Biomass

In order to avoid the characteristic limitations of first generation biofuels, future biofuels must reduce fossil energy input, reduce GHG emissions, and be sourced from inedible biomass to avoid previously encountered environmental drawbacks [59]. Second generation biofuels from the production of synthetic fuel and ethanol from inedible cellulosic materials such as stems, leaves, husks *etc.* and have the potential to overcome the inherent problems of first generation biofuels [59]. Among the fuel products from advanced biomass are: ethanol produced from crop residues [118,119],

perennial grasses [85,119,120], municipal solid waste (MSW) [121,122], biodiesel derived from microalgae [109,110,112], and jatropha [123] as well as Biomass-to-Liquid (BTL) from perennial grasses and wood residues [6,16]. Depending on where the biofuel feedstock is grown and whether it is sourced from dedicated plants, second generation biofuels may have the potential to either induce a carbon release or lead to substantial carbon sequestration [78]. Especially, biofuels derived from unwanted crop residues or MSW, have a more favorable GHG emissions balance than first generation biofuels, as their use has the potential to reduce the pressure on food crops and decrease land use.

The conversion of lignocellulose materials into biofuels holds a promising potential, due to the amount of energy stored in the biomass as well as the volume of unused residues, co-products, and wastes from various sectors at hand [59]. However, on technical grounds, the technology for converting inedible plant residues is currently not as mature as the sugar/starch fermentation processes [59,85]. While the chemical route of hydrolysation is highly expensive due to large heat requirements, the biological 'enzymatic' conversion route merely results in limited yields and is further restrained by the high costs of enzymes used during the process [59]. Innovative new research on the wood-degrading abilities and action of enzymes from termites has proven to be of potential usage to degrade the cellulosic biomass into sugars. However, the next conversion step from cellulose to sugars via cellulases-enzymes from bacteria or fungi, remains a slow process [124].

While the transition towards advanced biofuels synthesized from inedible cellulosic biomass may contribute towards a low carbon, sustainable fuel mix, it is unlikely to become the silver bullet for substituting the current energy demand of our global transport system [6]. Reasons for its marginal future application are driven by the

technological drawbacks, limited availability of suitable land mass [125] as well as the amount of crop residues recoverable without damaging soil quality.

Moreover, in an era of increasing concerns around the global 'water-food-energy nexus' the excessive water consumption of biofuels, both grown domestically or abroad, remains at the heart of the issue [126,127]. Compared to conventional fossil fuels many biofuels have water requirements that are of several magnitudes higher, see Figure 14.

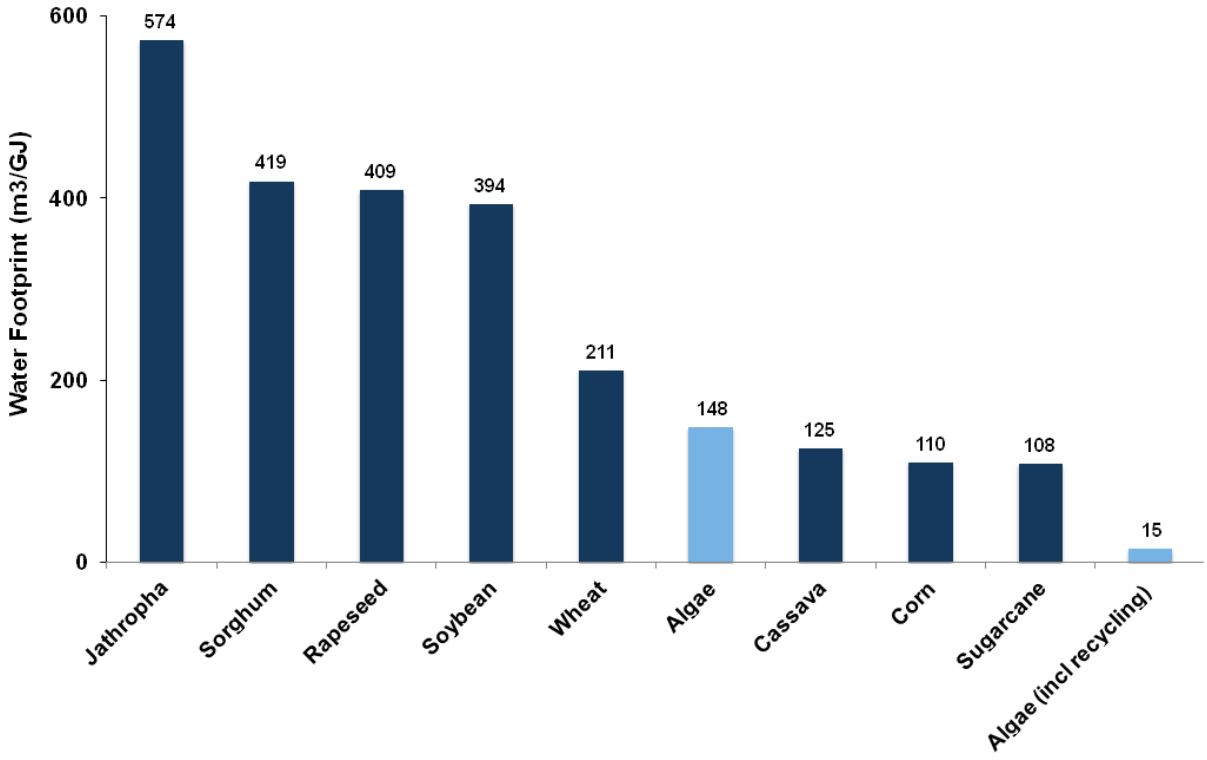

Figure 14: Water consumption volumes of biofuel feedstock [126]

Microalgae consume on average less water than terrestrial crops and therefore have the potential to reduce the pressure on global freshwater availability. Agave plants are also attracting attention as potential ethanol feedstock due to their high productivities, sugar content and ability to grow in naturally water-limited

environments. Ethanol derived from agave is likely to be superior, in terms of energy and GHG balances, to that from corn, switchgrass and sugarcane.

In addition, there are a number of social advantages attributed to the promotion of biofuels. When cultivating dedicated energy crops on marginal land in developing countries, new industries would emerge, that would create additional jobs in farming, transportation as well as fuel synthesis [59]. The concept of farming for both food and fuel [59], through the development of small-scale bio refineries would not only mitigate the urbanization process by job creation in rural areas and simultaneously assist in regional poverty alleviation. By ideally producing transportation fuels on-site, the lifecycle emissions and costs can be kept minimal. Figure 15 highlights an exemplary combined and sustainable carbon cycle for the simultaneous generation of food, fuel and electricity.

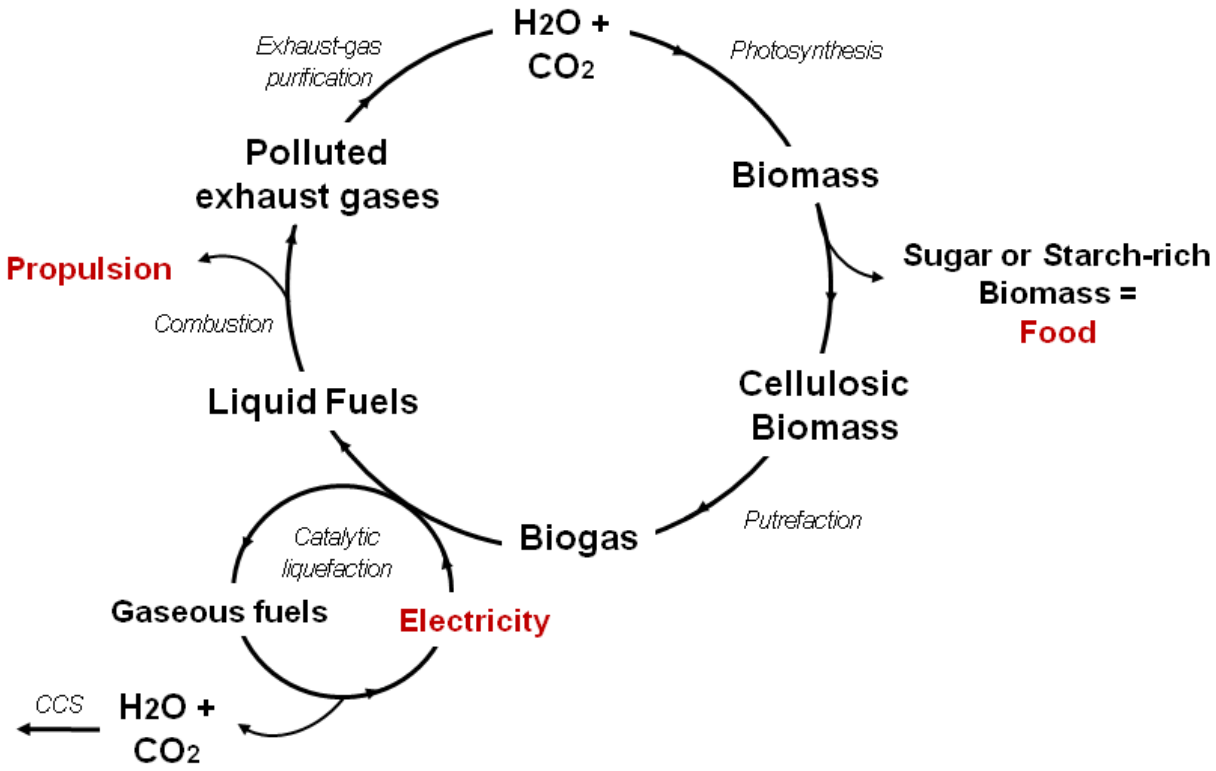

Figure 15: Combined carbon cycle with carbon capture and storage [59]

Parts of the generated biofuel can be blended into left-over gases from the FT synthesis process (i.e. CO, hydrogen and gaseous hydrocarbons) and then further combusted in gas turbines for the generation of electricity. The electricity can then be used to pressurize syngas for the synthesis of fuel and the final export to a local electricity grid. Here, the co-produced CO_2 emissions from electricity generation are further captured through carbon capture and storage which lowers the overall carbon footprint of the synthetic fuel production cycle. Any remaining side-pollutants from the biofuel combustion stage, such as CO, hydrocarbons, nitrous oxides and particulate matter, have to be eventually removed from the exhaust gases in order to close the combined carbon cycle. However, once again for a fuel cycle to be sustainable and environmentally viable, the simultaneous food, fuel and electricity production must be evaluated from a lifecycle perspective which accounts for both the net energy consumed throughout the production process as well as the GHG emissions generated per unit of energy produced [59]. In addition, to guarantee the initial economic feasibility of local biofuel projects, appropriate policy levers such as tariffs and government subsidies must be incorporated.

3.4.4 Microalgae Biomass

While second generation biofuels have the potential to be low carbon fuels, it remains unlikely for them to replace the current demand for fossil-based transport fuels with the limited availability of marginal land. Concerns surrounding the sustainable production of first and second generation biofuels have increased interest in producing renewable fuels from advanced biomass such as microalgae, which potentially help overcome land use and food security issues [7,112].

Algae production outlines several advantages over terrestrial crop cultivation for biofuel production. For example, microalgae can grow in waste, brackish and saltwater and are adapted to survive in naturally resource limited environments when producing superior biomass yields per hectare compared to other biofuel feedstock, see Table 3 [7,8].

Table 3: Comparison of biodiesel feedstock sources[112 7]

Crop	Oil yield (% of wt biomass)	Oil yield (L/ha)	Land area needed (M ha)	US cropping area (%)
Corn	44	172	1540	846
Soybean	18	446	594	326
Canola	41	1190	223	122
Jatropha	28	1892	140	77
Oil palm	36	5950	45	24
Microalgae [b)]	**30**	**58,700**	**4.5**	**2.5**

a) For meeting 50% of all transport fuel needs of the United States.
b) Values refer to the average productivity of *Chlorella Vulgaris* algae.

When comparing various renewable feedstock against algae biomass, the biofuel productivity rates per area unit (GJ/ha) vary considerably and range from high-yield sources such as microalgae, sugarcane, and cassava to low-yield sources such as corn, wheat and soybean, see Figure 16. Microalgae are capable of all year round production which increases the oil productivity of the feedstock and further attributes to exceeding the yields of most agricultural crops [9]. Given the feedstock's high production volumes and superior land-use efficiency, the global land mass necessary to satisfy global fossil fuel consumption could be reduced considerably [9 10].

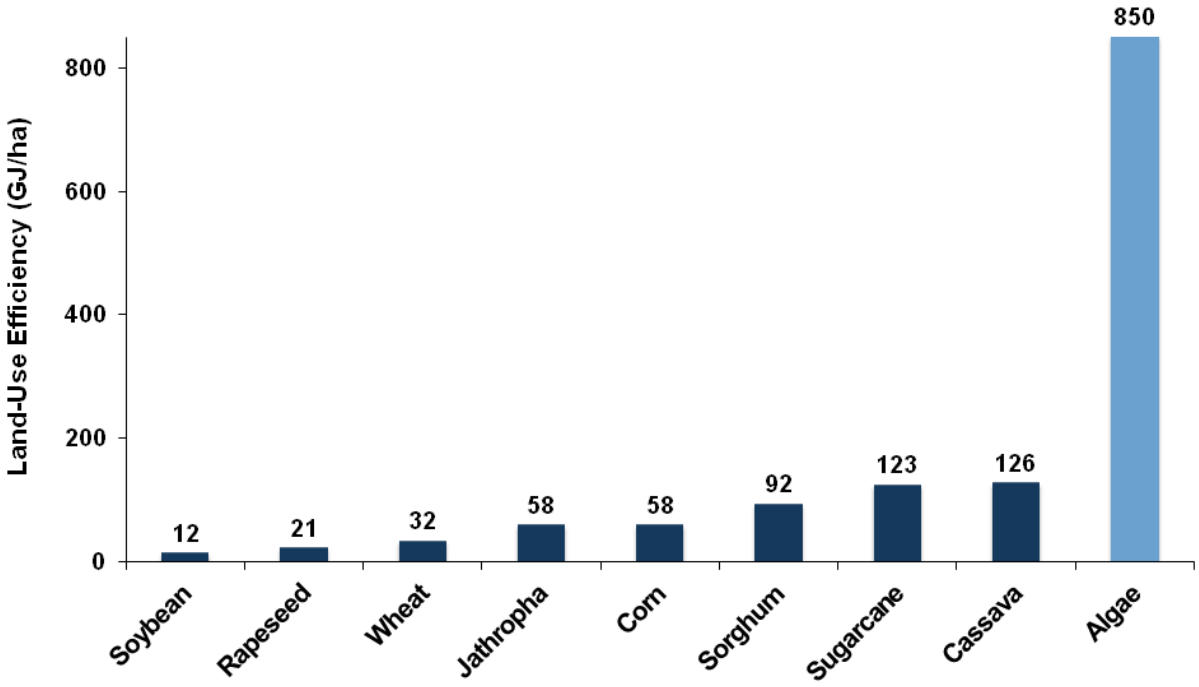

Figure 16: Land-use efficiency of different biomass feedstock [7,8]

In addition, the algae farming process does not require any form of pesticides or herbicides and can be further improved through the sourcing of nutrients (especially nitrogen and phosphorous) from wastewater sources. The production process can also generate valuable co-products such as protein and biomass cake after oil extraction, which can be used as feed or fertilizer source [9].

Compared to hydrocarbon based fuels the inherent potential advantage of biodiesel production from algae remains its lower lifecycle GHG emissions. Algae biomass converts atmospheric CO_2 through photosynthesis into bio plant material. The biomass will partly be converted into biodiesel that will be eventually released back into the atmosphere when used as a fuel, and consequently emitted in the form of engine tail pipe emissions. In comparison, fossil fuel combustion releases additional carbon which took millions of years to be removed from the atmosphere [11]. Some residual biomass leftover may be, in some

instances, converted into other products (e.g. glycerol co-produced during transesterification) and will not be burned. Likewise, it will be inevitable that a fraction of the biomass grown will remain waste, either in the shape of char or through biofouling in a closed reactor system or downstream processes [51]. As the captured carbon will remain in solid form and not converted into fuelstock, the cultivation stage remains carbon-negative even without co-products [51].

Regardless of the considerable potential of algae as biofuel feedstock several technological and economic drawbacks have limited the development of this feedstock to reach a stage of commercial viability. The issues of how to mass produce algae cultures with desirable characteristics while avoiding a culture collapse and keeping production costs to a minimum are at the heart of the debate. Other difficulties such as appropriate species selection, attaining higher photosynthetic efficiencies, CO_2 diffusion losses and potentially negative energy balances continue to hold back the large-scale development of this feedstock [9 10].

Generally, microalgae species are defined as eukaryotic photosynthetic microorganism whose cell walls are composed of saturated and unsaturated fatty acids with chain lengths of 12 to 22 carbon atoms [7]. From the existing 50,000 species of known microalgae, only a fraction are appropriate for biodiesel production, given the algae strains' varying lipid content and productivity levels [7,128]. The most important algae classes are: green algae *(Chlorophyta)*, red algae *(Rhodophyta)* and diatoms *(Bacillariophyta)* [9 10]. Typically, algae biomass can be grown either autotrophic, requiring inorganic compounds such as CO_2, salts and solar radiation, or non-photosynthetic, *i.e.* heterotrophic, involving external

sources of organic compounds (*e.g.* glucose) or nutrients [9]. The selection of appropriate microalgae strains is crucial for the overall success of both biofuel and animal feed production. An ideal algae species would i) have a superior lipid and protein yield, ii) be a stress-resistant strain which can dominate potentially competing algal blooms in open pond installations, iii) have limited fertilizer requirements, iv) be tolerant to changes in outdoor temperatures, v) provide valuable co-products and vi) have a high productivity cycle [9]. The literature outlines an extensive list of estimates for algae productivity yields from lows of 2.5 g/m^2/day to highs of 73 g/m^2/day [9] [10]. Research suggests that practically attainable yields are on average only one third to one tenth of the theoretical ones [10]. A conservative estimate for productivity yields attainable in open raceway ponds is between 20-25 g/m^2/day, which is expected to improve over time and with technological maturity to around 35-40 g/m^2/day [10]. Higher values of around 25-35 g/m^2/day have already been reported for cultivating algae in closed photobioreactors [10]. While there are marked differences in the composition of microalgae strains, protein is always the major organic constituent, usually followed by lipid and then by carbohydrate. Expressed as percentage of dry weight, the range for the level of protein, lipid, and carbohydrate are 12-35%, 7.2-23%, and 4.6-23%, respectively, see Table 4.

Table 4: Chemical composition and productivity of some microalgae [7] [129]

Algae Strain	Protein %	Carbohydrates %	Lipids %	Productivity ($g/m^2/day$)
Scendemus dimorphus	8-18	21-50	15-40	n/a
Chlorella vulgaris	**51-58**	**12-17**	**14-30**	**20.55-24.75**
Chlorella pyrenoidosa	57	26	2	72.5/130
Euglena gracilis	39-61	14-18	14-20	n/a
Prophyridium cruentum	28-39	40-57	9-14	25
Spirulina platensis	**46-63**	**8-14**	**4-17**	**24-51**
Spirulina maxima	60-71	13-16	4-19	25

[a)] Chlorella vulgaris strain is used in LCA on algae biodiesel and jet biofuel production
[b)] Spirulina platensis strain is used in LCA on Fish feed production in China

Some strains can under certain optimally induced conditions, among others the control of nitrogen level, light intensity, temperature, salinity, CO_2 concentration and harvesting procedure, accumulate superior lipid yields [111,112,130]. Most lipid accumulation occurs when nutrients, such as nitrogen or phosphorous, are depleted and growth rates are lowered [131-133]. The broad conclusion is that as nitrogen levels are depleted, the organisms are typically forced to terminate the production of nitrogen containing protein and nucleic acids, but will continue with synthesize lipids and carbohydrates [10]. However, lipid accumulation and biomass productivity are not directly correlated, and one parameter cannot be enhanced without lowering the other [9] [10]. Also, as lipid yields increase the percentage of the sum of other components must decrease, which raises the question of whether to lower the algae share of carbohydrates and keep the protein level constant or *vice versa*. Moreover, lower lipid content strains generally grow faster than high lipid content strains [115,134]. Lipids are mostly located in the interior of the algae

biomass and are surrounded by a cell wall or membrane. The presence of three phases (i.e. lipid, solids, and aqueous media) requires separation of each phase or at least a subset of the phases prior to further downstream processing [133]. Algae lipids are either mechanically or chemically extracted which can to a varying degree be performed in conjunction. Common mechanical extraction methods include: expression or ultrasonic-assisted extraction. Chemical methods include hexane solvent or supercritical fluid extraction [51]. Compared to chemical extraction methods, mechanical extraction ensures a solvent-free product stream that may be used to target niche "chemical-free" markets. It also guarantees the isolation of high-value products from the lipid prior to any optional chemical extraction or fuel conversions of the lower-value lipids. A novel lipid extraction technology involves the application of an electromagnetic field in order to crack the algae membrane wall and release the lipid share from the biomass [51]. Thereby, the lipid, water, and solid biomass are gravity separated .

Given the nutrient profile of microalgae, promising fuel paths include the conversion of algae biomass to synthetic oil products, such as jet fuel, synthetic diesel or gasoline. For the conversion of algae feedstock into biofuels, the availability of unsaturated fatty acids in the extracted lipids will be a key determinant of the fuel quality and cloud point value [10]. For example, the production of biodiesel will be highly dependent on the concentration of shorter chain fatty acids (alkyl chains that are C_{12}-C_{18} long). For the production of aviation fuels, such as kerosene, shorter chains ($<C_{16}$) are amenable while very long fatty acid chains ($>C_{20}$) are required for the lubricant industry [10]. A comparison between the fuel properties of biodiesel from microalgae, plant-based biodiesel

and standard diesel fuel is given in Table 5.

Table 5: Comparison of fuel properties for biodiesel from various feedstock [10]

Properties	Unit	Microalgae	Higher Plant	Diesel fuel	Biodiesel standard
Density	kg dm^{-1}	0.864	0.877-0.887	0.838	0.86-0.90
Viscosity	mm^2 s^{-1}@40^C	5.2	3.3-5.2	1.9-4.1	3.5-5.0
Flash Point	C	115	-	75	>100
Solidifying point	C	-12	-	-50 to -10	-
Acid Value	mg KOH g^{-1}	0.374	0.16-0.43	<0.5	<0.5
Heating Value	kJ g^{-1}	41	39.5-40.3	40-45	-

Recent findings also suggest that algae biomass is nutritionally suitable as resource for aquaculture feed, particularly fish meal and fish oil replacement. Algal protein content and amino acid profile are major factors which determine the nutritional viability of microalgae as animal protein source. Compared to standard high-quality protein sources, the mean amino acid profile of algal protein compares highly favorably with analogue animal and terrestrial sources, as shown in Figure 17.

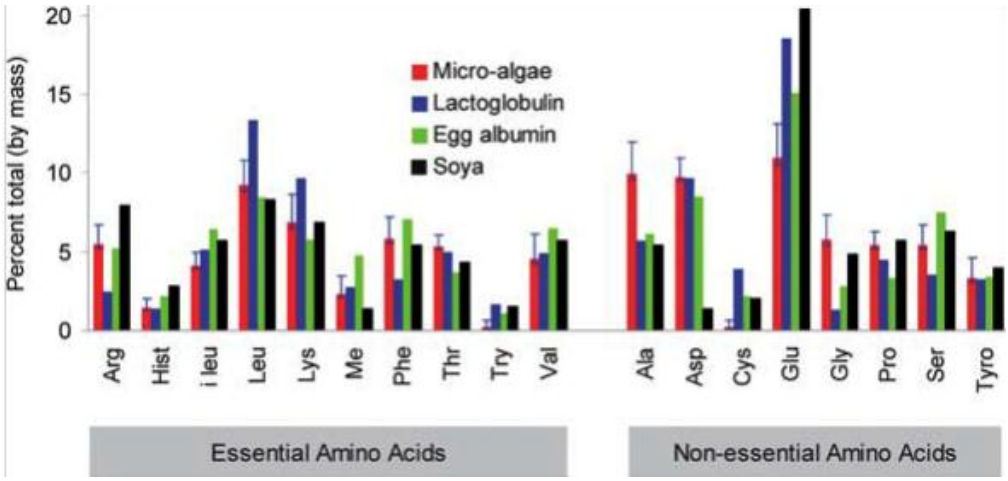

Figure 17: A comparison of the mean amino acid composition of algal protein.

Values are given for 28 species (9 classes) of eukaryotic algae and their characteristic values for standard high quality protein sources[10]

Cultured animals and marine animals also require, as part of their feed, the supply of marine lipids, mostly in the form of fish oil, which are rich in highly unsaturated fatty acids (HUFAs) with >3 double bonds and >20 carbon chain lengths [135]. Generally, HUFA-rich lipids are physiologically needed by all animals as a precursor in the synthesis of functional cell membranes, neural tissue and hormones [135]. Some phototropic and heterotrophic algae strains have a proven nutritional viability as alternative lipid and omega-3-fatty acid sources. Several algae strains are rich in fatty acid content, in particular eicosapentaenoic acid (20:5n-3, EPA), arachidonic acid (20:4n-6, ARA), and docosahexaenoic acid (22:6n-3, DHA) [135] which currently can only be sourced from other marine sources. While it is likely that in the short term the proper refinement and adaptation of vegetable proteins can contribute to the replacement of fish meal, marine lipids which are rich in fatty acid content are more challenging to substitute with plant by-products.

However, not all algae species are equally successful in supporting the growth and survival of a particular filter-feeding animal. Suitable algal species are mostly selected on the basis of mass-culture potential, cell size, digestibility, and overall food value for the feeding animal. For algae biomass to be used as aquaculture feed replacement, a microalgae strain has to meet various criteria regarding the ease of culturing, lack of toxicity, certain cell size, shape and level of digestible cell walls [136]. Currently, more than 40 different species of microalgae are cultured as pure strains in intensive systems and mostly used as algae feed for zooplankton, shrimp larvae and bivalve mollusc larvae [137]. The most frequently used species in commercial mariculture operations are the diatoms *Skeletonema costatum, Thalassiosira pseudonana, Chaetoceros gracilis, C. calcitrans,* the flagellates *Isochrysis galbana, Tetraselmis suecica, Monochrysis lutheri* and the *Chlorococcalean Chlorella spp* [137].Ultimately for algae feed to be a competitive alternative to standard fish meal and fish oil ingredients, it will have to be producible in reliable large volumes and well below current prices.

Relative to the cultivation requirements of other advanced feedstock, microalgae farming mainly requires solar radiation, carbon dioxide, water and nutrients in the form of inorganic salts [112]. A generalized set of conditions for culturing microalgae is given in Table 6.

Table 6: General conditions for farming microalgae [7]

Parameters	Range	Optima
Temperature (°C)	16-27	18-24
Salinity ($g.l^{-1}$)	12-40	20-24
Light intensity (lux)	1,000-10,000[a)]	2,500-5,000
Photoperiod (light: dark, hours)		16:8 (minimum) 24:0 (maximum)
pH	7-9	8.2-8.7

a) (depending on volume and density)

When using natural conditions for outdoor farming of algae biomass and sunlight as a free source of light, the viability of commercial production is likely to be limited to areas with high level of solar radiation. The maximum conversion efficiency of total solar energy into primary photosynthetic organic products remains limited at 10% [10]. Artificial lighting will facilitate the on-going production of microalgae, yet at the expense of higher energy costs [9]. Also, microalgae can fix CO_2 from various sources such as atmospheric CO_2, CO_2 in discharge gases and CO_2 from soluble carbonates (Na_2CO_3 and $NaHCO_3$) [9]. Atmospheric CO_2 is mostly limited by low concentration levels (360ppm), which makes its sourcing economically unfeasible. As most algae strains can tolerate and process high levels of CO_2 of up to 150,000 parts per million by volume (ppmv), flue gases from industrial processes are often fed into the algae pond. However, only selected algae strains are tolerant to high levels of CO_2 in flue gases and therefore need to be chosen carefully [9]. Also, to facilitate the synthesis of algae biomass and their productivity, nutrients such as nitrogen in the form of ammonia (NH_3) and phosphorus in the form of superphosphate (P_2O_5) have to be supplied

according to the algae cultures' stoichiometric requirements of the algae cultures [138]. In this regard, the molecular composition of dry algae is largely consistent with the range of photosynthetic species and can be in this thesis be defined as follows [139]:

$$\text{Algae} = C_{53\%}\ H_{7\%}\ O_{30\%}\ N_{8\%}\ P_{2\%}$$

While many nutrients can be recycled as part of the production process, the algae-to-biofuel water footprint can ultimately be as high as 3726 kg water/ kg biodiesel without the recycling of harvest water [140]. A certain volume of freshwater will have to be processed as part of the algae farming stage to compensate for water evaporation losses and avoid the likelihood of salt build-up [140]. Yet, when recycling wastewater as culture medium the effluent is redirected into the algae pond and the water footprint can be reduced considerably [112] [140]. Figure 18 gives an outline of the relative water footprints of biodiesel production using different microalgae strains. It shall be noted that algae also differ by strain in terms of water salinity requirements [112].

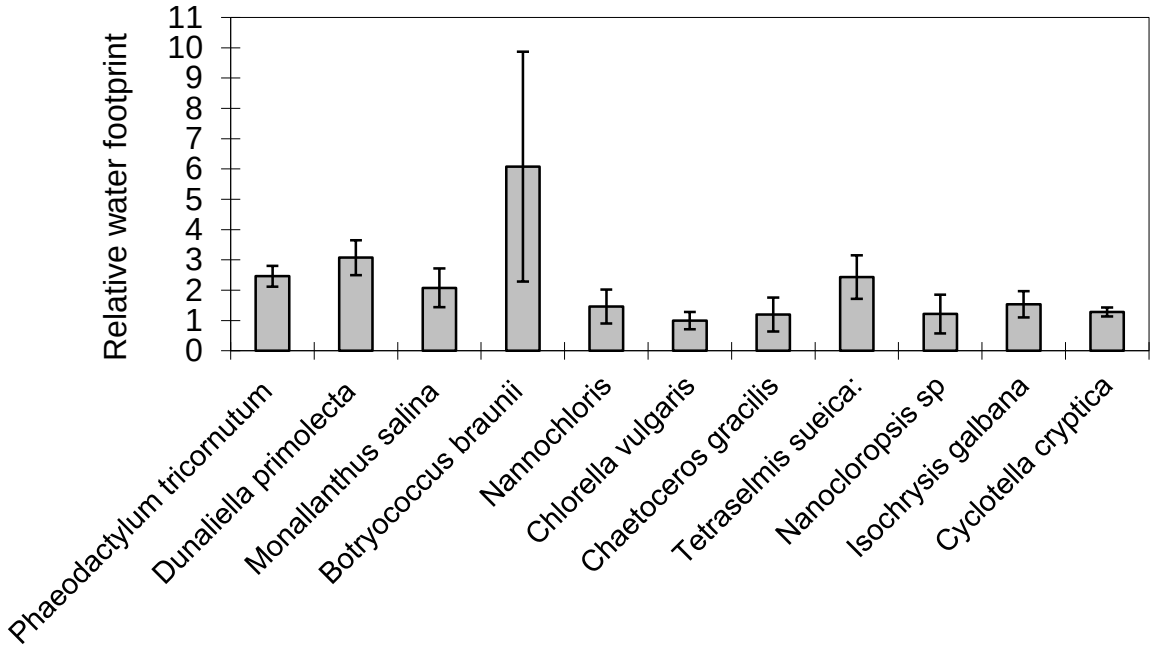

Figure 18: Water footprint of various algae species used for biodiesel production.
Data benchmarked against *Chlorella Vulgaris* strain [139]

The two most common algae cultivation systems are open raceway ponds and closed photobioreactors (PBR), each of which have been designed in a variety of operating configurations, see Figure 19 and 20 [7]. At present, most commercial scale cultivation occurs in raceway ponds of areas from 0.5 to 1 ha and corresponding depths of 0.2 to 0.3 m in which a paddle wheel circulates the algae at a mean velocity of ~0.3 m/s to stabilize algae growth, productivity levels and prevent sedimentation [141] [9]. When produced on a large-scale, the algae are kept at temperatures between 20 and 30C and as one stream of algae is continuously removed from the culture for processing, another supplying the necessary nutrients is continuously added [112]. Large outdoor ponds, with a natural bottom or lined with cement, polyethylene or PVC sheets have been used successfully for algal production.

However the pond cultivation system is limited by the few strains of microalgae that can be used, the lower efficiency of solar radiation utilization, lack of temperature control, poor batch to batch consistency and unpredictable culture crashes and contaminations caused by changes in weather, sunlight or water quality [7,128,142,143].

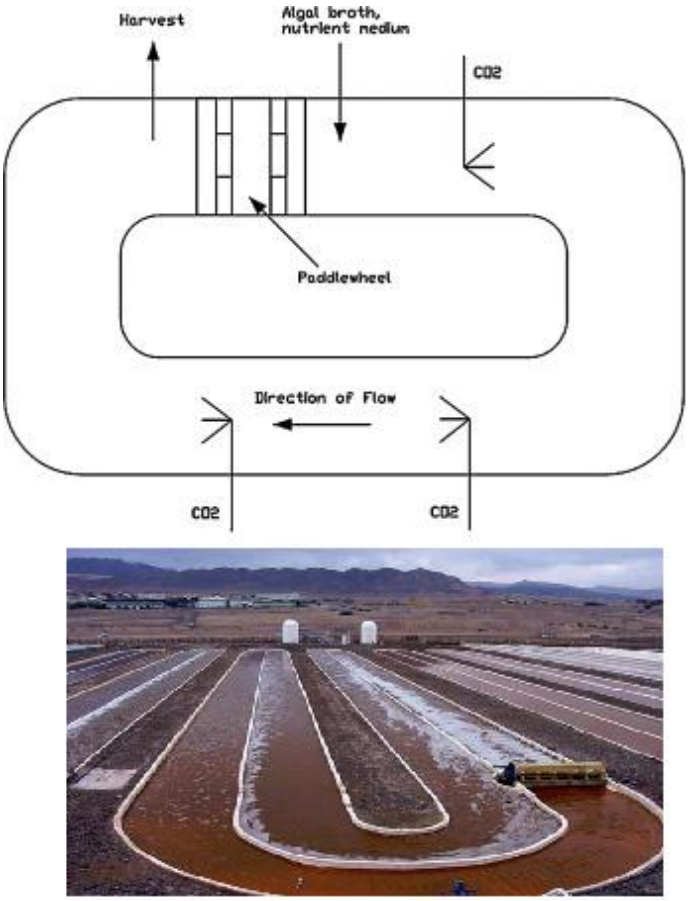

Figure 19: Plat view of algae cultivation in open raceway pond

The alternative is to grow algae in PBRs, which are closed cultivation systems with tubular or flat-plate reactors consisting of an array of plastic or glass tubes through which the culture flows constantly, see Figure 20.

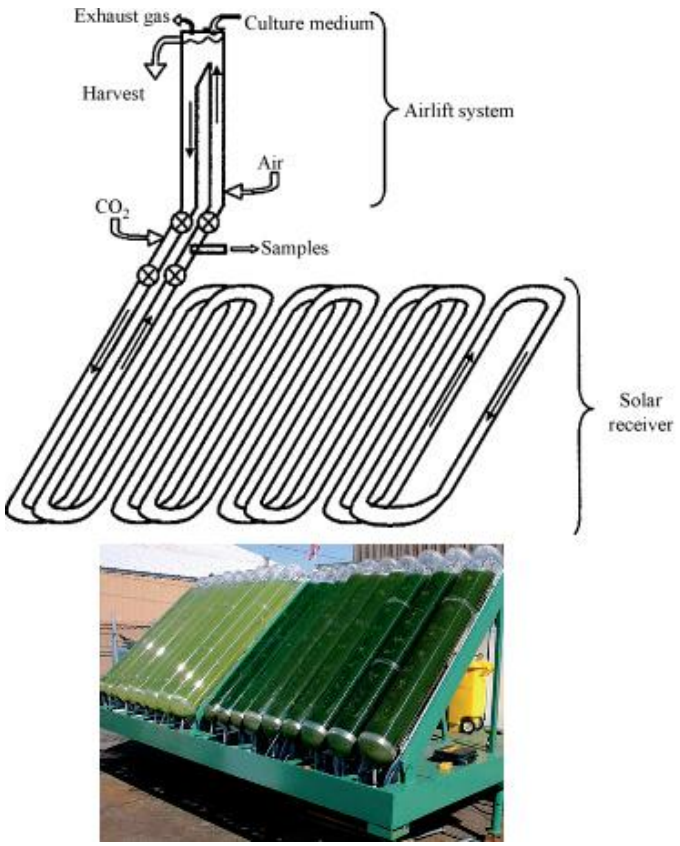

Figure 20: Plant view of algae cultivation in photobioreactors tubes [9] [10]

Agitation and mixing are highly important to guarantee a gas exchange in the tubes. Closed cultivation system offers better control of growth parameters, the prevention of evaporation losses, minimized risk of invasion by competing microorganisms and higher volumetric productivity levels [7]. Closed tubular PBRs can nearly generate 30 times higher biomass concentrations and require on average 30% less land area than open pond systems [112]. Currently PBR technology is mainly used for the cultivation of sensitive strains and the production of high-value algal products used in the pharmaceutical and cosmetics industry. Despite their advantages, the drawbacks of PBRs, such as the likelihood of overheating, scale-up difficulties and vast capital requirements, have overshadowed their large-scale development making their products uncompetitive

with petroleum derived fuels [7,112].

So far the economics of producing biofuels from microalgae at a commercially viable level still depends on government subsidies, tax breaks and the rising future price of crude oil. Both farming approaches are technologically immature and suffer from high costs of biomass harvesting and capital costs around machinery and pond installation. Likewise, the production of algae biomass in photobioreactors is also not cost-competitive with current prices of crude oil and almost 10 times more expensive [112]. Davis et al. [144] calculated the near-term selling price (10% ROI) of biodiesel to be around £1.56/liter when cultivated in open ponds. Algae biodiesel cultivation in closed PBR systems averages around £3.25/liter [144] [51]. Compared with the current retail price for diesel in the EU (weighted average, including taxes) at around £1/liter the further design and optimization of growth technology and production methodologies will remain of high importance.Taylor et al [51] have shown that a combination of algae biomass conversion technologies may offer more economically favorable production of biodiesel. Specifically, a single step extraction (extract wet biomass from water and lipid from biomass simultaneously) followed by transesterification and Fischer-Tropsch synthesis to convert algae to biodiesel was demonstrated to be a more economically favorable method when considering production on a small-scale [51]. However, considerable technological and financial advances have yet to be achieved to promote the large-scale production of cost-competitive algae biodiesel generation[145]. Yet, given the current price volatility around the crude oil market, the future feasibility of large-scale algae fuel production may still have a promising future investment outlook.

4. Life cycle energy and greenhouse gas analysis for algae-derived biodiesel

Based on: T. Shirvani, X. Yan, O. R. Inderwildi, P. P. Edwards and D. A. King, *Life Cycle Energy and Greenhouse Gas Analysis for Algae-Derived Biodiesel*, Energy and Environmental Science, 2011, vol. 4, 3773-3779

4.1 Introduction

In this chapter, I determine the life cycle energy balance and GHG emissions of producing microalgae (*Chlorella Vulgaris*) biodiesel compared to fossil diesel, the fuel displaced in the market [146]. I estimate the fossil energy consumed and GHG emissions released at all stages of the production cycle, including feedstock farming (algae cultivation in open raceway ponds), biomass harvesting and drying, algae oil extraction, feedstock conversion (transesterification of algae oil into biodiesel), fuel distribution, and combustion by the end user, see Figure 21.

Outputs of the production process, which include biodiesel and fuel co-products in the form of oilcake and glycerol respectively, are assigned with an energy content equal to the amount of energy released during combustion. The oilcake is derived from the algae oil extraction stage and glycerol is a co-product from the transesterification reaction. Glycerol, here seen as end product, is refined and sold to the pharmaceutical industry or as livestock feed [147]. For the algal oilcake, which stores 35%-73% of accumulated energy in the carbohydrate and protein content [109], three co-product utilization options are considered: i) an adjacent coal-fired power system that co-fires biomass residues [148,149]; ii) the direct combustion of oilcake in an

integrated biomass-heating system [77]; and iii) a biomass combined heat and power unit [150].

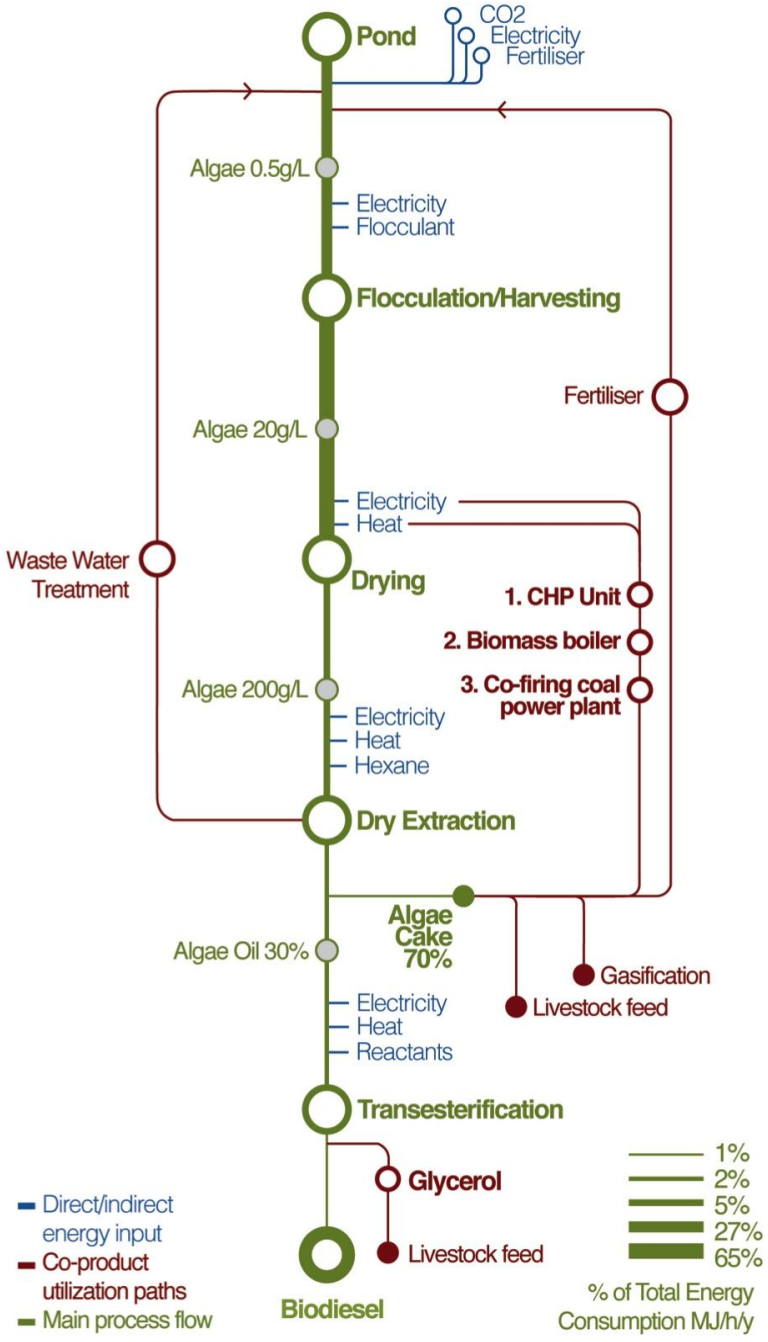

Figure 21: Energy flowchart of an algae-sourced biodiesel plan

In addition six nationally explicit life-cycle analyses for the UK, France, Brazil, China, Nigeria and Saudi Arabia have been conducted. Here GHG emissions and energy balance ratios are compared by simulating the sourcing of primary energy and

carbon intensity of the electricity and heat grids in each country. This quantitative analysis is based on the status quo of different grids and the current feasibility of algae-to-biodiesel plants through a 'smart utilization' approach for the algae oilcake. The overriding intention of this chapter is to analyze whether the algae-to-biodiesel production cycle demonstrates a future potential of becoming a relatively low carbon energy source, i.e. with GHG emissions considerably lower than conventional diesel. I therefore use the results of the base case and country specific life cycle analyses (LCA) to illustrate how changes to key input parameters affect the environmental feasibility of algae-sourced biodiesel production.

4.2 Results and Discussion

I investigate the fossil energy requirements of the algae-to-biodiesel production process to track the renewable nature of biodiesel from advanced biomass sources. The cumulative fossil fuel demand relative to the energy production associated with the algae-to-biodiesel fuel has been analyzed via the fossil Energy Balance Ratio (EBR), here defined as:

$$EBR = \frac{\text{Total fossil energy input (MJ)}}{\text{Total energy output (MJ)}}$$

At a fossil EBR smaller than 1, the fuel product provides more energy than the fossil energy required during the production process. Based on the assumption of an initial 30% oil content (22.5 ton/ha/year), the algae biodiesel production process is estimated to yield 851 GJ/ha/year biodiesel and co-products in the form of oilcake (689 GJ/ha/year) and glycerol (89 GJ/ha/year). These values highlight a

conservative average within a high-low scenario of 60% to 15% oil share [7] [129], which would result in a range of production volumes for biodiesel (1701 to 425 GJ/ha/year), oilcake (394 to 837 GJ/ha/year) and glycerol (179 to 44 GJ/ha/year).

In the first instance, a hypothetical baseline LCA study is conducted, which considers that all energy is produced by fossil fuels and that biodiesel is the sole fuel product, with both glycerol and oilcake as waste materials. This yields an EBR of 3.22, which compares unfavorably with an EBR of 1.2 for conventional diesel from the United States (Figure 22).

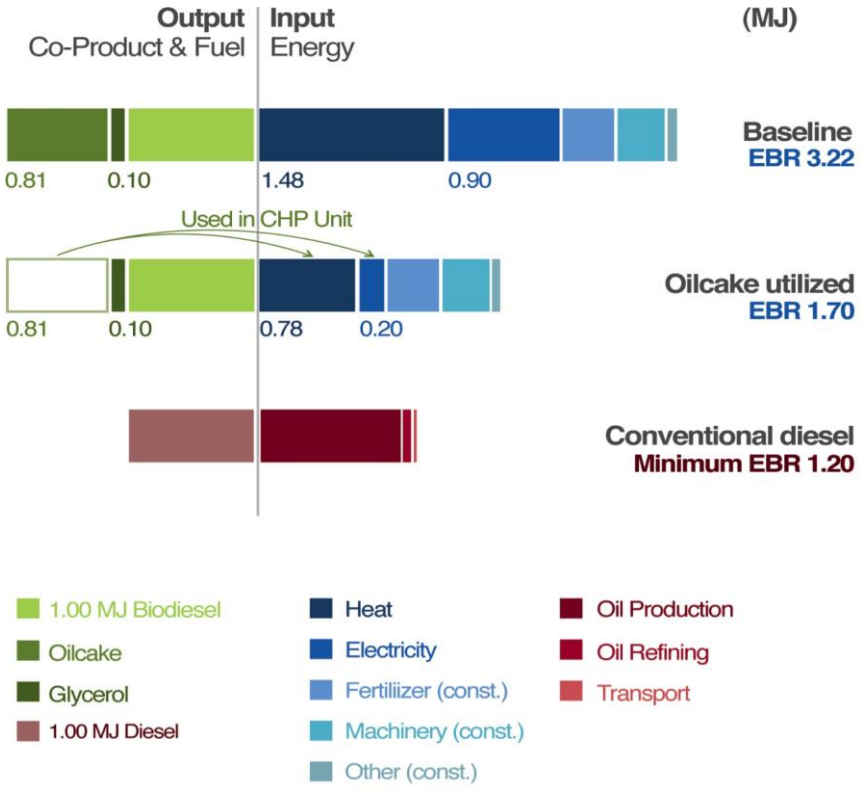

Figure 22: Lifecycle analysis results for algae to biodiesel production.

1) Baseline LCA excludes co-product utilization. Fossil EBR result accounts for biodiesel energy output (MJ) and considers co-products as waste; 2) Baseline LCA incl.co-product utilization via a CHP plant; 3) Fossil diesel shown as benchmark.

This is the major disadvantage inherent in biodiesel production from microalgae, as energy input is both directly and indirectly needed for the production of fertilizers;

pond, harvesting facilities as well as transport (see Appendix 2-7). It is noted that an EBR of 1.2 for conventional diesel reflects the minimum fossil energy requirements for oil-based diesel production. As conventional oil resources become depleted, the larger uptake of unconventional resources, here in the form of shale oil, should rather be reflected in a higher fossil EBR of 1.65 and GHG emissions of around 182 gCO_{2eq}/MJ_{fuel} [53].

In addition to environmental degradation, the drawbacks associated with synfuel production from oil shale, are: the production costs, which are three times higher than conventional oil extraction; and considerable water usage of roughly 3 barrels of water per barrel of fuel produced [53]. Moreover, atmospheric emissions from oil shale processing can reach Well-to-Tank (WtT) emissions around 4 to 6 times the level of conventional fuels [53]. In addition, the expanding large-scale industrial application of advanced oil recovery practices already accounts for 11% of total US crude oil production [11]. The two most common enhanced crude oil extraction methods require the underground injection of natural gas powered steam or CO_2 to raise the pressure level of the oil well and force the crude oil to the surface. With the crude oil extraction stage attributing 93% of primary fossil energy demand, advanced oil recovery consumes 2 times more primary energy and nearly 20 times more process energy than onshore conventional oil extraction. Since the amount of recoverable oil is lower than with conventional practices, more electricity, which is most likely fossil fuel based, is required per barrel of oil extracted [11]. In addition, the dependence on foreign oil production for most countries will result in higher transport costs and lifecycle energy requirements for conventional fuels which will in turn increase the fossil EBR and carbon footprint of hydrocarbon-sourced transport system.

As I compare Tank-to-Wheel (TtW) (i.e. fuel consumption) GHG emissions for conventional diesel and biofuels, the fuel combustion stage accounts for the largest share of pollutants and CO_2 emissions. TtW GHG emissions for conventional diesel are around 73 gCO_{2eq}/MJ_{fuel} [86] assuming that the full carbon content of the fuel becomes CO_2 once combusted. Figure 23 represents the inherent advantage of renewable biomass use and the carbon cycle for algae biofuel production. Overall GHG emissions for Well-to-Wheel (WtW) conventional diesel (i.e. comprised of feedstock cultivation, transport, fuel conversion, transport and fuel consumption), is in a range of 79 to 96 gCO_{2eq}/MJ_{fuel} with variations due to geographic electricity grid composition, transport mode and technology use [86].

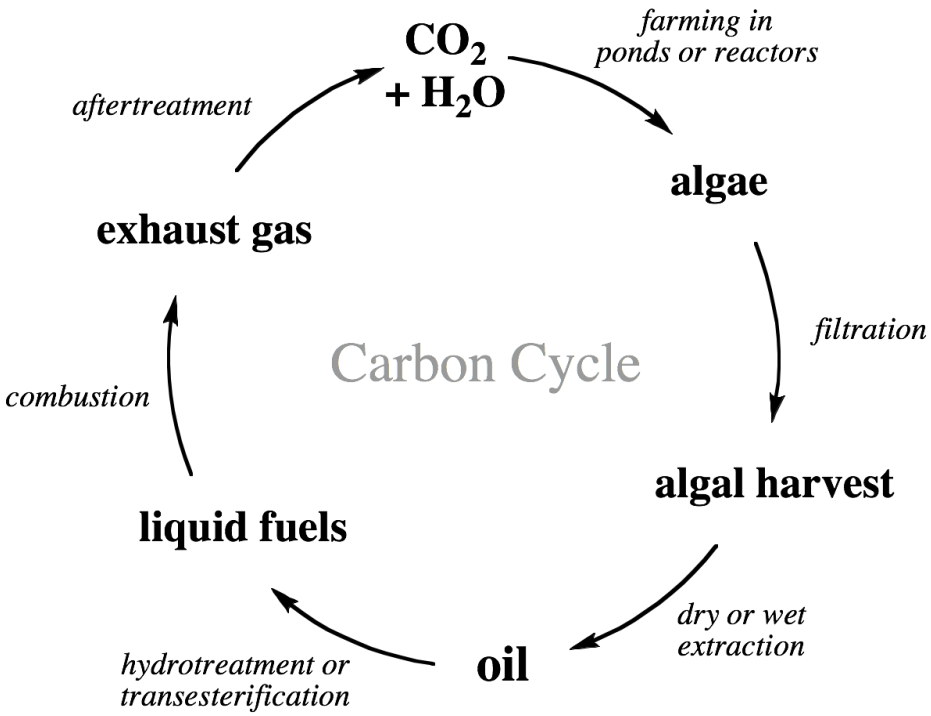

Figure 23: Carbon cycle of biodiesel production from algae biomass

Since the algae-sourced biofuel production is inherently energy intensive efficient energy management is critical. Varying the carbon intensity of the electricity grid

affects the final carbon footprint of the algal fuel cycle. Four hypothetical cases have been created to illustrate the significant improvement in carbon footprint levels that can be achieved through co-product utilization, decarbonisation of the electricity and heat grid as well as all other indirect energy sources in each step of the process. The results are illustrated in Figure 24. The results have been benchmarked against WTW GHG emissions of conventional diesel and shale oil [53,86]. Initially it is assumed that heat demand of the algal fuel cycle is supplied by natural gas. Here only the carbon intensity of the electricity grid is varied to determine the impact on total GHG emissions (gCO_{2eq}/MJ_{fuel}).

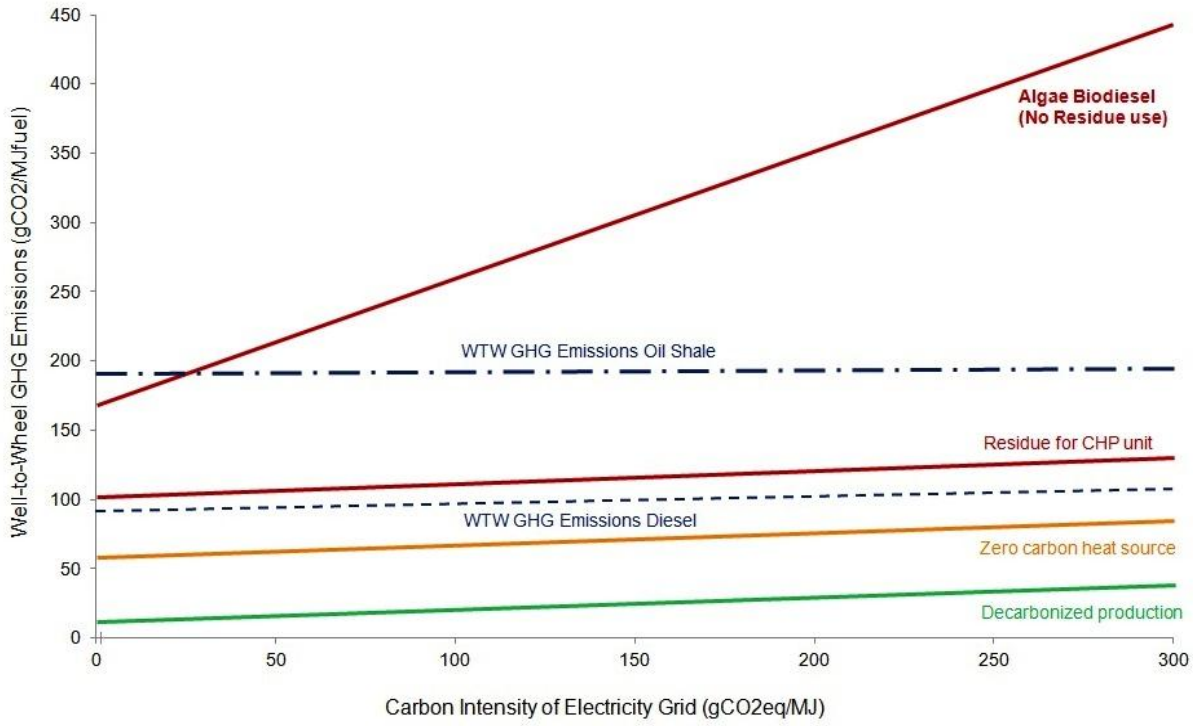

Figure 24: Impact of carbon intensity of electricity grid on final carbon footprint.

Results for sensitivity analysis are for 1) algae fuel production with co-products considered waste; 2) co-product processed via CHP unit; 3) heat grid is carbon neutral and 4) all remaining indirect energy input is low-carbon. Residual amount of energy required for transportation is not taken into account. Data benchmarked against EBR of fossil diesel and oil shale.

Figures for the first case, labeled as (1), and are based on algae fuel production, with oilcake and glycerol considered waste material. Under this assumption, the production of algae-derived biodiesel would be highly unfavorable and increase GHG emissions, with the high carbon intensity of the electricity grid, to around 450 gCO_{2eq}/MJ_{fuel}. This estimate is aligned with results by Williams et al [10].

The second scenario (2) is more closely aligned with current production practices whereby the oilcake product is utilized in a combined heat-and-power unit (CHP). Here co-product utilization results in emission levels competitive with fossil fuels, when operated on a fully decarbonised electricity grid. By reducing the consumption of grid fossil heat and electricity from 1.48 to 0.78 MJ/MJ and 0.9 to 0.2 MJ/MJ, the fossil EBR of 3.22 is lowered down to 1.7. The remaining high energy intensity of the algae biodiesel production cycle is carried by fossil-based heat production, fertilizer production, chemicals, machinery and transport.

In scenario 3, the analysis is taken a step further, by assuming that the production cycle's heat requirements are fully met by a zero-carbon energy source, such as geothermal or solar. Now the algae-to-biodiesel production cycle has the potential to become a relatively low-carbon energy source. Here, GHG emissions are considerably lower than petroleum-derived diesel values.

In scenario 4, (4), the algae-to-biodiesel fuel cycle is operated with fully decarbonised direct and indirect energy inputs in addition to the smart utilization of oilcake residues within the process. The high CO_2 intensity of algae biodiesel is finally overcome. However it shall be noted, that the expense is determined by the inherently high energy intensity (EBR 3.22) of the process.

4.2.1 Country Specific Results

As part of this analysis, I also focus on the current global potential for algae-sourced biodiesel. Six LCA studies for the UK, France, Brazil, China, Nigeria and Saudi Arabia have been conducted to determine a regional production preference, based on heat and electricity grid compositions from different primary energy sources. Figure 25 illustrates the EBR breakdown for the algae biodiesel production with oilcake utilization through a CHP unit and ranks the results according to the country-specific share of fossil fuel based heat and electricity generation.

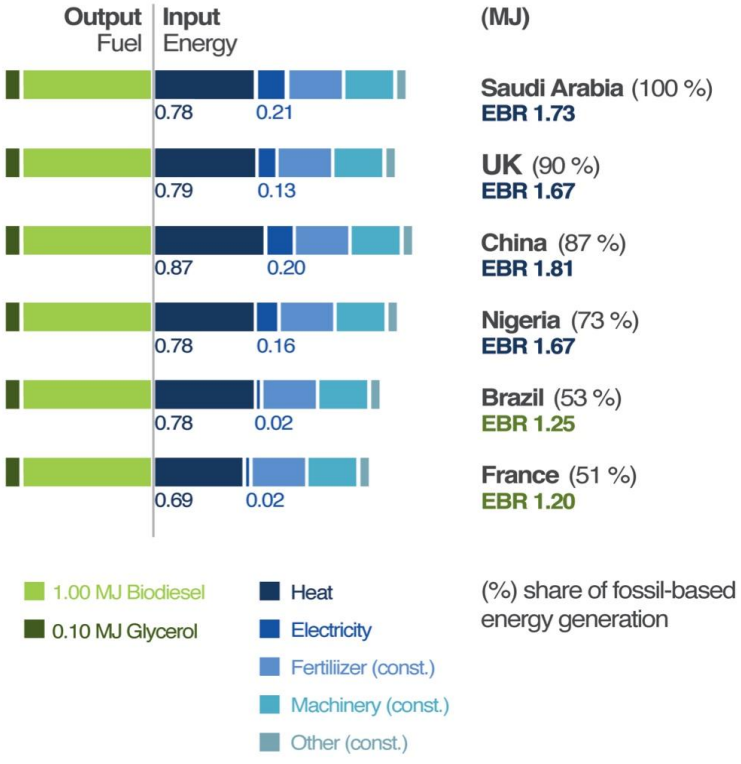

Figure 25: EBR results of six country scenarios.

Countries are ranked by their share of fossil-based energy generation (i.e. heat and electricity).

Given the varying share of fossil-based energy generation in different countries, three types of co-product utilization are again considered to offer a 'smart allocation' approach to avoid the potential displacement of low-carbon primary heat and electricity generation, see Figure 26.

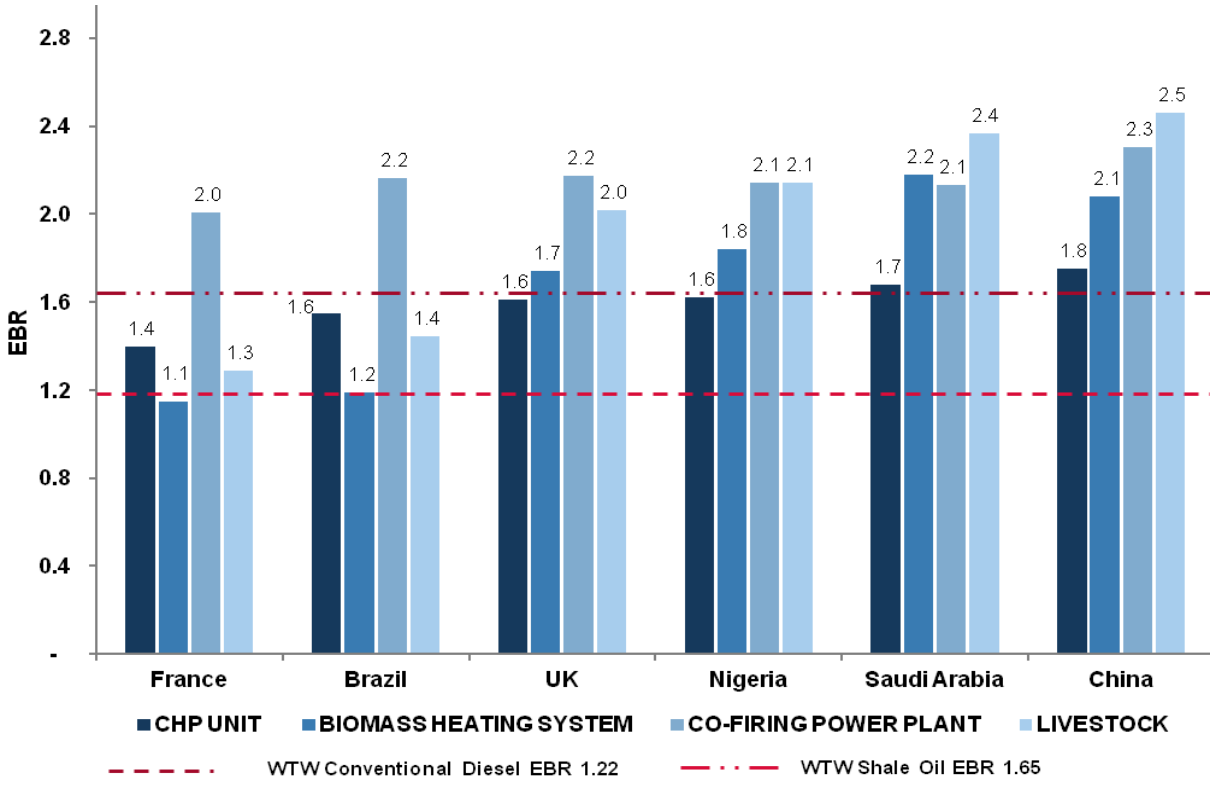

Figure 26: EBR results for algae-to-biodiesel production incl. co-product utilization. Data is benchmarked against the EBR for fossil diesel and shale oil.

The EBR results and further benchmarked against studies by Lardon et al [109], who considers the algae oilcake to be processed outside the algae fuel cycle and exported as livestock feed. For Saudi Arabia, the UK, China and Nigeria oilcake is used in CHP unit. In Brazil and France the oilcake is directly combusted to offset natural gas powered grid heat, as a result EBR values are closest to conventional diesel. Not surprisingly, countries with a high share of hydrocarbon-based primary energy sources onto electricity grids would eliminate the environmental benefits of

alternative fuels production. The objective for such countries remains to mainly improve the energy and environmental results, rather than achieve energy parity with conventional diesel. An outline of WTW GHG emissions for all countries is shown in Table 7. Values are compared with WTW GHG emissions from conventional diesel and unconventional shale oil.

Table 7: GHG emissions for algae biodiesel production with co-product usage

Country	**CHP**	**Direct Combustion**	**Co-firing power plant**
China	160	351	260
UK	118	177	172
France	102	**78**	147
Brazil	109	**82**	160
Nigeria	114	180	152
Saudi Arabia	122	302	154
WTW Diesel	**79- 96 CO_{2eq}/MJ_{fuel}[86]**		
WTW Shale Oil	**182 CO_{2eq}/MJ_{fuel}[53]**		

4.3 Conclusions

This study presents a major step towards a comprehensive understanding of the emissions and energy balance of algae biodiesel production. As part of this LCA study microalgae batches are cultivated in open pond farming installations, harvested and dried in subsequent stages to generate 75 tons/ha/year of dry algae biomass. The extracted 30% share of algae lipids (22.5tons/ha/year) is transester-ified to yield biodiesel (850 GJ/ha/year) and by-products in the form of glycerol (89 GJ/ha/year) exported for the animal feed industry. The remaining 70% residual algae biomass (689 GJ/ha/year) is used in various co-product utilization methods to offset

the substantial energy requirements of the production process. Considering all energy inputs of the biodiesel production cycle as fossil fuel sourced, the algae to biodiesel production cycle is 2.5 times as energy intensive as conventional diesel from the United States and nearly equivalent to the fuel-cycle energy use of oil shale diesel. The carbon footprint of the algae biodiesel production process ranges from 78 to 160 gCO_{2eq}/MJ_{fuel}, depending on the carbon intensity of national heat and electricity grids and the utilization method for algae residues. The large-scale production of algae biodiesel is limited by the high energy input in the form of heat and electricity which puts a large caveat on the financial and environmental feasibility of current algae biodiesel production. Through the smart usage of biomass leftover via a CHP unit and the processing of glycerol as livestock feed, economic running costs can be partially lowered as costly grid heat and electricity is displaced. Additional reductions in GHG emissions will require the sourcing of all direct energy input, in the form of heat and electricity, as well as indirect requirements for transport and building materials, to be from low-carbon energy sources.

By conducting country-specific LCAs for the production of algae biodiesel, I illustrate how nations with a high share of hydrocarbon-based primary energy sources onto electricity and heat grids would eliminate the environmental benefits of algae fuel production. Further improvements in the production cycle's carbon footprint can be achieved through the commercialization of new wet extraction technologies [151]. By eliminating the need to dry algae biomass to a 90% solid content required for the subsequent oil extraction in vegetable oil mills, considerable energy savings could be achieved.

4.4 Methods and Materials

4.4.1 Environmental Effects

In this study the functional unit is defined as 1 mega joule (MJ) of biodiesel produced from algae-oil. The stages of production, principal inputs required, and outputs produced are further described in Appendix 1-10 and illustrated in a detailed energy flow chart in Figure 21. Given that at present no algal-oil-extraction plant is in large-scale commercial operation, the majority of process information is based on literature reviews and our own analysis. As part of the corresponding Life Cycle Impact Assessment (LCIA) section this work focuses on the total global warming potential over a time horizon of 100 years and the total energy consumption in regards to the primary energy source used. All figures are analyzed in both a baseline and country-specific context. An LCA methodology is further used to calculate energy credits and the level of GHG emissions avoidance through the utilization of process' co-products, in our case algae residues.

4.4.2 Algae strain selection and large-scale cultivation

In the approach advanced here, *Chlorella vulgaris* algae is cultivated in open raceway ponds with an average size of 0.1 ha and a water volume of 0.03 m^3/ha. An initial algae biomass concentration of 0.5 kg/m^3 yields a wet algae biomass productivity of 24.75 kg/day for a cultivation site of 0.1 ha under typical operating conditions. For a dry algae biomass productivity of 75 tons/ha/year an average algae oil content of 30% and 70% oilcake [7], which is in line with earlier studies by Weyer et al[152].

To facilitate the synthesis of algae biomass and their productivity levels, nutrients such as nitrogen in the form of ammonia (NH3) and phosphorus in the form of superphosphate (P2O5) have to be supplied according to the algae cultures' stoichiometric requirements, (see Appendix 2). Based on the estimated elemental composition of the microalgae cells, the mass requirements for N and P in ton/ha can be obtained by multiplying the dry algae biomass productivity of 75 ton/h/y with the mean values for elemental nitrogen (8.0%) and phosphorus (2.0%) contents. The fossil energy utilized for ammonia production has frequently been reported at 57 GJ/ton which also accounts for other downstream energy costs such as granulation, natural gas recovery, product packaging, and transportation. The fossil energy consumption for superphosphate fertilizer production has been estimated at 4.1GJ/ton for average European production plants, for further details see Appendix 2. Flue gases with a carbon dioxide content of 12.5 Vol.-% (the maximum value for a natural gas-fired power station [153]) from an adjacent power-plant have been assumed as a direct source of CO_2 [109,154]. The carbon dioxide source is pressurized and injected along the pond through PVC pipes which has been calculated to require 0.043 MJ/kg of dry algae. I emphasize the substantial challenges involved in maintaining the mentioned biomass production yields in an open pond installation. Among other problems, the large-scale production of algae in open pond facilities faces the issue of likely culture contamination or collapse, poor light utilization efficiency, high water losses as well as immature harvesting technologies in consecutive stages [7,129].

4.4.3 Building Material

The main materials used for the building of the pond and harvesting facility includes concrete blocks, PVC, glass reinforced plastics and steel. The pond design is consistent with industrial standards around a benchmark of 10 m wide, 100 m long, and 30 cm deep oval-shaped built in concrete blocks, on a 10-cm-thick sole. For both the open raceway pond and the harvesting facility an average size of 0.1 ha and a lifetime of 30 years has been assumed. The exact quantities of building material needed for the manufacturing of the open pond and harvesting facilities (i.e. pipes, paddlewheels, foundations, rotary press, etc.) were calculated to estimate the associated environmental burden for the construction of the production plant and are illustrated in Appendix 3.

4.4.4 Algae Biomass Processing and Conversion

The main stages considered in the algae biomass processing step are (i) flocculation, (ii) drying and (iii) algae-oil extraction. The algal paste yielded by flocculation has to be further dried to reach a solid 90% biomass content and be processed in oil mill facilities, typically those used for vegetable oil extraction [109]. The heat and electricity requirements of the drying process are 13.8 MJ/kg dry algae and 1.4 MJ/kg dry algae, respectively and clearly induce a heavy impact on the final energetic balance and carbon footprint. Following the flocculation and drying step, 75 tons/ha/y of dry algae biomass is obtained, a value in line with literature estimates found of 90.3 tons/ha/y [109], 75.0 tons/ha/y [152] and 40.0 tons/ha/y [155]. Algae oil can be separated from the biomass by dry extraction methods and is based on the soybean

oil extraction method used by the GREET Transportation Model [17]. This study has focussed on dry extraction method due to data availability and industrial penetration for biodiesel production. Through the counter-current circulation of a hexane solution with an application rate of 0.48 MJ/kg, the algae oil is extracted from the dry biomass. Further information is given in Appendix 5.

4.4.5 Co-Product Utilization

A displacement method is applied as part of co-product allocation, to replace a pre-existing input product [18]. This LCA model focuses solely on the calculation of energy credits from the reuse of the algae-derived oilcake which accounts for 70% (52.5tons/ha/y) of dry biomass after extracting the 30% share of algae oil for further biodiesel processing. Glycerol, seen as end by-product in this study, is usually refined and sold to the pharmaceutical industry or as livestock feed. The co-product utilization options for biomass leftover which have been considered for the reduction of the carbon cycle's electricity and heat requirements are:

- **Combined heat and power (CHP)** plant. Based on the biomass CHP demonstration plant in Guessing, Austria [156], the installation operates on a thermal efficiency of 56.3% and an electrical efficiency of 25% [156]. Through the combustion of the residual oilcake, 541 GJ/ha/y of heat and 240 GJ/ha/y of electricity are generated from the biomass CHP unit. However, regardless of the higher efficiency level of the CHP unit the microalgae-to-biodiesel plant's electricity and heat inputs cannot be completely satisfied and in each case additional capacity must be purchased from the local grid, see Appendix 7.

- **Direct Combustion.** With an assumed 85% efficiency level, only 817 GJ/t/ha of end use heat can be generated [77]. This partially offsets the total heat requirements of 1,136 GJ/ha/y in the process and requires the further purchase of heat from the national grid, Appendix 7.
- **Co-firing coal power plant.** The option simulates the operation at an existing coal-fired power plant with a co-firing ratio of 10% biomass [148]. A plant efficiency of 33% has been estimated which is slightly below those of baseline power plants without co-firing [148,149]. The combustion of the oilcake as part of a coal-fired power station results in the production of 317 GJ/ha/y of end use electricity. In the country scenarios, the end use electricity volume is large enough to satisfy all the electricity requirements of the fuel cycle and result in a surplus which is used to displace electricity from the grid (Appendix 7).

5. Algae Jet Biofuel: A Flight Path for Sustainable Aviation Fuels

Based on: T. Shirvani, X. Yan, P. P. Edwards and D. A. King, *Algae Jet Biofuel: A Flight Path for Sustainable Aviation Fuels*, Environmental Science and Technology, 2012 (submitted)

5.1 Introduction

In this chapter, I have conducted a lifecycle assessment to evaluate the fossil energy requirements and GHG emissions from processing algae biomass for jet biofuel (hereafter also referred to as bio kerosene) production, see Figure 27.

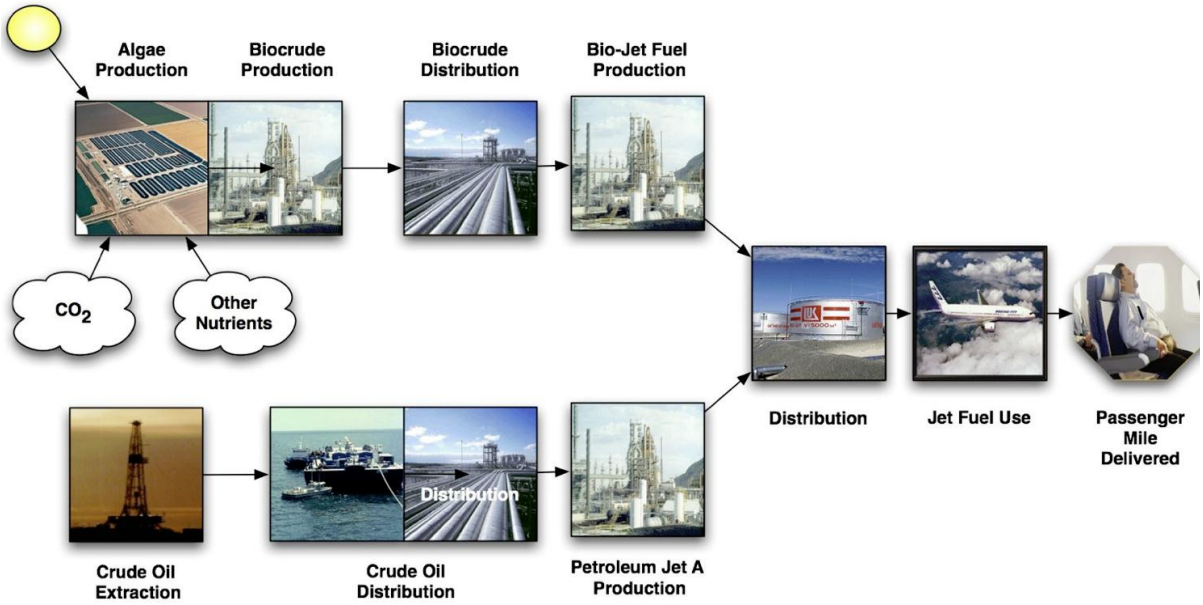

Figure 27: Well-to-Wake lifecycle of algae for jet biofuel production [157]

I determine potential avenues for lowering the technical bottlenecks around high fertilizer, fossil energy requirements and the engineering of superior algal oil yields, which currently prohibit jet biofuel from being a zero carbon fuel source. A comparison of the relative attractiveness of using algae biomass for biodiesel or jet biofuel production, from a marginal land use and economic costing perspective, is also given.

5.2 Results and Discussion

The main stages of the jet biofuel production process consist of algae farming, biomass harvesting, oil extraction, hydrogenation of bio-oil, fuel distribution and combustion, see Figure 28. Feedback loops have been determined that either offset carbon intensive energy input or generate additional fuel products from biomass residues (illustrated in Figure 28 in shades of blue).

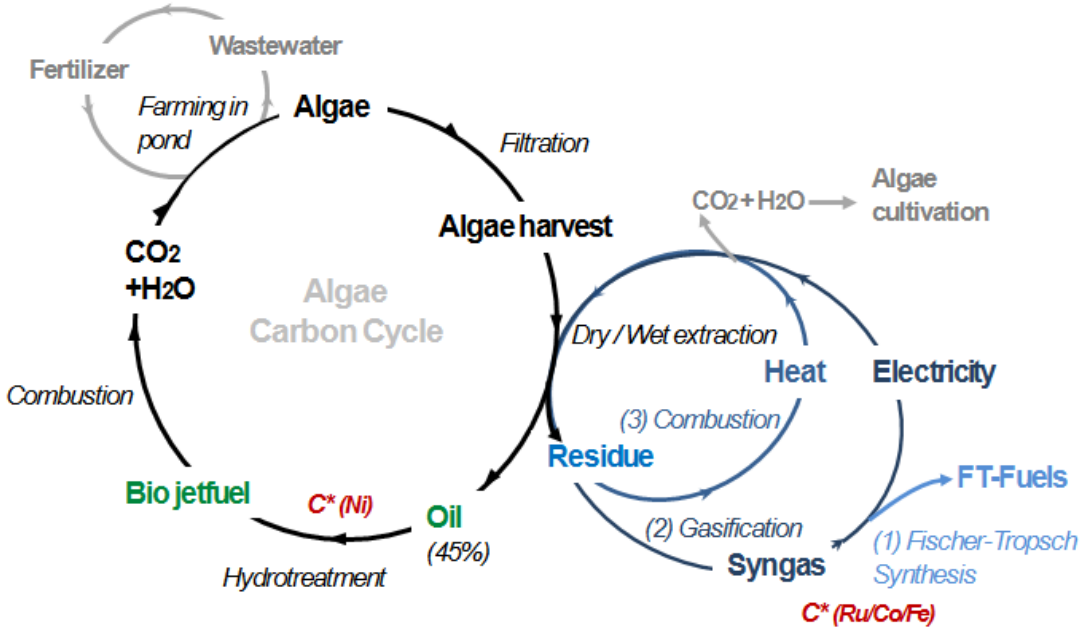

Figure 28: Carbon cycle for jet biofuel production with various feedback loops.

Fertilizers are offset via wastewater recycling, CO_2 input is partly offset by the circulation of exhaust gases from co-product utilization (colored in grey). Feedback loops in shades of blue illustrate three co-product utilization methods: The respective catalyst (C*) used in each process is highlighted in red.

As part of this LCA study, microalgae batches are modeled as being cultivated in open pond farming installations, harvested and dried in subsequent stages. In this LCA study I assume a 100% recycling rate for wastewater, a mixture of secondary effluents with low biochemical oxygen demands and high levels of inorganic nitrogen, potassium, magnesium and sulfur. The effluent is re-directed into the algae pond as culture medium whereby the nitrogen usage of algae biomass is reduced by approximately 94% and potassium requirements are fully offset [15, 21], (illustrated in grey in Figure 28). This LCA study assumes an average biomass productivity of 75 tons/ha/year and 45% algae oil content, values within the proven range of attainable algae yields. The extracted share of algae lipids (33.8 tons/ha/year) are then hydrogenated to yield around 1,265 GJ/ha/year of jet biofuel. 85 GJ/ha/year of propane fuel-mix is generated as a by-product from leftover biomass and is exported as Liquefied Petroleum Gas (LPG). The remaining 542 GJ/ha/year of algae biomass are used in various co-product utilization methods, which are discussed in the section 5.2.2 and illustrated in blue in Figure 28.

When considering all energy inputs of the jet biofuel production cycle as 100% fossil fuelled and leftover biomass as waste material, producing bio kerosene requires around 1.9 MJ/MJ_{fuel} total energy input and emits 213 gCO_{2eq}/MJ_{fuel}, which is higher than the lifecycle fossil energy requirements for kerosene from crude oil (1.1 MJ/MJ_{fuel}) or stranded natural gas (1.7 MJ/MJ_{fuel}) [53]. In the following sections I illustrate that microalgae can be optimized into a comparatively low carbon fuel source with a lifecycle fossil fuel usage in the range of 0.4 to 1.4 MJ/MJ_{fuel}. The exact value depends on the algae oil-to-biomass ratio, the co-product use and share of fossil energy input [158].

As the chemical composition of drop-in Jet A-1 kerosene fuels is pre-determined for all feedstock types, the GHG emissions profile of the Tank-to-Wake (TtW) (i.e. fuel combustion) stage will be constant, assuming that the carbon content of the fuel will be completely oxidized [86]. As a result, the majority of GHG emissions for renewable kerosene are emitted in the Well-to-Tank (WtT) stage, which consists of feedstock farming, harvesting, transportation, conversion and fuel distribution. Kerosene from biological feedstock has the inherent advantage of offsetting engine tail pipe emissions through the plant's net absorption of atmospheric CO_2 during the photosynthesis process [86].

5.2.1 Making Jet Biofuel feasible: *Algae Farming*

In recent years, the algae farming and harvesting stage has gained considerable attention as key driver of GHG emissions, given high fertilizer and CO_2 requirements [7,8,132]. While relative trade-offs remain between a high algae oil content and biomass productivity [7,142,159], one costly alternative on the rise is the engineering and design of microalgae strains with superior oil yields [8], which would improve the overall efficiency of the farming process. With the oil content of algae strains varying from anywhere between 15-77% of dry biomass [7,160] and some species able to double their biomass in as little as 24-48 hours [160], the productivity levels of microalgae are already considerably higher than that of plant-based ones [161]. However, I here highlight that for jet biofuel production the critical break-even algae lipid content at which the life-cycle fossil energy use of kerosene from crude oil is met, has already been reached, see Figure 29.

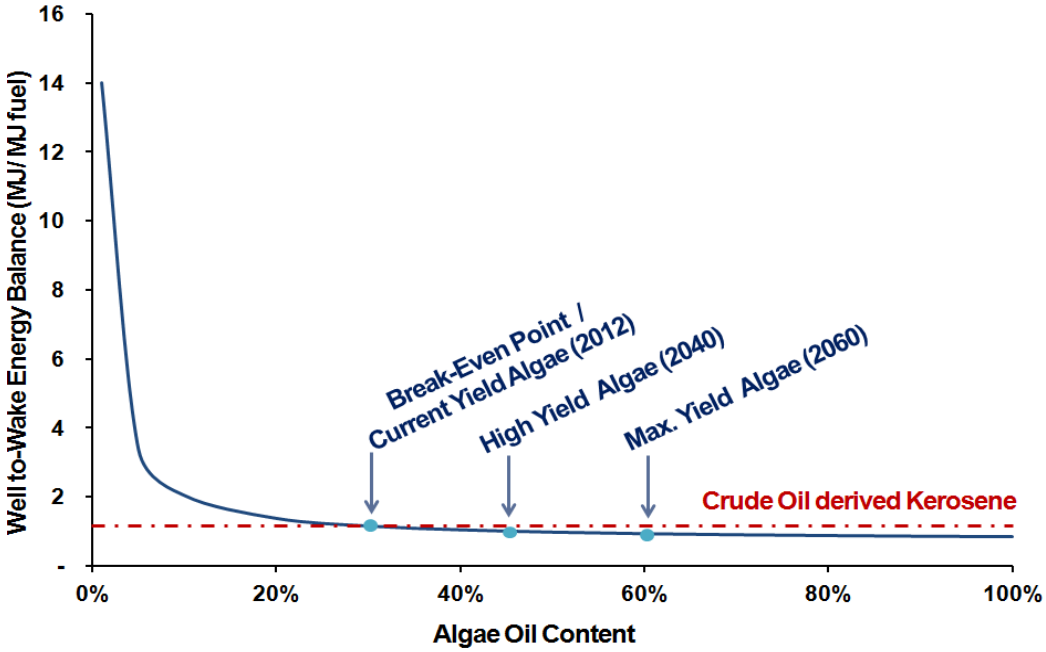

Figure 29 Sensitivity Analysis of algae-to-oil biomass ratio

An average 30% oil content corresponds to a break-even-point at which the algae oil-to-biomass ratio meets the WTW energy requirements of kerosene from crude oil. Ratios are expected to improve to 45% (2040) and eventually reach their theoretical maximum oil share of 60% (2060) [162].

By increasing the lipid content of a here chosen *Chlorella Vulgaris* algae strain (see Methods section for more details), I determine the relative improvement in the Well-to-Wake (WTW) energy balance for a jet biofuel production process which is operated on a UK based heat and electricity grid. The leftover biomass is here gasified to offset the grid electricity and heat input. The average 30% oil content of the chosen algae strain [7,162] corresponds to a break-even-point at which the algae oil-to-biomass ratio meets the WTW energy requirements of kerosene from crude oil (1.1 MJ/MJfuel), see Figure 29. Through future large-scale commercialization algae-to-biomass ratios are expected to improve to 45% (2040) and eventually reach their theoretical maximum oil share of 60% [162] (2060). However, an increase in algae lipid

rate only results in a marginal, and eventually shrinking, improvement of the jet biofuel WTW energy balance once the break-even 30% oil content is passed.

5.2.2 Making Jet Biofuel feasible: *Low Carbon Energy Supply*

By varying the share of life cycle fossil heat and electricity use as a function of total energy, I highlight the level of improvement in WTW energy balance and GHG emissions attainable on a fossil-free grid, shown in Figure 30. For each LCA scenario, the life cycle heat and electricity use was sourced from a hypothetical grid that is either 100% fossil fuel (see points in red, Figure 30), 50% fossil fuel (see points in orange, Figure 30) or 0% fossil fuel (see points in green, Figure 30) based.

Also, I included three co-product utilization methods which either offset grid electricity and heat inputs or are considered for additional fuel product generation. The options consist of: (1) gasification with surplus electricity generation, (2) fuel production through Fischer-Tropsch (FT) synthesis or (3) biomass combustion to offset grid heat (see Methods).

The highest improvements in GHG emissions and fossil energy use can be achieved when generating jet biofuel from algae oil and gasifying the leftover biomass, irrespective of the share of fossil based energy generation (see purple line (1), Figure 30). Regardless of a 100% fossil fuelled electricity grid (point in red), here the lifecycle energy balance and GHG emissions for algal jet biofuel production with residue gasification are here already lower than analogue crude-oil sourced aviation fuels. While these lifecycle results may be lower than analogue fossil fuel products, it does not reach a preferred low-carbon fuel standard.

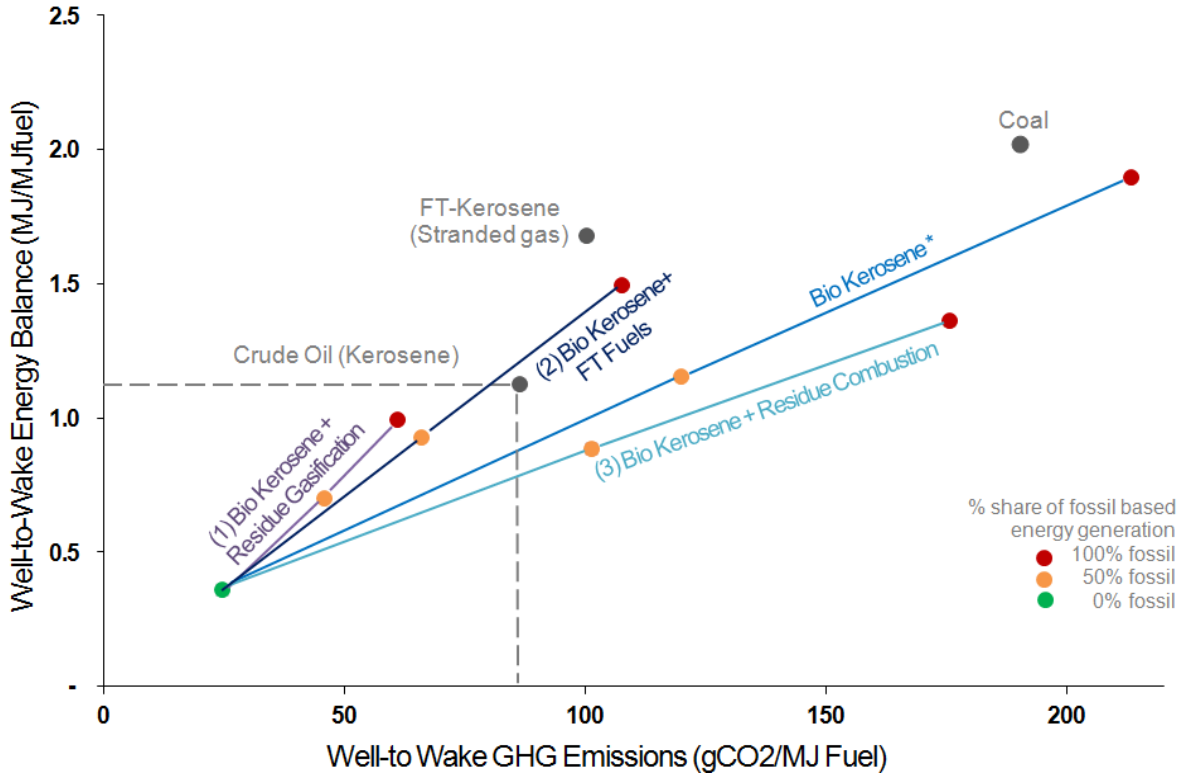

Figure 30: Life cycle fossil fuel use and GHG emissions for jet biofuel.

For each LCA scenario, the life cycle heat and electricity use was sourced from a hypothetical grid that is either 100% fossil fuel (points in red), 50% fossil fuel (points in orange) or 0% fossil fuel (points in green) generated. Three co-product utilization methods are included: (1) gasification with surplus electricity generation, (2) fuel production through FT synthesis or (3) biomass combustion to offset grid heat. *) Refers to bio kerosene production for which leftover biomass is considered waste. This selection of co-product uses has been chosen as co-product usage and allocation methodology can be a crucial source of variability in the final lifecycle GHG emissions and energy balance result[158]. A complete summary for all LCA results and individual co-product utilization methods is given in Table 8 and Appendix 10.2.

Compared to analogue Jet A-1 fuels from crude oil emitting 86 gCO_{2eq}/MJ_{fuel}, the WTW GHG emissions from algae jet biofuel incl. biomass gasification, can be further reduced by around 30%-80% (i.e., 27-61 gCO_{2eq}/MJ_{fuel}) depending on the relative carbon intensity of the grid, see Table 8. The importance of operating algae fuel production on a decarbonised electricity grid becomes clear, when considering the worst-case scenario of producing algae jet biofuel and assuming all leftover biomass as waste (sees Figure 30, line labeled Bio Kerosene). Here, the lifecycle GHG

emissions are almost as high as kerosene derived from coal. While, reducing the share of fossil heat and electricity to zero can lower a maximum total lifecycle energy demand of 1.9 MJ/MJ_{fuel} by 80% down to 0.4 MJ/MJ_{fuel} (27 gCO_{2eq}/MJ_{fuel}).

Table 8: Life cycle results for kerosene from algae incl. co-product allocation

Fossil Energy (%)	**100%**		**50%**		**0%**	
	$MJ/MJ^{a)}$	$gCO_2/MJ_{fuel}^{b)}$	$MJ/MJ^{a)}$	$gCO_2/MJ_{fuel}^{b)}$	$MJ/MJ^{a)}$	$gCO_2/MJ_{fuel}^{b)}$
Jet Biofuel +Gasification	**1.0**	**61**	0.7	44	**0.4**	**27**
Jet Biofuel+ FT fuel	1.5	107	0.9	66	0.4	24
Jet Biofuel	1.9	213	1.2	120	0.4	27
Jet Biofuel +Combustion	1.4	175	0.9	101	0.4	27
Crude Oil	**1.1**	**86**				
Stranded Gas	1.7	100				
Coal(no CCS)	2.0	190				

a) Life cycle fossil fuel use in MJ/MJ_{fuel}

b) WTW GHG emissions in gCO_{2e}/MJ_{fuel}

Still, in all of the above cases 0.4 MJ/MJ remains the fossil barrier achievable through a 100% uptake of renewable heat and electricity. This threshold accounts for all remaining input parameters in the form of transport, chemicals and infrastructure, which require fossil energy as part of their production process. Building material in the form of steel, concrete and glass needed for the construction of the algae farming pond and harvesting material will continue to place a large fossil and financial caveat on algae jet biofuel becoming a feasible zero-carbon fuel source [109,163], see Appendix 3.

5.2.3 Microalgae for Biodiesel or Jet Biofuel Production

For renewable kerosene from microalgae to be a viable low-carbon fuel substitute, ample volumes of oil-rich biomass must be cultivated on marginal land, at noticeably lower production costs and GHG emissions compared to existing fossil Jet-A fuels [164]. If globally we were to replace the total production of fossil-based kerosene of 10.7 EJ/year in 2010 with jet biofuel from microalgae at a theoretical average yield of 1,265 GJ/ha/year, a landmass of approximately 8.5 million hectares would be necessary for production and cultivation, see Appendix 14. This land mass approximates to an area size of Ghana which is less than the land requirement for kerosene production from second generation biomass such as Jatropha with a dry seed yield of 5-4 tons/ha/year [157].

Considering the concerns over the future availability of middle distillate fuel products from fossil sources [6,33,34], it is anticipated that the reliance and competition of the aviation and road transportation industry on a single finite fossil fuel source will eventually extend into the renewable biofuel sector. When comparing the global land requirements for processing microalgae for biodiesel or jet biofuel production, the relative attractiveness of the bio kerosene production becomes clear. To completely offset the predicted global fossil kerosene demand of 24-39 EJ/year in 2050 with a 100% jet biofuel blend, 19-28 million ha/year of marginal land must be used for algae feedstock cultivation and production, see Figure 31. By comparison, substituting global diesel demand of 61-86 EJ/year (2050) with algae-derived biodiesel will result in 60% higher land use requirements (48-67 million ha/y). The lower land use requirements are partly due to the relative size of the fossil kerosene market in

comparison to fossil diesel consumption by road transportation. However, with the prevailing uncertainty regarding the future large-scale uptake of jet biofuel into the aviation fuel mix, it shall be noted that a 25%-50% blend by 2030 will be a more realistic assumption.

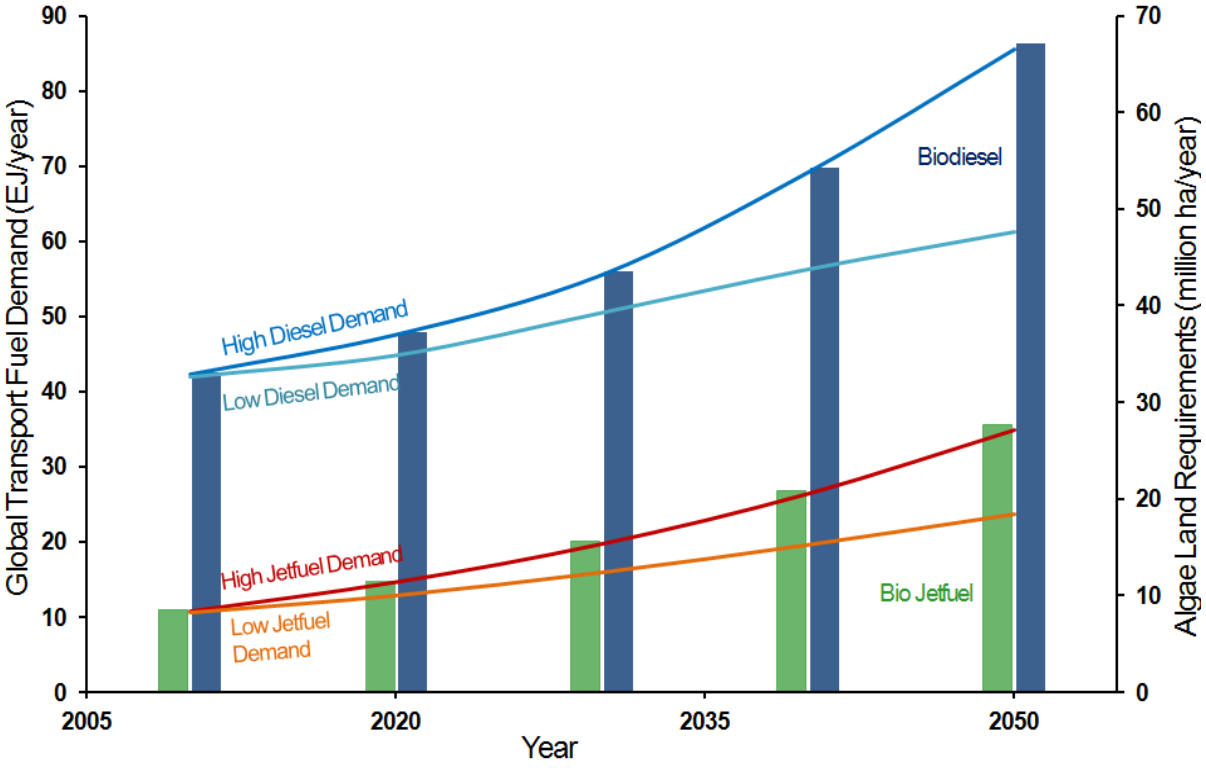

Figure 31: Projected algae fuel land use requirements.

Data given in million ha/year and specific to offsetting global diesel and jet biofuel demand (EJ/year) from 2010-2050. Jet biofuel and diesel demand projections are illustrated on the first y-axis (e.g. global transport fuel demand), and landmass necessary for jet biofuel or biodiesel production is given on second y-axis (e.g. algae land requirements). Values for fossil diesel and jet biofuel demand are given as part of a high-low scenario[165]. Fossil diesel projections are illustrated for their use in all transport modes from 2010-2050 [165]. Fossil jet biofuel use is given for the aviation industry from 2010-2050 [165]. Land requirements for algae biomass cultivation are based on the future uptake of a 100% jet biofuel blend. For further information on land requirements for a 25%-50% blend see Appendix 14.

In this case, the land mass necessary for algae biomass cultivation to substitute 25-50% of fossil Jet biofuel consumption in 2030 will still be 3 times lower than an analogue share of the fossil diesel market, see Appendix 14. All these values are

given as part of a high-low demand scenario as land use requirements ultimately depend on future predictions for global transport fuel demand [165] (see Appendix 14).

The cultivation of algae on marginal or desert land without displacing food crops [166-168] remains highly desirable as relative to the cultivation requirements of other advanced biofuels microalgae farming only requires solar radiation, carbon dioxide, water and nutrients in the form of inorganic salts [112]. However, I note that large-scale use of marginal land for algae cultivation is expected to remain limited given technological drawbacks. For example, issues around the injection of cheap CO_2 from nearby (i.e. <100km) power plants, the availability of suitably flat land areas for the installation of open raceway ponds and the viability of commercial production limited to areas with high levels of solar radiation, will be of practical concern.

5.3 Conclusions

To fully optimize the jet biofuel lifecycle fossil fuel use below analogous fossil Jet A-1 levels, fertilizer use must be reduced through wastewater recycling, leftover biomass must be used to compensate remaining carbon intensive heat and electricity input and process exhaust gases must be recovered as additional CO_2 input for algae farming.

This chapter shows that irrespective of a 100% fossil fuelled electricity grid, the lifecycle energy balance and GHG emissions for algal jet biofuel production with residue gasification is proven to be lower than analogue crude-oil sourced aviation fuels. The lifecycle results can be further reduced by up 30%-80% depending on the relative carbon intensity of the electricity grid. This chapter also highlights that there

is no apparent need to direct efforts at the engineering of microalgae strains with superior lipids, as the critical break-even algae oil content which meets the life-cycle fossil energy use of kerosene from crude oil has already been reached. Moreover, compared to biodiesel from algae feedstock, jet biofuel production requires 60% less marginal land to substitute global kerosene demand by 2050.. The main caveat for the large-scale expansion of jet biofuel remains its substantial cost basis which at current average oil prices of is almost up to 6 times higher than its fossil counterpart is.

Optimizing jet biofuel into a large-scale low carbon fuel option remains a challenging and ambitious scenario. With the asset intensive nature of the aviation industry, jet biofuel can only ever be a viable fuel substitute that either impacts the fuel price or the environmental footprint of the sector, once sufficient quantities of sustainable biomass feedstock are available at low cost. Nonetheless, an improvement in the financial viability of jet biofuel production through the future rise in crude oil prices is anticipated and I emphasize the importance of introducing governmental subsidies as part of a policy strategy which assists the roll-out of small-scale low-carbon fuel strategies. For the future production of jet biofuel in the UK, the government's objective of decarbonizing the economy through an increased electrification of transport and heating by 2050 will substantially improve the fossil fuel use of the fuel path. Such policy initiatives are recommended as a first important step for guaranteeing the future environmental viability of low-carbon fuel products such as biofuels from advanced feedstock, both on a small and large-scale basis.

5.4 Methods and Materials

5.4.1 Environmental Effects

This LCA study calculates the global warming potential over a 100 year time horizon and total fossil energy consumption associated with algae jet biofuel production. While current kerosene refinery processes mix jet biofuel with fossil fuels in a maximum 50:50 blend by volume [169], this paper assumes a 100% jet biofuel blend. This assumption is driven by the 2010 enacted legislative act by the ASTM International Aviation Fuels subcommittee, which will facilitate the level of commercialization for 100% fossil-free transport modes in by 2013. I also define the functional unit as 1 mega joule (MJ) of liquid fuel produced from algae-oil and the processing of biomass residue for extra fuel production. Details on the feedstock, process parameters, principal inputs values and additional liquid fuel products generated from co-product utilization methods are given in the Appendix 10.2.

5.4.2 Microalgae farming

This LCA study assumes the cultivation of *Chlorella Vulgaris* algae in open raceway ponds with an average size of 0.1 ha containing a water volume of 0.03 m3/ha. The initial algae biomass concentration in broth of 0.5 g/l generates a dry biomass productivity of 75tons/ha/year. For this LCA study, the additions of nutrients are calculated based on the algae broth concentration in the pond and its stoichiometric requirements (see Appendix 2). Flue gases with a carbon dioxide content of 12.5 Vol.-% (the maximum value for a natural gas fired power station) from an adjacent power-plant have been assumed as a direct source of CO_2 [154]. In addition, the

exhaust gases (CO_2 and H_2O) from the processing of algae co-products via gasification or combustion are redirected into the open ponds to absorb CO_2 and promote additional algae growth.

5.4.3 Biomass-to-Jet Biofuel Conversion

After the biomass harvesting and drying stage, 75 ton/ha/year of dry biomass are obtained. Values are in line with figures in the literature ranging from high-low end values of 90.3ton/ha/year to 40.0ton/ha/year. Data for the algae biomass drying and separation step are based on the GREET Transportation Model, and are further detailed in Appendix 10.2. The estimated 45:55% oil-to-biomass ratio results in the production of 33.8 ton/ha/year of algae oil and 41.3 ton/ha/year of residual dry biomass. Jet biofuel production via metal-catalyzed hydrogenation of oil rich biomass is an energy-efficient alternative compared to other fuel synthesis routes. The generated kerosene fuels are lighter and of pure hydrocarbon content with indistinguishable features from the analogue fossil-based Jet-A aviation fuel (C8-C16) [157,164]. These synthetic hydrocarbon fuels have superior combustion properties and are further characterized by enhanced low temperature stability and a higher energy content which makes them an excellent energy carrier for the aviation industry [6].

5.4.4 Co-Product Utilization

This LCA system expansion is adopted via a displacement method to account for GHG emissions avoidance through co-product utilization from biomass residue.

Co-product credits are further subtracted from the overall LCA energy balance and carbon footprint, in order to complete the analysis. 85 GJ/ha/year of propane fuel-mix is generated as a by-product from hydrogenating the algal oil share and is exported as Liquefied Petroleum Gas (LPG). This LCA model focuses solely on the calculation of energy credits from the reuse of the leftover biomass which accounts for 55% (542 GJ/ha/year) of total dry algae biomass. The co-product utilization options which have been considered are:

1. **FT-Fuel production:** Biomass is gasified and converted into synthetic fuels and electricity via high-pressure Fischer-Tropsch liquid synthesis integrated with gas turbine combined cycle electric power generation. I assume average 47.6% efficiency for the process while 53% of net power output is realized in liquid fuels and 47% in the form of electricity. 62% and 38% of the liquid fuels produced are diesel and gasoline respectively. Data sourced from ref [170,171].
2. **Biomass gasification**: Biomass integrated gasification combined cycle CHP process where gas engine is replaced by a combined cycle. I assume average efficiencies of 43% for electricity and 47% for heat. I assume a Lower Heating Value (LHV) of wood chips (24.64) as reference case for algae biomass feedstock. Data sourced from ref [172].
3. **Biomass combustion**: I assume an 85% efficiency level. Direct combustion will only partially offset the fossil heat requirements and source remaining heat input from the domestic grid. Data sourced from ref [77] .

6. Catalyst Sensitivity Index

In the past decades the chemical industry worldwide, and particularly the pharmaceutical industry, has become more aware of the problem of waste generation as part of chemical manufacturing. In the 1980's the first concept of the E(nvironmental) Factor was developed to assess the environmental impact of manufacturing processes and the environmental acceptability of chemical processes [173]. The E-factor is defined as the mass ratio of waste to desired product [173] . It is the sum of all raw materials input (kg), minus the desired product and divided by the final product outputs (kg). The equation includes all actual amount of waste produced in the process, chemical yields in the form of reagents and solvent losses, fuel used and process aids. The final product as well as the amount of water used is excluded from the E-factor calculation. Particularly, the inclusion of water consumption yields could distort E-factor results and not allow for the meaningful comparison of processes [173] . An outline of typical E-factors in different sectors of the chemicals industry is given in Table 9 [191].

Table 9: Outline of various E-factors in the chemicals industry

Industry segment	**Product tonnage**	**E factor (kg waste/kg product)**
Oil refining	10^6-10^8	<0.1
Bulk chemicals	10^4-10^6	<1-5
Fine chemicals	10^2-10^4	5-50
Pharmaceuticals	10-10^3	25-100

A higher E-factor would translate into more waste and by definition a larger environmental impact while an ideal E-factor is close to zero. Table 9 also illustrates the increase in E-factors results from bulk to fine chemical industry. The pharmaceutical industry accounts, by several magnitudes, as one of the most wasteful chemical industries mainly due to the inclusion of multi-step syntheses. While the absolute volume of waste is lower for pharmaceuticals than for bulk chemical sectors due to smaller production volumes, the widespread use of stoichiometric reagents rather than catalysts accounts for higher waste production and higher relative inefficiencies. For example, enormous amounts of waste, in the form of inorganic salts such as sodium chloride, sodium sulphate and ammonium sulphate, are formed as part of various reactions.

The green chemistry industry is based on the E-factor concept and tries to efficiently process mostly renewable, raw materials whilst reducing waste and the utilization of hazardous and toxic solvents or reagents. While the E-factor mainly takes into account the amount of waste generated, it is crucial to also consider for the environmental impact and nature of the waste. For example, according to this definition the inclusion of renewable primary energy as raw material is as important as waste remediation through end-of-pipe solutions [173]. Likewise, another important environmental consideration in green chemistry is the use of organic solvents, which has been estimated to account for up to 85% of total mass of chemicals used in the manufacturing of pharmaceutical [173]. The inherent inefficiency of containing, recovering and re-using organic solvents is a major pitfall for the sustainability of the sector and will need to be addressed through the development of more environmentally friendly alternative solutions in the near future.

In accordance with the issue of developing alternative sustainable reaction media is the recovery and re-use of catalysts. Heterogeneous catalysts, such as insoluble solids, are easily separated via filtration or centrifugation [173]. In comparison, homogeneous catalysts are more challenging to be quantitatively recovered from the reaction end products without any consequential contamination. Other potential damages include potential leaching of the metal, poor catalyst productivity, irreproducible selectivity and activity and potential degradation and damage of support base [173]. One practical method which allows for the preservation of advantages presented by homogeneous catalysts while providing for a facile separation of product and catalyst is liquid-liquid biphasic catalysis. Here, the catalyst is dissolved in a separate phase from the reactants and products, and afterwards recovered and recycled by simple phase separation. Ideally, the catalyst solution remains in the reactor system and is consequently re-used with a new set of reactants and without the further need for treatment. Another alternative would be the performance of reactions in aquatic biphasic systems in which the catalyst resides in the water phase and the product is dissolved in the organic phase [173]. The catalyst could then be easily recovered and recycled by simple phase separation. Also the use of renewable raw materials in the form of biomass instead of hydrocarbon sources will be crucial. The technologies used for the conversion of renewable feedstock, such as carbohydrates, triglycerides and terpenes, should preferably be catalytic to guarantee minimal waste and improved sustainability.

In light of further development and fostering of green chemistry practices, the question of what quantitative impacts would advances in catalysis have on the energy balance and GHG emissions of various fuel pathways, becomes of paramount importance. Catalysis is a key technology to achieve the objective of

energy efficiency and GHG emissions mitigation. Through the analysis of catalyst-dependent alternative fuel paths I here outline the critical importance of catalytic chemistry for the development of a low-carbon fuel mix. Through the preliminary definition of a Catalyst Sensitivity Index (CSI) I highlight the impact of catalyst efficiency on the total fossil energy consumption of selected fuel conversion technologies and the subsequent final carbon footprint of the fuel product. The CSI factor is defined as the sensitivity of the carbon footprint of any given process on the respective catalyst efficiency, see Equation 2. Here, catalyst efficiency is defined as the net energy consumption of a catalyst-dependent process, which would decrease through improvements in catalyst selectivity.

$$CSI^{*} = \frac{\Delta\ gCO_2/MJ_{Fuel}}{\Delta\ \text{Catalyst Efficiency}} \qquad (2)$$

**For a given* Δ-change in gCO_2/MJ_{fuel} or change in catalyst efficiency

The CSI index will allow the industry to highlight 'best practice catalysts' and draw conclusions for what efficiency gains one could theoretically anticipate with higher performance catalysts. An ideal (i.e. high) CSI-factor would be close to zero, and translate into processes, which are highly catalyst sensitive, and for which small improvements in catalyst efficiencies would yield considerable reductions in the total carbon footprint of the system. A low CSI factor would highlight catalyst insensitive processes where improvements in catalyst efficiencies would not impact the overall carbon footprint of the system. This new CSI concept outlines similarities to the previously presented E-factor and should, in the future, go hand-in-hand with the industries' decisions on sustainable practices and environmental efficiency gains. It is noted that the CSI concept here presented is in a preliminary format and will

require substantial additional work in the form of Aspen Plus simulations to give more precise results. However, a preliminary analysis for four different fuel conversion technologies is given to outline the importance and future significance this concept. I have highlighted the various CSI-factors for four fuel conversion processes: 1) Algae-to-Biodiesel, 2) Algae-to-Jet Biofuel, 3) Coal-to-Liquid and 4) Gas-to-Liquid, see Figure 32. A high CSI-factor is reported for the FT fuel conversion from both coal and gas feedstock. Sensitivity analyses are conducted to illustrate the impact of an increased catalyst activity on the relative reduction in net FT-fuel energy consumption as well as catalyst selectivity of the respective feed load to the FT fuel upgrading stage.

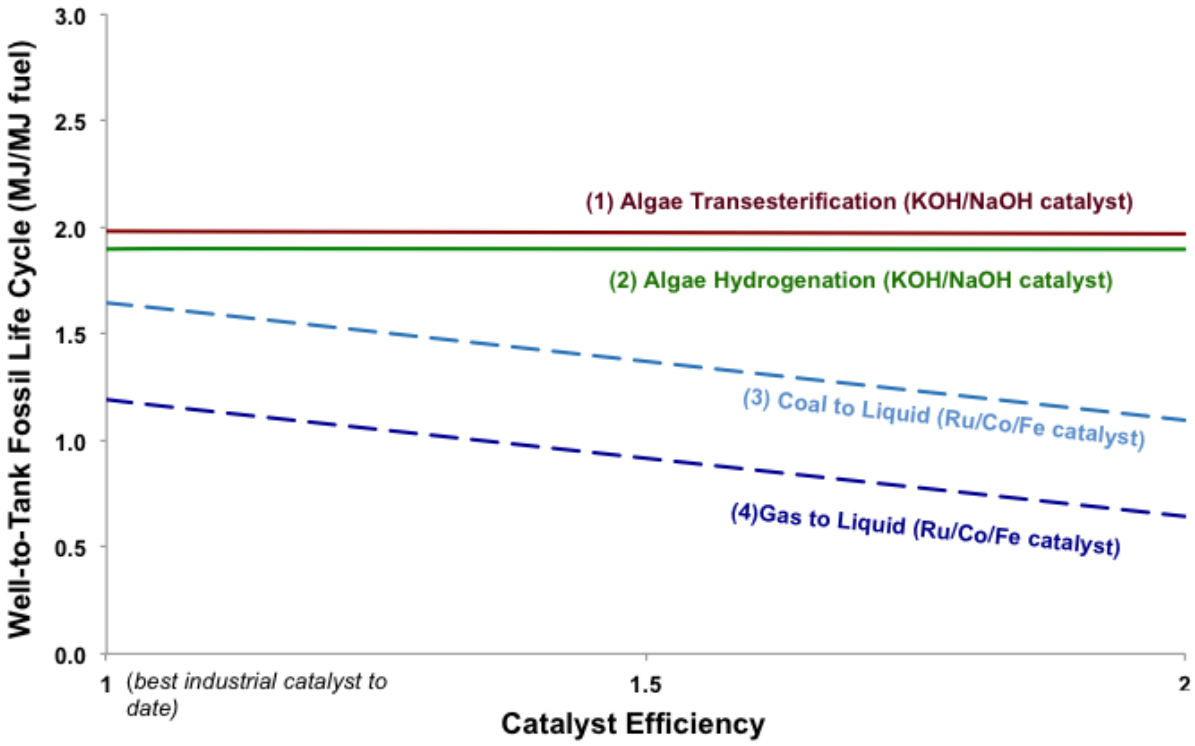

Figure 32: CSI-factor for four catalyst-dependent fuel conversion processes.

Algae Biodiesel and Jet Biofuel from Transesterification and Hydrogenation are given as benchmark values and outline a low CSI-factor by being catalyst insensitive. Fuels manufactured through Fischer-Tropsch synthesis (i.e. CTL and GTL) show a significant sensitivity on catalyst efficiency and therefore, par definition, exhibit a high CSI factor.

Here, for the production of Gas-to-Liquid (GTL) or Coal-to-Liquid (CTL) fuels a ruthenium, cobalt or iron catalyst is used during the Fischer-Tropsch (FT) reaction and zeolites for the FT-fuel upgrading step to refined fuel products. It is important to note, that for this study FT-fuel production volumes and mass balance are assumed as constant and no further consideration of heat recycling and feedback loops have been taken into account. This has mainly been assumed as the allocation of emissions for the separation and upgrading step is driven by recycled heat which has been generated by earlier gasification and water gas shift steps where heat and syngas are produced to power the whole system. Algae biodiesel and jet biofuel production from transesterification and hydrogenation are given as benchmark values and by definition outline a low (i.e. catalyst insensitive) CSI factor.

A breakdown of the Well-to-Tank lifecycle energy profile for the production of GTL and CTL fuels is also given in Figure 33. It outlines the relative contribution of the FT-fuel production stages and highlights the energy demand of the Ft reactor as the second largest fossil energy consumer after the FT gasification and syngas clean-up stage. The potential reduction in the FT-reactor's net energy consumption, through an increased catalyst activity, as well as improvements to the consequent feed load of the FT-fuel upgrading stage, through higher catalyst selectivity, are illustrated. However as part of the fuel upgrading and refining step, the contribution by zeolite catalysts to the overall energy and GHG emissions balance remain relatively small.

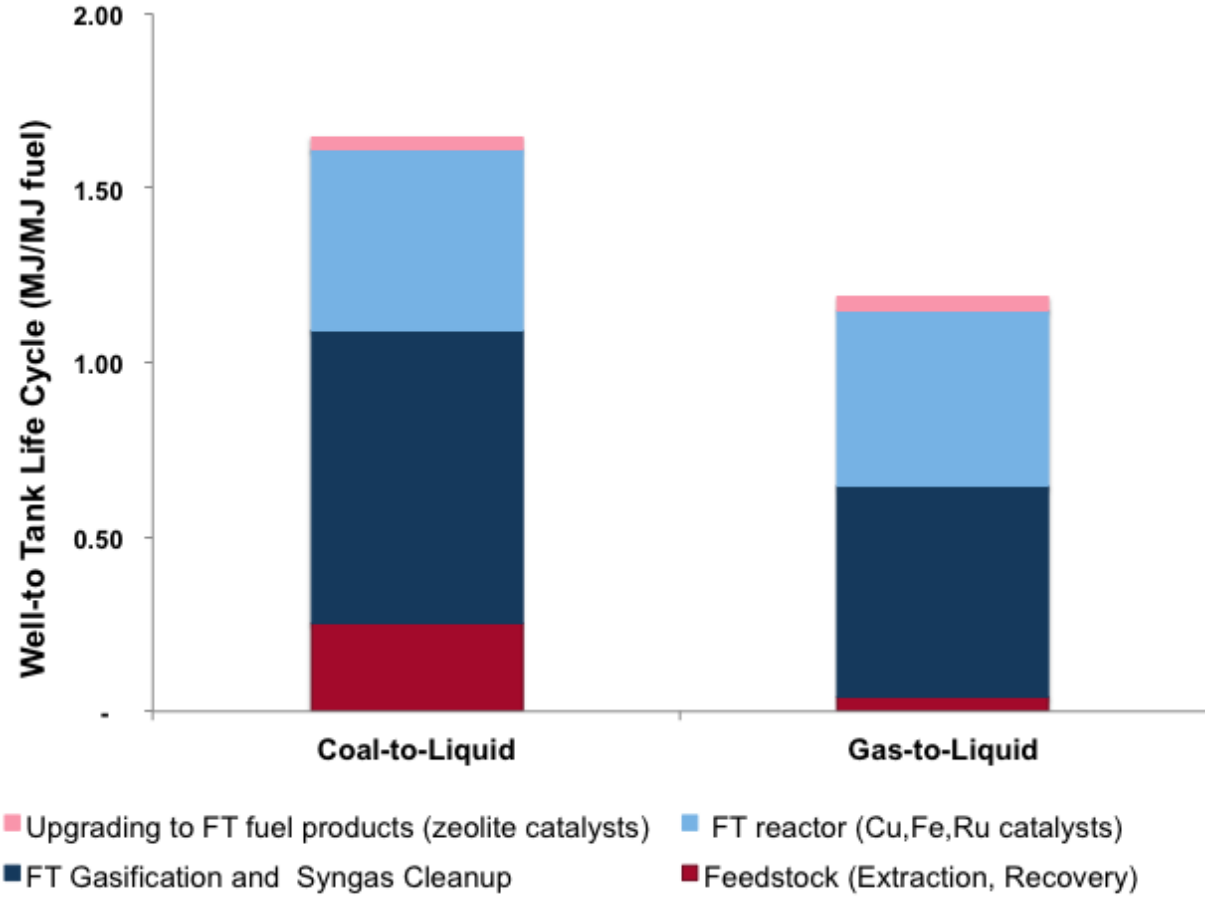

Figure 33: Well-to-Tank lifecycle energy demand for CTL and GTL fuels

7. Harvesting the algal bloom to meet a global fish feed crisis

Based on T.Shirvani, J.Sheehan, T.Searchinger and D.A. King, *Harvesting the algal bloom to meet a global fish feed crisis, Nature*, 2012, (in progress)

7.1 Introduction

In the period from 2010 to 2050 world population growth is projected to rise from 6.8 to 9 bn [2,174]. Since global middle class consumers are anticipated to rise from 1.8bn today to 4.8bn by 2030, to meet a global food demand production must increase by between 70 % and 100 %[2]. Meanwhile, the global rate of wild fish catch has become alarmingly unsustainable with 53% of wild fisheries fully exploited and 32% overexploited and depleted [175,176]. Following the peak in the global supply of wild fishery in 1996, production has settled at ~85-95 million tons (Mt) per year [175], with aquaculture now accounting for 4% (25.4 Mt) of global animal feed production and over one quarter of all fish directly consumed by humans [3,175]. From 1992 to 2006, aquafeed consumption increased more than three-fold, from 0.96 Mt to 3.7 Mt of fish meal and from 0.23 Mt to 0.83 Mt of fish oil [3]. Salmon, shrimp and trout farming account for less that 10% of global aquaculture production, yet consume 26% of global fish meal and 74% of fish oil supply [3].

If aquaculture is to sustain its current growth rate of 8.3% per year [3,176] and rise from 52.5 Mt in 2008 to 79-110 Mt by 2030 [177], it follows that the supply of aquafeed must grow at a similar rate to meet rising global demand. However, world supplies of wild pelagic fish are estimated to decline from 20 Mt to 15 Mt from 2006 to 2020 which is

potentially a serious risk for the future availability of fish meal and fish oil supplies [3]. Moreover, climate change impacts, induced by anthropogenic Greenhouse Gases (GHG) emissions, have already affected wild pelagic fish production through the rise in extreme weather events such as the El Niño–Southern Oscillation (El Nino) phenomenon [174].

Nowhere is the supply of pelagic fish, in the form of fish meal and fish oil, more critical than in Asia which accounts for 90% of global aquaculture. China now accounts for 62% of the total [175,176]. The rising demand from China alone has the potential to consume 70% of total global fish meal supplies by 2030 and cause the depletion of 40% of global fish oil by 2015. The entire world's supply could be consumed well before 2030 [4]. Faced with the paradox of aquaculture acting as both a possible solution and contributing factor to the collapse of global fish stocks [175], international prices for fish meal and fish oil have reached highs of $1379/ton (2007) and $1700t/ton (2008), as shown in Figure 34 [3].

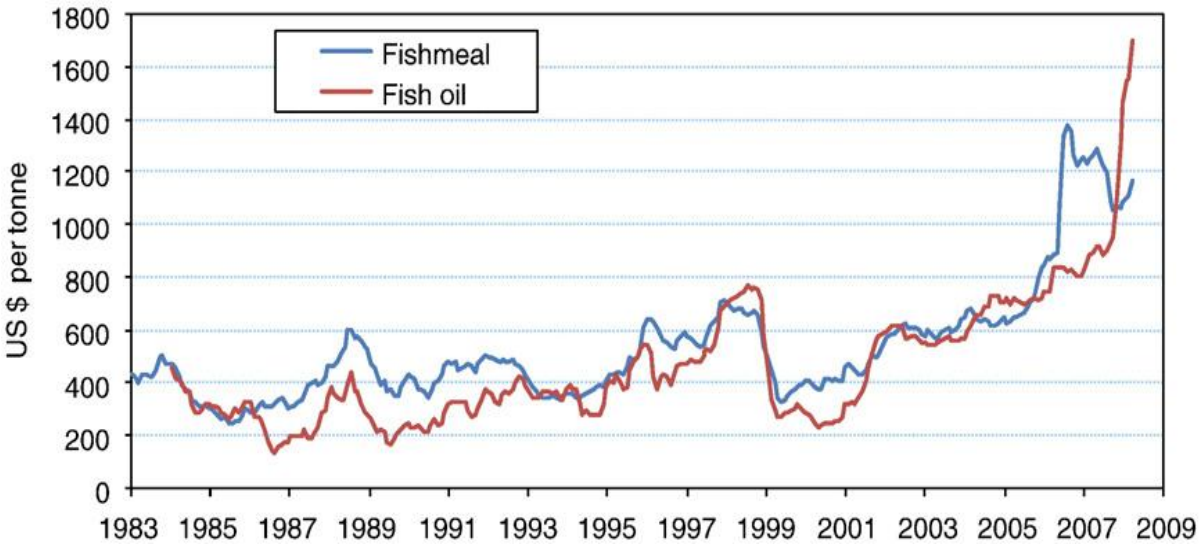

Figure 34: International Prices for Fish meal and Fish oil from 1983- 2009 [196]

This trend is expected to increase with static global aquafeed supplies, rising energy costs and increased demand from China. While fish meal and fish oil are likely to be transformed from bulk feed to a high value specialty feed ingredient, it is speculative to consider what will fill the rising aquafeed gap [175,178].

With fish feed accounting for the largest share of aquaculture production costs, an improvement in the efficiency of production and utilization of feed is crucial [3,175]. From 1995 to 2007, aquaculture managed to become a net fish producer by improving its resource use, herein measured in terms of Feed Conversion Ratios (FCRs) and later by FIFO (Fish In Fish Out) ratios [3,174]. Unless alternative feed sources are found which are sustainable and affordable, the advances in feed conversion ratios and reduced FIFO ratios will be insufficient to offset the rise in global aquaculture demand.

Fish meal, a vital source of marine proteins, is commonly replaced by cheaper vegetable meals and terrestrial animal by-products.[179] But these sources have their own sets of problems related to unsustainable agriculture practices that exacerbate deforestation, land-use change, air and water pollution, and excessive water consumption [180,181]. The substitution of fish oil poses as great a challenge owing to the absence of essential fatty acids in most alternative feed sources [175,178,182 136].

Microbial oil or single-cell oil (SCO) production is a relatively new concept with numerous comparable advantages. Microalgae feedstock, rich in unsaturated marine oils and protein, benefits from higher algae feed consumption efficiencies compared to standard aquafeed utilization, superior land-use efficiencies and production volumes [10,14-19]. So far, the relative advantages of algae have mostly raised interest from the transport industry for its potential as renewable fuel source [183]. However,

currently available commercial algae biofuel production suffers from the environmental and financial pitfalls around energy intensive biomass drying, harvesting and algae oil extraction [183,184]. Algae technology developers are aware of the present financial hurdles, and considerable research is still required to build affordable and efficient extraction technologies, which can be deployed, the earliest, by mid-century.

This chapter focuses on the alternative use of microalgae for fish feed instead of low carbon fuel production. Considering that in the year 2030, the demand for fish meal (10.4 Mt) and fish oil (5.9 Mt) is expected to exceed the relative supply by marine sources (6.5 Mt and 1.3 Mt) [4], the superior land-use efficiency of photosynthetic microalgae can provide a vital solution to feeding a protein-hungry human population with limited marginal land availability. To satisfy the demand for fish oil and fish meal in 2030 with algae feed, at an average yield of 60 to 70 tons/ha/y [9,10] with a 35% lipid content and 45% protein share equivalent to the share of algae strains appropriate for aquafeed replacements [136,185], an arid land mass between 2,713 and 2,325 km^2/year will be necessary. This area approximates to roughly three times the size of Hong Kong or somewhat larger than the island of Mauritius, as shown in Appendix 10.3. In comparison, replacing fish meal demand in 2030 with soybean, at a dry yield of 2.7 tons/ha/y [186], will require 38,431 km^2/year of global land mass.

Ultimately, microalgae can only act as a sustainable food source when produced in large reliable volumes, at affordable prices and as part of a resource-efficient and low carbon farming process that maintains essential ecosystems.

This study, the first of its kind, is a quantitative assessment of all these factors and represents a major step towards a comprehensive understanding of the emissions

and energy balance of algae feed production. I describe a new cost-effective method of dewatered algae feed production for intensive shrimp farming systems with minimal transport costs for localized domestic use. This farming process, coupled with improved biomass productivity yields, promises the cost-competitive production of algae feed for standard fish feed replacement by the year 2030. In addition, a lifecycle analysis outlines the improvements in fossil energy demand and GHG emissions for shrimp *(Litopenaeus vannamei)* production in China cultivated on algae feed mixtures. Future projections for improved LCA results by 2030 and 2050 as a factor of increased algae productivity yields are also given.

As water, energy and land usage in aquaculture are all interactive the results of this study should act as an essential first step to quantify the potential environmental and economic value of future microalgae use in an area of depleting traditional feed supplies.

7.2. Results and Discussion

As part of this study, the total production costs, lifecycle GHG emissions and fossil energy demand of generating algae biomass as shrimp feed replacement have been modeled for three selected timeframes: 2010, 2030 and 2050.

The system framework focuses on the cultivation of three different phototrophic microalgae strains (*Spirulina Platensis, Pavlova Lutheri* and *Nannocloropsis sp)* in separate on-site open raceway ponds. The selected algae species outline a compatible nutrient profile to fish meal and fish oil ingredients and are chosen as direct source of protein and highly unsaturated fatty acids, see Methods 7.4.2. Crop-based proteins such as soybean meal, corn and wheat are considered as feed

additives. An outline of the general conditions assumed for farming microalgae feed are given in Table 10.

Table 10: Algae Feed Production: Parameters and Key Assumptions

Parameter	Value	Assumption	Reference
Growth system	*Ex situ*	Separate shrimp and algae growth	
Algae Growth system		Open Raceway Pond, operating 330days/year	
Open Pond Depth	30 cm		
Single Pond Area	0.1 ha	LCA-study boundary	
Single Pond Area	2.0 ha	Cost analysis boundary	
Evaporation Rate	0.6 cm/ha		
Pond Algae Concentration	0.1-0.15	Depending on algae strain (see Table 11)	
Algae Strain: *Spirulina Platensis*	(46-63% protein; 11g/m^2/d) [a)]	Fish Meal alternative	187-191
Algae Strain: *Pavlova Lutheris*	(36% lipid; 15g/m^2/d) [a)]	Partial Fish Oil alternative. [DHA-rich]	135,179
Algae Strain: *Nannocloropsis Sp.*	(53% lipid; 5g/m^2/d) [a)]	Partial Fish Oil alternative. [EPA-rich]	135,179
CO_2 sourcing	14% vol. concentration	Power Plant- direct, compressed, dried, cleaned and piped Flue Gas. Located within a < 100km radius.	192
Fertilizer	60-70% reduction	Harvest/wastewater culture medium is used and partially offsets NH_3, P_3O_5 and $FeSO_4$ requirements	193
Electricity input	2.6 MJ primary fossil energy	Chinese Electricity Grid Mix	194,195
Primary Algae Dewatering	50x biomass concentration	Settler	184
Secondary Algae Dewatering	20% solid, 100x biomass concentration	Centrifuge	184
Transport		Transport for algae fertilizer, plant feed, shrimp larvae and brood stock considered. No transport costs are considered for dewatered algae feed pond which is adjacent to shrimp pond.	194

a) Values for the year 2010. Productivity yields for 2030 and 2050 are given in Table 11.

This study assumes the primary and secondary dewatering of algae biomass as part of the algae feed production stage. Typical algae production systems designed for fuel and other products also use a two stage dewatering system that achieves ~100x concentration of biomass and an average 20% solid content [184]. No additional

downstream processing, in the form of drying, harvesting or extraction, of algae biomass has been considered. Here, algae feed is only used for direct local consumption, not storage or mass commodity export. With drying and oxidation of algae biomass proven likely to lower the essential fatty acid content of the feed, lead to the dissolution of feedstock and dissipate water soluble solutions which may interfere with the quality of the culture medium, this step has explicitly been excluded from the analysis [136,196]. The algae feed is then piped into an adjacent shrimp hatchery and grow-out pond, which in turn lowers relative transport costs compared to standard feed production. This study only considers the separate production (*ex situ*) of microbial biomass, particularly as *in situ* cultivation of algae and marine species in the same system can lead to contamination or anoxic algae blooms [197,198]. The separate on-site algae open raceway ponds are of an average size of 0.1ha and depth of 30cm. The production process is located in the province of Hainan, China and electricity input is sourced from a domestic electricity grid. This closed cycle system approach combines the removal of nutrients from the shrimp pond and the recycling of wastewater with the production of microbial biomass in a separate tank. A conservative 60-70% reduction in synthetic fertilizer requirements, in the form of ammonia (NH_3), superphosphate (P_2O_5) and ferrous sulphate ($FeSO_4$), is assumed. Several studies have reported considerable nutrient availabilities in typical harvest/wastewater mediums used for algae biomass cultivation, that are sufficiently high to allow for up to a 90% offset of fertilizers needs [29,30]. I suppose the delivery of recovered, compressed, dried and cleaned CO_2, at 14% vol. concentration, from flue gases emitted by a standard 500 MW power plant which is located within a 100 km radius [192]. This farming approach outlines similarities to existing microbial-floc technology used for shrimp cultivation in South East Asia [197,199,200]. It facilitates

intensive shrimp cultivation while reducing investment and maintenance costs and incorporates the potential to recycle feed and minimize fertilizer requirements [9], see Figure 35.

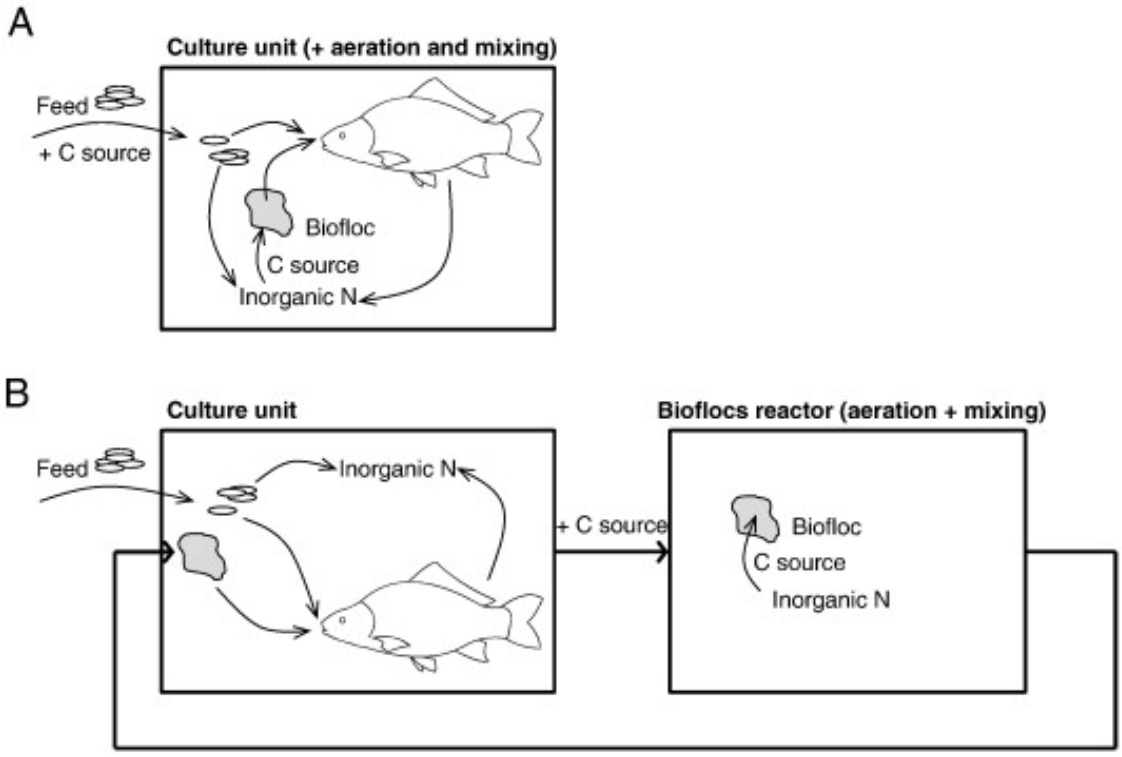

Figure 35: Illustration of in situ and ex situ microbial floc technology

A) Integration of bioflocs within the culture unit by using feed with a relatively low N content and/or the addition of a carbon source. The bioflocs consume inorganic N waste together with the carbon source, thereby producing microbial biomass that can be used as a feed by the animals. (B) Use of a separate bioflocs reactor. The waste water from the culture tank is brought into the biofloc reactor, where a carbon source is added in order to stimulate biofloc growth. The water of the biofloc reactor can be recirculated into the culture tank and/or bioflocs can be harvested and used as a supplementary feed[197,199,200].

Nonetheless, it is noted that freshwater use remains a critical issue in aquaculture. Extreme water use has been documented for intensive pond farming of shrimp (11-43m^3/kg product) comparable to beef (15-43m^3/kg product) and substantially higher than chicken farming (3.5-4 m^3/kg product). The reuse and cage aquaculture systems used in this study, is expected to reduce land and freshwater usage

considerably. For determining the lifecycle fossil energy savings and GHG emissions of using algae feed instead of standard fish feed for shrimp production, a ‘cradle-to-farm-gate’ system framework has been assumed, see Figure 36.

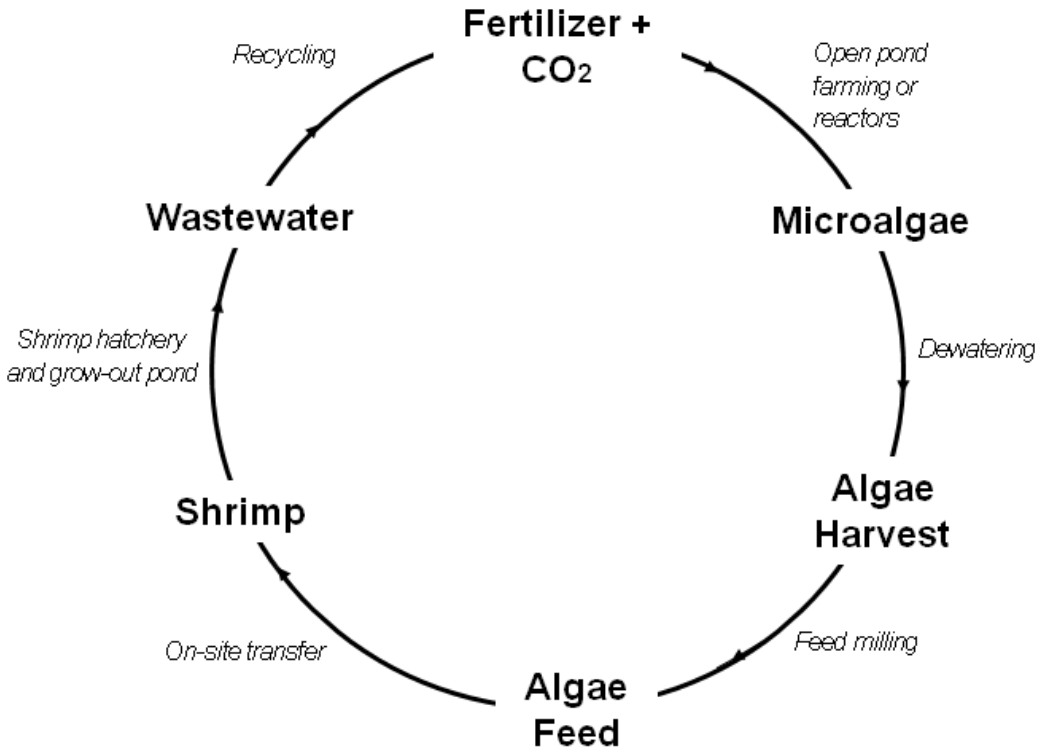

Figure 36: Carbon cycle for shrimp farming with on-site algae feed production.

The closed system approach shows similarities to existing microbial-floc technologies where waste water from the culture tank is diverted into the adjacent algae pond and used as nitrogen source for the harvesting of microbial floc. Crop-based meals are added to the shrimp diet.

Apart from the above detailed cultivation of selected microalgae strains for the replacement of fish meal and fish oil, the system boundaries have been extended to account for feedstock farming of plant meal additives, feed milling, production of shrimp larvae at hatcheries and cultivation of marketable-size shrimp at the farm level.

Here, the global warming potential over a 100-year time horizon and total fossil energy consumption associated with shrimp cultivation on algae diets has been assessed. The functional unit is defined as one ton of live-weight shrimp for a cradle-to-farm-gate system grown on different shrimp diets with varying algae biomass content. Primary operating data, direct and indirect energy requirements are all based on literature values for shrimp farming systems located in Hainan Province, China[194]. The subsequent processing, packaging, distribution and consumption of live shrimp have not been considered.

This study assumes an industrial-scale shrimp hatchery system that is characterized by high densities, water exchange rates and the year-round cultivation of U.S imported specific-pathogen free (SPF) brood stock into shrimp larvae [194]. Harvested shrimp are then transported to intensive shrimp farms, to grow into marketable size and shape. With the high rates of stocking, aerating and water exchange of intensive shrimp farms, no fertilizer inputs and mainly shrimp feed is required. At present, intensive shrimp farms only account for 15% of China's farming systems while small-scale semi-intensive systems provide 85% of domestic supply [194]. As the Chinese government has begun to increase the subsidization of intensive farming for export and the promotion of economic development [194], the focus of this study is on intensive shrimp farming methods.

It is noted that the results of this chapter are subject to uncertainty as substantial challenges are involved in maintaining the biomass production yields of the specifically selected algae strains in an open pond installation. The limitations for large-scale microalgae production in open pond systems are mostly technical with the likelihood of a culture collapse, contamination, poor light utilization, high water losses and immature harvesting technologies. In addition to enhancing biomass

productivity yields attention should also be paid to generating a reliable and constant supply of algae feed which can then be transferred to the shrimp farming systems. Yet, it is suggested that the here made assumptions are plausible and conceivable, particularly as certain microalgae strains grow in highly selective environments which guarantee that while cultivated in open air ponds contamination by other algae strains is kept to a minimum [136]. For example, *Spirulina platensis* algae typically grows in saline and alkaline waters with a pH value of 10-11 and an appropriate concentration of bicarbonates [136].

7.2.1 Life Cycle Analysis Results

Industrial aquafeed is processed from a mix of fish meal, fish oil and crop-based proteins such as soybean meal, corn and wheat [177]. Since fish feed accounts for 40-50% of total production costs [197,199], algae-based diets are expected to yield significant cost and GHG emissions savings when replacing fish meal and fish oil ingredients in a standard shrimp diet.

The large-scale replacement of aquafeed with algae must comply with an array of criteria ranging from nutritional suitability, ready availability, ease of handling, reduced pollution, improved health benefits and competitive pricing [136]. The use of dewatered algae biomass as direct on-site feed source has shown to not affect the survival and growth rate of cultured shrimp species [136,179,183,185,190,191,197,198]. Despite shrimp being animals which naturally graze the bottom of ponds for food from algal, bacterial and fungal sources [198], additional future feeding trials will be necessary to confirm that species are able to digest higher levels of algae feed [190]. However, preliminary studies have shown that given compositional parity, several marine

species are able to consume higher shares of algae feed as part of their diet [179,187,188,190,196,197,200,201].

Here, the on-site open pond cultivation of three phototrophic microalgae strains (*Spirulina Platensis, Pavlova Lutheri* and *Nannocloropsis sp)* is assumed as direct source of protein and highly unsaturated fatty acids, further described in the Methods section. The selected microalgae batches highlight superior productivity yields which are of several magnitudes higher than comparable vegetable oil crops [132, 208, 226], see Table 11.

Table 11: Composition and productivity of plant-meal and algae

Feedstock	**Proteins**	**Carbo-hydrates**	**Lipids**	**Other**	**Productivity [b)]**				
					2010			**2030[c)]**	**2050**
	%	%	%	%	t/ha/y	g/L	$g/m^2/d$	$g/m^2/d$	$g/m^2/d$
Wheat	10-12	70-74	2-3	10-17	4.3				
Rapeseed	20-32	5-10	38-50	30-34	1.8				
Sunflower	10-25	10-15	38-54	15-20	2.5				
Soybean	32-50	25-30	18-24	15-20	1.8				
Spirulina platensis	46-63	8-14	11	2-5	38	0.15	11	21	32
Pavlova Lutheri	-	-	36	-	55	0.1	15	30	45
Nannochloropsis sp.	-	-	53	-	19	0.1	5	11	16

a) The values given for microalgae are based on open pond cultivation.
b) Figures for increased algae biomass productivities for the years 2030 and 2050 are part of a high-low scenario approach and are based on the assumptions that with technical maturity and increased efforts higher yields with be engineered in the mid-term future. Average Values are here given.
c) This LCA analysis is based on the assumption of achieving improved productivity yields around 11-30$g/m^2/d$ by 2030 and 16-45 $g/m^2/day$ by 2050.

In this study, a carefully selected mixture of algae strains is chosen to mimic the exact nutritional profile of fish oil and fish meal ingredients. So far these highly sensitive phototrophic microalgae batches have mainly been cultivated, in reliable

volumes and at low productivity yields (around 5-11g/m^2/day), only on a laboratory scale and in closed bioreactor [28]. However, as the commercial use of microalgae for animal feed replacement is still in its infantry, improvements in productivity yields to 11-30g/m^2/d by 2030 and 16-45 g/m^2/day by 2050 are assumed.

This LCA study shows results for the lifecycle fossil energy demand and GHG emissions of processing algae as shrimp feed replacement in the year 2010, 2030 and 2050 at the respective higher biomass productivity levels. For each timeframe, it considers three different algae-based diets which vary in their respective share of fish meal, fish oil and plant meal replaced, see Table 12. Different compositions aim to account for variations in digestibility and palatability of the feed mixtures by the cultivated marine species.

Table 12: Outline of three algae feed diets and a generic shrimp feed diet

Shrimp Feed	**Fish oil**	**Fish meal**	**Crop meal**	**Algae meal**	**Algae oil**	**Other** [a)]	**FCR** [b)]
Standard Diet	3%	46%	44%	-	-	7%	1.6
Diet 1	-	-	67%	**23%**	**3%**	7%	1.15
Diet 2	-	-	44%	**46%**	**3%**	7%	1.15
Diet 3	-	-	-	**90%**	**3%**	7%	1.15

a) Other refers to a mixture of vitamins, colors and minerals.

b) FCR ratio outlines the feed conversion ratio i.e. the efficiency of converting fish feed per unit of weight gain. FCR values are considerably lower for shrimp diets with a considerable portion of algae feed

Diet 1 translates into a low-case scenario, which replaces half of fish meal and all of fish oil input with algae and the remaining protein share with crop meal, a mix of corn, soybean meal and wheat. Diet 2 involves a balanced feed mixture of mainly plant meal, algae meal and algae oil. Diet 3 is a high-case scenario, which completely replaces both crop meal and all fish-based ingredients with microalgae. An improved FCR ratio of 1.15 (i.e. 1150 kg feed per 1000 kg live-shrimp) is

assumed for all algae-based diets compared to a standard shrimp FCR value of 1.6. This assumption is based on other studies [17,23,30] highlighting that a larger share of microbial biomass improves animal growth level and lowers the feed consumption of marine species. A detailed outline of the specific algae feed compositions assumed for all three diets per kg of feed and kg feed per ton shrimp produced, can be found in Appendix 10.3. The results show that compared to the lifecycle fossil energy demand (61.5± 6.1 GJ/ton shrimp) and GHG emissions (5.3± 0.5 ton CO_2/ton shrimp) of a Chinese intensive shrimp farm operated on standard aquafeed [194], the use of all three algae diets, in each respective time period, will result in lower environmental burdens, see Figure 37. In fact by 2050, the use of algae diet 1 can result in savings of up to 22% in GHG emissions (4.1 ton CO_2/ton shrimp) and 30% in lifecycle fossil energy demand (43 GJ/ton shrimp).

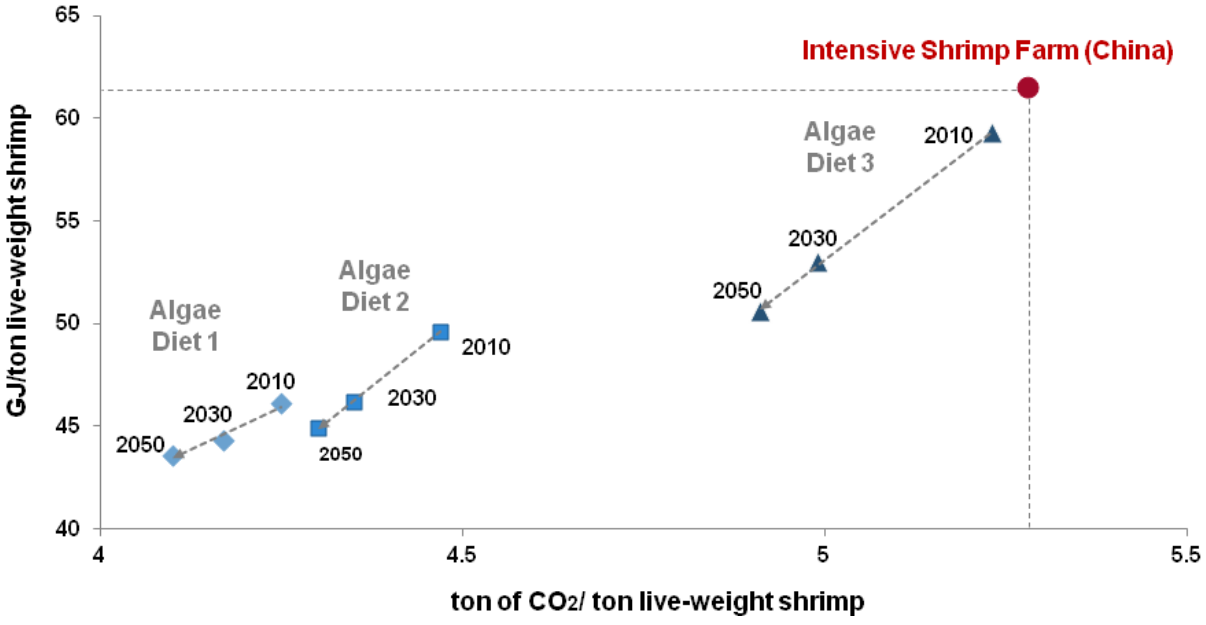

Figure 37: Lifecycle results for the production of algae feed from 2010-2050

Summary of lifecycle results for the fossil energy demand (GJ/ton shrimp) and GHG emissions (ton CO_2/ton shrimp) of operating an intensive shrimp farm on three algae diets in different time periods (2010, 2030, 2050). Standard shrimp feed processed in an intensive shrimp farm is given as benchmark value [194].

The relative lifecycle contributions of Diet 1-3 against the use of a standard shrimp feed diet are further detailed for the year 2030 and illustrated in Figure 38. A detailed breakdown of the lifecycle results for the year 2010 and 2050 is given in Appendix 10.3. With the algae-rich feed composition of Diet 1, the total system requires 44 GJ/ton shrimp compared to standard shrimp feed with 62 GJ/ton shrimp, and emits 4.2 tons CO_2/ton shrimp relative to 5.28 ton CO_2/ton shrimp, see Figure 38. In Diet 1, the share of algae feed production accounts for 12% (5.5 GJ/ton shrimp) of total fossil energy demand. With the inclusion of plant meal additives, the relative contribution of the feed stage increases to 23% of total fossil energy demand (10.2 GJ/t shrimp).

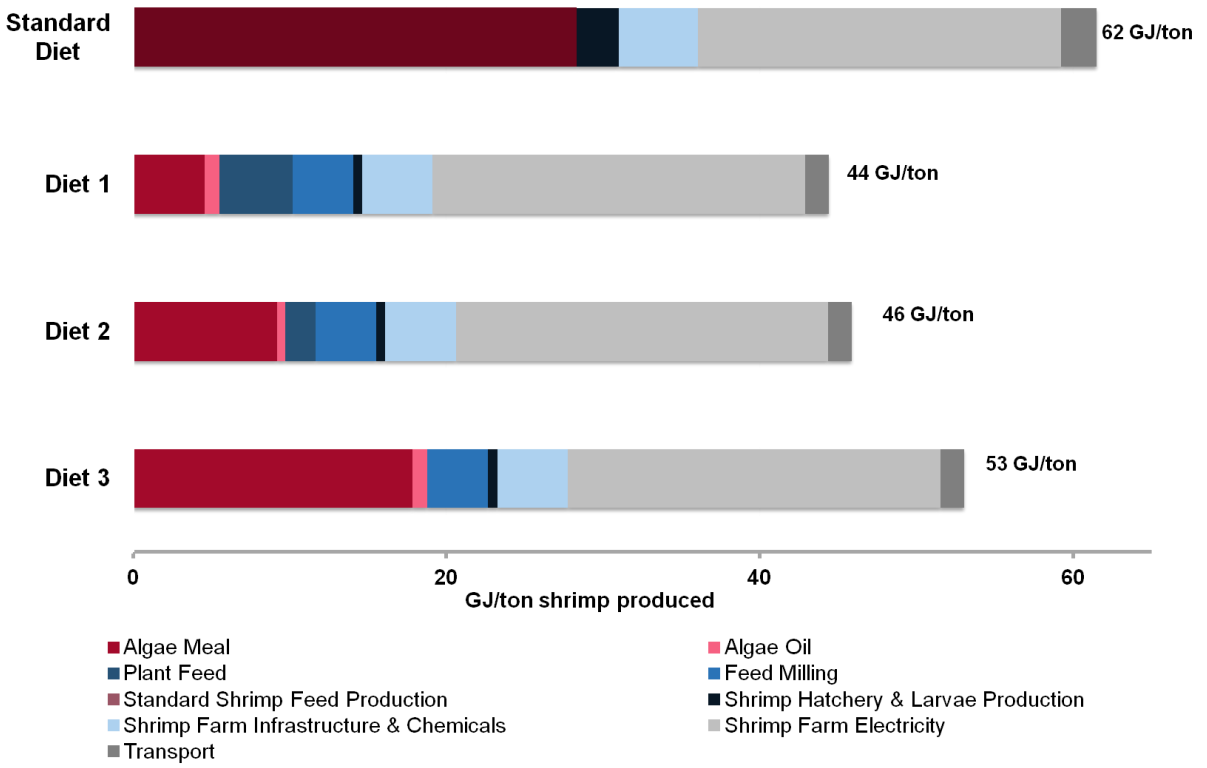

Figure 38: 2030 lifecycle energy demands of Chinese intensive shrimp farms.

The 2030 cumulative energy demand of an intensive shrimp farming process in China is presented for three algae-based diets and standard shrimp feed. Diet 1 to 3 replace plant and fish-based feed ingredients in various compositions with selected microalgae strains that are cultivated in on-site open ponds. For the year 2030, the overall reduction in lifecycle fossil energy use through the replacement of feed input ranges from 14%-28%.

In comparison, standard shrimp feed production (28.3 GJ/ton shrimp and 2.1 ton CO_{2eq}/ton shrimp) would account for almost 54% of the total farming system. Here, fish meal, wheat and feed milling are the largest contributors, with fish meal alone accounting for 47% of the process' global warming potential and lifecycle fossil energy demand[194]. Apart from feed production, carbon-intensive electricity (38-46%) input continues to impair the respective lifecycle fossil energy demand and GHG emissions balance [194]. Likewise, the total lifecycle fossil energy consumption of Diet 2, around 46 GJ/ton shrimp and GHG emissions balance at 4.3 tons CO_{2eq}/ton shrimp, are still 25% and 18% lower than standard shrimp cultivation, see Figures 39. The feed production stage of Diet 2 consists of a balanced mixture of plant meal and algae biomass and requires 11.7 GJ/ton shrimp while emitting 929 kg CO_{2eq}/ton shrimp. Diet 3 mirrors a future feed composition with no plant meal additive or fish-feed ingredients but a mixture of several microalgae strains. The complete substitution of fish and plant-based ingredients would result in a relative increase in the lifecycle energy demand (11.7 GJ/ton) and GHG emissions balance (1.5 tons CO_{2eq}/t shrimp) of the feed farming stage, compared to Diet 1 and 2. In this case, the lowest improvement in relative environmental performance would be achieved, with a 14% reduction in lifecycle energy demand and 8% reduction in GHG emissions.

No further substantial energy and emissions savings can be achieved as all additional reductions are held back by the carbon-intensity of China's coal-based electricity and heat grid. Electricity input accounts after feed as the next environmental hotspot with large contributions of 45%-53% to both impact categories. The carbon footprint of the intensive shrimp farming system can only be further minimized through the successful decarbonisation of the electricity grid and the sourcing of all indirect energy requirements for fertilizers, transport and building

materials, from low-carbon energy sources. In other key shrimp farming nations, which operate on a defossilized electricity grid, such as Brazil, more substantial savings in fossil energy demand and GHG emissions can be expected. These results are in direct agreement with conclusions from chapter 4 and 5, and highlight a similar dependence of effective GHG mitigation potential on the carbon footprint of electricity generation [183,202]. The results of this LCA study also confirm previous work stressing that most environmental impacts for both shrimp and salmon farming are concentrated at the production level, and are low for subsystems and marginal for infrastructure and transport [194].

7.2.2. Cost Calculations

Although there are considerable reductions attainable in GHG emissions and fossil fuel consumption, the economic constraints on the production of phytoplankton have so far been recognized as the main barrier for the development of mass feed production from microalgae. Currently, microalgae are mostly marketed as high-value food additive for human and animal nutrition, both in tablet or powder form. As dried, pressed and pellet-shaped feed ingredient, algae additives have reached prices anywhere between $40 per kg and $2800 per kg [9,182,203 136]. However, the commercial potential for microalgae represents a largely untapped resource, which will undoubtedly gain in importance given its superior efficiency in respect to land, water and energy use.

Here the future cost effectiveness of on-site algae feed production for direct consumption is examined. The cost calculations are based on the assumption of large-scale algae feed production in open raceway ponds at an average size of 2 ha,

similar in size to standard intensive aquaculture farms. This chapter outlines how in the mid-term future microbial feed production has the potential to become a financially viable alternative to standard fish feed production, under the condition of appropriate farming methods (detailed in the above section), and the continuous improvement in biomass productivities. This analysis outlines total production costs for each of the three processed algae strains in 2010, 2030 and 2050. For each year a certain level of algae production per hectare per year and a certain level of wild fish meal cost is assumed. Break-even points for algae feed production relative to fish meal and fish oil costs at different levels of algal production efficiency are shown, considering all other factors remaining the same.

Firstly, I illustrate current (2010) break-even costs for the production of *Spirulina Platensis, Pavlova Lutheris and Nannocloropsis sp* algae strains at low productivity yields, around 5-10 g/m^2/day. At such low efficiency levels for algae biomass production, the total production costs for algae feed are not financially competitive compared to the relatively cheaper cost of wild fish meal and fish oil ingredients, see Figure 39. Here, total algae production costs range from $2839/ton (*Pavlova Lutheris)* to $3981/ton (Spirulina Platensis) and $7813/ton (*Nannocloropsis sp*), which is several magnitudes higher than respective fish meal ($1356/ton) and fish oil prices ($1162/ton). However, in the coming decades the limited global supply of fish meal and fish oil will undoubtedly lead to a considerable further increase in international fish feed prices, which will affect the relative attractiveness of processing algae as a mass feed source. According to reports by the Organisation of Economic Co-operation and Development (OECD) and the Food and Agriculture Organisation of the United Nations (FAO) [204], fish meal prices are expected to increase by 43% until 2020 compared to 2008-2010 levels. During the same period,

fish oil prices are projected to grow by 19% [204]. With future projections beyond 2020 being unavailable, I here assume the on-going linear price trend for fish meal and fish oil until 2050. I also expect the rising consumption in plant-based proteins as bulk feed source for terrestrial animals to raise global prices for vegetable crops, such as soybean meals [22,28], and influence the future viability of algae as an alternative protein source. Here the predicted future price for soybean meal is based on today's average standard food price inflation of around 4.5% per year [205,206].

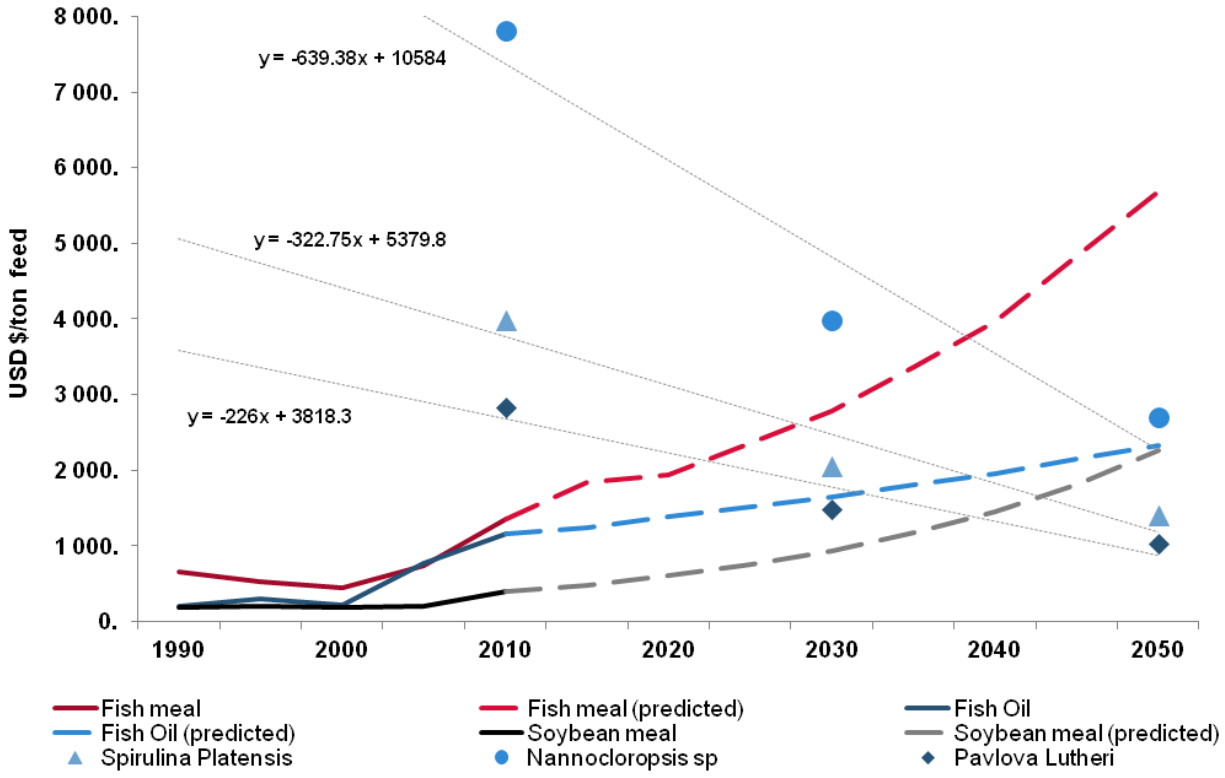

Figure 39: Cost breakdown for the cultivation of microalgae feed

Estimated cost breakdown for the cultivation of three phototrophic microalgae strains in an open raceway pond. Algae Feed production costs are given for the year 2010, 2030 and 2050 and assume different levels of algal production efficiency while all other factors remain constant. Historic and projected prices for fish meal, fish oil and soybean meal are given as benchmark values.

By the year 2030, international prices for fish meal, fish oil and soybean are expected to have risen to around $2777/ton, $1645/ton and $938/ton. During the same period, it is assumed that an increase in algae biomass productivity yields to conservative averages around 10-30g/m^2/day has been achieved, given the technical maturity around the engineering of superior algae yields. Relative to the rising price of marine feed sources, the commercial production of algae species, such as *Spirulina Platensis* ($2045/ton) and *Pavlova Lutheris,* ($1483/ton) will show early signs of becoming a cost competitive alternative to fish feed. Soybean meal will remain a cheaper source of protein for the foreseeable future.

By 2050, global supplies of fish meal and fish oil are likely to be almost fully depleted. The rising demand for marine protein sources will have pushed fish meal prices to unprecedented highs which are almost four times the level of 2010 [204]. Assuming that the industry has responded accordingly to a likely threat of a looming fish feed depletion crisis and fortified efforts to process algae as a large-scale feed source, this particular analysis will outline a high-end case of algae productivity yields around 30-45g/m^2/day. All other algae production costs remaining constant, all three algae species outline cost-competitive production costs below the rising price of marine feed sources. In addition, by the year 2050 the total production costs for *Pavlova Lutheri and Spirulina Platensis* algae strains at around $1031/ton and $1399/ton, would be lower than predicted soybean meal prices around $2263/ton.

This study translates the individual algae strain price predictions into estimates for the open pond based production costs for Diets 1 to 3, with a varying share of microbial biomass, see Table 13. Values are compared against the relative price of a standard shrimp feed diet, designed at the same composition as seen in Table 12.

Table 13: Total production costs of three algae diets in 2010, 2030 and 2050

Values are given in $/ton feed.

Year	**(2010)**	**(2030)**	**(2050)**
Diet 1	1336	1181	1894
Diet 2	2162	1435	1695
Diet 3	3743	1922	1315
Standard Diet	**830**	**1739**	**3677**

It is noted that these cost estimates are only indicative and depend among others things on the final composition of feed, type of organic carbon source and inclusion of various degrees of biomass drying. By 2030, the production costs for Diet 1 ($1181/ton) and Diet 2 ($1435/ton) will be comparatively lower than for standard feed mixtures at $1739/ton. This result is in agreement with the break-even price calculations for individual algae strains against the rising price of fish meal and fish oil sources. With relatively lower prices for soybean, it is suggested that algae feed should be mixed with affordable crop-based ingredients for the foreseeable future to guarantee their financial viability and address any remaining concerns regarding animal palatability and digestibility, further shown in Methods below. Otherwise, a 100% algae-based shrimp diet (Diet 3) could only be produced at a higher cost of $1922/ton.

In addition, it is anticipated that once economics of scale for mass algae feed production are implemented, expenditures around CO_2 injection, nutrient supply, maintenance and labor can be considerably reduced. Fertilizer requirements are already reduced by 60-70% through the recycling of wastewater and effluents from the shrimp culture pond. Likewise, while the type of carbon source used is important for controlling water quality in open pond systems and the nutritional properties and

digestibility of cultured organisms [199], flue gases from coal-fired power stations, which are directly pumped into the pond, or similar by-products of local industries can provide future low-cost external carbon sources. A detailed summary of all calculations and cost-break down for each algae strain is given in Appendix 10.3.

7.3 Conclusions

Skyrocketing global marine protein consumption linked to depletion of wild fisheries and rising demand levels from China have left the aquaculture industry facing a global tipping point in an era of finite fish meal and fish oil resources. Well before the year 2030, the superior land-use efficiency of microalgae may provide a vital solution to feeding a protein-hungry human population with likely depleted marine sources of fish oil and fish meal as well as limited marginal land and freshwater available.

This chapter provides a quantitative assessment to show how microbial feed production can act, under certain farming conditions, as a sustainable future food source producible at affordable prices and as part of a resource-efficient and low carbon farming process that maintains essential ecosystems. Herein, the *ex situ* cultivation of microalgae at relatively enhanced biomass yields in on-site open raceway ponds is assumed. The dewatered algae biomass is not removed from the culture fluid for further drying, harvesting or processing and only considered for direct local consumption rather than feed storage or mass commodity export. This model farming approach reduces investment and maintenance costs and incorporates the potential to recycle feed and reduce fertilizer requirements, similar to existing microbial-floc technology. The results show that the production of dewatered algae feed suitable for local on-site consumption would result in 18-29% lower capital and

operating costs in 2030 compared to standard feed production. By the year 2030, algae feed production as part of the above mentioned farming process and at enhanced average biomass yields around 10-30g/m^2/day, will become cost-competitive against the elevated prices for depleting fish meal and fish oil resources. Preliminary costs estimates for producing algae ingredients by 2030 range between $2045/ton to $1483/ton and demonstrate the feed's financial feasibility against the skyrocketing price of fish meal and fish oil at $2777/ton and $1645/ton, respectively.
In addition, the results for 2030 future projected performance show that compared to standard shrimp farming on commercial fish feed diets, algae-based cultivation can provide savings of up to 14-28% in lifecycle fossil energy demand and 8-21% in GHG emissions. Additional reductions can be achieved through the successful decarbonisation of a fossil fuel based electricity grid and the sourcing of all indirect energy requirements for fertilizers, transport and building materials, from low-carbon energy sources.

As water, energy and land usage in aquaculture are all interactive, the results of this study act as an essential first step to quantify the potential environmental and economic value of future microalgae use. In an era in which the rise of global middle class consumers is faced with depleting marine protein sources, marginal land availability and rising freshwater needs, microalgae feed production has the potential act as a future game changer and transform a global tipping point into a turning point.

7.4 Materials and Methods

7.4.1 Cradle-to Farm-Gate:

The pond systems assumed for this LCA study are of an average size of 0.1 ha, 30 cm depth and holds a water volume of 0.03 m^3/ha. The supply of nutrients is based on the initial algae broth concentration in the pond and its particular stoichiometric requirements. Fertilizer requirements include nitrogen in the form of ammonia (NH_3), phosphorous in the form of superphosphate and potassium (K_2O).Through the recycling of wastewater the nitrogen and phosphorous usage of microalgae batches can be reduced by roughly 60%. A certain amount of freshwater will have to be processed as part of the algae farming stage to compensate for water evaporation losses and avoiding substantial salt build-ups. Fish cage farming and shrimp aquaculture use on average less land and freshwater but are among the highest energy consuming aquatic farming methods, comparable to intensive animal feedlots. The quantities of building material needed for the manufacturing of the open pond, the larvae hatchery facility and shrimp grow-out pond facilities (i.e. pipes, paddle- wheels, foundations, rotary press, etc.) are calculated to estimate the associated environmental burden for the construction of the production plant and are outlined in Appendix 10.3. Details on the feedstock, process parameters, stages of production, principal inputs required, and outputs produced are given in Appendix 10.3. Given that at present no large-scale algae feed plant is commercial operation, the majority of process information is based on literature reviews and analyses.

7.4.2 Aquafeed composition

Aquafeed input varies by fish species and the marine animal's tropic level which indicates its position on the food chain [207]. While carnivorous fish naturally require larger amounts of fish-based feed to produce a unit of weight gain, herbivorous species have been adapted via intensification [175] to the same aquafeed diet to increase animal growth rates and nutritional values [208].

For the replacement of marine proteins such as fish meal, *Spirulina Platensis* microalgae outlines a compatible and balanced amino acid profile in addition to a high protein content, low nucleic acid content (<4%), high levels of β-carotene, folic acid, vitamin E, B12 and biotin [185,190,191] [190], see Table 14.

Table 14: Amino acid profile for microalgae, fish meal and soybean meal [208]
Values in (g/100g protein).

Essential amino acid	Fish meal	Soybean meal	Spirulina platensis
Isoleucine	3.02	5.3	6.7
Leucine	4.84	7.7	9.8
Valine	3.41	5.3	7.1
Lysine	**5.05**	**6.4**	**4.8**
Phenylalanine	2.69	5	5.3
Methionine	**1.87**	**1.3**	**2.5**
Tryptophan	0.72	1.4	0.3
Threonine	2.71	4	6.2
Arginine	3.67	7.4	7.3
Histidine	1.55	2.6	2.2

For some marine species, substitution levels of more than 50% algae meal as primary protein source may lead to adverse effects on growth and feeding efficiency [190]. Experimental studies on tilapia fish have shown a tendency to reject higher levels of algae meal inclusion (+50%) due to increased particle hardness from high spirulina content [190].However, with most studies on the digestibility of algae feed by carnivorous species have been successful [179,187,188,201], and I believe a similar inclusion rate or even higher ones for shrimp species are reasonable. Especially as shrimp are detritivores animals which naturally graze the bottom of ponds for food from algal, bacterial and fungal sources [198] and therefore are able to digest higher levels of algae-based protein without any adverse health effects [137].

Fish oil provides important long-chain highly unsaturated fatty acids (HUFAs), in form of dososahexaenoic acid (DHA) (22:6n-3), eicosapentaenoic acid (EPA) (20:5n-3) and docosapentaenoic acid (DPA) (22:5n-6) [135]. These long chain fatty acids, with ≥ 3 double bonds, mostly in the n-3 and n-6 series, and ≥ 20 carbon chain length are essential in the synthesis of neural tissue and the regulatory physiology of marine carnivorous species [136,182]. Owing to the balance of essential fatty acids and the absence of DHA and EPA chains, the replacement of fish oil with plant oils is yield as greater challenge [175,178]. However the lipid share of certain phototrophic microalgae strains, such as *Pavlova Lutheri* and *Nannochloropsis sp*, is compatible in combination, with present fish oil ingredients, see Table 15 [182 136].

Nannochloropsis sp, algae outlines an appropriately high level of EPA fatty acid ingredients and is in this study considered as one of two potential marine lipid sources. Pavlova Lutheri, algae outlines an appropriately high level of DHA fatty acid ingredients and is considered as the other potential marine lipid source, which must

be used in combination with Nannochloropsis sp to outline a compatible fatty acid profile to standard marine oil sources.

Table 15: Fatty acid profile of marine species and microalgae [134, 218, 234]

Average Percentage of Fatty Acids	Anchovy	Cod Liver	Krill	Nannochlo-ropsis sp a)	Pavlova lutheri b)	Spirulina Platensis c)
14:0	8	6	9	3	14	0
16:0	18	14	22	14	11	28
16:1n-7	11	8	4	19	10	2
18:0	6	3	1	11	-	6
18:1n-9 oleic acid	15	19	16	-	3	33
18:2n-6 linoeic acid	1	2	2	6.77	-	10
18:3n-3	1	1	2	-		1
18:4n-3	3	3	4	-	4	1
20:0	4	-	-	3	-	-
20:1n-9	3	10	1	-	-	-
20:4n-3	1	1	1		-	-
20:4n-6	1	1	1	1	-	0.3
20:5n-3 (eicosapentaenoic acid)	**12**	**9**	**22**	**18**	**12**	**2.3**
22:0	1	1	-	-	-	-
22:1n-11	2	13	-	-	-	-
22:5n-3	2	2	1	-	-	-
22:6n-3 (dososahexaenoic acid)	**12**	**9**	**13**	**-**	**7**	**3.3**
SFA	36	23	32	31.3	25	34
MUFA	30	49	22	19.5	13	35
PUFA (< 20 carbon)	**5**	**6**	**3**	**6.8**	**4**	**12**
lcPUFA	26	21	43	19.7	19	6
n-3 FA	**30**	**24**	**43**	**18.2**	**23**	**7**
n-6 FA	**2**	**3**	**3**	**8.2**	**0**	**11**

a) *Nannochloropsis sp*, algae outlines an appropriately high level of EPA fatty acid ingredients and is in this study considered as one of two potential marine lipid sources.

b) *Pavlova Lutheri* algae outline an appropriately high level of DHA fatty acid ingredients and is in this study considered as another potential marine lipid source.

c) In this study *Spirulina Platensis* algae, is considered a suitable substitute for marine proteins but not for fish oil given its unbalanced and comparatively low fatty acid profile.

8. Conclusions and Future Work

8.1 The Role of Algae Biomass for Fuel and Feed Production

The world's supplies of food, energy and water are in greater demand than at any other time in human history, yet these vital natural resources are finite. Meeting future demand in an environmentally responsible manner will be an enormous challenge given the rise in anthropogenic greenhouse gases [1]**.** In the transport sector, the search for alternative fuels is relentlessly underway with 90% of liquid fuels being hydrocarbon sourced [5] and uncertainty around depletion levels of conventional oil reserves mounting. Global vehicle ownership is forecast to reach two billion [5] in the near future and climate change concerns are expected to rise. Fuels derived from unconventional oil resources could initially solve the issue of falling conventional oil resources, but will inevitably exacerbate the problem of increased environmental pollution [6] and increased cost. Biofuels can be a viable substitute for fossil fuels, most notably when produced in a sustainable manner and from feedstock that is not in direct competition with food or animal feed production. While the myriad of new green fuel technologies can collectively have a significant impact on replacing a share of the current energy demand of our global transport system, relatively few technologies can individually make major contributions. Still, biofuels are potentially a crucial player in the design of a low carbon, sustainable fuel mix that will drive efforts to decarbonize our global economy.

Food security is also nearing the top of the global political agenda, with a projected 2050 population of 9-10 billion – including many more global middle class consumers

seeking a protein-rich diet. Skyrocketing global marine protein prices linked to the depletion of wild fisheries and rising demand from China have left the aquaculture industry facing a global tipping point of finite fish meal and fish oil resources. If aquaculture is to sustain its current growth rate of 8.3% per year [3,176] and rise to 79-110 Mt by 2030 [177], it follows that the supply of aquafeed must grow at a similar rate to meet rising global demand. Yet, it has been estimated that the future rising demand from China alone can deplete the entire world's supply of fishmeal and fish oil by 2030 [4].

In an era of increasing concerns around the global water-food-energy nexus, coupled with the issue of marginal land availability and land-use change, this thesis provides a systematic lifecycle assessment on how best to use abandoned or degraded land to address, through the use of microalgae feedstock, the issue of global food and fuel demand.

Algae biomass production possesses several advantages over terrestrial crop cultivation for biofuel production. Microalgae, rich in lipids and protein, can grow in waste and saltwater and are adapted to survive in naturally resource limited environments when producing superior biomass yields per hectare compared to other feedstock [7,8]. Microalgae have high growth rates which allow for a doubling of biomass productivities in relatively short time periods, and are capable of all year round production, which increases the oil productivity of the feedstock[9 10]. Relative to the cultivation requirements of other advanced feedstock, microalgae farming require mainly solar radiation, carbon dioxide, water and nutrients in the form of inorganic salts. The algae farming process does not require any form of pesticides or herbicides and can be improved through the sourcing of nutrients (especially nitrogen and phosphorous) from wastewater sources which in turn also reduces

freshwater consumption. Compared to hydrocarbon based fuels the inherent potential advantage of biodiesel production from algae remains its lower lifecycle GHG emissions. Algae biomass converts atmospheric CO_2 through photosynthesis into bio plant material which is eventually released back into the atmosphere when used as a fuel and consequently emitted in the form of engine tail pipe emissions. In comparison, fossil fuel combustion releases additional carbon which took millions of years to be removed from the atmosphere [11].

Given the nutrient profile of microalgae, promising fuel paths include the conversion of algae biomass to synthetic oil products, such as jet fuel, synthetic diesel or gasoline. However, to be a viable substitute for fossil fuels, an alternative fuel should emit less GHGs than the fossil fuel it displaces, provide a net energy gain above the fossil energy input [12], use all residual co-products within the cycle, be producible at prices competitive with crude oil, and be available in meaningful volumes to impact on energy demand.

With rising concerns over the availability of middle distillate fuel products from fossil sources [6,33,34], the reliance of the aviation and road transportation industry on a single finite fossil fuel source is expected to eventually extend into the algae biofuel sector. For the road transportation sector there are several options available to lower carbon emission, including electric vehicles, hybrids and compressed natural gas technologies. In comparison, when mapping out ways to reduce emissions from aviation, several critical issues remain. For example, it is of crucial importance to guarantee the ongoing safety through the provision of only proven and technologically sound applications in aircraft. Secondly, with the very long lifetimes of commercial aircraft fleets and the highly asset-intensive nature of the industry, drop-in low carbon liquid fuels seem to be the only alternative in the foreseeable future.

Otherwise, reduced noise or pollutant emissions can lead to tradeoffs with the overall efficiency of the propulsion system.

From a lifecycle perspective, producing biodiesel from algae biomass consumes 2.5 times more total energy (3.2 MJ/MJ_{fuel}) than conventional diesel (1.2 MJ/MJ_{fuel}) from the United States and nearly as much as the high fuel-cycle energy use of oil shale diesel. The carbon footprint ranges between 78 to $160_{g}CO2/MJ_{fuel}$, depending on the carbon intensity of national heat and electricity grids and the utilization method for algae residues. Over time conventional oil resources are being depleted and unconventional resources, in the form of shale oil, will account for a larger uptake. Hence, the fossil energy demand of algal biodiesel should instead be compared to the higher fossil energy requirements ($1.65MJ/MJ_{fuel}$) and GHG emissions (182 gCO_{2eq}/MJ_{fuel}) of unconventional resources.

Similarly, the production of algae jet biofuel from fossil fuel sources requires 1.9 MJ of total fossil energy input while emitting 213 g CO_{2eq}/MJ_{fuel} which is considerably higher than the lifecycle fossil energy requirements for analogue kerosene from crude oil (1.1 MJ/MJ_{fuel}) or stranded natural gas (1.7 MJ/MJ_{fuel}) [53]. The majority of GHG emissions for both algae biodiesel and jet biofuel production are emitted in the Field-to-Tank stage, which consist of energy intensive feedstock farming, harvesting, drying, conversion and fuel distribution. The high energy input, which is both directly and indirectly needed for the production of fertilizers, CO_2 injection, biomass drying pond and harvesting facilities, puts a large caveat on the financial and environmental feasibility of low carbon algae fuel production. One option to partially lower the economic running costs of the process is to displace costly grid heat and electricity through the smart usage of biomass leftover, investigated here through the application of gasification, Fischer-Tropsch fuel synthesis, biomass combustion and

combined heat and power generation. To further optimize the lifecycle fossil fuel use and GHG emission balance of both algae jet biofuel and biodiesel below analogue fossil fuel levels, fertilizer use must also be offset through wastewater recycling which in turn is expected to lower freshwater consumption of open pond installations. In addition, exhaust gases from nearby power plants (e.g. within 100km distance) should be recovered as a cheap source of CO_2. Most importantly, biofuel production from algae biomass can only ever realize its inherent environmental advantages of GHG emissions reduction, once every step of the production chain is fully optimized and decarbonized, which includes the sourcing of all direct energy input in the form of heat and electricity, as well as indirect requirements for fertilizers, transport and building materials, from low-carbon energy sources.

In light of current research efforts and investments being directed at the engineering of microalgae strains with superior lipid content to raise the relative productivity of algae biofuels, this thesis also highlights that the critical break-even algae lipid content which meets the life-cycle fossil energy use of fossil kerosene has already been reached. The break-even-point, at which the algal oil-to-biomass ratio meets the fossil energy requirements of kerosene from crude oil (1.1 MJ/MJ_{fuel}), is met at an average 30% oil content (*Chlorella Vulgaris* algae strain). Once this threshold is passed, any further increases in lipid rates only result in marginal improvements of the cumulative energy demand of algae jet biofuel production.

Once all these farming conditions are guaranteed, the lifecycle results for both biodiesel and jet biofuel production are considerably improved. For example, jet biofuel from algae feedstock can operate on an improved fossil energy balance which is 30-80% lower than that of analogue Jet A-1 fuels from crude oil. Specifically, algae jet biofuel can be optimized into a comparatively low carbon fuel

source with lifecycle fossil fuel usage ranging from as low as 0.4 MJ/MJ_{fuel} to 1.4 MJ/MJ_{fuel}. The exact value depends on the algae oil-to-biomass ratio, the co-product use and share of fossil energy input. Here, the threshold value of 0.4 MJ/MJ_{fuel} accounts for all remaining input parameters in the form of transport, chemicals and infrastructure, which require fossil energy as part of their production process. Building material in the form of steel, concrete and glass fiber needed for the construction of the algae farming pond and harvesting material will continue to place a large fossil and financial deterrent on algae jet biofuel becoming a feasible zero-carbon fuel source. For algae biodiesel production, co-product utilization to offset carbon intensive grid heat and electricity can improve lifecycle fossil energy use from 3.2 MJ/MJ_{fuel} to 1.7 MJ/MJ_{fuel}, respectively.

Moreover, with the asset intensive nature of the transport industry, alternative liquid fuels can only ever be viable substitute which impact the fuel price or the environmental footprint of the sector, once sufficient quantities of sustainable biomass feedstock are available at low cost and with a minimal impact on marginal land availability. Based on the high production volumes and superior land-use efficiency of algae biomass, the global land mass necessary to satisfy fossil fuel consumption could be reduced considerably. When comparing the global land requirements for processing microalgae for biodiesel or jet biofuel production, the relative attractiveness of the bio kerosene production becomes clear.

For algae-derived biodiesel with a yield of 850 GJ/ha/y (30% oil content), to replace the current total production of 1.1 billion tons of petroleum-derived diesel per year, a land size of around 57 million hectares would be required which approximates to an area somewhat larger than Spain and smaller than Texas. However, replacing the total production of fossil-based kerosene of 10.7 EJ/year in 2010 with algae jet

biofuel at a theoretical yield of 1,265 GJ/ha/year (45% oil content), an arid land mass of 8.5 million hectares would be necessary for production and cultivation. This area approximates to the size of Ghana and would be considerably lower than the land requirements for kerosene production from second generation biomass, such as Jatropha with a dry seed yield of only 5-4 tons/ha/year. Considering the future availability of marginal land and the projected demand for transport fuels by 2050, a complete replacement of global fossil kerosene demand (24-39 EJ/year) with a future 100% algae jet biofuel blend would require between 19 and 28 million ha/year of marginal land for feedstock cultivation and fuel production. By comparison, to fully replace global diesel demand in 2050 (61-86 EJ/year) with algae biodiesel, 60% higher land use (48-67 million ha/y) will be needed. The results partly outline the relative scale of both industries. When the relative attractiveness of processing algae for biodiesel and jet biofuel is compared on a unit production cost, both renewable fuel products remain considerably more expensive than fossil fuels. While the economics of producing algae fuels needs to improve substantially to make it competitive with the currently prevailing price of crude oil, the level of improvement necessary appears to be attainable with the assistance of governmental subsidies.

It is important to note that the reliability of life cycle assessment is affected by the dependence on input parameters from various countries, unit operations and sources as well as datasets which are not always collected for LCA purposes [19-21].Thus far, detailed uncertainty analyses is rarely performed as part of LCA studies partly due to the lack of consensus about standardized methodology, varying levels of uncertainty and practical guidance provided by handbooks such as the ISO standards. However, sensitivity and uncertainty analysis are an important part of LCA studies their application is highly valuable for increasing the overall credibility,

reliability and robustness of LCA studies[19-21]. In this thesis I have decided to test the robustness and reliability of my LCA studies through the application of one-way sensitivity analysis. As the main focus of my thesis is not the treatment of uncertainty in LCA studies or the modeling of probabilistic and stochastic risk factors, I have excluded the application of more detailed uncertainty and sensitivity analyses from this thesis. All LCA results presented in this thesis should therefore be considered under this caveat. Future research in the form of stochastic and probabilistic simulation will complement the results provided in this thesis and strengthen the credibility and robustness of datasets and LCA results.

As a priority, countries will need to defossilize primary energy sources used by their electricity grids, as only then can the transport sector move towards low GHG emissions. Countries such as China operating on a carbon-based electricity and heat grid, would eliminate the inherent environmental advantages of algal fuel production, while Brazil and France which essentially operate on defossilized electricity grids, have the potential for biofuels from algae to be a viable alternative to conventional fossil fuels. For the future production of algae biofuel production in the UK, the government's objective of decarbonizing the economy through an increased electrification of transport and heating by 2050 will substantially reduce the fossil fuel use of the fuel path. The results of this thesis are in direct agreement with previous studies on indirect emissions from electric vehicles, which show a similar dependence of effective GHG mitigation potential on the carbon footprint of electricity generation [209]. Such policy initiatives are recommended as a first important step for guaranteeing the future environmental viability of low-carbon fuel products such as biofuels from advanced feedstock, both on a small and large-scale basis.

To date, several metrics are widely used throughout green chemistry practices to determine the efficiency and environmental impact of chemical processes. The E-factor, or the Environmental Impact Factor, is most commonly used to measure the environmental acceptability of chemical process. As catalysis is a key technology to achieve the objective of energy efficiency and GHG emissions mitigation, this thesis introduces the novel concept of a CSI-factor, or Catalyst Sensitivity Index, to emphasize the crucial importance of catalytic processes for green chemistry practices. The CSI attempts to underline the impact catalyst efficiency can have on the total fossil energy consumption of fuel conversion technologies and their subsequent carbon footprint. Here, catalyst efficiency is defined as the net energy consumption of a catalyst-dependent process, which would decrease through improvements in catalyst selectivity.

An ideal (i.e. high) CSI-factor would be close to zero, and translate into processes, which are highly catalyst dependent, and for which small improvements in catalyst efficiencies would yield considerable reductions in the total carbon footprint of the system. For example, a high CSI-factor is reported for the FT-fuel conversion from both coal and natural gas feedstock. In this case improvements in catalyst activity and selectivity can result in considerable reductions in the fossil energy consumption of the FT-fuel conversion process and the respective feed load by the FT-fuel upgrading stage. The development of a CSI index will allow the industry to highlight ‘best practice catalysts’ and draw conclusions for what efficiency gains one could theoretically anticipate with higher performance catalysts. This new CSI concept outlines similarities to the previously presented E-factor and should, in the future, go hand-in-hand with the industries’ decisions on sustainable practices and environmental efficiency gains.

Furthermore, in countries where a decarbonized electricity and heat grid is currently not present and the looming resource scarcity around marine protein sources has become a more pressing economic problem, an alternative path for the use of algae biomass is recommended as part of this thesis.

Given the considerable environmental and financial hurdles faced by energy intensive algae biomass drying, harvesting and oil extraction, I here propose an alternative use of microalgae for fish feed, instead of low carbon fuel production. Algae biomass can be used as feed additive for the aquaculture industry, due to its superior protein content and crucial availability of highly unsaturated fatty acids. Considering that by the year 2030 the demand for fish meal (10.4 Mt) and fish oil (5.9 Mt) is expected to exceed the relative supply by marine sources (6.5 Mt and 1.3 Mt)[4], the superior land-use efficiency of microalgae can provide a vital solution to feeding a protein-hungry human population with limited marginal land available. To satisfy the future global demand with algae-based feed production at an average yield of 70 to 85 tons/ha/year, an arid land mass between 2,325 and 2,713 km^2/year will be necessary. This area approximates to three times the size of Hong Kong or somewhat larger than the island of Mauritius.

In comparison, replacing fish meal demand in 2030 with soybean, at a dry yield of 2.7 tons/ha/y[186], will require 38,431 km^2/year of global arid land mass.

Coupled with improved biomass productivity yields, this algae biomass farming process promises the cost-competitive production of algae feed for standard fish feed replacement by the year 2030. By then algae feed has the potential to act as a sustainable future food source producible at affordable prices and as part of a resource-efficient and low carbon farming process that maintains essential

ecosystems. Here, the ex situ cultivation of microalgae at relatively enhanced biomass yields in on-site open raceway ponds is assumed. The dewatered algae biomass is not removed from the culture fluid for further drying, harvesting or processing and only considered for direct local consumption rather than feed storage or mass commodity export. This model farming approach reduces investment and maintenance costs and incorporates the potential to recycle feed and reduce fertilizer requirements, similar to existing microbial-floc technology.

In the coming decades, fish meal prices are expected to increase by 43% until 2020 compared to 2008-2010 levels and fish oil prices are projected to grow by 19%. This price trend will undoubtedly affect the relative attractiveness of processing algae as a mass feed source. The results show that the production of dewatered algae feed suitable for local on-site consumption would result in 18-29% lower capital and operating costs in 2030 compared to standard feed production. By then, algae feed production as part of the above mentioned farming process and at enhanced average biomass yields around 10-30g/m^2/day, will become cost-competitive against the elevated prices for depleting fish meal and fish oil resources. For example, relative to the rising price of marine feed sources, the commercial production of algae species, such as *Spirulina Platensis* ($2045/ton) and *Pavlova Lutheris*, ($1483/ton) will show early signs of becoming a cost competitive against the skyrocketing price of fish meal and fish oil around $2777/ton and $1645/ton.

In addition, the results for 2030 show that compared to standard shrimp farming on commercial fish feed diets algae-based cultivation can provide savings of up to 14-28% in lifecycle fossil energy demand and 8-21% in GHG emissions. Again additional reductions can be achieved through the successful decarbonisation of a

fossil fuel based electricity grid and the sourcing of all indirect energy requirements for fertilizers, transport and building materials, from low-carbon energy sources.

In an era where the rise of global middle class consumers is faced with depleting marine protein sources, with consequential price increases, marginal land availability and rising freshwater needs, microalgae feed production has the potential to transform a pressing global tipping point into a turning point. This is of particular importance to countries without a decarbonized electricity and heat grid that is essential to guaranteeing low-carbon fuel production from algae feedstock. In this case, algae biomass cultivation can also be directed towards fish feed rather than renewable fuel production.

8.2 Contribution and Significance

The contributions of this study to the fields of renewable energy, energy security, lifecycle analysis and aquaculture can be summarized as follows.

This thesis represents a first step, through life cycle analyses, towards the comprehensive understanding of the emissions and energy balance of jet biofuel and biodiesel production from algae biomass. It examines all stages of the algae-to-biofuel production cycle whilst determining potential avenues for lowering technical bottlenecks around high fertilizer inputs, fossil-fuel intensity of electricity and heat production, the engineering of superior algal oil yields and alternative optimized uses for co-products. It is hoped that this thesis will help benchmark the environmental impact and the economics of various alternative fuels with conventional crude oil derived fuels. Also, the definition of a CSI-factor can provide the green chemistry

industry with the opportunity to emphasize ‘best practice catalysts’ and draw conclusions for what efficiency gains one could theoretically anticipate with higher performance catalysts. In addition, here the impact of alternative fuels on energy security and emissions reduction, combining both socio-economic and technological aspects, has been discussed in detail.

Furthermore, this thesis includes a novel first quantitative assessment of the emissions and energy balance of algae feed production for the large-scale replacement of standard fish feed. As part of the findings I describe a new future cost-effective method of algae feed production for fish meal and fish oil replacement, and present a lifecycle analysis outlining improvements in fossil energy demand and GHG emissions for shrimp production in China cultivated on algae feed. As water, energy and land usage in aquaculture are all interactive the results of this study should act as an informative first step to quantify the potential environmental and economic value of future microalgae use in an area of depleting traditional fish feed supplies.

This thesis, based at the science-policy interface, should contribute insight into matters of global energy and food security, and hence to policy decisions by both governments and the private sector. Segments of this thesis have also received attention from the media. For instance research conducted on algae biodiesel production has been covered by The Times of London and The Economist [210,211].

8.3 Concluding Remarks

Due to the high photosynthetic yields and the potential to be cultivated on marginal lands, microalgae have gained a significant attention as a feedstock for biofuels over the past few years. In spite of substantial improvements both in the production and processing of microalgae, there are still several major barriers towards the production of liquid algal fuels, majority of which related to the low concentration (e.g. 0.05 wt%) and the need to isolate a certain fraction (e.g. lipids) from the feedstock. It shall be noted that that substantial challenges are involved in maintaining the mentioned biomass production yields in an open pond installation.

The limitations for large-scale microalgae production in open pond systems are mostly technical with the likelihood of a culture collapse, contamination, poor light utilization, high water losses and immature harvesting technologies. Also, the large-scale use of marginal land for algae cultivation is expected to remain limited given several practical and technological drawbacks. For example, issues around the injection of cheap CO_2 from nearby (i.e. <100km) power plants, the availability of suitably flat land areas for the installation of open raceway ponds and the viability of commercial production limited to areas with high levels of solar radiation, will be of practical concern. Rather than maximizing biomass productivity yields attention should be paid to generating a reliable and constant supply of algae biomass. Yet, particular microalgae strains grow in highly selective environments, which guarantee that while cultivated in open air ponds contamination by other algae strains is kept to a minimum [7,142,159].

8.4 Recommendation for Future Work

8.4.1 Catalytic Hydrogen and Methane Production from Microalgae

Catalytic hydrogen production is among the most important industrial processes for the production of high-quality fuels. Currently, hydrogen is primarily produced by steam reforming of natural gas. However due to increasing concerns over the adverse environmental impact of fossil fuels and their depletion the utilization of biomass as a feedstock for hydrogen production is expected to gain a more significant share in the future.

The catalytic processes that utilize water as a reaction medium for the reforming of oxygenated organic molecules fall into three categories, i) Aqueous phase reforming (APR), ii) Supercritical water gasification (SCWG), and iii) Steam reforming (SR). The major products of biomass catalytic reforming include hydrogen, methane, and carbon dioxide along with smaller quantities of carbon monoxide and ethane. Although APR, SCWG, and SR processes share the same underlying fundamentals, the substantial variations in the operating conditions and the physical state of water results in unique strengths and challenges for each of these processes.

It is highly desirable to develop new technologies which allow for the utilization of the chemically stored energy in algae without implementing energy and carbon-intensive steps such as feedstock drying and extraction. In this regard, catalytic reforming, in absence of an oxidizing agent, could be a viable choice for algae conversion as the reforming technologies can effectively handle feedstock with low organic content. Furthermore, reforming would enable the utilization of algae strains with highest productivity as the final product distribution has little dependence on the relative amounts of lipids, proteins, and carbohydrates in feedstock. The catalytic reformation

of algae holds a great potential to produce low carbon energy in the future. Yet, the available literature regarding the practical aspects of such conversion, and in particular on the pre-treatment and reforming steps, is very limited.

A key objective of future research should be to evaluate the environmental impacts and the fossil energy use of the catalytic routes for the conversion of wet algae feedstock to hydrogen and gaseous fuels, and to assess the technical and economic feasibility of such processes. Complementary experimental work should focus on the hydrothermal liquefaction of algae and ash removal from different microalgae strains, and on the performance of nickel and ruthenium catalysts for the reforming of the hydrolysis products. The catalyst screening will be based on the promising catalysts previously developed for the reforming of other biomass-derived oxygenated compounds in the literature. In addition, the life cycle environmental impacts of the large scale gas production from algae, in terms of greenhouse gas emissions and fossil fuel consumption have not been evaluated. The results of such analysis should be benchmarked against both commercial hydrogen production processes as well as the other renewable routes to realize the potential of algae in a low carbon economy.

In addition, the production of biogas, a mixture of methane and carbon dioxide, in anaerobic digestion (AD) is another promising alternative solution for realizing the chemical energy of microalgae. It bypasses the drying and extraction processes, two of the most energy and carbon-intensive steps in production of liquid biofuels from dewatered algae feedstock, and allows for partial recycling of the fertilizers.

In comparison, catalytic supercritical water gasification (SCWG) holds great promise as a route towards the use of microalgae feedstock for biofuel production. Future research endeavors should also focus on the catalytic decomposition of microalgae

in supercritical water. This technology has the potential to generate methane-rich gas with notably lower life cycle greenhouse gas emission and fossil energy consumption compared to both conventional natural gas and a biogas produced from anaerobic digestion of the same microalgae feedstock. Similar to anaerobic digestion, it eliminates the need for feedstock drying and consequently realizes the full potential of microalgae. Prior to contacting with catalyst, algae feedstock must be pre-treated in hydrothermal conditions to hydrolyze the organic matters and separate the ash as precipitates. Subsequently, It gasification of the ash-free feedstock in presence of metal catalysts, which are preliminary based on nickel and ruthenium, essentially converts the hydrolyzed feedstock into gas mixtures containing varying percentages of methane, hydrogen, and carbon dioxide. The yield of carbon monoxide would be minimal as such catalysts are also highly active for water-gas shift reaction. Moreover, process flexibility with respect to feedstock composition would allow for switching between algae strains with highest seasonal productivity, which in turn increases the overall annual biomass production. Likewise, a hybrid approach towards algae biodiesel, in which the required process heat and electricity are partially offset by methane from catalytic conversion of algae, would reduce the overall GHG emission and consumption of external fossil energy.

The catalytic SCWG route could not only drastically improve the environmental and economic benefits of algal bioenergy but also significantly reduce the vulnerability of the supply security.

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10. Appendix

10.1 Appendix: Algae-to-Biodiesel Production

Appendix 1: Algae strain parameters and biomass productivity

Algae Strain	Chlorella Vulgaris	Biomass productivity	Value	Source
Carbon	53%	Algae concentration in water	0.5 kg/m^3	[23]
Phosphorous	2%	Wet biomass production per day	24.75 kg/d	[23]
Nitrogen	8%	Wet biomass production per area	32.97 kg/ha	[23]
Hydrogen	8%	Annual wet biomass productivity	90.34 ton/ha/y	[23]
Oxygen	31%	Dry biomass production per day	20.55 kg/d	[23]
Protein	282(g*kg^{-1})	Dry biomass production per area	27.38 kg/ha	[109]
Lipid	175(g*kg^{-1})	Annual dry biomass productivity	75.0 tons/ha/y	[109]
Carbon content	0.48(g*g^{-1})	Annual dry biomass productivity	67.5 tons/ha/y	[109]
Oil content (LHV)	0.18(g*g^{-1})	(90% solid)		[109]
Oil density	0.981(t/m^3)			[152]

Appendix 2: Cultivation data used for the microalgae farming stage

Agro-nutrients	Application rate	Embedded energy	Embedded GHG (gCO_2/t)	Source
NH_3	6.0(t/ha)	57.0(GJ/t)	2.309,126	[17,23,85]
TSP	1.5(t/ha)	4.1(GJ/t)	888,410	[17,23]
K2O	0.001(kg/kg)	6.8(GJ/t)	591.880	[85]

To facilitate the synthesis of algae biomass and their productivity levels, nutrients such as nitrogen in the form of ammonia (NH3) and phosphorus in the form of superphosphate (P2O5) have to be adequately supplied according to the algae cultures' stoichiometric requirements.

- Based on the estimated elemental composition of the microalgal cells, the mass requirements for N and P in t/ha can be obtained by multiplying the dry algae biomass productivity of 75.0 t/h/y with the mean values for elemental nitrogen (8.0%) and phosphous (2.0%) contents [161,212].
- The fossil energy utilized for ammonia production has frequently been reported at 57 GJ/t which also accounts for other downstream energy costs such as granulation, natural gas recovery, product packaging, and transportation [213,214]. The fossil energy consumption for superphosphate fertilizer production has been estimated at 4.1 GJ/t for average European production plants [213,214].
- Flue gases with a carbon dioxide content of 12.5 vol-% (the maximum value for a natural gas-fired poIr station [153]) from an adjacent poIr-plant have been assumed as a direct source of CO2 [109,154]. The carbon dioxide source is pressurized and injected along the pond through PVC pipes which has been calculated to require 0.043 MJ/kg of dry algae.

Appendix 3: Pond and Harvesting Machinery

	Material	**Unit**	**Embedded energy**	**Embedded GHG**	**Source**
Pond Machinery		kg	MJ/kg	$kgCO_2/kg$	
Foundations	Concrete	4500	0.95	0.13	[109,215]
Pipes	PVC	687	67.5	2.50	[109,215]
Paddlewheel	Steel	50	24.4	1.77	[109,215]
	Glass fibre	256	28.0	1.53	[109,215]
Pump	Steel	20	24.4	1.77	[109,215]
Harvesting Machinery					
Concrete	Concrete	344000	0.95	0.13	[109,215]
Rotary Press	Steel	2100	24.4	1.77	[109,215]
Dryer	Steel	4000	24.4	1.77	[109,215]

- The main materials used for the building of the pond and harvesting facility include concrete blocks, PVC, glass, reinforced plastics and steel [8,109]. The pond design is consistent with industrial standards [8,109] around a benchmark of 10 m wide, 100 m long, and 30 cm deep oval-shaped built in concrete blocks, on a 10-cm-thick sole. For both the open raceway pond and the harvesting facility an average size of 0.1 ha and a

lifetime of 30 years has been assumed.

Appendix 4: Energy and Heat requirements

Input	Value	Unit	Source
CO_2 injection	0.04	MJ/kg dry	[109]
Paddlewheel electricity	0.87	MJ/kg dry	[109]
Pumping to settler electricity	1.23	MJ/kg dry	[109]
Dryer- heat	13.80	MJ/kg dry	[109]
Dryer-electricity	1.44	MJ/kg dry	[109]
Press-electricity	0.23	MJ/kg dry	[109]
Oil extraction-electricity [a]	0.25	MJ/kg dry	[109]
Oil extraction-heat[a]	1.19	MJ/kg dry	[109]
Transesterification-electricity	0.15	MJ/kg dry	[109]
Transesterification-heat	0.90	MJ/kg dry	[109]

[a] Heat and Electricity values are calculated for 90% dry algae biomass content

Appendix 5: Oil extraction and transesterification chemicals

Input	Value	Unit	Embedded GHG (gCO_2/kg biodiesel)	Source
N-Hexane	0.48	MJ/kg dry	n/a	[17]
Methanol	1.86	MJ/kg oil	35.9	[11,17]
Sodium Hydroxide	0.61	MJ/kg oil	2.1	[11,17]
Sodium methoxide	0.02	MJ/kg oil	23.2	[11,17]
Hydrochlorid Acid	0.07	MJ/kg oil	7.6	[11,17]

- The algal paste yielded by flocculation has to be further dried to reach a solid 90% biomass content and be processed in oil mill facilities, typically those used for vegetable oil extraction[109]. The heat and electricity requirements of the drying process are 13.8 MJ/kg dry matter and 1.4 MJ/kg dry matter, respectively [109] and clearly induce a heavy impact on the final energetic balance and carbon footprint. Following the flocculation and drying step, typically 75.0 t/h/y of dry algae biomass are obtained, a value in line with litreature estimates found of 90.3 t/h/y [109], 75.0 t/h/y [162] and 40.0 t/h/y .

- This study has focussed on dry extraction method due to data avilability and industrial penetration for biodiesel production, e.g. soybean-based biodiesel. Through the counter-current circulation of a hexane solution with an application rate of 0.48 MJ/kg ss, the algae oil is extracted from the dry biomass. The 30% algae oil content and the remaining 70% of algae cake result in the production of 22.5 t/h/y of algae oil and 52.5 t/h/y of dry algal residue[162].

Appendix 6: Transportation

Transport	**Value**	**Unit**
Distance for agro-input	50.0	km
Transport service agro-input	2270.8	t-km/ha
Distance algae to biorefinery	50.0	km
Transport service algae	450.0	t-km/ha
Diesel truck efficiency	0.02	l/t-km
Diesel lower heating value	37.8	MJ/l
Mean Diesel lifecycle GHG emissions	86.0	gCO_2eq/MJ

Appendix 7: Supplementary grid energy required by co-product method[a]

	CHP system[b]		**Direct Combustion**[c]	**Co-firing coal power plant**[d]
	Heat	Electricity	Heat	Electricity
China	738.0	167.9	395.8	-31.1
UK	673.5	114.0	361.2	-21.1
France	590.7	15.7	316.8	-2.9
Brazil	660.1	16.0	354.0	-3.0
Nigeria	660.8	113.3	354.4	-24.7
Saudi Arabia	660.8	182.4	354.4	-33.8

[a]Values show complementary grid energy supply or displaceable surplus (highlighted by negative values), related to amount of final energy generated by each co-product utilization method.
[b]541 GJ/ha/y end heat and 240 GJ/ha/y end electricity generated in biomass CHP plant.
[c]817 GJ/ha/y end heat generated in biomass heating system.
[d]317 GJ/ha/y end electricity generated in co-fired coal poIr plant.

Appendix 8: Energy and carbon intensity of national heat grid [241]

	Final Heat Demand	Primary Fossil Energy	Primary Fossil Energy/Final Heat[a]	Carbon Intensity/ Heat[b]
Unit	**PJ**	**PJ**	**PJ/PJ**	**gCO_{2eq}/MJ**
China	2586.0	3209.3	1.24	130.4
UK	49.8	49.8	1.13	83.4
France	160.8	159.7	0.99	74.9
Brazil[c]	15.7	-	1.11	84.1
Nigeria	-	-	1.11	79.1
Saudi Arabia[c]	-	-	1.11	81.6

[a] Primary Energy consumption/MJ heat is based in Brazil, Nigeria and Saudi Arabia on the energy intensity of a natural gas powered grid

[b] Carbon Intensity per primary fuel burned for the production of heat is sourced from ref [85]

[c] The calculations for the carbon intensity/ MJ of heat produced in Saudi Arabia and Brazil are based on the nations' consumption figures and availability of fossil fuel sources

Appendix 9**:** Energy and carbon intensity of national electricity grid [222, 241]

	Final Electricity Demand	Primary Fossil Energy	Primary Fossil Energy/Final Electricity[a]	Carbon Intensity/ Electricity[b]
Unit	**TWh**	**TWh**	**MJ/MJ**	**gCO_{2eq}/MJ**
China	279.3	8490.1	2.59	275.6
UK	396.1	696.5	1.76	155.7
France	569.8	137.9	0.24	24.7
Brazil	445.1	109.8	0.25	24.4
Nigeria	22.9	47.3	2.06	13.0
Saudi Arabia	189.1	531.9	2.81	222.5

[a] Country specific grid efficiency data: ref [195].

[b] Carbon intensity data per MJ of primary energy consumed: ref[216] [85].

Appendix 10: Global land requirements for algae biodiesel production

Global fossil derived diesel consumption	1,126 billion tons ref.[217]
Total algae-derived biodiesel production	850,500 MJ/ha/y
Algal fuel required land mass	57,3million

Electricity Generation Data for 6 Country Scenarios. Source IEA

		UNIT	TOTAL	COAL	OIL	GAS	BIOMASS	WASTE	NUCLEAR	HYDRO	GEOTHERMAL	SOLAR PV	WIND	TIDE	OTHER
	Efficiency	%			country specific		32%	22%	38%	90%	0%	12%	35%	0%	0%
	Carbon Intensity/MJ primary E	gCO2/MJ		**107**	**90**	**66**	19.7		3.1	2.2		15.8	3.9		
CHINA	ELECTRICITY PRODUCTION	GWh	3,279,349	2,656,434	33,650	30,539	2,310		62,130	485,264	116	116	8,790		
		%	100%	81%	1%	1%	0%		2%	15%	0%	0%	0%	0%	0%
	Grid efficiency	%		**32%**	**34%**	**39%**	**32%**	**22%**	**38%**	**90%**	**0%**	**12%**	**35%**	**0%**	**0%**
	Carbon Intensity	gCO2e/MJ	Elec produced	334.4	264.7	169.2									
	Primary E	GWh	8,490,147	8,301,356	98,971	89,821									
	Primary E/Electricity	MJ/MJ	2.59												
	Carbon Intensity/Electricity	gCO2e/MJ	275.56	270.9	2.7	1.6	0.0		0.1	0.3		0.0	0.0		
UK	ELECTRICITY PRODUCTION	GWh	396,143	138,321	4,692	164,474	8,114	3,281	63,028	8,948		11	5,274	-	
		%	100%	35%	1%	42%	2%	1%	16%	2%		0%	1%	0%	
	Grid efficiency	%		**38%**	**29%**	**52%**	**32%**	**22%**	**38%**	**90%**	**0%**	**12%**	**35%**	**0%**	**0%**
	Carbon Intensity	gCO2e/MJ		281.6	310.3	126.9									
	Primary E	GWh	696,478	364,003	16,179	316,296									
	Primary E/Electricity	MJ/MJ	1.76												
	Carbon Intensity/Electricity	gCO2e/MJ	155.68	98.3	3.7	52.7	0.4	-	0.5	0.1		0.0	0.1		
FRANCE	ELECTRICITY PRODUCTION	GWh	569,840	28,197.0	6,163.0	21,987.0	2,008.0	3,506.0	439,730.0	63,662.0		16.0	4,052.0	519.0	-
		%	100%	4.9%	1.1%	3.9%	0.4%	0.6%	77.2%	11.2%		0.0%	0.7%	0.1%	
	Grid efficiency	%		**39%**	**31%**	**48%**	**32%**	**22%**	**38%**	**90%**	**0%**	**12%**	**35%**	**0%**	**0%**
	Carbon Intensity	gCO2e/MJ		274.4	290.3	137.5									
	Primary E	GWh	137,987	72,300	19,881	45,806									
	Primary E/Electricity	MJ/MJ	0.24												
	Carbon Intensity/Electricity	gCO2e/MJ	24.72	13.6	3.1	5.3	0.1	-	2.4	0.2		0.0	0.0		
BRAZIL	ELECTRICITY PRODUCTION	GWh	445,142	10,114.0	13,767.0	15,497.0	17,401.0		12,350.0	374,015.0			559.0		1,439.0
		%	100%	2.3%	3.1%	3.5%	3.9%		2.8%	84.0%			0.1%		0.3%
	Grid efficiency	%		**29%**	**34%**	**45%**	**32%**	**22%**	**38%**	**90%**	**0%**	**12%**	**35%**	**0%**	**0%**
	Carbon Intensity	gCO2e/MJ		369.0	264.7	146.7									
	Primary E	GWh	109,805	34,876	40,491	34,438									
	Primary E/Electricity	MJ/MJ	0.25												
	Carbon Intensity/Electricity	gCO2e/MJ	24.40	8.4	8.2	5.1	0.8	-	0.1	1.9		-	0.0		
NIGERIA	ELECTRICITY PRODUCTION	GWh	22,978		1,137.0	15,435.0				6,406.0					
		%	100%		4.9%	67.2%				27.9%					
	Grid efficiency	%		**32%**	**36%**	**35%**	**32%**	**22%**	**38%**	**90%**	**0%**	**12%**	**35%**	**0%**	**0%**
	Carbon Intensity	gCO2e/MJ		334.4	250.0	188.6									
	Primary E	GWh	47,258	-	3,158	44,100				-					
	Primary E/Electricity	MJ/MJ	2.06												
	Carbon Intensity/Electricity	gCO2e/MJ	139.66	-	12.4	126.7	-	-	-	0.6		-	-		
Saudi A	ELECTRICITY PRODUCTION	GWh	189,076		104,323.0	84,753.0									
		%	100%		55.2%	44.8%									
	Grid efficiency	%		**32%**	**36%**	**35%**	**32%**	**22%**	**38%**	**90%**	**0%**	**12%**	**35%**	**0%**	**0%**
	Carbon Intensity	gCO2e/MJ		334.4	250.0	188.6									
	Primary E	GWh	531,938	-	289,786	242,151									
	Primary E/Electricity	MJ/MJ	2.81												
	Carbon Intensity/Electricity	gCO2e/MJ	222.46	-	137.9	84.5	-	-	-	-		-	-		
USA	ELECTRICITY PRODUCTION	GWh	4,188,214	1,892,661	50,445	949,776	49,850	22,441	830,210	298,410	17,046	2,514	74,226		635
		%	100%	45%	1.2%	23%	1%		20%	7%	0%	0%	2%	0%	0%
	Grid efficiency	%		**36%**	**35%**	**43%**	**32%**	**22%**	**38%**	**90%**	**0%**	**12%**	**35%**	**0%**	**0%**
	Carbon Intensity	gCO2e/MJ	Elec produced	297.2	257.1	153.5									
	Primary E	GWh	8,856,392	5,914,566	148,368	2,793,459									
	Primary E/Electricity	MJ/MJ	2.11												
	Carbon Intensity/Electricity	gCO2e/MJ	173.30	134.3	3.1	34.8	0.2		0.6	0.2		0.0	0.1		

Heat Generation Data for 6 Country Scenarios. Source IEA 2007/2009

			UNIT	TOTAL	COAL	OIL	NATURAL GAS	BIOMASS	WASTE	OTHER
	Efficiency		%		80%	90%	90%	85%	0%	0%
	Carbon Intensity/prima		gCO2/MJ		107	90	**66**	0		
	Carbon Intensity/MJ h		gCO2/MJ		134	100	73			
CHINA	HEAT PRODUCTION		TJ	2,586,027	2,413,239	98,593	62,532	11,663		
			%	100%	93.3%	3.8%	2.4%	0.5%		
	Primary E		TJ	3,209,298	3,016,549	109,548	69,480	13,721		
	Primary E/Heat		TJ/TJ	1.24						
	Carbon Intensity/Primary		gCO2/MJ	337,215,696	322,770,716	9,859,300	4,585,680			
			gCO2e/MJ Heat pro	130.4						
UK	HEAT PRODUCTION		TJ	49,826	7,686	1,426	40,714			
			%	100%	15.4%	2.9%	81.7%			
	Primary E		TJ	56,430	9,608	1,584	45,238			
	Primary E/Heat		TJ/TJ	1.13						
	Carbon Intensity/Primary		gCO2/MJ	4,156,296	1,028,003	142,600	2,985,693			
			gCO2e/MJ	83.4						
FRANCE	HEAT PRODUCTION		TJ	160,806	15,244	27,313	99,301		18,948	
			%	88%	9.5%	17.0%	61.8%			
	Primary E		TJ	159,737	19,055	30,348	110,334			
	Primary E/Heat		TJ/TJ	0.99						
	Carbon Intensity/Primary		gCO2/MJ	12,052,258	2,038,885	2,731,300	7,282,073			
			gCO2e/MJ	74.9						
BRAZIL	HEAT PRODUCTION		TJ	15,701						15,701.0
			%	100%						1
	Primary E		TJ	-						
	Primary E/Heat		TJ/TJ	1.11						
	Carbon Intensity/Primary		gCO2/MJ	1.11						
			gCO2e/MJ	84.1						
Nigeria	HEAT PRODUCTION		TJ							
			%	0%						
	Primary E		TJ							
	Primary E/Heat		TJ/TJ	1.11						
	Carbon Intensity/Primary		gCO2/MJ	0.00						
			gCO2e/MJ	79.1						
SAUDI A	HEAT PRODUCTION		TJ							
			%	0%						
	Primary E		TJ							
	Primary E/Heat		TJ/TJ	1.11						
	Carbon Intensity/Primary		gCO2/MJ	0.00						
			gCO2e/MJ	81.6						
USA	HEAT PRODUCTION		TJ	520,524	104,037.0	39,334.0	329,761.0	31,838.0	15,554.0	
			%	100%	19.99%	7.56%	63.35%	6.12%	3%	
	Primary E		TJ	577,608	130,046	43,704	366,401	37,456		
	Primary E/Heat		TJ/TJ	1.11						
	Carbon Intensity/Primary		gCO2/MJ	42,030,822	13,914,949	3,933,400	24,182,473			
			gCO2e/MJ	80.7						

ALGAE BIODIESEL: LIFECYCLE FOSSIL ENERGY DEMAND- BIOMASS RESIDUE USE via CO-FIRING POWER PLANT

ALGAE BIODIESEL	Unit	Product flow	GENERIC	CHINA	UK	FRANCE	BRAZIL	NIGERIA	SAUDI ARABIA
						MJ/h/y			
ALGAE OPEN POND CULTIVATION									
CO2 injection	MJ/kg dry algae	0.04	3,197	8,276	5,620	774	789	6,575	8,994
Ammonia (NH3) as nitrogen source	t/h	6.00	342,000	342,000	342,000	342,000	342,000	342,000	342,000
Superphosphate as phosphorus sour	t/h	1.50	6,150	6,150	6,150	6,150	6,150	6,150	6,150
Potassium (K2O)	kg/kg dry algae	0.001	587	587	587	587	587	587	587
Paddlewheel electricity	MJ/kg dry algae	0.87	64,958	168,174	114,205	15,730	16,023	133,597	182,749
Machinery and pond infrastructure	MJ/kg material	482,748.50	160,916	160,916	160,916	160,916	160,916	160,916	160,916
Water/algae volume processed	m3/h/y	150,000							
SUB TOTAL (Pond)			577,807	686,103	629,478	526,156	526,465	649,824	701,395
HARVESTING AND Flocculation									
Harvesting facilities own calc.	MJ/kg material	475,640.00	158,547	158,547	158,547	158,547	158,547	158,547	158,547
Pumping to settler electricity	MJ/kg dry algae	1.23	92,025	238,250	161,794	22,284	22,700	189,266	258,899
BIOMASS DRYER									
Heat	MJ/kg dry algae	13.80	1,035,000	1,284,450	1,172,174	1,028,121	1,148,850	1,150,000	1,150,000
Electricity	MJ/kg dry algae	1.44	108,000	279,609	189,880	26,152	26,641	222,121	303,842
Press	MJ/kg dry algae	0.23	16,875	43,689	29,669	4,086	4,163	34,706	47,475
Dry algae biomass (tons/ha/year)	t/h/y	75.00							
SUB TOTAL (Harvesting/Dryer)			1,410,447	2,004,545	1,712,063	1,239,190	1,360,900	1,754,640	1,918,763
ALGAE OIL EXTRACTION									
Heat	MJ/ 90% dry algae	1.19	80,393	99,768	91,047	79,858	89,236	89,325	89,325
Electricity	MJ/ 90% dry algae	0.25	16,643	43,087	29,260	4,030	4,105	34,228	46,821
N-Hexane	MJ/kg material	0.48	3,216	3,216	3,216	3,216	3,216	3,216	3,216
Extraction products; Algae oil I	%	0.30							
Algae oil II	t/h/y	22.50							
Algae cake I	%	0.70							
Algae cake II	t/h/y	52.50							
SUB TOTAL (Extraction)			100,251	146,072	123,524	87,105	96,557	126,770	139,363
TRANSPORTATION									
Transport distance for agro inputs	km	50.0							
Transport service for agro inputs	t-km/ha	2,270.8							
Transport distance for algae to biorefi	km	20.0							
Transport service for algae	t-km/ha	450.0							
Diesel truck fuel efficiency	l/t-km	0.02							
SUB TOTAL (Transport)	MJ/t algae		30,095	30,095	30,095	30,095	30,095	30,095	30,095
TRANSESTERIFICATION									
Methanol	MJ/kg oil	1.86	12,552	12,552	12,552	12,552	12,552	12,552	12,552
Sodium hydroxide	MJ/kg oil	0.61	4,126	4,126	4,126	4,126	4,126	4,126	4,126
Sodium methoxide	MJ/kg oil	0.02	157	157	157	157	157	157	157
Hydrochlorid Acid	MJ/kg oil	0.07	502	502	502	502	502	502	502
Heat	MJ/kg oil	0.90	20,184	25,049	22,860	20,050	22,405	22,427	22,427
Electricity	MJ/kg oil	0.15	3,327	8,612	5,848	806	821	6,842	9,359
SUB TOTAL (Transesterification)			40,848	50,999	46,045	38,193	40,563	46,606	49,123
Esterficiation product; Biodiesel	t/h/y	22.50							
Glycerol	t/h/y	4,792.50							
Co-product credit - oil cake	MJ/h/y	960,750	317,048						
Electricity surplus	MJ/h/y		12,024	- 31,130	- 21,140	- 2,912	- 2,965.99	- 24,729.38	- 33,827.61
Total fossil energy input incl co-produ	MJ/h/y			2,096,986	1,983,789	1,843,966	1,976,372	1,955,870	1,946,772
TOTAL Biodiesel energy	MJ/h/y			850,500	850,500	850,500	850,500	850,500	850,500
TOTAL Oilcake energy	MJ/h/y			689,483	689,483	689,483	689,483	689,483	689,483
TOTAL Glycerol	MJ/h/y			88,853	88,853	88,853	88,853	88,853	88,853
ENERGY BALANCE RATIO	**MJ/MJ**			**2.30**	**2.20**	**1.96**	**2.20**	**2.08**	**2.07**

ALGAE BIODIESEL: GHG EMISSIONS - BIOMASS RESIDUE USE IN CO-FIRING POWER PLANT

ALGAE BIODIESEL	Unit	Product flow	CHINA	UK	FRANCE	BRAZIL	NIGERIA	SAUDI ARABIA
					gCO2eq			
ALGAE OPEN POND CULTIVATION								
CO2 injection	MJ/kg dry algae	0.04	880,923	497,691	79,041	78,013	446,462	711,175
Ammonia (NH3) as nitrogen s	t/h	6.00	14,195,549	14,195,549	14,195,549	14,195,549	14,195,549	14,195,549
Superphosphate as phosphoi	t/h	1.50	1,395,142	1,395,142	1,395,142	1,395,142	1,395,142	1,395,142
Potassium (K2O)	kg/kg dry algae	0.001	53,007	53,007	53,007	53,007	53,007	53,007
Paddlewheel electricity	MJ/kg dry algae	0.87	46,342,601	17,779,928	388,912	391,027	18,658,024	40,655,175
Machinery and pond infrastruc	MJ/kg material	482,749	12,146,616	12,146,616	12,146,616	12,146,616	12,146,616	12,146,616
SUB TOTAL (Pond)			75,013,838	46,067,933	28,258,267	28,259,354	46,894,800	69,156,664
HARVESTING AND Flocculation								
Harvesting facilities own calc.	MJ/kg material	475,640	11,103,400	11,103,400	11,103,400	11,103,400	11,103,400	11,103,400
Pumping to settler electricity	MJ/kg dry algae	1.23	65,653,190	25,188,681	550,968	553,965	26,432,672	57,595,859
BIOMASS DRYER								
Heat	MJ/kg dry algae	13.80	167,491,213	97,778,342	77,056,701	87,041,803	81,892,983	84,478,700
Electricity	MJ/kg dry algae	1.44	77,050,199	29,561,288	646,613	650,130	31,021,229	67,594,162
Press	MJ/kg dry algae	0.23	12,039,094	4,618,951	101,033	101,583	4,847,067	10,561,588
SUB TOTAL (Harvesting/Dryer)			333,337,096	168,250,661	89,458,715	99,450,881	155,297,352	231,333,708
ALGAE OIL EXTRACTION								
Heat	MJ/ 90% dry algae	1.19	13,009,698	7,594,826	5,985,295	6,760,877	6,360,948	6,561,791
Electricity	MJ/ 90% dry algae	0.25	11,873,282	4,555,335	99,642	100,184	4,780,309	10,416,125
N-Hexane	MJ/kg material	0.48						
SUB TOTAL (Extraction)			24,882,979	12,150,162	6,084,937	6,861,061	11,141,258	16,977,916
TRANSPORTATION								
SUB TOTAL (Transport)	MJ/t algae		168,792	168,792	168,792	168,792	168,792	168,792
TRANSESTERIFICATION								
Methanol	MJ/kg oil	1.86	951,316	951,316	951,316	951,316	951,316	951,316
Sodium hydroxide	MJ/kg oil	0.61	47,345	47,345	47,345	47,345	47,345	47,345
Sodium methoxide	MJ/kg oil	0.02	546,642	546,642	546,642	546,642	546,642	546,642
Hydrochlorid Acid	MJ/kg oil	0.07	171,579	171,579	171,579	171,579	171,579	171,579
Heat	MJ/kg oil	0.90	3,266,397	1,906,863	1,502,752	1,697,481	1,597,069	1,647,495
Electricity	MJ/kg oil	0.15	2,373,221	910,516	19,916	20,025	955,484	2,081,966
SUB TOTAL (transesterification)			7,356,500	4,534,262	3,239,550	3,434,387	4,269,435	5,446,343
Esterficiation product; Biodies	t/h/y	22.50						
Glycerol	t/h/y	4,792.50						
AVOIDED Emissions oil-cake			- 3,313,366	- 1,871,937	- 297,292	- 293,427	- 1,679,253	- 2,674,904
TOTAL GWP incl oilcake offs	gCO2eqv		221,233,329	146,187,482	125,026,845	135,986,122	128,951,135	130,792,470
TOTAL Biodiesel energy	MJ/h/y		850,500					
TOTAL Oilcake energy	MJ/h/y		689,483					
TOTAL Glycerol	MJ/h/y		88,853					
GHG BALANCE	**gCO2eqv/MJ**	**90**	**260**	**172**	**147**	**160**	**152**	**154**
	DIESEL (g/MJ)		**289%**	**191%**	**163%**	**178%**	**168%**	**171%**

ALGAE BIODIESEL: LIFECYCLE FOSSIL ENERGY DEMAND - BIOMASS RESIDUE USE via DIRECT COMBUSTION

ALGAE BIODIESEL	Unit	Product flow	GENERIC MJ/h/y	CHINA	UK	FRANCE	BRAZIL MJ/h/y	NIGERIA	SAUDI ARABIA
ALGAE OPEN POND CULTIVATION									
CO2 injection	MJ/kg dry algae	0.04	3,197	8,276	5,620	774	789	6,575	8,994
Ammonia (NH3) as nitrogen sour	t/h	6.00	342,000	342,000	342,000	342,000	342,000	342,000	342,000
Superphosphate as phosphorus	t/h	1.50	6,150	6,150	6,150	6,150	6,150	6,150	6,150
Potassium (K2O)	kg/kg dry algae	0.001	587	587	587	587	587	587	587
Paddlewheel electricity	MJ/kg dry algae	0.87	64,958	168,174	114,205	15,730	16,023	133,597	182,749
Machinery and pond infrastructure	MJ/kg material	482,748.50	160,916	160,916	160,916	160,916	160,916	160,916	160,916
Water/algae volume processed	m3/h/y	150,000							
SUB TOTAL (Pond)			577,807	686,103	629,478	526,156	526,465	649,824	701,395
HARVESTING AND Flocculation									
Harvesting facilities own calc.	MJ/kg material	475,640.00	158,547	158,547	158,547	158,547	158,547	158,547	158,547
Pumping to settler electricity	MJ/kg dry algae	1.23	92,025	238,250	161,794	22,284	22,700	189,266	258,899
BIOMASS DRYER									
Heat	MJ/kg dry algae	13.80	1,035,000	1,284,450	1,172,174	1,028,121	1,148,850	1,150,000	1,150,000
Electricity	MJ/kg dry algae	1.44	108,000	279,609	189,880	26,152	26,641	222,121	303,842
Press	MJ/kg dry algae	0.23	16,875	43,689	29,669	4,086	4,163	34,706	47,475
Dry algae biomass (tons/ha/year)	t/h/y	75.00							
SUB TOTAL (Harvesting/Dryer)			1,410,447	2,004,545	1,712,063	1,239,190	1,360,900	1,754,640	1,918,763
ALGAE OIL EXTRACTION									
Heat	J/ 90% dry alg	1.19	80,393	99,768	91,047	79,858	89,236	89,325	89,325
Electricity	J/ 90% dry alg	0.25	16,643	43,087	29,260	4,030	4,105	34,228	46,821
N-Hexane	MJ/kg material	0.48	3,216	3,216	3,216	3,216	3,216	3,216	3,216
Extraction products; Algae oil I	%	0.30							
Algae oil II	t/h/y	22.50							
Algae cake I	%	0.70							
Algae cake II	t/h/y	52.50							
SUB TOTAL (Extraction)			100,251	146,072	123,524	87,105	96,557	126,770	139,363
TRANSPORTATION									
Transport distance for agro input	km	50.0							
Transport service for agro inputs	t-km/ha	2,270.8							
Transport distance for algae to bi	km	20.0							
Transport service for algae	t-km/ha	450.0							
Diesel truck fuel efficiency	l/t-km	0.02							
SUB TOTAL (Transport)	MJ/t algae		30,095	30,095	30,095	30,095	30,095	30,095	30,095
TRANSESTERIFICATION									
Methanol	MJ/kg oil	1.86	12,552	12,552	12,552	12,552	12,552	12,552	12,552
Sodium hydroxide	MJ/kg oil	0.61	4,126	4,126	4,126	4,126	4,126	4,126	4,126
Sodium methoxide	MJ/kg oil	0.02	157	157	157	157	157	157	157
Hydrochlorid Acid	MJ/kg oil	0.07	502	502	502	502	502	502	502
Heat	MJ/kg oil	0.90	20,184	25,049	22,860	20,050	22,405	22,427	22,427
Electricity	MJ/kg oil	0.15	3,327	8,612	5,848	806	821	6,842	9,359
SUB TOTAL (Transesterification)			40,848	50,999	46,045	38,193	40,563	46,606	49,123
Esterficiation product; Biodiesel	t/h/y	22.50							
Glycerol	t/h/y	4,792.50							
Co-product credit - oil cake	MJ/h/y	960,750	816,638						
HEAT DEBT	MJ/h/y		318,939	395,809	361,210	316,820	354,022.81	354,377.18	354,377.18
Total fossil energy input incl co-p	MJ/h/y		1,342,811	1,904,354	1,616,335	1,109,529	1,148,112	1,700,560	1,931,364
TOTAL Fossil Energy input (lard	MY/h/y		2,159,448						
TOTAL Biodiesel energy	MJ/h/y		850,500						
TOTAL Oilcake energy	MJ/h/y		689,483						
TOTAL Glycerol	MJ/h/y		88,853						
ENERGY BALANCE RATIO	**MJ/MJ**		**1.43**	**2.03**	**1.72**	**1.18**	**1.22**	**1.81**	**2.06**

ALGAE BIODIESEL: GHG EMISSIONS - BIOMASS RESIDUE USE via DIRECT COMBUSTION

ALGAE BIODIESEL	Unit	Product flow	CHINA	UK	FRANCE	BRAZIL	NIGERIA	SAUDI ARABIA
			gCO2eq					
ALGAE OPEN POND CULTIVATION								
CO2 injection	MJ/kg dry algae	0.04	880,923	497,691	79,041	78,013	446,462	711,175
Ammonia (NH3) as nitrogen source	t/h	6.00	14,195,549	14,195,549	14,195,549	14,195,549	14,195,549	14,195,549
Superphosphate as phosphorus source	t/h	1.50	1,395,142	1,395,142	1,395,142	1,395,142	1,395,142	1,395,142
Potassium (K2O)	kg/kg dry algae	0.001	53,007	53,007	53,007	53,007	53,007	53,007
Paddlewheel electricity	MJ/kg dry algae	0.87	46,342,601	17,779,928	388,912	391,027	18,658,024	40,655,175
Machinery and pond infrastructure own calc.	MJ/kg material	482,749	12,146,616	12,146,616	12,146,616	12,146,616	12,146,616	12,146,616
SUB TOTAL (Pond)			75,013,838	46,067,933	28,258,267	28,259,354	46,894,800	69,156,664
HARVESTING AND Flocculation								
Harvesting facilities own calc.	MJ/kg material	475,640	11,103,400	11,103,400	11,103,400	11,103,400	11,103,400	11,103,400
Pumping to settler electricity	MJ/kg dry algae	1.23	65,653,190	25,188,681	550,968	553,965	26,432,672	57,595,859
BIOMASS DRYER								
Heat	MJ/kg dry algae	13.80	167,491,213	97,778,342	77,056,701	87,041,803	81,892,983	84,478,700
Electricity	MJ/kg dry algae	1.44	77,050,199	29,561,288	646,613	650,130	31,021,229	67,594,162
Press	MJ/kg dry algae	0.23	12,039,094	4,618,951	101,033	101,583	4,847,067	10,561,588
SUB TOTAL (Harvesting/Dryer)			333,337,096	168,250,661	89,458,715	99,450,881	155,297,352	231,333,708
ALGAE OIL EXTRACTION								
Heat	MJ/ 90% dry alga	1.19	13,009,698	7,594,826	5,985,295	6,760,877	6,360,948	6,561,791
Electricity	MJ/ 90% dry alga	0.25	11,873,282	4,555,335	99,642	100,184	4,780,309	10,416,125
N-Hexane	MJ/kg material	0.48						
SUB TOTAL (Extraction)			24,882,979	12,150,162	6,084,937	6,861,061	11,141,258	16,977,916
TRANSPORTATION								
SUB TOTAL (Transport)	MJ/t algae		168,792	168,792	168,792	168,792	168,792	168,792
TRANSESTERIFICATION								
Methanol	MJ/kg oil	1.86	951,316	951,316	951,316	951,316	951,316	951,316
Sodium hydroxide	MJ/kg oil	0.61	47,345	47,345	47,345	47,345	47,345	47,345
Sodium methoxide	MJ/kg oil	0.02	546,642	546,642	546,642	546,642	546,642	546,642
Hydrochlorid Acid	MJ/kg oil	0.07	171,579	171,579	171,579	171,579	171,579	171,579
Heat	MJ/kg oil	0.90	3,266,397	1,906,863	1,502,752	1,697,481	1,597,069	1,647,495
Electricity	MJ/kg oil	0.15	2,373,221	910,516	19,916	20,025	955,484	2,081,966
SUB TOTAL (transesterification)			7,356,500	4,534,262	3,239,550	3,434,387	4,269,435	5,446,343
Esterficiation product; Biodiesel	t/h/y	22.50						
Glycerol	t/h/y	4,792.50						
ADDITIONAL emissions oil-cake			41,589,432	26,604,720	23,904,213	26,822,286	25,235,656	26,032,455
TOTAL GWP incl oilcake offset	gCO2eqv		298,581,330	150,496,497	66,569,725	69,496,600	153,156,292	256,427,893
TOTAL Biodiesel energy	MJ/h/y		850,500					
TOTAL Oilcake energy	MJ/h/y		689,483					
TOTAL Glycerol	MJ/h/y		88,853					
GHG BALANCE	gCO2eqv/MJ		**351.1**	**177.0**	**78.3**	**81.7**	**180.1**	**301.5**
	DIESEL (g/MJ)	90	390%	197%	87%	91%	200%	335%

ALGAE BIODIESEL: LIFECYCLE FOSSIL ENERGY DEMAND - BIOMASS RESIDUE USE IN CHP UNIT

ALGAE BIODIESEL	Unit	Product flow	Baseline MJ/h/y	Baseline NGAS powered	CHINA	UK	FRANCE	BRAZIL	NIGERIA	SAUDI ARABIA
						MJ/h/y				
ALGAE OPEN POND CULTIVATION										
CO2 injection	MJ/kg dry algae	0.04	3,197	7,992	8,276	5,620	774	789	6,575	8,994
Ammonia (NH3) as nitrogen source	t/h	6.00	342,000	342,000	342,000	342,000	342,000	342,000	342,000	342,000
Superphosphate as phosphorus source	t/h	1.50	6,150	6,150	6,150	6,150	6,150	6,150	6,150	6,150
Potassium (K2O)	kg/kg dry algae	0.001	587	587	587	587	587	587	587	587
Paddlewheel electricity	MJ/kg dry algae	0.87	64,958	162,394	168,174	114,205	15,730	16,023	133,597	182,749
Machinery and pond infrastructure	MJ/kg material	482,748.50	160,916	160,916	160,916	160,916	160,916	160,916	160,916	160,916
Water/algae volume processed	m3/h/y	150,000								
SUB TOTAL (Pond)			577,807	680,039	686,103	629,478	526,156	526,465	649,824	701,395
HARVESTING AND Flocculation										
Harvesting facilities own calc.	MJ/kg material	475,640.00	158,547	158,547	158,547	158,547	158,547	158,547	158,547	158,547
Pumping to settler electricity	MJ/kg dry algae	1.23	92,025	230,063	238,250	161,794	22,284	22,700	189,266	258,899
BIOMASS DRYER										
Heat	MJ/kg dry algae	13.80	1,035,000	1,148,850	1,284,450	1,172,174	1,028,121	1,148,850	1,150,000	1,150,000
Electricity	MJ/kg dry algae	1.44	108,000	270,000	279,609	189,880	26,152	26,641	222,121	303,842
Press	MJ/kg dry algae	0.23	16,875	42,188	43,689	29,669	4,086	4,163	34,706	47,475
Dry algae biomass (tons/ha/year)	t/h/y	75.00								
SUB TOTAL (Harvesting/Dryer)			1,410,447	1,849,647	2,004,545	1,712,063	1,239,190	1,360,900	1,754,640	1,918,763
ALGAE OIL EXTRACTION										
Heat	MJ/ 90% dry algae	1.19	80,393	89,236	99,768	91,047	79,858	89,236	89,325	89,325
Electricity	MJ/ 90% dry algae	0.25	16,643	41,606	43,087	29,260	4,030	4,105	34,228	46,821
N-Hexane	MJ/kg material	0.48	3,216	3,216	3,216	3,216	3,216	3,216	3,216	3,216
Extraction products; Algae oil I	%	0.30								
Algae oil II	t/h/y	22.50								
Algae cake I	%	0.70								
Algae cake II	t/h/y	52.50								
SUB TOTAL (Extraction)			100,251	134,059	146,072	123,524	87,105	96,557	126,770	139,363
TRANSPORTATION										
Transport distance for agro inputs	km	50.0								
Transport service for agro inputs	t-km/ha	2,270.8								
Transport distance for algae to biorefinery	km	20.0								
Transport service for algae	t-km/ha	450.0								
Diesel truck fuel efficiency	l/t-km	0.02								
SUB TOTAL (Transport)	MJ/t algae		30,095	30,095	30,095	30,095	30,095	30,095	30,095	30,095
TRANSESTERIFICATION										
Methanol	MJ/kg oil	1.86	12,552	12,552	12,552	12,552	12,552	12,552	12,552	12,552
Sodium hydroxide	MJ/kg oil	0.61	4,126	4,126	4,126	4,126	4,126	4,126	4,126	4,126
Sodium methoxide	MJ/kg oil	0.02	157	157	157	157	157	157	157	157
Hydrochlorid Acid	MJ/kg oil	0.07	502	502	502	502	502	502	502	502
Heat	MJ/kg oil	0.90	20,184	22,405	25,049	22,860	20,050	22,405	22,427	22,427
Electricity	MJ/kg oil	0.15	3,327	8,316	8,612	5,848	806	821	6,842	9,359
SUB TOTAL (Transesterification)			40,848	48,058	50,999	46,045	38,193	40,563	46,606	49,123
Esterficiation product; Biodiesel	t/h/y	22.50								
Glycerol	t/h/y	4,792.50								
Co-product credit to Electricity	MJ/h/y	960,750	240,188	240,188						
Grid Electricity demand	MJ/h/y		- 64,836	162,090	167,859	113,991	15,700	15,993	133,347	182,407
Co-product credit - to Heat		960,750	540,902	540,902						
Grid Heat demand			- 594,675	660,089	738,000	673,490	590,722	660,089	660,750	660,750
Total fossil energy input incl co-product	MJ/h/y		1,919,261	1,541,027	1,624,707	1,506,329	1,325,270	1,394,930	1,512,944	1,562,004
TOTAL Fossil Energy input (lardon)	MY/h/y		2,159,448	2,741,897						
TOTAL Biodiesel energy	MJ/h/y		850,500							
TOTAL Oilcake energy	MJ/h/y		689,483							
TOTAL Glycerol	MJ/h/y		88,853							
ENERGY BALANCE RATIO	**MJ/MJ**			**3.22**	**1.8**	**1.6**	**1.4**	**1.6**	**1.6**	**1.7**

ALGAE BIODIESEL: GHG EMISSIONS - BIOMASS RESIDUE USE IN CHP UNIT

ALGAE BIODIESEL	Unit	Product flow	CHINA	UK	FRANCE	BRAZIL	NIGERIA	SAUDI ARABIA
					gCO2eq			
ALGAE OPEN POND CULTIVATION								
CO2 injection	MJ/kg dry algae	0.04	880,923	497,691	79,041	78,013	446,462	711,175
Ammonia (NH3) as nitrogen source	t/h	6.00	14,195,549	14,195,549	14,195,549	14,195,549	14,195,549	14,195,549
Superphosphate as phosphorus source	t/h	1.50	1,395,142	1,395,142	1,395,142	1,395,142	1,395,142	1,395,142
Potassium (K2O)	kg/kg dry algae	0.001	53,007	53,007	53,007	53,007	53,007	53,007
Paddlewheel electricity	MJ/kg dry algae	0.87	46,342,601	17,779,928	388,912	391,027	18,658,024	40,655,175
Machinery and pond infrastructure own ca	MJ/kg material	482,749	12,146,616	12,146,616	12,146,616	12,146,616	12,146,616	12,146,616
SUB TOTAL (Pond)			75,013,838	46,067,933	28,258,267	28,259,354	46,894,800	69,156,664
HARVESTING AND Flocculation								
Harvesting facilities own calc.	MJ/kg material	475,640	11,103,400	11,103,400	11,103,400	11,103,400	11,103,400	11,103,400
Pumping to settler electricity	MJ/kg dry algae	1.23	65,653,190	25,188,681	550,968	553,965	26,432,672	57,595,859
BIOMASS DRYER								
Heat	MJ/kg dry algae	13.80	167,491,213	97,778,342	77,056,701	87,041,803	81,892,983	84,478,700
Electricity	MJ/kg dry algae	1.44	77,050,199	29,561,288	646,613	650,130	31,021,229	67,594,162
Press	MJ/kg dry algae	0.23	12,039,094	4,618,951	101,033	101,583	4,847,067	10,561,588
SUB TOTAL (Harvesting/Dryer)			333,337,096	168,250,661	89,458,715	99,450,881	155,297,352	231,333,708
ALGAE OIL EXTRACTION								
Heat	MJ/ 90% dry algae	1.19	13,009,698	7,594,826	5,985,295	6,760,877	6,360,948	6,561,791
Electricity	MJ/ 90% dry algae	0.25	11,873,282	4,555,335	99,642	100,184	4,780,309	10,416,125
N-Hexane	MJ/kg material	0.48						
SUB TOTAL (Extraction)			24,882,979	12,150,162	6,084,937	6,861,061	11,141,258	16,977,916
TRANSPORTATION								
SUB TOTAL (Transport)	MJ/t algae		168,792	168,792	168,792	168,792	168,792	168,792
TRANSESTERIFICATION								
Methanol	MJ/kg oil	1.86	951,316	951,316	951,316	951,316	951,316	951,316
Sodium hydroxide	MJ/kg oil	0.61	47,345	47,345	47,345	47,345	47,345	47,345
Sodium methoxide	MJ/kg oil	0.02	546,642	546,642	546,642	546,642	546,642	546,642
Hydrochlorid Acid	MJ/kg oil	0.07	171,579	171,579	171,579	171,579	171,579	171,579
Heat	MJ/kg oil	0.90	3,266,397	1,906,863	1,502,752	1,697,481	1,597,069	1,647,495
Electricity	MJ/kg oil	0.15	2,373,221	910,516	19,916	20,025	955,484	2,081,966
SUB TOTAL (transesterification)			7,356,500	4,534,262	3,239,550	3,434,387	4,269,435	5,446,343
Esterficiation product; Biodiesel	t/h/y	22.50						
Glycerol	t/h/y	4,792.50						
Co-product credit - oil cake to Heat	gCO2/h/y	HEAT	77,545,071	49,605,508	44,570,310	50,011,169	47,052,837	48,538,499
Co-product credit - oil cake to Electricity		ELECTRICITY	17,866,479	10,093,939	1,603,069	1,582,232	9,054,941	14,423,736
TOTAL GWP incl oilcake offset	gCO2eqv		136,190,939	100,478,835	86,952,767	92,372,788	96,887,166	103,741,623
TOTAL Biodiesel energy	MJ/h/y		850,500					
TOTAL Oilcake energy	MJ/h/y		689,483					
TOTAL Glycerol	MJ/h/y		88,853					
gCO2eqv/ per 1MJ biodiesel	**gCO2eqv/MJ**		**160.1**	**118.1**	**102.2**	**108.6**	**113.9**	**122.0**
	DIESEL (g/MJ)	86	186%	137%	119%	126%	132%	142%

10.2. Appendix: Algae-to Jet Biofuel Production

Algae strain parameters and annual dry biomass productivities- see Appendix 1

Cultivation data used for the microalgae farming stage Appendix 2

Pond and Harvesting Machinery Appendix 3

Transportation Appendix 6

Appendix 11: Energy and Heat requirements

	Value	**Unit**	**Source**
CO_2 injection	0.04	MJ/kg dry	[109]
Paddlewheel electricity	0.87	MJ/kg dry	[109]
Pumping to settler electricity	1.23	MJ/kg dry	[109]
Dryer- heat	13.80	MJ/kg dry	[109]
Dryer-electricity	1.44	MJ/kg dry	[109]
Press-electricity	0.23	MJ/kg dry	[109]
Oil extraction-electricity[a]	0.25	MJ/kg dry	[109]
Oil extraction-heat[a]	1.19	MJ/kg dry	[109]

Appendix 12: Energy and Carbon Intensity of Fossil Electricity and Heat Grid

Input	**Value**	**Unit**
Energy and carbon intensity of 100% fossil heat grid (powered by natural gas)	1.1	(MJ/MJ Primary Fossil Energy/ Final Heat)
	66	gCO_{2eq}/MJ Heat
Energy and carbon intensity of a 100% fossil electricity grid (powered by crude oil and natural gas)	2.5	(MJ/MJ of Primary Fossil Energy/ Final Electricity)
	222.46	gCO_{2eq}/MJ Electricity

Appendix 13: Hydrogenation

Hydrogenation	Value	Unit	Source
Electricity	0.04	MJ/kg jet biofuel	[218]
Natural Gas -Heat	0.05	MJ/kg jet biofuel	[218]
Hydrogen	5.86	MJ/kg jet biofuel	[218]

Appendix 14: Algae Jet Biofuel Land Requirements

Algae fuel production	MJ/ha/y
Jet Biofuel	1,264,608
Biodiesel	1,275,750
Algae Productivity assumption (g/m2/d)	24.75
Productivity assumption (t/h/y)	75.00
Lipid content (%)	45%
Lipid content (t/h/y)	33.8

Fuels for all Transport [165]						
	Unit	**2010**	**2020**	**2030**	**2040**	**2050**
Fossil Jetfuel Demand (High)	(EJ)	10.7	14.6	19.7	26.4	34.9
(100% jet biofuel blend)	mha/y	8.5	11.5	15.6	20.9	27.6
(50% jet biofuel blend)	mha/y	4.2	5.8	7.8	10.4	13.8
offset 50% with 50% blend	mha/y	2.1	2.9	3.9	5.2	6.9
Fossil Jetfuel Demand (Low)	(EJ)	10.5	12.8	15.9	19.6	23.7
(100% jet biofuel blend)	mha/y	8.3	10.1	12.6	15.5	18.7
(50% jet biofuel blend)	mha/y	4.2	5.1	6.3	7.7	9.4
offset 50% with 50% blend	mha/y	2.1	2.5	3.1	3.9	4.7
Fossil Diesel Demand (High)	(EJ)	42.2	47.5	55.5	69.2	85.6
(100% biodiesel blend)	mha/y	33.1	37.2	43.5	54.2	67.1
(50% biodiesel blend)	mha/y	16.5	18.6	21.8	27.1	33.5
offset 50% with 50% blend	mha/y	8.3	9.3	10.9	13.6	16.8
Fossil Diesel Demand (Low)	(EJ)	41.9	44.8	50.5	56.3	61.3
(100% biodiesel blend)	mha/y	32.8	35.1	39.6	44.1	48.1
(50% biodiesel blend)	mha/y	16.4	17.6	19.8	22.1	24.0
offset 50% with 50% blend	mha/y	8.2	8.8	9.9	11.0	12.0

ALGAE JET BIOFUEL: LIFECYCLE FOSSIL ENERGY DEMAND- 100% FOSSIL

EBR (100% FOSSIL)	Unit	Product flow	(MJ/h/y)	Jet biofuel (JB)	JB+FT	JB+gasification	JB+combustion
ALGAE OPEN POND CULTIVATION							
CO2 injection	MJ/kg dry	0.04	3,197	7,992	7,992	7,992	7,992
Ammonia (NH3) as nitrogen source	t/h	5.25	17,955	17,955	17,955	17,955	17,955
Superphosphate as phosphorus source	t/h	0.75	3,075	3,075	3,075	3,075	3,075
Potassium (K2O)	kg/kg dry	0.001	-	-	-	-	-
Paddlewheel electricity	MJ/kg dry	0.87	64,958	162,394	162,394	162,394	162,394
Machinery and pond infrastructure own calc.	MJ/kg material	482,748.50	160,916	160,916	160,916	160,916	160,916
Water/algae volume processed	m3/h/y	150,000					
SUB TOTAL (Pond)			250,101	**352,332**	**352,332**	**352,332**	**352,332**
HARVESTING AND Flocculation							
Harvesting facilities own calc.	MJ/kg material	475,640.00	158,547	158,547	158,547	158,547	158,547
Pumping to settler electricity	MJ/kg dry	1.23	92,025	230,063	230,063	230,063	230,063
BIOMASS DRYER							
Heat	MJ/kg dry	13.80	1,035,000	1,148,850	1,148,850	1,148,850	1,148,850
Electricity	MJ/kg dry	1.44	108,000	270,000	270,000	270,000	270,000
Press	MJ/kg dry	0.23	16,875	42,188	42,188	42,188	42,188
Dry algae biomass (tons/ha/year)	t/h/y	75.00					
SUB TOTAL (Harvesting/Dryer)			1,410,447	**1,849,647**	**1,849,647**	**1,849,647**	**1,849,647**
ALGAE OIL EXTRACTION							
Heat	MJ/ 90% dry	1.19	80,393	89,236	89,236	89,236	89,236
Electricity	MJ/ 90% dry	0.25	16,643	41,606	41,606	41,606	41,606
N-Hexane	MJ/kg material	0.48	4,825	4,825	4,825	4,825	4,825
Extraction products; Algae oil I	%	0.45					
Algae oil II	t/h/y	33.75					
Algae cake I	%	0.55					
Algae cake II	t/h/y	41.25					
SUB TOTAL (Extraction)			101,860	**135,667**	**135,667**	**135,667**	**135,667**
SUB TOTAL (Transport)	MJ/t algae		29,265	**29,265**	**29,265**	**29,265**	**29,265**
HYDROGENATION							
Electricity	MJ/kg RD	0.04	1,290	3,224	3,224	3,224	3,224
Hydrogen	MJ/kg RD	5.86	168,532	168,532	168,532	168,532	168,532
Natural Gas	MJ/kg RD	0.05	1,444	1,602	1,602	1,602	1,602
SUB TOTAL (Hydrogenation)			171,265	**173,358**	**173,358**	**173,358**	**173,358**
RD fuel output	t/h/y	28.75					
RD energy content	MJ/kg RD	43.99					
Propane fuel mix output	MJ/kg RD	2.55					
Propane fuel mix energy content	MJ/kg RD	43.16					
Hydrogen Energy content		121.4					
OIL CAKE GASIFICATION							
Final Heat input for hydrogen production via gasification (II)							
Oil cake to Electricity	MJ/h/y	754,875	324,596				
Oil cake to Heat	MJ/h/y		354,791				641,644
Final Grid Electricity Demand	MJ/h/y		- 21,610				
Final Grid Heat Demand	MJ/h/y		762,045				475,192
Primary Energy required to satisfy Grid Electricity						- 54,024	
Primary Energy required to satisfy Grid Heat						845,870	527,464
FISCHER-TROPSCH SYNTHESIS							
Oil cake to Electricity	MJ/h/y		121,197				
Final Grid Electricity Demand	MJ/h/y		181,789				
Primary Energy required to satisfy Grid Electricity	MJ/h/y				454,473		
Oil cake to Synfuel	MJ/h/y		136,669				
Synfuel to FT Diesel	MJ/h/y				84,735		
Synfuel to FT Gasoline	MJ/h/y				51,934		
TOTAL Fossil Energy input incl co-product	MJ/h/y		**1,283,549**	**2,540,269**	**2,237,275**	**1,388,984**	**1,828,044**
TOTAL RD energy	MJ/h/y		1,264,608	1,264,608	1,264,608	1,264,608	1,264,608
TOTAL Oilcake energy	MJ/h/y		541,737				
TOTAL Propane fuel mix	MJ/h/y		73,237		84,955	84,955	84,955
TOTAL FT Diesel	MJ/h/y		84,735		94,903		
TOTAL FT Gasoline	MJ/h/y		51,934		61,802		
SURPLUS Electricity credit	MJ/h/y					54,024	
EBR II (MJ of LIQUID TRANSPORT FUEL)				**1.90**	**1.50**	**1.00**	**1.37**

ALGAE JET BIOFUEL: GHG EMISSIONS BALANCE- 100% FOSSIL

GHG BALANCE (100% FOSSIL)	Unit	Product flow	Jet biofuel (JB)	JB+FT	JB+gasification	JB+combustion
ALGAE OPEN POND CULTIVATION						
CO2 injection	MJ/kg dry	0.04	711,175	711,175	711,175	711,175
Ammonia (NH3) as nitrogen source	t/h	5.25	745,266	745,266	745,266	745,266
Superphosphate as phosphorus source	t/h	0.75	697,571	697,571	697,571	697,571
Potassium (K2O)	MJ/kg dry	0.001	-	-	-	-
Paddlewheel electricity	MJ/kg dry	0.87	36,126,976	36,126,976	36,126,976	36,126,976
Machinery and pond infrastructure own calc.	MJ/kg material	482,749	12,146,616	12,146,616	12,146,616	12,146,616
SUB TOTAL (Pond)			50,427,605	50,427,605	50,427,605	50,427,605
HARVESTING AND Flocculation						
Harvesting facilities own calc.	MJ/kg material	475,640	11,103,400	11,103,400	11,103,400	11,103,400
Pumping to settler electricity	MJ/kg dry	1.23	51,180,796	51,180,796	51,180,796	51,180,796
BIOMASS DRYER						
Heat	MJ/kg dry	13.80	75,824,100	75,824,100	75,824,100	75,824,100
Electricity	MJ/kg dry	1.44	60,065,481	60,065,481	60,065,481	60,065,481
Press	MJ/kg dry	0.23	9,385,231	9,385,231	9,385,231	9,385,231
SUB TOTAL (Harvesting/Dryer)			207,559,008	207,559,008	207,559,008	207,559,008
ALGAE OIL EXTRACTION						
Heat	MJ/ 90% dry	1.19	5,889,555	5,889,555	5,889,555	5,889,555
Electricity	MJ/ 90% dry	0.25	9,255,971	9,255,971	9,255,971	9,255,971
N-Hexane	MJ/kg material	0.48				
SUB TOTAL (Extraction)			15,145,525	15,145,525	15,145,525	15,145,525
TRANSPORTATION	MJ/t algae		164,139	164,139	164,139	164,139
HYDROGENATION						
Electricity	MJ/kg RD		717,240	717,240	717,240	717,240
Hydrogen	gCO2/ha/y	28.75	10,936,150	10,936,150	10,936,150	10,936,150
Natural Gas	MJ/kg RD		105,759	105,759	105,759	105,760
SUB TOTAL (hydrogenation)			11,759,149	11,759,149	11,759,149	11,759,150
GASIFICATION						
Final Grid Electricity Demand	gCO2/h/y			40,441,717		
Final Grid Heat Demand	gCO2/h/y				50,294,961	31,362,696
TOTAL GWP incl oilcake offset	gCO2eqv		**285,055,426**	**158,054,273**	**86,088,103**	**234,598,708**
TOTAL RD energy	MJ/h/y	1,264,608	1,264,608	1,264,608	1,264,608	
TOTAL Oilcake energy	MJ/h/y	541,737				
TOTAL Propane fuel mix	MJ/h/y	73,237		5,346,303	5,346,303	
TOTAL FT DIESEL	MJ/h/y	84,735		7,033,005		
TOTAL FT GASOLINE	MJ/h/y	51,934		4,362,486		
Surplus ELECTRICITY CREDIT					4,807,369	
TOTAL GHG emissions per bioenergy outp	gCO2eqv/MJ LIQUID FUELS		**213**	**107.2**	**60.8**	**175.4**

ALGAE JET BIOFUEL: LIFECYCLE FOSSIL ENERGY DEMAND- 50% FOSSIL

EBR (50% FOSSIL)	Unit	Product flow	(MJ/h/y)	Jet biofuel (JB)	JB+FT	JB+gasification	JB+combustion
ALGAE OPEN POND CULTIVATION							
CO2 injection	MJ/kg dry	0.04	3,197	3,996	3,996	3,996	3,996
Ammonia (NH3) as nitrogen source	t/h	5.25	17,955	17,955	17,955	17,955	17,955
Superphosphate as phosphorus source	t/h	0.75	3,075	3,075	3,075	3,075	3,075
Potassium (K2O)	kg/kg dry	0.001	-	-	-		-
Paddlewheel electricity	MJ/kg dry	0.87	64,958	81,197	81,197	81,197	81,197
Machinery and pond infrastructure own calc.	MJ/kg material	482,748.50	160,916	160,916	160,916	160,916	160,916
Water/algae volume processed	m3/h/y	150,000					
SUB TOTAL (Pond)			250,101	**267,139**	**267,139**	**267,139**	**267,139**
HARVESTING AND Flocculation							
Harvesting facilities own calc.	MJ/kg material	475,640.00	158,547	158,547	158,547	158,547	158,547
Pumping to settler electricity	MJ/kg dry	1.23	92,025	115,031	115,031	115,031	115,031
BIOMASS DRYER							
Heat	MJ/kg dry	13.80	1,035,000	574,425	574,425	574,425	574,425
Electricity	MJ/kg dry	1.44	108,000	135,000	135,000	135,000	135,000
Press	MJ/kg dry	0.23	16,875	21,094	21,094	21,094	21,094
Dry algae biomass (tons/ha/year)	t/h/y	75.00					
SUB TOTAL (Harvesting/Dryer)			1,410,447	**1,004,097**	**1,004,097**	**1,004,097**	**1,004,097**
ALGAE OIL EXTRACTION							
Heat	MJ/ 90% dry	1.19	80,393	44,618	44,618	44,618	44,618
Electricity	MJ/ 90% dry	0.25	16,643	20,803	20,803	20,803	20,803
N-Hexane	MJ/kg material	0.48	4,825	4,825	4,825	4,825	4,825
Extraction products; Algae oil I	%	0.45					
Algae oil II	t/h/y	33.75					
Algae cake I	%	0.55					
Algae cake II	t/h/y	41.25					
SUB TOTAL (Extraction)			101,860	**70,246**	**70,246**	**70,246**	**70,246**
SUB TOTAL (Transport)	MJ/t algae		29,265	**29,265**	**29,265**	**29,265**	**29,265**
HYDROGENATION							
Electricity	MJ/kg RD	**0.04**	1,290	1,612	1,612	1,612	1,612
Hydrogen	MJ/kg RD	**5.86**	168,532	168,532	168,532	168,532	168,532
Natural Gas	MJ/kg RD	**0.05**	1,444	801	801	801	801
SUB TOTAL (Hydrogenation)			171,265	**170,945**	**170,945**	**170,945**	**170,945**
RD fuel output	t/h/y	**28.75**					
RD energy content	MJ/kg RD	**43.99**					
Propane fuel mix output	MJ/kg RD	2.55					
Propane fuel mix energy content	MJ/kg RD	43.16					
Hydrogen Energy content		121.4					
OIL CAKE GASIFICATION							
Final Heat input for hydrogen production via gasification (II)							
Oil cake to Electricity	MJ/h/y	754,875	324,596				
Oil cake to Heat	MJ/h/y		354,791				641,644
Final Grid Electricity Demand	MJ/h/y		- 21,610				
Final Grid Heat Demand	MJ/h/y		762,045				475,192
Primary Energy required to satisfy Grid Electricity						- 27,012	
Primary Energy required to satisfy Grid Heat						422,935	263,732
FISCHER-TROPSCH SYNTHESIS							
Oil cake to Electricity	MJ/h/y		121,197				
Final Grid Electricity Demand	MJ/h/y		181,789				
Primary Energy required to satisfy Grid Electricity	MJ/h/y				227,237		
Oil cake to Synfuel	MJ/h/y		136,669				
Synfuel to FT Diesel	MJ/h/y				84,735		
Synfuel to FT Gasoline	MJ/h/y				51,934		
TOTAL Fossil Energy input incl co-product	MJ/h/y		**1,283,549**	**1,541,691**	**1,390,195**	**966,049**	**1,185,579**
TOTAL RD energy	MJ/h/y		1,264,608	1,264,608	1,264,608	1,264,608	1,264,608
TOTAL Oilcake energy	MJ/h/y		541,737				
TOTAL Propane fuel mix	MJ/h/y		73,237		84,955	84,955	84,955
TOTAL FT Diesel	MJ/h/y		84,735		94,903		
TOTAL FT Gasoline	MJ/h/y		51,934		61,802		
SURPLUS Electricity credit	MJ/h/y					27,012	
EBR II (MJ of LIQUID TRANSPORT FUEL)				**1.15**	**0.93**	**0.70**	**0.89**

ALGAE JET BIOFUEL: GHG EMISSIONS BALANCE- 50% FOSSIL

GHG BALANCE (50% FOSSIL)	Unit	Product flow	Jet biofuel (JB)	JB+FT	JB+gasification	JB+combustion
ALGAE OPEN POND CULTIVATION						
CO2 injection	MJ/kg dry	0.04	355,588	355,588	355,588	355,588
Ammonia (NH3) as nitrogen source	t/h	5.25	745,266	745,266	745,266	745,266
Superphosphate as phosphorus source	t/h	0.75	697,571	697,571	697,571	697,571
Potassium (K2O)	MJ/kg dry	0.001	-	-	-	-
Paddlewheel electricity	MJ/kg dry	0.87	18,063,488	18,063,488	18,063,488	18,063,488
Machinery and pond infrastructure own calc.	MJ/kg material	482,749	12,146,616	12,146,616	12,146,616	12,146,616
SUB TOTAL (Pond)			32,008,529	32,008,529	32,008,529	32,008,529
HARVESTING AND Flocculation						
Harvesting facilities own calc.	MJ/kg material	475,640	11,103,400	11,103,400	11,103,400	11,103,400
Pumping to settler electricity	MJ/kg dry	1.23	25,590,398	25,590,398	25,590,398	25,590,398
BIOMASS DRYER						
Heat	MJ/kg dry	13.80	37,912,050	37,912,050	37,912,050	37,912,050
Electricity	MJ/kg dry	1.44	30,032,741	30,032,741	30,032,741	30,032,741
Press	MJ/kg dry	0.23	4,692,616	4,692,616	4,692,616	4,692,616
SUB TOTAL (Harvesting/Dryer)			109,331,204	109,331,204	109,331,204	109,331,204
ALGAE OIL EXTRACTION						
Heat	MJ/ 90% dry	1.19	2,944,777	2,944,777	2,944,777	2,944,777
Electricity	MJ/ 90% dry	0.25	4,627,985	4,627,985	4,627,985	4,627,985
N-Hexane	MJ/kg material	0.48				
SUB TOTAL (Extraction)			7,572,763	7,572,763	7,572,763	7,572,763
TRANSPORTATION	MJ/t algae		164,139	164,139	164,139	164,139
HYDROGENATION						
Electricity	MJ/kg RD		358,620	358,620	358,620	358,620
Hydrogen	gCO2/ha/y	28.75	10,936,150	10,936,150	10,936,150	10,936,150
Natural Gas	MJ/kg RD		52,880	52,880	52,880	52,880
SUB TOTAL (hydrogenation)			11,347,649	11,347,649	11,347,649	11,347,649
GASIFICATION						
Final Grid Electricity Demand	gCO2/h/y			20,220,858		
Final Grid Heat Demand	gCO2/h/y				25,147,480	15,681,348
TOTAL GWP incl oilcake offset	gCO2eqv		**160,424,284**	**96,923,708**	**60,940,623**	**135,195,925**
TOTAL RD energy	MJ/h/y	1,264,608	1,264,608	1,264,608	1,264,608	
TOTAL Oilcake energy	MJ/h/y	541,737				
TOTAL Propane fuel mix	MJ/h/y	73,237		5,346,303	5,346,303	
TOTAL FT DIESEL	MJ/h/y	84,735		7,033,005		
TOTAL FT GASOLINE	MJ/h/y	51,934		4,362,486		
Surplus ELECTRICITY CREDIT					2,403,685	
TOTAL GHG emissions per bioenergy output	gCO2eqv/MJ LIQUID FUELS		**120**	**65.7**	**43.8**	**101.1**

ALGAE JET BIOFUEL: LIFECYCLE FOSSIL ENERGY DEMAND- 0% FOSSIL

EBR (0% FOSSIL)	Unit	Product flow	(MJ/h/y)	Jet biofuel (JB)	JB+FT	JB+gasification	JB+combustion
ALGAE OPEN POND CULTIVATION							
CO_2 injection	MJ/kg dry	0.04	3,197	-	-	-	-
Ammonia (NH_3) as nitrogen source	t/h	5.25	17,955	17,955	17,955	17,955	17,955
Superphosphate as phosphorus source	t/h	0.75	3,075	3,075	3,075	3,075	3,075
Potassium (K_2O)	kg/kg dry	0.001	-	-	-		-
Paddlewheel electricity	MJ/kg dry	0.87	64,958	-	-	-	-
Machinery and pond infrastructure own calc.	MJ/kg material	482,748.50	160,916	160,916	160,916	160,916	160,916
Water/algae volume processed	m3/h/y	150,000					
SUB TOTAL (Pond)			250,101	**181,946**	**181,946**	**181,946**	**181,946**
HARVESTING AND Flocculation							
Harvesting facilities own calc.	MJ/kg material	475,640.00	158,547	158,547	158,547	158,547	158,547
Pumping to settler electricity	MJ/kg dry	1.23	92,025	-	-	-	-
BIOMASS DRYER							
Heat	MJ/kg dry	13.80	1,035,000	-	-	-	-
Electricity	MJ/kg dry	1.44	108,000	-	-	-	-
Press	MJ/kg dry	0.23	16,875	-	-	-	-
Dry algae biomass (tons/ha/year)	t/h/y	75.00					
SUB TOTAL (Harvesting/Dryer)			1,410,447	**158,547**	**158,547**	**158,547**	**158,547**
ALGAE OIL EXTRACTION							
Heat	MJ/ 90% dry	1.19	80,393	-	-	-	-
Electricity	MJ/ 90% dry	0.25	16,643	-	-	-	-
N-Hexane	MJ/kg material	0.48	4,825	4,825	4,825	4,825	4,825
Extraction products; Algae oil I	%	0.45					
Algae oil II	t/h/y	33.75					
Algae cake I	%	0.55					
Algae cake II	t/h/y	41.25					
SUB TOTAL (Extraction)			101,860	**4,825**	**4,825**	**4,825**	**4,825**
SUB TOTAL (Transport)	MJ/t algae		29,265	**29,265**	**29,265**	**29,265**	**29,265**
HYDROGENATION							
Electricity	MJ/kg RD	**0.04**	1,290	-	-	-	-
Hydrogen	MJ/kg RD	**5.86**	168,532	168,532	168,532	168,532	168,532
Natural Gas	MJ/kg RD	**0.05**	1,444	-	-	-	-
SUB TOTAL (Hydrogenation)			171,265	**168,532**	**168,532**	**168,532**	**168,532**
RD fuel output	t/h/y	**28.75**					
RD energy content	MJ/kg RD	**43.99**					
Propane fuel mix output	MJ/kg RD	2.55					
Propane fuel mix energy content	MJ/kg RD	43.16					
Hydrogen Energy content		121.4					
OIL CAKE GASIFICATION							
Final Heat input for hydrogen production via gasification (II)							
Oil cake to Electricity	MJ/h/y	754,875	324,596				
Oil cake to Heat	MJ/h/y		354,791				641,644
Final Grid Electricity Demand	MJ/h/y		- 21,610				
Final Grid Heat Demand	MJ/h/y		762,045				475,192
Primary Energy required to satisfy Grid Electricity						-	
Primary Energy required to satisfy Grid Heat						-	-
FISCHER-TROPSCH SYNTHESIS							
Oil cake to Electricity	MJ/h/y		121,197				
Final Grid Electricity Demand	MJ/h/y		181,789				
Primary Energy required to satisfy Grid Electricity	MJ/h/y				-		
Oil cake to Synfuel	MJ/h/y		136,669				
Synfuel to FT Diesel	MJ/h/y				84,735		
Synfuel to FT Gasoline	MJ/h/y				51,934		
TOTAL Fossil Energy input incl co-product	MJ/h/y		**1,283,549**	**543,114**	**543,114**	**543,114**	**543,114**
TOTAL RD energy	MJ/h/y		1,264,608	1,264,608	1,264,608	1,264,608	1,264,608
TOTAL Oilcake energy	MJ/h/y		541,737				
TOTAL Propane fuel mix	MJ/h/y		73,237		84,955	84,955	84,955
TOTAL FT Diesel	MJ/h/y		84,735		94,903		
TOTAL FT Gasoline	MJ/h/y		51,934		61,802		
SURPLUS Electricity credit	MJ/h/y					-	
EBR II (MJ of LIQUID TRANSPORT FUEL)				**0.41**	**0.36**	**0.41**	**0.41**

ALGAE JET BIOFUEL: GHG EMISSIONS BALANCE- 0% FOSSIL

GHG BALANCE (0% FOSSIL)	Unit	Product flow	Jet biofuel (JB)	JB+FT	JB+gasification	JB+combustion
ALGAE OPEN POND CULTIVATION						
CO2 injection	MJ/kg dry	0.04	-	-	-	-
Ammonia (NH3) as nitrogen source	t/h	5.25	745,266	745,266	745,266	745,266
Superphosphate as phosphorus source	t/h	0.75	697,571	697,571	697,571	697,571
Potassium (K2O)	MJ/kg dry	0.001	-	-	-	-
Paddlewheel electricity	MJ/kg dry	0.87	-	-	-	-
Machinery and pond infrastructure own calc.	MJ/kg material	482,749	12,146,616	12,146,616	12,146,616	12,146,616
SUB TOTAL (Pond)			13,589,454	13,589,454	13,589,454	13,589,454
HARVESTING AND Flocculation						
Harvesting facilities own calc.	MJ/kg material	475,640	11,103,400	11,103,400	11,103,400	11,103,400
Pumping to settler electricity	MJ/kg dry	1.23	-	-	-	-
BIOMASS DRYER						
Heat	MJ/kg dry	13.80	-	-	-	-
Electricity	MJ/kg dry	1.44	-	-	-	-
Press	MJ/kg dry	0.23	-	-	-	-
SUB TOTAL (Harvesting/Dryer)			11,103,400	11,103,400	11,103,400	11,103,400
ALGAE OIL EXTRACTION						
Heat	MJ/ 90% dry	1.19	-	-	-	
Electricity	MJ/ 90% dry	0.25	-	-	-	
N-Hexane	MJ/kg material	0.48				
SUB TOTAL (Extraction)			-	-	-	-
TRANSPORTATION	MJ/t algae		164,139	164,139	164,139	164,140
HYDROGENATION						
Electricity	MJ/kg RD		-	-	-	-
Hydrogen	gCO2/ha/y	28.75	10,936,150	10,936,150	10,936,150	10,936,150
Natural Gas	MJ/kg RD		-	-	-	-
SUB TOTAL (hydrogenation)			10,936,150	10,936,150	10,936,150	10,936,150
GASIFICATION						
Final Grid Electricity Demand	gCO2/h/y			-		
Final Grid Heat Demand	gCO2/h/y				-	-
TOTAL GWP incl oilcake offset	gCO2eqv		**35,793,142**	**35,793,142**	**35,793,142**	**35,793,143**
TOTAL RD energy	MJ/h/y	1,264,608	1,264,608	1,264,608	1,264,608	
TOTAL Oilcake energy	MJ/h/y	541,737				
TOTAL Propane fuel mix	MJ/h/y	73,237		5,346,303	5,346,303	
TOTAL FT DIESEL	MJ/h/y	84,735		7,033,005		
TOTAL FT GASOLINE	MJ/h/y	51,934		4,362,486		
Surplus ELECTRICITY CREDIT					-	
TOTAL GHG emissions per bioenergy output	gCO2eqv/MJ LIQUID FUELS		**27**	**24.3**	**26.8**	**26.8**

10.3 Appendix: Algae for Fish Feed Production

Appendix 15: Landmass needed for global aquafeed production by 2030

Projected Fish Feed Use		**Microalgae biomass**	
GLOBAL (FAO 1998)	2030	70/t/h/a Land (ha/year)	60t/ha/y Land (ha/year)
Fish meal (tonnes)	159%		
Supply	6,526,000		
Demand	**10,376,340**	148,233	172,939
Fish oil (tonnes)	460%		
Supply	1,283,000		
Demand	**5,901,800**	84,311	98,363
Total Land Demand	ha/year	232,545	271,302
	km2/y	2,325	2,713

Appendix 16: Summary of dewatered algae feed production costs

SUMMARY OF DEWATERED ALGAE FEED PRODUCTION COSTS					
Feedstock	Lipid %	Pond size	**2010**	**2030**	**2050**
Spirulina Platensis	11	Yields (g/m2/d)	10.5	21	31.5
		$/ton	3981	2045	1399
Nannocloropsis sp	53	Yields (g/m2/d)	5.3	10.6	15.9
		$/ton	7813	3977	2698
Pavlova Lutheri	36	Yields (g/m2/d)	15	30	45
		$/ton	2839	1483	1031
Fishmeal			1125	2250	3375
Fish oil			1330	2660	3990
Soybean			560	728	946

A detailed cost-break down for total production costs of all three algae strains in 2010,2030 and 2050 is given in the following pages 213-230.

SPIRULINA PLATENSIS (2010) CAPITAL COSTS

Number of Ponds	1
Total Pond Area (ha)	2
Total Oil Production (gallons per year)	2,091
Operating Days per Year	330

Capital Cost	Total Cost	Cost per ha	Cost per kg algae	Cost per gallon
Growth Ponds	$70,718	$35,359	$1.020	$33.82
Site Prep, Grading, Compaction	$6,428	$3,214	$0.093	$3.07
Pond levees, geotextiles	$9,000	$4,500	$0.130	$4.30
Mixing (Paddle Wheels)	$12,857	$6,428	$0.186	$6.15
CO2 Sumps, diffuser	$10,285	$5,143	$0.148	$4.92
Water Supply	$10,901	$5,450	$0.157	$5.21
Water Distribution	$3,120	$1,560	$0.045	$1.49
CO2 Distribution	$824	$412	$0.012	$0.39
Nutrient Supply System	$2,476	$1,238	$0.036	$1.18
Land Cost	$14,826			
Primary Dewatering	$9,863	$4,931	$0.142	$4.72
Secondary Dewatering		$0	$0.000	$0.00
Spray Dryer		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Dryer		$0	$0.000	$0.00
Extraction		$0.00	$0.000	$0.00
Purchase Price		$0.00	$0.000	$0.00
Other Direct Costs for Extraction		$0.00	$0.000	$0.00
Algae Coproduct Processing		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Algae Coproduct		$0	$0.000	$0.00
Steam Generator		$0	$0.0000	$0.0000
Purchase Price		$0	$0.0000	$0.0000
Other Direct Costs for Steam Generator		$0	$0.0000	$0.0000
Anaerobic Digester		$0	$0.0000	$0.0000
Electricity Gen		$0	$0.0000	$0.0000
System-wide Cost for growth and harvest	$18,305	$9,152	$0.2641	$8.75
Buildings (excluding Harvest Systems)	$1,817	$908	$0.0262	$0.87
Roads and Drainage per ha	$1,652	$826	$0.0238	$0.79
Electrical Distribution	$4,233	$2,116	$0.0611	$2.02
Electrical Supply	$1,868	$934	$0.0269	$0.89
Machinery	$1,322	$661	$0.0191	$0.63
Additional Land Cost	$7,413	$3,707	$0.1070	$3.55
Total Direct Capital	$98,887	$49,444	$1.4269	$47.29
Fees and Contingency	$14,833	$7,417	$0.2140	$7.09
Total Project Cost	$113,720	$56,860	$1.6410	$54.38
Annualized Capital	$16,791	$8,395	$0.2423	$8.03

Financial Summary				
Total Annual Operating and Capital Cost	$275,906	$137,953	**$3.9813**	$131.95
Coproduct Revenue	$0	$0	$0.0000	$0.00
Electricity Revenue	$0	$0	$0.0000	$0.00
Net Cost Algae Oil	$275,906	$137,953	$3.9813	$131.95

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$166,579	$12,008	$178,587
Primary Dewatering*	$1,395	$1,675	$3,069
Secondary Dewatering	$90,385	$0	$90,385
Drying	$0	$0	$0
Oil Extraction	$0	$0	$0
Algae Coproduct Recovery	$0	$0	$0
System-wide	$757	$3,108	$3,866
Total	$259,116	$16,790	$275,906

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$79.66	$5.74	$85.41
Primary Dewatering*	$0.67	$0.80	$1.47
Secondary Dewatering	$43.23	$0.00	$43.23
Drying	$0.00	$0.00	$0.00
Oil Extraction	$0.00	$0.00	$0.00
Algae Coproduct Recovery	$0.00	$0.00	$0.00
System-wide	$0.36	$1.49	$1.85
Total	$123.92	$8.03	$131.95

	Annual Costs by Type
Raw Materials	$6,121
Cost of Capital	$16,790
Labor and Overhead	$102,393
Maintenance	$2,967
Utilities	$1,200
Total Annual Capital Charge	$16,790

*Labor and Overhead included in growth ponds

	Capital Cost
Growth Ponds	$70,718
Primary Dewatering	$9,863
Secondary Dewatering	$0
Spray Dryer	$0
Extraction	$0
Algae Coproduct Processing	$0
System-wide Cost for growth and harve	$18,305
Fees and Contingency	$14,833
Total Project Cost	$113,720

SPIRULINA PLATENSIS (2010) OPERATING COSTS

Operating Cost	Annual Cost	Cost per ha per year	Cost per MT algae	Cost per gallon oil
Growth Ponds	$178,587	$89,293	$2,577	$85.41
Nutrients other than CO2	$1,313	$657	$19	$0.63
Nitrogen as NH3	$216	$108	$3	$0.10
P as Superphosphate	$603	$302	$9	$0.29
Fe as FeSO4	$494	$247	$7	$0.24
CO2 Delivered	$3,133	$1,566	$45	$1.50
Electricity	$1,200		$17	$0.57
Mixing	$215	$107	$3	$0.10
Water	$953	$477	$14	$0.46
Nutrients	$32		$0	$0.02
Water			$0	$0.00
Maintenance	$2,122	$1,061	$31	$1.01
Labor and Overhead	$160,012	$80,006	$2,309	$76.52
Annual Capital Charge	$12,008	$6,004	$173	$5.74
Primary Dewatering*	**$3,069**	**$1,535**	**$44**	**$1**
Electricity	$0	$0	$0	$0.00
Maintenance	$296	$148	$4	$0.14
Flocculant	$1,099	$549	$16	$0.53
Annual Capital Charge	$1,675	$837	$24	$0.80
Secondary Dewatering	**$90,385**	**$45,192**	**$1,304**	**$43**
Electricity	$0	$0	$0	$0.00
Maintenance	$0	$0	$0	$0.00
Labor and Overhead	$90,385	$45,192	$1,304	$43.23
Annual Capital Charge	$0	$0	$0	$0.00
Spray Dryer		$0	$0	$0.00
System-wide Cost for growth and harvest	$3,866	$1,933	$56	$1.85
Maintenance	$549	$275	$8	$0.26
Buildings	$208	$104	$3	$0.10
Annual Capital Charge	$3,108	$1,554	$45	$1.49
Total Operating Cost	$275,906	$137,953	**$3,981**	$131.95
Total Annual Capital Charge	$16,790	$8,395	**$242**	$8.03

SPIRULINA PLATENSIS (2030) CAPITAL COSTS

Number of Ponds	1
Total Pond Area (ha)	2
Total Oil Production (gallons per year)	4,182
Operating Days per Year	330

Capital Cost	Total Cost	Cost per ha	Cost per kg algae	Cost per gallon
Growth Ponds	$70,718	$35,359	$0.510	$16.91
Site Prep, Grading, Compaction	$6,428	$3,214	$0.046	$1.54
Pond levees, geotextiles	$9,000	$4,500	$0.065	$2.15
Mixing (Paddle Wheels)	$12,857	$6,428	$0.093	$3.07
CO2 Sumps, diffuser	$10,285	$5,143	$0.074	$2.46
Water Supply	$10,901	$5,450	$0.079	$2.61
Water Distribution	$3,120	$1,560	$0.023	$0.75
CO2 Distribution	$824	$412	$0.006	$0.20
Nutrient Supply System	$2,476	$1,238	$0.018	$0.59
Land Cost	$14,826			
Primary Dewatering	$19,726	$9,863	$0.142	$4.72
Secondary Dewatering		$0	$0.000	$0.00
Spray Dryer		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Dryer		$0	$0.000	$0.00
Extraction		$0.00	$0.000	$0.00
Purchase Price		$0.00	$0.000	$0.00
Other Direct Costs for Extraction		$0.00	$0.000	$0.00
Algae Coproduct Processing		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Algae Coproduct		$0	$0.000	$0.00
Steam Generator		$0	$0.0000	$0.0000
Purchase Price		$0	$0.0000	$0.0000
Other Direct Costs for Steam Generator		$0	$0.0000	$0.0000
Anaerobic Digester		$0	$0.0000	$0.0000
Electricity Gen		$0	$0.0000	$0.0000
System-wide Cost for growth and harvest	$18,305	$9,152	$0.1321	$4.38
Buildings (excluding Harvest Systems)	$1,817	$908	$0.0131	$0.43
Roads and Drainage per ha	$1,652	$826	$0.0119	$0.40
Electrical Distribution	$4,233	$2,116	$0.0305	$1.01
Electrical Supply	$1,868	$934	$0.0135	$0.45
Machinery	$1,322	$661	$0.0095	$0.32
Additional Land Cost	$7,413	$3,707	$0.0535	$1.77
Total Direct Capital	$108,750	$54,375	$0.7846	$26.00
Fees and Contingency	$16,313	$8,156	$0.1177	$3.90
Total Project Cost	$125,063	$62,531	$0.9023	$29.90
Annualized Capital	$18,466	$9,233	$0.1332	$4.42

Financial Summary				
Total Annual Operating and Capital Cost	$283,422	$141,711	**$2.0449**	$67.77
Coproduct Revenue	$0	$0	$0.0000	$0.00
Electricity Revenue	$0	$0	$0.0000	$0.00
Net Cost Algae Oil	$283,422	$141,711	$2.0449	$67.77

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$171,025	$12,008	$183,033
Primary Dewatering*	$2,789	$3,349	$6,138
Secondary Dewatering	$90,385	$0	$90,385
Drying	$0	$0	$0
Oil Extraction	$0	$0	$0
Algae Coproduct Recovery	$0	$0	$0
System-wide	$757	$3,108	$3,866
Total	$264,957	$18,465	$283,422

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$40.90	$2.87	$43.77
Primary Dewatering*	$0.67	$0.80	$1.47
Secondary Dewatering	$21.61	$0.00	$21.61
Drying	$0.00	$0.00	$0.00
Oil Extraction	$0.00	$0.00	$0.00
Algae Coproduct Recovery	$0.00	$0.00	$0.00
System-wide	$0.18	$0.74	$0.92
Total	$63.36	$4.42	$67.77

Annual Costs by Type	
Raw Materials	$12,241
Cost of Capital	$18,465
Labor and Overhead	$102,393
Maintenance	$3,262
Utilities	$1,235
Total Annual Capital Charge	$18,465

*Labor and Overhead included in growth ponds

	Capital Cost
Growth Ponds	$70,718
Primary Dewatering	$19,726
Secondary Dewatering	$0
Spray Dryer	$0
Extraction	$0
Algae Coproduct Processing	$0
System-wide Cost for growth and harv	$18,305
Fees and Contingency	$16,313
Total Project Cost	$125,063

SPIRULINA PLATENSIS (2030) OPERATING COSTS

Operating Cost	Annual Cost	Cost per ha per year	Cost per MT algae	Cost per gallon oil
Growth Ponds	$183,033	$91,516	$1,321	$43.77
Nutrients other than CO2	$2,626	$1,313	$19	$0.63
Nitrogen as NH3	$431	$216	$3	$0.10
P as Superphosphate	$1,206	$603	$9	$0.29
Fe as FeSO4	$989	$494	$7	$0.24
CO2 Delivered	$6,266	$3,133	$45	$1.50
Electricity	$1,235		$9	$0.30
Mixing	$215	$107	$2	$0.05
Water	$956	$478	$7	$0.23
Nutrients	$64		$0	$0.02
Water			$0	$0.00
Maintenance	$2,122	$1,061	$15	$0.51
Labor and Overhead	$160,012	$80,006	$1,154	$38.26
Annual Capital Charge	$12,008	$6,004	$87	$2.87
Primary Dewatering*	**$6,138**	**$3,069**	**$44**	**$1**
Electricity	$0	$0	$0	$0.00
Maintenance	$592	$296	$4	$0.14
Flocculant	$2,197	$1,099	$16	$0.53
Annual Capital Charge	$3,349	$1,675	$24	$0.80
Secondary Dewatering	**$90,385**	**$45,192**	**$652**	**$22**
Electricity	$0	$0	$0	$0.00
Maintenance	$0	$0	$0	$0.00
Labor and Overhead	$90,385	$45,192	$652	$21.61
Annual Capital Charge	$0	$0	$0	$0.00
Spray Dryer		$0	$0	$0.00
System-wide Cost for growth and harvest	$3,866	$1,933	$28	$0.92
Maintenance	$549	$275	$4	$0.13
Buildings	$208	$104	$2	$0.05
Annual Capital Charge	$3,108	$1,554	$22	$0.74
Total Operating Cost	$283,422	$141,711	**$2,045**	$67.77
Total Annual Capital Charge	$18,465	$9,233	**$133**	$4.42

SPIRULINA PLATENSIS (2050) CAPITAL COSTS

Number of Ponds	1
Total Pond Area (ha)	2
Total Oil Production (gallons per year)	6,273
Operating Days per Year	330

Capital Cost	Total Cost	Cost per ha	Cost per kg algae	Cost per gallon
Growth Ponds	$70,718	$35,359	$0.340	$11.27
Site Prep, Grading, Compaction	$6,428	$3,214	$0.031	$1.02
Pond levees, geotextiles	$9,000	$4,500	$0.043	$1.43
Mixing (Paddle Wheels)	$12,857	$6,428	$0.062	$2.05
CO2 Sumps, diffuser	$10,285	$5,143	$0.049	$1.64
Water Supply	$10,901	$5,450	$0.052	$1.74
Water Distribution	$3,120	$1,560	$0.015	$0.50
CO2 Distribution	$824	$412	$0.004	$0.13
Nutrient Supply System	$2,476	$1,238	$0.012	$0.39
Land Cost	$14,826			
Primary Dewatering	$29,589	$14,794	$0.142	$4.72
Secondary Dewatering		$0	$0.000	$0.00
Spray Dryer		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Dryer		$0	$0.000	$0.00
Extraction		$0.00	$0.000	$0.00
Purchase Price		$0.00	$0.000	$0.00
Other Direct Costs for Extraction		$0.00	$0.000	$0.00
Algae Coproduct Processing		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Algae Coproduct		$0	$0.000	$0.00
Steam Generator		$0	$0.0000	$0.0000
Purchase Price		$0	$0.0000	$0.0000
Other Direct Costs for Steam Generator		$0	$0.0000	$0.0000
Anaerobic Digester		$0	$0.0000	$0.0000
Electricity Gen		$0	$0.0000	$0.0000
System-wide Cost for growth and harvest	$18,305	$9,152	$0.0880	$2.92
Buildings (excluding Harvest Systems)	$1,817	$908	$0.0087	$0.29
Roads and Drainage per ha	$1,652	$826	$0.0079	$0.26
Electrical Distribution	$4,233	$2,116	$0.0204	$0.67
Electrical Supply	$1,868	$934	$0.0090	$0.30
Machinery	$1,322	$661	$0.0064	$0.21
Additional Land Cost	$7,413	$3,707	$0.0357	$1.18
Total Direct Capital	$118,613	$59,306	$0.5705	$18.91
Fees and Contingency	$17,792	$8,896	$0.0856	$2.84
Total Project Cost	$136,405	$68,202	$0.6561	$21.74
Annualized Capital	$20,140	$10,070	$0.0969	$3.21

Financial Summary				
Total Annual Operating and Capital Cost	$290,937	$145,468	**$1.3994**	$46.38
Coproduct Revenue	$0	$0	$0.0000	$0.00
Electricity Revenue	$0	$0	$0.0000	$0.00
Net Cost Algae Oil	$290,937	$145,468	$1.3994	$46.38

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$175,471	$12,008	$187,479
Primary Dewatering*	$4,184	$5,024	$9,208
Secondary Dewatering	$90,385	$0	$90,385
Drying	$0	$0	$0
Oil Extraction	$0	$0	$0
Algae Coproduct Recovery	$0	$0	$0
System-wide	$757	$3,108	$3,866
Total	$270,797	$20,140	$290,937

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$27.97	$1.91	$29.89
Primary Dewatering*	$0.67	$0.80	$1.47
Secondary Dewatering	$14.41	$0.00	$14.41
Drying	$0.00	$0.00	$0.00
Oil Extraction	$0.00	$0.00	$0.00
Algae Coproduct Recovery	$0.00	$0.00	$0.00
System-wide	$0.12	$0.50	$0.62
Total	$43.17	$3.21	$46.38

	Annual Costs by Type
Raw Materials	$18,362
Cost of Capital	$20,140
Labor and Overhead	$102,393
Maintenance	$3,558
Utilities	$1,270

Total Annual Capital Charge	$20,140

*Labor and Overhead included in growth ponds

	Capital Cost
Growth Ponds	$70,718
Primary Dewatering	$29,589
Secondary Dewatering	$0
Spray Dryer	$0
Extraction	$0
Algae Coproduct Processing	$0
System-wide Cost for growth and harve	$18,305
Fees and Contingency	$17,792
Total Project Cost	$136,405

SPIRULINA PLATENSIS (2050) OPERATING COSTS

Operating Cost	Annual Cost	Cost per ha per year	Cost per MT algae	Cost per gallon oil
Growth Ponds	$187,479	$93,739	$902	$29.89
Nutrients other than CO2	$3,940	$1,970	$19	$0.63
Nitrogen as NH3	$647	$324	$3	$0.10
P as Superphosphate	$1,809	$905	$9	$0.29
Fe as FeSO4	$1,483	$742	$7	$0.24
CO2 Delivered	$9,398	$4,699	$45	$1.50
Electricity	$1,270		$6	$0.20
Mixing	$215	$107	$1	$0.03
Water	$959	$479	$5	$0.15
Nutrients	$96		$0	$0.02
Water			$0	$0.00
Maintenance	$2,122	$1,061	$10	$0.34
Labor and Overhead	$160,012	$80,006	$770	$25.51
Annual Capital Charge	$12,008	$6,004	$58	$1.91
Primary Dewatering*	**$9,208**	**$4,604**	**$44**	**$1**
Electricity	$0	$0	$0	$0.00
Maintenance	$888	$444	$4	$0.14
Flocculant	$3,296	$1,648	$16	$0.53
Annual Capital Charge	$5,024	$2,512	$24	$0.80
Secondary Dewatering	**$90,385**	**$45,192**	**$435**	**$14**
Electricity	$0	$0	$0	$0.00
Maintenance	$0	$0	$0	$0.00
Labor and Overhead	$90,385	$45,192	$435	$14.41
Annual Capital Charge	$0	$0	$0	$0.00
Spray Dryer		$0	$0	$0.00
System-wide Cost for growth and harvest	$3,866	$1,933	$19	$0.62
Maintenance	$549	$275	$3	$0.09
Buildings	$208	$104	$1	$0.03
Annual Capital Charge	$3,108	$1,554	$15	$0.50
Total Operating Cost	$290,937	$145,468	**$1,399**	$46.38
Total Annual Capital Charge	$20,140	$10,070	**$97**	$3.21

NANNOCLOROPSIS SP (2010) CAPITAL COSTS

Number of Ponds	1
Total Pond Area (ha)	2
Total Oil Production (gallons per year)	5,085
Operating Days per Year	330

Capital Cost	Total Cost	Cost per ha	Cost per kg algae	Cost per gallon
Growth Ponds	$70,718	$35,359	$2.022	$13.91
Site Prep, Grading, Compaction	$6,428	$3,214	$0.184	$1.26
Pond levees, geotextiles	$9,000	$4,500	$0.257	$1.77
Mixing (Paddle Wheels)	$12,857	$6,428	$0.368	$2.53
CO2 Sumps, diffuser	$10,285	$5,143	$0.294	$2.02
Water Supply	$10,901	$5,450	$0.312	$2.14
Water Distribution	$3,120	$1,560	$0.089	$0.61
CO2 Distribution	$824	$412	$0.024	$0.16
Nutrient Supply System	$2,476	$1,238	$0.071	$0.49
Land Cost	$14,826			
Primary Dewatering	$4,978	$2,489	$0.142	$0.98
Secondary Dewatering		$0	$0.000	$0.00
Spray Dryer		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Dryer		$0	$0.000	$0.00
Extraction		$0.00	$0.000	$0.00
Purchase Price		$0.00	$0.000	$0.00
Other Direct Costs for Extraction		$0.00	$0.000	$0.00
Algae Coproduct Processing		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Algae Coproduct		$0	$0.000	$0.00
Steam Generator		$0	$0.0000	$0.0000
Purchase Price		$0	$0.0000	$0.0000
Other Direct Costs for Steam Generator		$0	$0.0000	$0.0000
Anaerobic Digester		$0	$0.0000	$0.0000
Electricity Gen		$0	$0.0000	$0.0000
System-wide Cost for growth and harvest	$18,305	$9,152	$0.5233	$3.60
Buildings (excluding Harvest Systems)	$1,817	$908	$0.0519	$0.36
Roads and Drainage per ha	$1,652	$826	$0.0472	$0.32
Electrical Distribution	$4,233	$2,116	$0.1210	$0.83
Electrical Supply	$1,868	$934	$0.0534	$0.37
Machinery	$1,322	$661	$0.0378	$0.26
Additional Land Cost	$7,413	$3,707	$0.2119	$1.46
Total Direct Capital	$94,003	$47,001	$2.6873	$18.48
Fees and Contingency	$14,100	$7,050	$0.4031	$2.77
Total Project Cost	$108,103	$54,052	$3.0904	$21.26
Annualized Capital	$15,961	$7,981	$0.4563	$3.14

Financial Summary				
Total Annual Operating and Capital Cost	$273,304	$136,652	**$7.8131**	$53.74
Coproduct Revenue	$0	$0	$0.0000	$0.00
Electricity Revenue	$0	$0	$0.0000	$0.00
Net Cost Algae Oil	$273,304	$136,652	$7.8131	$53.74

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$165,496	$12,008	$177,504
Primary Dewatering*	$704	$845	$1,549
Secondary Dewatering	$90,385	$0	$90,385
Drying	$0	$0	$0
Oil Extraction	$0	$0	$0
Algae Coproduct Recovery	$0	$0	$0
System-wide	$757	$3,108	$3,866
Total	$257,343	$15,961	$273,304

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$32.54	$2.36	$34.90
Primary Dewatering*	$0.14	$0.17	$0.30
Secondary Dewatering	$17.77	$0.00	$17.77
Drying	$0.00	$0.00	$0.00
Oil Extraction	$0.00	$0.00	$0.00
Algae Coproduct Recovery	$0.00	$0.00	$0.00
System-wide	$0.15	$0.61	$0.76
Total	$50.60	$3.14	$53.74

	Annual Costs by Type
Raw Materials	$4,209
Cost of Capital	$15,961
Labor and Overhead	$102,393
Maintenance	$2,820
Utilities	$1,183
Total Annual Capital Charge	$15,961

*Labor and Overhead included in growth ponds

	Capital Cost
Growth Ponds	$70,718
Primary Dewatering	$4,978
Secondary Dewatering	$0
Spray Dryer	$0
Extraction	$0
Algae Coproduct Processing	$0
System-wide Cost for growth and harv	$18,305
Fees and Contingency	$14,100
Total Project Cost	$108,103

NANNOCLOROPSIS SP (2010) OPERATING COSTS

Operating Cost	Annual Cost	Cost per ha per year	Cost per MT algae	Cost per gallon oil
Growth Ponds	$177,504	$88,752	$5,074	$34.90
Nutrients other than CO2	$468	$234	$13	$0.09
Nitrogen as NH3	$58	$29	$2	$0.01
P as Superphosphate	$161	$80	$5	$0.03
Fe as FeSO4	$250	$125	$7	$0.05
CO2 Delivered	$2,896	$1,448	$83	$0.57
Electricity	$1,183		$34	$0.23
Mixing	$215	$107	$6	$0.04
Water	$952	$476	$27	$0.19
Nutrients	$16		$0	$0.00
Water			$0	$0.00
Maintenance	$2,122	$1,061	$61	$0.42
Labor and Overhead	$160,012	$80,006	$4,574	$31.46
Annual Capital Charge	$12,008	$6,004	$343	$2.36
Primary Dewatering*	**$1,549**	**$775**	**$44**	**$0**
Electricity	$0	$0	$0	$0.00
Maintenance	$149	$75	$4	$0.03
Flocculant	$555	$277	$16	$0.11
Annual Capital Charge	$845	$423	$24	$0.17
Secondary Dewatering	**$90,385**	**$45,192**	**$2,584**	**$18**
Electricity	$0	$0	$0	$0.00
Maintenance	$0	$0	$0	$0.00
Labor and Overhead	$90,385	$45,192	$2,584	$17.77
Annual Capital Charge	$0	$0	$0	$0.00
Spray Dryer		$0	$0	$0.00
System-wide Cost for growth and harvest	$3,866	$1,933	$111	$0.76
Maintenance	$549	$275	$16	$0.11
Buildings	$208	$104	$6	$0.04
Annual Capital Charge	$3,108	$1,554	$89	$0.61
Total Operating Cost	$273,304	$136,652	**$7,813**	$53.74
Total Annual Capital Charge	$15,961	$7,981	**$456**	$3.14

NANNOCLOROPSIS SP (2030) CAPITAL COSTS

Number of Ponds	1
Total Pond Area (ha)	2
Total Oil Production (gallons per year)	10,171
Operating Days per Year	330

Capital Cost	Total Cost	Cost per ha	Cost per kg algae	Cost per gallon
Growth Ponds	$70,718	$35,359	$1.011	$6.95
Site Prep, Grading, Compaction	$6,428	$3,214	$0.092	$0.63
Pond levees, geotextiles	$9,000	$4,500	$0.129	$0.88
Mixing (Paddle Wheels)	$12,857	$6,428	$0.184	$1.26
CO2 Sumps, diffuser	$10,285	$5,143	$0.147	$1.01
Water Supply	$10,901	$5,450	$0.156	$1.07
Water Distribution	$3,120	$1,560	$0.045	$0.31
CO2 Distribution	$824	$412	$0.012	$0.08
Nutrient Supply System	$2,476	$1,238	$0.035	$0.24
Land Cost	$14,826			
Primary Dewatering	$9,957	$4,978	$0.142	$0.98
Secondary Dewatering		$0	$0.000	$0.00
Spray Dryer		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Dryer		$0	$0.000	$0.00
Extraction		$0.00	$0.000	$0.00
Purchase Price		$0.00	$0.000	$0.00
Other Direct Costs for Extraction		$0.00	$0.000	$0.00
Algae Coproduct Processing		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Algae Coproduct		$0	$0.000	$0.00
Steam Generator		$0	$0.0000	$0.0000
Purchase Price		$0	$0.0000	$0.0000
Other Direct Costs for Steam Generator		$0	$0.0000	$0.0000
Anaerobic Digester		$0	$0.0000	$0.0000
Electricity Gen		$0	$0.0000	$0.0000
System-wide Cost for growth and harvest	$18,305	$9,152	$0.2616	$1.80
Buildings (excluding Harvest Systems)	$1,817	$908	$0.0260	$0.18
Roads and Drainage per ha	$1,652	$826	$0.0236	$0.16
Electrical Distribution	$4,233	$2,116	$0.0605	$0.42
Electrical Supply	$1,868	$934	$0.0267	$0.18
Machinery	$1,322	$661	$0.0189	$0.13
Additional Land Cost	$7,413	$3,707	$0.1060	$0.73
Total Direct Capital	$98,981	$49,491	$1.4148	$9.73
Fees and Contingency	$14,847	$7,424	$0.2122	$1.46
Total Project Cost	$113,828	$56,914	$1.6270	$11.19
Annualized Capital	$16,807	$8,403	$0.2402	$1.65

Financial Summary				
Total Annual Operating and Capital Cost	$278,216	$139,108	**$3.9768**	$27.35
Coproduct Revenue	$0	$0	$0.0000	$0.00
Electricity Revenue	$0	$0	$0.0000	$0.00
Net Cost Algae Oil	$278,216	$139,108	$3.9768	$27.35

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$168,860	$12,008	$180,868
Primary Dewatering*	$1,408	$1,691	$3,098
Secondary Dewatering	$90,385	$0	$90,385
Drying	$0	$0	$0
Oil Extraction	$0	$0	$0
Algae Coproduct Recovery	$0	$0	$0
System-wide	$757	$3,108	$3,866
Total	$261,410	$16,806	$278,216

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$16.60	$1.18	$17.78
Primary Dewatering*	$0.14	$0.17	$0.30
Secondary Dewatering	$8.89	$0.00	$8.89
Drying	$0.00	$0.00	$0.00
Oil Extraction	$0.00	$0.00	$0.00
Algae Coproduct Recovery	$0.00	$0.00	$0.00
System-wide	$0.07	$0.31	$0.38
Total	$25.70	$1.65	$27.35

Annual Costs by Type	
Raw Materials	$8,417
Cost of Capital	$16,806
Labor and Overhead	$102,393
Maintenance	$2,969
Utilities	$1,200
Total Annual Capital Charge	$16,806

*Labor and Overhead included in growth ponds

Capital Cost	
Growth Ponds	$70,718
Primary Dewatering	$9,957
Secondary Dewatering	$0
Spray Dryer	$0
Extraction	$0
Algae Coproduct Processing	$0
System-wide Cost for growth and harv	$18,305
Fees and Contingency	$14,847
Total Project Cost	$113,828

NANNOCLOROPSIS SP (2030) OPERATING COSTS

Operating Cost	Annual Cost	Cost per ha per year	Cost per MT algae	Cost per gallon oil
Growth Ponds	$180,868	$90,434	$2,585	$17.78
Nutrients other than CO2	$936	$468	$13	$0.09
Nitrogen as NH3	$115	$58	$2	$0.01
P as Superphosphate	$322	$161	$5	$0.03
Fe as FeSO4	$499	$250	$7	$0.05
CO2 Delivered	$5,791	$2,896	$83	$0.57
Electricity	$1,200		$17	$0.12
Mixing	$215	$107	$3	$0.02
Water	$953	$477	$14	$0.09
Nutrients	$32		$0	$0.00
Water			$0	$0.00
Maintenance	$2,122	$1,061	$30	$0.21
Labor and Overhead	$160,012	$80,006	$2,287	$15.73
Annual Capital Charge	$12,008	$6,004	$172	$1.18
Primary Dewatering*	**$3,098**	**$1,549**	**$44**	**$0**
Electricity	$0	$0	$0	$0.00
Maintenance	$299	$149	$4	$0.03
Flocculant	$1,109	$555	$16	$0.11
Annual Capital Charge	$1,691	$845	$24	$0.17
Secondary Dewatering	**$90,385**	**$45,192**	**$1,292**	**$9**
Electricity	$0	$0	$0	$0.00
Maintenance	$0	$0	$0	$0.00
Labor and Overhead	$90,385	$45,192	$1,292	$8.89
Annual Capital Charge	$0	$0	$0	$0.00
Spray Dryer		$0	$0	$0.00
System-wide Cost for growth and harvest	$3,866	$1,933	$55	$0.38
Maintenance	$549	$275	$8	$0.05
Buildings	$208	$104	$3	$0.02
Annual Capital Charge	$3,108	$1,554	$44	$0.31
Total Operating Cost	$278,216	$139,108	**$3,977**	$27.35
Total Annual Capital Charge	$16,806	$8,403	**$240**	$1.65

NANNOCLOROPSIS SP (2050) CAPITAL COSTS

Number of Ponds	1
Total Pond Area (ha)	2
Total Oil Production (gallons per year)	15,256
Operating Days per Year	330

Capital Cost	Total Cost	Cost per ha	Cost per kg algae	Cost per gallon
Growth Ponds	$70,718	$35,359	$0.674	$4.64
Site Prep, Grading, Compaction	$6,428	$3,214	$0.061	$0.42
Pond levees, geotextiles	$9,000	$4,500	$0.086	$0.59
Mixing (Paddle Wheels)	$12,857	$6,428	$0.123	$0.84
CO2 Sumps, diffuser	$10,285	$5,143	$0.098	$0.67
Water Supply	$10,901	$5,450	$0.104	$0.71
Water Distribution	$3,120	$1,560	$0.030	$0.20
CO2 Distribution	$824	$412	$0.008	$0.05
Nutrient Supply System	$2,476	$1,238	$0.024	$0.16
Land Cost	$14,826			
Primary Dewatering	$14,935	$7,468	$0.142	$0.98
Secondary Dewatering		$0	$0.000	$0.00
Spray Dryer		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Dryer		$0	$0.000	$0.00
Extraction		$0.00	$0.000	$0.00
Purchase Price		$0.00	$0.000	$0.00
Other Direct Costs for Extraction		$0.00	$0.000	$0.00
Algae Coproduct Processing		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Algae Coproduct		$0	$0.000	$0.00
Steam Generator		$0	$0.0000	$0.0000
Purchase Price		$0	$0.0000	$0.0000
Other Direct Costs for Steam Generator		$0	$0.0000	$0.0000
Anaerobic Digester		$0	$0.0000	$0.0000
Electricity Gen		$0	$0.0000	$0.0000
System-wide Cost for growth and harvest	$18,305	$9,152	$0.1744	$1.20
Buildings (excluding Harvest Systems)	$1,817	$908	$0.0173	$0.12
Roads and Drainage per ha	$1,652	$826	$0.0157	$0.11
Electrical Distribution	$4,233	$2,116	$0.0403	$0.28
Electrical Supply	$1,868	$934	$0.0178	$0.12
Machinery	$1,322	$661	$0.0126	$0.09
Additional Land Cost	$7,413	$3,707	$0.0706	$0.49
Total Direct Capital	$103,959	$51,980	$0.9907	$6.81
Fees and Contingency	$15,594	$7,797	$0.1486	$1.02
Total Project Cost	$119,553	$59,777	$1.1393	$7.84
Annualized Capital	$17,652	$8,826	$0.1682	$1.16

Financial Summary				
Total Annual Operating and Capital Cost	$283,129	$141,565	**$2.6980**	$18.56
Coproduct Revenue	$0	$0	$0.0000	$0.00
Electricity Revenue	$0	$0	$0.0000	$0.00
Net Cost Algae Oil	$283,129	$141,565	$2.6980	$18.56

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$172,223	$12,008	$184,231
Primary Dewatering*	$2,112	$2,536	$4,648
Secondary Dewatering	$90,385	$0	$90,385
Drying	$0	$0	$0
Oil Extraction	$0	$0	$0
Algae Coproduct Recovery	$0	$0	$0
System-wide	$757	$3,108	$3,866
Total	$265,477	$17,652	$283,129

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$11.29	$0.79	$12.08
Primary Dewatering*	$0.14	$0.17	$0.30
Secondary Dewatering	$5.92	$0.00	$5.92
Drying	$0.00	$0.00	$0.00
Oil Extraction	$0.00	$0.00	$0.00
Algae Coproduct Recovery	$0.00	$0.00	$0.00
System-wide	$0.05	$0.20	$0.25
Total	$17.40	$1.16	$18.56

Annual Costs by Type	
Raw Materials	$12,626
Cost of Capital	$17,652
Labor and Overhead	$102,393
Maintenance	$3,119
Utilities	$1,218
Total Annual Capital Charge	$17,652

*Labor and Overhead included in growth ponds

Capital Cost	
Growth Ponds	$70,718
Primary Dewatering	$14,935
Secondary Dewatering	$0
Spray Dryer	$0
Extraction	$0
Algae Coproduct Processing	$0
System-wide Cost for growth and harv	$18,305
Fees and Contingency	$15,594
Total Project Cost	$119,553

NANNOCLOROPSIS SP (2050) OPERATING COSTS

Operating Cost	Annual Cost	Cost per ha per year	Cost per MT algae	Cost per gallon oil
Growth Ponds	$184,231	$92,115	$1,756	$12.08
Nutrients other than CO2	$1,403	$702	$13	$0.09
Nitrogen as NH3	$173	$86	$2	$0.01
P as Superphosphate	$482	$241	$5	$0.03
Fe as FeSO4	$749	$374	$7	$0.05
CO2 Delivered	$8,687	$4,343	$83	$0.57
Electricity	$1,218		$12	$0.08
Mixing	$215	$107	$2	$0.01
Water	$955	$477	$9	$0.06
Nutrients	$49		$0	$0.00
Water			$0	$0.00
Maintenance	$2,122	$1,061	$20	$0.14
Labor and Overhead	$160,012	$80,006	$1,525	$10.49
Annual Capital Charge	$12,008	$6,004	$114	$0.79
Primary Dewatering*	**$4,648**	**$2,324**	**$44**	**$0**
Electricity	$0	$0	$0	$0.00
Maintenance	$448	$224	$4	$0.03
Flocculant	$1,664	$832	$16	$0.11
Annual Capital Charge	$2,536	$1,268	$24	$0.17
Secondary Dewatering	**$90,385**	**$45,192**	**$861**	**$6**
Electricity	$0	$0	$0	$0.00
Maintenance	$0	$0	$0	$0.00
Labor and Overhead	$90,385	$45,192	$861	$5.92
Annual Capital Charge	$0	$0	$0	$0.00
Spray Dryer		$0	$0	$0.00
System-wide Cost for growth and harvest	$3,866	$1,933	$37	$0.25
Maintenance	$549	$275	$5	$0.04
Buildings	$208	$104	$2	$0.01
Annual Capital Charge	$3,108	$1,554	$30	$0.20
Total Operating Cost	$283,129	$141,565	**$2,698**	$18.56
Total Annual Capital Charge	$17,652	$8,826	**$168**	$1.16

PAVLOVA LUTHERI (2010) CAPITAL COSTS

Number of Ponds	1
Total Pond Area (ha)	2
Total Oil Production (gallons per year)	9,776
Operating Days per Year	330

Capital Cost	Total Cost	Cost per ha	Cost per kg algae	Cost per gallon
Growth Ponds	$70,718	$35,359	$0.714	$7.23
Site Prep, Grading, Compaction	$6,428	$3,214	$0.065	$0.66
Pond levees, geotextiles	$9,000	$4,500	$0.091	$0.92
Mixing (Paddle Wheels)	$12,857	$6,428	$0.130	$1.32
CO2 Sumps, diffuser	$10,285	$5,143	$0.104	$1.05
Water Supply	$10,901	$5,450	$0.110	$1.12
Water Distribution	$3,120	$1,560	$0.032	$0.32
CO2 Distribution	$824	$412	$0.008	$0.08
Nutrient Supply System	$2,476	$1,238	$0.025	$0.25
Land Cost	$14,826			
Primary Dewatering	$14,090	$7,045	$0.142	$1.44
Secondary Dewatering		$0	$0.000	$0.00
Spray Dryer		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Dryer		$0	$0.000	$0.00
Extraction		$0.00	$0.000	$0.00
Purchase Price		$0.00	$0.000	$0.00
Other Direct Costs for Extraction		$0.00	$0.000	$0.00
Algae Coproduct Processing		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Algae Coproduct		$0	$0.000	$0.00
Steam Generator		$0	$0.0000	$0.0000
Purchase Price		$0	$0.0000	$0.0000
Other Direct Costs for Steam Generator		$0	$0.0000	$0.0000
Anaerobic Digester		$0	$0.0000	$0.0000
Electricity Gen		$0	$0.0000	$0.0000
System-wide Cost for growth and harvest	$18,305	$9,152	$0.1849	$1.87
Buildings (excluding Harvest Systems)	$1,817	$908	$0.0184	$0.19
Roads and Drainage per ha	$1,652	$826	$0.0167	$0.17
Electrical Distribution	$4,233	$2,116	$0.0428	$0.43
Electrical Supply	$1,868	$934	$0.0189	$0.19
Machinery	$1,322	$661	$0.0134	$0.14
Additional Land Cost	$7,413	$3,707	$0.0749	$0.76
Total Direct Capital	$103,114	$51,557	$1.0416	$10.55
Fees and Contingency	$15,467	$7,734	$0.1562	$1.58
Total Project Cost	$118,581	$59,291	$1.1978	$12.13
Annualized Capital	$17,509	$8,754	$0.1769	$1.79

Financial Summary				
Total Annual Operating and Capital Cost	$281,013	$140,506	**$2.8385**	$28.74
Coproduct Revenue	$0	$0	$0.0000	$0.00
Electricity Revenue	$0	$0	$0.0000	$0.00
Net Cost Algae Oil	$281,013	$140,506	$2.8385	$28.74

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$170,370	$12,008	$182,378
Primary Dewatering*	$1,992	$2,392	$4,385
Secondary Dewatering	$90,385	$0	$90,385
Drying	$0	$0	$0
Oil Extraction	$0	$0	$0
Algae Coproduct Recovery	$0	$0	$0
System-wide	$757	$3,108	$3,866
Total	$263,505	$17,508	$281,013

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$17.43	$1.23	$18.66
Primary Dewatering*	$0.20	$0.24	$0.45
Secondary Dewatering	$9.25	$0.00	$9.25
Drying	$0.00	$0.00	$0.00
Oil Extraction	$0.00	$0.00	$0.00
Algae Coproduct Recovery	$0.00	$0.00	$0.00
System-wide	$0.08	$0.32	$0.40
Total	$26.95	$1.79	$28.74

Annual Costs by Type	
Raw Materials	$10,629
Cost of Capital	$17,508
Labor and Overhead	$102,393
Maintenance	$3,093
Utilities	$1,215
Total Annual Capital Charge	$17,508

*Labor and Overhead included in growth ponds

Capital Cost	
Growth Ponds	$70,718
Primary Dewatering	$14,090
Secondary Dewatering	$0
Spray Dryer	$0
Extraction	$0
Algae Coproduct Processing	$0
System-wide Cost for growth and harv	$18,305
Fees and Contingency	$15,467
Total Project Cost	$118,581

PAVLOVA LUTHERI (2010) OPERATING COSTS

Operating Cost	Annual Cost	Cost per ha per year	Cost per MT algae	Cost per gallon oil
Growth Ponds	$182,378	$91,189	$1,842	$18.66
Nutrients other than CO2	$1,547	$774	$16	$0.16
Nitrogen as NH3	$222	$111	$2	$0.02
P as Superphosphate	$620	$310	$6	$0.06
Fe as FeSO4	$706	$353	$7	$0.07
CO2 Delivered	$6,689	$3,345	$68	$0.68
Electricity	$1,215		$12	$0.12
Mixing	$215	$107	$2	$0.02
Water	$954	$477	$10	$0.10
Nutrients	$46		$0	$0.00
Water			$0	$0.00
Maintenance	$2,122	$1,061	$21	$0.22
Labor and Overhead	$160,012	$80,006	$1,616	$16.37
Annual Capital Charge	$12,008	$6,004	$121	$1.23
Primary Dewatering*	**$4,385**	**$2,192**	**$44**	**$0**
Electricity	$0	$0	$0	$0.00
Maintenance	$423	$211	$4	$0.04
Flocculant	$1,570	$785	$16	$0.16
Annual Capital Charge	$2,392	$1,196	$24	$0.24
Secondary Dewatering	**$90,385**	**$45,192**	**$913**	**$9**
Electricity	$0	$0	$0	$0.00
Maintenance	$0	$0	$0	$0.00
Labor and Overhead	$90,385	$45,192	$913	$9.25
Annual Capital Charge	$0	$0	$0	$0.00
Spray Dryer		$0	$0	$0.00
System-wide Cost for growth and harvest	$3,866	$1,933	$39	$0.40
Maintenance	$549	$275	$6	$0.06
Buildings	$208	$104	$2	$0.02
Annual Capital Charge	$3,108	$1,554	$31	$0.32
Total Operating Cost	$281,013	$140,506	**$2,839**	$28.74
Total Annual Capital Charge	$17,508	$8,754	**$177**	$1.79

PAVLOVA LUTHERI (2030) CAPITAL COSTS

Number of Ponds	1
Total Pond Area (ha)	2
Total Oil Production (gallons per year)	19,552
Operating Days per Year	330

Capital Cost	Total Cost	Cost per ha	Cost per kg algae	Cost per gallon
Growth Ponds	$70,718	$35,359	$0.357	$3.62
Site Prep, Grading, Compaction	$6,428	$3,214	$0.032	$0.33
Pond levees, geotextiles	$9,000	$4,500	$0.045	$0.46
Mixing (Paddle Wheels)	$12,857	$6,428	$0.065	$0.66
CO2 Sumps, diffuser	$10,285	$5,143	$0.052	$0.53
Water Supply	$10,901	$5,450	$0.055	$0.56
Water Distribution	$3,120	$1,560	$0.016	$0.16
CO2 Distribution	$824	$412	$0.004	$0.04
Nutrient Supply System	$2,476	$1,238	$0.013	$0.13
Land Cost	$14,826			
Primary Dewatering	$28,180	$14,090	$0.142	$1.44
Secondary Dewatering		$0	$0.000	$0.00
Spray Dryer		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Dryer		$0	$0.000	$0.00
Extraction		$0.00	$0.000	$0.00
Purchase Price		$0.00	$0.000	$0.00
Other Direct Costs for Extraction		$0.00	$0.000	$0.00
Algae Coproduct Processing		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Algae Coproduct		$0	$0.000	$0.00
Steam Generator		$0	$0.0000	$0.0000
Purchase Price		$0	$0.0000	$0.0000
Other Direct Costs for Steam Generator		$0	$0.0000	$0.0000
Anaerobic Digester		$0	$0.0000	$0.0000
Electricity Gen		$0	$0.0000	$0.0000
System-wide Cost for growth and harvest	$18,305	$9,152	$0.0924	$0.94
Buildings (excluding Harvest Systems)	$1,817	$908	$0.0092	$0.09
Roads and Drainage per ha	$1,652	$826	$0.0083	$0.08
Electrical Distribution	$4,233	$2,116	$0.0214	$0.22
Electrical Supply	$1,868	$934	$0.0094	$0.10
Machinery	$1,322	$661	$0.0067	$0.07
Additional Land Cost	$7,413	$3,707	$0.0374	$0.38
Total Direct Capital	$117,204	$58,602	$0.5919	$5.99
Fees and Contingency	$17,581	$8,790	$0.0888	$0.90
Total Project Cost	$134,785	$67,392	$0.6807	$6.89
Annualized Capital	$19,901	$9,950	$0.1005	$1.02

Financial Summary				
Total Annual Operating and Capital Cost	$293,634	$146,817	**$1.4830**	$15.02
Coproduct Revenue	$0	$0	$0.0000	$0.00
Electricity Revenue	$0	$0	$0.0000	$0.00
Net Cost Algae Oil	$293,634	$146,817	$1.4830	$15.02

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$178,607	$12,008	$190,615
Primary Dewatering*	$3,984	$4,785	$8,769
Secondary Dewatering	$90,385	$0	$90,385
Drying	$0	$0	$0
Oil Extraction	$0	$0	$0
Algae Coproduct Recovery	$0	$0	$0
System-wide	$757	$3,108	$3,866
Total	$273,734	$19,901	$293,634

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$9.13	$0.61	$9.75
Primary Dewatering*	$0.20	$0.24	$0.45
Secondary Dewatering	$4.62	$0.00	$4.62
Drying	$0.00	$0.00	$0.00
Oil Extraction	$0.00	$0.00	$0.00
Algae Coproduct Recovery	$0.00	$0.00	$0.00
System-wide	$0.04	$0.16	$0.20
Total	$14.00	$1.02	$15.02

Annual Costs by Type	
Raw Materials	$21,259
Cost of Capital	$19,901
Labor and Overhead	$102,393
Maintenance	$3,516
Utilities	$1,265
Total Annual Capital Charge	$19,901

*Labor and Overhead included in growth ponds

Capital Cost	
Growth Ponds	$70,718
Primary Dewatering	$28,180
Secondary Dewatering	$0
Spray Dryer	$0
Extraction	$0
Algae Coproduct Processing	$0
System-wide Cost for growth and harv	$18,305
Fees and Contingency	$17,581
Total Project Cost	$134,785

PAVLOVA LUTHERI (2030) OPERATING COSTS

Operating Cost	Annual Cost	Cost per ha per year	Cost per MT algae	Cost per gallon oil
Growth Ponds	$190,615	$95,307	$963	$9.75
Nutrients other than CO2	$3,095	$1,547	$16	$0.16
Nitrogen as NH3	$443	$222	$2	$0.02
P as Superphosphate	$1,239	$620	$6	$0.06
Fe as FeSO4	$1,413	$706	$7	$0.07
CO2 Delivered	$13,379	$6,689	$68	$0.68
Electricity	$1,265		$6	$0.06
Mixing	$215	$107	$1	$0.01
Water	$958	$479	$5	$0.05
Nutrients	$92		$0	$0.00
Water			$0	$0.00
Maintenance	$2,122	$1,061	$11	$0.11
Labor and Overhead	$160,012	$80,006	$808	$8.18
Annual Capital Charge	$12,008	$6,004	$61	$0.61
Primary Dewatering*	**$8,769**	**$4,385**	**$44**	**$0**
Electricity	$0	$0	$0	$0.00
Maintenance	$845	$423	$4	$0.04
Flocculant	$3,139	$1,570	$16	$0.16
Annual Capital Charge	$4,785	$2,392	$24	$0.24
Secondary Dewatering	**$90,385**	**$45,192**	**$456**	**$5**
Electricity	$0	$0	$0	$0.00
Maintenance	$0	$0	$0	$0.00
Labor and Overhead	$90,385	$45,192	$456	$4.62
Annual Capital Charge	$0	$0	$0	$0.00
Spray Dryer		$0	$0	$0.00
System-wide Cost for growth and harvest	$3,866	$1,933	$20	$0.20
Maintenance	$549	$275	$3	$0.03
Buildings	$208	$104	$1	$0.01
Annual Capital Charge	$3,108	$1,554	$16	$0.16
Total Operating Cost	$293,634	$146,817	**$1,483**	$15.02
Total Annual Capital Charge	$19,901	$9,950	**$101**	$1.02

PAVLOVA LUTHERI (2050) CAPITAL COSTS

Number of Ponds	1
Total Pond Area (ha)	2
Total Oil Production (gallons per year)	29,329
Operating Days per Year	330

Capital Cost	Total Cost	Cost per ha	Cost per kg algae	Cost per gallon
Growth Ponds	$70,718	$35,359	$0.238	$2.41
Site Prep, Grading, Compaction	$6,428	$3,214	$0.022	$0.22
Pond levees, geotextiles	$9,000	$4,500	$0.030	$0.31
Mixing (Paddle Wheels)	$12,857	$6,428	$0.043	$0.44
CO2 Sumps, diffuser	$10,285	$5,143	$0.035	$0.35
Water Supply	$10,901	$5,450	$0.037	$0.37
Water Distribution	$3,120	$1,560	$0.011	$0.11
CO2 Distribution	$824	$412	$0.003	$0.03
Nutrient Supply System	$2,476	$1,238	$0.008	$0.08
Land Cost	$14,826			
Primary Dewatering	$42,270	$21,135	$0.142	$1.44
Secondary Dewatering		$0	$0.000	$0.00
Spray Dryer		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Dryer		$0	$0.000	$0.00
Extraction		$0.00	$0.000	$0.00
Purchase Price		$0.00	$0.000	$0.00
Other Direct Costs for Extraction		$0.00	$0.000	$0.00
Algae Coproduct Processing		$0	$0.000	$0.00
Purchase Price		$0	$0.000	$0.00
Other Direct Costs for Algae Coproduct		$0	$0.000	$0.00
Steam Generator		$0	$0.0000	$0.0000
Purchase Price		$0	$0.0000	$0.0000
Other Direct Costs for Steam Generator		$0	$0.0000	$0.0000
Anaerobic Digester		$0	$0.0000	$0.0000
Electricity Gen		$0	$0.0000	$0.0000
System-wide Cost for growth and harvest	$18,305	$9,152	$0.0616	$0.62
Buildings (excluding Harvest Systems)	$1,817	$908	$0.0061	$0.06
Roads and Drainage per ha	$1,652	$826	$0.0056	$0.06
Electrical Distribution	$4,233	$2,116	$0.0143	$0.14
Electrical Supply	$1,868	$934	$0.0063	$0.06
Machinery	$1,322	$661	$0.0045	$0.05
Additional Land Cost	$7,413	$3,707	$0.0250	$0.25
Total Direct Capital	$131,294	$65,647	$0.4421	$4.48
Fees and Contingency	$19,694	$9,847	$0.0663	$0.67
Total Project Cost	$150,988	$75,494	$0.5084	$5.15
Annualized Capital	$22,293	$11,147	$0.0751	$0.76
Financial Summary				
Total Annual Operating and Capital Cost	$306,256	$153,128	**$1.0312**	$10.44
Coproduct Revenue	$0	$0	$0.0000	$0.00
Electricity Revenue	$0	$0	$0.0000	$0.00
Net Cost Algae Oil	$306,256	$153,128	$1.0312	$10.44

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$186,844	$12,008	$198,852
Primary Dewatering*	$5,977	$7,177	$13,154
Secondary Dewatering	$90,385	$0	$90,385
Drying	$0	$0	$0
Oil Extraction	$0	$0	$0
Algae Coproduct Recovery	$0	$0	$0
System-wide	$757	$3,108	$3,866
Total	$283,963	$22,293	$306,256

	Operating	Annual Capital	Total Operating Cost
Growth Ponds	$6.37	$0.41	$6.78
Primary Dewatering*	$0.20	$0.24	$0.45
Secondary Dewatering	$3.08	$0.00	$3.08
Drying	$0.00	$0.00	$0.00
Oil Extraction	$0.00	$0.00	$0.00
Algae Coproduct Recovery	$0.00	$0.00	$0.00
System-wide	$0.03	$0.11	$0.13
Total	$9.68	$0.76	$10.44

Annual Costs by Type	
Raw Materials	$31,888
Cost of Capital	$22,293
Labor and Overhead	$102,393
Maintenance	$3,939
Utilities	$1,315
Total Annual Capital Charge	$22,293

*Labor and Overhead included in growth ponds

	Capital Cost
Growth Ponds	$70,718
Primary Dewatering	$42,270
Secondary Dewatering	$0
Spray Dryer	$0
Extraction	$0
Algae Coproduct Processing	$0
System-wide Cost for growth and harv	$18,305
Fees and Contingency	$19,694
Total Project Cost	$150,988

PAVLOVA LUTHERI (2050) OPERATING COSTS

Operating Cost	Annual Cost	Cost per ha per year	Cost per MT algae	Cost per gallon oil
Growth Ponds	$198,852	$99,426	$670	$6.78
Nutrients other than CO2	$4,642	$2,321	$16	$0.16
Nitrogen as NH3	$665	$332	$2	$0.02
P as Superphosphate	$1,859	$929	$6	$0.06
Fe as FeSO4	$2,119	$1,059	$7	$0.07
CO2 Delivered	$20,068	$10,034	$68	$0.68
Electricity	$1,315		$4	$0.04
Mixing	$215	$107	$1	$0.01
Water	$962	$481	$3	$0.03
Nutrients	$138		$0	$0.00
Water			$0	$0.00
Maintenance	$2,122	$1,061	$7	$0.07
Labor and Overhead	$160,012	$80,006	$539	$5.46
Annual Capital Charge	$12,008	$6,004	$40	$0.41
Primary Dewatering*	**$13,154**	**$6,577**	**$44**	**$0**
Electricity	$0	$0	$0	$0.00
Maintenance	$1,268	$634	$4	$0.04
Flocculant	$4,709	$2,354	$16	$0.16
Annual Capital Charge	$7,177	$3,589	$24	$0.24
Secondary Dewatering	**$90,385**	**$45,192**	**$304**	**$3**
Electricity	$0	$0	$0	$0.00
Maintenance	$0	$0	$0	$0.00
Labor and Overhead	$90,385	$45,192	$304	$3.08
Annual Capital Charge	$0	$0	$0	$0.00
Spray Dryer		$0	$0	$0.00
System-wide Cost for growth and harvest	$3,866	$1,933	$13	$0.13
Maintenance	$549	$275	$2	$0.02
Buildings	$208	$104	$1	$0.01
Annual Capital Charge	$3,108	$1,554	$10	$0.11
Total Operating Cost	$306,256	$153,128	**$1,031**	$10.44
Total Annual Capital Charge	$22,293	$11,147	**$75**	$0.76

Life Cycle Impact assessment (LIFECYCLE FOSSIL ENERGY BALANCE) for production of 1 live-weight ton of Shrimp in China

2010 Cradle-to-Mill Gate	Unit	Product Flow	Base	CHINA DIET 1	DIET 2	DIET 3
(1) Feed Production			*unit/ t shrimp*		**MJ/t shrimp**	
Algae meal				6,157	12,314	23,909
Algae oil (Nc)				694	694	694
Algae oil (Sc)				403	403	403
Crop Feed				4,678	1,941	-
Subtotal	(feed used in intensive Shrimp farm step)			**11,932**	**15,351**	**25,006**
Feed Milling						
Electricity	MJ/t feed	360	414	1,071	1,071	1,071
Diesel	MJ/t feed	176	202	233	233	233
Subtotal				**1,304**	**1,304**	**1,304**
Farm Electricity	MJ/t feed	270	310.5	803	803	803
Steam	kg/t feed	250	675	1,332	1,332	1,332
Plastic Packaging (LDPE)	kg/t feed	5	5.75	449	449	449
Subtotal				2,584	2,584	2,584
Total				**15,820**	**19,240**	**28,894**
(2) Industrial Hatchery						
Infrastructure	MJ/t larvae	53,091	57.25	57	57	57
Chlorine	kg/t larvae	2.4	0.0026	0.03	0.03	0.03
Egg yolk	kg/t larvae	2000	2.16	79	79	79
Feed	kg/t larvae	8800	9	*93*	*120*	*196*
EDTA	kg/t larvae	1.2	n/a	0	0	0
Electricity	kWh/ t larvae	30800	120	309	309	309
Total				**539**	**566**	**642**
(3) Intensive Shrimp Farm						
Infrastructure	MJ/t shrimp			2,281	2,281	2,281
Diesel (infrastructure)	L/ t shrimp	7.08	268	308	308	308
Chlorine	kg/t shrimp	44.7	490.8	491	491	491
CaCO3	kg/t shrimp	419	126	126	126	126
CaO	kg/t shrimp	195	1,320	1,320	1,320	1,320
Feed	kg/t shrimp	1600	15,351			
Electricity	kWh/t shrimp	2550	9180	23,752	23,752	23,752
Total				**28,278**	**28,278**	**28,278**
(4) Transport						
Transport distance for algae fertilizer	km	50	arbitrary value			
Transport service for algae fertilizer	t-km/ha	2632.75		1.3	1.3	1.3
Transport distance for algae feed	onsite production facility			0	0	0
Transport distance for plant feed	km	300	arbitrary value			
Transport service for plant feed	t feed-km/ t shrimp	150		124	124	124
Larvae Transport				1020	1020	1020
Other Transport (broodstock)				360	360	360
Total				**1,506**	**1,506**	**1,506**
CUMULATIVE ENERGY DEMAND (CED)			**GJ/t shrimp**	**46.1**	**49.6**	**59.3**
Benchmark Standard Fish Diet CED	ref Cao et al 2011		61.51			
CED Savings				**25%**	**19%**	**4%**

Life Cycle Impact assessment (GHG EMISSIONS BALANCE) for production of 1 live-weight ton of Shrimp in China

2010				CHINA		
Cradle-to-Mill Gate	**Unit**	**Product Flow**	**Base**	**DIET 1**	**DIET 2**	**DIET 3**
(1) Feed Production			*unit/ t shrimp*		kg CO2/ t shrimp	
Algae meal				423	847	*1,754*
Algae oil				43	43	43
Algae oil (Sc)				33	33	33
Crop Feed				353	158	-
Subtotal	(feed used in intensive Shrimp farm step)			**852.0**	**1,080**	**1,829**
Feed Milling						
Electricity	MJ/t feed	360	414	114.1	114.1	114.1
Diesel	MJ/t feed	176	202	17.4	17.4	17.4
Subtotal				**131.5**	**131.5**	**131.5**
Farm Electricity	MJ/t feed	270	310.5	85.6	85.6	85.6
Steam	kg/t feed	250		79.2	79.2	79.2
Plastic Packaging (LDPE)	kg/t feed	5	5.75	10.2	10.2	10.2
Subtotal				**174.9**	**174.9**	**174.9**
Total				**1,158.4**	**1,386.6**	**2,135.8**
(2) Industrial Hatchery						
Infrastructure	kgCO2/kg- t larvae	1,329	1.4	1.4	1.4	1.4
Chlorine	kg/t larvae	2.4	0.0026	0.0028	0.0028	0.0028
Egg yolk	kg/t larvae	2000	2.16	31.4	31.4	31.4
Feed	kg/t larvae	8800	9.5	*6.7*	*8.5*	*14.32*
EDTA	kg/t larvae	1.2	n/a	0	0	0
Electricity	kWh/ t larvae	30800	120	32.9	32.9	32.9
Total				**72.4**	**74.2**	**80.1**
(3) Intensive Shrimp Farm						
Infrastructure	kgCO2/kg- t shrimp			47.5	47.5	47.5
Diesel (infrastructure)	L/ t shrimp	7.08	268	23.0	23.0	23.0
Chlorine	kg/t shrimp	44.7	48.4	48.4	48.4	48.4
CaCO3	kg/t shrimp	419	5.41	5.41	5.41	5.41
CaO	kg/t shrimp	195		270	270	270
Feed	kg/t shrimp	1600	1,080.1			
Electricity	kWh/t shrimp	2550	9180	2,530	2,530	2,530
Total				**2,924.0**	**2,924.0**	**2,924.0**
(4) Transport						
Transport service for algae fertilizer	t-km/ha	2632.75		0.1	0.1	0.1
Transport service for algae feed	onsite production facility			0	0	0
Transport service for plant feed	t feed-km/ t shrimp	150		9.3	9.3	9.3
Larvae Transport	Cao et al 2011			56.4	56.4	56.4
Other Transport (broodstock)	Cao et al 2011			24.5	24.5	24.5
Total				**90.3**	**90.3**	**90.3**
TOTAL GHG emissions				**4,245**	**4,475**	**5,230**
Benchmark Standard Fish Diet GHG	ref Cao et al 2011		5,300.0			
GHG Savings				**20%**	**16%**	**1%**

Life Cycle Impact assessment (LIFECYCLE FOSSIL ENERGY BALANCE) for production of 1 live-weight ton of Shrimp in China

2030 Cradle-to-Mill Gate	Unit	Product Flow	Base	CHINA DIET 1	DIET 2	DIET 3
					MJ/t	
(1) Feed Production			*unit/ t shrimp*		**shrimp**	
Algae meal				4,608	9,216	17,894
Algae oil (Nc)				456	456	456
Algae oil (Sc)				331	331	331
Crop Feed				4,678	1,941	-
Subtotal	(feed used in intensive Shrimp farm step)			**10,073**	**11,944**	**18,681**
Feed Milling						
Electricity	MJ/t feed	360	414	1,071	1,071	1,071
Diesel	MJ/t feed	176	202	233	233	233
Subtotal				**1,304**	**1,304**	**1,304**
Farm Electricity	MJ/t feed	270	310.5	803	803	803
Steam	kg/t feed	250	675	1,332	1,332	1,332
Plastic Packaging (LDPE)	kg/t feed	5	5.75	449	449	449
Subtotal				2,584	2,584	2,584
Total				**13,962**	**15,832**	**22,569**
(2) Industrial Hatchery						
Infrastructure	MJ/t larvae	53,091	57.25	57	57	57
Chlorine	kg/t larvae	2.4	0.0026	0.03	0.03	0.03
Egg yolk	kg/t larvae	2000	2.16	79	79	79
Feed	kg/t larvae	8800	9	*79*	*93*	*146*
EDTA	kg/t larvae	1.2	n/a	0	0	0
Electricity	kWh/ t larvae	30800	120	309	309	309
Total				**525**	**540**	**592**
(3) Intensive Shrimp Farm						
Infrastructure	MJ/t shrimp			2,281	2,281	2,281
Diesel (infrastructure)	L/ t shrimp	7.08	268	308	308	308
Chlorine	kg/t shrimp	44.7	490.8	491	491	491
CaCO3	kg/t shrimp	419	126	126	126	126
CaO	kg/t shrimp	195	1,320	1,320	1,320	1,320
Feed	kg/t shrimp	1600	11,944			
Electricity	kWh/t shrimp	2550	9180	23,752	23,752	23,752
Total				**28,278**	**28,278**	**28,278**
(4) Transport						
Transport distance for algae fertilizer	km	50	arbitrary value			
Transport service for algae fertilizer	t-km/ha	2780.75		0.9	0.9	0.9
Transport distance for algae feed	onsite production facility			0	0	0
Transport distance for plant feed	km	300	arbitrary value			
Transport service for plant feed	t feed-km/ t shrimp	150		124	124	124
Larvae Transport				1020	1020	1020
Other Transport (broodstock)				360	360	360
Total				**1,505**	**1,505**	**1,505**
CUMULATIVE ENERGY DEMAND (CED)			**GJ/t shrimp**	**44.3**	**46.2**	**52.9**
Benchmark Standard Fish Diet CED	ref Cao et al 2011		61.51			
CED Savings				**28%**	**25%**	**14%**

Life Cycle Impact assessment (GHG EMISSIONS BALANCE) for production of 1 live-weight ton of Shrimp in China

2030				CHINA		
Cradle-to-Mill Gate	**Unit**	**Product Flow**	**Base**	**DIET 1**	**DIET 2**	**DIET 3**
(1) Feed Production			*unit/ t shrimp*		kg CO2/ t shrimp	
Algae meal				367	734	*1,534*
Algae oil				34	34	34
Algae oil (Sc)				30	30	30
Crop Feed				353	158	-
Subtotal	(feed used in intensive Shrimp farm step)			**784.2**	**956**	**1,599**
Feed Milling						
Electricity	MJ/t feed	360	414	114.1	114.1	114.1
Diesel	MJ/t feed	176	202	17.4	17.4	17.4
Subtotal				**131.5**	**131.5**	**131.5**
Farm Electricity	MJ/t feed	270	310.5	85.6	85.6	85.6
Steam	kg/t feed	250		79.2	79.2	79.2
Plastic Packaging (LDPE)	kg/t feed	5	5.75	10.2	10.2	10.2
Subtotal				**174.9**	**174.9**	**174.9**
Total				**1,090.7**	**1,262.3**	**1,905.2**
(2) Industrial Hatchery						
Infrastructure	kgCO2/kg- t larvae	1,329	1.4	1.4	1.4	1.4
Chlorine	kg/t larvae	2.4	0.0026	0.0028	0.0028	0.0028
Egg yolk	kg/t larvae	2000	2.16	31.4	31.4	31.4
Feed	kg/t larvae	8800	9.5	*6.1*	*7.5*	*12.51*
EDTA	kg/t larvae	1.2	n/a	0	0	0
Electricity	kWh/ t larvae	30800	120	32.9	32.9	32.9
Total				**71.9**	**73.2**	**78.3**
(3) Intensive Shrimp Farm						
Infrastructure	kgCO2/kg- t shrimp			47.5	47.5	47.5
Diesel (infrastructure)	L/ t shrimp	7.08	268	23.0	23.0	23.0
Chlorine	kg/t shrimp	44.7	48.4	48.4	48.4	48.4
CaCO3	kg/t shrimp	419	5.41	5.41	5.41	5.41
CaO	kg/t shrimp	195		270	270	270
Feed	kg/t shrimp	1600	955.9			
Electricity	kWh/t shrimp	2550	9180	2,530	2,530	2,530
Total				**2,924.0**	**2,924.0**	**2,924.0**
(4) Transport						
Transport service for algae fertilizer	t-km/ha	2780.75		0.1	0.1	0.1
Transport service for algae feed	onsite production facility			0	0	0
Transport service for plant feed	t feed-km/ t shrimp	150		9.3	9.3	9.3
Larvae Transport	Cao et al 2011			56.4	56.4	56.4
Other Transport (broodstock)	Cao et al 2011			24.5	24.5	24.5
Total				**90.3**	**90.3**	**90.3**
TOTAL GHG emissions				**4,177**	**4,350**	**4,998**
Benchmark Standard Fish Diet GHG	ref Cao et al 2011		5,300.0			
GHG Savings				**21%**	**18%**	**6%**

Life Cycle Impact assessment (LIFECYCLE FOSSIL ENERGY BALANCE) for production of 1 live-weight ton of Shrimp in China

2050 Cradle-to-Mill Gate	Unit	Product Flow	Base	CHINA DIET 1	DIET 2	DIET 3
(1) Feed Production			*unit/ t shrimp*		MJ/t shrimp	
Algae meal				4,031	8,062	15,653
Algae oil (Nc)				395	395	395
Algae oil (Sc)				308	308	308
Crop Feed				4,678	1,941	-
Subtotal	(feed used in intensive Shrimp farm step)			**9,412**	**10,705**	**16,356**
Feed Milling						
Electricity	MJ/t feed	360	414	1,071	1,071	1,071
Diesel	MJ/t feed	176	202	233	233	233
Subtotal				**1,304**	**1,304**	**1,304**
Farm Electricity	MJ/t feed	270	310.5	803	803	803
Steam	kg/t feed	250	675	1,332	1,332	1,332
Plastic Packaging (LDPE)	kg/t feed	5	5.75	449	449	449
Subtotal				2,584	2,584	2,584
Total				**13,300**	**14,593**	**20,244**
(2) Industrial Hatchery						
Infrastructure	MJ/t larvae	53,091	57.25	57	57	57
Chlorine	kg/t larvae	2.4	0.0026	0.03	0.03	0.03
Egg yolk	kg/t larvae	2000	2.16	79	79	79
Feed	kg/t larvae	8800	9	*74*	*84*	*128*
EDTA	kg/t larvae	1.2	n/a	0	0	0
Electricity	kWh/ t larvae	30800	120	309	309	309
Total				**520**	**530**	**574**
(3) Intensive Shrimp Farm						
Infrastructure	MJ/t shrimp			2,281	2,281	2,281
Diesel (infrastructure)	L/ t shrimp	7.08	268	308	308	308
Chlorine	kg/t shrimp	44.7	490.8	491	491	491
CaCO3	kg/t shrimp	419	126	126	126	126
CaO	kg/t shrimp	195	1,320	1,320	1,320	1,320
Feed	kg/t shrimp	1600	10,705			
Electricity	kWh/t shrimp	2550	9180	23,752	23,752	23,752
Total				**28,278**	**28,278**	**28,278**
(4) Transport						
Transport distance for algae fertilizer	km	50	arbitrary value			
Transport service for algae fertilizer	t-km/ha	2940.75		0.8	0.8	0.8
Transport distance for algae feed	onsite production facility			0	0	0
Transport distance for plant feed	km	300	arbitrary value			
Transport service for plant feed	t feed-km/ t shrimp	150		124	124	124
Larvae Transport				1020	1020	1020
Other Transport (broodstock)				360	360	360
Total				**1,505**	**1,505**	**1,505**
CUMULATIVE ENERGY DEMAND (CED)			**GJ/t shrimp**	**43.6**	**44.9**	**50.6**
Benchmark Standard Fish Diet CED	ref Cao et al 2011		61.51			
CED Savings				**29%**	**27%**	**18%**

Life Cycle Impact assessment (GHG EMISSIONS BALANCE) for production of 1 live-weight ton of Shrimp in China

2050				CHINA		
Cradle-to-Mill Gate	**Unit**	**Product Flow**	**Base**	**DIET 1**	**DIET 2**	**DIET 3**
(1) Feed Production			*unit/ t shrimp*		kg CO2/ t shrimp	
Algae meal				345	691	*1,452*
Algae oil				32	32	32
Algae oil (Sc)				29	29	29
Crop Feed				353	158	-
Subtotal	(feed used in intensive Shrimp farm step)			**759.7**	**910**	**1,513**
Feed Milling						
Electricity	MJ/t feed	360	414	114.1	114.1	114.1
Diesel	MJ/t feed	176	202	17.4	17.4	17.4
Subtotal				**131.5**	**131.5**	**131.5**
Farm Electricity	MJ/t feed	270	310.5	85.6	85.6	85.6
Steam	kg/t feed	250		79.2	79.2	79.2
Plastic Packaging (LDPE)	kg/t feed	5	5.75	10.2	10.2	10.2
Subtotal				**174.9**	**174.9**	**174.9**
Total				**1,066.2**	**1,216.5**	**1,819.2**
(2) Industrial Hatchery						
Infrastructure	kgCO2/kg- t larvae	1,329	1.4	1.4	1.4	1.4
Chlorine	kg/t larvae	2.4	0.0026	0.0028	0.0028	0.0028
Egg yolk	kg/t larvae	2000	2.16	31.4	31.4	31.4
Feed	kg/t larvae	8800	9.5	*5.9*	*7.1*	*11.84*
EDTA	kg/t larvae	1.2	n/a	0	0	0
Electricity	kWh/ t larvae	30800	120	32.9	32.9	32.9
Total				**71.7**	**72.9**	**77.6**
(3) Intensive Shrimp Farm						
Infrastructure	kgCO2/kg- t shrimp			47.5	47.5	47.5
Diesel (infrastructure)	L/ t shrimp	7.08	268	23.0	23.0	23.0
Chlorine	kg/t shrimp	44.7	48.4	48.4	48.4	48.4
CaCO3	kg/t shrimp	419	5.41	5.41	5.41	5.41
CaO	kg/t shrimp	195		270	270	270
Feed	kg/t shrimp	1600	910.1			
Electricity	kWh/t shrimp	2550	9180	2,530	2,530	2,530
Total				**2,924.0**	**2,924.0**	**2,924.0**
(4) Transport						
Transport service for algae fertilizer	t-km/ha	2940.75		0.1	0.1	0.1
Transport service for algae feed	onsite production facility			0	0	0
Transport service for plant feed	t feed-km/ t shrimp	150		9.3	9.3	9.3
Larvae Transport	Cao et al 2011			56.4	56.4	56.4
Other Transport (broodstock)	Cao et al 2011			24.5	24.5	24.5
Total				**90.3**	**90.3**	**90.3**
TOTAL GHG emissions				**4,152**	**4,304**	**4,911**
Benchmark Standard Fish Diet GHG	ref Cao et al 2011		5,300.0			
GHG Savings				**22%**	**19%**	**7%**

BUILDING MATERIAL LCA ASSUMPTIONS

(1) ALGAE POND	Material	Amount kg	EE Mj/kg	EC kg Co2/kg	Total EE MJ
Foundation	Concrete	450000	0.95	0.13	427500
Pipes	PVC	687	67.5	2.5	46373
Paddleweel	Steel	50	24.4	1.77	1220
	Glass fibre	256	28	1.53	7168
Pump	Steel	20	24.4	1.77	488
TOTAL				**12,146.6**	**482,749**

(1) ALGAE HARVESTING	Material	Amount kg	EE Mj/kg	EC kg Co2/kg	Total EE MJ
Concrete	Concrete	344000	0.95	0.13	326800
Rotary press	Steel	2100	24.4	1.77	51240
Dryer	Steel	4000	24.4	1.77	97600
TOTAL				11,103.4	**475,640**

(2) INDUSTRIAL HATCHERY	Amount kg	EE Mj/kg	EC kg Co2/kg	Total EE MJ	per 1 ton/ larvae
Concrete	0.01	0.95	0.13	0.01	
PVC	72	67.5	2.5	4860	
Steel	47.8	24.4	1.77	1166	
HDPE Liner	9.8	76.7	1.53	752	
LDPE Liner	593	78.1	1.77	46313	
TOTAL			**1,329**	**53,091**	

(3) INTENSIVE SHRIMP FARM	Amount kg	EE Mj/kg	EC kg Co2/kg	Total EE MJ	per 1 ton/ shrimp
Concrete	1.95	0.95	0.13	2	
PVC	1.5	67.5	2.5	101	
HDPE Liner	28.4	76.7	1.53	2,178	
TOTAL			**47**	**2,281**	

Additional Data	
Lifespan hatchery/s	years 20
Size of industrial ha	ha/pond 0.1
Size of intensive shi	ha/pond 0.27

Inclusion Rates for the production of 1ton shrimp feed

Feed sources	Standard Diet			Algae Diet 1			Algae Diet 2			Algae Diet 3		
	kg feed	%	kg/t shrimp	kg feed	%	kg/ t shrimp	kg feed	%	kg/ t shrimp	kg feed	%	kg/ t shrimp
Fish meal	422	42%	675									
Squid meal	40	4%	64									
Fish oil	28	3%	45									
Total Fish Feed Distributed	490	49%	784									
Algae for Fishmeal				231	23%	266	462	46%	531	897	90%	1032
Algae for Fishoil (Nc)				14	1%	16	14	1%	16	14	1%	16
Algae for Fishoil (Sc)				14	1%	16	14	1%	16	14	1%	16
Replacing Algae Biomass				259	26%	298	476	48%	547	925	93%	1064
Corn	85	9%	136	85	9%	98	85	9%	98	-		
Soybean meal	110	11%	176	341	34%	392	110	11%	127	-		
Wheat flour	240	24%	384	240	24%	276	240	24%	276	-		
Total Plant Feed Distributed	**435**	**44%**	**696**	666	67%	766	435	44%	500	0	0%	0
Other (vitamins, colour, minerals)	75	8%	120	75	8%	86	75	8%	86	75	8%	86
Total Shrimp Feed Production	1000	100%	1600	1,000	100%	1,150	1,000	100%	1150	1,000		1,150

Algae Diet	**FCR**	**1.15**
Standard Diet	**FCR**	**1.6**