CRANFIELD UNIVERSITY

Fatima Usman Madugu

Modelling and Analysis of the Techno-Economic and Social Impacts of an Algal oil Production Facility

School of Energy, Environment and Agrifood
Offshore Renewable and Energy Engineering

PhD Thesis

CRANFIELD UNIVERSITY

School of Energy, Environment and Agrifood
Offshore Renewable and Energy Engineering Centre

PhD

Academic Year 2012 - 2015

Fatima Usman Madugu

Modelling and Analysis of the Techno-Economic and Social Impacts of an Algal oil Production Facility

Supervisor:
Dr M Collu
Prof. F P Brennan

March, 2015

This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

ABSTRACT

The economic viability for a microalgae production facility for the production of algal oil and bioproducts remains challenging and unanswered. Important aspects not investigated in assessment of the economic viability of algal oil are the social benefits, such as employment, local earnings and outputs created from such facilities. A model that is able to include both techno-economic and social benefits can help provide answers on the future of these technologies. The development of this type of model requires a combination of techno-economic and social impact theory. This thesis presents an integrated model that estimates the social (employment earnings, and output) and techno-economic impacts generated from a microalgae production facility.

A process and system configuration of the algal production chain is selected first. The construction costs of the equipment are then calculated, followed by overall capital cost calculation. Then, the operating costs are estimated by multiplying the resources and energy usage rate by a unit price. Employment, earnings, and output generated from constructing and operating the facility is then calculated using output from the capital and operating cost with input – output multipliers to measure the impact of the series of effects generated by expenditure. The model as far as the author knows, is the first techno-economic model that addresses the social impact. A parametric analysis is carried out using two different methods to determine the viability of an algal oil production facility. Taking the economic costs and the operating parameters from the socio- techno-economic model, some key parameters are changed across a range of values, and their influence on the final cost of algal oil and job impact are analysed. The results shows highest cost contributor to the algal oil cost comes from capital costs. Productivity rate and lipid content have the highest impact both on the final algal oil costs, and the social impact outputs. Improvement would need to be made both in biology and system units.

Sponsored by
PETROLUEM TECHNOLOGY DEVELOPMENT FUND (PTDF)

La hauwla wala kuwatah illah billah
Murjannat

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. Collu Maurizio for his guidance and support throughout my PhD, he was patient and understanding. He mentor and taught me and at the same time allowed me to be myself. My appreciation also goes to my co-supervisor Prof. F. Brennan for offering me the opportunity to gain knowledge through conferences and training.

I would like to acknowledge my sponsor's "The Petroleum Technology Development Fund (PTDF), for giving me the financial support from the beginning to the completion of my studies.

Finally I would like to thank my family, for their immense support, throughout the period of my PhD. To my late mother who is the inspiration behind my success, she believed in me more than I believed in myself. To my dad who took the role of being both a mother and a father, listening to my endless complains, and continued to encouraging me. To my husband for being patient, supportive, and encouraging, I love you. To my sisters and brothers thanks for your love and support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

AACE	American Association of Cost Engineers
AD	Anaerobic digester
ANL	Argonne National Laboratory
bbl	Barrel
C:N:P	Carbon : Nitrogen : Phosphorus
CO_2	Carbon dioxide
DAP	Diammonium phosphate
dw	Dewatered
FAME	Fatty methyl ester
FTE	Full time employment
gal	Gallons
GREET	Greenhouse gas regulatory environmental emission technology
HDPE	High density polyethylene
IRR	Internal rate return
ISBL	Inside battery limit
kWh	Kilowatt hour
L/W ratio	Length to width ratio
LCA	Life cycle analysis
M	Millions
m	Meters
MEC	Major equipment cost
MGY	Million gallon per year
N	Nitrogen
NREL	National renewable energy laboratory
O & M	Operating & maintenance
OP	Open pond

OSBL	Outside battery limit
PBR	Photobioreactor
PCE	Personal consumption expenditure
PW	Paddlewheel
REA	Renewable energy association
TDC	Total direct cost
TEA	Techno economic analysis

1 INTRODUCTION

1.1 Context

Interest in biofuels and bio-products is increasing dramatically due to the increasing energy demand, diminishing oil reserves, geo-political problems, and environmental issues associated with the use of fossil fuels[1][2][3]. Microalgae based biofuels and bio-products are being considered as one of the most feasible options to tackle both the problems associated with fossil fuels and those impeding the large scale production of the conventional biofuels[4][5][6]. Microalgae biomass can be converted into biofuels and bio- products through similar processes used for converting lignocelluloses biomass to fuels, that is, thermochemical conversion, biochemical conversion and direct conversion. Within each of these conversion processes there are various routes which are shown in Table 1-1. The middle column shows the process route and the resulting fuels produced are shown in the last column. Figure 1-1 shows an example of different process and stages of microalgae production to various products.

Table 1-1 Technical routes for producing biofuels and bio-products from microalgae

Route to producing biofuels from Microalgae		
Process	Route	Fuel
Thermochemical Conversion	Gasification	Syngas
	Pyrolysis	Bio-oil, Bio-char, Syngas
	Liquefaction	Bio-oil
	Combustion	Electricity
Biochemical Conversion	Anaerobic Digestion	Biogas
	Fermentation	Ethanol
	Photobiological hydrogen production	Hydrogen
Direct conversion	Oil extraction and transesterifiction	Biodiesel
	Oil extraction and hydrogen	Renewable Diesel

The concept of using microalgae evolved during the twentieth century, when it was used as a source of human nutrition. The initial small-scale industrial cultivation started in Japan and the United States, and other countries that were producing protein for human consumption and the first microalgae strain to be cultivated on an industrial scale was chlorella (green algae). Currently the products being produced from microalgae include, among others, ω-polyunsaturated fatty acids and carotenoids (β-carotene and astaxanthin). These products are marketed and sold as enhanced value for human food, animal feeds, and are incorporated into cosmetics. The earliest companies reported to have produced biofuels from microalgae was Petrosun Biofuel(s) Inc., a USA based company incorporated in 2007, operating a biodiesel refinery since 2008, and Solix, also located in the USA has been involved with cultivation facilities since 2006.

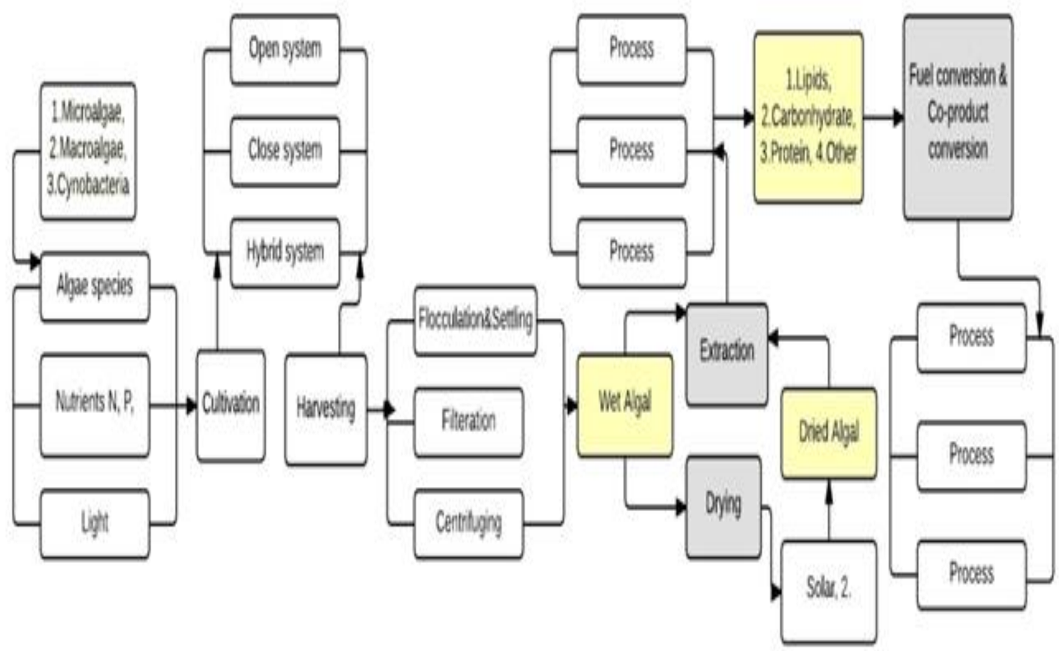

Figure 1-1 Example of various microalgae production pathways

As of 2008 global market size of microalgae products was estimated at a retail value of US$ 7.4 billion [7] see Figure 1-2. Among the many advantages of microalgae is in the use of wastewater purification in MWS treatment systems. However, the major drawback is that there is minimal control of algae productivity, making the algal biomass difficult to

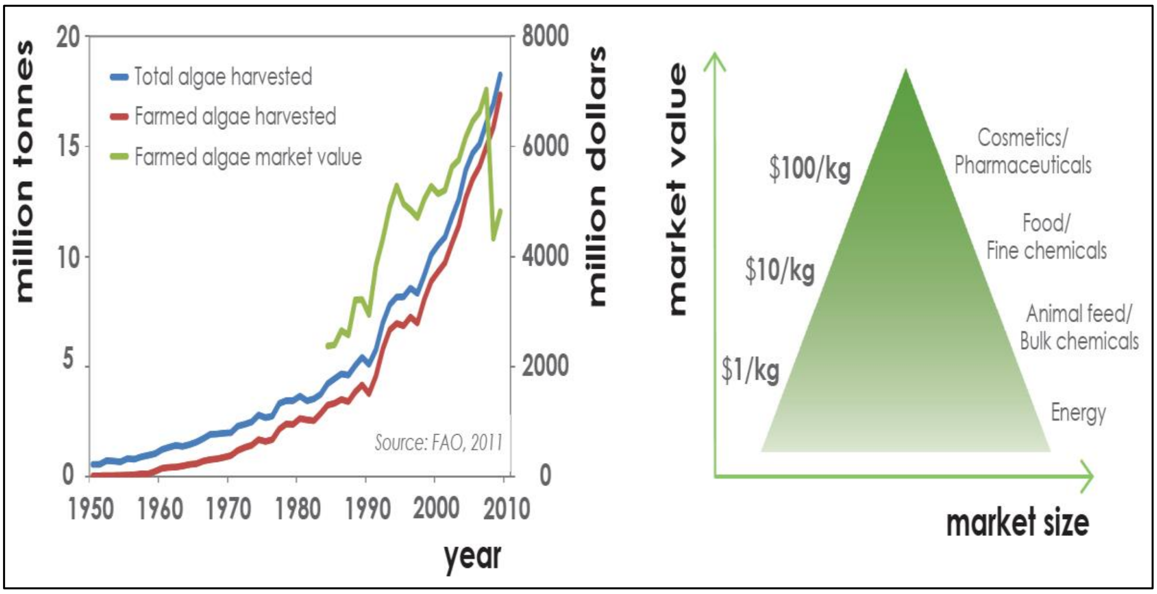

Figure 1-2: Global market for algae (sources: NNFCC 2012)

Harvest [8]. Consequently although microalgae cultivation is practised at an industrial scale, the scale of the industry is still relatively small in regard to the demand needed to produce large quantity of biofuels.

1.1.1 Microalgae oil as a sustainable source of biofuels and bio-products

Microalgae are multicellular and unicellular photosynthetic organisms. They are plant-like organisms but do not have roots or stems and can be found in marine or fresh water. They use sunlight for energy, and carbon dioxide, phosphorous and potassium as sources of food to grow. They are composed of lipid, carbohydrate and protein [4][5], allowing them to be used for the production of biofuel, animal feeds, chemicals, cosmetics and pharmaceuticals. Microalgae are predicted to be among the oldest forms of life on earth, with a diverse mix of organisms and varying characteristics [6]. There are two main categories of microalgae; Prokaryotic (cyanobacteria), and Eukaryotic, each consisting of thousands of species, summing to more than 50,000 species extant. Depending on the type of species, some microalgae are autotrophic, meaning they perform photosynthesis by naturally absorbing sunlight, CO_2 and inorganic salts to grow, while some are heterotrophic, as they rely on external substrate in a stirred tank or fermenters. Also there are microorganisms that are both Autotrophic and Photoautotrophic, a system which is known as Mixotrophic.

There are a number of other biofuel feedstock's that have shown significant potential as sources to help meet global biofuel targets. Algal biomass feedstock stands to have some unique advantages over these other feedstock. It is these comparative advantages that have attracted the interest of many researchers and investors throughout the world, towards microalgae. Such advantages are:

- Land economy - unlike other biofuel feedstocks, microalgae does not require arable land which may conflict with agricultural land for food production. as presented in Table 1-2 they required less land compared to other feedstock's

- Growth rate - microalgae species come from a wide range of species and have a high growth rate, growing within a ten day period. They are capable of doubling their biomass within 24 hours, and the doubling time is usually as short as 3.5 hours during the exponential growth. The biomass productivity has been estimated to be more than

50% compared with that of one of the fastest growing terrestrials' plants (i.e. switch grass).

- High lipid content - many of the species have high lipid content, commonly from 20% to 50% oil content.

- Water conservation – microalgae do not need fresh water for growth, they can be grown in saline water unlike other agricultural crops, and can be applied as a wastewater treatment in which it utilises the nutrient for growth.

- Carbon dioxide (CO_2) mitigation – it can absorb CO_2 from coal power plants and stationary sources.

- Co-efficient products – algal bio-refinery has the ability to integrate different conversion technologies to produce biofuels as well as other co-products such as protein, carbohydrate and oil.

- Depending on the microalgae species, other compounds with valuable applications (like omega 3 fatty acid) may also be extracted to improve the economics of the biofuel(s) production.

Table 1-2 Comparison of other biofuel feedstock with microalgae (Chisti, 2007)

Crop	Oil yield (L/ha)	Land area needed (M ha)
Corn	172	1540
Soybean	446	594
Canola	1190	223
Jatropha	1892	140
Coconut	2689	99
Oil palm	5950	45
Microalgae[a]	136,900	2
Microalgae[b]	58,700	4.5

a. Lipid content 70% wt
b. Lipid content 30% wt

1.2 Research Description

1.2.1 Problem statement

Technically it may be feasible to grow microalgae for the production of biofuel on a commercial scale, but the question remains: "What is the viability of the technology, how does it attract investment, and which technology is most suitable to minimise the cost to produce crude algal oil, and maximise profits?" Over the years, several models have been developed by many researchers with the aim to establish an economically viable process for algal oil production [9]. The major drawback of these models is that they present a wide range of values for different assessment models (technical, economic, and life cycle analysis), making it difficult to determine the most viable technology and the most suitable process to achieve economic viability. For microalgae technology to be economically viable, it would have to be produced at a price capable of competing with fossil fuel. Some prominent researchers have focused their research towards economic viability by analysing the overall algal oil production process [10][11][9][12], with a future focus on commercial scale production. These models still present costs that are highly disparate from the current petroleum price. The issues of economically viable models are that they do not balance with other economic benefits, such as employment, local earnings and outputs created from such facilities. Therefore, developing a model that is able to estimate the overall economic impact associated with developing microalgae facility would help provide a critical understanding of the future development of this technology, and attract the confidence of researchers and investors.

1.2.2 Aim and objectives

The aim of this research work is to develop an integrated techno-economic and social impact modelling tool that can help in strategic planning and decision making, to direct the development of the production of microalgae facility towards the establishment of economically viable technology. The purpose of this model is:

- to achieve an economically viable algae oil production facility.
- to establish a tool capable of providing information for different investors who are willing to invest in microalgae technology.
- to help the researcher identify the key areas needed for technical improvement and
- guide policy makers in strategic decision making.

The model would be developed through a numerical model and systems configuration of the algal production chain, using Techno-Economic Modelling and social impact theory.

1.2.3 Methodology

Two different models are developed using Microsoft Excel software. The first model is the techno-economic model, which estimates the material and cost of producing microalgae oil, the second model is the social impact model, which estimates the employment, earnings, and output generated.

The techno-economic model analyses the construction and operating costs of a microalgae production facility. The capital cost estimates utilise unit construction costs from Spon's Architect and Builders Price Book Davis Langdon, 137th edition 2012 [37], excluding the cultivation ponds. Engineering design and costs for cultivation ponds adopt data from several major works published by J.C. Weissman [11], J.R. Benemann [12], and Lundquist et al [13]. The infrastructural material for the system excluding the ponds is adopted from the algae process description model developed by Argonne National Laboratory (ANL). The operating cost estimates are based on energy and material requirement to operate the process annually, and are calculated utilising parameters from several literatures and equations adopted from the GREET LCA model (Greenhouse gas regulatory environmental emission technology), and the variable operating cost is calculated by multiplying the energy or material usage by the unit price, while some fixed operating costs are calculated as a percentage of certain capital and variable costs.

The social impact model is the first to be developed for microalgae production facility. It is designed to demonstrate the social impact associated with developing and operating an algal biofuel manufacturing plant in the United Kingdom. The model provides a reasonable estimate of the jobs and economic impacts as well as the estimates on land lease and property tax revenues, when appropriate. The model also allow for incorporation of various financing structures. The social impact model represents specific jobs, earnings and output results. It does not include such impacts as health, education or wellbeing.

The social impact model is the first model available that will provide microalgae producers, renewable energy advocates, government officials, decision makers, and probable users with a tool that identifies the potential local economic impacts, including job creation potential associated with constructing and operating an algal biofuel manufacturing plant. The methodology adopted for this analysis was taken from the NREL Job Impact model for cellulosic ethanol. The model uses input – output multipliers measuring the impact of series of effects generated by expenditure (i.e., input). These region-by-region multipliers, for employment, wage and salary incomes and output (economic activity) and personal expenditure patterns, are derived from Scottish economic multipliers and the UK input-output analytical table.

1.3 Structure of thesis

Chapter 2 is an extensive literature review of a previous modelling effort that has been published publically on microalgae technology. In this chapter a summary of the type of biofuels and bio-products that can be produced from microalgae biomass are discussed.

Chapter 3 provides a detailed explanation for selecting a particular design, and the specific details relating to its construction. The various factors that influence the growth pond size and geometry are discussed. Also, the particular configuration chosen, and lists of the design parameters that are important to pond construction are specified.

Chapter 4 looks at the economic model. It describes the methods used to ascertain the required calculations in the economic model. It also describes the sources of the unit costs and quantity of material used.

Chapter 5 provides analysis of the local jobs, earnings and output (economic activity) generated as a result of the project – broken out by direct, indirect and induced impacts. This includes the one-time impacts resulting from the construction phase as well as the annual or ongoing impacts that result from the annual operations.

Chapter 6 is set to perform a comparative analysis using the final algal oil production costs from the base case (case study) model and compare it with various algal costs reported in the literature, to determine how close the model input and output values are, compared to similar analysis.

Chapter 7 covers a parametric analysis conducted with the use of two different methods to determine the viability of an algal oil production facility. Taking the economics costs and the operating parameters from the economic model, some key parameters are changed across a range of values and their influence on the final cost of algal oil and job impact are analysed. Each of the parameters are analysed across a range of production scales, from $5g/m^2/d$ - $75g/m^2/d$.

In this section a parametric analysis of the influence of change in each parameter regarding the jobs and earning that can be generated both during the construction and operations is examined. The necessary inputs include direct, indirect multipliers for employment, earnings and output (per million dollars)

The conclusions and recommendations arising from this research are presented in Chapter 8.

References used in the thesis are presented after the conclusion.

Derivations used in the development of the models are presented in the Appendix. Most of the graphs and tables are also presented in the Appendix. Published articles taken from the earlier stage of this research are also presented in the Appendix.

2 LITERATURE REVIEW

2.1 Introduction

To develop an economic and social model for microalgae oil, an extensive literature review is carried-out on the existing models and types of biofuels and bio-products that can be produced from microalgae biomass. In particular, this literature has been focused on the issues preventing their economic viability.

2.2 Biofuels, and bioproducts

Biofuels are liquid and gaseous biomass- derived from aqueous and agricultural organic matter, and considered as alternative fuel that can replace existing fossil fuel. Most especially in the transport sector, bioproducts are the corresponding products/chemicals produced from the same source and technical route. They are a source of renewable energy and most prominent among the other alternatives. The many advantages of biofuels are: they contain carbon that is absorbed from atmospheric carbon dioxide during photosynthesis, which when combusted they return that carbon as carbon dioxide to the atmosphere, making them carbon-neutral, they can reduce CO_2 emissions by 50 – 60 % [13]report that if by 2050 biofuel(s) can provide 27% of total transport fuel it will avoid around 2.1GtCO_2 emission per year, they do not require engine modification when used in vehicles and aircraft unlike hydrogen which requires technology readiness, it can help reduce public health risk associated with environmental impact, it reduces emissions of many air pollutants, such as; particulate matters, carbon monoxide (co), hydrocarbon (HC), sulfur oxides (SOx), nitrogen oxides (NOx) and air toxics[14]. Among the biofuels, there are some that are preferable for use in the transport sector because of their liquid nature at a standard condition, while others are not. The most common biofuels used for transportation are biodiesel derived from plants and fatty acids, and bioethanol from starch and sugars.

2.2.1 Biofuels classification

Biofuels are commonly classified into first, second and third generation biofuels, or in some literatures, conventional and advanced biofuels, depending on the feedstock used or the maturity of the technology - Table 2-1. Biodiesel produced from agricultural plants or animal fats, and bioethanol produced from sugar and starches, are commonly referred to as first generation biofuels or conventional biofuels, as they are well established processes that are currently produced in large-scale. The downside of the first generation biofuels is the limit to which they can produce biofuel without threatening the food sector [15]. Some literatures have even questioned the sustainability of these biofuels, saying that depending on the plants Nitrogen fertiliser uptake efficiency, much higher emissions of N_2O than fossil fuel can be caused. Subsequently, there is great interest in second generation biofuel technologies, which are produced from a variety of non-edible lignocellulose sources. However, the second generation biofuels have drawbacks as they compete in terms of resources with agriculture. Thus, advanced biofuels like microalgae based biofuels are being considered as the most feasible option to tackle both the problems associated with fossil fuels and those impeding the large scale production of conventional biofuels [3].

Table 2-1 Biofuels(s) Classification

Biofuel(s) Classification			
Conventional	Feedstock Use	Advantages	Disadvantages
First generation	Soybean, Oil Reap Seed, Wheat And Palm Oil, Sugar Beet, Starch Grain, Animal Fat And Waste Cooking Oil	• Lower carbon footprint • Compatible with existing distribution systems and vehicle engine • Matured technology	• Edible food crops • Requires arable land and • Freshwater to be nurtured and cultivated
Advance			
Second generation	Agricultural Residues, Municipal Solid Waste, And Wood Waste	• Non-edible crops • Lower carbon footprint	• Technology is at pilot phase • Low scalability • Agricultural resources required
Third generation	Microalgae	• Non-competitive with agricultural land • Fast growth rate	• Technology is at demonstration phase

2.2.2 Bioproduct classification

Phytochemicals (plant chemicals) are plant compounds that occur naturally. They may affect human health by their preventive or protective properties. They are non-nutritive and nonessential to human beings, but have demonstrated the ability to protect against diseases. There are many varieties of phytochemicals in plants generally, and in different microalgae species. The most commonly known phytochemicals obtained from microalgae include beta carotene, lutein, and other carotenoids, vitamin E, vitamin B, etc.

The phytochemicals are extracted from microalgae mostly using different solvent extraction methods. The most commonly used methods of phytochemicals extraction from microalgae are discussed hereunder.

Table 2-2: Bio-products from microalgae (sources: Bello and Madugu 2015)

Phytochemical	Microalgae strain	Application
Arachidonic acid	*Phorphyridium cruentum*	Infant formula, nutritional supplement
Astaxanthin	*Haematococcus pluvialis Chlorella vulgaris,*	Antioxidant, anti-inflammatory, anti-cancerous, immune system enhancer, anti-depressant, treating carpal tunnel syndrome, food supplement and colorant, animal feed additive, cosmeceutical applications in protection against skin aging,
Beta-carotene	*Chlorella vulgaris, Dunaliella salina, Spirulina platensis*	Antioxidant, Anti-inflammatory, anti-depressant, food supplement, feed surrogates
Carbohydrate extract	Chlorella	Immune system booster, anti-flu
EPA (Eicosa Pentaenoic acid)	*Chlorella vulgaris, Haematococcus pluvialis,*	Anti-inflammatory, anti-depressant, nutritional supplement, aquaculture
Chlorophyll	*Chlorella vulgaris,*	Antioxidant, anti-cancerous, constipation reliever, food colorant
Glycerol	*Dunaliella salina*	Food additive, humectant, lubricant and laxative
Lutein	*Chlorella vulgaris*	Nutritional supplement especially for patients with degenerative human diseases, like AMD (age-related macular degeneration) or cataract, and also for skin health
Phycoerythrin	*Haematococcus pluvialis*	natural colorants in food, cosmetics and pharmaceuticals
Phycocyanin	*Spirulina platensis*	natural colorants in food, cosmetics and pharmaceuticals
Crude Polysaccharides	*Chlorella vulgaris* and *Phorphyridium cruentum*	Antioxidant, Anti-inflammatory, antiviral
Sulphated polysaccharide	*Phorphyridium cruentum*	Antioxidant, Anti-inflammatory, antiviral

GLA (Gamma Linolenic Acid)	*Spirulina platensis*	Infant formula, nutritional supplement Health foods, cosmetics
Vitamin B12	*Spirulina*	Helps immune system

2.3 Prior Microalgae biofuels production system modelling efforts

Over the years, several researchers have presented different modelling efforts to develop viable microalgae production systems. Most of the initial models focused on wastewater treatment, CO_2 sequestration, and high value chemicals, while more recent studies focus on the technology development for algal oil production, such as novel extraction techniques or compatibility of algae oil methyl ester to conventional diesel engines. Many of these analyses are carried out using assumed processes, with a set of linked operations that allow performance to be modelled numerically. The analyses vary in either their input or output values. For example, their energy value can vary, or the weight of the biomass. In some analyses it is the type of lipid extract or even the processed fuel or bio-product produced. The major drawback of these studies is; they are limited to a particular area of research, e.g they either assess the engineering aspect or economic impact of producing algal biofuels, energy and resources demand, or just evaluate the environmental impact of the production process, or focus on the biofuel that is being produced. Consequently the simultaneous analysis of the performance for a feasible biofuel production process that includes technical, economic, environmental impact, and social performance is not taken into account.

Table 2-3 Previous and current articles on microalgae analysis

Review type	Product	Ref
Techno-economic	Biogas	[8]
Techno-economics	Microalgal oil	[16]
Techno-economics	Microalgal oil	[8]
Life-Cycle Analysis	Microalgal Biomass	[17]
Techno-economics	Microalgal oil	[18]
Life-Cycle Analysis	Biodiesel	[19]
Life-Cycle Analysis	Biodiesel	[20]
Life-Cycle Analysis	Microalgal Biomass	[21]
Techno-economics	Microalgal oil	[22]
Life-Cycle Analysis	Biodiesel	[23]
Net Energy Balance	Microalgal oil	[24]
Life-Cycle Analysis	Biodiesel	[25]
Net Energy Balance	Biogas and Biodiesel	[26]

One of the earliest and most detailed articles published on cost analysis of microalgae was the work by Oswald and Golueke in 1960. The article proposed the cultivation of algae in a high rate open pond, using wastewater as the source of nutrient and because of the content of the water in the pond, this method is identified as having a very high potential to an economically viable approach to cultivate algae for biofuel production [27]. Another detailed article is a recent publication by Lundquist et al [22] the article describes extensively, technical and financial analysis of how microalgae are cultivated and processed into a final product.

In addition to these previous studies, there are other studies that review the production of biofuels and bioproducts from microalgae, some of which are presented in Table 2-3. Most of these articles focus on the state of Microalgal biofuel science and technology, but with minimal information on financial and social performance of the different Microalgal biofuel production systems. This may be due to the fact that there are no commercial scale microalgal biofuel production facilities in operation to provide reliable cost and consider the social impact.

Table 2-4 Previous technical analysis carried out on microalgae

Review Type	Product	Ref
Technical	*Biomass`*	[28]
Technical	*Biomass*	[29]
Technical	*Numerous*	[30]
Technical	*Biodiesel*	[31]
Technical	*Numerous*	[32]
Technical	*Numerous*	[33]
Technical & LCA	*Biomass*	[34]
Technical	*Biodiesel*	[35]
Technical	*Biodiesel, Bioethanol & biogas*	[36]
Technical	*Biomass*	[37]

The characteristics of the earlier Microalgal biofuel manufacturing modelling efforts only included one or very few scenarios that provided results based on a narrowly defined set of input parameters, consequently making difficult or even impossible to determine how alternative production processes or different input parameters impact the results, other than in the most general terms. Even though there are many studies published, the range of process options, selection of input parameters, system boundaries, and desired fuel is so wide, that rarely are two studies sufficiently similar to make a detailed comparison. This is especially so for the economic assessment, which is dependent on outputs from both the engineering and life cycle assessment.

Despite the many alternative technologies available for growing microalgae, harvesting and extracting the oil, being able to identify the technology most suitable to minimise the cost of producing crude algal oil, and maximising profits remains challenging. Thus, some articles focus on techno-economic analyses of alternative pathways to produce algal oil, with the aim to project probable economic viability on a commercial scale for a microalgae production facility. Some of the recent analyses on economic viability are works published by Davis, Chisti, Norsker [38][10][12] etc. These articles estimated algal oil production costs, comparing open pond systems with Photobioreactors (PBR's). Davis et al.[38] Estimated the minimum selling price of algal oil to be $8.52/gal when cultivating in an open pond system and $18.1/gal for PBR's to achieve a 10% internal rate of return with a facility producing 10 million gallons per year. Chisti[10] also estimated the cost of producing algal using the open pond and PBR's, the analyses found the cost per gal to be $2.95 for open pond and $3.80 for PBR's for a facility producing 100,00 kg of biomass annually. Norsker, et al. [12], estimated algal oil production costs at €4.95/kg for the open pond, €4.16/kg for tabular PBR's, and €5.96/kg for flat panel PBR's for a facility area of 100 hectares.

Error! Reference source not found. presents lists of published articles on the production costs of algal crude oil. These articles are a comprehensive analysis based on a project for a large scale production facility, assuming the technology has reached a mature stage.

Table 2-5 Prior Results Reported on Algal oil cost

Bio-product	**Cultivation**	**Cost**	**Scenario**	**Areal productivity**	**Ref**
Algal oil TAG	Open pond	$8.52/gal	hydrotreating	25 $g/m^2/d$	[38]
	PBR	$18.10/gal	hydrotreating	1.25 $kg/m^{-3}/d$	
Algal oil	Open pond	$4.95/gal		0.003 $kg/m^{-2}\ h^{-1}$	[12]
	PBR tabular	$4.15/gal		0.025 $kg/m^{-3}h^{-1}$	
	PBR flat	$5.96/gal		0.025 $kg/m^{-3}h^{-2}$	
Algal oil	PBR	$396.52/gal	esterification		[39]

Algal oil	Open pond	$1087/gal	solvent extraction	20 $g/m^2/d$	[11]
Algal oil	Open pond	$2.95/gal	transesterification		[10]
	PBR	$3.80gal	transesterification		
Algal oil	Open pond	$12.74/gal	Solvent extraction		[9]
	PBR	$32.57/gal	Solvent extraction		

The issues of economic viability for a microalgae production facility revolve around the fact that they are not balanced with regard to other economic benefits, such as employment, local earnings, and outputs created from such facilities. Currently, there is no available data on microalgae production facilities that include assessment of such economic benefits. The only available data is from analyses for other liquid biofuels/bioenergy. Some of these analyses have provided important data for the modelling efforts described in this research. Among which is the Jobs and Economic Development Impact (JEDI) model developed by the National Renewable Energy Laboratory (NREL) [40]. This model is used to estimate the local economic impacts of constructing and operating a cellulosic bioethanol plant. Another important analysis is the joint publication by the Renewable Energy Association (REA) and Innovas, which estimates the employment and some key economic matrix for the UK liquid biofuel sector [41]. An overview of the UK biofuel industry published by Ecofys shows that since 2005 the UK has a total biofuel production capacity of over 1500 million litres per year, of which 60% is bioethanol and 40% biodiesel, and a total of 517 people employed directly, with 3500 employed across the supply chain (e.g production, supply and distribution), with a turnover of £485 million. These biofuels are mostly produced from used cooking oil, municipal solid waste and wheat [42]. For microalgal oil to play a role in the economy, it needs to be economically viable. Therefore, it is deemed necessary to analyse the overall supply chain in such a way that includes the social benefits that can be created from developing such a plant.

Table 2-6 Review of social impact models for other liquid biofuels and bioenergy sources

Model	Review type	Ref
JEDI	Local economic impacts of constructing and operating a cellulosic bioethanol plant	[40]
Ecofys	Overview of the biofuel production plants operating in the UK, along with insights into the challenges the industry faces, particularly focusing on smaller biofuel producers	[42]
REA	Renewable energy sector and its supply chains in the UK	[41]
REA	Employment and some key economic matric for UK liquid biofuel sector	[43]
NFCC	UK jobs in the biomass combustion (for heat and power) and anaerobic digestion sectors by 2020	[44]
Enagri	Size, feedstock and estimates of the number of construction/operation/indirect jobs associated biomass plant in the UK	[45]
Thorley	Quantified the expected employment impacts of individual bioenergy developments	[46]
CEBR	Estimates economic value of the wood fuel industry in the UK economy by 2020	[47]
Northwoods	The value of north east economy from biomass related activities, and levels of activity and value at a future date	[48]
Energy Institute	Supply chain mapping and analysis of the main end uses of biomass identified areas where there are currently UK based manufacturing and engineering capabilities	[49]

Table 2-7 shows list of possible jobs that can be created from a liquid biofuel industry. Sources: Renewable Energy Association

Table 2-7: Jobs from liquid biofuels

Industry	Jobs
Design and Development	Design Engineer; Project Manager; Economist; Chemist; Environmental Engineer; Electrical Systems Designer; Environmental; Engineer; Biotechnologist; Agriculturalist, Aquatic engineers; Environmental Consultant; Feed-Stock Handling Systems Designer
Manufacturing	Design Engineer; Project Manager; Welder; Sheet Metal Worker; Chemist; Agricultural Specialist; Microbiologist; Biochemist, Electrical Engineer, Mechanical Engineer
Construction and Installation	Planning Consultant; Environmental Consultant; Project Management And Construction Workers; Electrical Engineer; Power Generation Engineer; Project Manager; Health And Safety Manager; Pipefitter; Welder; Electrician; Service Engineer
Feed stock production	Aquatic engineers; Farmer; Agricultural Operative; Waste Operative; Civil Engineer; Water Engineer; irrigation engineer; process engineer; chemical engineer; electrical engineer; field technician; tanker driver; warehouse manager.
Operations and maintenance	Laboratory staff, aquatic biologist, electrical engineer; power generation engineer; energy trader; boiler engineer; pipefitter; welder; electrician; service engineer; construction worker; electrical/electronic technician; plant operator; mechanic, project manager, supervisor, labourer; maintenance manager
Distribution	Distribution manager; tanker driver; blend operative

Some industrial analyses have reported various potential of an algae farming industry. With various products that can be produced from algae, the economic benefits shows to be very promising. One of these analyses is the Algal Biomass Organisation annual industrial survey [50].

The 2015 Algal biomass Organisation annual industrial survey – of the algae industry shows high prospects for continued growth in the sector as well as increased production of a wide range of algae-derived products [50]. Despite the uncertainty in the price of fossil fuel, the shows that researchers are optimistic that algae biofuels would like be competitive with fossil fuel by 2020, and that other products produced from microalgae such as, chemicals and plastics will be commercially available at around the same timeframe. Algal biofuels are project to cost less than $3.00 per gallon to $5.00 per gallon by 2020. These would be as a result of increase in production capacity by many producers, and trends of employment through 2015 and beyond [50]. The main findings from their survey are:

Shows that the algae industry supports wide range of jobs in science and research, operations and production, executive and administration, finance, students and professors in various organization.

Projects significant growth in job creation by 2022, with more than 220,000 skilled works expected to be employed. Currently there is algae industry activity in at nearly every part of the globe, at universities and research institute. The industry employs directly and indirectly employs thousands of workers around 200 companies.

Another report by an Australian independent strategic analyst “Future Direction International” [51]examined the economic benefits that can be generated from algae farming in the country. The report states that algae farming has the potential to generate $50 billion in economic benefits a year and create up to 50,000 new jobs from producing Omega 3 oils, biofuels and aquaculture feed. In a region like Australia it is suitable to build an algae farm because of the huge land availability, abundant sunshine and innovative farming [51]. These shows huge potential in the algae industry, considering this is an analyses carried out for just one country. Countries with larger economic and higher energy demand, point to an even larger potential globally.

A $30 million seawater pipeline contract was awarded to support algae cultivation at the Aurora Algae Facilities, the largest algae operating company in Australia [52]. The pipeline which expected to support Aurora as well as other industries [53], is a huge economic development that can create wealth and jobs from the algae industry, and will spur as the advancement in achieving viable large sale algae industry. The different infrastructure required, such as pipelines and processing facilities to transfer water to the algae farm, transportation of carbon dioxide from flue gas power or plant or suppliers can benefits economic in construction industry, and technical professionals in growth, harvesting and other operations.

These studies shows that algae industry is not only an institution for professionals alone, but for a wide range of skilled workers. Like the biorefinery and other energy industries, it requires wide range of workers from labour, transportation, business, shipping, trading and finance. With most of the work done locally, almost all the jobs will come from within the region or country.

2.4 Summary

It is clear from the number of researchers listed in Table 2-4 through to Table 2-7 that a considerable amount of work is being done to assess the performance of potential microalgal oil production facility. However, these studies are yielding widely divergent results, leaving it unclear as to whether microalgal biofuels are sustainable alternatives to conventional fossil fuels. Some of the large variations in the reported values of key performance metrics [12] are due to the differences in assumptions and input parameter selections made by different models. With the current impact of cheap petroleum fuel, microalgae need to be produced at an even more competitive price. Therefore, there is a substantial need for a detailed yet flexible model for which those assumptions and parameter choices can be systematically varied, thus enabling the main drivers of the system performance, costs and economic value to be identified and making it possible for the sensitivities of key performance metrics to specific inputs to be found.

3 ENGINEERING AND TECHNICAL ESTIMATION

3.1 Introduction

This section examines the basis for selecting a particular design, and presents specific details relating to its construction. The various factors that influence the growth pond size and geometry are discussed. The particular configuration chosen, and lists of the design parameters that are important to pond construction are specified. The technology used in the facility designs has been selected to meet three feasible criteria: scalability, low parasitic energy demand, and low cost. Cultivation systems are open ponds; a technology already used in commercial microalgae production plants and some pilot – scale biofuel projects. The pond design differs in having larger individual ponds and is lined with plastic liners. The biomass is harvested by bioflocculation, (natural flocculation of the algae). Secondary dewatering is through dissolved air floatation and centrifugation. Cellular disruption by high-pressure homogenisation is then followed by a hexane extraction process.

3.1.1 Microalgae production systems and processing to biofuels and bio-products

The entire concept of producing biofuels and bio-products from microalgae begins with the selection of a suitable strain, growing to conversion into desired biofuels and bio-products, and along each of these steps lays many technical and economic challenges.

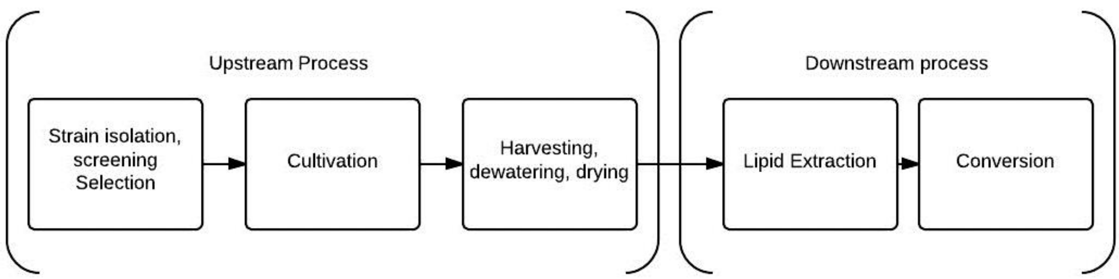

Figure 3-1 Whole process system stages

Figure 3-1 shows the process production, separating the upstream which includes screening and selection of suitable species, cultivation, harvesting, dewatering, and drying, and finally converting into the desired biofuels or co-products.

3.2 Strain screening and selection

The main aim of screening and selection of the microalgae strain is to be able to identify and maintain a suitable strain for cultivation and development. As the most suitable strain for large scale cultivation is still unknown, new strains are isolated to provide the largest metabolic versatility possible. The main characteristics for selecting an ideal strain are: growth physiology, metabolite production, and strain robustness [54].

The growth physiology refers to maximum specific growth rate, maximum cell density, biomass generated per unit, tolerance to the environment such as pH, temperature, oxygen levels, CO_2 levels, salinity [26; 35], nutrient accessibility and requirements.

Metabolite production identifies the cellular composition of lipids, proteins and carbohydrates, and determines the productivity of organisms regarding metabolites useful for biofuel generation. The exact approach to be adopted is solely dependent on the type of cultivation system and type of end fuel to be produced. This can be helpful in providing a fatty acid profile and distinguishing between neutral and polar lipids. Some strains can secrete metabolites into the growth medium, of which, a number can provide some valuable co-products

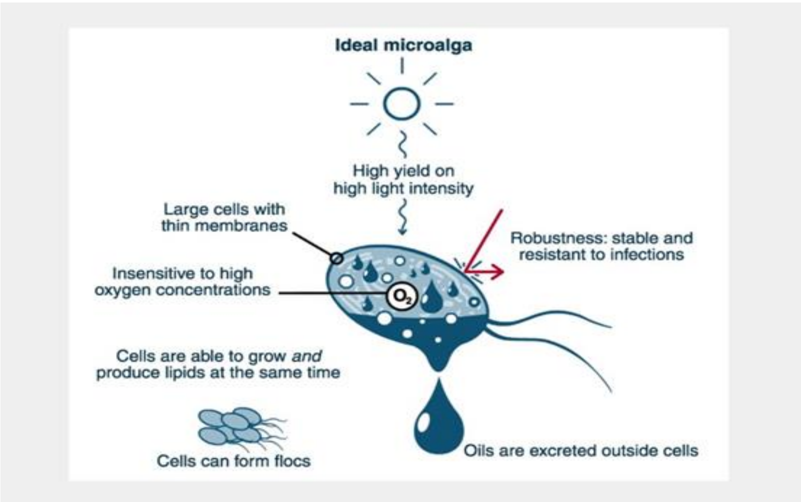

Figure 3-2 Example of an ideal microalgae strain [37]

Strain robustness refers to culture consistency, resilience, community stability and susceptibility to predators present in a given environment; these parameters are all of considerable importance when considering large scale production. To determine strain robustness, small-scale simulations of mass culture conditions will need to be performed. The development of small-scale but high-throughput screening technologies is an important step to enable the testing of hundreds to thousands of different algal isolates. As previous studies have shown, algae strains tested in the laboratory do not always perform similarly in outdoor mass cultures [55]

3.3 Cultivation pond system design

Ponds are excavated and built in concrete circular close loop channels lined with a white plastic material, their sizes range between a few m^2 to 250 hectares, with of depth of between 0.2m and 0.5m [14]. In the pond, algae, water and nutrients circulate around the pond, with paddlewheels providing the flow. Algae are kept suspended in the water, and circulated back to the surface on a regular frequency. The ponds are usually shallow because the algae need to be exposed to sunlight, and sunlight can only penetrate the pond water to a limited depth. They are operated in a continuous manner, with CO_2 and nutrients being constantly fed to the ponds, while algae-containing water is removed at the other end.

3.3.1 Pond size selected

The design of the growth ponds is based on many geometric parameters, which include the pond size, channels and the centre wall. The length of the centre wall is the same as the length of a single channel excluding the bends; they are referred to as the L/W ratio (Length to Width ratio). They are one of the most costly items in pond construction.

The choice of size and shape of the pond would depend on many economic factors and how it affects other items related to its construction. Ponds built with a narrow width will not be cost effective, as they would affect the scale of production, which would lead to an increase in construction materials in order to meet demand. Ponds built with a wider channel width base on a low L/W ratio, would also be costly, due to the cost of those elements dependent on the channel width such as the paddle wheel and carbonation station, the size of these items would have to increase. Another issue related to the L/W ratio is when the pond width becomes too wide, thus the flow pattern is likely to meander, causing an increase in wind influence and algae sedimentation within the unmixed zones.

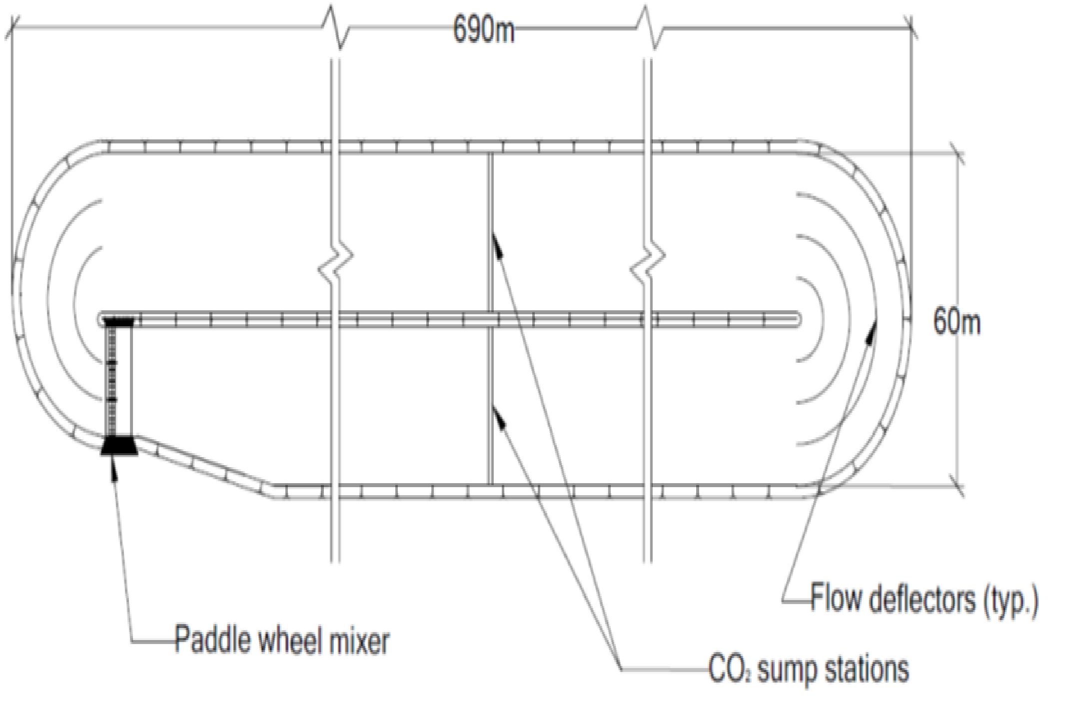

Figure 3-3 Single pond design [22]

A single loop, 4 hectare pond is selected, with a 30m channel width and 30 cm water depth. This size is selected based on the analysis presented in [22]. The author estimates that a single pond size of 4 hectares is the most suitable size in order to achieve economic viability. The larger the area of the pond, the more it benefits from economies of scale. This size is estimated to be about 10m wider than the 1.25 ha pond in Christchurch New Zealand which is the largest existing algae biofuel production pond currently in operation.

Other factors need to be taken into consideration in terms of the channel length, such as the supply of carbon dioxide to the culture, which in the summer period can impose a scale limit during a period when the highest productivity can be achieved. The length is also limited by the lift required to overcome the head loss of flow around the channel circuit.

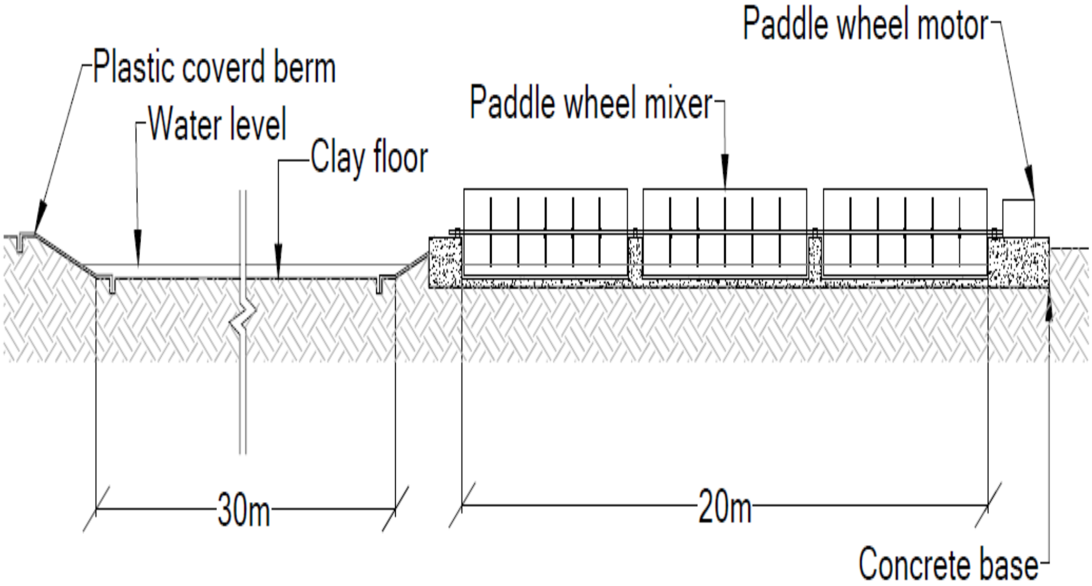

Figure 3-4 cross section on the pond [22]

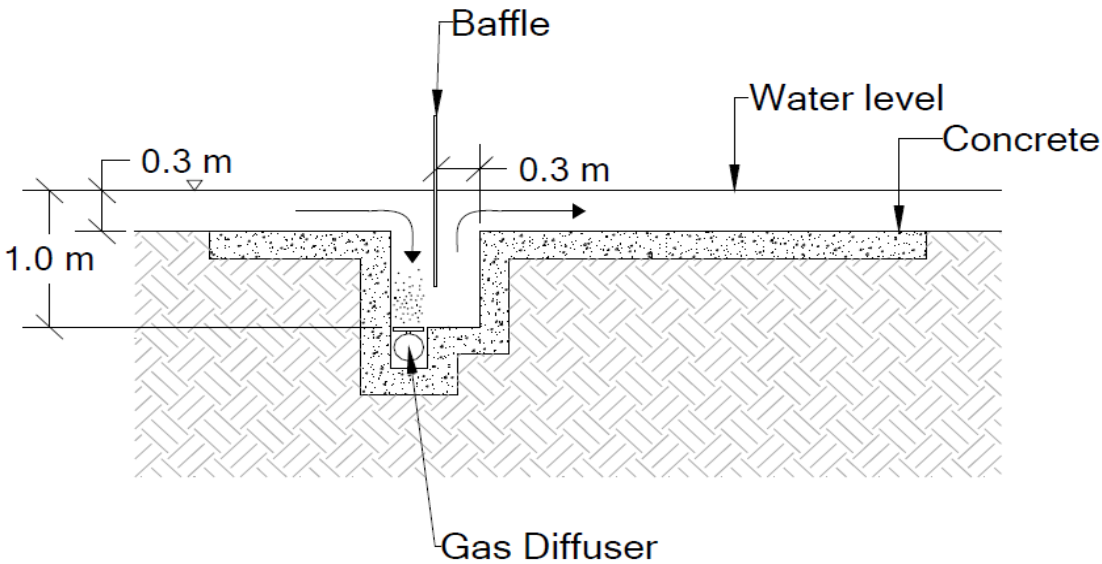

Figure 3-5 example sump for flue gas transfer[22]

Table 3-1 Single pond design parameters

Single Pond design		
Description	Value	Unit
Pond area	4	Hectares (690 x 60m)
No of channels	2	nr
Length - width ratio	20	nr
Depth	30	cm
Channel velocity	0.25	m/s
Manning n	0.018	sec/m^0.33
Paddle eff.	60%	%
Drive eff.	70%	%
Paddle wheel/Chan Width	0.75	m
Evaporation rate	1.5	cm/day
Blowdown rate	0.21	cm/day
Detention time	4	days
Wall height (above grade)	40	cm
Wall height (below grade)	10	cm
Sump depth	1.5	meters

Once the size of the pond is established, each would require a paddlewheel mixer and other operational apparatus. The paddlewheel is the most preferred mixing option in raceway pond, due to their simple mechanical nature, easy to maintain and match the basic requirement in mixing a raceway pond. The major drawback of this system is the operational cost, mainly derived from the energy required to operate the paddlewheel. The energy required to mix the pond is major parasitic loss in microalgae cultivation systems. The cost and energy needed will depend on the mixing speed (i.e velocity), which increases with cube of the velocity. A typical mixing velocity ranging between 0.20 to 0.30 m/s is reported by Benemann and Oswald 1996. Lindquist et al 2010 extend the analyses done by Benemann to considered possible power reduction from the mixing, and reported 0.25 m/s as a considerable mixing velocity. For this study the 0.25 m/s mixing velocity analysed by Lundquist 2010 is adopted.

The energy requirement for mixing the cultivation pond is calculated using Manning equation. This is the most widely used formula for open flow channels; it can be calculated through the following steps:

[1] The headloss in bend (h_b), which is loss from water flow around the two 180^o bends at the end of the pond, and headloss from the two carbonation station $h_{s,}$ are calculated using the following equation [22].

$$h_b = \frac{(k.v^2)}{2.g} \tag{3-1}$$

K = is the kinetic loss coefficient for 180° bends (theoretically = 2),

v = is the velocity of the raceway (0.25 m/ s^{-1}*)*

g = is the acceleration due to gravity (9.8 m/s^{-2}*).*

[2] Friction loss across the length of the pond (h_L) is calculated using the following equation[22]:

$$H_L = v^2 n^2 \left[\frac{L}{R^{4/3}}\right] \tag{3-2}$$

n = is the roughness factor (0.015 for polyethylene)

R = is the channel hydraulic radius (0.29 m)

L = is the channel length (630 m^2 *= 1260 m).*

[3] The energy requirement per pond is calculated using the following equation[22]:

$$W = 9.80 \left[\frac{Qwh}{e}\right] \tag{3-3}$$

Q = is the volumetric flowrate (1.1 m3 s−1),

w = is the unit mass of water (998 kg m3),

h = is the total head loss (Head loss in bend + head loss in sump + frictional loss),

e = is the paddle wheel and drive system efficiency (40% assumed),

9.8 = is the conversion factor in W-s kg-m−1.

One of the most important reasons for mixing algae is to bring the algae in and out of the light zone, allowing equal distribution of light to the cells to achieve optimal photosynthesis. Although this does not mean that productivity will be increased, high mixing intensities will result in greater outgassing of CO_2 and thus a loss of these vital nutrients, with a reduction in the maximum scale of the ponds. It will also increase O_2 outgassing and thus reduce O_2 tension, which is beneficial to many algae. Reduced O_2 tensions are a possible cause of the improved productivity reported in the literature under higher mixing regimes. However, the “flashing light effect,” in which a millisecond of light flashes increase productivity, is not applicable to algae mass cultivation, as the power densities involved would be enormous.

3.3.2 Pond construction

Lindquist [22] suggests that in order to minimise shading, it is ideal to arrange the ponds in an east-west orientation. Although this might not be necessary for large scale ponds of this size, this study assumes the ponds are laid in an east-western orientation. The other operations, for pre-treatment and handling are assumed to be placed between the facilities to allow easier access for distributing and receiving materials. The pond is designed to be constructed using grading and laser levelling. To prepare the site for laser levelling, the pond is graded using earth moving equipment. The cost of grading will vary depending on the terrain. With flat favourable terrain the cost would be very minimal, while for rough terrain, requiring fills or cuts, and has rocks, roots or other materials present, significant cost can be added to the rough grading. The rough grading cost used in this study is assumed based on a favourable terrain. Laser levelling is used to achieve the tolerance required for shallow pond operation and to achieve flat channel slopes to meet hydraulic requirements. The walls and centre divider are constructed using a concrete block wall. Mixed concrete is poured into a footing of 15 cm x 30 cm 6"x 12", and 2 courses of 4" x 8" x 16" blocks are laid on top. For adequate longitudinal strength, the blocks would be filled with concrete gravel with a #4 reinforcement bar at the top.

Inoculation ponds are a scaled down version of the cultivation ponds, they are also built with plastic liners with individual paddle wheels. The total area is 1% of the production area. One important difference is that the inoculation ponds will be covered with a plastic greenhouse shelter to extend the growing season and to provide greater protection from contamination from non-desired algae. The infrastructural materials are listed in Table 3-2 below.

Table 3-2 Infrastructural material for inoculation ponds

Inoculum Ponds		
	Value	Unit
LDPE cover thickness	6	mil
Liner surface area for reference facility	1235000	m^2
Surface area plastic cover per pond	10157	m^2
HDPE liner for inoculum ponds	138	m^3
Geotextile liner	27578	kg
LDPE liner 1% inoculum ponds	1.55	m^3
Volume of Excavated Material	100553	m^3
Concrete	146	m^3
Scaling factor for facility area	56	nr

3.3.2.1 Liner

The liner is one of the most expensive items used in the construction of cultivation ponds, and the use of the liner allows ponds to be built in unsuitable terrain. The purpose of using a liner is to prevent water seepage and loss of nutrients, as well as to prevent contamination by wastewater or other nutrients in the growth media. Liners can be made from materials such as clay, concrete, asphalt, fiberglass, and HDPE. Although ponds can be located in areas where clay can be found in abundance and less costly, the drawback of this method is a loss of nutrients and water, due to cracks developing when the pond is dry, and risk of contamination as this type of liner cannot be cleaned like the HDPE liner. Although the HDPE liners are very expensive, they are the most efficient and reliable option compared to others (e.g crushed rock layers used by Weismann and

Goebel, compacted clay-lined used by Lundquist) to mitigate these problems. Liners account for 32% of the capital cost in this study.

3.3.2.2 CO_2 and Nutrients supply

The maximum biomass is assumed to contain 50% dry wt% carbon with an average of 25% lipid content requiring 1.9 g of CO_2 per gram of algae biomass. The CO_2 is supplied through a 1.5 m sump with utilisation efficiency of 85%, totalling to 2.24 g of CO_2 per gram of algae biomass. The 85% used in this study is based on the estimate by ANL [56] a comprehensive study by Lundquist [22] estimates CO_2 efficiency at 75% for flue gas and 90% for pure CO_2. Although the 85% in this study is optimistic, it was selected to find the best case scenario.

The design and distribution system for the CO_2 supply would depend on the pressure at which the CO_2 is supplied to the site. With pressure of >50 psi, the piping network can consist of very small 6” or less, pipe sizes. For medium pressure ranging between 10 psi and 30 psi, pipe size ranging from 8” to 3” is required. And for very low pressures between 3.5 psi to 1 psi, the pipe size would range from 12” to 4”. Usually, the pipe sizes ranging 12” and 4” are used when recovering un-purified flue gas at atmospheric pressure. At low pressure the capital cost becomes higher and operating cost reduces, for low medium pressure the capital cost is low, and operating costs become high. For the study, the medium pressure pipes are used for the CO_2 distribution network. Table 3-3 illustrate the construction parameters of the CO_2 distribution system.

Table 3-3 CO_2 Distribution system

CO_2 Distribution system	Value	Unit
Volume of concrete for 84" Pipes	7942	m^3
Volume of concrete for 54" Pipes	558	m^3
Volume of concrete for 42" pipes	92	m^3
Volume of concrete for 36" pipes	143	m^3
Volume of concrete for 33" pipes	125	m^3
Volume of concrete for 31" pipes	108	m^3
Volume of concrete for 21" pipes	48	m^3
Number of blowers	9	
Weight of each blower	9100	Kg
Valves	N/A	
Fittings	N/A	
Miscellaneous	N/A	

Ammonia and diammonium phosphate (DAP) are used as nutrient sources, and the nutrient consumption was calculated using GREET lifecycle analysis software. The estimated nutrient demand is 0.019 g per gram of Nitrogen (N) of algae and 0.017 g per gram of algae of DAP (P). Nutrients are usually added at the beginning of the process during the media culture, except when there is a need for additional ammonia during the first few days' culture. An ammonia tank is located at each set of ponds for supplemental ammonia. The facility for nutrient supply is located at the harvesting station, where nutrients are added into the return flow network.

3.3.2.3 Water supply system

The capacity of water supply system is based on the maximum evaporative rate of 0.33 in/day. Maximum rates are used due to the assumption that the rates are likely to persist during the summer. Additional water is required for the initial filling of the ponds, but this is assumed to take place during the non-summer months, when excess capacity is available. The supply and distribution system will be sized based on the flowrate.

Table 3-4 Construction material requirement for water supply system

Makeup Water System	Value	Unit
Volume of PVC for 12" pipes	5.2	m^3
Volume of PVC for 18" pipes	57.4	m^3
Volume of PVC for 24" pipes	91.5	m^3
Volume of concrete for 30" pipes	89.9	m^3
Volume of concrete for 42" pipes	15.3	m^3
Volume of concrete slab	828	m^3
Volume of concrete wall	330	m^3
Volume of excavated material for open channel	1668	m^3
Volume of excavated material for ponds	45307	m^3
Volume of excavated material	9680	m^3
Number of pump	12	
Weight of each pump	544	m^3
Liner surface area	12302	m^3

3.4 Harvesting system design

The recovery step is one of the most challenging process, because of microalgae strain size (3 -30 µm) with a diluted broth of 0.5kg m-3 [57], making it difficult to recover the biomass which accounts for 20 – 30% of the total cost of algal production [39]. So far, there is no available harvesting method that can be applied to every process. The harvesting stage is the process where algae biomass is recovered from the growth medium before extraction. The process starts with primary harvesting, followed by secondary harvesting. Primary harvesting removes the microalgae from the culture medium in large quantities, which can be through flocculation, floatation, or gravitational sedimentation. Secondary harvesting is the process after bulk harvesting which can take place through filtration or centrifugation.

3.4.1 Primary harvesting

The primary harvesting system assumed for this study is settling tanks, based on the process described by Benemann et al.[8]. The use of settling for microalgae harvesting is based on the observation that nitrogen starves cultures, and non-nitrogen can settle at a rate of 30 cm/hr or greater naturally without adding any chemicals. The addition of a small quantity of polymer can increase these rates and produce a more compact rate. The settling systems used in this study are above the ground water settlers and made of steel and concrete which are normally used for municipal and industrial wastewater treatments.13 settling tanks are assumed to be required for the large scale growth ponds assumed in this study.

Figure 3-6 Example of settling tank [58]

Table 3-5 Construction material for settling tank

Settling Tank		
	Value	Unit
Number of tanks	13	
Volume of each tank	300781	ft^3
Volume of excavated material for CAPDET design	15100	m^3
Volume of slab concrete	991	m^3
Volume of concrete walls	152	m^3
Volume of excavated material for plastic lined walls	9508	m^3
Surface area walls	1613	m^3
Liner volume	1.64	m^3

3.4.2 Secondary harvesting

The secondary harvesting system adopted in this study is flotation, using dissolved air floatation system followed by centrifugation. Flotation is the process of inducing suspended particles to rise to the surface of a tank where they can be collected and removed. Dissolved Air Flotation (DAF) is one of several flotation techniques employed for sewage water treatment and later for algae harvesting [54]. DAF is commonly used to extract free and dispersed oil and grease from oily wastewater. The system consists of a feed unit, a chemical addition mix tank and a flotation tank.

Table 3-6 Infrastructural material for DAF system

Dissolved Air Flotation		
	Value	Unit
Volume of Concrete Slab for DAF Facility	2680	m^3
Volume of Wall Concrete for DAF Facility	2630	m^3
Volume of Excavated Material	31000	m^3

The energy power used for operating the DAF is based on an estimate by Harris et al. at 1.33 × 10-4 kWh/dry-g assumed for process algae grown at 25 $g/m^2/d$ in an area of 2000 ha [59]. Other power numbers reported are 1.48 × 1 0-4 kWh/dry-g by Sim et al [60]. This is very similar to that of Harris et al. and 1.67 × 10-3 kWh/dry-g by Uduman et al. [61], and this estimate was much higher than the other two, and an algae retention efficiency of 90% was assumed. 40 mg/L chitosan used is coagulant.

3.5 Extraction system

Separation of the oil from the algae after harvesting takes place through disruption of the cell wall, either through mechanical or chemical extraction. This step of the process is the most critical aspect of the process, as the process is highly energy intensive and very costly [19; 20]. The mechanical extraction which requires the algae to be dried before extracting the oil is an energy intensive process, while the use of chemicals is highly dangerous, and requires health and safety measures to be put into place. The extraction process includes multiple approaches; supercritical fluid, solvent, ultrasound, microwave, live and single step extraction [21-23].

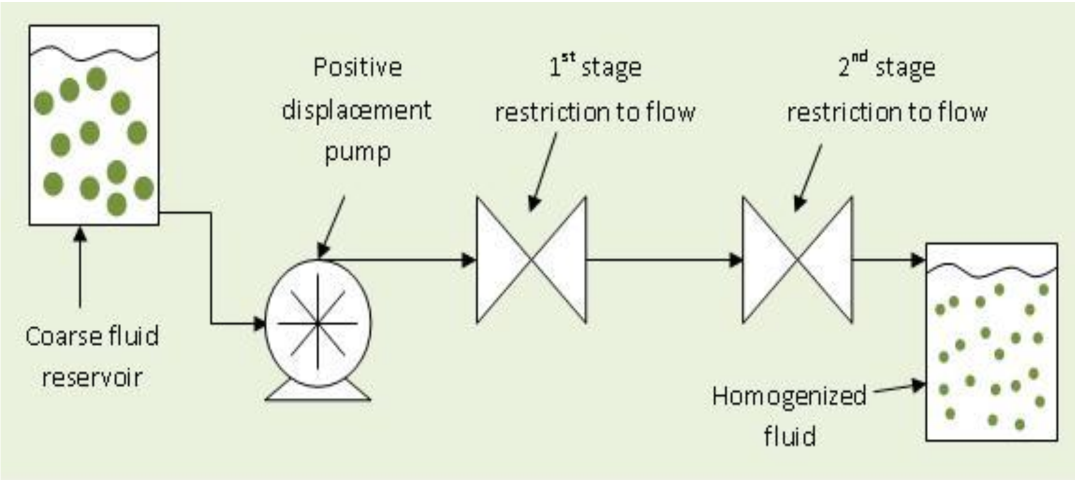

Figure 3-7 Basic diagram of a valve homogenisation system [62]

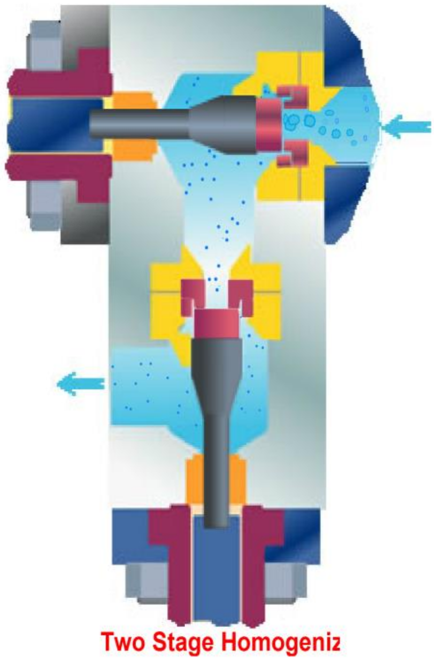

Figure 3-8 GEA Niro Soavi two stage homogenizer [63]

Pressure homogenisation is an established fluid mechanical process that is used to disrupt bacteria in waste activated sludge [25]. This study adopts this system using values from Frank et al. 2011[25] at 183 kWh per dry metric ton and 90% efficiency, corresponding to 20 wt % input. This is based on the assumption of undisrupted cell flow to recovery system [25]. Figure 3-8 shows a tow phase flow homogeniser by GEA Soavi, handling fluids under high pressure, up to 1,500 bars / 21,750 psi under continuous full-scale operation [63]. This facility has observed 79% homogenisation of *Chlorella* per pass at 600 bar and 2,000 L/h. At 10 wt.% solids, this is 365 kWh/dry ton for two passes [25; 63]. Davis 2010 [38] assumes 200 kWh/dry-ton with 90% disruption efficiency, while Stephenson et al. 2010 [23] process model assumes 22 wt.% from the decanter centrifuge (i.e., 168 kWh/dry ton for homogenisation). However, Frank et al. 2011[23] stated that it is unusual to work above 20% solids because of pumping difficulties and homogenising efficiency [25].

Due to the high cost of extraction, this process has become the most debated process in terms of commercialisation of algal technology. Many manufactures and researchers are working hard to find the most efficient and cost effective extraction process. Recently a manufacturing company [24] announced a breakthrough and developed a single step extraction system that does not require chemicals or a significant amount of capital cost. Also an on-going research by the University of Iowa involves an extraction process using mesoporous nanoparticles to selectively extract and sequester targeted relevant fuel [25].

3.6 Summary

For the facility considered, the microalgae are grown in an open pond (OP) cultivation system, a single pond size of 4 hectares (690 X 60m) is assumed, with L/W ratio of 20/1. Productivity rate of 25 g/m2/d and lipid content of 25 wt% are assumed, based on publication by Davis et al. 2011 [38], and the operation is assumed to be maintained for 330 days. Nutrients fed into the growth media for culture are CO_2, Nitrogen, and Phosphorous (P), assumed to be consumed stoichiometrically based on molar composition of carbon: nitrogen: phosphorus (C:N:P) of 103 : 10 : 1 [7]. Pure CO_2 is assumed to be transferred through a 1.5m sump pipe and delivered to the site with a gross CO_2 requirement of 2.24 g/g algal biomass. In the raceway ponds, paddlewheels are used to maintain a constant mixing of the algae. Paddlewheel power is driven by electricity at 25 cm/s mixing velocity [8]. Energy required to pump water to the site and into the culture is 1.23E-04 kWh/L, and energy to pump culture to the downstream process is 2.50E-05 kWh/L. The energy requirement is estimated by using GREET LCA software [9]. The grown microalgae are harvested continuously above the ground in 13 simple settling tanks that concentrate the algae at 0.5 g/L via auto flocculation, and the remnant algae that have moved into the clarified effluent are recycled back to the growth pond. This settling process and growth process accounts for most of the water used for the entire process. Water consumption is estimated based on evaporation loss of 0.229 g/L per day. Once the algae are settled and the water is returned to the culture, the next step is flocculation with Chitosan and collected by dissolved air flotation to thicken the algae with an energy consumption of 1.478E-04 kWh/g-dw [10]. The algae paste is then further concentrated using a centrifuge to minimise the cost of the downstream processes. Cellular disruption takes place using a combination of high-pressure homogenizer and hexane extraction. These two processes are assumed to achieve 90% extraction efficiency. Remnants, including lost solvent and unrecovered lipids, are sent to an anaerobic digestion (AD) facility for energy and nutrient recycling.

4 ECONOMIC MODEL

4.1 Introduction

Microalgae are considered as one of the most feasible options, having the potential to serve as a major feedstock for bio-product production. However, the existence of multiple process pathways, varying productivity assumptions and limited commercial-scale production makes it difficult to establish a reliable economic model. The purpose of this model is to provide a robust economic model that can span the entire algae-to-oil process chain, able to supply feedback on every aspect of the process to support research and investment, leading to a successful realisation of the technology.

The economic model is designed to estimate the capital and the fixed and variable operating costs of constructing an algal oil production plant. The model is developed using the baseline process specified in Chapter 3, and is able to estimate the production cost of algal oil produced from the plant. The construction cost of the major equipment is estimated by using the designed parameters described in Chapter 3, and other reports from similar processes. Variable operating costs are calculated by multiplying the raw materials and energy usage value by the unit price. While some fixed costs are calculated as percentages of certain capital costs, others are estimated and entered directly.

The economic analysis for each process step (cultivation, harvesting, processing) is estimated in separate steps. Each of the analyses assembles the construction cost and operating cost for its process step. These analyses are sufficient when detailed cost data is available for all the processes. The model includes a summary sheet which presents the overall costs of the system. The model also adjusts cost to price inflation that occurs between the period of construction and commissioning or, when a basis design is used, the cost estimate reported is adjusted according to the period in which it is being modelled.

4.1.1 System analysed

The systems analysed are based on facilities presented in the Argonne National Laboratory (ANL) Life-cycle Analysis report [25] and used in their Greenhouse Gases, Regulated Emissions, and Energy Usage Transportation Model (GREET)[56]. The size of the systems are the same except for some slight changes made to the design structure, the major changes are mainly concerned with the growth pond. For example, in the ANL report it is assumed that the pond is excavated and uses an earthen berm wall, and in the economic model a concrete wall is assumed. A detailed description of the structure is presented in Chapter 3.

The microalgae are grown in an open pond mixed by paddle wheels for which previous detailed economic analyses are available. The microalgae are then dewatered in several progressive steps: bio-flocculation, dissolved air flotation (DAF), and centrifugation. The bio-flocculation process allows settling and flocculation of the algae without chemical input, bio-flocculation is explained in greater detail in the engineering design section. Cellular disruption by high-pressure homogenisation is then followed by a wet hexane extraction process.

Other similar processes are analysed using the same systems (see Chapter 6), although the model was developed based on the process parameters presented in the NREL harmonisation report [25; 56], the values adopted are presented in Table 4-1 and Figure 4-1. For the base case scenario (i.e process analysed in the developed model) a scale of 1000 barrels of crude algae oil per day (bbl d^{-1}) is assumed as the basis scale. Nutrient demands are assumed from Lardon et al. 2010 [19], based on the elemental composition of carbon: nitrogen: phosphorus ratio ($C_{103}N_{10}P_1$). 100% of the water is assumed to be recovered from the first level of dewatering; growth rate and lipid fraction used followed the analysis from Davis et al. 2011 [38].

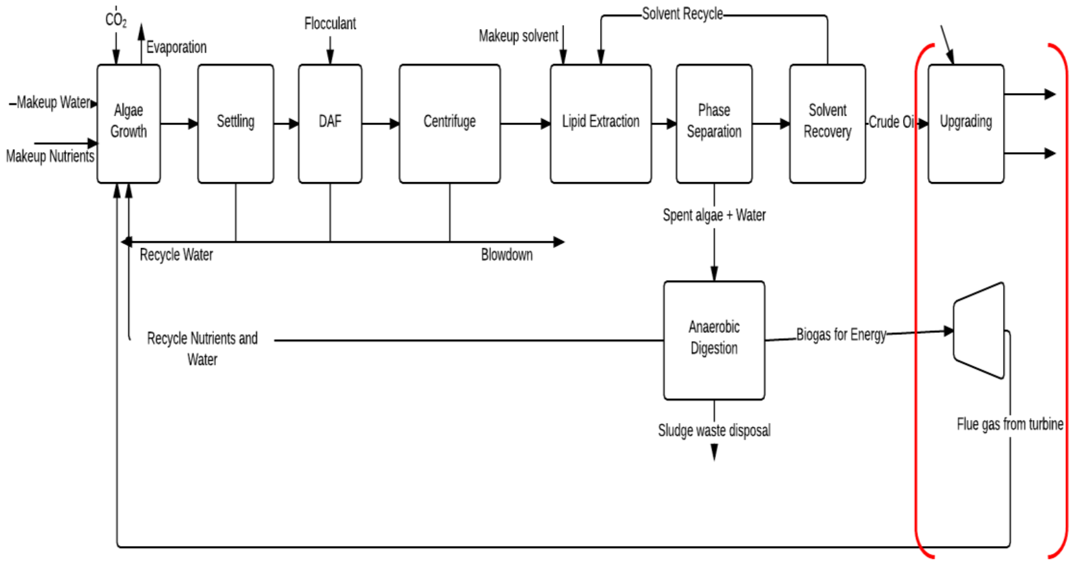

Figure 4-1 Baseline pathway excluding the section in red

Figure 4-1 shows the baseline process starting from growth stage showing resources input and output. The section in red is the upgrading stage which is not considered in this analysis, but would be good to be considered for future development.

Table 4-1 Key assumptions used in the process baseline

Algae strain	Chlorella vulgaris
Productivity rate	25 g/m^2/day
Lipid content	25%
Density	920 kg/m^3
Extraction efficiency	80%
Scale of production	1000 bbl/day
Total biomass required	7.31 M kg
Growth surface area	2925 ha
Single pond area	4 hectare
Total number of ponds	731
Culture density	0.5 g/L
Net N demand,	0.019 g/g algae
Net P demand,	0.017 g/g algae
CO_2 recovery to culture	85%
Nitrogen recovery to culture	90%
P recovery to culture	90%
Flocculants / Coagulants	4.00E-03 g/g dw algae
Evaporation loss	0.23 g/L algae
Makeup water	4.79E-02 L/net g algae
Dissolved Air Flotation	1.478E-04 kWh/g-dw
Centrifuge power	1.930E-05 kWh/g-dw
Pressure homogenisation	2.04E-04 kWh/g-dw
Hexane Extraction	9.27E-04 kWh/g Lipid
Anaerobic Digestion	8.50E-05 kWh/g algae
Energy to pump water to site & into culture	0.000123 kWh/L
Energy to pump culture	0.000025 kWh/L
CO_2 total supply rate	2.24 g/g algae
Circulation power for pond	48 kWh/ha/d

The economic model calculates the construction and operating costs based on several process inputs. The overall facility area depends on the scale of the production, biomass required, and area required. The construction material augments or decreases when the scale is changed, this also applies to the operating resources and labour. The major inputs that affect the costs are: the productivity rate, lipid fraction, biomass concentration, number of ponds, harvesting and extraction efficiency, and scale of productivity. To calculate the biomass and area required, the following method is used [64; 65]:

$$Biomass_{daily}\ (BM_{daily}\ g/dw/d) = \frac{Productivity\ scale\ (L/d)}{Lipid\ content\ (\%\ wt)} \tag{4-1}$$

$$Total\ biomass\ required\ (BM_T\ g/dw/d) = \frac{BM_{daily}\ \ g/dw/d}{Extraction\ _{eff.}\ (E_{eff.})} \tag{4-2}$$

Where:

BM_{daily} = biomass produced gram of dewatered algae per day

BM_T = Total biomass required in cultivation pond gram of dewatered algae per day

$E._{eff.}$ = Extraction Efficiency (80%)

Productivity scale 1000 bbl/d = 158,987 litres per day

4.1.2 Accuracy of the estimate

Capital cost and operating costs are estimated in detail, implementing the recommended cost estimating practice provided by The American Association of Cost Engineers (AACE 18r-97) guidelines [66]. The accuracy of an estimate depends on the amount of design details available, the accuracy of the cost data available and the time spent on preparing the estimate. The five definitions of the estimate are as follows:

Level 1: Order of magnitude (Conceptual estimate, Variable accuracy -20% to $\pm$30%).

Level 2: Study estimate (using scaling factors, pre-designed estimate, accuracy up to -15% to +20%).

Level 3: Preliminary estimate (generally for authorisation, accuracy -10% to +20%), this includes processes and conceptual utility diagrams, site layout drawings, and a nearly complete listing of major equipment and assemblies.

Level 4: Definitive estimate (more detailed information, accuracy -5% to +5%). The engineering is completed through preparation of diagrams showing the process flow, utility flow, piping, and instrumentation; heat and mass balances; final layout drawings; complete equipment lists; vendor quotes, etc.

Level 5: Detailed estimate (quotation, contractors estimate, accuracy -3% to $\pm$ 3%), which is based on detailed unit cost and quantity take-off estimates from final plans.

The present economic model can be considered, overall, as of level 2, even if the cost estimates are taken from several literatures, and therefore this aspect can be considered as level 3. The pond design is estimated based on a detailed design presented from several literatures; this can be considered level 4

4.2 Capital cost analysis

The majority of the cost analyses have been based on unit construction costs from Spon's Architect and Builders Price Book Davis Langdon, 137th edition 2012 [67]. Engineering design and costs for the specialised processes unit utilise information from several major works published by J.C. Weissman, J.R. Benemann, and Lundquist et al. [8; 22; 68; 69].

The engineering design and construction cost estimates of the algae biofuel production facilities straddle the major divide between standard practices of agricultural engineering and those of chemical and civil engineering [8]. Algae biofuel production, using hundreds of ponds, each one consisting of several hectares, is essentially a form of agriculture, actually aquaculture, and thus would use the same low-cost approaches and practices used in agricultural and aquaculture engineering, rather than chemical or civil engineering practices. Of course, where municipal wastewaters are used for algae growth, or when solvents are required for algae oil extraction, aspects of civil and chemical engineering practices and costs will need to be applied [54]. For example, for domestic wastewater treatment facilities, legal mandates could require bidding processes, use of union labour, and higher standards of health and safety than applicable to agricultural systems. In the following facility design and cost estimates, agricultural engineering components and costs are used for the algae production facilities (the ponds, water and nutrient supplies, harvesting, and algae biomass handling facilities), with chemical and-or municipal practices and cost estimates applied for the algae biomass processing (e.g. oil extraction) facilities.

4.2.1 The total capital investment

The total capital investment is the total cost of designing, constructing, and installing a plant, and the associated modifications needed to prepare the plant site [70]. The total capital costs include the cost of the plant itself, site preparation, labour construction and indirect capital cost. The total capital investment (TCI) is defined as:

$$TCI = FCI + LC + WC \tag{4-3}$$

Where:

FCI = fixed capital investment (total direct cost + indirect costs)

LC =land cost

WC = working capital

$$FCI = TDC + IC \tag{4-4}$$

Where:

TDC = total direct cost (total equipment cost + direct cost)

IC = indirect capital cost (contingency, field expenses, Prorateable cost, and other costs related to construction.)

$$TDC = ISBL + DC \tag{4-5}$$

Where:

$ISBL$ = inside battery limit (major equipment cost + labour construction cost)

DC = direct cost (site development + warehouse)

Pond construction cost is calculated on an area basis, the area required for cultivation would depend on the amount of biomass needed to be grown, to achieve the desired scale. If the following definitions are adopted:

a_{sp} *= area of a single pond (h)*

a_{rqd} *= area required (h), total area required to cultivate the desired biomass*

n_p*= number of ponds*

The scale of the facility can be calculated as,

$$a_{sp} = \frac{a_{rqd}}{n_p} \tag{4-6}$$

for the analyses where the area of the single pond is changed, the total number of ponds is fixed. Alternatively, it can be calculated as

$$n_p = \frac{a_{rqd}}{a_{sp}} \tag{4-7}$$

When the area of the single pond is fixed, in order to scale up the cultivation area, more ponds of the same size are added.

Equation (4-6) is used calculating area of single pond, while Equation (4-7) is used to determine the total number of ponds where the area of a single pond is given. Assuming, a production scale of 1000 bbl/day growing at 25g/m2/day to be cultivated in an algae farm that has 1013 ponds. Equation (4-6) can be applied to calculate the area of each pond; in this case, Equation (4-7) is not needed as the total number of ponds is already given. The techno-socioeconomic model uses Equation (4-7) because the size of the pond affects many economic and technical factors. The criteria for pond sizing are explained in section 3.3.1.

Table 4-2 Number of equipment's

Equipment	**# required**
CO_2 blowers	9
Paddlewheels	1 per pond
Flocculent	2
Settling tanks	13
Centrifuges	4
Homogeniser	28
Lipid extraction (Centrifuge)	5
Anaerobic Digester	8
Make-up water system	12
Pumps	

In this analysis, land is assumed to cost $34,000/ha (£20060/ha - £8024/acre). The land cost was based on an analysis presented in Lundquist et al. 2011[22], and this corresponds closely to the £8,626/acre value of arable land in the UK. In some literatures the land cost is assumed as a percentage of the major equipment cost (MEC). Molina et al. 2003 [39] assumed land cost at 6% of MEC. The cost of land is related mainly to location, for example, the land cost in the northern part of England would have a lower cost than land in the southern part of England.

Land cost can be a significant factor in the context of algae farming along with other location logistics such as access roads, availability of power supply and most importantly significant water and CO_2 supply. Land availability is an important factor for algae production, the location of the site should be specific to the facility designed. In selecting a suitable land for algae production facilities, there are many siting criteria that affect the algae production facilities, Algae' farming requires a very large area for operation. There are various physical, social economic, legal and political factors that need to be considered (algal biofuel roadmap).

Characteristics such as Topography, and soil can affect the suitability of land for open pond algae cultivation. Soil characteristics affect the construction costs and design of open pond systems, as these factors define the need for pond lining or sealing. Topography would also be a limiting factor for these systems because the installation of large shallow ponds requires relatively flat terrain. Areas with more than 5% slope could well be eliminated from consideration due to the high cost that would be needed for site preparation and levelling.

Although there is a relationship between land suitability and availability for algae production facilities, with the factors that affect the cost of land, how much the cost of the land itself can affect the cost of the facilities is not determined, as large tracts of land that are available might be located in an area with low cost of land. While a more suitable land with good soil characteristics and access to resources required for algae production, such as, water, carbon dioxide, electricity and transportation which can reduce the cost of constructing and operating algae facilities. For example wastewater lands, which are located near population centres, would have high cost as compared to lands that are located outside the city.

4.2.2 Indirect capital cost

The total estimated cost of the plant facility includes all the plant facilities, equipment and utilities, ready for start-up. These costs are those developed in the model and were based on a detailed engineering design and cost estimation from Spon’s (Spon’s 2012). To determine the overall annual capital cost, other indirect cost factors must be added to determine the total capital investment. These indirect factors include site development and warehouse costs, based on the inside-battery-limits (ISBL) equipment costs, and are considered as part of the total direct cost. Contingency, field expenses, home-office engineering and construction activities, and other costs related to construction are computed relative to the TDC and give fixed capital investment when summed [71].

Warehousing is the cost of on-site storage equipment and supplies. Site development includes costs of fencing, curbing, parking lot, roads, well drainage, rail system, soil borings and general paving. These factors allow for minimum site development assuming a clear site with no unusual problems, such as right of way, difficult land clearing, or unusual environmental problems. Proratable costs include fringe benefits, burdens, and insurance of the construction contractor. Field expenses include consumables, small tool and equipment rental, field services, temporary construction facilities, and field supervision. Home-office and construction involves professional services such as engineering, purchasing and construction. A contingency is the extra money reserved for unforeseen issues during construction. Other costs are costs for start-up and commissioning, land, right-of-way, permits, surveys, and fees.

4.3 Operating cost analysis

The basic operation of a large scale microalgae production system is done in a raceway pond, it is a continued growth process followed by accumulation of lipids (to 50% of the ash free dry weight) induced by nitrogen limitation [72]. The grown microalgae are harvested continuously by a two-stage settling process [72]. Followed by centrifuging the material, concentrated by a factor of 50. Primary harvesting is not expected to be 100% efficient, 90% efficiency is assumed for the process in this study. Carbon must be supplied as purified CO_2, introduced into the ponds through sumps 1.5 m deep. The sources of the carbon can either be commercial or from a nearby flue gas power plant. The water resource is either from a waste water system or supplied commercially as fresh water. The salts produced per algal biomass will be transported to a large body of salt water or disposal site (detailed of the process used in this analysis in discussed in chapter 3).

All operating costs are given on a per hectare per year basis. For the chemical inputs, the unit requirement and the unit costs are given as well. Power unit cost, assumed for the baseline model is at £0.11/kWh; the value is varied in a sensitivity analysis to determine the impact of this input to the overall algal oil production costs. Cost of salts contained in the blow down (evaporated and transported to a disposal site) is taken into consideration.

Estimating of the production costs and revenues is a key step in determining the profitability of a process. An understanding of the breakdown of production costs is critically important, regardless of whether the project is a new design or a revamp or expansion of an existing plant. The operating cost in the model is calculated based on conventional terminology used in the economic analysis. The operating costs is classified into variable production costs and fixed production costs.

Variable costs of production are costs that are proportional to the plant output or operation rate, which include raw materials consumed by the process [70]. These include utilities – fuel burned, water, electricity, nutrients, waste disposal, and by-product credits. These costs are incurred only when the process is operating.

Fixed production costs are generally incurred in full, regardless of the plant operation rate or output. These costs include operating labour, maintenance, other finances and various overhead items [73].

4.3.1 Estimating Variable Production costs

Variable production costs are those production costs that are directly proportional to the rate of production. For most of algal oil production plant, the major variable costs are the costs of raw materials and utilities.

4.3.1.1 Nutrients and energy

The major nutrients needed in cultivating microalgae are carbon, nitrogen, and phosphorous. For CO_2 90% nutrient utilisation efficiency is assumed. The carbon sources are purified CO_2 at low cost of £24/t ($40/tonne)[74]. Nitrogen is derived from Ammonia, the cost of Ammonia being at £204/t ($407/t), and used with a 76% efficiency to cover losses. The phosphorous is derived from Diammonium Phosphate (DAP), and phosphorous £260/t ($442/t)[74]. A high molecular weight polymer is included to flocculate the algal biomass prior to primary concentration in a settling pond. It is assumed that 1 ppm of polymer is required for each 500 ppm biomass. The cost of the polymer is £5/kg. Quantities of raw materials used and energy used are estimated using material balance and output of energy from the GREET model [25], except for the energy in the open pond, which is calculated separately under pond construction. Mixing is required to maintain cells in suspension, and to disperse nutrients in an open pond system this is discussed previously in Chapter 3.

4.3.1.2 Blowdown Rate

Blowdown is a process, in which portion of the culture medium is removed from the pond, and an equivalent volume of freshwater is added to the pond for controlling salinity in the pond (Murphy and Allen, 2011),. Due to evaporation in open pond system, the salt concentration of the pond water increases, requiring continues supply of make-up water and disposal of blowdown, this will be concentrated in relation to the input water. The need for blowdown would depend on the type of water the facility is using; e.g. facilities operating with brackish water would require more blowdown than facilities using wastewater. When operating an inland pond, further concentration may be required of saline water, which can then be injected underground or even as dry salt, which may be disposed to landfill. For algae facilities located on or close to a coastline, can send the concentrated saline water back to the ocean at lesser cost and less environmental impact, although it would likely not meet the environmental regulations protecting coastal environment from pollution, because aquaculture is sometimes classified as an industrial activity that is subject to strict effluent standards, however, this depends on whether algae biofuel production is classified as aquaculture or agricultural farming. Because algae industry is still at its conceptual stage, there are no specific guidelines set in place yet [22]. In this analysis, a blowdown rate equivalent of 14% of the evaporative losses (specified by Weissman and Goebel, 1987) [37]is used. For an average evaporative rate of 1 cm/day, this represents total blowdown flow rate of 2700m3/day. Disposal is with truck to a suitable landfill.

.

4.3.2 Estimating Fixed Production Costs

Fixed production costs are those costs that do not vary with the rate of production. They include labour, maintenance, overhead charges, and taxes [75]. Some finance charges are also counted as fixed costs, as described in the following sections.

4.3.2.1 Labour

The number of employees was estimated by considering the likely degree of automation for each area and adding a reasonable number for management and support employees. The labour requirement is estimated in Table 4-3, based on Weissman et al. [72]. For a 330 day operation, with around the clock algae harvesting, operating personnel must be present at all times.

Operating labour requirements are considered as rough assumptions, as it is not certain how much supervision and time will be required for each major equipment item [69; 72]. The pond area is very large, requiring long travel times to any outlying area, and all major equipment is located along the central corridor, minimising key travel distances. However the minimum staff required for a 100 hectare facility was estimated by Lundquist (Lundquist et al. 2011) to include: a supervisor, two lab assistants, a manager, an administrative assistant, four pond operators, two secondary harvesting operators, and two extraction process operators, making a total number of 13 operators.

Pond operators are calculated based on 50 ponds per operator for open pond systems. The harvesting and processing operators are estimated based on the scale of production. It is assumed that for a production scale of 1000 barrel per day, 8 operators are required for harvesting (13 settling tanks, 4 centrifuges) and processing (28 homogenisers, 5 centrifuges). The plant manager, laboratory workers and operators will be present carrying out routine activities such as sampling, cleaning, repairing, etc.

Table 4-3 Operating personnel used for this study

Labour	Number of Operators	Source
Plant Manager	1	Lundquist et al., 2011
Operators manager	4	based on major operating groups Weissman., 1982
Lab manager/Aquatic biologist	2	Richardson et. al., 2010
Total management	7	
Admin/secretary	2	Richardson et. al., 2010
Pond operators	20	50 pond per operator Rayan d. et al, 2011
Secondary harvesting operators	8	For 1000 bbl./day
Processing operators	8	For 1000 bbl./day
Field Operators	36	
Procurement	0	Not required
Marketing	0	Not required
Fisheries biologist	0	Not required

The techno-socioeconomic model estimates the labour cost based on the size of the facilities and scale of production. Labour cost are categorised into labour required during the construction phase and labour required during annual operation. In Chapter 7, analysis of the effect that a change of the plant size would have on both the economic and social impact (jobs) has been undertaken. Based on the analysis, it is evident that constructing a large scale algae farm would create jobs; both in the short time construction phase and long-time operating phase than small scale plant (See Table 7-7 for the detailed breakdown of the analysis). However, large scale plants requires huge amount of investment, which results in high cost of algal oil. Therefore, if investment in a new algae plant is needed in terms of job creation, the large-scale plant can contribute to creating jobs, but in the context where the economics of algal oil production is targeted to be viable, job creation would not be a meaningful concept. In conclusion, the choice of plant size would depend on the economic or political interest.

4.3.2.2 Maintenance costs

Maintenance is a fixed cost, as the plant must be kept in good repair, regardless of the level of production. Operating at less than full capacity can actually increase the rate of maintenance expenditure, as damage to plant equipment is more likely during start-up, shutdown, or turndown than during steady-region operation at design capacity.

Maintenance costs are typically estimated as a fraction of ISBL investment, ranging from 3% for a process that handles liquids and gases to 5% for a process that involves solids handling or other large mechanical equipment [76]. If a process is known to require regular equipment replacement, the design engineer should make an estimate of the annualised replacement cost and add this to the maintenance costs. The labour for maintenance is included in personnel breakdown. The estimates are based on five shifts per week per 360 days per operation, and a rough estimate of people needed at hand.

4.3.2.3 Land, Rent, and Local Property Taxes

Most plants are constructed on rented land or in rented buildings, as it is usually easier and financially more attractive to lease land or property than to tie up capital in land purchase, putting in the necessary infrastructure, and constructing buildings. Land is assumed to be purchased in this analysis, although the economic model is designed in such a way that it can incorporate land lease costs, where the land use is leased.

Tax parameters for estimating local property taxes used here are generic (i.e., not specific to the region being analysed). The economic model, can identify and input local tax rates or if possible the actual tax amount.

4.3.2.4 Insurance

All plants require insurance to cover third party liability as well as potential plant damage. Most companies maintain insurance coverage through insurance brokers, although some choose to self-insure, essentially setting aside a part of their operating income to cover liabilities. Insurance premiums are based on prior performance and risk assessments carried out by specialist risk management companies and are typically about 1% of ISBL plus OSBL capital cost per year.

4.3.2.5 Interest payments

If the project is financed by bonds or loans, the regular payments of interest (or interest plus amortisation of principal) are a fixed cost of the project. Creditors have a primary claim on earnings over shareholders, so payments on debt must be made as a cost of production rather than set aside to be paid out of retained earnings.

Most companies do not break out the relative proportion of debt and equity financing on a project-by-project basis and instead evaluate projects using an overall average cost of capital [76]. Repayment of debts associated with the fixed capital investment is therefore included with the overall expected return on capital of the project.

When a company has only one plant, for example, when a new venture is being considered, then it is best to separate debt financing from equity financing and calculate the cost of servicing the debt as a fixed cost of production. This provides a truer picture of the likely return on equity from the project.

For this analysis, it was assumed that the plant would be 100% equity financed by cooperate investors. The returns on equity are taken at 10% interest for 20 years. The principal is taken out in stages over the 20 year construction period.

The financial activities included in the structure of this economic model are:

- percentage financed: is the percentage of the project construction costs that was financed through loan;
- years financed (term): is the number of years to payback the amount borrowed (initial loan amount);
- interest rate: is the annual rate charged by the lender for example 10 =10%;

- percentage equity: is the share of project construction cost after accounting for the share from debt financing) secured through investment by individuals and/or corporate investors;
- individual investors: it refers to households that provide resources (invest) towards equity in the project, rather than direct loans for debt financing;
- corporate investor: it refers to business that provides equity investment. This calculation is automatically derived from the percentage entered in by the individual (above) - the sum of the two equals 100 percent.
- Tax parameters for estimating local property taxes used here are generic (i.e., not specific to the region being analysed). Users should identify and input local tax rates or the actual tax amount if possible.

4.3.3 Deflators and Inflators

The economic model includes deflators and inflators, which can allow the adjustment of the cost to a specific year. The main reason to include these co-efficient is to be able to capture the fact that the construction phase will last for a number of years. They can also be used to inflate or adjusts costs when using published costs of previous years. The data used for the economic model is sourced from HM Treasury [77] . Inflation and deflation are calculated as presented in Table 4-4

Table 4-4 Deflators and inflators coefficients (HM Treasury, 2013)

GDP deflator at market prices			GDP (£ million)	
Financial Year	GDP deflator 2011-12 =100	Percentage change on Previous year	Money GDP Cash	Money GDP Real Terms 2011-12 Prices
2006-07	89.254	2.69	1,350,438	1,513,028
2007-08	91.478	2.49	1,432,887	1,566,373
2008-09	93.975	2.73	1,422,290	1,513,477
2009-10	95.389	1.50	1,415,654	1,484,085
2010-11	97.978	2.71	1,480,569	1,511,124
2011-12	100.000	2.06	1,524,550	1,524,550
2012-13	*101.300*	1.3	1,546,000	1,526,160
2013-14	*103.630*	2.3	1,595,000	1,539,131

Deflating figure:

E.g How much 7.40m in 2009-2012 is worth in 2013-2014?

£7.40m x (103.630/95.389) = £8.04m

Inflating figure:

E.g 85.32m in 2011-12 is worth in 2007-08

=£85.32mx (91.478/100) = 78.05

4.3.4 Generalization capability of the model

The techno-socioeconomic model is a tool designed to provide for an economic and social (employment, earning and benefits) analysis for an open pond raceway system of 4-hectare size pond, and other specific facilities for processing the microalgae to algal oil; for the employment impact analysis it is specific to UK region. It is possible that many potential users might wish to perform a similar level of analysis for a smaller or larger plant, and for different regions (different country or localized region) to capture better the particular country or regional benefits. It is, however, to be noted that the model is limited to the specific process facilities specific to the base model.

To accommodate users who desire to perform a similar analysis for a plant of different size/scale. An INPUT data worksheet feature is provided in the model. This feature allows the user with the capability to derive the necessary data to complete the analysis of a particular size/scale plant of interest with the base model. The necessary inputs include the scale of production (barrel per day or gallons per day), growth rate (g/m2 /day), lipid content (% wt.) and the algal oil density. All other calculations are in the OPERATING worksheet, except for pond that is calculated in a separate worksheet named GROWTH worksheet.

In the GROWTH worksheet, users can enter the appropriate data according to their specification. The required inputs include, individual pond size (width and length to calculate the number of pond and construction material), add plastic liners (user can select yes or no), liner thickness (the base model uses 40 mm thickness). Users can also define operating parameters that include operating days per year (to estimate annual production), carbon dioxide usage (tons per year) nitrogen, and phosphorus. There is also a water model available on the OPERATING worksheet of the model, which estimates the makeup water requirement; this feature also allows users to define the necessary data based on the specific evaporation rate.

For the other facilities, the user can enter information regarding the harvesting, extraction and water distribution systems. For harvesting they are; the number of settling tanks; the number of the centrifuge, power consumption, harvesting efficiency and biomass concentration. For extraction; number homogenizer, extraction efficiency and power supply. All prices can be updated in the techno-socioeconomic model. All energy and resources requirements are calculated in the OPERATING worksheet, Data for energy requirement can be changed by the user if they differ from the default data defined by the base model. Information for energy and resources requirements comes from the LCA GREET model.

A separate JOB worksheet is provided for the analyses of the jobs impact, the necessary inputs required here are; input and output multipliers. The analysis utilizes information from the capital and operating costs calculations. Once the user data in entered into the techno-socioeconomic model, the user can proceed with the analysis

4.3.5 Summary

The design parameters from the economic model are used to determine the size and costs of capital equipment. After the equipment costs are determined, other indirect and direct costs factors would be added to determine the total capital investment (TCI) [71]. The total equipment costs are based on several literature, models, and the Spon's Architects and Builders price book. The sum of the total equipment costs and construction labour costs are defined as the ISBL costs (Inside battery limit Investment) [75]. Once the ISBL costs are estimated, then other direct costs, including site development and warehousing, are added to sum the total direct cost (TDC), the total direct cost with indirect costs such as project contingencies, proratable costs, field expenses and other costs added result in the fixed capital investment (FCI)[70]. Working capital costs are then added to the FCI to obtain the total capital investment (TCI)[78]. Thus the indirect cost is estimated using percentage factors, although each project must be independently evaluated for the reasonableness of standard factors [72]. Thus standard factors used in other alternative fuel projects are deemed not applicable for such projects like microalgae farming. For example, the $10,000/acre land costs, used in many bio-refinery projects, are not applicable to algae projects, and therefore land costs are taken as agricultural land costs. Similarly, the 3 to 5 year construction period used for alternative fuel projects is not applicable to the simple construction needs of a microalgae plant, which can go from design to operation in less than that [72]. Algae' farming is more appropriately viewed as agricultural/aquaculture farming [79], and thus would use the same low costs approaches and practices as the agriculture [22].

Indirect capital costs would need to be included, and as mentioned previously these are estimated as a percentage and are added to obtain the overall costs production cost, and are summarised in Table 4-6 and section 4.2.2. The factors are estimated based on ethanol production system, since the system is very similar to the process of algal oil production.

Table 4-5 Indirect capital cost factors

Other indirect costs			
Warehouse/buildings	4%	ISBL	On-site storage equipment and supplies
Additional piping	4.5%	ISBL	For supply of resources
Site development	9%	ISBL	Fencing, curbing, parking lot, roads, well drainage, rail system, soil borings and general paving
Field expenses	10%	TDC	Consumables, small tool and equipment rental, field services, temporary construction facilities, and field supervision
Home office and construction cost	20%	TDC	Professional services such as engineering, purchasing and construction
Prorateable cost	10%	TDC	Include fringe benefits, burdens, and insurance of the construction contractor
Contingency	10%	TDC	Extra money reserved for unforeseen issues during construction
Other costs (i.e start up, right of way, fright e.t.c)	10%	TDC	Costs for start-up and commissioning, land, right-of-way, permits, surveys, and fees. Pilling, Soil compacting, unusual foundations, other taxes, insurance, materials and transportation
Construction labour	10%	MEC	Labour during construction phase
Maintenance	3%	TDC	Plant condition and repair

Source: the indirect capital costs are based on NREL ethanol model by humbird 2011. Although in recent articles these costs are considered too high for some of the items, where costs are most dominated by simple items such as pond construction and liner. For the purpose of optimisation some of the items that have been adjusted by recent articles (frank et al 2012) are warehouse from 4% to 1%, home office construction from 20% to 10%, other costs from 10% to 5%

To derive the cost of algal oil, the return on equity rate is set at 10% interest over the period of 20 years. The plant is assumed to be financed 100% through cooperate investments. The annual capital charge is then added to the annual operating costs to arrive at the final algal oil cost. The economic model is developed to accommodate estimations of various financing schemes (see section 4.3.2.5 for detailed information). Once these estimates have been obtained, a reduction and elimination of components that contribute to the costs would be applied to arrive at the optimum cost. Then a parametric analysis of the social impact of the system is performed to identify areas that can benefit the economy in terms of job creation and earnings.

4.3.5.1 Baseline estimated cost

The capital costs and operating costs were estimated using the assumptions described above. The annual production cost for the 1000bbl/ algal oil per day is £98M. The total biomass required to achieve the desired production is estimated to be 7.31E-04ton/dw (dewatered) per day with a total land requirement of 2,925ha. Total daily production is equivalent to 158,987 L/day (52,465,817 L/year). The estimated annual charge including the return on equity rate is set at 10% interest over the period of 20 years. The plant is assumed to be financed 100% through cooperate investments. The annual capital charge is then added to the annual operating cost to arrive at the final algal oil cost. The total capital investment is estimated at £403M including indirect capital costs (estimated as percentage). The annual operating cost is estimated to be £55M. The estimated final algal oil production cost is £1.87/L. Indications are that capital cost investment is the main contributor to the algal oil costs.

Pond and liner costs are found to be the highest contributors to the capital costs with a 64% contribution. This is followed by harvesting with 11% (including settling tanks, DAF and centrifuge) and inoculation pond at 9%, the high cost of the inoculum pond is a result of the use of 40mm HDPE liner to line the bottom of the tanks. For the operating costs the larger driver of cost is the energy consumption at 48%, followed by nutrients costs at 27%, labour cost is the lowest contributor to the annual operating costs at 23%. The breakdown costs of the capital and operating costs are presented in Table 4-6 and

Table 4-6 Summary of Estimated Capital Costs @ 1000 barrel per day (158,987 L/day)

	Cost Millions/ £	**% contribution**		**£/L contribution**
Ponds	£138	39%		£2.63
Inoculum Pond	£31	9%		£0.60
Pond liner	£87	25%		£1.66
Algae settling tank	£9	3%		£0.19
Dewatering DAF	£2	1%		£0.04
Dewatering centrifuge	£19	6%		£0.37
Algae Extraction plant	£14	4%		£0.27
Anaerobic digester	£7	2%		£0.15
Water transfer system (makeup water piping)	£2	1%		£0.05
CO_2 distribution system	£11	3%		£0.23
Major Equipment subtotal		93%		£ £6.18
Construction labour	£32	10%	MEC	£0.77
Labour subtotal			9%	£0.77
Total installed capital costs (ISBL)	**£356**			**£8.42**
Site development	£3	9%	ISBL	£0.07
Warehouse	£12	4%	ISBL	£0.31
Additional piping		4.5%	ISBL	
Total Direct Costs (TDC)	**£371**			
Field expenses	£3	10%	TDC	£0.08
Home office and construction cost	£6	20%	TDC	£0.15
Proratable cost	£3	10%	TDC	£0.08
Contingency	£3	10%	TDC	£0.08
Other costs (i.e. start up, right of way, fright etc.)	£3	10%	TDC	£0.08
Total Indirect Costs	**£18**			**£0.83**
Fixed Capital Investment	**£388**			£9.25
Land cost	£15	7%		£0.56
Working capital	£0	5%	TDC	
Total Capital Investment	**£407**			

Table 4-7 Summary of Estimated Operating costs @ 1000 barrel per day (158,987 L/day)

	Cost Millions/ £	% contribution	£/L contribution
Ammonia	£1.11	2%	£0.02
DAP	£1.08	2%	£0.02
Carbon dioxide consumption	£12.76	23%	£0.24
Nutrient subtotal	£14.94	27%	£0.28
Flocculent	£0.06	0%	£0.00
Makeup Water Supply	£0.92	2%	£0.00
Growth and first dewatering	£8.36	15%	£0.16
Remaining dewatering	£4.65	8%	£0.09
Lipid extraction	£4.92	9%	£0.09
Anaerobic digestion	£2.26	4%	£0.04
Off-site CO_2 transfer into pond	£1.12	2%	£0.00
Recovered CO_2 transfer into pond	£5.28	10%	£0.00
Power subtotal	£26.58	48%	£0.35
Buildings	£0.01	0%	£0.00
Total Variable Costs	**£41.52**	75%	**£0.63**
Manager/Lab management/Aquatic biologist	£0.51	1%	£0.01
Techs, Operators	£0.77	1%	£0.01
Admin	£0.04	0%	£0.00
Overhead	£0.49	1%	£0.01
Labour Subtotal	£1.81	3%	£0.03
Salt disposal	£1.13	2%	£0.02
Maintenances	£9.72	18% of	£0.19

			TDC	
Total Fixed Costs	£12.66	23%		**£0.24**
Total Operating expenses	**£55.17**	**100%**		**£1.05**
Total revenue	**£0.00**	**0%**		**£0.00**
Total production cost	**£55.17**	**100%**		**£1.05**
Financing (avg ann debt payment)	£0.00		0%	
Equity payment -Individuals (avg ann payment)	£0.00		0%	
Equity payment -corporations (avg ann payment)	£39.69		100%	
Property Tax	£3.46		1%	
Land Lease	£0.00		0%	
Total (With Financing)	£98.97			**£1.87**
Total (Without debt, Equity, taxes, lease)	£55.17			**£0.89**
Total cost per Litre of fuel produced	£0.89			**£1.87**

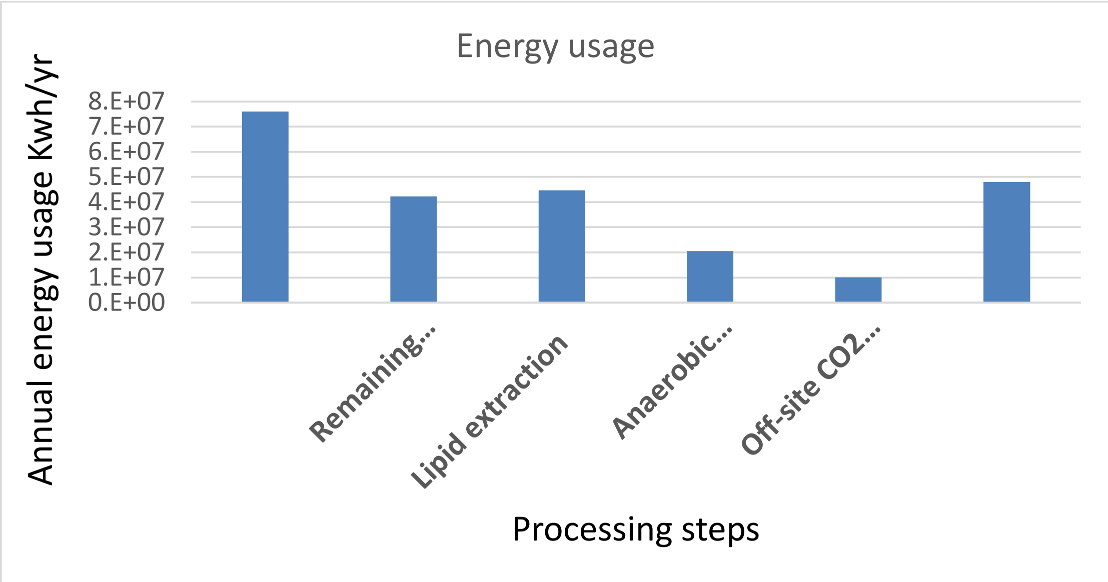

Figure 4-2 Facility energy usage

Table 4-8 facility water and energy usage

Individual Equipment's	Requirement	Units	Total requirement	Cost
				£/L 0.00008
Water consumption	4.79E-02	L/net g algae	2.41E+11	9.24E+05
			7.31E+08	£0.11 per kWh
Growth and first dewatering	3.15E-04	KWh/g algae	7.60E+07	£8,355,983.14
Remaining dewatering	1.75E-04	KWh/g algae	4.22E+07	£4,645,848.16
Lipid extraction	9.27E-04	KWh/g lipid	4.47E+07	£4,921,944.28
Anaerobic digestion	8.50E-05	KWh/g algae	2.05E+07	£2,256,554.82
Off-site CO_2 transfer into pond	4.20E-05	KWh/g algae	1.01E+07	£1,115,003.56
Recovered CO_2 transfer into pond	1.99E-04	KWh/g algae	4.80E+07	£5,282,993.05

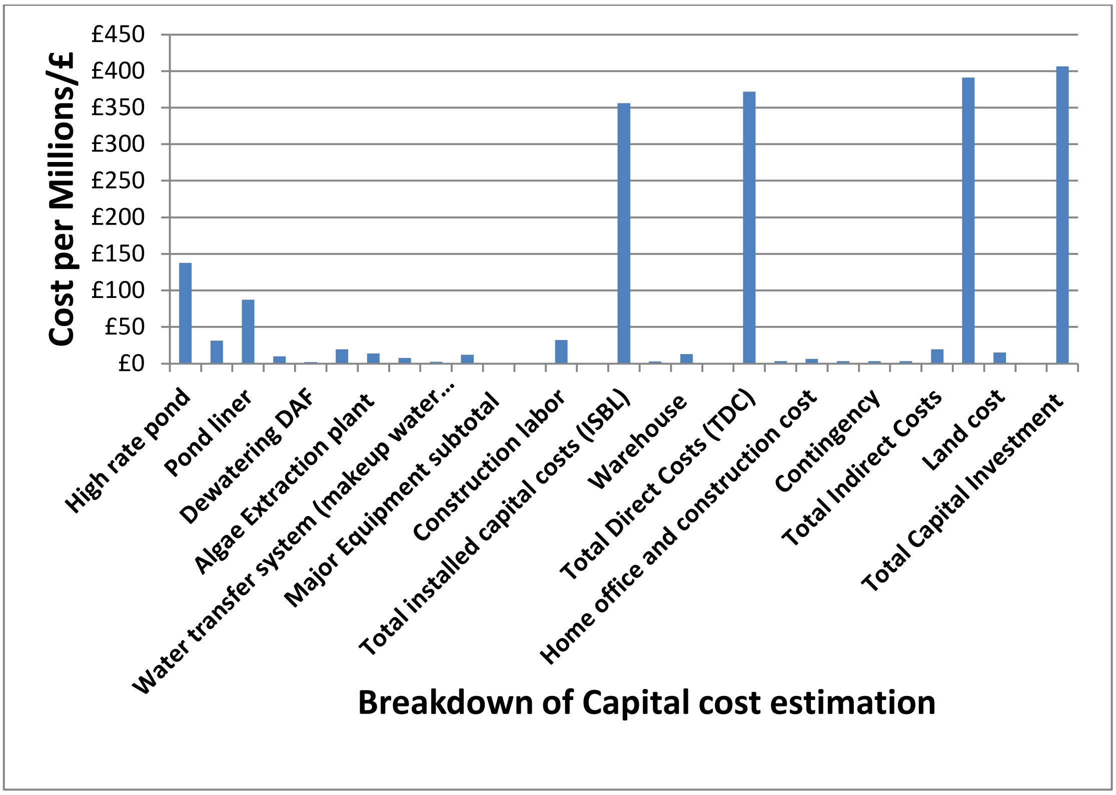

Figure 4-3 Plant capital cost

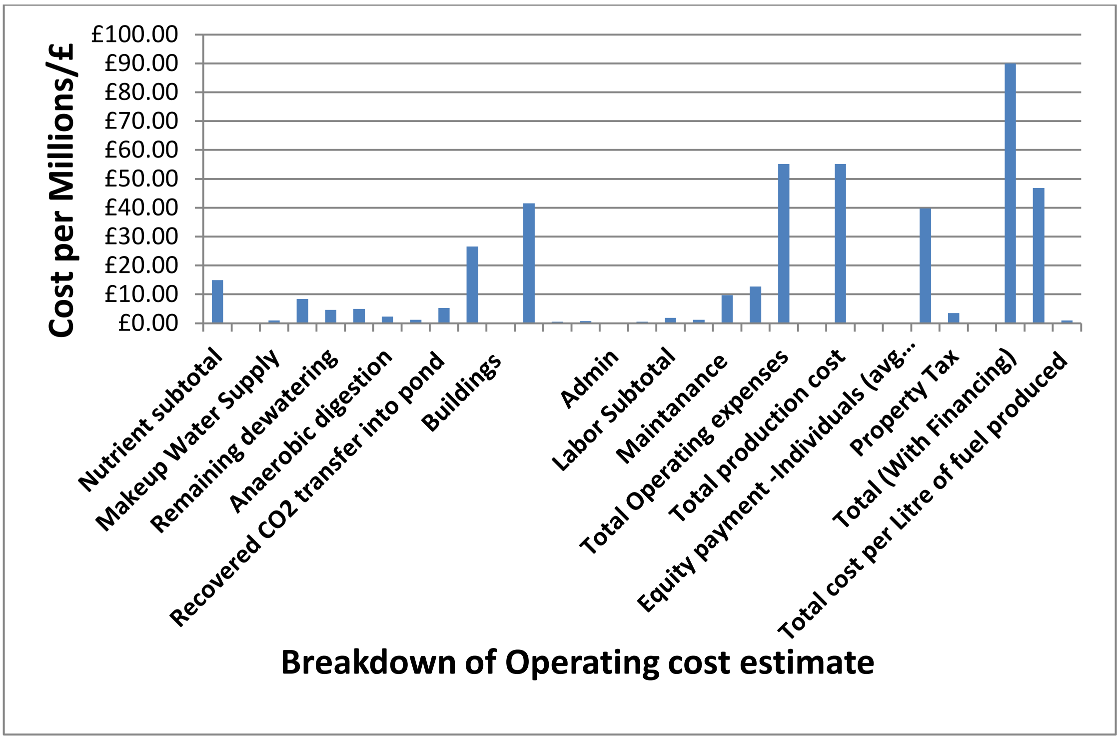

Figure 4-4 Plant operating cost

5 JOB IMPACT MODEL

5.1 Introduction

The microalgae jobs and economic impact model is designed to demonstrate the economic impact associated with developing and operating an algal oil production plant. The purpose of this model is to provide microalgae researchers, academia, and policy and decision makers with a tool that identifies the potential local economic impacts, including job creation potential associated with constructing and operating the microalgal production plant. The economic impacts are classified into direct, indirect, and induced effects regarding site labour and professional services impact, local revenue and equipment, supply chain impacts and induced impacts [40].

The model is designed in such a way that it can easily be modified to match different levels of project specific information. This section describes the use of the model, the output of the results, and technical assumptions and cost models used within the model. The model relies on the output from the cost model to develop default values.

5.1.1 Overview of the microalgal job impact model

The model can analyse a microalgae production plant using either open race pond or photobioreactor (PBR). The basic input information for the model regards the plant in the cost model, and if additional information is available, it can be added (such as region where the plant is to be located, the year of construction, and scale of production). Once the capital and operating costs have been estimated by the economic model, the number of jobs, income (wages and salary), and economic activity that a region will accrue from the project can be estimated. To analyse these impacts, input – output multipliers are used.

Input-output multipliers show the additional or direct change to the economy resulting from each change in a selected industry [80]. For example they show how construction and purchase of the microalgae plant's equipment not only benefits the equipment's manufacturers, but also the construction industry and other industries that supply inputs to those manufacturers. The benefits generated from the microalgae job and impact model expenditure depends on the extent to which those expenditures are spent locally and the structure of the local economy. Depending on the spending pattern and region specific economic structure, different levels of employment, income, and output are supported by different expenditures.

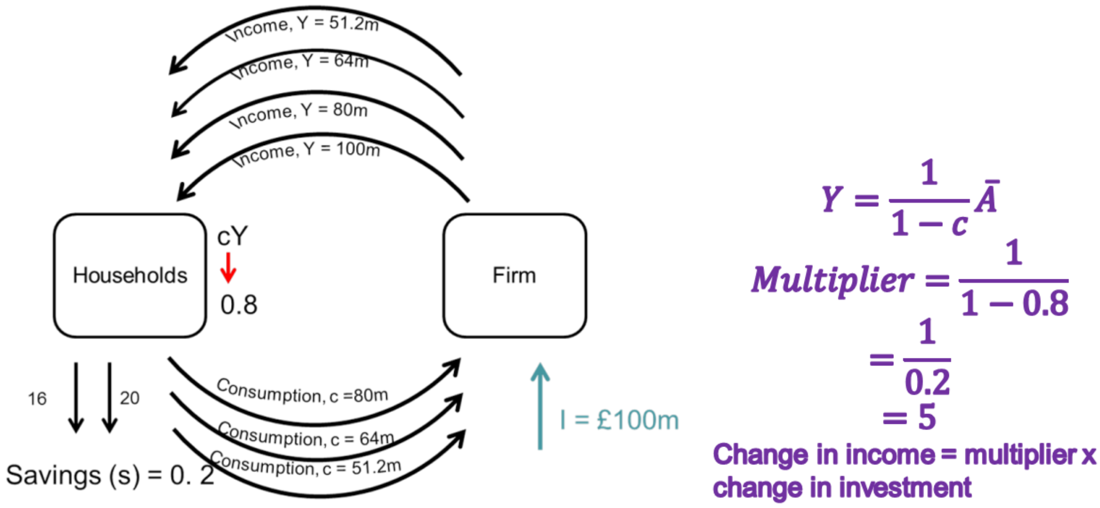

Figure 5-1 circular flow model

Example of a circular flow model regarding the effect of change in investment spending, it depicts how a change in investments changes demand, and spending

Input-output analysis can be thought of as a method to measure the impacts of a series of effects generated by an expenditure (i.e., input). To evaluate the total effect of developing a microalgae production plant, three separate impacts are examined for the expenditure, and these include: direct effect, indirect effect and induced effect. These impacts are defined in the model as follows:

- **on-site labour impacts and project development (Direct Effect):** These are the on-site or immediate effects created by expenditure. In constructing the microalgae production plant, it refers to the on-site jobs of the contractors and crews hired to construct the plant. It also refers to the jobs at the manufacturing plant that build the boilers and process equipment, among others;

- **local revenue and supply chain (Indirect Effect):** This refers to the increase in economic activity that occurs when a contractor, vendor or manufacturer receives payment for goods or services and in turn is able to pay others who support their business. For instance, this includes the banker who finances the contractor, the accountant who maintains the contractor's books, and the steel mills and electrical manufacturers and other suppliers who provide the necessary materials, among others. The indirect effect would also apply to the construction of the microalgae cultivation pond; this would include, earthwork, wall construction, etc.;

- **induced effect:** This refers to the change in wealth that occurs or is induced by the spending of those persons directly and indirectly employed by the project. The sum of the three effects yields a total effect that results from a single expenditure. To accomplish this analysis, regional specific multipliers and personal expenditure patterns are used to drive the results. The changes in expenditures brought about by investments in developing biofuels plant are matched with their appropriate multipliers for each industry sector affected by the change in expenditure.

The sum of direct, indirect, and induced impact yields the total economic effects from expenditure. These region-by-region multipliers, for employment, wage and salary income and output (economic activity) and personal expenditure pattern are derived from Scottish economic multipliers [80].

5.2 Data input and output

Evaluating the economic impacts of constructing and operating a microalgae production plants requires a large amount of data, region specific input – output multipliers and personal expenditure patterns, and price deflators. The project specific data includes a built up rate for items (costs associated with actual construction of facility, roads, etc., as well as costs for equipment and other services and fees required) annual operating and maintenance costs and data on the portion of expenditures spent locally, financing terms, and tax rates among others. More specifically, the model requires the following project inputs:

- Construction costs (labour, infrastructure)
- Equipment costs (biomass storage, centrifuges, process, etc.)
- Indirect capital costs (engineering, insurance, etc.)
- Annual operating and maintenance costs (personnel, materials and services)
- Other parameters (financial – debt and equity, taxes and lad lease)

The necessary inputs include direct, indirect multipliers for employment, earnings and output (per million dollars change in final demand) and personal consumption expenditures PCE (i.e average consumer expenditures on goods and services – calculated as a percentage for each industry – totalling 100 percent combined) for the fourteen aggregated industries [81] including:

- Aquaculture
- Mining
- Construction
- Manufacturing
- Fabricated metals

- Machinery
- Electrical equipment
- TCPU
- Wholesale trade
- Retail trade
- FIRE (Financial Insurance Real Estate)
- Miscellaneous services
- Professional services
- Government
- Plant and equipment

The model provides default values for the inputs used in the model. The values represent cost from the economic model (detailed information described in Chapter 4). The spending pattern was developed from a number of resources, including research analyses of previous microalgal models, and resources from the NREL Job Impact model.

5.3 Model output and results

The output from the model provides information on local jobs, earnings and output (economic activity) generated as a result of the project – broken out by direct, indirect and induced impacts. The results are presented in two categories; the one-time jobs, earnings and outputs created during the construction phase, and the on-going jobs, earnings, and output created during the operating phase. The outputs are presented as follows:

- construction period jobs refer to full-time equivalent jobs for the entire construction period. Operating year jobs refers to full-time equivalent jobs for a full year;

- earnings: they refer to wage and salary compensation paid to workers;
- output: this refers to economic activity or the value of production in the region or local economy;
- total cost per gallon: it does not include land easement and debt financing costs;
- local share: this refers to the percentage of expenditure spent in a particular region where the plant is in a construction period;
- percentage of total cost: due to the large variation of land easement arrangements, this calculation does not include land easement or debt financing costs;
- percentage of total costs for O&M: this calculation does not include the costs for land lease, purchase or debt financing;
- other financial costs;
- percentage financed: this is the percentage of the project construction costs that was financed through loan;
- years financed (term): is the number of years to payback the amount borrowed (initial loan amount);
- interest rate: this is the annual rate charged by the lender for example 10 =10%;
- percentage equity: this percentage is the share of project construction cost after accounting for the share from debt financing) secured through investment by individuals and/or corporate investors;
- individual investors: this refers to households that provide resources (invest) towards equity in the project, rather than direct loans for debt financing;
- corporate investor: refers to business that provides equity investment. This calculation is automatically derived from the percentage entered in individually (above) - the sum of the two equals 100 percent;
- tax parameters: the parameters for estimating local property taxes used here are generic (i.e., not specific to the region being analysed). Users should identify and input local tax rates or the actual tax amount if possible;

- wage per hour: is the average base wage only, it does not include employer payroll costs, which are automatically included in the impact analysis.

5.4 Case study – Jobs, Earnings, and Outputs

Using the baseline study presented in Chapter 4, the output from the techno-economic model is adopted to analyse the jobs impact of the process. The results from the model show that 1106 full-time equivalent (FTE) jobs are supported, generating over £115 million in earnings and over £166 million in total economic activity during project development and construction. These include a total of 753 FTE jobs from project development (679 construction labour only and 75 construction services), 289 equipment and supply chain, and 63 from induced impacts. Once the project is up and running, producing algal oil or biofuels, 45 full-time operations and maintenance jobs are created and sustained for the life of the facility, with another 152 supporting jobs through supply chain and induced impacts, for a total of 197 full-time jobs associated with O&M operations.

Table 5-1Output using the baseline inputs

Local Economic Impacts - Summary Results			
		Earnings	Output
	Jobs	(Millions)	(Millions)
During construction period			
Direct Impacts	753	£88.87	£104
Onsite Construction Only (labour)	679	£84.57	£95
Other Onsite Construction Related Services			
(Engn. and Prof. Services)	75	£4.31	£9
Indirect Impacts	289	£17.51	£36
Induced Impacts	63	£8.31	£26
Total Impacts (Direct, Indirect, Induced)	1106	£106.66	£157
	1106	£114.69	£166
During operating years (annual)			
Direct Impacts	45	£19	£59
Onsite Plant Labour Only	45	£19	£59
Indirect Impacts	132	£251	£303
Induced Impacts	20	£8.31	£83.20
Total Impacts (Direct, Indirect, Induced)	197	£278.3	£445.92
	197	£278.3	£445.92

Table 5-1 shows an example of how the results are presented in the model.

A parametric analysis of these results is presented in Chapter 7 to determine the effect of change productivity rate.

6 MODELS VERIFICATION AND VALIDATION: COMPARATIVE ANALYSIS

6.1 Introduction

This section is set to perform a comparative analysis using the final algal oil production costs from the base case model and compare it with various algal costs reported in the literature, to determine how close the model output values are when compared to similar analyses in literature. The economic and social model is designed using a facility process adopted in the Argonne National Laboratory ANL report (Frank. E et al. 2011) [25]: this process is used as the base-case in this analysis. The base-case is used to validate the economic model, although the base-case from the ANL report was limited to analysis on the life-cycle analysis, excluding the economic aspect. However, there is a collaboration between NREL and ANL on reports that have adopted a similar process and incorporated a techno-economic model. This similar analysis will be used for comparison and verification. The different outputs are then used to calculate the outputs for the social model. It is important to mention that the selected articles are not intended to represent the best or the optimum approach in verification/validation, but represent the most suitable comparative analysis possible. Given that no such large-scale process exists and a number of the process steps have not even been demonstrated on a relevant scale, the results here carry a degree of uncertainty in both the capital and operating costing method. However, both the assumptions and values used correspond well to the parameter range presented in most of the literatures.

With regard to the job impact model, no data has been found in the literature that can be used to validate that section of the model. The only available model on job impact is the JEDI model developed for cellulosic ethanol, for which only the conversion of biomass to fuel is similar to algal production process. The ethanol model would be run as a means of verification.

Since large scale algae production facility is still in a preliminary stage, and the model developed needs validation against experimental data from an existing plant. unfortunately there is no specific model for microalga production that includes the social impact either separately as techno-economic analysis that takes into account social assessment linked to together to a model that assess the social impact. A parametric analysis is carried out in chapter 7 with two main purposes. To design experiment to acquired data. To develop such experiment, a rough estimate of the production processes that have the most influence on the economics of algae production facility and affect the social impacts needs to be analysed. By doing a parametric analysis, a propose optimization configuration can be calculated to determine the best trade off value of each parameter.

6.2 Baseline study – Technical Model

The baseline study refers to microalgae grown in an open pond (OP) cultivation system. The two key parameters for growth are productivity rate and lipid fractions, units for the productivity rate are given in $g/m^2/d$ rather than g/L/d. The lipid fraction is expressed as weight percentage (wt%), the dry weight fraction of the algae mass from lipids. In general they depend on the type of species and cultivation system. The baseline model here follows the input from ANL, which employs $25g/m^2/d$ and 25wt%, growing for 365 days. The major nutrients that are fed into the growth media to improve productivity are CO_2, Nitrogen, and Phosphorous, and they are assumed to be consumed stoichiometrically based on an elemental composition of carbon : nitrogen : phosphorus (C:N:P) of 103 : 10 : 1. Pure CO_2 is sourced from the flue gas power plant and transferred through a 1.5m sump pipe and delivered to the site: the gross CO_2 requirement is 2.24g/g algal biomass. Ammonia and DAP are used as the source of Nitrogen and Phosphorus, gross nutrient demand per dry gram of algae was 55.5mg N and 12. mg P. In the raceway ponds, paddlewheels are used to ensure constant mixing of the algae. Paddle wheel circulation power is driven by electricity [22] and it scales with the cube of the mixing velocity, which is typically between 20 and 30cm/s. In the baseline model an average of 25cm/s is assumed. Pumping power, in principle, can be computed from the pumping velocity, pipeline characteristics (including length), pump efficiency, and elevation changes (see Chapter 3 for detailed explanation of the whole concept of growing microalgae).

The grown microalgae are harvested through several stages; the first stage is the primary harvesting (P-Hvst) through settling. The settling and growth process accounts for most the water used throughout the entire process, as water movement occurs when the ponds are mixed to keep algae in suspension, and when the algae culture is moved to settling tanks, when the supernatant is returned from the settling tanks back to the growth ponds, and when the water is lost to evaporation. The baseline study assumes a pan evaporation of 0.3in/d.

Secondary harvesting is done by dissolved air flotation (DAF). Energy numbers for DAF are (1.33 × 10-4 kWh/dry-g and 1.48 × 1 0-4 kWh/dry-g), next are the centrifuges, the baseline uses 95% algae retention and 3.3 × 10–3kWh/g-algae of electricity for centrifugation, and cellular disruption by high-pressure homogenisation, followed by a wet extraction process. Remnants, including lost solvent and unrecovered lipids, are sent to an anaerobic digestion (AD) facility for energy and nutrient recycling. Energy recycling was accomplished by biogas combustion in a combined heat and power (CHP) system that was heat-integrated with the solvent recycle loop. Waste heat was sent to a steam turbine combined cycle to raise additional power. Extracted lipids were converted to biodiesel by transesterification. AD solids (digestates) were disposed as waste. Brackish makeup water replaced losses to evaporation and blowdown (see Chapter 3). In this analysis we focus on algal oil as the final product. Although the technology for conversion to algal oil to biodiesel (fatty acid methyl esters or FAMEs) is mature and conversion costs and yields are well modelled, biodiesel is not the only fuel product that can be made from algal oil. Progress is being made in the conversion of algal lipids to hydrocarbons through the standard refinery processes of hydro-treating, catalytic cracking, and reforming, to allow algal oil conversion to a more conventional, renewable-based fuel such as diesel or jet fuel [38]. Because these algal oil-based processes are not as well established as the conversion to biodiesel, but are however of great interest to a growing number of end users, this analysis determined that the models should focus on the production cost of algal oil, the feedstock common to all fuel producers. Furthermore, the algal oil production costs will represent the dominant cost of the final fuel product, regardless of the conversion process used [79].

6.2.1 Comparative analysis

For the comparative analysis, the first three articles analysed [79] are based on the same facility design as the baseline study and analysed using the economic model. The process parameters used in this model are similar to the baseline; therefore it is considered a suitable source of data for validation.

6.2.2 Comparative analysis with harmonization study

The first case study refers to a current report from NREL [79], which defines a baseline algal biofuel production scenario with model-based quantitative metrics for cost, scale-up potential, and sustainability. The model harmonises three DOE modelling efforts in TEA, LCA, and RA around consistent, well understood with reasonable assumptions that are publically available. The process parameter is similar to the baseline model, but with differences in some process consideration: Table 6-1 shows the parameters for both the baseline and harmonisation model. The model is based on 10 million gallons of algal oil per year (MGY) scale. The pond design and cost [$34,000/hectare (ha) in 2009 USD], were based on analysis presented in Lundquist et al. 2011, namely, unlined ponds, sized at 4 ha/pond and paddle-wheel mixing stations, consuming an average of 2.0 kilowatts per hectare (kW/ha) (Lundquist 2011). As mentioned previously, the facility design is the same as the baseline.

Table 6-1 Design parameters

Assumption	Units	Harmonization	Baseline Economic model
Cultivation			
Algae productivity	$g/m^2/d$	13.2	25
Lipid content	%	25	25
Scale of production(open pond size)	ha	4050, 4850	4712
Liners for ponds?	Miles or feet's	No plastic liners	Plastic liners
Days of operation	days	330	365
C:N:P molar ratio	C:N:P	106:15:01	103:10:01
Gross nitrogen as N,	g/dry-g algae	0.087	N/A
Gross phosphorous as P,	g/dry-g algae	0.013	N/A
N nutrient	N (NH3)	Ammonia	Ammonia
P nutrient	P	DAP	DAP
CO_2 source	Captured	CO_2	Flue gas
Blow down	% of recycle rate	5	0
Water on-site pumping circulation power demand	ft head	20	38
Evaporation loss	cm/d	0.3	0.3
Harvesting			
Dewatered algal biomass concentration	g/L	200	200
Harvesting	%	90	85
Extraction			
Solvent system	Type	Butanol	Hexane
Extraction efficiency	%	85.5	85
Spent Biomass usage			
Fate of spent biomass		AD	AD

Electricity efficiency of gas turbine	% (LHV)	33.7	33

After incorporating the inputs presented in Table 6-1, the results shows algal oil production cost of £2.51/L, which corresponds closely to the $16.69/gal ($4.40/L which translates to £2.60/L) of algal oil published in the original report. This shows that the model is most likely to produce an accurate result, compared to other models already published.

Table 6-2 Breakdown of capital cost from NREL Harmonization study

	Capital cost Millions £		£/L contribution		% contribution	
	harmonization	baseline	harmonization	baseline	harmonization	baseline
Ponds	82	126	£0.54	£0.78	24%	33%
Liners	121	124	£0.80	£0.76	35%	32%
CO_2 delivery	23	24	£0.15	£0.15	7%	6%
Water delivery	2	1	£0.02	£0.01	1%	0%
Harvesting	31	35	£0.21	£0.22	9%	9%
Extraction	11	10	£0.07	£0.06	3%	3%
Digestion	8	10	£0.05	£0.06	2%	3%
Power generation	4		£0.02	£0.00	1%	0%
Inoculum system	30	31	£0.19	£0.19	9%	8%
Hydrotreating	**4**		**£0.02**	**£0.00**	**1%**	**0%**
Pumps	**8**		**£0.05**	**£0.00**	**2%**	**0%**
Land cost	21	21	£0.14	£0.13	6%	6%
Total	345	382	£2.28	£2.36	100%	100%

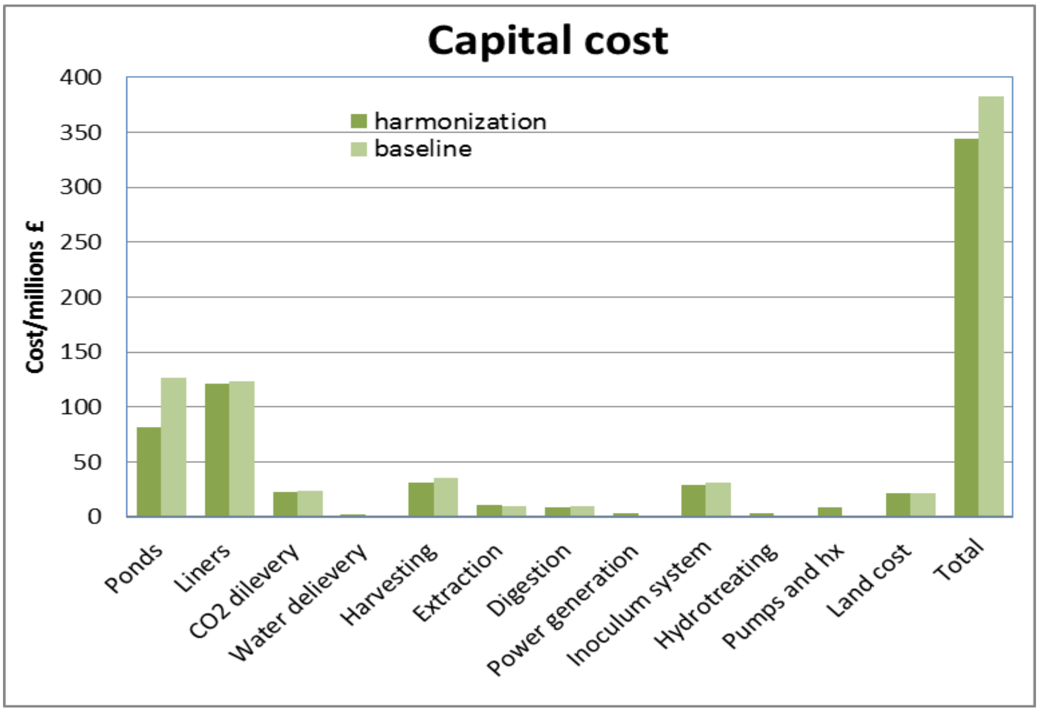

Figure 6-1 Breakdown of capital cost from NREL Harmonization study compared with the baseline study

Table 6-2 and Table 6-3 show the breakdown of cost contribution of each component to the final algal oil production cost. Both cases show the major contributor to the capital cost is the pond liner used in pond construction. The difference between the two cases is the approach used for economic estimation. For the baseline it includes construction labour, and other costs that cover indirect construction costs. For the operating costs, the cost components between the cases differ widely. For the harmonisation study the highest cost contributor is the maintenance, insurance, and taxes, while the baseline study does not include taxes in its cost breakdown. However the study breakdowns' are quite similar with minor differences, mainly due to the method used for estimation.

Pond cost for the harmonisation study $34,000/ha based on analysis from Lundquist (Lundquist et al. 2011), while the pond calculation in the baseline model is based on a detailed breakdown of material required for construction, therefore making it difficult to compare the cost from this perspective. The costs closest to each other are liner and land costs, with liner costs estimated at a rate of $0.47/ft, and land costs estimated at $30,000/acre for both studies.

Table 6-3 Breakdown of operating cost from NREL Harmonization study compared with the baseline study

	Operating cost Millions £		£/L contribution		% contribution	
	harmonization	baseline	harmonization	baseline	harmonization	baseline
Nutrients	£2.83	£5.96	£0.02	£0.03	9%	19%
Power	£3.25	£4.77	£0.02	£0.02	10%	15%
Flocculant	**£4.90**	**£5.96**	**£0.03**	**£0.03**	**15%**	**19%**
Solvent	£1.12	£0.40	£0.01	£0.00	3%	1%
Hydrogen	£0.89		£0.01	£0.00	3%	0%
Waste disposal	£0.00	£0.00	£0.00	£0.00	0%	0%
Utilities	£0.47	£0.01	£0.00	£0.00	1%	0%
Labor & Ovhd	**£5.84**	**£2.10**	**£0.04**	**£0.01**	**18%**	**7%**
Maint, Tax, Ins.	£13.63	£15.80	£0.09	£0.08	41%	49%
	£32.92	£32.02	£0.22	£0.15	100%	100%

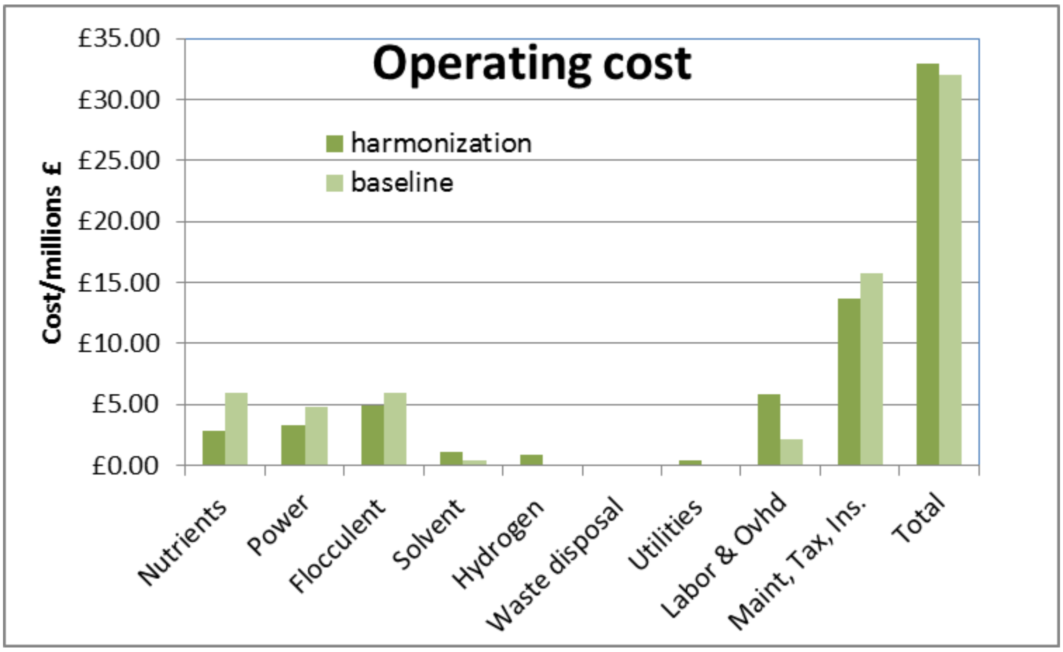

Figure 6-2 Breakdown of operating cost from NREL Harmonization study compared with the baseline study

Table 6-3 shows the cost contribution of each major unit step. Labour and overhead costs are the components that show the major differences between the two studies. Labour cost calculation for the baseline study is based on 2080hrs/yr (52 weeks x 40hrs) at a wage/hr cost of £34.86 for management, £12.02 for technicians and operators, and £9.69 for admin. Overhead costs were estimated as the sum of labour operatives multiplied by the total percentage of benefits (Health, Insurance, Government share). Associated costing and financial assumptions can be found in section 4.3.2.1, and Weissmann [72] . For the comparative analysis, labour costs are not broken down into detail but rather are presented as a lump sum, therefore making it impossible to compare each unit to the other. Maintenance cost is calculated at 3% of the total equipment costs. The unit costs for nutrients for both studies are set at $442/ton (£260) DAP, $407/ton (£240) Ammonia and $40/ton (£23) for CO_2. This analysis was not able to estimate the total nutrient requirement to perform the comparative analysis.

This analysis shows total operating cost components for both the baseline and comparative analysis to be consistent with each other. Even so the cost per litre is different for the two scenarios, because the capital cost of the baseline model contributes 94% to the algal oil product cost and the operating cost contributes only 6.5%, while for the harmonisation model capital costs contributes 91% and operating cost 9%. There are minor variations among the assumptions for both models, which the comparative model did not account for, which makes comparing cost information more effective than the elements of the capital costs. The assessment provides an indication that the baseline model can produce the same or nearest output, when a defined process is established.

6.2.3 Comparative analysis with baseline study

The second case-study is an analysis of the comparative costs of algal oil production for biofuel by [11]. In this article, the author adopted previous models for algal costs analysis, in order to capture information from the previous model that can be used to describe recent progress. Four models are selected (Sandia, NREL, NMSU and Seambiotic) and a common framework, consisting of uniform metrics and assumptions is applied by a subset of the original models [79]. The list of assumptions (see Table 6-4) used are applied uniformly to all the original sources to eliminate variability. The open pond system is used, the target oil produced is algal oil, and the financial terms include plant life, depreciation period, and rate of return.

Table 6-4 Parameters for comparison analysis

Assumptions	Unit	Value
Oil content	%	25%
Productivity	g/m^2/day	20
Pond cell density	g/L	0.7
% return	%	10
Operating factor	days/year	330
Plant life	years	15
Depreciation	years	10
Electricity cost	USD/kWh	0.08
Natural gas cost	USD/MM Btu	8
Price Index	year	2008
GDP deflator	year	2008
Tax rate	%	35%
TAG end use	/	Transportation fuel

Table 6-5 lists the costs summary from the NREL, Sandia, NMSU, Seambiotic and the present model based on the new assumptions described in Table 6-4. It shows the cost per gallon obtained from the original article and cost obtained from the economic model. Depending on the scenario posed by each source, each cost's sub category may or may not be further broken down into greater detail.

Table 6-5 Costs result before and after harmonization from comparative case study

	NREL	SNL	NMSU	Seambiotic	
		Case study			Economic model (Present model)
USD gal-1	$10.87	$11.10	$13.32	$11.02	
After £/L	£1.69	£1.73	£2.08	£1.72	£1.78

Based on the results, there is a wide range of diversity between the original results and the economic model. The main reason for this is that other than the parameters described in Table 6-5, the NREL, SNL, NMSU, and Seambiotic cases all have different target production scales, water and power management strategies, and co-products. These are the attributes that reflect the diversity in the final production costs. The models discussed did not include capital costs or list the geometric of the facilities adopted. It is therefore difficult to make critical elemental comparisons for all the cases when so many assumptions varied in comparison to the economic model. Nevertheless, the assessment provides an indication of what needs to be addressed to end the lack of agreement regarding diversified microalgae production costs. Although the variation has reduced across recent published articles, it is important to achieve a more uniform model to assess algal oil production costs in order to achieve commercial scale production (an explanation for the diversified microalgae production cost is described in Chapter 2).

6.2.4 Techno-economic analysis model (TEA) with baseline study

The third comparative analysis is the model for techno-economic analysis for autotrophic microalgae for fuel production published by Rayan Davis in 2011 [38]. Although the author evaluates the economics of both the open pond and PBR options, this analysis is only focussed on open pond systems, and has only considered the open pond analysis. The article assumes a target scale of 10 M gal/yr of raw oil, with the facility receiving adequate solar radiation to achieve the respective production target, operating 330 days/yr. The facility is located in south west US, an area that can sustain 85-90% operating factor. The growth systems are assumed to achieve a steady state algae cell density of 0.5 g/L. Pure CO_2 concentrate is transferred through a 1.5 meter deep sumps and delivered to the facility from a nearby flue gas power plant at the rate of $40/metric ton, the ponds are unlined and mixed using paddle wheels. Water evaporation is assumed at a rate of 0.3 cm/day. Nutrient demand for algal growth is met, using Ammonia as a source for Nitrogen and Diammonium Phosphate (DAP) as the source for Phosphate. Algal elemental composition used is $C_{106}H_{181}O_{45}N_{15}P$. The grown microalgae are harvested through several stages, first in a settling tank that concentrates the algae at 10g/L (1%) through auto-flocculation, it then flocculates with chitosan, and collection is made by dissolved air flotation (DAF) which thickens the material to 100 g/L (10%). The slurry is further concentrated to 200 g/L (20%), using a centrifuge. Extraction is accomplished by a combination of a mechanical method using high pressure homogenisers, followed by solvent extraction with butanol, achieving 90% extraction efficiency. Spent biomass plus water is sent to anaerobic digestion to produce biogas for power production.

The operative cost assumptions for fixed operating cost are for labour at 50 operators per pond, overheads at 60% of labour, maintenance 2% of installed equipment’s cost, insurance and taxes 1.5% of total installed cost, contingency 30% , working capital 25% of operating costs, IRR 10%, plant life time 20 years, tax rate 35%, and 7 years depreciation schedule. Table 6-6 shows the summary of the process, resources requirement and economic output presented in the techno-economic analysis.

Table 6-6 Output of resources and economic of the techno-economic study

Assumptions	**Unit**	**Value**
Lipid Production	M gal/yr	10
Pond area	Acre	4820
Total facility area	Acre	7190
Net water demand	M gal/yr	10,000
CO_2 Demand	ton/yr	145000
Ammonia for growth	ton/yr	5100
DAP for growth	ton/yr	4800
Power coproduce	M kw h/yr	80
Naptha coproduce	gal/yr	340000
Total capital cost	$/M	390
Net Operating costs	$M/yr	37
Total coproduce credit	$M/yr	6

Table 6-7 Breakdown Capital costs TEA with Baseline model

	TEA model	Baseline model
Ponds	£18	£110
CO_2 delivery system	£7	£12
Harvesting	£24	£26
Extraction	£9	£14
Digestion	£14	£8
Inoculum pond	£14	£31
Hydrotreating	£5	N/A
OSBL equipment	£12	N/A
Land cost	£13	£6
Total equipment cost	£117	£207

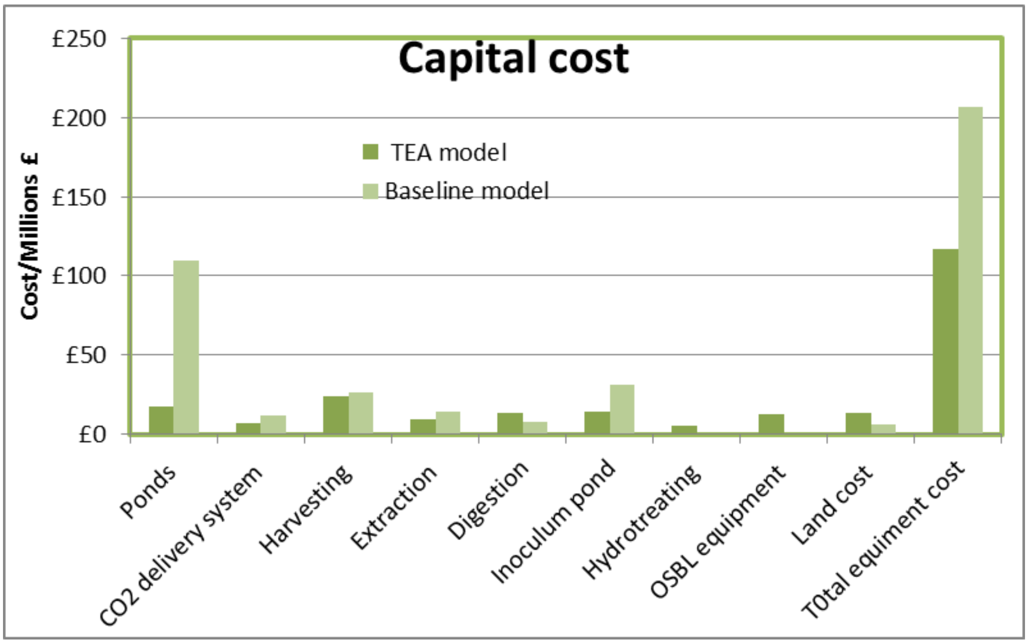

Figure 6-3 Breakdown Capital costs TEA with Baseline model

For consistency with the baseline study all inputs are converted into British pounds. The resulting production cost for the algal oil for the techno-economic analysis was reported at \$8.52/gal translated to £1.33/L. After incorporating all the inputs to the economic model, the algal oil production cost was found to be £1.61/L. The calculation of the operating cost was much easier to estimate compared to the capital cost. The annual operating cost obtained from the baseline model is £19.72M/yr this value is near to the original cost of £21.83 M/yr (\$37M/yr). The equipment cost for the baseline model is estimated at £207 M, which is about 40% more than the TEA cost of £117 M (\$195 M). The cost of the TEA scenario is evaluated on a unit level basis, making the cost smaller when compared to the baseline economic model.

6.2.5 Summary

As mentioned previously all the comparative scenarios are selected on the basis that all the articles adopted the same facility design. Capital costs of all cases are expected to fall within the same range. The first and second article, including the baseline model, present similar capital costs. The TEA scenario, presents a very low capital costs, the major variation found for this study comes from the equipment costs, the scenario considers very low equipment costs compared to the cost calculated in the baseline model and the two previous studies. The study estimated pond cost at $30 million for a 1950 hectares of pond area (4820 acres) translating to $15,385 per hectare, this value is very low compared to the standard $34000 per hectare commonly used in several studies[22][78][25]. This low figures suggest that the TEA scenario does not represent a realistic capital costs.

6.3 Comparative analysis for Job Impact model

The job impact model analysis is estimated using the final output of capital and annual operating costs obtained from the economic model. It estimates the number of jobs, income (wages and salary), and economic activity that a region will accrue from the project using input –output multipliers (see Chapter 5). No available data has been found to validate this model, as it solely depends on the input–output multipliers. The only literature available regarding job impact is the JEDI model developed for cellulosic ethanol, and only the conversion step of biomass to fuel is similar to the algal production process. An attempt to use this model for comparisons was not possible, although the baseline model could incorporate the capital and operating costs of the cellulosic model, the region multipliers were not available to carry out the comparisons. The input-output multiplier values are not clear from the cellulosic model, therefore the only possible analysis carried out for the job impact analysis is a sensitivity analysis. A comprehensive parametric analysis examining each parameter of the model is presented in section 7.4.

7 PARAMETRIC ANALYSIS

7.1 Introduction

A detailed list of design parameters and cost estimates are presented in the socio-techno-economic model (Chapter 4), on which to base an economic analysis of an algal oil production facility. In this chapter a parametric analysis is carried out using two different methods to determine the viability of an algal oil production facility.

This parametric analysis has also been carried out to compensate the uncertainty of the data availability in the literature and the lack of commercial-scale facility figures. Furthermore, at this preliminary stage it is more important to understand how much a change in the input can change the output values (in particular the final algal oil cost), rather than obtaining an exact value.

Taking the economic costs and the operating parameters from the economic model, some key parameters are changed across a range of values, and their influence on the final cost of algal oil and job impact are analysed. Each of the parameters are analysed across a range of growth rates from 5g/m^2/d to 75g/m^2/d. The implications of these changes when applied cumulatively will then be examined.

The microalgae production facility is still at a preliminary stage, while the socio-techno-economic model has been developed based on a large scale microalgae production facility. There are a number of uncertainties resulting from the lack of sufficient data regarding microalgae productivity, processing units, operating parameters and jobs that can be used to validate the model. Therefore the purpose of this parametric analysis is to firstly develop some analytical data to estimate the parameters that have the most influence on both the algal oil production costs and job impact results and secondly, to perform a parametric analysis that can be used to determine an acceptable price of algal oil when compared to the current price of petroleum fuel, and assess jobs created by the facility.

The parametric analyses are carried out separately for the economic and social impact models: the influence of the change for the economics of the algal oil cost is analysed in the first part of this chapter, and the influence of some changes to the job impact in the second part.

7.2 Baseline – socio-techno-economic model

This parametric analysis takes the baseline model assessments as input data for the analysis below. The system configuration and process parameters used are illustrated in Table 7-1.

As illustrated in Chapter 4 and Chapter 5, the approach of this study includes capital cost estimation, operating cost estimation, and social impact assessment. The socio-techno-economic mode is comprised of:

- the economic model, which accounts for all the facility and materials for the construction of and operating the microalgae facility,
- the social impact model, which estimates the jobs, earnings and outputs generated for the specific region.

Table 7-1 System configuration and process parameters for the baseline model (socio – economic model)

	Value	Design
Process configuration		
Productivity $g/m^2/d$	25	Davis 2011 [38]
Lipid content % wt	25	Davis 2011 [38]
Water demand	0.442	Evaporation loss 0.225 in/d
Net N demand g/g algae	0.019	Mass balance from GREET
Net P demand g/g algae	0.017	Mass balance from GREET
Energy to pump water to site & into culture, kWh/L	1.23E-04	30m head, 67% total pump/motor efficiency
Energy to pump culture kWh/L	2.50E-05	15 feet head, 67% total pump/motor efficiency
CO_2 total supply rate, g/g algae	2.02E+00	
DAF energy demand, kWh	1.33E-04	Harris et al 1982
Centrifuge energy demand, kWh/g-dw	1.930E-05	Disc stack. Leung 1998
Pressure Homogenization, kWh/ g algae	1.83E-04	Harris et al 1982
Hexane Extraction Net heat required, KWh/g-oil produced	1.38E-03	Computed from the assumption of 50 wt% carbon in the algae and mol wt of CO_2
System configuration		
Facility footprint	2925 ha	Calculated based on 4 ha pond
Pond and liner construction	4 ha	Single Pond design 690 x $60m^2$, liner Thickness (40 mm)
Settling Tank design	13 tanks	Over the ground tank (concrete WWTP Capdet Design)
Extraction	N/A	Stainless steel
Water transfer system (makeup water piping)		PVC and steel pipes
CO_2 distribution system		
Social Impact model		
During construction period	N/A	Jobs, earnings, and output
During operating year (annually)	N/A	Jobs, earnings, and output

For the process configuration, only the productivity rate, nutrients (ammonia and phosphorus) are varied. Productivity rate and lipid content have great influence on several of the process parameters, as operating resources required would depend on the rate and quantity of production. For Nutrients requirements, it will depend on many factors, such as, sources, accessibility of resources close to the algae farm, and the quantity required for growth. .

The system configuration shows high cost for the cultivation ponds. There are many areas in which a detailed system configuration would probably allow some cost reductions in the construction of the system, for e.g large scale nature of the construction activity can reduce the cost of earthwork. Paddlewheel cost can also be reduced due to the fact that more than 100 of them would be installed –installation costs may be lower than expected, due to the repetitive nature of the installation. In some cases cheaper materials may be used.

The social impact model is analysed separately in section 7.6.

7.3 Influence of each parameter on the algal oil costs

In this section, the effect of the chosen parameters on the costs of algal oil is analysed. Each parameter is varied across range of values, and they are presented as a percentage of the comparison value. The comparison value is indicated as 100%, which is the base case value used in the economic model, therefore 50% indicates half and 200% double of the base case value.

7.3.1 Parameters analysed

The set of parameters that are examined are listed in Table 7-2 below.

Table 7-2 Parameters varied

Parameter	Baseline value	Values analysed	
Productivity rate	25 $g/m^2/d$	50, 100, 200%	12.5, 25, 50 g/m2/d
Lipid content	25 wt %	50, 100, 200%	12.5, 25, 50 wt%
Harvesting	£3 M /ha	50, 100, 200%	1.5, 3, 6 £/M/ha
Pond and Liners cost	0.026£/m^2	0, 70, 100, 200%	0.018, 0.026, 0.052£/m^2
Facility footprint	2925 ha	50, 100, 200%	1463, 2925, 5850 ha
Ammonia	240 £/ton	50, 100, 200%	120, 240, 480 £/ton
DAP	260 £/ton	50, 100, 200%	130, 260, 520 £/ton

It should be noted that the parameters are examined independently. Microalgae oil production is not a commercial mature technology, therefore it is difficult to choose a representative set of parameter ranges. Nonetheless, each parameter is varied based on assumptions and values that has been presented in literature, and this range is discussed.

7.3.1.1 Productivity rate and lipid content

Productivity is the specific rate of biomass growth of the culture. In open ponds, light attenuation in the culture causes growth to quench rapidly with depth, and therefore the productivity for ponds is expressed per unit area in $g/m^2/d$. The lipid fraction, expressed as weight percentage (wt. %), is the dry-weight fraction of the lipids with respect to the total algal mass.

The assumptions about productivity rate and lipid content can easily be made, but very difficult to justify. Although the lipid content in microalgae can reach up to 75% by weight of dry biomass, most common algae have oil levels between 20 and 50% [29]. Based on current literature and existing plants, there is not any credible evidence that productivity much higher than 20 $g/m^2/day$ [82]can be achieved. A recent benchmark has been set at the Algal Biomass Summit in 2011 for 3706 – 4942 gallons per hectare per year for a combination of productivity and lipid content, which roughly translates to a lipid content of 25% of an algal productivity value of 20 g/m^2/day, or 32% at 15 g/m^2/day (by Jose Olivares of the NAABB). This corresponds closely to a comprehensive survey on growth performance in outdoor ponds published by Griffiths 2009 [83], which projects roughly 2300 gal/acre/year at an average 26% lipid content, and to a thorough analysis, stipulating 2000 gal/acre/year at 25% lipid content, projected to be plausible in the near term [22]. However, it is not possible to overlook the potential for improved productivity on a large scale microalgae cultures; this analysis therefore examines the increase and decrease of productivity and lipid content and how much it affects the algal oil cost.

This analysis explores the impact on the 1000 bbl/day scale doubling and reducing productivity from the baseline scenario (25 g/m^2/d). The scale of productivity is set as a constant, therefore an increase in productivity, and/or an increase in lipid content would not change the quantity of the total algal oil produced.

Doubling productivity to 200% (50 g/m^2/d) reduced growth surface area by 50%, since the area required to produce the desired algal biomass of 7.31E-04t (dried weight) per day decreases from 2,925 ha to 1,463 ha. Water usage is also reduced by half from 4.79E-01 to 2.84E-01 L/g of algae, these value compared with other microalgae feedstock’s represented in Table 7-3 shows to be very competitive with other biofuel feedstock’s. And overall water per unit of algal oil usage in the system is reduced by 41%.

Reducing productivity by half (50%, or 25g/m^2/d) increases the required growth surface by 100%. Water usage increases by 50% from the baseline. The change in land growth surface area means possible cost reduction in land cost can be achieve.

Although the cost production are greatly affected by the quantity of lipid produced, the extraction efficiency of lipid of an algae strain change the quantity of the lipid content. These efficiency impacts the quantity of algae biomass produced, but in these case where the algal oil produce is set constant at 1000 bbl/day, it does not have effect on the construction costs. However, the processing cost is expecting change.

Table 7-3 Comparison of microalgae water footprint with other feedstock [84]

Feedstock’s	L water/g biodiesel	Ref
Maize	4.015	[85][86]
Potatoes	3.748	[85][86]
Sugar cane	3.931	[85][86]
Sugar beet	2.168	[85][86]
Sorghum	15.331	[85][86]
Soybean	13.676	[85][86]
Switch grass	2.189	[85][86]
Corn	0.263 - 0.956	[86][21]
Microalgae	0.280 – 0. 400	[87][6]
Microalgae	0.399	[84]
Microalgae	0.472	Baseline study

Figure 7-1 illustrates the influence of the change in lipid content on the algal oil production cost. Doubling the algal lipid content to 200% (50 % wt) decreases biomass required from 7.31E+08 g dw algae/d to 3.66E+08 g dw algae/d resulting in algal oil cost per litre to reduce by 29%. Reducing the lipid content by half 50% (to 15 % wt) increases the biomass required to 1.22E+09, increasing algal oil costs from the baseline cost by 36%.

Figure 7-2 Shows that cost is strongly and non-linearly dependent on productivity rate and lipid content, and changes rapidly at lower values of both. Therefore even small changes in the non-linear region can make significant changes to the overall results. The effects of the non-linear region are more pronounced below a growth rate of 35 g/m^2/day and below a lipid content of 35% wt, this is also the region of values where the present facility operates (25 g/m^2/d and 25% lipid content), therefore it is particularly important to take into consideration this non-linear behaviour. It should be noted this is not an absolute result, as the final algal oil cost depends upon other details of the process, this will be discussed later in this chapter.

The non-linear region shows that cost are strongly dependant on scale of productivity, and since production scale is define by productivity and lipid content, therefore, any change in this two parameters would change the behaviour of the basis value. At low productivity and lipid fractions, the capital costs are affected by low production volume and poor outputs. While at higher productivity and lipid fraction the values that approach asymptote reflects the values that are determined by scale of production. Poor outputs and low scale can be as a result of many factors, the technology used in the production process can limit the out of yield so also, the type of algal strain can be a limiting factor. So the only way to improve cost is to consider either changing the underlying technology or the biological process adopted.

7.3.1.2 Harvesting

Current costs of harvesting technologies are mainly derived from wastewater technologies. Standard wastewater operations are not cost effective when used for algal oil production. Even if there are a number of novel technologies currently being developed for these operations, unfortunately the access to process and cost data for such technologies are limited. However it is still useful to consider generic cost assumptions to understand the influence of the cost of harvesting on the overall economic of the algal oil production costs. The cost is examined by doubling and reducing by half the baseline cost of harvesting used in the socio-techno-economic model.

The current harvesting system used in this study is an above the ground water settlers system made of steel and concrete which is normally used for municipal and industrial wastewater treatment. There are simpler tanks used for agricultural practices that are built into the ground with plastic lined walls and a concrete floor, which are assumed to be more cost-efficient, with an assumed costs reduction of up to 50% compared to the traditional water treatment settlers [79]. Another potential option for the harvesting system is the use of electrocoagulation (EC) for the operation, instead of flocculants.

Although the costs of such systems are similar to that of agricultural settlers, it is assumed there is potential to reduce operating costs and have a higher concentration factor of up to 15% solids [88]. Hence, the use of EC could potentially reduce about 50% capital cost of harvesting.

Reducing the cost of harvesting by 50% reduces the annual capital costs by 2%, bringing the overall production costs down by 1%. In Chapter 6 the cost contribution of each facility is discussed, and harvesting is the fourth major contributor to the overall capital cost. As mentioned previously in Chapter 4 the socio-techno-economic model is design to calculate the facility infrastructure based on microalgae biomass productivity, where an increase in productivity results in a decrease of construction materials used: the results shown in

Figure **7-3** are based on the baseline scenario of 25 $g/m^2/d$. Doubling harvesting annual capital cost by 3% and increase the overall production cost by 2%.

7.3.1.3 Pond and liner costs

As mentioned in Chapter 6, the main cost drivers in the economic model are the ponds and pond liners. Improving these two factors is critical to the economics of the algal oil cost. Thus, this can be very challenging, as pond design is very simple and easy to build [22]. Therefore a full 50% reduction assumed for harvesting and productivity may not be easily achievable. Rather, many published articles suggest that a 30% cost reduction can be achieved, by either reducing the land grading and excavation requirements, or through fundamental redesigning of the pond system. An example of the latter is a simple trench pond and liner with a low cost mechanical system installation for the liner; this patent technology is developed by Pysco Bioscience, which claims that the system can achieve up to 30% reduction in capital costs relative to the tradition raceway ponds [89]. Another example is when the characteristics of the site permits, liners would not be necessary, and the use of an alternative lining approach for the ponds, such as clay lined ponds used by Lundquist [22] or crushed rock layers by Weismann and Goebel [72] can be adopted.

Therefore the analysis examined the influence of pond and liner costs by reducing costs by 30%, and doubling the cost from the baseline scenario. Also the idea of removing the liner entirely is also considered. As shown in

Figure 7-4, after reducing the pond and liner cost by 30%, the costs are found to improve by 10%, while removing the liner entirely would reduce cost by 33%, and by doubling, the cost increases by 33%.

7.3.1.4 Facility footprint

Land costs are a further challenge. However, in light of the high capital costs of such systems, land costs of even £5,900/ha ($10,000/ha) would not make a significant difference in the overall algal oil cost [22]. The cost of land is related mainly to location, alternative uses, and ownership. For wastewater treatment, land costs will generally be higher, as they would be located near populated areas. However, the wastewater treatment function would also allow for greater investment in land. In brief, land cost can become a significant factor, in terms of access to required facilities such as, roads, power, CO_2, and water, but how much land costs would influence the overall algae oil costs remains to be determined [22].

Because in the baseline socio-techno-economic model facility the area is calculated based on productivity scale (see Chapter 4), it can be assumed that, when a higher growth rate is achieved, the required land area decreases. Therefore the analysis would examine the facility footprint by assuming a 50% reduction from the baseline land requirement, based on the assumption that a higher growth can be achieved, and doubling of the land requirement assumes a lower productivity scale.

Figure 7-5 illustrates the implications of these changes on the algal oil cost. When the land requirement reduces by half, it means that land cost is also reduced by half. This change reduces the algal oil costs by 15%, and increases by 50% when the land requirement doubles. The influence of the land cost is much greater when the land area increases with a low productivity rate. This may be as a result of using a baseline productivity rate of 25 $g/m^2/d$. It can be seen from the figure that, when the land requirement is reduced and a higher productivity is achieved, the cost becomes very low. This chapter will later explore possible cost reduction by examining each parameter closely, based on several details of the process.

7.3.1.5 Nutrients costs

Nutrients are essential components in microalgae cultivation. The cost and sustainability of the nutrients depends greatly on the type of nutrient and sources. Advancement in microalgae technology would involve co-locating algal farm with a power plant or wastewater treatment plant for the supply of nutrients [90]. Limited resources and suitable locations are among the serious challenges preventing commercial production of microalgal oil. There are several reasons that can cause an increase in nutrient demand, such as volatilisation of ammonia, which can cause nitrogen loss [15]. Other reasons that can increase nutrient demand include: loss of media due to pond failure, or flushing, to control the accumulation of salts or growth inhibitors [56]. The nutrients used here are ammonia, as the sources of nitrogen, and DAP (diammonium phosphate), as the source of phosphorus.

The influence of nitrogen and phosphate on the algal cost is examined by doubling and reducing by half the costs. Nitrogen contributes to the final cost with about £1.1 million, which is about 2.69% of the annual operating cost. The processing of 1000 bbl/d used in the economic model is estimated to require 4,610 metric tons of ammonia per year at 0.019 g/g dw algae. Doubling and reducing the ammonia cost changes the algal oil cost by only 1%. The curve illustrated in

Figure **7-6** shows those trends overlapping each other, because change in the price is so insignificant.

Figure **7-7** illustrates the influence of change in DAP, and the trend is similar to that of the ammonia. DAP accounts for 2.62% of the annual operating cost at £1.08 million. The annual DAP requirement is 4,151 metric tons per year

7.4 Magnitude of each parameter on algal oil cost

This section evaluates the impact of each parameter on the final algal oil cost, normalised to 100%. These parameters are examined very closely and varied with a minimal interval between the ranges, to allow understanding of the slightest change that occurs.

Table 7-4: Parameters Analysed.

Variable	**Base case value**	**Ranges**	**Interval**	**Range**	**Interval**
Productivity $g/m^2/d$	25 $g/m^2/d$	50 to 200%	10%	12.5 to 50 $g/m^2/d$	2.5 $g/m^2/d$
Lipid content wt %	25 wt %	50 to 200%	10%	12.5 to 50 wt %	2.5 wt%
Harvesting	£3 M/ha	50 to 200%	10%	£1.5 to £6M/ha	£0.99 m
Pond and liner cost	0.026 £/m^2	70 to 200%	10%	0.018 to 0.052 £/m^2	0.03 £/sq ft
Facility footprint	2925 ha	50 to 200%	10%	1463 to 5851	293 ha
Ammonia	240 £/t	50 to 200%	10%	120 to 480	26 £/t
DAP	260£/t	50 to 200%	10%	130 to 520	24 £/t

Results of this analysis are presented with a graph. The x axis represents the range over which the parameters are analysed, and the y axis the cost of algal oil. For each parameter one figure is presented (see Figure 7-8 - Figure 7-14) that shows the highest costs and lowest cost of the algal oil. The parameters taken into account for this analysis are presented in Table 7-4.

7.4.1 Analysis of the average change

For an increase of 100% of each parameter value, it is shown to change the algal oil price. If this value is negative, its means that the algal price has been improved, therefore a positive effect is obtained. If positive, it means that the algal oil price level is increasing, leading to an undesirable effect. The value is calculated through a cost range where the production rate is constant.

Table 7-5: Average change of algal cost for an increase of 100%

Parameter	Calculation	Average change @ an increase of 100%
Productivity g/m^/d	$\frac{1.35-1.50}{200-50} * 100$	- 0.10
Lipid content, wt %	$\frac{0.81-1.23}{200-50} * 100$	- 0.28
Harvesting	$\frac{1.82-1.78}{200-50} * 100$	+ 0.03
Pond and liner cost	$\frac{2.38-1.62}{200-70} * 100$	+ 0.58
Facility footprint	$\frac{0.49-0.52}{200-10} * 100$	+ 0.01
Ammonia	$\frac{1.80-1.78}{200-50} * 100$	+ 0.02
DAP	$\frac{1.80-1.78}{200-50} * 100$	+ 0.02

7.4.1.1 Productivity rate and lipid content

The productivity rate and lipid content are the most important parameters to be consider in order to analyse the viability of algal oil production process. As it can be seen in Figure 7-8 - Figure 7-9, if the growth rate and lipid fraction increases, the algal oil price decreases, therefore has a positive effect on the algal oil costs.

The values indicated in the table is the average across the 50 – 200% parameter range, to give an initial indicative measure of comparison, but to be considered carefully as the trend is not linear.

7.4.1.2 Harvesting

Figure 7-10 illustrates that harvesting has a slight influence on the algal oil costs compared to the productivity and lipid content. As the harvesting cost increases the algal oil costs increases, leading to a negative effect.

7.4.1.3 Pond and Liner cost

The influence of pond and liner costs, presented in Figure 7-11, are second most important parameter after productivity rate and lipid content. Since these parameters have shown to be the major contributor to the capital costs, increase in these two parameters, the cost of algal oil increases greatly.

7.4.1.4 Facility footprint

The effect of the facility footprint, presented in Figure 7-12, is the lowest among all parameters. It is about one fifth of the productivity and lipid content influence, and if the facility footprint increase the algal oil price increases, leading to a negative effect.

7.4.1.5 Ammonia and DAP

Ammonia and DAP are the only operating parameters considered, as all other parameters are capital cost related. Nutrients are important parameters in microalgae cultivation, with many factors to be taken into account. Figure 7-13 - Figure 7-14 presents the influence of the nutrients on the algal oil costs. It should be noticed that the parameters cannot be largely varied.

7.5 Improving the economics of the algal system

For user acceptance, microalgal oil will need to have the potential to compete with petroleum source of fuels that are, presently, the cheapest transport fuels. Whether microalgae biofuels are competitive, it will depend mainly on the costs of producing algal oil. Therefore, to approach the competitive issue, the maximum price for algal oil compared with the prevailing price of petroleum needs to be estimated.

To estimate the maximum price of algal biofuel, the energy equivalent of algal oil needs to be compared with the energy content of crude petroleum. The energy content of crude algal oil is 35,800 kJ per kg, or 5048 MJ per barrel, and the average energy content of a barrel of petroleum is 6287 MJ [91]. Therefore, from an energy point of view, a barrel of petroleum is equivalent to 1.25 barrels of algal crude oil. With these, for algal oil to be economically viable, 1.25 barrels of algal oil needs to be produced at a price that does not exceed the market price of a barrel of petroleum. This is based on the assumption that the costs of processing the algal crude oil to end products, such as biodiesel, get fuel or gasoline would be similar to the cost of processing a barrel of petroleum to the same products [10; 91; 92].

Chisti [10] estimated the cost of producing microalgal biodiesel, and then derived the maximum cost of producing microalgae biomass, with an energy equivalent of a barrel of petroleum, using equation (7-1) and (7-2).

$$M = \frac{E_{petroluem}}{q(1-w)E_{biogas} + ywE_{biodiesel}} \tag{7-1}$$

Where:

M = quantity of algal biomass (tons)

$E_{petroleum}$ = energy contained in a barrel of crude petroleum (MJ)

q = is the biogas volume produced by anaerobic digestion of residual biomass (400 m^3/ton)

w = oil content of biomass in % weight (/)

y = yield of biodiesel from algal oil (80% by weight) (/)

E_{biogas} = energy content of biogas (23.4 MJ/m^3)

$E_{biodiesel}$ = average energy content of biodiesel (37,800 MJ per metric tonne)

$$Acceptable\ price\ of\ biomass\ (\$/t) = \frac{Price\ of\ barrel\ of\ petroluem\ (\$)}{M} \qquad (7\text{-}2)$$

The estimate was carried out using different levels of oil content. With a prevailing cost of petroleum oil at $100 per barrel as at 2009, it shows that microalgae biomass with oil content of 55% will need to be produced at less than $340/ton to be competitive with petroleum fuel.

In another article Chisti [91] also calculated the costs of producing algal oil using eq. (7-3)

$$C_{algal\ oil} = 6.9\ x\ 10^{-2} C_{petroluem} \qquad (7\text{-}3)$$

where:

$C_{algal\ oil}$ = *the price of microalgal oil ($ per Litre)*

$C_{petroluem}$ = *the price of crude petroleum oil ($ per barrel)*

The results shows that for algal oil to be competitive with crude petroleum price at $100 per barrel as at 2010, algal oil needs to be produced at $0.69/L (£0.41/L).

These sections explore the possibility of achieving an acceptable price by improving the baseline socio-techno-economic model. The main drivers of the algal oil production costs describe above is mainly coming from the capital costs such as, pond and liner costs, harvesting and others. The improvements investigated are:

- reduced harvesting cost by 50%
- Reduced pond costs by 30%
- remove liner costs completely

The baseline model reflects a conservative analysis, therefore the implication of applying some few changes cumulatively to the system configuration and performance is analysed. The purpose of this is to quantify the performance associated with the changes, and show which values of the parameters presents an acceptable price.

7.5.1 Cumulative analysis

Since there are certain parameters that affect the production cost, some of the selected parameters were re-examined, through a cumulative analysis as shown in Figure 7-15 through to Figure 7-17. The analysis first calculated each parameter change individually. Change in the harvesting cost, shows very poor economic improvement, with only 1% reduction to the algal oil cost. Although harvesting is a well-established and efficient technique, it still remains economically unfavourable. The current most efficient technique commonly uses is centrifuge, but the high energy consumption makes it more costly, other techniques such as filtration and flocculation are less costly but are also less efficient, finding a technology that can balance the cost with efficiency makes it possible to achieve substantial cost reduction. An alternative option is the electrochemical/electrocoagulant (EC) harvesting. Based on preliminary costing estimate electrochemical harvesting could potentially present a similar cost as the simple agricultural settler tanks, but with drastically reduced operating cost and higher concentration factors of up to 15% solids [88]. In a recent article by (A. Guldhe, et al., 2015) it shows that (EC) has much lower energy consumption than centrifuge. With EC being an established technology used for industrial application and cost reduction of up to 50% was discussed and verified by many participants at the algal biomass summit [Algal Biomass Summit plenary session 2011], it is likely to achieve lower cost of harvesting

As discussed in previous section, the pond cost has the potentially to be greatly reduced as new technologies and research in the field of microalgae comes to fruition, in figure 7-15 pond shows an economic improvement of 5% on the algal oil cost. Reduction in pond costs would likely be achieved in the near future, by either reducing the construction cost or by achieving efficient operation. For example if ponds can be redesigned to be more efficient by becoming smaller is size whilst producing large volume. This will not only lower land requirement, it will also lower the evaporation rate and minimize energy consumption or by adopting a simpler design like the patent pond designed by Phyco Bioscience Inc., which was discussed in the previous section; it is a simple trench type pond with low cost mechanical installation system. The company stated that this system can achieve more than 30% reduction in capital cost. Another patent technology is the hanging adjustable V- shaped pond (HAVP) developed by UniVerve [111]. These ponds are suspended, modular and scalable triangular structures with transparent walls that allows light to penetrate from all sides, this type of design can lower operational costs and reduced the cost of land and site development. The company says it can contained 100m^3 productions medium.

The parametric analysis and economic estimate for a 1000 bbl of algal oil per day facility shows that microalgae production cost can be reduced, if certain improvements can be made to the system process and configuration, as well as to the productivity rate and lipid content of a suitable algal strain. In particular, productivity rate and lipid content have shown to have the biggest impact on the production cost, since they also influence the costs relative to the other parameters as shown in Figure 7 17 were all changes are applied, in function of the lipid content, for three productivity curves. the costs starts to approach an asymptote of £0.61/L for the high growth rate scenario (50 g/m^2/d), £0.69/L for the medium growth rate scenario (12.5 g/m^2/d), and £0.85/L for baseline growth rate scenario (25 g/m^2/d).

Although base on this analysis the cost of producing algal oil is still very high, even considering the lowest costs scenario at 50 g/m^2/d at £0.61 /L, compared to the £0.40/L acceptable price analysis above which is the energy equivalent of 100 $/barrel of fossil fuel, this is still not enough to achieve an acceptable price. With the current diminishing price of petroleum fuel at $60/barrel (translate to £0.24/L or $0.41/L), achieving economically viable is still challenging. However, if great improvement can be made to parameters both from a technical and economic aspect: adopting alternative techniques and equipment’s, can make great cost reduction in the capital costs. Another way to improve economic viability of the facility is, when the spent biomass can be utilized to produce other by-products, such as electricity, animal feeds, e.t.c. The facility could also benefit from economy of scale with large scale production.

7.6 Parametric Analysis for Job Impact analysis

Part of the output of the socio-techno-economic model is to provide an analysis of the local jobs, earnings and output (economic activity) generated as a result of the project – broken out by direct, indirect and induced impacts. This includes the one-time impacts resulting from the construction phase as well as the annual or ongoing impacts that result from the annual operations. The methodology adopted for this analysis is inspired by the NREL job impact model for cellulosic ethanol, as explained in Chapter 5. In this section a parametric analysis of the influence of each parameter on the number and quality of jobs and earnings that can be generated is examined. The necessary inputs includes direct, indirect multipliers for employment, earnings and output (per million dollars change in final demand), and personal consumption expenditures PCE (i.e. average consumer expenditures on goods and services –calculated as a percentage for each industry) for the fourteen aggregated industries selected.

7.6.1 Effect of change in parameters to Job Impact

This section determines how the effect of changes in system configuration and performance can affect the jobs created. The aim of these is to quantify the developments associated with the changes, and explore to see if the model can serve as a metric for assessing job impacts for a microalgae production facility. Table 7-6 shows the parameters used for the baseline job impact model.

Table 7-6 Calculation for scale of productivity

1,000	barrels per day
42,000	gallons per day
1,750	gallons/hr
6624	L/hr
920	g oil/ L
6,094,514	g oil/hr
25% wt	lipid content
24,378,056	g DW/hr
80%	extraction efficiency
30,472,570	g DW/hr
731,341,701	g DW/ day
15 g/m^2/day	productivity rate
48,756,113	m^2
4,875	ha

As stated previously, there is significant uncertainty in microalgae productivity and lipid content. The daily algal oil yield for the baseline model is 1,000bbl/day (6,624L/hr). The microalgae strain has shown to have common oil lipid contents between 20% and 50%, resulting in an oil yield of 3706 – 4942 gal/ha/year. The baseline economic model is conservative, relative to the experimental yield published and is so in terms of potential technology improvement.

7.6.1.1 Scenario A: changing scale and growth rate

The first analysis is to explore the impact when doubling or halving the production scale, starting from the baseline model of 1,000bbl/day, therefore respectively to 2,000bbl/day and 500bbl/day, then varying the growth rate for each scale. This could result to an increase or decrease in the pond cultivation area. The magnitudes of these would likely influence the jobs created during the construction phase, due to the dependence of the facility area on scale and productivity rate. However, for the initial analysis, the productivity scale is assumed base on simple doubling and halving, while an average of 15 g/m^2/day and 25g/m^2/day is assumed for the growth rate. The estimated changes in terms of number of job created during the operation phase are evaluated for the harvesting operators and the processing operators, and these estimates are based on a scale of production. It is assumed that for a production scale of 1000 barrels per day, 8 operators are required for harvesting (13 settling tanks, 4 centrifuges) and processing (28 homogenisers, 5 centrifuges).

Doubling the production scale and maintaining a growth rate of 15g/m^2/day increased the number of jobs created. The required land area is increased by 100%, equivalent to a 6% increase in jobs created during the construction phase and 19% for the operating phase (Table 7-7). Land costs would double and pond construction cost will increase by 39%. Cost per litre of algal oil would reduce from £2.43 to £1.28.

Reducing the production scale to half and maintaining growth rate of 15g/m^2/day reduces the number of jobs created. The required land area is reduced to about 50% of the baseline scenario. Labour required during the construction phase is reduced, due to the smaller area of construction. Construction jobs decrease by just 3%, while operating jobs decrease by 9%. The algal oil cost per litre is much higher in this scenario than the two scenarios with higher productivity scale.

These productivity changes were explored further using a different growth rate of 25g/m^2/day. In these scenarios the pond area decreases for all the scenarios. When a higher growth rate is maintained within the same system specification, the land area requirements reduces because the production scale desired can be achieved with a lower land area (see section 7.3.1). Construction jobs created at 1000 bbl/d is 1061 and 197 for annual operation, the pond area requirement is 2925 about 40% less than the area required at 15 g/m^2/d. Reducing the scale by half to 500 bbl/d at 25g/m^2/day creates 1036 jobs during construction and 179 for annual operation, the pond area requirement decrease by 40% compared to the 15 g/m^2/d scenario. Doubling the scale to 2000 bbl/d creates 1106 jobs during construction phase, and 235 jobs for annual operation. The pond area requirement is 5851 ha that is 40% less than the scenario at 15 g/m^2/d. Jobs created during construction phase in these scenario are less than the once created at 15 g/m^2/d because, the construction requirement decrease with smaller area. The operating cost remain the same for both scenario, as final production scale remains the same, irrespective of the area of production, processing demand remains the same.

7.6.1.2 Scenario B: changing only the growth rate (scale fixed at 1000bbl/d)

The second analysis is to explore the implication of maintaining the baseline scenario production scale of 1000 bbl/d (158987 L/day, 42000 gal/day), and vary the growth rate ranging from 15 to 40 g/m^2/day. The selection of the varied growth rates are based on published experimental growth rate.

In this scenario the number of annual operators is not affected because production output remains at 197 jobs created, requiring the same number of operations. Obviously the scenario with a larger construction area has a larger employment impact. In the table it is shown that the result is very sensitive to the productivity.

For construction jobs the numbers decrease, compared to the first scenario. Land area reduces, needing lower construction labour. 69% of the jobs created during this phase come from direct impact, 25% indirect and 6% from induced impact. These show that on-site jobs of the contractors and crews hired to construct the plan would not benefit with this scenario.

7.6.1.3 Scenario C: changing the production scale and the growth rate (fixed cultivation area)

The third scenario explores a fixed area of 4ha/pond (4052 ha), and varying growth rate. The production scale increases with higher growth rate. Construction jobs increase in these scenario because other operational facilities which include harvesting and processing equipment are estimated based on a productivity basis. Therefore increase in productivity affects the area factor of the processing units.

Increase in productivity, while maintaining the pond area, shows to have greater influence on algal oil production costs. Growing microalgae at the maximum growth rate of 40 g/m^2/day in a pond area of 4052 ha would drastically reduce the algal oil cost, but in terms of the employment generated during the construction phase the impact is negative.

Table 7-7 shows all the output obtained from the several changes made. The costs of the algal oil are presented by per litre, per gallon and per barrel. The jobs created are listed in the two last columns of the table.

Table 7-7 Job Impact associated with varying parameters

Scenario A: changing scale and growth rate							
Growth rate	**Barrel oil/d**	**Pond area (h)**	**£/L**	**£/gal**	**£/bbl**	**Job (const. phase)**	**Job (Operation. phase)**
15	1000	4876	£2.43	£9.20	£386.30	1282	197
15	500	2438	£4.75	£17.98	£755.11	1245	179
15	2000	9751	£1.28	£4.84	£203.48	1356	235
25	1000	2925	£2.06	£7.80	£327.48	1061	197
25	500	1463	£4.04	£15.29	£642.24	1039	179
25	2000	5851	£1.07	£4.05	£170.10	1106	235
Scenario B: changing only the growth rate (scale fixed at 1000bbl/d)							
15	1000	4876	£2.43	£9.20	£386.30	1282	197
25	1000	2925	£2.06	£7.80	£327.48	1061	197
30	1000	2438	£1.97	£7.46	£313.17	1006	197
40	1000	1828	£1.85	£7.00	£294.09	937	197
Scenario C: changing the scale and the growth rate (fixed cultivation area)							
15	831	4052	£2.90	£10.98	£461.01	1270	191
25	1385	4052	£1.51	£5.72	£240.04	1078	212
30	1662	4052	£1.21	£4.58	£192.35	1031	222
40	2216	4052	£0.86	£3.26	£136.71	971	243

7.6.1.4 Comparison with published economic estimates and forecast

The report titled “Renewable Energy: Made in Britain, jobs, turnover and policy framework by technology” [41] published by The Renewable Energy Association (REA) in 2012, provides estimate of the companies and jobs that are supported in the entire renewable energy sectors see Table 7-8, including number of other key economic metrics. About 103,000 jobs are set to be created from the UK renewable energy sector, with liquid biofuels contributing to 3509 jobs in 2012/2013 from 200 companies from the supply chain [43].

Table 7-8 UK biofuel Operating Companies

Company	Fuel type	Feedstock	Investment £ million	Capacity million litres	Jobs
Argent energy	Biodiesel	UCO, tallow, sewage grease	£18.8	60	70
Harvest Energy (formerly Biofuel Corporation	Biodiesel	Primarily waste oils	£250	284	50
British Sugar	Bioethanol	Sugar beet		70	30
Convert 2 Green	Biodiesel	UCO		20	60
Greenergy	Biodiesel	Waste oils	£50	220	56
Gasrec	Bio-LBM	Municipal Solid Waste		5	21
Ensus	Bioethanol	Wheat	£310	400	100
Olleco (formerly Agri Energy)	Biodiesel	UCO		16	450
Vivergo	Biodiesel	Wheat	£350	420	80
Baseline model	Algal oil	Microalgae	£98	52	197

Table 7-9 presents an overview of the key facts presented in the REA report. The data is presented at an aggregated level for Britain for the period of 2010/2011 and 2012/2013. The biofuel sector includes jobs from feedstock production, manufacturing, construction, operation and maintenance, and distribution. It also estimates that the UK biofuels consumption could reach 4.205 million tons of oil equivalents in 2020, from an estimated 2.153 million tons of oil equivalent in 2014 [42].

Table 7-9 Biofuels economic key factors for 2010/2012 to 2012/2013

Economic metric	2010/2011	2012/2013
Current employment	3500	3509
Number of UK companies	200	200
UK turnover	£485 million	£525 million
Global market value	£15.4 billion	Not Available
UK export value	£25 million	Not Available

The REA estimated the total number of people employed across the UK biofuel supply chain at 3509, across 200 companies, with a production capacity of 1,500 million litres per year. That is average of 7.5 million litres per company per year and average of 18 jobs created from each company. The baseline job impact model estimates that the algal facility would support 45 full-time operations and maintenance jobs for the life of the facility, with another 152 supporting jobs through supply chain and induced impacts, for a total of 197 full-time jobs associated with O&M operations, at a total production capacity of 52 million litres per year, the algal facility has the capacity to produce the equivalent 6 to 7 companies. Based on the REA estimates that translate to a total number of jobs ranging from 108 to 126 across the whole the supply chain, compared with the 197 jobs generated from the baseline job impact model that's, these shows that about 45% more jobs can be created from the algal facility when producing at the same scale.

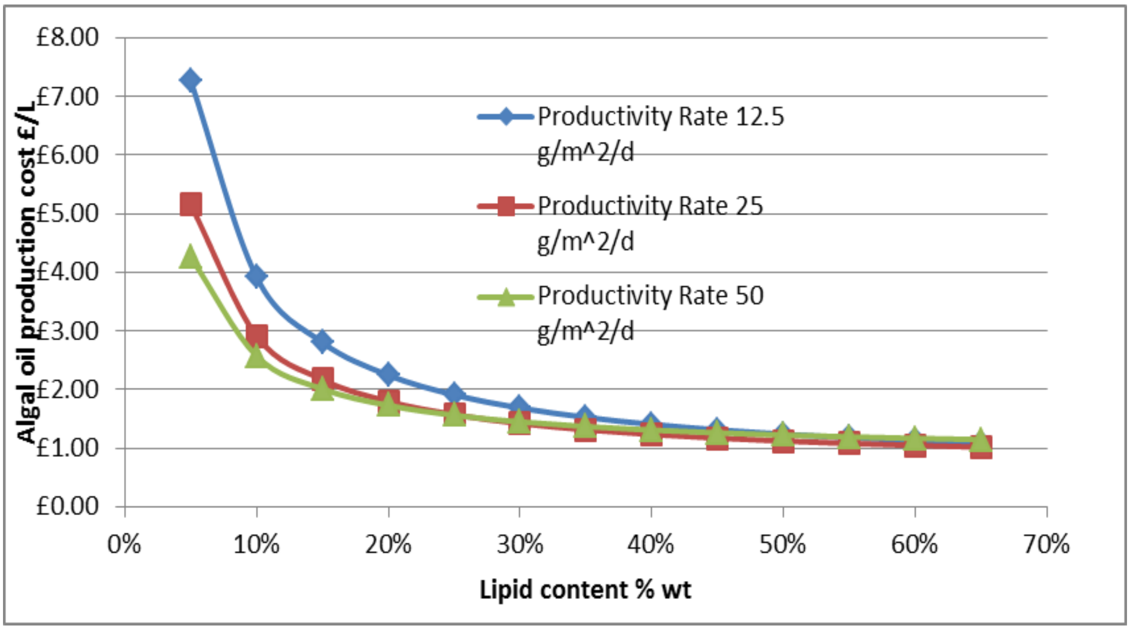

Figure 7-1 Effect of change in productivity rate

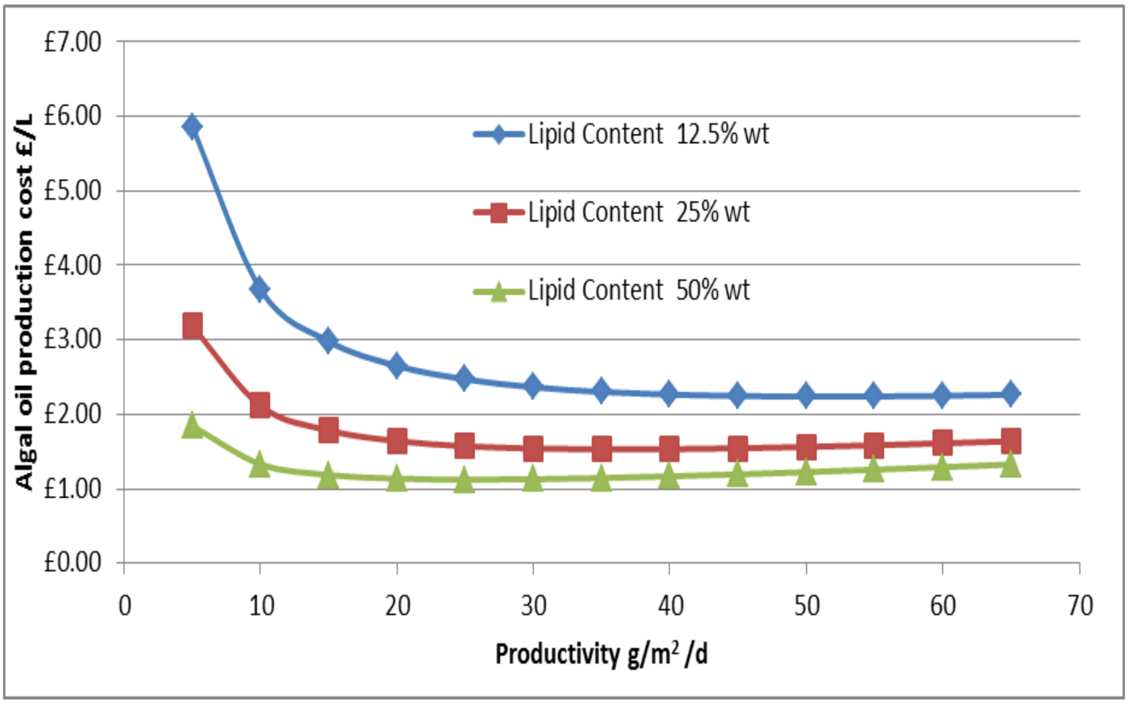

Figure 7-2 Effect of change in lipid content

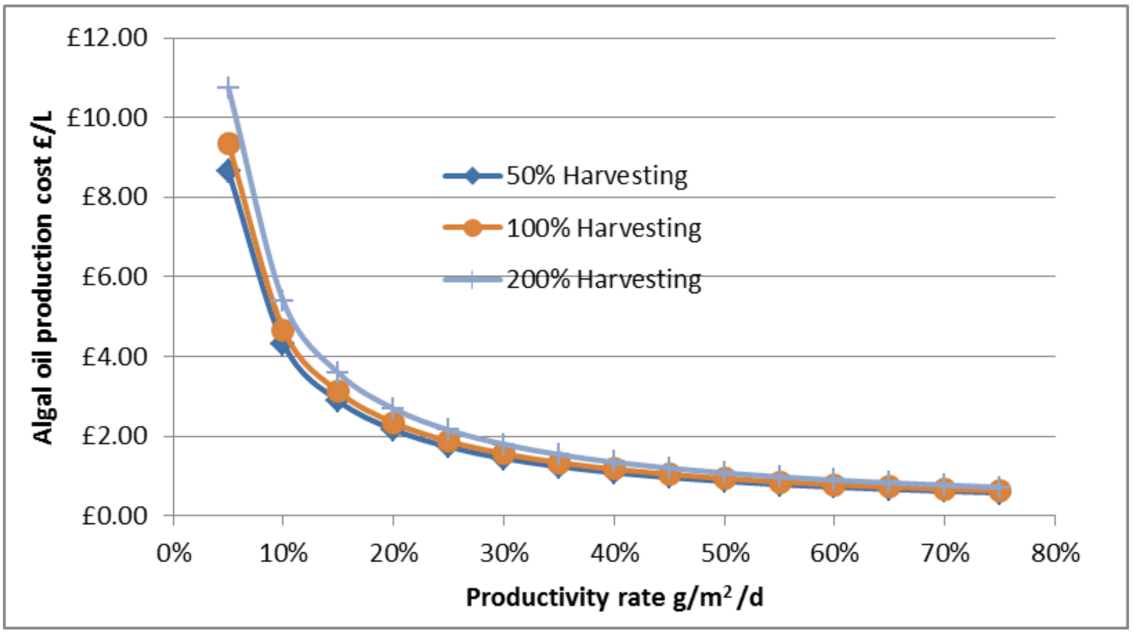

Figure 7-3 Effect of change in harvesting cost

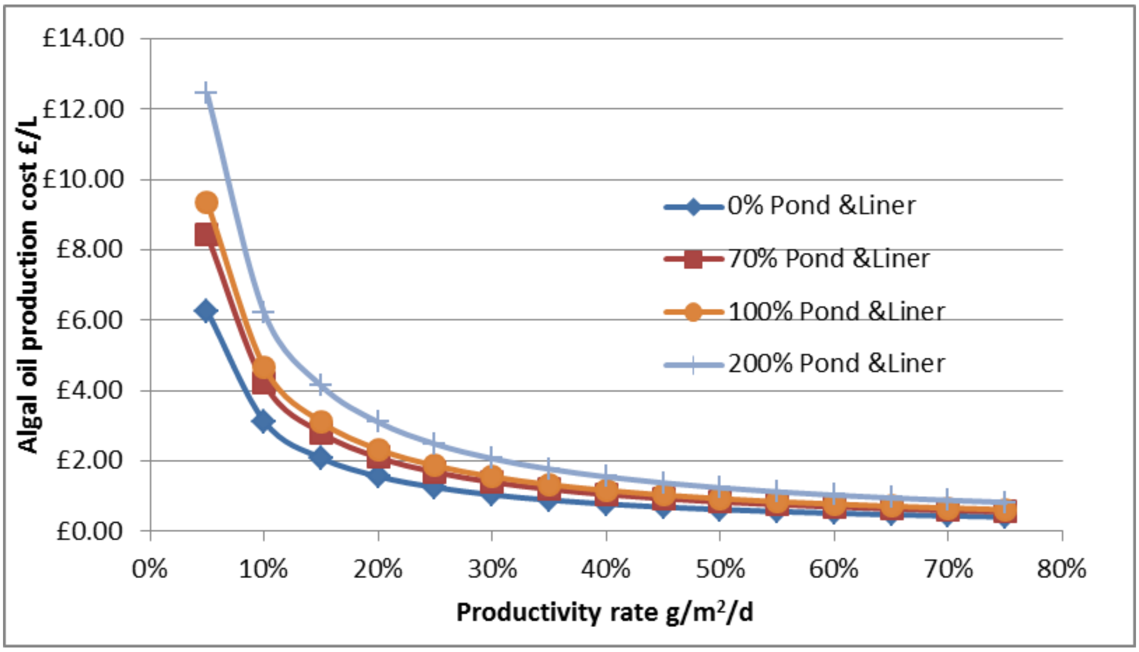

Figure 7-4 Effect of change in Pond liner cost

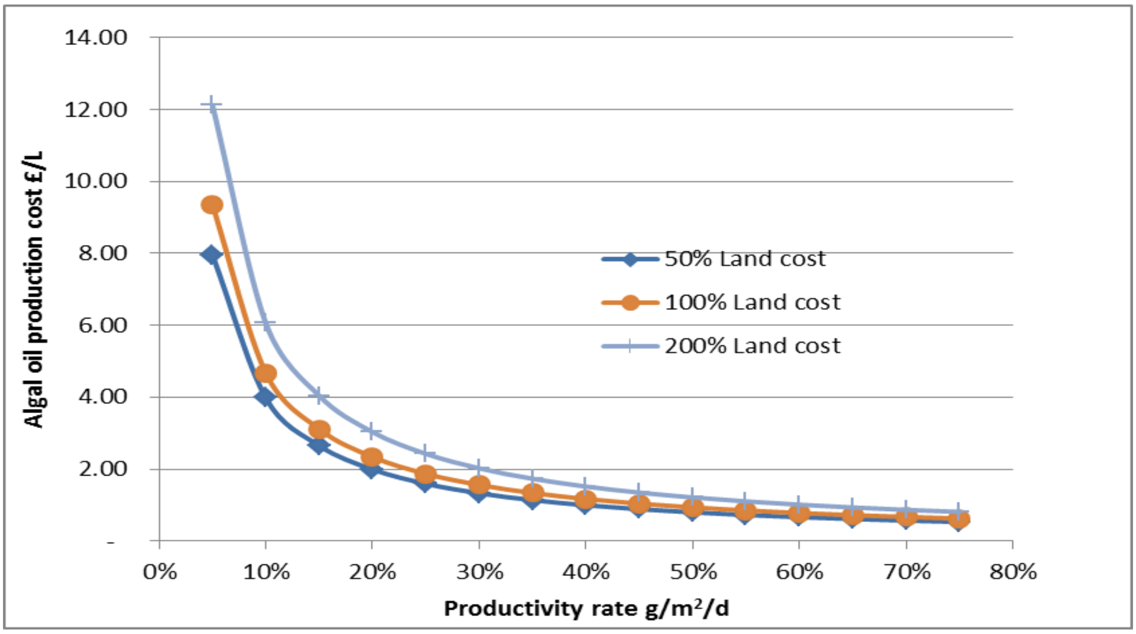

Figure 7-5 Effect of change in land cost

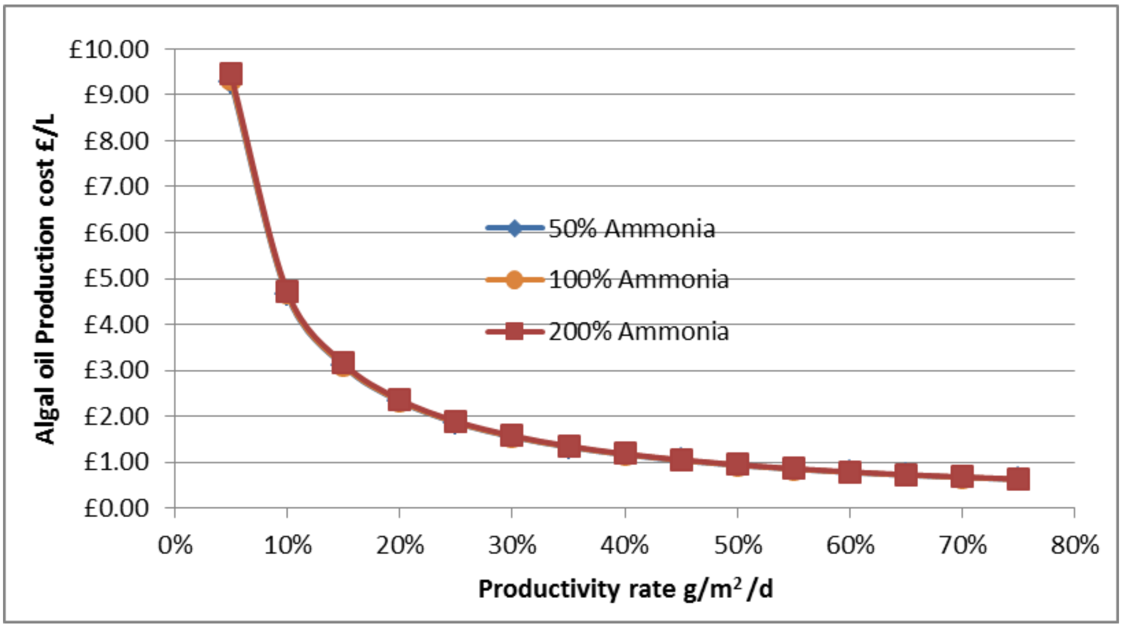

Figure 7-6 Effect of change in nutrients cost (ammonia)

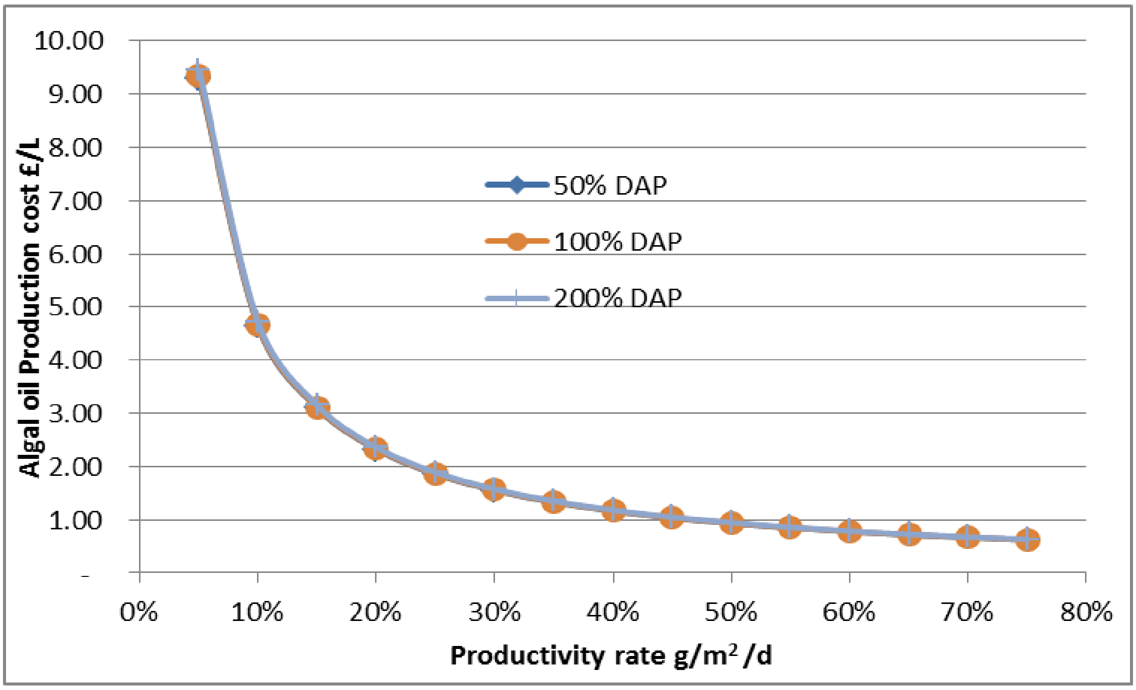

Figure 7-7 Effect of change in nutrients cost (DAP)

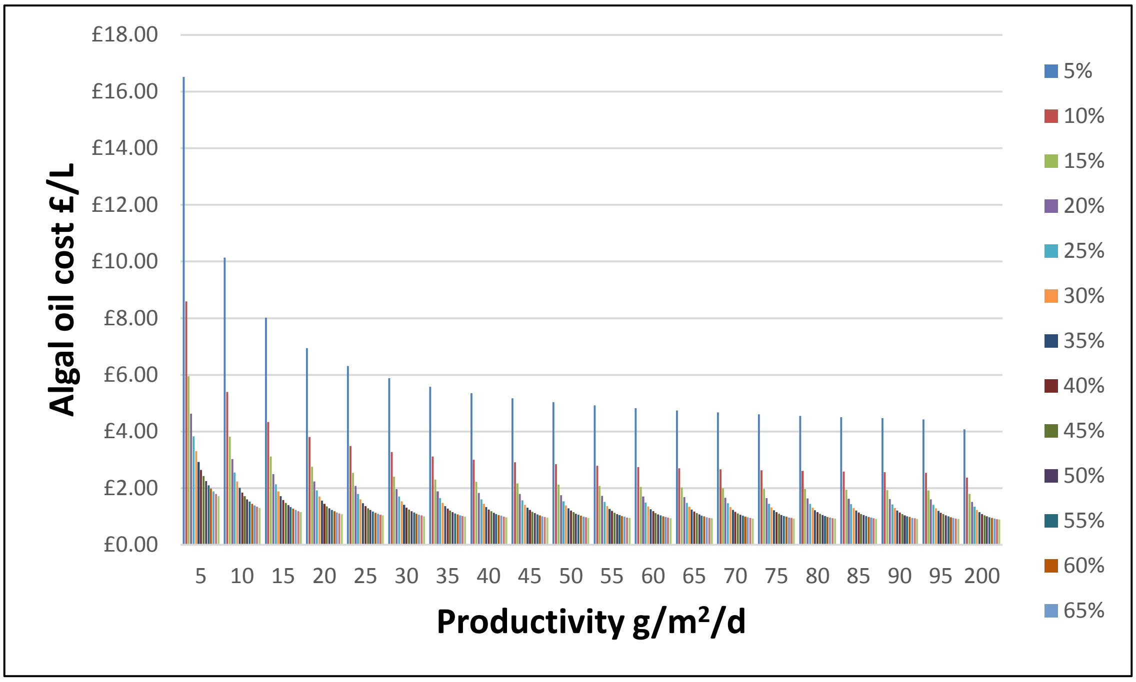

Figure 7-8 analysis of average change in productivity g/m^2/d

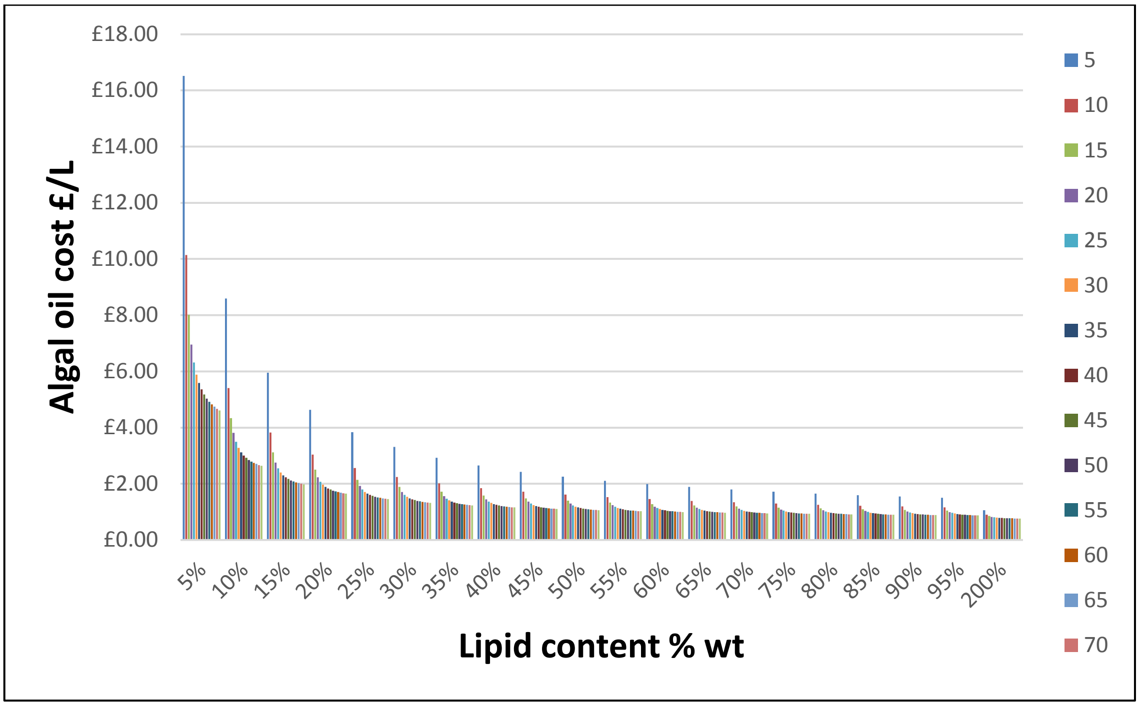

Figure 7-9 analysis of average change in lipid content % wt

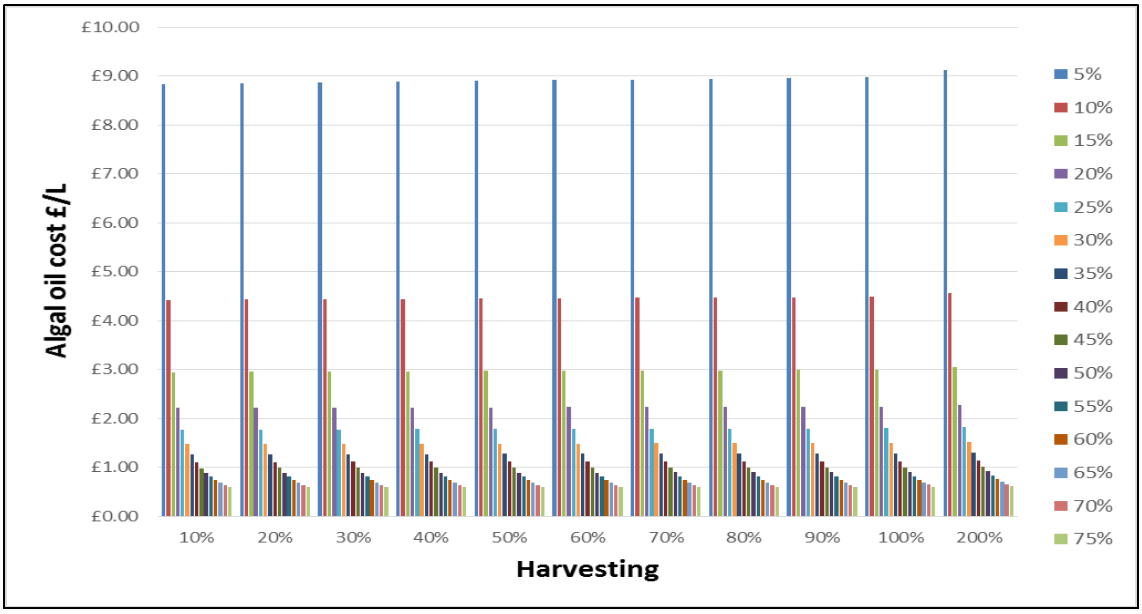

Figure 7-10 analysis of average change in harvesting

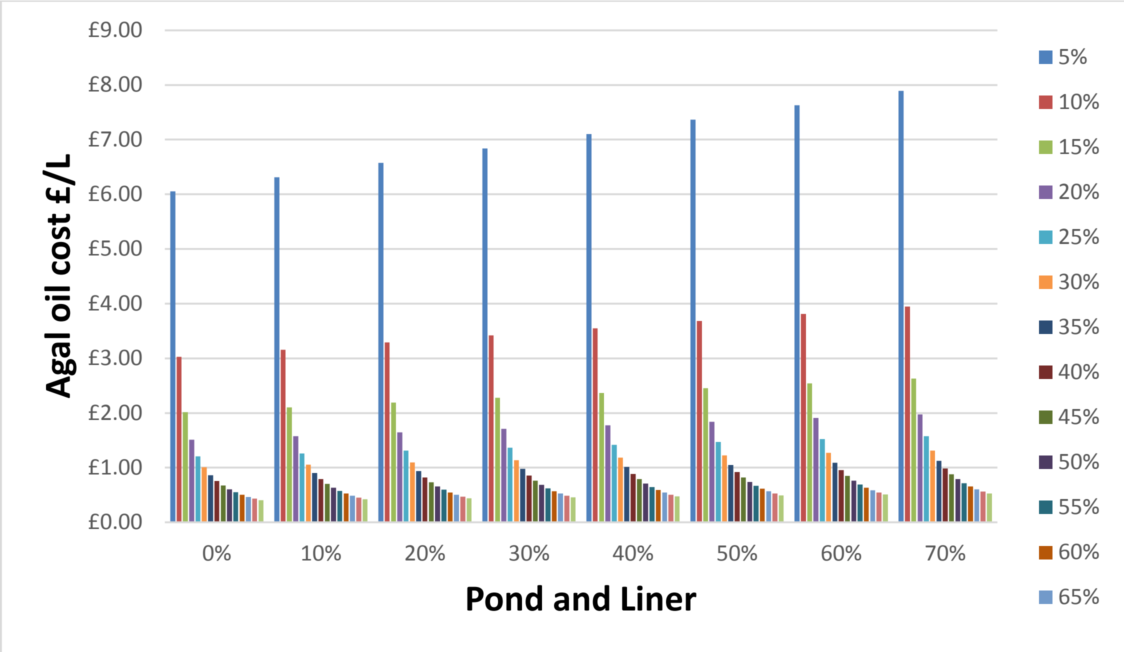

Figure 7-11 analysis of average change in pond and liner

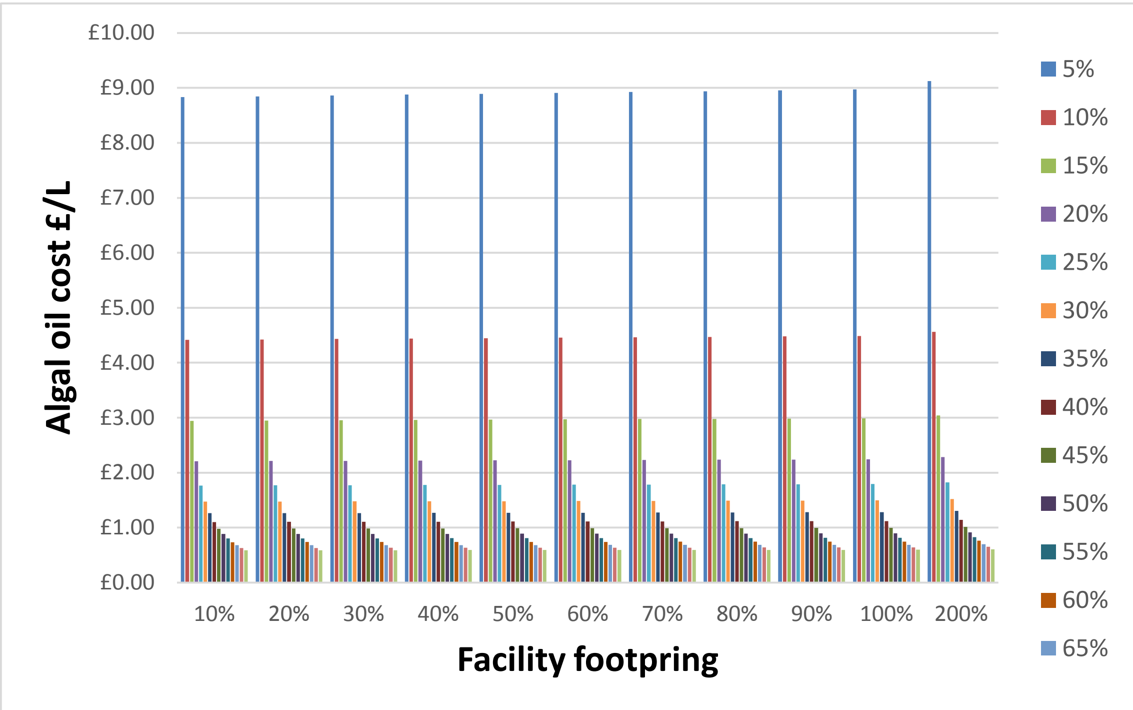

Figure 7-12 analysis of average change in facility footprint

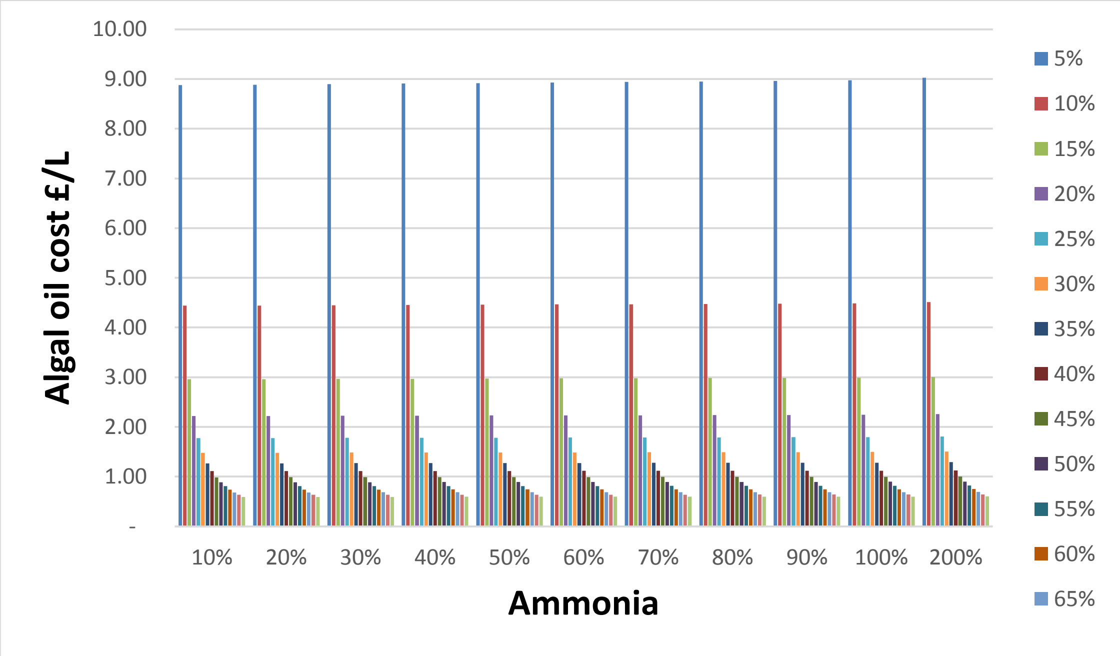

Figure 7-13 analysis of average change in Ammonia

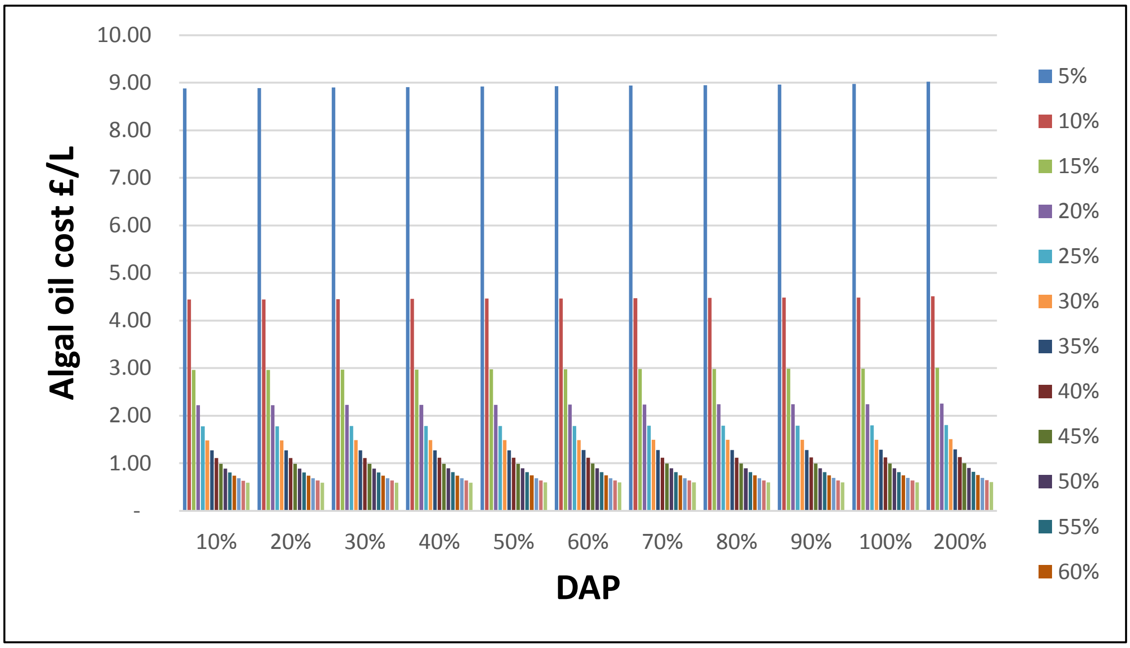

Figure 7-14 analysis of average change in DAP

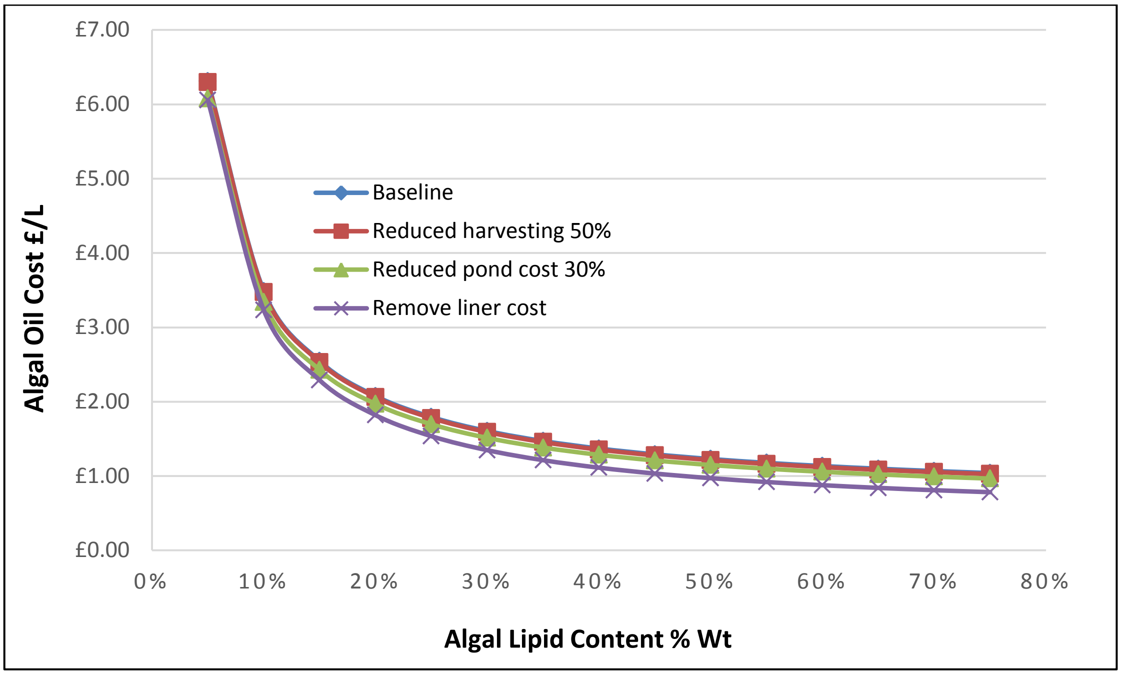

Figure 7-15 analysis of algal oil cost applied singularly

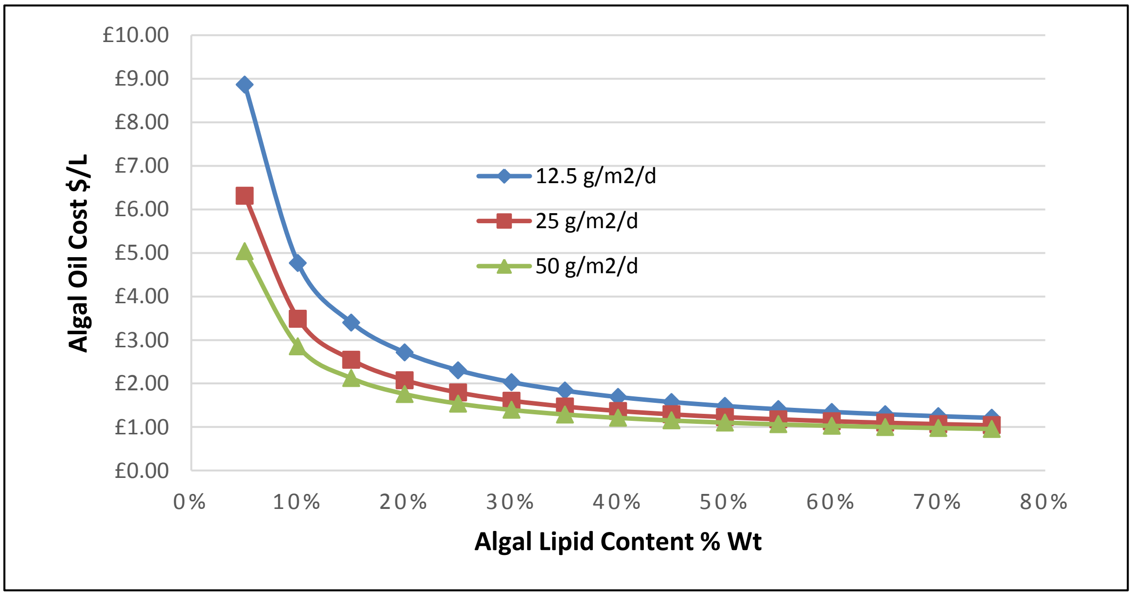

Figure 7-16 Algal oil cost before changes are applied

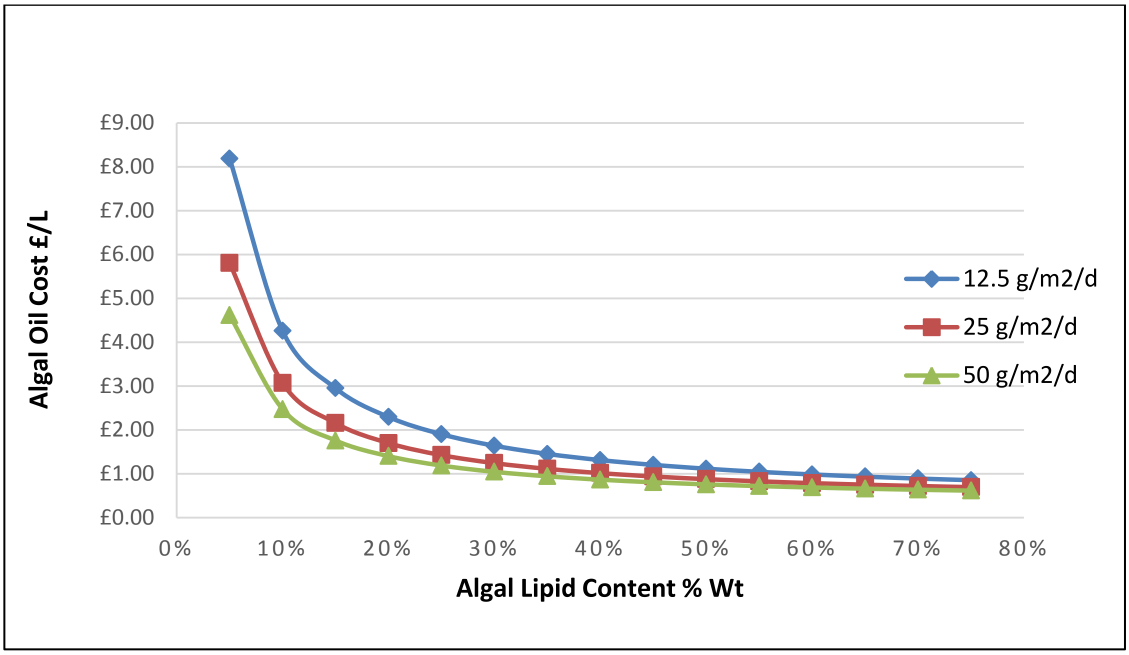

Figure 7-17 analysis on change applied cumulatively

7.7 Discussion

The parametric analysis was intended to identify areas in the different process parameters that influence the economics and employment impact of an algal oil production facility. As a practical matter, the parametric analysis was required to obtain data, which was used as an optimization analysis to the techno-socioeconomic model and was necessary due to the early stage of algae technology. The parametric uses the design and cost parameters of the base case model, and varied each parameter across a range values using 100% as indication value for the base case model, the same approach was also done for the job impact analysis.

While the goal of accomplishing a parametric analysis was a success, there a number of uncertainties that remain in the techno-economic model. Most of which are as a result of insufficient public data on the biological data and large scale processing units for algae production. Productivity and lipid content, especially for large scale production are very uncertain, although they have a strong influence on the economic results especially at lower productivity and lipid rate. The curves in Fig 7-1 and figure 7 -2 where it shows the lower values means that little changes in these parameters lead to lies in the lower part of the curve. The current productivity and lipid content values used in these study lies just in this range, the can cause the operating process to suffer due to the size of the facility. Changing the operating point to a higher point can have a large effect on the results. Improving productivity and lipid content would help the system to become more stable. These results are base the base case scenario only, a different scenario can change depending on the parameters used

Apart from the productivity and lipid content, there are other process variables that were examined. From figure 7 -3 to 7 -7 shows the changes in different process variables. The first parameter with the high-cost impact is the pond liner, as noted previously; the use of a liner is optional depending on many sitting and design criteria. Liners prevent leakages, helping to reduce the risk of wasting water and contamination. The base case model uses a plastic liner which added 33% to the total cost of production as shown in figure 7-4. Since liner is not a technical requirement in pond construction, and the siting criteria are suitable for an unlined pond. It would be more economical to look at alternatives lining options, such as natural material, which have the potentially to be less costly. Although natural material can be used as a cost-effective lining option, there are certain issues to be considered, like compacting, regulatory (not yet set for algae production) e.t.c.

The continuing effort to decarbonising the transport sector by reducing our dependence on liquid petroleum fuels has brought a growing interest on biofuels. Adopting the use of biofuels can help provide a shift from petroleum fuel to low-carbon fuels and create new employment opportunity. Despite the undeniable advantage of this technology, there are certain concerns related to the kind of economic benefits that can be generated from this technology, whether it is job creation or energy demand or whether is to reduce carbon emission. The question is whether the high cost of energy production when compared with the number of jobs created if it would make economic sense. Most policies argue that employment benefit is part of the justification for investment in biofuels; however this depends on the specific reason for the adaptation of the technology. For example, in the case of economic stimulus, which are programs designed to create employment [93], and if this programme is the sole justification of investment, then it should focus on technology that offers the highest employment generated per pound invested, rather than on technology with the highest economic benefits. If energy is the reason for investment in biofuels, there is a need to determine whether it can meet the required demand and at an acceptable price when compared to other sources, even among the different biofuels sources, algal oil has more advantages when compared to other biofuel sources but its major drawback is the high cost of production.

The combination of factors such as climate change mitigations, geopolitical and agro-economic reasons has encouraged many countries around the world to set out policies aimed at promoting the use biofuels. In the EU adopting new low-carbon, technology would not only help them reduce their carbon emission but also reduce their dependence on imported fuel and provide them with better energy security. In 2003, a biofuel directive (2003/30/EC) to achieve 2% share substitute to liquid petroleum by 2005 and

5.7% by 2010 was adopted by the EU member states to promote the use of biofuels. Despite the effort, in 2007, a progress report shows that only 1% share has been achieved, due to lack of appropriate policies that can subsidise the production cost of biofuels compared to the production costs of fossil fuel [107].

The justification of setting out policies for the promotion of green energy often claims that it will provide the most secure economy and sustainable job creation [103] [99] [100]. Many organizations such as OECD, ILO international labour organization, and UNFCCC have professed that taken action to reduce climate emissions would create sustainable employment [13] [94] [95] [101]. However, many literatures are claiming that policies that are specifically designed to promote green energy do not have an attractive consequence for labour market [103] [108] [110] [109], particularly when the policies require subsidies that are paid through bills and taxes [106]. It is clear that debate on the economic benefits base on the impacts of climate change mitigation and policies would be going on for a long time. [93].

To resolve this debate, analysis of the economic and employment implication of biofuels have been carried out by several researchers. One research by Bio Economic Research associates (Bio-era) on 2030 perspective for US economic impact of advanced biofuel technology, the analysis indicated existing refineries for advanced biofuels made from algae cellulosic ethanol, sugar cane, sorghum, production can generate up to 807,000 new employments by the year 2022 [105]. It also states that investment in advanced biofuels could contribute to the US economic growth of 37 billion dollars by 2020. Other literature that looks at these benefits includes F, Neuwahl., et. al who analysed employment impact that are relevant to biofuels under different financial scheme [104]. With much ongoing researches and appropriate policy implementation biofuels, commercialization would be realized. An article written by Winters a spokesperson for the Biotechnology Industry Organization (BIO) states the algal biofuels, in particular, would need substantial investment for R& D.

An important aspect that needs to be considered when calculating the job impact is to measure the number of jobs by some metric of activity of the project; either by dividing the number of jobs by investment or production capacity. This will help give an accurate understanding of the economic implication of the technology. A report by the

UKERC Technology & Policy Assessment Function states that dividing the number of jobs created by some measure scale of activity allows different projects to be compared. The report also stated that measuring the number of jobs per pound invested may not provide adequate resolution between the Capex and Opex [106]. Another method of measuring the job impact is to divide to number jobs by the production capacity or installation capacity. Measuring the job impact can be very complex as to determine the accurate job impact would require taken account of the costs and benefits, as projects differ in different countries and technology characteristics [96] [93].

8 CONCLUSIONS AND FUTURE DEVELOPMENT

8.1 Introduction

Microalgae are considered as one of the most feasible options to serve as a feedstock for biofuels and bio-products production, due to their comparative advantage over other biofuel feedstocks.

- Unlike other biofuel feedstocks, microalgae does not require arable land that can conflict with agricultural land for food production, therefore it does not pose a threat to food production.

- Microalgae species have typically a high growth rate, and one cycle can be as short as ten days period.

- High lipid content - Many of the species have a high lipid content, commonly from 20% to 50% of their dry weight.

- Water conservation – microalgae do not need fresh water for growth, they can be grown on saline water unlike other agricultural crops, and can be applied as a wastewater treatment in which they utilise the nutrient for growth.

- Microalgae can recycle CO2 from coal power plants and stationary sources.

- An algal bio-refinery has the ability to integrate different conversion technologies to produce biofuels as well as other co-products such as protein, carbohydrate and oil.

- Depending on the microalgae species, other compounds with valuable applications (like omega 3 fatty acid) may also be extracted to improve the economics of the biofuel(s) production.

Despite their many advantages, the economic viability of microalgae remains questionable, as stated by many researchers and investors, due to the several uncertainties in the technology for growing and processing microalgae into usable products. Previous studies have carried out different economic analysis with an aim of analysing the economic viability of algal oil production, the issue with this studies is that they do not take into account the benefits of the socio-techno-economic benefits that can be generated.

To tackle this issue, this study developed a socio-techno-economic model that can highlight not only the technical and economical characteristics and impacts of a large microalgae oil producing facility, but is able also to estimate the impact on the local economy. This model, as far as the author knows, is the first model to be produced for microalgae production facility that addresses the social impact. The analysis shows the potential routes to ensure the economic viability of the facility, reducing the final algal oil costs, assessing in parallel the impact on the local economy in terms of jobs and wealth created.

8.2 Main results

The main results obtained from the present work can be summarised as follows:

- Development of a facility design for the microalgae production system and plausible process for sustainable production of algal oil.

- Development of techno-economic model, that estimates the material and energy requirements and the final production cost of the algal oil.

- Development of a social impact model that estimates the employment benefits, local earnings, and output generated from the development of the algal biofuel plant.

- Comparative analysis of the process proposed in this study against various models in the literature, verifying and validating it wherever possible.

- Parametric analysis on the influence of some key parameters on the final algal oil cost.

The main output from the socio techno-economic model shows that some of the design parameters have the highest impact on the algal oil cost and the social impact outputs.

The largest cost contribution shows to come from pond and liners. Although the use of plastic liners can allow for greater flexibility in site selection and prevent pond contamination and leakage, their use increases cost higher than any other single operation and results in much more challenging pathway towards achieving economic viability.

The overall operating system shows to be sensitive to productivity and lipid content, small changes in these two parameters results in large changes in the final algal oil cost. This occurs because productivity determines the desired scale of production and several operating materials required in operation of these technologies.

To achieve economic viability, improvements to cell biology (both growth and lipid) and systems unit, reducing unit costs while improving performance will be required together Social impact analysis indicates that low productivity could result in high jobs creation both during construction and annual operating phase, annual operating jobs increase with increase in scale of production, but this does not indicate viability of the algal oil cost.

8.2.1 Facility design and process parameters

In Chapter 3, the design parameters for an algae production facility, considering the processes from cultivation to oil extraction, and the processing parameters are analysed and developed. The engineering and the design parameters for cultivation ponds are selected based on several works published by J.C. Weissman [72], J.R. Benemann [8], and Lundquist et al [22]. The infrastructural material for the system, excluding the cultivation pond, are adopted from the algae process description model developed by Argonne National Laboratory (ANL).

The microalgae are grown in an open pond (OP) cultivation system, where a single pond size of 4 hectare (690 X 60m) is assumed, with L/W ratio of 20. Productivity rate of 25 $g/m^2/d$ and lipid content of 25 wt% are assumed, based on publication by Griffiths [6], and the facility is assumed to be operational for 330 days. Nutrients fed into the growth media for culture are CO_2, Nitrogen, and Phosphorous, assumed to be consumed stoichiometrically, based on the molar composition of carbon: nitrogen: phosphorus (C:N:P) of 103 : 10 : 1 [7]. Pure CO_2 is assumed to be transferred through a 1.5m sump pipe and delivered to site with gross CO_2 requirement of 2.24 g/g algal biomass.

In the raceway ponds, paddlewheels are used to maintain constant mixing of the algae. Paddlewheel power is driven by electricity at 25 cm/s mixing velocity [8]. Energy required to pump water to site and into culture is 1.23E-04 kWh/L, and energy to pump culture to downstream process is 2.50E-05 kWh/L. Energy requirement is estimated using the GREET LCA software [9].

The grown microalgae are harvested continuously to an over the ground unit with 13 simple settling tanks, which concentrate the algae at 0.5 g/L through auto-flocculation: the concentrated algae biomass move to the next processing steps, while the effluent is recycled back to the growth pond. The settling process and growth process accounts for most of the water used throughout the entire process. The estimate of the water consumption is based on evaporation loss of 0.229 g/L. Once the algae are settled and the water is returned to the culture, the next step is flocculation with chitosan and collected by dissolved air flotation to thicken the algae with an energy consumption of 1.478E-04 kWh/g-dw [10]. The algae paste is further concentrated, using a centrifuge to further minimise the cost of the downstream process.

Cellular disruption is done, using a combination of high-pressure homogeniser and the hexane extraction. These two processes are assumed to achieve 90% extraction efficiency. Remnants, including lost solvent and unrecovered lipids, are sent to an anaerobic digestion (AD) facility for energy and nutrient recycling.

8.2.2 Economic model

In Chapter 4 the economic model is developed estimating the capital and operating costs of constructing and operating a microalgae production plant. The baseline process size specified in Chapter 3 is used for the calculations. The capital equipment cost estimates utilise unit construction costs from Spon's Architect and Builders Price Book Davis Langdon [37], except for the cultivation ponds. The costs for the cultivation ponds are based on data from several sources [11][12][13]. Variable operating costs are calculated by multiplying the raw materials and energy usage value by a unit price. While some fixed costs are calculated as percentages of certain capital costs, others are estimated and entered directly.

A plausible process is assessed, based on an assumed production scale of 1000bbl/ algal oil per day. The annual production cost for the 1000bbl/ algal oil per day is estimated at £98M. The total biomass required to achieve the desired production is estimated to be 7.31E-04 ton dw (dewatered) per day, with a total land requirement of 2,925 ha. Total daily production is equivalent to 158,987 L/day (52,465,817 L/year). The estimated annual charge including the return on equity rate is set at 10% interest over the period of 20 years. The plant is assumed to be financed 100% through cooperate investments. The annual capital charge is then added to the annual operating costs to arrive at the final algal oil cost. The total capital investment is estimated at £403M including indirect capital costs (estimated as a percentage). The annual operating cost is estimated to be £55M. The estimated final algal oil production cost is £1.87/L. The major contributor to the algal oil costs shows to come from the capital costs investment.

Pond and liner costs are found to be the highest contributors to the capital costs (64%), followed by harvesting with 11% (including settling tanks, DAF and centrifuge) and inoculation pond at 9%. The high cost of the inoculum pond is a result of the use of 40mm HDPE liner to line the bottom of the tanks. For the operating costs the larger driver of cost is the energy consumption at 48%, followed by nutrients costs at 27%.

Interestingly, labour cost is the lowest contributor among these three, with an annual operating costs contribution at 23%.

8.2.3 Social impact model

The social impact model is designed to demonstrate the economic impact on the local economy associated with developing and operating an algal oil production plant.

The model presents two types of output: the one-time jobs, earnings and outputs created during the construction phase, and the on-going jobs, earnings, and output created during the operating phase.

The results from the model show that 1106 full-time equivalent (FTE) jobs are created, generating over £115 million in earnings and over £166 million in total economic activity during project development and construction. These include a total of 754 FTE jobs from project development (679 construction labour only and 75 construction services), 289 equipment and supply chain, and 63 from induced impacts. Once the project is up and running and producing algal oil or biofuels, 45 full-time operations and maintenance jobs are created and sustained for the life of the facility, with another 152 supporting jobs through supply chain and induced impacts, making a total of 197 full-time jobs associated with O&M operations.

The model shows to be static, because it relies on inter-industry relationships and personal consumption patterns existing in the particular year the multipliers were derived.

8.2.4 Comparative analysis

Three studies presented in the literature [18] [15] with a similar facility design as the baseline study are analysed. The parameters presented for each of the articles are analysed using the economic model developed in Chapter 4. The models output from the articles are compared with the output obtained from the economic model.

The first case study is a current report from NREL, which defines a baseline algal biofuel production scenario with model-based quantitative metrics for cost, scale-up potential, and sustainability. After incorporating the inputs presented in Table 6 1, the results shows that the algal oil production cost estimated with the model developed here corresponds closely to the algal oil cost published in the original report.

The second case-study is an analysis of the comparative costs of algal oil production for biofuel [18]. This analysis shows a wide range of diversity between the original results and the economic model, due to differences in the production scale, the water and power management strategies, and the co-products considered. The models discussed did not account for capital costs or list the geometrics of the facilities adopted. It is therefore difficult to make a critical element-by-element comparison among all the cases, when so many assumptions varied from the models to the economic model. Nevertheless, the assessment provides an indication of what needs to be addressed to end the lack of agreement regarding diversified microalgae production costs. Although the variation has reduced across recent published articles, it is important to achieve a more uniform model to assess algal oil production costs in order to achieve commercial scale production. (Explanation on diversified microalgae production cost is described in Chapter 2).

The third comparative analysis is the model for techno-economic analysis for autotrophic microalgae for fuel production published by Davis [15]. The calculation of the operating costs was much easier to estimate, compared to the capital costs. The annual operating cost obtained from the economic model developed in the present work is £19.72M/yr, this value is near to the original cost of £21.83 M/yr ($37M/yr). The equipment cost for the economic model is estimated at £207 M, which is about 40% more than the TEA cost of £117 M ($195 M). The cost of the TEA scenario is evaluated on a unit level basis, making the cost smaller when compared to the baseline economic model. The major variation found for this study comes from the capital costs, the analysis considers very low equipment costs compared to the cost calculated in the economic model and the two previous studies. The study estimated a pond cost at $30 million for a 1950 hectares of pond area (4820 acres) translating to $15,385 per hectare, this value is very low compared to the standard $34000 per hectare commonly used in several studies.

8.2.5 Parametric analysis on the influence of some key parameters on the final algal oil cost

In this chapter a parametric analysis is carried out using two different methods to determine the viability of an algal oil production facility. Taking the economic costs and the operating parameters from the economic model, some key parameters are changed across a range of values and their influence on the final cost of algal oil and job impact are analysed. Each parameter is analysed across a range of production scales from $5g/m^2/d$ to $75g/m^2/d$.

The parameters are examined to highlight the influence of each parameter independently. Because microalgae oil technology is still at the pilot stage, the values are not set on a practical scale. Each parameter is varied, based on assumption, and what has been presented in literature.

The list of parameters analysed are:

- doubling and reducing productivity from the baseline scenario (25 $g/m^2/d$),

- doubling and reducing by half the baseline cost of harvesting used in the socio-techno-economic model,

- explore the influence of pond and liner costs by reducing costs by 30%, and doubling the cost from the baseline scenario. Also the assumption of removing the liner entirely is also considered,

- examine the facility footprint by assuming 50% reduction from the baseline land requirement and doubling by 200% of the land requirement.

- influence of nitrogen and phosphate on the algal cost is examined by doubling the costs and reducing by half.

8.3 Future development

Microalgae oil production facilities are still at an early stage of development, and the model developed here including the social-impact is the first to be developed. Therefore the author will propose the following direction in which to be investigated for future development.

The research into techno-economic and social impacts linked together would provide a future development for an economically viable algal oil industry.

8.3.1 The techno - economic model

The techno-economic model was developed to estimate the economic viability a microalgae production facility. This model includes detailed construction costs of the equipment for cultivation of microalgae and processing of algal oil. The operating parameters include nutrients required for growing and processing the algae into oil and energy needed to operate the facilities. The model is designed to allow for specific values to be entered as inputs, calculation has then taken place and an output is obtained. Although the model is designed with a certain level of accuracy the following major improvements are suggested:

- It can be modified to assess different processes. The model currently accommodates one specific route and technology. It can be improved to include Photobioreactors (PBR's) for the growth step, and other alternatives can be modelled for other steps.

- The conversion process of the algal oil to usable fuels and byproducts can be added

- The model can be informed with data for a specific site, such as availability of resources required and local price structure (e.g utility and labour rates) can help compare economic viability

Although the functionality of the model has been verified, other uncertainty analyses should be considered for future development, so as to determine hidden or complex interdependencies in the model.

8.3.2 Social impact model

The intent of the socio-techno-economic impact model is to construct a reasonable profile of expenditures and demonstrate the magnitude of economic impacts that will likely result, assuming that a project occurs during the stated period of analysis. Given the unique nature of microalgae technology and the rapidly changing nature of the industry, changes are expected as the technology matures. The analysis should be viewed as an estimate of the overall magnitude impacts.

Currently the model relies on multipliers derived from inter-industry relationships and personal expenditure pattern existing in a particular year. The model can include feedbacks from inflation or potential constraint on labour, goods or money supplies. Currently the model assumed there are adequate local resources and production and services capability to meet the levels of demand identified in the modelling assumptions. The model can be improve to include feedbacks from final demand increase or decrease that occurs from price change.

A cash flow projection analysis is not carried out in the current model. Including this analysis in future development can benefit man investors to identify the profitability of the business.

REFERENCES

[1] BP (2012), *BP Energy Outlook 2030*, available at: http://www.bp.com/liveassets/bp_internet/globalbp/STAGING/global_assets/downloads/O/2012_2030_energy_outlook_booklet.pdf (accessed 02/24).

[2] BP (2011), *BP Statistical Review of World Energy June 2011*, available at: http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2011.pdf (accessed 02/24).

[3] Christof, R., Appleby, P., Fennema, J., Naumov, A. and Schaffer, M. (2012), *Economic Development and Demand for Energy: A Historical Perspective of the Next 20 years*, , * BP plc. Heriot-Watt University, Edinburgh.

[4] " IEA, '. (2011), *Technology Roadmap: Biofuels for Transport*, 15, Cedex, Paris.

[5] DECC (2011), *UK Renewable Energy Roadmap*,, Department of energy and climate change, uk.

[6] Jone, F., Valarie, S. R (2012), *National Algal Biofuels Technology Roadmap*, available at: http://www.scribd.com/Sica/d/38482268-Algal-Biofuels-Roadmap (accessed 03/28).

[7] NFCC (2015), *NNFCC Newsletter -Issue 23. Algae Special Issue* available at: http://www.nnfcc.co.uk/publications/nnfcc-newsletter-issue-23.-algae-special-issue (accessed 03/2015).

[8] Benemann, J. R. and Oswald, W. (1996), *Systems and Economic Analysis of Microalgae Ponds for Conversion of CO to Biomass* , U.S. Department of Energy, U.S.A.

[9] James, W. R., and Myriah, D. J., (2010), "Economic and Financial Assessment of Algae Biofuels Technologies", .

[10] Chisti, Y. (2007), "Biodiesel from microalgae", *Biotechnology Advances*, vol. 25, no. 3, pp. 294-306.

[11] Sun, A., Davis, R., Starbuck, M., Ben-Amotz, A., Pate, R. and Pienkos, P. T. (2011), "Comparative cost analysis of algal oil production for biofuels", *Energy*, vol. 36, no. 8, pp. 5169-5179.

[12] Norsker, N., Barbosa, M. J., Vermuë, M. H. and Wijffels, R. H. (2011), "Microalgal production — A close look at the economics", *Biotechnology Advances*, vol. 29, no. 1, pp. 24-27.

[13] IEA/OECD (2009), *Transport Energy and CO2, Moving Towards Sustainability,*, IEA, Paris, France.

[14] AllgeroB.Com (2012), *How Much Does Biodiesel Reduce Air Pollutants?*, available at: http://www.allegrobiodiesel.com/howmuchdoesbiodieselreduceairpollutants.html (accessed 09/17).

[15] Chisti, Y. (2007), "Biodiesel from microalgae", *Biotechnology Advances*, vol. 25, no. 3, pp. 294-306.

[16] Benemann, J. R. and Oswald, W. J. (1994), *Systems and Economic Analysis of Microalgae Ponds For Conversion Of CO_2 To Biomass*, DOE/PC/93, Department of Energy, Barkeley.

[17] Kadam, K. L. (2001), "Microalgae Production from Power Plant Flue Gas: Environmental Implications on a Life Cycle Basis", *DO11.4010,*, pp. NREL/TP-510-29417.

[18] Huntley, M. and Redalje, D. G. (2004), "CO_2 Mitigation And Renewable Oil From Photosynthetic Microbes: A New Appraisal".

[19] Lardon, L., Arnaud, H., Bruno, S., Jean-Philippe, S., and Olivie, B., (2009), "Life-Cycle Assessment of Biodiesel Production from Microalgae",.

[20] Liaw, B., Jason, q., Bryan, w. and thomas, b. (2010), "Net Energy and Greenhouse Gas Emission Evaluation of Biodiesel Derived from Microalgae", vol. 44, pp. 7975–7980.

[21] Clarens, A., Resurreccion, E. and Colosi, M. W. (2009), "Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks ", vol. 44, pp. 1813-1819.

[22] Lundquist, T. J., Woertz, I. C., Quinn, N. W. T. and and Benemann, J. R. (2010), *A Realistic Technology and Engineering Assessment of Algae Biofuel Production*, , Energy Biosciences Institute University of California, California.

[23] Anna, L. S., Elena, K., John, S. D., Christopher, J. H., Stuart, A. S., and Alison, G. S., (2010), "Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors", *American Chemical Society*, , no. 10, pp. 4062-4077.

[24] Cooney, M., Young, G. and Nagle, N. (2009), "Extraction of Bio-Oils from microalgae", *Separation and Purification Reviews*, vol. 38, no. 4, pp. 291-325.

[25] Frank, E. D., Han, J., Palou-Rivera, I., Elgowainy, A. and Wang, M. Q. (2011), *Life-cycle Analysis \of Algal Lipid Fuels wth the GREET Model*, 11-5, Argonne National Laboratory, Chicago.

[26] Tan, T., Lu, J., Nie, K., Deng, L. and Wang, F. (2010), "Biodiesel production with Immobilized Lipase: A Rview", *Biotechnology Advances,* vol. 28, no. 5, pp. 628-634.

[27] Borowitzka, M. A. and Moheimani, N. R. (2013), *Algae for Biofuels and Energy,* 5th ed, Springer, Netherlands.

[28] Spolaore, P., Joannis-Cassan, C., Duran, E. and Isambert, A. (2006), "Commercial applications of microalgae", *Journal of Bioscience and Bioengineering,* vol. 101, no. 2, pp. 87-96.

[29] Dismukes, G. C., Carrieri, D., Bennette, N., Ananyev, G. M. and Posewitz, M. C. (2008), "Aquatic phototrophs: efficient alternatives to land-based crops for biofuels", *Current opinion in biotechnology,* vol. 19, no. 3, pp. 235-240.

[30] Qiang, L., Wei, D., and Dehua, L., (2008), "Perspectives of microbial oils for biodiesel production", *10.1007/s00253-008-1625-9,* vol. 80, no. 9, pp. 749-756.

[31] Schenk, M. P., Skye, R. T., Evan, S., Ute, C. M., Jan, H. M., Clemens, P., Olaf, K. and Ben, H. (2008), "Second Generation Biofuels: High-Efficiency Microalgaefor Biodiesel Production", vol. 10.1007/s12155-008-9008-8, no. 43, pp. 1:20.

[32] Brennan, L. and Owende, P. (2010), "Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products", *Renewable and Sustainable Energy Reviews,* vol. 14, no. 2, pp. 557-577.

[33] Harun, R., Singh, M., Forde, G. M. and Danquah, M. K. (2010), "Bioprocess engineering of microalgae to produce a variety of consumer products", *Renewable and Sustainable Energy Reviews,* vol. 14, no. 3, pp. 1037-1047.

[34] Singh, R. K., Murty, H. R., Gupta, S. K. and Dikshit, A. K. (2012), "An overview of sustainability assessment methodologies", *Ecological Indicators,* vol. 15, no. 1, pp. 281-299.

[35] Mata, T. M., Martins, A. A. and Caetano, N. S. (2010), "Microalgae for biodiesel production and other applications: A review", *Renewable and Sustainable Energy Reviews,* vol. 14, no. 1, pp. 217-232.

[36] Singh, J. and Gu, S. (2010), "Commercialization potential of microalgae for biofuels production", *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 2596-2610.

[37] Wijffels, R. H., Barbosa, M. J. and Eppink, M. H. (2010), "Microalgal for the Production of bulk chemicals and biofuels", *Biofuels, Bioproducts and Biorefiing,* vol. 4, no. 3, pp. 287-295.

[38] Davis, R., Aden, A. and Pienkos, P. T. (2011), "Techno-economic analysis of autotrophic microalgae for fuel production", *Applied Energy*, vol. 88, no. 10, pp. 3524-3531.

[39] Grima, M. E., Belarbi, E. H., Fernández, F. G. A., Medina, A. R. and Chisti, Y. (2003), "Recovery of microalgal biomass and metabolites: process options and economics", *Biotechnology Advances*, vol. 20, no. 7–8, pp. 491-515.

[40] NREL (2012), *Jobs and Economic Development Impact Models*, available at: http://www.nrel.gov/analysis/jedi/results.html (accessed 09/29).

[41] REA (2014), *Renewable Energy: Made in Britain, Jobs, turnover and policy framework by technology*, available at: http://www.r-e-a.net/resources/rea-publications (accessed 12/10).

[42] Sacha, A., and Gemma, T. (2013), *UK biofuels industry overview*, BIOUK10553, Ecofys, London.

[43] REA (2014), *REVIEW - Renewable Energy View 2014" as a source of data for my research*, available at: http://www.r-e-a.net/resources/rea-publications (accessed 12/10).

[44] Fiona, M., (2012), *NFCC: UK jobs in the bioenergy sectors by 2020*, 11-025, DECC, UK.

[45] EnAgri (2015), *UK Biomass Directory*, available at: www.ukbiomassdirectory.enagri.info (accessed 02/18).

[46] Thornley, P., Rogers, J., and Huang, Y., (2008), "Quantification of employment from biomass power plants", *Renewable Energy*, vol. 33, no. 33, pp. 1922-1927.

[47] CEBR, (2010), *Report for the Forestry Commission. The economic value of the woodfuel industry to the UK economy by 2020*, , CEBR, UK.

[48] Northwoods (2014), *A study for the Forestry Commission, north east region, and for the NEWHeat programme of One NorthEast. An economic evaluation of current and prospective value to the north east of England from biomass-related activities*, available at: http://www.ruraldevelopment.org.uk/files/rdi/BiomassValue_northeast_1.pdf. (accessed 02/18).

[49] The Energy Institute (2009), *Scoping Study on the review of the manufacturing and engineering capabilities for manufacture and supply of key plant components and services for the biomass industry*, available at: www.energyinst.org/home (accessed 02/18).

[50] Algae Biomass Organisation (2015), *2015 Algae Industrial Survey: Full speed ahead*, available at: http://www.algaebiomass.org/blog/8611/2015-algae-industry-survey-full-speed-ahead/ (accessed 03/28).

[51] Julian, C. (2015), *Food and Fuel forever*, available at: http://www.futuredirections.org.au/publications/associate-papers/1044-food-and-fuel-forever.html (accessed 03/27).

[52] ABO (2015), *What kind of Algae Jobs?*, available at: http://www.algaebiomass.org/blog/5034/what-kind-of-algae-jobs/ (accessed 03/28).

[53] Algae Biomass Organisation (2015), *Thousand Algae Farming Jobs: Billion of dollars*, available at: http://www.algaebiomass.org/blog/5721/thousands-of-algae-farming-jobs-billions-of-dollars/ (accessed 03/28).

[54] Fishman, D., Majumdar, R., Morello, J., Pate, R. and Yang, J. (2010), *National algal biofuel technology roadmap. US Department of energy and Renewable Energy, Biomass Program* , U.S. DOE, Maryland, U.S.A.

[55] Sheehan, J., Dunahay, T., Benemann, J. and Roessler, P. (1998), *A Look Back at the U.S. Department of Energy's Aquatic Species Program—Biodiesel from Algae*, , DOE, USA.

[56] ANL (2012), *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*
, available at: http://greet.es.anl.gov/ (accessed 27/08/2013).

[57] Demirbas, A. and Fatih Demirbas, M. (2011), "Importance of algae oil as a source of biodiesel", *Energy Conversion and Management*, vol. 52, no. 1, pp. 163-170.

[58] OWASA (2015), *WW - Biodiesel report*, available at: http://www.owasa.org/ww-biosolidsreportfy2012 (accessed 03/28).

[59] Harris, R. W., Cullinane, J., M. John and Sun, P. T. (1982), *Process Design and Cost Estimating Algorithms for the Computer Assisted Procedure for Design and Evaluation of Wastewater Treatment Systems (CAPDET)*, , U.S. Environmental Protection Agency, USA.

[60] Sim, T. -., Goh, A. and Becker, E. W. (1988), "Comparison of centrifugation, dissolved air flotation and drum filtration techniques for harvesting sewage-grown algae", *Biomass*, vol. 16, no. 1, pp. 51-62.

[61] Danquah, M. K., Ang, L., Uduman, N., Moheimani, N. and Forde, G. M. (2009), "Dewatering of microalgal culture for biodiesel production: exploring polymer flocculation and tangential flow filtration. J. Chem. Technol. Biotechnol", vol. 84, no. 7, pp. 1078-1083.

[62] UT (2015), *The University of Tennessee - Valve homogenization*, available at: http://web.utk.edu/~fede/high%20pressure%20homogenization.html (accessed 02/28).

[63] GEA Niro Soavi (2015), *High pressure homogenization technology*, available at: http://www.nirosoavi.com/high-pressure-homogenization-technology.asp (accessed 02/28).

[64] K. Sudhakar and M. Premalatha (2012), "Theoretical Assessment of Algal Biomass Potential for Carbon Mitigation and Biofuel Production", vol. 3, no. 3, pp. 232-240.

[65] Weyer, K. M., Daniel, R. B., Al, D. and Bryan, D. W. (2009), "Theoretical Maximum Algal Oil Production", , pp. 3:204–213.

[66] AACE *Recommended cost estimating practice* , 18r - 97, U.S.A.

[67] Langdon, D. (2012), *Spon's Architect and Builders Price Book* , 137th ed, Spon Press, USA and Canada.

[68] Benemann, J. R. (2008), "Opportunity and Challenges in Algae Biofuels Production ", .

[69] Weissman, J. C., Tillett, D. M. and Goebel, R. P., (1989), *Design and Operation of an Outdoor Microalgae Test Facility - Final Subcontract Report,* XK-7-06113-1, SERI, USA.

[70] Towler, G. and Sinnott, R. (2013), "Chapter 7 - Capital Cost Estimating", in Towler, G. and Sinnott, R. (eds.) *Chemical Engineering Design (Second Edition),* Butterworth-Heinemann, Boston, pp. 307-354.

[71] Humbird, D. e. a. (2009), *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol,* NREL Technical Report, NREL Technical Report, http://www.nrel.gov/docs/fy11osti/47764.pdf.

[72] weissman, J. C., and Goebel, R. P. (1987), *Design and Analysis of "' Microalgal Open Pond Systems for the Purpose of Producing Fuels,* DE87001164, SERI, Florida USA.

[73] Towler, G. and Sinnott, R. (2013), "Chapter 8 - Estimating Revenues and Production Costs", in Towler, G. and Sinnott, R. (eds.) *Chemical Engineering Design (Second Edition),* Butterworth-Heinemann, Boston, pp. 355-387.

[74] James, W. R., Joe, L. O. and Allison, M. (2010), "The Economics of Microalgae Oil", *2,* vol. 13, no. 4, pp. 119-130.

[75] Gerrard, A. M., (2001), *Guide to capital cost estimating,* 4th ed, IChemE, UK.

[76] Towler, G. and Sinnott, R. (2013), "Chapter 9 - Economic Evaluation of Projects", in Towler, G. and Sinnott, R. (eds.) *Chemical Engineering Design (Second Edition)*, Butterworth-Heinemann, Boston, pp. 389-429.

[77] HM Treasury (2014), *Gross Domestic Product Deflators: Users Guide*, available at: https://www.gov.uk/government/statistics/gdp-deflators-at-market-prices-and-money-gdp-march-2013 (accessed 11/07).

[78] Ryan E. Davis, Daniel B. Fishman, Edward D. Frank, Michael C. Johnson, Susanne B. Jones, Christopher M. Kinchin, Richard L. Skaggs, Erik R. Venteris, and Mark S. Wigmosta (2014), "Integrated Evaluation of Cost, Emissions, and Resource Potential for Algal Biofuels at the National Scale", *Environmental Science & Technology*, vol. (10), no. 48, pp. 6035-6042.

[79] ANL, NREL, and PNNL, ((June 2012).), *Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model.* ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437, Argonne, IL: Argonne National Laboratory; Golden, CO: National Renewable Energy Laboratory; Richland, WA: Pacific Northwest National Laboratory.

[80] The Scottish government (2014), *Economic Input-output Table*, available at: http://www.scotland.gov.uk/Topics/Statistics/Browse/Economy/input-output (accessed 11/14).

[81] Sanjiv Mahajan (ed.) (2006), *United Kingdom Input-Output Analysis Consistent with the 2006 Blue Book and 2006 Pink Book*, 6th ed, National statictics, London: Office for National Statistics.

[82] Algae Biomass Organisation (2015), *Algal Biomass Summit plenary session 2011*, available at: http://www.algaebiomass.org/resource-center/references/reports-studies/ (accessed 03/2015).

[83] Griffiths, M., and Harrison, S. T. L., (2009), "Lipid productivity as a key characteristic for choosing algal species for biodiesel production", *J Appl Phycol*, vol. 21, no. 5, pp. 493-507.

[84] Yang, J., Xu, M., Zhang, X., Hu, Q., Sommerfeld, M. and Chen, Y. (2011), "Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance", *Bioresource technology*, vol. 102, no. 1, pp. 159-165.

[85] Gerbens-Leenesa, W., , A., Y. Hoekstraa, , Theo, H. van der Meerb and , (2009), "The water footprint of bioenergy", *PNAS*, , no. 106, pp. 10219-10223.

[86] Dominguez-Faus, R., Powers, S. E., Burken, J. G., and Alvarez, P. J., (2009), "The water footprint of biofuels: A drink or drive issue?", *Environ. Sci. Technol.*, vol. 43, pp. 3005-3010.

[87] Chinnasamy, S., Bhatnagar, A., Hunt, R.W., Das, K.C., (2010), "Microalgae cultivation in a wastewater dominated by carpet mill effluents for biofuel applications", *Bioresour. Technol.,* vol. 101, pp. 3097-3105.

[88] Vandamme D, , Pontes SCV, , Goiris K, , Foubert I, , Pinoy LJJ, and Muylaert K (2011), "Evaluation of electro-coagulationflocculation for harvesting marine and freshwater microalgae", *Biotechnol Bioeng*, vol. 10, no. 108, pp. 2320-2329.

[89] Phyco, B. (2015), *Phyco Biosciences Super Trough System*, available at: http://www.phyco.net/Technology.html (accessed 11/2015).

[90] Jonathan, N. R., Julian, N. R., Bernardo, J. G., Victor, H., Luz Elena, M., Abbas, G., Michael, J. B., George, A. O. and Marc, D. D. (2013), "A critical analysis of paddlewheel-driven raceway ponds for algal biofuel production at commercial scales", vol. 4, pp. 76-88.

[91] Chisti, Y. (2012), "Raceways-based Production of Algal Crude Oil", in Clemens Posten, C. W. (ed.) *Microalgal Biotechnology: Integration and Economy*, 978-3-11-022501-3 ed, De Gruyter, , pp. 112-146.

[92] Chisti, Y. and Yan, J. (2011), "Energy from algae: Current status and future trendsAlgal biofuels – A status report", vol. 88, pp. 3277–3279.

[93] Bacon, R., Kojima, M., 2011. Issues in estimating the employment generated by energy sector activities, Background paper for the World Bank Group energy sector strategy. Washington DC: Sustainable Energy Department, World Bank.

[94] International Labour Organization (ILO), 2013. Sustainable development, decent work and green jobs. Reportof the 102nd session of the International Labour Conference. Geneva: ILO.

[95] International Labour Organization (ILO), 2015. World employment and social outlook – Trends 2015. Geneva: ILO.

[96] Kammen, D.M., Kapadia, K., Fripp, M., 2004. Putting renewables to work: how many jobs can the clean energy industry generate? Report of the Renewable and Appropriate Energy Laboratory. Berkley, CA: University of California, Berkeley (corrected January 2006).

[97] Kojima, M., Johnson, T., 2005. Potential for biofuels for transport in developing countries, Energy Sector Management Assistance Programme. Washington DC: The World Bank.

[98] Martinez-Fernandez, C., Hinojosa, C., Miranda, G., 2010. Greening Jobs and Skills: Labour Market Implications of Addressing Climate Change, OECD Local Economic and Employment Development (LEED) Working Papers, 2010/2. Paris: Organisation for Economic Co-operation and Development.

[99] United Nations Environmental Programme (UNEP), 2011. Towards a green economy: pathways to sustainable development and poverty eradication – a synthesis for policy makers. Geneva: United Nations Environmental Programme.

[100] United Nations Environmental Programme (UNEP), 2014. Measuring the environmental goods and services sector: Issues and challenges. Geneva: United Nations Environmental Programme

[101] United Nations Framework Convention on Climate Change (UNFCCC), 2007. Investment and financial flows to address climate change. Bonn: United Nations Framework Convention on Climate Change.

[102] Bowen, A., 2012. "Green" Growth, "Green" Jobs and Labor Markets, Policy Research Working Paper No.5990. Washington DC: World Bank.

[103] Bowen, A., K, Kuralbayeva., 2015 Looking for green jobs: the impact of green growth on employment, Policy Briefs

[104] F, Neuwahl., A, Löschel., I, Mongelli., and L, Delgado., Employment Impacts of EU Biofuels Policy: Combining Bottom-up Technology Information and Sectoral Market Simulations in an Input-output Framework. Centre for European Economic Research. Discussion Paper No. 08-049

[105] Bio-era, 2009., U.S. Economic Impact of Advanced Biofuels production: perspective to 2030. Bio Economic Research Associates

[106] UKERC., 2014., Low carbon jobs: The evidence for net job creation from policy support for energy efficiency and renewable energy. UK energy research centre.

[107] EC - Commission of the European Communities, 2003a. Biofuels directive: DIRECTIVE 2003/30/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport.

[108] Michaels, R., Murphy, R.P., 2009. Green jobs: fact or fiction? Houston: Institute for Energy Research.

[109] Morriss, A.P., Bogart, W.T., Dorchak, A., Meiners, R.E., 2009. Green jobs myths, University of Illinois Law & Economics Research Paper No. LE09-001 and Case Western Reserve University Research Paper Series No. 09-15. Champaign, IL: University of Illinois, Case Western Reserve University

[110] Hughes, G., 2011. The myth of green jobs, Report No.3. London: The Global Warming Foundation

[111] A novel technology to produce microalgae biomass as feedstock for biofuel, food, feed and more. http://phys.org/news/2015-10-technology-microalgae-biomass-feedstock-biofuel.html

APPENDICES

Appendix A

A.1 Introduction

The main purpose of this appendix is to provide the derivation of the primary relationship of the several sheets linked in the techno-socioeconomic model. And to show the several assumptions used in the model. Understanding the bases for the techno-socioeconomic model makes it easier to assess the reliability and accuracy.

The main goal of this appendix is to provide the derivation of the primary relationship of the several sheets linked in the techno-socioeconomic model, also, to show the several assumptions used in the model. Understanding the basis for the techno-socioeconomic model would make it easier to assess the reliability and accuracy of the model.

A.2 Input data worksheet

The first calculation in this worksheet is the areal productivity of the microalgae, this calculation determines the pond surface area required to produce the desired biomass, operating parameters required, and calculation of the capital and operating cost. The method of estimating the areal productivity of microalgae is adopted from equation used by (K. Sudhakar and M. Premalatha, 2012).

$$Biomass_{daily}\ (BM_{daily}\ g/dw/d) = \frac{Productivity\ scale\ (L/d)}{Lipid\ content\ (\%\ wt)}$$ **Eq A-1**

$$Total\ biomass\ required\ (BM_T\ g/dw/d) = \frac{BM_{daily}\ \ g/dw/d}{Extraction\ _{eff.}\ (E_{eff.})}$$ **Eq A-2**

Where:

BM_{daily} = biomass produced gram of dewatered algae per day

BM_T = Total biomass required in cultivation pond gram of dewatered algae per day

$E._{eff.}$ = Extraction Efficiency (80%) Productivity scale 1000 bbl/d = 158,987 litres per day

A.3 Calculations of energy requirement for mixing open pond

Continues mixing of the culture medium using paddlewheels to keep the algae on the surface for even distribution of sunlight, and nutrient distribution is require. Mixing is discussed in chapter 3.

$h_b = \frac{(k.v^2)}{2.g}$	**Eq A-3**

K = is the kinetic loss coefficient for 180° bends (theoretically = 2),

v = is the velocity of the raceway (0.25 m/ s^{-1})

g = is the acceleration due to gravity (9.8 m/s^{-2}).

$H_L = v^2 n^2 \left[\frac{L}{R^{4/3}}\right]$	**Eq A-4**

n = is the roughness factor (0.015 for polyethylene)

R = is the channel hydraulic radius (0.29 m)

L = is the channel length (630 m^2 = 1260 m).

$W = 9.80 \left[\frac{Qwh}{e}\right]$	**Eq A-5**

Q = is the volumetric flowrate (1.1 m3 s−1),

w = is the unit mass of water (998 kg m3),

h = is the total head loss (Head loss in bend + head loss in sump + frictional loss),

e = is the paddle wheel and drive system efficiency (40% assumed),

9.8 = is the conversion factor in W-s kg-m−1.

Capital and operating cost calculations

$$TCI = FCI + LC + WC$$	**Eq A-6**

Where:

FCI = fixed capital investment (total direct cost + indirect costs)

LC =land cost

WC = working capital

$$FCI = TDC + IC$$	**Eq A-7**

Where:

TDC = total direct cost (total equipment cost + direct cost)

IC = indirect capital cost (contingency, field expenses, Prorateable cost, and other costs related to construction.)

$$TDC = ISBL + DC$$	**Eq A-8**

Where:

$ISBL$ = inside battery limit (major equipment cost + labour construction cost)

DC = direct cost (site development + warehouse)

$$a_{sp} = \frac{a_{rqd}}{n_p}$$	**Eq A-9**

$$n_p = \frac{a_{rqd}}{a_{sp}}$$	**Eq A-10**

a_{sp} *= area of a single pond (h)*

a_{rqd} *= area required (h), total area required to cultivate the desired biomass*

n_p*= number of ponds*

Appendix B Construction cost estimation

B.1 Introduction

B.1.1 Pond construction cost

The main geometric parameters for pond are:

- Pond size
- Number of channels
- L/W ratio (centre wall divider) – (length of single pond without bend)/(width single channel)

$$Biomass_{daily}\ (BM_{daily}\ g/dw/d) = \frac{Productivity\ scale\ (L/d)}{Lipid\ content\ (\%\ wt)}$$	**Eq B-1**

The pond size and shape depends on:

- Economic factors
- Effect on other system designs
- mixing
- carbonation

Earthwork

Rough grading is clearing, cutting backfilling and compacting to prepare site for construction. This process is done with conventional earth moving equipment. The cost rough grading would depend on the characteristics of the terrain, grading a rough or sloping terrain can be a significant cost factor. This step is necessary in algae farm construction to prevent settlement.

$$costs\ of\ rough\ grading = total\ pond\ area\ X\ unit\ price$$

Laser levelling equipment is used to achieve the tolerance required for shallow ponds, to achieve flat channels to meet hydraulic requirement, high cost process in pond construction, as each slope set separately

Wall

Concrete block

- concrete footing 15cmx30cm 6”x12”
- 2 courses 4” x 8” x 16” blocks set on top
- block cell is filled with gravel concrete and reinforcement bar
- the estimated costs

Poured concrete

- divider wall on a 15 cm x 30 cm footing cm thick and 40 cm high
- custom made reusable forms are propose
- 4 no reinforcement bar would be set along the upper part of the wall to hold the walls together and minimize cracking
- sealed with silicone costs is estimated

Curved flow deflectors

- minimize the extent of eddy formation and eliminate solid deposition
- can be built with the same material with the straight wall

Sumps

- necessary to provide deepen area for CO2 additions
- helps achieve high absorption
- collection point when draining the pond
- may also provide an area of reduce velocity where inert solids and organic matter accumulate
- a sump depth of 1.5 meters will results in 95% absorption of CO_2

Solid removal

- is the accumulation of inert and organic solids
- they settle in stagnant area within the ponds

Carbonation

- to supply CO_2
- distribution pipes span the channel on downstream side of the sump
- spare spaced along its length

Instrumentation

- information to ensure temperature and dissolved oxygen, pH, CO_2 flow rate and makeup water flowrate will be provided for each pond
- it is a microcomputer based data acquisition unit which records data and prepare summary reports
- low cost
- would be installed at each harvesting station

731 ponds	4 hectare each						
Item No:	**Description**	**Quantity**	**Units**	**Unit Cost**	**Total**	**Hectares**	
	Growth Ponds						
1	Earthworks						
1.1	Rough Grading	2925	hectare	1230	£3,598,201	£888.01	3.3%
1.2	Lazer levelling	2925	hectare	1200	£3,510,440	£866	3.2%
1.3	Finish Grading	2925	hectare	2100	£6,143,270	£1,516	5.6%
1.4	Sump Excavation	37040031	m^3	1.911	£70,797,839	£17,472	64.2%
1.5	Pond liner	314884092.1	sq ft	0.28	£87,317,359	£21,549	44.2%
						£20,743	76.2%
2	Walls & Structural						
2.1	Straight Walls	43062	m	4	£172,248	£43	0.2%
2.1	Curved Walls	6494	m	5	£32,470	£8	0.0%
2.1	Flow Deflectors	10485	sq ft	5	£52,425	£13	0.0%
2.1	Sump bottom	1956	cu yd	100	£195,600	£48	0.2%
2.1	Sumps ends	104	cu yd	200	£20,800	£5	0.0%
2.1	Rails & Piers	13559	ft	12	£162,708	£40	0.1%
2.1	Solids Removers				£61,000	£15	0.1%
3	Mixing System						
3.1	Paddle Wheels	731	nr	£20,790	£15,204,880	£3,752	13.8%
3.2	P.W Structural	731	nr	1500	£1,097,013	£271	1.0%
3.3	P.W Depression	331	cu yd	150	£49,650	£12	0.0%
						£4,035	
4	Carbonation System	731.3417016	Ponds	8637.6	£6,317,037	£1,559	5.7%
5	Instrumentation	731.3417016	Ponds	4000	£2,925,367	£722	2.7%
						£0	0.0%

	Total without liner	£110,340,948	£27,231.23	100.0%
	Total with liner	£197,658,307	£48,780.43	

Table 0-1 Estimate of pond construction cost

B.1.2 Harvesting

Table 0-2 Breakdown harvesting costs

PIPE	
All pipe is "100 ft head PVC includes installation	
Pond drain lines	
22" dia x 2300 ft @ £20/ft	£46,000
Effluent return lines	
22" dia x 1100 ft @ £20/ft	£22,000
Settling ponds supernant drain system	
16" dia x 200 ft @ £12/ft	£2,400
Valves	
All valves are low head type with epoxy coated cast iron bodies, stainless steel; structures, installed	
Pond drain (2 per pond)	
16 x 22" canal gate @ £1200	£19,200
Effluent return	
8 x 22" canal gate @ £ 1200	£9,600
4 x 18" adapt to line gates @ £1500	£6,000
Check valves at pumps 3 @ £600	£1,800
Air release valves 10 @£250	£2,500
Pumps	
Primary supernant, includes motor, smarter and installation	
3 x 12" vertical mixed flow pumps @ £9000	£27,000
Sumps with pump support	£7,000
Fittings and Misc.	£12,500
Total cost harvesting station	£156,000
Total cost /hectare	

Appendix C

Operating cost estimation

C.1 Introduction

The operating costs estimate describe below is used for the baseline study used that is used as a reference in the economic model, and also for the parametric analysis in chapter 7.

C.2 Water model

The required make up water was model from net evaporation loss of 0.225 inches per day from an open pond based on average pan evaporation of 0.3 inches per day, and a lake correlation factor of 0.75.

Table 0-3 Estimated evaporation loss

Water Model	Per unit	grams of algae
Inputs required		
Evaporation loss L/g algae		2.29E-02
Productivity rate g/m^2/d		
	25.00	
Evaporation loss L/m^2/d		5.72E-01
Pan evaporation in/d		0.03
Pan correlation factor		0.75
Inches to m conversion factor		0.0254

Table 0-4 Water consumption calculation

Culture concentration g/L	5.00E-01
Output of algae concentration from 1st dewatering g/L	10
Algae retention efficiency	90%
Fraction of 1st dewatering stage separated water sent to waste	0%
Fraction of 1st dewatering returned to process	100%
Evaporative loss L/net g algae	4.23E-02
Media loss overhead per g algae, L/net g algae	0.00E+00
Growth media, L/net g algae	2.00E+00
Total water, L/net g algae	2.04E+00
Water passed downstream from 1st dewatering, L/net g algae	1.00E-01
Water separated in 1st dewater, L/net g algae	2.12E+00
Water sent to waste, L/net g algae	0.00E+00
Water returned for media make up, L/net g algae	2.12E+00
Water returned from other operations, L/net g algae	9.44E-02
New water introduced for media make-up, L/net g algae	4.79E-02
New water introduced for cooling, L/net g algae	0.00E+00
Water Consumption	
Water consumption, L/net g algae	0.047855556

C.3 Energy requirement

Table 0-5 Energy requirement for each stage of the process

Growth and first	6.20E-03	KWh/g algae		

dewatering			1,495,142,691	164,465,696
Remaining dewatering	1.75E-04	KWh/g algae	42,234,983	4,645,848
Lipid extraction	9.27E-04	KWh/g lipid	44,744,948	4,921,944
Anaerobic digestion	8.50E-05	KWh/g algae	20,514,135	2,256,555
Off-site CO_2 transfer into pond	4.20E-05	KWh/g algae	10,136,396	1,115,004
Recovered CO_2 transfer into pond	1.99E-04	KWh/g algae	48,027,210	5,282,993

C.4 Nutrients requirement

	g/g dw algae of CO_2	Total grams	grams to metric to	grams to metric tons p	£/L	Total cost
CO_2 required	2.24	1,638,205,412	1638.21	540,608	£23.6/tonne	12,758,343.75
	g/g dw algae N, P					
DAP	0.017	12,579,077	12.58	4,151	260	1,079,285
Ammonia	0.019	13,968,627	13.97	4,610	240	1,106,315
Chitosan	4.00E-03	2,925,367	2.93	965	59	56,957

	g/g dw algae of CO2	Total grams	grams to metric to	grams to metric tons p	£/tonne	
CO_2 required	2.24	1,638,205,412	1638.21	540,608	£23.6/tonne	12,758,343.75
g/g dw algae N, P						
DAP	0.017	12,579,077	12.58	4,151	260	1,079,285
Ammonia	0.019	13,968,627	13.97	4,610	240	1,106,315
Chitosan	4.00E-03	2,925,367	2.93	965	59	56,957

Appendix D

Table 0-6 Equity repayment estimate

Equity - Corporate Investment Repayment Schedule			
Year	Interest Pmt	Principal Pmt	Total Pmt
1	£36,321,465.27	£6,675,359.52	£42,996,824.79
2	£34,409,809.20	£7,342,895.48	£41,752,704.68
3	£32,498,153.13	£8,077,185.02	£40,575,338.16
4	£30,586,497.07	£8,884,903.53	£39,471,400.59
5	£28,674,841.00	£9,773,393.88	£38,448,234.88
6	£26,763,184.93	£10,750,733.27	£37,513,918.20
7	£24,851,528.87	£11,825,806.59	£36,677,335.46
8	£22,939,872.80	£13,008,387.25	£35,948,260.05
9	£21,028,216.73	£14,309,225.98	£35,337,442.71
10	£19,116,560.67	£15,740,148.58	£34,856,709.24
11	£17,204,904.60	£17,314,163.43	£34,519,068.03
12	£15,293,248.53	£19,045,579.78	£34,338,828.31
13	£13,381,592.47	£20,950,137.75	£34,331,730.22
14	£11,469,936.40	£23,045,151.53	£34,515,087.93
15	£9,558,280.33	£25,349,666.68	£34,907,947.02
16	£7,646,624.27	£27,884,633.35	£35,531,257.62
17	£5,734,968.20	£30,673,096.69	£36,408,064.89
18	£3,823,312.13	£33,740,406.35	£37,563,718.49
19	£1,911,656.07	£37,114,446.99	£39,026,103.06
20	£0.00	£40,825,891.69	£40,825,891.69
21	FALSE	FALSE	£0.00
22	FALSE	FALSE	£0.00
23	FALSE	FALSE	£0.00
24	FALSE	FALSE	£0.00

25	FALSE	FALSE	£0.00
26	FALSE	FALSE	£0.00
27	FALSE	FALSE	£0.00
28	FALSE	FALSE	£0.00
29	FALSE	FALSE	£0.00
30	FALSE	FALSE	£0.00
Total	£363,214,652.67	£382,331,213.33	£745,545,866.00
Avg/annu	£18,160,732.63	£19,116,560.67	£37,277,293.30

Appendix E

E.1 Introduction

E.2 Multipliers

Jobs Per Million GBP Change in Employment									
	Jobs Direct Multipliers		Jobs Indirect Multipliers		Jobs Induced Multipliers			(PCE)	
	My County	My Region	My County	My Region	My County	My Region		MyCounty	MyRegion
Aquaculture		1.6		17		0.2			0.1
Mining		1.0		102		1.0			1.0
Construction		7.2		2		0.6			1.0
Manufacturing		1.6		23		0.3			0.6
Fabricated Metals		1.3		89		0.5			1.3
Machinery		1.3		80		0.4			0.6
Electrical Equipment		1.4		60		0.4			0.3
TCPU		4.8		2		0.4			0.7
Wholesale Trade		1.5		38		0.5			0.3
Retail Trade		1.5		29		0.5			0.3
FIRE		3.9		2		0.4			0.5
Misc.Services		6.5		3		0.4			0.6
Professional Services		7.6		3		0.6			0.3
Government		1.4		0		0.5			0.3

Figure 0-1 Multipliers spreadsheet from the socio-techno-economic model

Appendix F

F.1 Introduction

F.2 Input data and results summary

MAIN INPUT		Checks
Barrels per day	1,000.00	
gallons per day	42,000.00	13,860,000.00
gallons/hr	1,750.00	
L/hr	6,624.47	158,987.33
g oil/ L	920.00	
g oil/hr	6,094,514.18	
Biomass required (after extraction) (g DW/hr)	24,378,056.72	
Biomass required (before extraction) (g DW/hr)	30,472,570.90	
g DW/ day	731,341,701.62	
Algae Productivity Rate(g/m^2.d)	25	
Algae Lipid content (% wt)	25%	
Total annual algae areal biomass yield (g/yr)	241,342,761,534.15	
Extracted lipid yield L/yr	52,465,817.72	52,465,817.72
Total pond area (m^2)	29,253,668.06	
Total pond area (h)	2,925	
Total facility area (h)	3,510	3503

Figure 0-2 Input sheet as represented in the socio-techno-economic model