Life Cycle Assessment of microalgae-derived biodiesel

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Abstract

The primary purpose of this research was to determine the environmental impacts of microalgae-derived biodiesel, through the use of real-world data. The secondary purpose was to propose methods to reduce the environmental impacts of the production of microalgae-derived biodiesel.

The research and analysis were undertaken using data from three sites;

1. An autotrophic/heterotrophic based novel 1-hectare demonstration facility containing four 15m^3 photobioreactor systems and various fermenter systems in Olhão, Portugal (part of the InteSusAl FP7 project)
2. A 1m^3 novel bag based heterotrophic system in Wilton, UK (part of the Innovate UK BioMOD project)
3. A 100m^3 photobioreactor based system in Lisbon, Portugal (part of the Horizon 2020 MAGNIFICENT project)

The data from these three sites was used to construct LCA models within the software GaBi and OpenLCA, utilising Ecoinvent as the primary source of secondary data. Uncertainty analysis was undertaken through sensitivity analysis and through a Monte Carlo based method utilising pedigree matrices. Within this work, ReCiPe hierarchist midpoints and endpoints were considered, in addition to AR5 based climate change indicators (GTW100/20, GTP 100/50/20).

The purpose of this work was to fill a current knowledge gap within the literature, where very few articles on the LCA of microalgae-derived biofuels (including biodiesel) consider data from real world facilities. In addition, no papers consider an autotrophic/heterotrophic based system such as that within this work. The LCA models constructed within this work, and the following publications in the literature, will fill this knowledge gap.

The key findings of this work have been that;

- Algae production facilities as described within this work currently produce higher impacts (AR5 and ReCiPe) than petroleum derived fossil fuels
- As an animal feed alternative, algae does not compete well with soy, although this comparison is more favourable than with fuels.
- The decisions made based on standard arithmetic models within OpenLCA are different to those decisions based on models involving pedigree matrix based Monte Carlo analysis.
- Primary source of impacts were electricity and feedstock (yeast)
- Infrastructure impacts could be reduced through using glass photobioreactors instead of glass.

Key reconditions are;

- Algae producers consider alternative products to produce from microalgae
- Improvements of photobioreactors should be considered to reduce the electricity demand of pumps, even if this is at the expense of productivity
- Productivity must be increased to at least >25.6 tonnes/hectare/year
- Photobioreactors should be made from glass
- There must be further research into uncertainty methods within LCA, and their impacts on decision making processes.

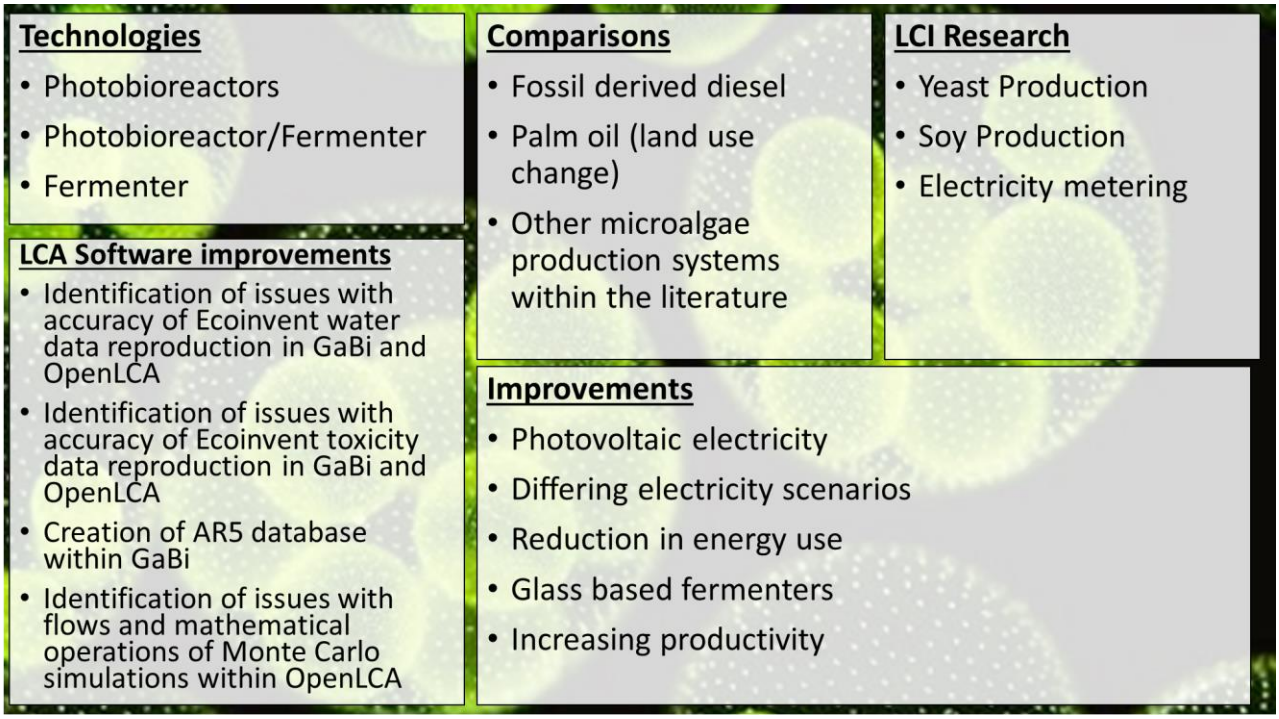

Figure 1: Summary of the various elements of the thesis.

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- InteSusAl, which received funding from the European Union's Seventh Programme for research, technological development and demonstration (Grant Agreement 268164)
- MAGNIFICENT (Microalgae As a Green source for Nutritional Ingredients for Food/Feed and Ingredients for Cosmetics by cost-Effective New Technologies), which received funding from the European Union's Bio-based Industries Research and Innovation action (Grant Agreement 745754)
- BIOMOD. Which received funding from the UK Government's Advanced Manufacturing Supply Chain Initiative.

Contents

Figures

Tables

Abbreviations

Term	Description
AR5	IPCC Fifth Assessment Report
B100	100% Biodiesel
GWP100	Global Warming Potential over a 100-year period
GWP20	Global Warming Potential over a 20-year period
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
MC	Monte Carlo
NER	Net Energy Ratio
NMVOC	Non-Methane Volatile Organic Compounds
NREL	National Renewable Energy Laboratory
PM	Particulate Matter
S-LCA	Social Life Cycle Assessment
SUT	Single-Use Technology
VOC	Volatile Organic Compounds

List of Publications

Published

Bradley, T., Maga, D. and Anton-Lopez, S. (2015) "Unified approach to Life Cycle Assessment between three unique algae biofuel facilities", Applied Energy, 154, pp. 1052-1061.

Ramirez, A.R., Khamlichi, A.E., Markowz, G., Rettenmaier, N., Baitz, M., Jungmeier, G. and Bradley, T. (2020) LCA4CCU: Guidelines for Life Cycle Assessment of Carbon Capture and Utilisation (LCA4CCU001). European Commission.

Bradley T., Maga D. (2019) Life Cycle Analysis of Producing Microbial Lipids and Biodiesel: Comparison with Plant Lipids. In: Balan V. (eds) Microbial Lipid Production. Methods in Molecular Biology, vol 1995. Humana, New York, NY. https://doi.org/10.1007/978-1-4939-9484-7_13

Posters

Bradley, T. (2015) "Life Cycle Assessment of the InteSusAl Algae Biofuel Pilot Facility", European Biomass Conference: The Algae Event, Austria

Bradley, T. (2017) "Life Cycle Assessment of algae production within the BioMOD project", International Bioenergy Conference 2017, Manchester.

Submitted

Bradley, T., Heidrich, O., Kenny, A., Hainsworth, C., Pino, V.d., Inclán, Y.d.V., Povoa, I., Mendonça, P., Brown, L., Smallbone, A., Roskilly, A.P., Joyce, S. and Rajaeifa, M.A. (2020) 'Life Cycle Assessment of microalgae biofuel production from a case study large-scale pilot facility', Applied Energy.

Conferences and Workshops (Speaking)

2nd European Workshop on LCA for Algal Biofuels & Biomaterials (Brussels, Belgium, 24 April 2014)

2014 Algae Cluster Meeting (Seville, Spain, 8 May 2014)

3rd European Workshop on LCA for Algal Biofuels & Biomaterials (Brussels, Belgium, 11 May 2015)

1st InteSusAl Workshop on Sustainable Microalgae Biomass Production (Olhão, Portugal, 21 May 2015)

Algae Europe 2015 (Lisbon, Portugal, 2 December 2015)

European Roadmap for an Algae-Based Industry (Olhão, Portugal, 6-8 April 2016)

Carbon Capture and Utilisation Conference (Brussels, Belgium, 28th April 2017)

Life Cycle Management 2017 (Luxembourg City, Luxembourg, 3rd-6th September 2017)

Additional Events

Presentations at the InteSusAl and MAGNIFICENT project meetings every six months (InteSusAl 2013-2016, MAGNIFICENT 2017-2021).

Regular yearly talk at Bede Academy in Blyth on algae biofuel technologies for Year 11 students.

Chapter 1. Introduction

There is an almost unanimous consensus of 97.1% (Cook *et al.*, 2013) (Cook *et al.*, 2016) amongst climate scientists in the peer-reviewed literature that the majority of the increase in global warming since the year 1750 has been due to human activity. Computer models of the climate have reached a high degree of accuracy, validated by both hindcasting (Solomon *et al.*, 2007) and comparisons of predations with measurements (Hansen *et al.*, 2006; Allen *et al.*, 2013; Hausfather *et al.*, 2020). These models predict that with current emission rates, there will be major issues with flood, drought, famine and disease (Stocker *et al.*, 2013). Even a modest increase in global temperatures of 1.5°C against pre-industrialised levels will cause significant damage to society and life on Earth (Intergovernmental Panel on Climate Change, 2018). Looking to current global plans to fight climate change, under the Paris Agreement, then it can be seen that the world is on track for a 3.4°C temperature increase compared with pre-industrial levels (United Nations Environment Programme, 2019). Society desperately needs solutions to reduce global emissions of greenhouse gases.

Biofuels have been considered one part of the solution; however, there is concern over the impacts of land-use change, which can lead to biofuels having a greater climate change impact than simply using fossil fuels (Fargione et al., 2008; Gibbs et al., 2008; Lapola et al., 2010).

Microalgae-derived biodiesel are one of many possible directions for biofuels (Darzins et al., 2010; Darocha et al., 2013). Microalgae are single-celled organisms, which contain carbon-rich lipids, these lipids can be converted into biodiesel through transesterification, with glycerol as a waste product (Wijffels and Barbosa, 2010; Darocha et al., 2013). The non-lipid parts of the microalgae can be used as high-value products (Borowitzka, 2013) or biomass for energy generators. However, it is very important to ensure that the environmental impacts of producing biodiesel from microalgae are lower than that of the extraction and processing of petroleum-derived diesel fuel. These impacts do not just include climate change, but eutrophication, toxicity, particulate matter and many more. For this reason, the field of research known as Life Cycle Assessment (LCA) is used to assess the processes within microalgae biofuel production, to identify and quantify the levels of environmental impacts. LCA is a moderately new science, which follows the standards ISO 14040 (Environmental management - Life cycle assessment - Principles and framework: ISO 14040, 2006) and ISO14044 (Environmental management - Life cycle assessment - requirements and guidelines: ISO 14044, 2006), as well as guidance such as the International Reference Life Cycle Data System (ILCD) Handbook (Wold et al., 2012). It is important to stress that the purpose for LCA is not to purely say if a product is good or bad, but to understand why, in terms of the environmental hotspots, and what can be done to improve this. It is also very useful to compare two products, to help make a decision on which product to use. It is

not a scoresheet, but a guide towards enhanced environmental and social sustainability.

LCA of microalgae biofuels has shown that results vary significantly due to researchers applying differing methodologies and assumptions (Azadi et al., 2014; Collet et al., 2014; Quinn and Davis, 2015). However, to date, studies have all been based on literature data, estimated growth and scaled-up lab experiments, with very few examples (Passell et al., 2013) (Maga, 2016) which offer evidence-based on real data from large scale real-world facilities. This PhD will address this data gap, through LCA studies of facilities used the InteSusAl, BIOMOD, and MAGNIFICENT projects.

Chapter 2. Literature review

2.1 Microalgae and biofuels

Algae are a diverse group of similar organisms; they include large macroalgae (such as giant kelps) and unicellular microalgae. Microalgae are polyphyletic organisms, which means they have not evolved from a common ancestor (Barsanti and Gualtieri, 2005). Depending on the definition chosen, microalgae can be purely eukaryotes (which means they have a cell membrane) or both eukaryotic and prokaryotic organisms. This means that cyanobacteria (commonly known as blue-green microalgae) are sometimes defined as microalgae, and sometimes not. Whilst both microalgae and plants may well have a common ancestor, they can be regarded as two separate groups (Barsanti and Gualtieri, 2005). Microalgae can gain energy from the environment through either phototrophic (via photosynthesis) or heterotrophic (without light) methods, this energy can then be stored as carbohydrates, protein and oils (lipids).

Microalgae are found in a range of extreme temperature, salinity and pH environments; cyanobacteria have been observed surviving in temperatures up to 73–74°C (Brock, 1967) whilst the highest temperatures eukaryotic microalgae have been observed at 57°C (*Cyanidium caldarium*) (Seckbach and Oren, 2007). Looking at lower temperatures, there are numerous species of algae living on snow and ice, such as *Chlamydomonas nivalis*, *Mesotaenium berggrenii*, *Ancylonema nordenskioldii*, and *Cylindrocystis brébissonii* (Takeuchi, 2001).(Benson *et al.*, 2007). With regard to salinity, *microcoleus chthonoplastes* cyanobacteria have been found in salinities up to 200g/l, whilst *Dunaliella viridis*, a type of green microalgae, can tolerate salinities up to 230g/l. (Seckbach and Oren, 2007) Looking to pH, types of cyanobacteria have been found to tolerate pH levels as low as 2.9, whilst *Cyanidium caldarium* can survive in the pH range of 0 to 4, and the green microalgae *Chlamydomonas acidophila* can survive in pH levels down to the range 1 to 2 (Seckbach and Oren, 2007). With regard to of high pH values, *Euhalothece* (a type of cyanobacteria) has been found in the Sambhar Salt Lake in Rajasthan, India, where there is a range of pH values up to 12. Algae can survive in a range of extreme and changing radiation and temperature environments, (Baqué *et al.*, 2017) showed that *Nostoc sp.* (cyanobacteria) and *Sphaerocystis sp* (a eukaryote) could survive at least 15 months on board the International Space Station (ISS) in Lunar and Martian simulated environments.

Microalgae contain lipids, energy stores of natural oil. These are made up of triacylglycerols (TAGs), three long chains of fatty acids attached to a glycerol backbone. Through processes such as transesterification, these can be converted into Fatty Acid Methyl Esters (FAME), which is commonly known as biodiesel (Peterson, 1986). Prior to the processing stage, the microalgae are grown

(commonly in photobioreactors, raceways or fermenters), harvested, dewatered and separated (Passell *et al.*, 2013; Mohan *et al.*, 2014). The harvesting and dewatering can be implemented through flocculation, centrifuging, solar drying, screening, coagulation, floatation, sedimentation, filtration, or a mixture of these processes (Show and Lee, 2014). The parts of the microalgae which are not lipids contain various complex proteins and carbohydrates and can be used for energy production through anaerobic digestion (Dębowski *et al.*, 2013), pyrolysis (Chaiwonga *et al.*, 2013), hydrothermal liquefaction (Tian *et al.*, 2014) or other processes. Further processing can then include the production of renewable diesel via the Fischer–Tropsch process (Atsonios *et al.*, 2015). These processes can also be used for the whole microalgae, including the lipids, instead of the purely the non-lipid parts.

2.2 History of Microalgae Production for fuel

There is a long history of research into producing biofuels from microalgae. In the 1950s, the idea of generating methane from microalgae was first investigated (Meier, 1955). From 1978 to 1996 the US based National Renewable Energy Laboratory (NREL) carried out the Aquatic Species Program. This research was funded by the United States Department of Energy (Sheehan *et al.*, 1998), and focussed on the use of raceways fed by waste CO_2. The project did not show a positive energy balance for microalgae-based biofuels. Within the Aquatic species program, several demonstration facilities were constructed, including the “Outdoor Test Facility” (OTF) at the site of an abandoned water treatment plant in Roswell, New Mexico. This gave a mean production of 37 tonnes/hectare/year but had maximum productivity of 187 tonnes/hectare/year. CO_2 absorption was at >90%. The facility was shut down in 1990 and has not operated since. The program funded a range of other demonstration facilities, in addition to the lab-based R&D work.

The program led to the isolation of 3,000 species of microalgae, due to funding cuts all but 300 were lost at the end of the program, 51 of which were considered high value strains for biodiesel production. However, after the additional end of a National Science Foundation grant to preserve part of the collection, more were lost. Of the 51 high-value strains, 23 have been lost. Additionally, of the total 3,000 microalgae species isolated, only 150 remain (Madrigal, 2009). The program achieved a number of world firsts, increasing understanding of microalgae species, demonstrating methodologies to increase lipid fractions and genetically engineering of microalgae (Sheehan *et al.*, 1998)

Microalgae research began once more in the US back in 2009, with funding from the American Recovery and Reinvestment Act in 2009, investments included $49 million ($17 million cost share) for the National Alliance for Advanced Biofuels and Bioproducts (NAABB). NAABB is the flagship R&D enterprise of the Bioenergy Technologies Office’s Algal Biofuels Initiative. $35 million ($15 million in

cost-share) was provided to the National Advanced Biofuels Consortium (NABC), and $18 million to establish a process development unit for national laboratories, academia, and industry partners to demonstrate advanced biofuels processes. (*American Recovery and Reinvestment Act of 2009: Bioenergy Technologies Office Investments*, 2009). Whilst priorities within the US have since changed in terms of energy and willingness to fight climate change, work on microalgae biofuels has continued. The Department of Energy has provided various grants for research between research institutes and commercial organisations. In 2019 the Bioeconomy Initiative, a coordinated federal effort to expand the sustainable use of the US's biomass resources for biofuels, bioproducts, and biopower were published by the US Biomass Research and Development Board. The Board is co-chaired by senior officials from the US Departments of Energy (DOE) and Agriculture (USDA) (Biomass Research and Development Board, 2019). Funding for microalgae has continued, and in January 2020 the Department of Energy announced $96m for biofuel development (including advanced microalgae biofuels). Clearly, as demonstrated by the Aquatic Species Program, it is important that the funding continues to ensure that deliverables are not lost after the funding boost.

The European Commission through the Framework Program has invested several million euros in numerous projects and continues to do so. Funding has historically been mainly through the Framework Programme series, the latest of which is Horizon 2020. Specifically, at the moment, the Bio-based Industries Joint Undertaking (BBI JU) is a core part of the Horizon 2020 funded microalgae projects. Relevant past projects funded through the Framework Programme have included the Algae Cluster (InteSusAl, All-Gas and BIOFAT), DEMA, BIOWALK4BIOFUELS, FUEL4ME, D-Factory, AQUAFUELs, AUFWIND, and MIRACLES.

The Algae Cluster deserves special mention; this was an initiative to design, build and operate microalgae biofuel demonstration facilities, utilising a range of technologies, including a harmonised LCA between all three projects (InteSusAl, All-Gat, BIOFAT) (Bradley *et al.*, 2015). InteSusAl (a core part of this thesis) utilised a novel mixture of heterotrophic and autotrophic systems, BIOFAT utilised a raceway-based system, whilst All-Gas integrated the microalgae system with wastewater treatment. InteSusAl and BIOFAT both produced biodiesel, whilst All-Gas produced biogas. The microalgae facilities built as part of InteSusAl have gone on to be utilised within the MAGNIFICENT microalgae bioproduct project, which also features as a data source for this work, and All-Gas also has a follow-on project.

Commercially, there are many facilities producing microalgae for various purposes, usually vitamin supplements, fish food, and high-value products. The companies Algafarm, Necton and Sparos concentrate on the fish feed industry, whilst some other companies such as Algenol, Solazyme, Cellena Inc, and Solix who were primarily focuessed on biofuels have now diversified to nutritional products.

Some of the formers rising stars of the microalgae biofuel industry, such as Sapphire Energy, have now sadly gone.

2.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is the study of the environmental impacts of a particular process or product. The scope of the LCA study can include the full life cycle of a product, from the mining of the original raw materials to the end of life, where it is either disposed of or recycled. LCA can be used to compare the impact of different products on the environment, and to identify hot spots in a process to prioritise improvements to enable reductions in environmental damage.

This is a very young science, which is still developing. The Coca Cola Company carried out the first LCA in 1969. The purpose of this was to understand the impacts of producing glass bottles as opposed to plastic bottles (Hunt and Franklin, 1996). Since then the field has expanded, with numerous standards produced to guide methodology. Detailed independent databases (free and subscription-based) exist on standard processes, allowing researchers to create generic LCA models. The latest major developments within LCA in terms of a policy context have been the creation of the Product Environmental Footprint (PEF) system by the European Commission (European Commission, 2020).

The outline flow of work for an LCA is controlled by the standards ISO 14040 and ISO 14044, (*Environmental management - Life cycle assessment - requirements and guidelines: ISO 14044*, 2006; *Environmental management - Life cycle assessment - Principles and framework: ISO 14040*, 2006), further guidance is given by the International Reference Life Cycle Data System (ILCD) handbook (Wold *et al.*, 2012). Specific methodologies for the LCA of biofuels, purely with regard to climate change impacts are given by the European Commission's Renewable Energy Directive (European Commission, 2019). However, it is important to stress that an ISO 14040/14044 compliant LCA must include a wide range of environmental impacts.

The four stages of ISO 14040 LCA are:

1. **Goal and Scope definition**: The assumptions behind the analysis and the intended purpose for the LCA
2. **Life Cycle Inventory analysis (LCI)**: Data collection and calculation procedures to quantify relevant inputs and outputs of a product system.
3. **Life Cycle Impact Assessment (LCIA)**: Evaluating the significance of potential environmental impacts using the LCI results.
4. **Life Cycle Interpretation**: Analysis of the previous stages, resulting in recommendations for the process studied.

These stages run iteratively, as the LCA study adapts based on data and various factors discovered throughout the study. These are presented in Figure 2-1, and in Figure 2-2 how the chapters of this

thesis relate to this methodology is demonstrated.

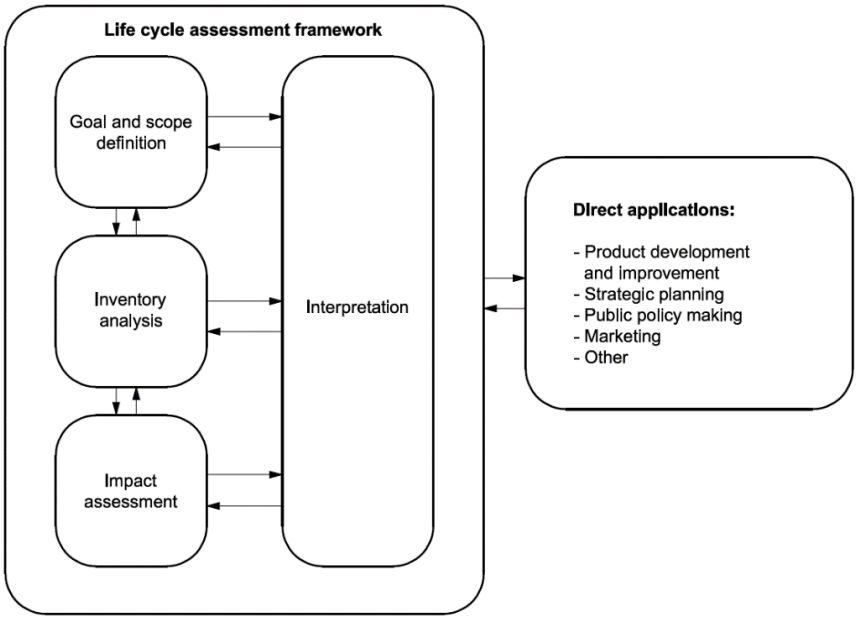

Figure 2-1: Basics of an LCA (Environmental management - Life cycle assessment - Principles and framework: ISO 14040, 2006)

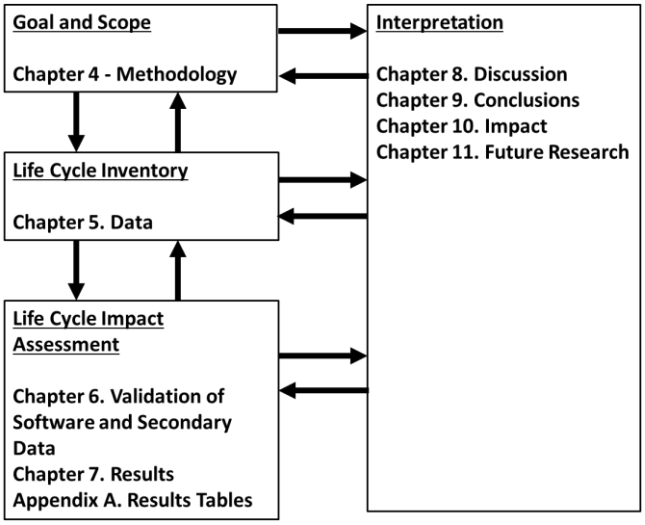

Figure 2-2: How the structure of this thesis fits with the ISO methodology

These four parts of an LCA are described in detail below.

2.3.1 *Goal and Scope Definition*

This is essentially the decision of what is to be studied, and why. It includes the definition of the functional unit, the boundary conditions and impact categories. However, the standards have no formal way of guiding the researcher on these decisions. These are described within ISO 14040 as in Table 2-1.

Table 2-1: ISO Goal and Scope requirements

Decision	Description
Goal	The reason for carrying out the study, including who it is for, and if the analysis is a comparative assessment
Function	The function of the system which is being studied, so in the case of this work, the production of biodiesel from microalgae
Functional Unit	The unit that all measurements are to be made against. In this particular case, it could be 1MJ of fuel, 1kg of fuel, enough fuel for 1 km of travel, or many others.
Boundary Conditions	The limit of what is being measured. So going outwards to the chemicals used, where they came from, how they were refined, etc. Ultimately, a line must be drawn around a process to know when to stop.
Allocation procedures	Systems create co-products or use co-products from other systems. Therefore it is important to work out how to deal with this. Methods can include system expansion (including the co-product processes within the boundary conditions).
Data requirements	What level of data accuracy is needed?
Assumptions	There will be assumptions within an analysis, as data is sometimes difficult to source. What assumptions are expected and how acceptable are they?
Limitations	Based on the above, what limitations will the study include?
Initial data quality requirements	What level of accuracy is required from the data?
Type of critical review, if any	Who will review the resulting report, and to what level?
Type and format of the report required for the study?	What type of report will be the result of this work? A peer-reviewed journal article? A conference paper? A confidential internal report?

2.3.2 *Life Cycle Inventory analysis (LCI)*

This is the process of gathering all of the data necessary for the LCA. This includes a detailed understanding of all the processes within the boundary conditions, their relationship to each other, and how the processes relate to the functional unit.

2.3.3 *Life Cycle Impact Assessment (LCIA)*

The LCIA is the process of analysing the data from the LCI. There is a range of software tools that can significantly assist with this task, including GaBi, SimaPro, OpenLCA and AMEE. The impacts from the system can then be normalised according to the impact categories, to show the impacts with respect to various methodologies. Numerous Impact Categories exist and must be chosen according to their relevance to a particular study. Impact methodologies include; Anthropogenic stock extended Abiotic Depletion Potential (AADP), Centrum voor Millikunde Leiden (CML), Environmental Development of Industrial Products (EDIP), Impact 2002+, International Reference Life Cycle Data System (ILCD) Recommendation. ReCiPe, Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1, UBP 2006, USEtox, Eco-Indicator 99 and PE LLCIA Survey 2012.

The types of impacts which are considered can include resource usage and different forms of pollution to the land, sea, water supplies and air. One example of impacts is that of the ReCiPe methodology for Life Cycle Impact Assessment (LCIA)*; this covers Mid Points and End Points. Mid-points look at the result in the short term, so for climate change, this can be the increase in radiative forcing in CO_2 equivalent over a period of 100 or 20 years, whilst End Points are the eventual result of the environmental impact. So, for example, human life lost, species extinct etc. The Mid Points for ReCiPe include:

1. Climate change [kg CO_2 eq]
2. Ozone depletion [kg CFC-11 eq]
3. Terrestrial acidification [kg SO_2 eq]
4. Freshwater eutrophication [kg P eq]
5. Marine eutrophication [kg N eq]
6. Human toxicity [kg 1,4-DB eq]
7. Photochemical oxidant formation [kg NMVOC]
8. Particulate matter formation [kg PM10 eq]
9. Terrestrial ecotoxicity [kg 1,4-DB eq]
10. Freshwater ecotoxicity [kg 1,4-DB eq]

* Designed by Netherlands National Institute for Public Health and the Environment (RIVM), University of Leiden Institute of Environmental Sciences (CML), PRé Consultants, and Radboud Universiteit Nijmegen Dębowski, M., Zieliński, M., Grala, A. and Dudek, M. (2013) 'Algae biomass as an alternative substrate in biogas production technologies—Review', *Renewable and Sustainable Energy Reviews*, 27, pp. 596-604.

11. Marine ecotoxicity [kg 1,4-DB eq]
12. Ionising radiation [kg 235-U eq]
13. Agricultural land occupation [m^2a]
14. Urban land occupation [m^2a]
15. Natural land transformation [m^2]
16. Water depletion [m^3]
17. Metal depletion [kg oil eq]
18. Fossil depletion [kg Fe eq]

2.3.4 *Life Cycle Interpretation*

This phase is essentially the assessment of the data provided by the LCIA, and relating this to the Goal and Scope. This phase includes giving recommendations for improvements in a system and comments on how it compares to other systems, as carbohydrates, protein and oils (lipids).

2.4 Microalgae Biofuel LCA

Over the past two decades, the interest in microalgae biofuel LCA has increased significantly. Based on a search of Elsevier's ScienceDirect.com, in 2000 there were no papers published on LCA of microalgae biofuels. In 2019 the number was 179. The majority of microalgae biofuel LCA research is based on hypothetical facilities. Some of these extrapolate data from smaller lab tests, whilst others compare multiple scenarios through Monte Carlo simulations. There are a number of issues with these, as they are based on either dramatically extrapolated data from laboratory tests, or on data from multiple sources which are not representative of a particular single microalgae biofuel facility. There are a small number of LCAs based on real facilities, which will be discussed later.

There are numerous issues with microalgae biofuel based LCA. Some of these issues are generic, applicable to the whole of LCA as a field, whilst others can be argued to be more specific to microalgae-based biofuels. One significant issue, which can be argued to be general to LCA, is the lack of comparability within apparently similar LCAs. Although ISO 14040 and 14044 give a general methodology, they do not give methods for making the various choices within the LCA. The functional unit, boundary conditions, and impact categories are left up to the particular researcher to decide upon. Even guidelines developed specifically to the LCA of microalgae fuels leaves these decisions to the researcher (Hosseinzadeh-Bandbafha *et al.*, 2019). This means that seemingly similar LCAs are in fact quite different. Additionally, areas of ISO 14040/14044, such as the range of impact categories to be studied are often not followed. This is an issue because it means that the wealth of knowledge of the impacts of products, such as microalgae, cannot easily be compared, and thus the literature does

not integrate well together. Having a strict methodology per product would allow for greater comparison, just as the European Union's Product Environmental Footprint (PEF) does. However, in turn, this would mean that subtleties would be lost in the studies, the microalgae industry's biorefineries are still not mature on the level of petrochemical refineries, and when undertaking an LCA for lower TRL facilities, as is the case in microalgae, LCA studies need to be adaptive, with Goal and Scopes designed around what data is available, impact categories based around what is specifically of interest for that study, and Life Cycle Inventories based around what is possible to achieve.

2.4.1 *Functional Unit*

The functional unit essentially describes what is measured. Whilst some research uses 1kg of microalgae (Collotta *et al.*, 2018), typically, microalgae biofuel LCA seems to focus on the energy content of the fuel, and so have a functional unit of 1 MJ (Batan *et al.*, 2010; Azari *et al.*, 2019) (whilst (Sander and Murthy, 2010) uses 1000 MJ. (Brentner *et al.*, 2011) uses 10000 MJ and (Clarens *et al.*, 2010) uses 317 GJ). However, some of the literature uses a functional unit of 1 kg of fuel (Lardon *et al.*, 2009; Wu *et al.*, 2019; Branco-Vieira *et al.*, 2020a), 1 ton (Stephenson *et al.*, 2010) or one tonne-km (Campbell *et al.*, 2011). Using these functional units in itself seems logical; however, there are problems. Initially, it needs to be stated that there is no current consensus of the energy content or density of algal oil or algal methylester. Within the literature, the energy content value ranges from 42 MJ/kg (Khoo *et al.*, 2011) to 24 MJ/kg (Clarens *et al.*, 2010). Ultimately, though, these systems are hypothetical, so there is no real fuel to carry out an energy content analysis test on. Looking to general values for the energy content of biofuels, according to (Tesfa *et al.*, 2013) and data within it from (Giakoumis, 2013) values for traditional biofuels range from 36.49 MJ/kg for karanja derived biodiesel to 39.54 MJ/kg for linseed derived biodiesel.

Additionally, this energy content (which has no consensus) can be based on either the lower heating value (LHV) or higher heating value (HHV). (Collet *et al.*, 2014) LHV is more appropriate for vehicle purposes, where no effort is taken to extract the energy from exhaust gases. Hence, LCAs which appear to have the same functional unit might not. By using energy contents which are too high, the impacts of microalgae biofuels are artificially reduced.

Furthermore, some of the literature uses algal biomass as the functional unit, not the end product fuel. For example, (Soratana and Landis, 2011) uses a functional unit of 3650 kg of microalgae. All of these differences make it complex to fairly compare LCA studies of microalgae biofuels.

2.4.2 *Boundary Conditions*

The boundary conditions vary for microalgae-based biofuels. Whilst some work will consider the fuel

production up to the finished production, others will include the transport to pumping stations, whilst others include the use phase in a vehicle. These methods are known as well to gate (Branco-Vieira *et al.*, 2020b), well to pump (used by (Sander and Murthy, 2010) and (Stephenson *et al.*, 2010)) and well-to-wheel (used by(Azadi *et al.*, 2014)). There is nothing intrinsically wrong with any of these methods, but this range of methods give another reason why many microalgae biofuel LCA studies are hard to compare.

2.4.3 *Co-products*

One difficult issue within LCA is how to deal with a process which creates more than one product. How do we allocate the impacts from each? As detailed within (Wang *et al.*, 2011) There are five methods;

- **Mass-based method:** This splits the impacts between the product and co-products based on the ratio of masses.
- **Energy-content based method:** This splits the impacts between products and co-products based on the ratio of energy contents. This is the methodology favoured by the European Commission within the RED.
- **Market-based method:** With this, the ratio of impacts is based purely on the commercial value of the product and co-products
- **Process-purpose based method**: This is based on understanding of if individual processes are to be allocated towards the production of the product or the co-product. However, as various processes within a facility may be involved in the production of multiple products, these processes need to use the above methods to allocate impacts.
- **System Expansion**: This method, as used by ISO 14040/44, involves the expansion to the modelling of the co-products, and the calculating the impacts of the co-products relative to the production of this same co-product by the status quo. The difference between these is then a benefit or addition to the main product's impact.

These five different methods are used throughout microalgae LCA, although due to the preference for following either the RED or ISO standards, methods one and five are usually used. However, as shown by (Wang *et al.*, 2011), the choice of co-product method can lead to significant differences between impacts. However, conversely, (Menten *et al.*, 2013) suggests that actually there is little difference between the energy-based method and allocation method. A good list of co-products is included in (Pérez-López *et al.*, 2014).

2.4.4 *Impact Categories*

The range of impact categories assessed within the literature varies. The most common areas for LCA

to look at are the energy balance (which is technically an LCI indicator and not an impact category) and the 100-year climate change impact using global warming potentials (GWP100).

In some rare cases other impact categories are used, for example, (Soratana and Landis, 2011; Beach *et al.*, 2012; Soratana *et al.*, 2014) use some of, or the full range of, TRACI methodologies, whilst (Itoiz *et al.*, 2012) (Hou *et al.*, 2011; Adesanya *et al.*, 2014) use a range of the CML methodology impact categories. (Passell *et al.*, 2013) uses Net energy ratio, GWP100, particulate matter, photochemical ozone formation potential, NOx, and SOx, however, does not make it clear exactly which methodology is used for these. Generally, it seems that eutrophication and toxicity impacts are lower for microalgae derived fuels than fossil-derived fuels. However, with regard to climate change impacts these can be higher than fossil fuels. It is unfortunate that the majority of impacts are ignored in the literature and only climate change is focused on. Climate change is an extremely significant global issue, but it is important to stress that environmental impacts are not purely about climate change.

Some Impact Categories which should be used are very rarely considered. Specifically, the fertiliser use of microalgae biofuel facilities is rarely considered, despite the clear importance of this issue on a global scale. Within (Cordell *et al.*, 2009) there is the hypothesis of Peak Phosphorus, which the paper predicts may happen within the next 50-100 years. The issue of potassium supplies is discussed within (Manning, 2015). Therefore, it would be advisable for fertiliser use to be included within LCA. Within (Canter *et al.*, 2015), this issue is discussed, and the view is that biomass production is not limited by fertiliser availability if recycling and alternative sources of nutrients are utilised. However, the issue is discussed within (Shurtza *et al.*, 2017) compared with the US Department of Energy 2030 goal of 60 billion gallons of biodiesel per year. This shows, for an HTL based microalgae industry, wastewater would only supply 6% of the nutrients required. The remaining 94% of nutrients required would match that currently required by the whole US farming industry. This shows this is clearly an issue which should be investigated more often in LCA of microalgae.

Use of impact categories, or rather misuse, is an issue endemic throughout LCA. Even the application of similar impact assessment methodologies can lead to different results. For example, as detailed in (Collet *et al.*, 2014), there are two well-used methods for calculating the eutrophication potential. The CML methodology uses phosphate equivalent as the categorisation factor, whereas the TRACI methodology uses nitrogen equivalent. This means that studies in different papers (such as (Kadam, 2002) and (Bretner *et al.*, 2011)) cannot be easily compared.

Climate Change impacts are another source of differences between LCA studies. This is partly because as the understanding of global warming potentials has increased, some LCA studies have used updated figures, and others have not. The recently released updated EU Renewable Energy Directive (RED)

(European Commission, 2019) uses values for GWP integrated over 100 years (GWP100) for methane and nitrous oxide taken from the IPCC Working Group I Fourth Assessment Report (Solomon *et al.*, 2007) from 2007. However, subsequently the Working Group I Fifth Assessment Report (AR5) (2013)(Myhre *et al.*, 2013a) have modified these figures, as the understanding of biogenic and chemical processes regarding these gases has increased. The data within AR5 also contains a consistent approach to feedback cycles, which previous IPCC reports did not. Additionally, different databases of climate change impacts contain different numbers of characterisation factors, from the Renewable Energy Directive (CO_2, methane, N_2O), whilst ReCiPe considers 93 gases. TRACI 2.1 and ReCiPe 2013 both also consider more gases than CML 2013.

Additionally, usually, the 100-year global warming potential is considered, however, the 20-year time horizon is also important, this is detailed within (Bradley *et al.*, 2015) and (Ramirez *et al.*, 2020)(Chapter 10 written by Bradley), and the following is taken from these two sources written by the author.

Generally, a 100-year time window is used for the Global Warming Potential of emissions, referred to as GWP 100. This is used, as when the initial Intergovernmental Panel on Climate Change (IPCC) report was released, globally the concept of 100-year time periods for CFCs was understood after the success of the Montreal Agreement on CFCs. Therefore, politically, it was chosen as a good concept to allow policymakers to understand the concepts on climate change being published. It is important to state there is no scientific reason for the use of GWP100, it was purely to help policy makers within the 1990s.

It is important that both 20 year and 100-year climate change impacts are considered. This is on that basis that the climatic system is possibly on the verge of the activation of various feedback cycles which could lead to runaway climate change. On the other hand, it is unwise to simply reduce the timescale to 20 years for the impact category, as this could then incentivise other emissions and lead to poor decision-making processes. (Howarth et al., 2011), Therefore, we propose the use of both 20 year and 100-year GWP impact categories. The figures for GWP20 are given within the same IPCC reports that GWP100 is sourced from.

2.4.5 *Meta-Analysis*

To deal with the various different methodologies used within microalgae biofuel LCAs, there have been different attempts at Meta-Analysis. Within LCA in general, this is becoming an increasingly discussed topic; however, the technique has now reached microalgae biofuels. Meta-Analysis is essentially the collation of multiple datasets, which are then corrected for differences in the experimental techniques, and methodological issues (functional unit, boundary conditions, co-products, etc.). With regard to

microalgae, significant work began in 2012 (for example, (Liu *et al.*, 2012), (Menten *et al.*, 2013), (Slade and Bauen, 2013)) and has continued with larger studies as the years have gone by, and the amount of available studies to analyse has increased. Recent Meta-analysis includes (Ketzer *et al.*, 2018; Tu *et al.*, 2018; Schade and Meier, 2019; Garcia *et al.*, 2020).

Partially due to the lack of literature, early metal analysis of microalgae LCA tended to concentrate on a core of papers such as (Lardon *et al.*, 2009), (Stephenson *et al.*, 2010), (Campbell *et al.*, 2011) and (Sander and Murthy, 2010). These core papers usually feature in meta-analyses undertaken more recently. More recent papers tend to consider a broader range of microalgae LCA research, much of which published in 2013 or later.

Most meta-analysis focus on climate change, over a 100-year time horizon. The figures given vary between meta-analyses. For example, (Liu *et al.*, 2012) produced a result of 0.19 $kgCO_2eq/km$. Taking a basic assumption of 2.4MJ/km for a car, then this gives 0.45 $kgCO_2eq$ /MJ. (García *et al.*, 2018) found a range of −0.7 to 3.8 $kgCO_2eq$ /MJ. (Tu *et al.*, 2018) found a median value of 0.099 (0.055–0.151) $kgCO_2eq$ /MJ. The reasons for this variation in terms of methodological differences between the available Meta-analysis, in terms of the boundary conditions, treatment of co-products, and functional units. This means that each metal analysis gives quite different results. Ultimately, this shows that as with the papers they deal with, the meta-analyses also need harmonisation; otherwise, they are simply replicating the same issue they seek to solve.

An important note is that many meta-analyses are focused on the maximum amount of quality literature, but not the maximum amount of quality data. As time has moved on, there is now a small number of papers using real data, as detailed in Section 2.5. What would be of true value would be a meta-analysis which focuses on the real data from these papers, this is something which I wish to do after this PhD

2.4.6 *Harmonisation*

In an effort to reduce the issues discussed, two strategies have been taken by the European Commission, the first of these was to form the Algae Cluster, which was three microalgae bioenergy demonstration projects intended to have the same LCA methodology for each of their different microalgae biofuel LCAs(Bradley *et al.*, 2015). The second move by the Commission was to start a series of conferences, known as the European Workshop on Life Cycle Analysis of Algal based Biofuels. The first of these occurred in 2012, with the second in April 2014 and third in April 2015. However, after this, these workshops sadly ceased.

Within the US, work was undertaken by the Microalgae Biomass Organisation (ABO)(Algae Biomass

Organisation, 2013). The ABO have created the Green Box Approach, which expands upon the microalgae biofuel part of the GREET methodology developed by Argonne National Laboratory(Davis *et al.*, 2012). This is essentially a modelled set of assumptions for LCAs of hypothetical facilities, and should not be confused with the Algae Cluster approach, which is harmonising the methodologies used for modelling of microalgae biofuels, specifically aimed at the modelling of real facilities. It is worth noting though that both approaches use similar boundary conditions. However, they do differ in aspects such as impact categories.

2.4.7 *Scale of systems*

Many of these LCAs are based on extrapolation of small experimental trials. This is compared with commercial biofuel facilities, which produce hundreds of litres per year (for example, Ensus in Teesside produced 400 million litres per year(*UK biofuel industry overview*, 2013)). Looking to commercial fossil fuel refineries, there are facilities with outputs of over 1000 million litres per year (*Refinery Capacity Report*, 2014). There is no real way to know for certain how microalgae biorefineries would work at this scale, as large systems do not exist yet, and thus scaling up of systems follows no set methodology with papers using their own different view on how to do this.

2.4.8 *Yields and Energy Density*

When considering yields from microalgae facilities, it is important to keep in mind the theoretical photosynthetic limit for microalgae to convert solar radiation to energy. Hypothetical models are accused of often showing yields far higher than those observed in reality; an issue stressed by Prof. Wijffels at the AquaFUELs Roundtable in 2009(*Proceedings of the AquaFUELs Roundtable*, 2010). Generally, light within the region of 400-700nm can be utilised for photosynthesis (known as the Photosynthetically Active Region)(Kong and Vigil, 2014). However, it should be stated that under certain conditions, a wider range of wavelengths can be utilised. This means around 40-50% of the global short wave solar energy coming to Earth can be utilised for photosynthesis (Papaioannou *et al.*, 1993; Jacovides *et al.*, 2003). For the fixation of one CO_2 molecule, the photosynthesis process requires >8 photons, which therefore results in a maximum theoretical photosynthetic efficiency of 8-10% (Melis, 2009). Due to reflection, etc., this has not been observed in nature. Real efficiencies for microalgae have been measured at 5% (Norsker *et al.*, 2011), 3% (Dubinski *et al.*, 1979) (Ben-Amotz, 1980; Ben-Amotz and Avron, 1990), down to 0.5% for spirulina (Lee, 1997; Dismukes *et al.*, 2008).

Assuming the lipid fraction of microalgae is 75%, and that this contains 38MJ/kg of energy, then using irradiance data from PVGIS, the kg lipid oil per hectare can be calculated, as shown in *Table 2-2*. (Weyer *et al.*, 2010) provides calculations on the maximum yields possible at various locations. This gives

33g/m^2/day for Kuala Lumpar, up to 42g/m^2/day for Phoenix, Arizona, US. This fits well with (Goldman, 1979) which gives maximum values of 30-40g/m^2/day for sites across the US.

Table 2-2: Maximum annual tonnes/hectare of crude algal oil-based on solar irradiance data. Assumptions; photosynthetic efficiency = 5%, lipids make up 75% of algal energy, energy density of algal oil = 38MJ/kg. Data for European sites and Tunisia from Climate-SAF PVGIS database, the rest from PVGIS Helioclim. No modifications have been made for air mass impacts on the PAR.

Location	Solar radiation/year [Wh/m^2]	Photosynthetic energy [J/m^2]	Crude algal oil [kg/m^2]	Crude algal oil [tonne/ha]	Algae biomass [tonne/ha]
Newcastle (UK)	1160	250,560	4.1	41.2	54.9
Constanta (Romania)	1580	341,280	5.6	56.1	74.8
Genoa (Italy)	1710	369,360	6.1	60.8	81.1
Tunis (Tunisia)	2110	455,760	7.5	75.0	100.0
Faro (Portugal)	2180	470,880	7.7	77.4	103.2
Port Louis (Mauritius)	2190	473,040	7.8	77.8	103.7
Djibouti (Djibouti)	2350	507,600	8.3	83.5	111.3

2.4.9 *Growth technologies*

The technologies used for the growth of microalgae biofuels are bioreactors (which can be either phototrophic or heterotrophic) or raceways, which are otherwise known as “open ponds”. Bioreactors, where the microalgae is grown phototrophically, are known as photobioreactors. As described earlier, due to the significant differences in LCA methodologies, it is not informative to compare one study of a raceway and one of a photobioreactor. Rather, insights can be gained by reviewing literature which includes comparisons between the technologies.

Within (Jorquera *et al.*, 2010), two types of photobioreactors (horizontal tubular photobioreactors and flat-plate photobioreactors) were compared with raceways. Within this work, it was found that horizontal tubular photobioreactors had an energy ratio <1, whilst the other methods had ratios of 4.33 and 7.01, respectively. It was found that the individual results do not agree with others in the literature; however, the point of interest within this work is that three systems trialled with the same methodology showed raceways to have the lowest energy ratio. The main issue for horizontal systems

was the pumping. These results were reconfirmed by (Weschler *et al.*, 2014) using some data from (Jorquera *et al.*, 2010) and additional literature sources. (Sarat Chandra *et al.*, 2018) showed similar results, comparing airlift photobioreactors with raceways, showing that the primary energy demand and climate change impacts of airlift photobioreactors was 3.7 times that of raceways.

However, it must be remembered that photobioreactors, though, do have a higher productivity per land area (Efroymson and Dale, 2015). The only literature which exists to compare photobioreactors, raceways and fermenters using the same methodology appears to be (Alabi *et al.*, 2009). This compared the three technologies for use in Canada, and analysed the raceways for a case where they were based in the Tropics. The work was to produce algal oil, not biodiesel, and hence the transesterification step is not included. This gave energy ratios of 1.76, 1.23 and 1.93 for raceways, photobioreactors and fermenters respectively. For a raceway based in the Tropics, it gave a ratio of 2.03 to 2.51. (Stephenson *et al.*, 2010) considered a hypothetical microalgae biodiesel facility based in the UK, whereby a raceway system was compared with an airlift tubular photobioreactor. As with (Efroymson and Dale, 2015), the energy of the pumps meant that the higher productivity of the photobioreactor was still not enough to compete with the raceways for Climate Change impacts or energy ratios. The climate change impacts were 0.32 $kgCO_{2eq}$/MJ and 0.09$kgCO_{2eq}$/MJ respectively. (Stephenson *et al.*, 2010) included the construction of the facilities within the LCA boundary conditions, whilst (Efroymson and Dale, 2015) did not include this.

One major advantage of fermentation is that it can use wastewater as a carbon source, such as used within the All-Gas project, as detailed within (Maga, 2016). This can dramatically improve the results of an LCA.

It is important to note that one of the major issues with photobioreactors is the impacts of the electricity used to power them. If this can come from an on-site renewable source, then the impacts would be substantially lowered. It seems that there is some consensus within the literature that under the present electricity grid mix, raceways are superior to photobioreactors, whilst fermenters are suggested to be the lowest climate change impact option by (Alabi *et al.*, 2009), this does need backing up by further research. This will be studied by the author working with the organisation GreenCoLab and the company Allmicroalgae in 2022.

2.4.10 ***Harvesting microalgae.***

There are numerous harvesting technologies and stages. Some of the technologies used include flocculation, solar drying and centrifuges (Collotta *et al.*, 2017). These can be used in combination or separately. As with the growth technologies, these can only be really compared using papers which

compare the techniques using the same methodology.

Solar drying is used in India where microalgae is grown for food supplements. It is the lowest energy method; however, it is also the one which takes the highest land area. Existing technology has been developed for drying of various crops (tea, cocoa, rice, corn, hay, tobacco, rubber, and a number of others) (Kadam, 2002). There are already microalgae production facilities (usually open pond based facilities producing nutraceuticals) which use solar drying

Flocculation is essentially adding an additive to the water to cause the microalgae to floc together. This can be through changing the pH of the medium or adding fine powders such as starch. (Salim *et al.*, 2012). One issue to be aware of is that in some cases the additive must then be removed from the algal medium during the downstream processing.

Other methods include:

- Acoustic focusing
- Hybrid captive deionization/electrophoresis
- Novel materials for traditional membranes
- Bioflocculation using *skeletonema* to co-bioflocculate Nannochloropsis or lime(Cheng and Ogden, 2011)
- electro-coagulation

Centrifuges are the fastest way of removing the water from the water/microalgae mix. However, they do take significant amounts of energy.

A range of papers compares these different technologies. (Kadam, 2002) looks at a comparison of using a filter press or centrifuge to dewater microalgae prior to using solar drying. This showed that the emissions (AR4 GWP100) were −0.0209 and 0.1357 kgCO2eq/MJ of biodiesel (well to pump) for the filter press and centrifuge techniques respectively.

One possible alternative method for both the dewatering and oil extraction phase is that of ultrasound. (Natarajan *et al.*, 2015) Ultrasound can be used for mixing and cell disruption. A detailed review within (Rodriguez *et al.*, 2015) covers both of these technologies.

2.5 Real World Facilities

There is limited data available on existing and operational microalgae biofuel facilities. Some research uses data from microalgae production facilities which utilise microalgae for high-value products instead of biofuels. This is the usual commercial use for microalgae at the moment. There is some work on real

facilities, which is worth further mention.

2.5.1 *Seambiotic/Valicor*

(Passell *et al.*, 2013)performed an LCA based on data from Seambiotic, Inc., (which has now ceased trading) in Israel and Solution Recovery Services (SRS) Inc. (now trading as Valicor), based in Dexter, Michigan, USA. This paper combined data from the two facilities which produce microalgae for commercial purposes. Seambiotic produced microalgae for high-value dietary supplements at a 1000m^2 facility in Ashken. Whilst Valicor is the producers of the AlgaFrac technology, used for microalgae biodiesel production. Although Valicor is involved in the production of biofuel, the biofuel production side was modelled using the GREET 1_2011 software. ('GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation,' 2011). The boundary conditions of this research were based on a pond to wheels model. In this case, the functional unit was 1MJ of energy produced by combusting the fuel in a compression-ignition direct-injection (CIDI) passenger car, although the energy content used is the HHV of biodiesel, given as 16,200 BTU/lb (37681.MJ/kg). Technically the LHV should be used for cars, although interestingly the figure quoted is actually the LHV for biodiesel anyway. The Seambiotic Inc. facility covers 1000m^2, so is one tenth of the size of the initial InteSusAl prototype facility, and a fraction of the size of a true commercial biofuel or fossil fuel refinery.

The following impact categories are included:

Table 2-3: Impact categories used by(Passell et al., 2013).

Impact Category	Unit of measure
Climate Change	kg $CO_{2eqGWP100}$
NER (net energy ratio, energy in/energy out)	MJ/MJ
PM (particulate matter) formation	kg PM10-equivalents
Water depletion	m^3
PCOP (photochemical oxidation potential)	kg NMVOC-equivalents
NOx (oxides of nitrogen)	kg NOx
SOx (oxides of sulphur)	kg SOx

The Seambiotic facility was co-located with a fossil fuel power station, which means the CO_2 is free and has no additional impacts associated with it. It would be worth re-analysing the data from this paper with the latest approaches for Carbon Capture and Utilisation as described within the work by the European Commissions' LCA4CCU (Ramirez *et al.*, 2020) and the work through the Global CO2 Initiative (Zimmermann *et al.*, 2018).

The microalgae strains produced were *Nannochloris sp*. and *Nannochloropsis salina sp*. The facility used raceways with paddle wheels. These are a low energy/low yield method for producing microalgae. The production rate of microalgae from the facility was 3 g/m2/day, which equated to 11 tonnes/ha/year, far lower than the theoretical maximum discussed in section 2.4.8. This is also substantially lower than the target for InteSusAl (90-120 dry tonnes microalgae/year = 24.6-32.9 g/m^2/day)

The LCA shows that the facility performs poorly in comparison to fossil fuel based diesel. However, this is to be expected considering the small scale of the facility; this is not really comparable with a commercial system. As stated in the paper, electricity use is a major source of impacts, and by using a German electricity mix as opposed to a US one, the impacts can be significantly reduced. This demonstrates how location, via the grid mix, can have a large effect on the impacts of a microalgae biofuel system.

Table 2-4: Comparison of microalgae biofuel production with soy biodiesel and petroleum-derived diesel (Passell et al., 2013).

Impact Category	Microalgae Biodiesel	Petroleum-derived diesel	Soy Biodiesel
Climate Change [kg CO_2eqGWP100]	2.8800	0.1200	0.0250
NER (net energy ratio, energy in/energy out) [MJ/MJ]	33.4400	0.1800	0.8000
PM (particulate matter) formation [kg PM10-equivalents]	0.0046	0.0001	0.0001
Water depletion a [m3]	0.0800	0.0000	0.0000
PCOP (photochemical oxidation potential) [kg NMVOC-equivalents]	0.0074	0.0001	0.0001
NOx (oxides of nitrogen) [kg NOx]	0.0055	0.0001	0.0001
SOx (oxides of sulphur) [kg SOx]	0.0150	0.0000	0.0000

2.5.2 *University of Texas*

Work has been carried out by the University of Texas, measuring the production of *Chlorella protothecoides* for biofuels. The data for this is discussed in (Beal *et al.*, 2012a) and(Beal *et al.*, 2012b). Within these papers, data was taken from the processing of five batches at the University of Texas (UT; with a total processed volume of roughly 7,600 L). As stressed by the papers, this was a research facility, and so was not built for efficient running. Hence, for example, pumps were oversized. For this study, the microalgae had been inoculated in bioreactors and then fed into raceways. As with (Passell *et al.*, 2013) the oil was not refined into biodiesel, so this had to be modelled. The yield from the microalgae

facility, in this case, was 0.002g/(L-day). It is worth noting that this work is not an LCA, as it focussed purely on the energy, not the impacts. However, it certainly does provide enough detailed data to create an LCA model of microalgae production, and so this paper is a valuable resource.

2.5.3 *Sapphire facility*

As discussed in(Liu *et al.*, 2013), data was analysed from the two pilots at the HTL Industries' Sapphire Facility in Las Cruces, New Mexico, US. Unlike the previous two projects discussed, this facility uses Hydrothermal Liquefaction instead of transesterification. This work compared results with that of MABEL, using as similar a methodology as possible. The end results were that under current technology, HTL produces (per MJ) gasoline with lower climate change impacts to that of corn ethanol and about twice that of soy-based biodiesel. However, this is without the inclusion of land use (or indirect land use) impacts. An important point made by the paper is that this is a developing technology, and so should reduce its impacts. The HTL process produces diesel with lower Climate Change impacts than those of transesterified algal biofuels according to the MABEL model; unfortunately, the only impact category within this work was that of GWP100, and it would be interesting to compare HTL with transesterified algal oil to compare these impacts.

2.5.4 *Kona Demonstration Facility (KDF)*

The KDF is run by Cellana LLC. The facility is based in Hawaii and contains 25m^2 of photobioreactors and 400m^2 of open ponds. The facility was constructed in 2009, and the data from various trials (Huntley *et al.*, 2015).

The paper provides detailed data on the production from the photobioreactors and open ponds, including the maximum productivity (~ 75 tonnes ha^{-1} yr^{-1}), and the energy ratio under numerous scenarios, which is in several cases >~1. These productivities, however, are based on several trials, and according to the official company website, the total production of the KDF since 2009 has been 11 tonnes of microalgae ('Cellana - Production Facilities,' 2015).

A full LCA is calculated on a hypothetical 100-hectare facility, based on the trial data (Beal *et al.*, 2015). The LCA provides data in Impact 200+ categories and IPCC 2007 AR4 GWP100. However, no detailed LCA of the real facility has been published.

2.5.5 *All-Gas plant in Chiclana de la Frontera (Spain)*

The All-Gas project was part of the Algae Cluster, and as such, the results should be easily comparable with the results of this thesis without any need for a detailed meta-analysis. The project focused on treating wastewater using a mix of bacteria and microalgae, which functioned as a small ecosystem.

The site covered two hectares of raceways. A comprehensive life cycle assessment was carried out for the All-Gas pilot plant in 2015 (Maga, 2015; Maga, 2016). Against the ReCiPe categories and AR5 climate change impacts, the majority showed improvements, with acidification impacts and terrestrial eutrophication as exceptions. In terms of climate change and wastewater treatment, the facility showed advantages over conventional fossil fuels and over conventional wastewater treatment.

2.5.6 *Concepción, Chile.*

(Branco-Vieira *et al.*, 2020b) uses data from a 2.5-hectare facility in Concepción, Chile. The LCI is provided within (Branco-Vieira *et al.*, 2020a) and the details on the facility within (Branco-Vieira, 2018), the microalgae species is *Phaeodactylum tricornutum*, and the boundary conditions are cradle-to-gate. The data is taken from a single photobioreactor on the site, which is then scaled up using the methodologies from the Enalgae project (Spruijt, 2015). In terms of climate change, the impacts of microalgae biodiesel are 5.74 $kgCO_2$/MJ.

2.5.7 *ABACUS Project*

As described within (Onorato and Rösch, 2020), within this EU funded project (Funded via the Bio-Based Industries Consortium, through Horizon 2020), three types of photobioreactors were tested; Flat Panel Airlift (FPA), Unilayer Horizontal Tubular PBR (UHT-PBR), and the Green Wall Panel (GWP). These were tested at real facilities, specifically Subitec Gmbh, A4F and Microphyt respectively. The Subiyrc and A4f data was based on 93m^3 volume systems, whilst the Green Wall Panel data was based on a small 0.1m^3 system. One of the functional units used within the article was 1kg of *Haematococcus pluvialis* (80% dry weight), which makes it easy to compare with other analyses. Dependent on the technology and electricity source, the paper shows that climate change impacts varying from 20.93 to 265.21 $kgCO_2eq$/kg microalgae. Considering a value of approximately 38MJ/kg of microalgae, then this gives us a range of 0.55 to 9.6 $kgCO_2eq$/kg.

2.5.8 *MicroalgaePARC*

MicroalgaePARC is a system constructed at Wageningen University & Research (Wageningen UR) for the research into various technologies for microalga production and harvesting. It caters for research at lab and pilot scale. (Pérez-López *et al.*, 2017), studied the MicroalgaePARC system which compares different photobioreactor technologies, but does not compare them with alternative biofuels or petroleum ones. The technologies considered were Horizontal PBRs, Vertical PBRs and raceways.

Table 2-5: Basic details of microalgae LCAs based on real data

Facility	Ref	Technology	Location	Boundary Condition	Functional Unit
Seambiotic/Valicor	(Passell *et al.*, 2013)	Raceways	Israel and US	well-to-pump	1 MJ of energy produced in a passenger car
University of Texas	(Beal *et al.*, 2012b).	Open ponds	US	cradle-to-gate	N/A
Sapphire facility	(Liu *et al.*, 2013)	Open ponds with HTL	US	cradle-to-gate	one barrel biocrude
Kona Demonstration Facility (KDF)	(Huntley *et al.*, 2015) (Beal *et al.*, 2015)	PBRs and open ponds	Hawaii	cradle-to-gate	1 ha of facility area
All-Gas	(Maga, 2015; Maga, 2016)	Sewerage treatment with raceways	Spain	cradle-to-grave	'1 m3 treated wastewater' (fu 1) and '1 MJ CNG (LHV) used in a gas engine'
Concepción, Chile.	(Branco-Vieira *et al.*, 2020a)	Bubble-column PBR	Chile	cradle-to-gate	1 MJ of biodiesel (Lower Heating Value)
ABACUS Project	(Onorato and Rösch, 2020)	Flat Panel Airlift (FPA), Unilayer Horizontal Tubular PBR (UHT-PBR), Green Wall Panel (Green WP)	Germany (FPA), Portugal (UHT), France (Green WP) outside.	cradle-to-gate	1 kg of H. pluvialis (80% DW) and 1 kg of astaxanthin
MicroalgaePARC	(Pérez-López *et al.*, 2017)	Horizontal PBRs, Vertical PBRs and raceways.	Netherlands	cradle-to-gate	1 kg of produced biomass dry weight, contained in a 22% DW slurry

It is difficult to compare the results from these papers, requiring a full meta-analysis. There are clear methodological differences, including the software, impact categories, and treatment of co-products. For example, (Branco-Vieira *et al.*, 2020a) allocates almost 90% of the impacts to the co-products of residual biomass and glycerol, leaving the biodiesel with a far reduced impact. However, it still has an impact of 5.75kgCO_2eq/MJ. Table 2-6, provides comparison of the results from the studies.

Table 2-6: Impacts for three impact categories for those papers which used energy as a functional unit. Note, the data from (Branco-Vieira et al., 2020a) could not be compared as it used different units for the impact categories. Liu only addressed climate change. Also, (Liu et al., 2013) and (Branco-Vieira et al., 2020a) were cradle-to-gate, but the CO2 emissions from burning would be biogenic, hence their inclusion within this table.

Facility name	Article	Fuel	Climate Change (100-year)	photochemical oxidant formation	Particulate matter
			kgCO2eq	kg NMVOC eq	kg PM10 eq
Seambiotic / Valicor	(Passell *et al.*, 2013)	Microalgae-derived biodiesel	2.88	0.0074	0.0046
		Hypothetical improved microalgae	0.18	0.00035	0.00015
		Low sulphur Diesel	0.12	0.0001	0.0001
Sapphire facility	(Liu *et al.*, 2013)	Microalgae HTL based fuel	0.320	-	-
		Diesel	0.086	-	-
All-Gas	(Maga, 2015; Maga, 2016)	Microalgae-based biomethane	0.0208	5.71E-04	5.26E-04
		CNG	0.0766	5.81E-05	2.47E-05
Concepción, Chile.	(Branco-Vieira *et al.*, 2020a)	Microalgae-based biodiesel	5.74	-	-

As is clear, from real data, the only case in which microalgae-based fuels provide an advantage for these three impact categories is in the All-Gas project. The other impact categories considered by (Maga, 2015; Maga, 2016) back this up. Whilst there is too little real data on real-life microalgae production, and the majority of real data that is available does not include full impact categories or well-to-wheel, it seems wastewater treatment may be the best direction for microalgae-based fuels. Some theoretical work backs up this position(Bussa *et al.*, 2020).

In terms of other impact categories, some work does contain a good range of impacts. (Onorato and Rösch, 2020) uses the full range of ReCiPe 2016. Based on an assumed 38MJ/kg of microalgae it is then possible to compare with petroleum-derived diesel using Ecoinvent 3.6 (assuming a value of 42.7MJ/kg (Azad *et al.*, 2017) for petroleum-derived diesel). This simplistic approach does not take account of a range of engine emissions from the microalgae-derived biodiesel and does not deal with allocation correctly. However, despite these drawbacks, it shows that the microalgae systems within (Onorato and Rösch, 2020) show a greater impact in every category than petroleum diesel.

2.5.9 *Currently running non-biofuel projects*

There are a number of projects globally which are researching microalgae production for high-value purposes. Whilst many commercial facilities (in fact the majority) produce microalgae for non-fuel purposes; there is an even more limited selection of literature on the LCA of non-fuel products from microalgae than there is for microalgae-based biofuels. Projects currently working on such products

include MAGNIFICENT, BIOSEA, and SpiralG.

2.6 Microalgae Bioproducts

Microalgae is a good source of carotenoids. These are terpene derived pigments which are used to support photosynthesis in plants and other photosynthetic organisms. There are two types of carotenoids, those which contain oxygen (xanthophylls) and those which do not (carotenes) which contain purely carbon and hydrogen. A number of high-value products considered are carotenoids. Xanthophylls include lutein, fucoxanthin, astaxanthin, and zeaxanthin. Carotenes include β-carotene, α-carotene and lycopene. Carotenoids are known to have numerous health benefits for humans. (Cuj-Laines *et al.*, 2018).

2.7 Bag Based Fermenters

There is little literature on LCA of bag type fermentation systems compared with traditional steel fermenters. There is no literature on the use of bag type fermenters for microalgae. The two major LCCA papers on this subject are Pietrzykowski 2013(Pietrzykowski *et al.*, 2013), and GE Healthcare 2013(GE Healthcare UK Limited, 2013)) in which comparative life cycle assessments of single-use systems and stainless steel bioreactors were carried out. Both of these are attached to GE, either published by GE Healthcare or through the Eco assessment Centre of Excellence at GE Global Research. Further research into this area includes (Budzinski, 2015; G.Lopes, 2015) and (A.Shukla and Gottschalk, 2013).

Much of the literature which looks into Single-Use Technology (SUT) purely considers the Global Warming Potential over 100 years and does not consider other environmental impacts. Technically this means that the LCA studies published on SUT do not comply with ISO 14040/14044 and therefore are not LCA studies. This is different in the case of (Pietrzykowski *et al.*, 2013), which uses a full ReCiPe Endpoint (H) version 1.05 of impacts. This paper sources its data from BioPharm Services Ltd., which according to the authors is a high-quality source which can be regarded as industry average based on a variety of primary and secondary sources drawn from relevant geographies. The article found that for a full commercial process of monoclonal antibodies, all ReCiPe End Points were less for SUT than for traditional fermenter systems, and also for IPCC AR5 GWP CO_2eq over 100 years. The reason for this was the lower energy use and less steam cleaning and cleaning chemicals. The work is also detailed within (Pietrzykowski *et al.*, 2011; GE Healthcare UK Limited, 2013; Pietrzykowski *et al.*, 2014).

Conclusions

Microalgae biofuel LCA has increased in use dramatically over the past decade. However, many different studies use such significantly different methodologies that it is difficult to compare, and thus the effectiveness of the LCA studies are reduced. The various studies have shown multiple methods in which microalgae biofuel production can be improved, however, very rarely do studies use industrial data for microalgae production, purely because there are very few facilities, and those that do exist are small and are unlikely to give away commercially sensitive information. Uncertainties exist over productivity, industrial processes and energy content.

As has been stated in several other studies, it is vital that there is increased harmonisation in methodology by microalgae LCA researchers, and greater use of industrial data, to allow LCA to become a truly valuable tool for the development of microalgae biofuels.

Chapter 3. Research Aim and objectives

3.1 Aim

To quantify, through Life Cycle Assessment (LCA), the environmental impacts of a prototype microalgae production facility built in Portugal, and to compare this with the production and use of petroleum-derived diesel and non-algae sources for biodiesel. This will then add to knowledge on various options to reduce the environmental impact of microalgae-derived biodiesel.

The facility under study was part of the European Commission Framework Programme 7 (FP7) project InteSusAl and is currently within the Horizon 2020 (H2020) project MAGNIFICENT. Further data has been gathered from the BioMOD project, which designed a bag-based fermenter applicable to InteSusAl. Using this data, LCA models have been constructed to understand the environmental impacts of microalgae-derived biodiesel. This has been compared with fossil fuel data and that of crop-based biodiesel. In addition, work has been undertaken on land-use change, based on the real productivity of microalgae biodiesel. This together has highlighted various areas where microalgae biodiesel can be improved, and where there is a cause for concern with their impacts.

3.2 Description of the Project

The research is linked with the European FP7 project InteSusAl and integrating work carried out by the *National Renewable Energy Centre* spin-off company *Narec Distributed Energy*. InteSusAl was part of the European Commission's Algae Cluster project, which encompassed three microalgae FP7 projects; InteSusAl, BIOFAT and All-Gas. Further data is being used from the follow-on Horizon 2020 project, MAGNIFICENT, of which *Narec Distributed Energy* is a partner.

The majority of microalgae biofuel LCA studies are based on hypothetical facilities. This study is be based on a real functioning prototype system of 1-hectare, which is intended to be scaled up to 10 hectares. The 1-hectare system was constructed in Olhão, Portugal, and ran productivity trials from October 2015 to June 2016, with further trials of the photobioreactor sections ran throughout 2018 and 2019. The InteSusAl concept is a unique system, using a mixture of heterotrophic and phototrophic growth, and recycling of various by-products. The intention of InteSusAl was to ultimately have a production level of 90-120 dry tonnes of microalgae per hectare per year post-project. As a unique and new system, no LCA has ever been carried out on this type of microalgae-derived biofuel production, and in general LCAs of microalgae-derived biodiesel are poor in data. The LCA will inform the development of the facility from the 1-hectare prototype to the 10-hectare facility. Additionally,

collaboration with the aforementioned BIOFAT and All-Gas microalgae biofuel projects will provide additional data to the thesis.

3.3 Novelty

The major unique factors of this work are:

- Few LCA studies in the peer-reviewed literature use real facilities for the microalgae production
- A literature search has found very few papers taking a real-world pilot microalgae biofuel facility's LCA and compared it with petroleum-derived diesel
- The InteSusAl facility is unique in several ways, including the type of microalgae used, and the recycling of glycerol and CO_2. As such, no LCA exists for this microalgae biofuel production methodology
- Through the LCA, various methods to decrease the environmental impact of the microalgae-derived biodiesel will be investigated
- Through using OpenLCA for the final models, statistical analysis considered standard within other fields can be applied to LCA; this is important as the LCA literature has a major problem with statistical analysis of results.

This project follows the principles of the ISO 14040/14044 (International Organization for Standardization, 2006a; International Organization for Standardization, 2006b) methodology for carrying out LCA, while also additionally paying close attention to the recommendations and guidance contained within the ILCD Handbook(M-A *et al.*, 2012). It follows the iterative process of 1) Goal and Scope definition, 2) Life Cycle Inventory Analysis (LCI), 3) Life Cycle Impact Assessment (LCIA), and 4) Interpretation of the results.

Data is being provided from InteSusAl and other different microalgae biodiesel projects. Close attention has been paid to ensuring that the LCA methodology provides results comparable with other projects so that comparisons with other work will help provide useful results on optimising microalgae biodiesel.

The result of this project will be a series of recommendations for reducing the environmental impacts of microalgae-derived biofuel production.

3.4 Objectives

1. To understand the environmental impacts of microalgae derived biodiesel based on real data

2. To understand the main sources of environmental impacts of microalgae derived biodesel
3. To compare the impacts of microalgae derived biodiesel with that of fossil derived diesel
4. To propose improvements that could lead to lower environmental impacts for the production of microalgae derived biodiesel

Chapter 4. Methodology

4.1 Goal and Scope

4.1.1 *Goal and Scope*

4.1.1.1 Introduction

In order to ensure the results of InteSusAl were comparable with the rest of the Algae Cluster, a common LCA Goal and Scope was developed. This Goal and Scope was published in 2015 as *"Unified approach to Life Cycle Assessment between three unique microalgae biofuel facilities"* within the journal Applied Energy (Bradley *et al.*, 2015). Through publishing this methodology, other projects can choose to ensure that their microalgae LCAs are also comparable with that of the Algae Cluster. This methodology was developed through extensive discussions between the project teams, and through academic and industrial feedback from the "*2nd European Workshop on LCA for Algal Biofuels & Biomaterials"* held in Brussels in 2014. The Goal and Scope was disseminated at various events, including the *8th International Microalgae Congress* and the *European roadmap for an Algae-based Industry*. This chapter replicates substantial content from this work(Bradley *et al.*, 2015), but had extended the methodology due to developments throughout the thesis, as earlier stated.

Within the development of the Goal and Scope, it was important that the following requirements were considered:

1. Must align with ISO 14040/44.
2. Impact categories (as used within the LCIA) align with the latest science (for example, using the latest data from Intergovernmental Panel on Climate Change Fifth Assessment (IPCC AR5)).
3. Allow comparison with LCA carried out using the Renewable Energy Directive[†].
4. Replicable by all three practitioners.
5. Suitably transparent, whilst respecting intellectual property protection by partners.

The Goal and Scope followed, as closely as possible, these requirements.

4.1.1.2 Goal

The goal of this LCA study is:

[†] Note that during the Renewable Energy Directive is under consultation for a new version to be released.

To find the levels of environmental impacts within a commercial microalgae biofuel system based on pilot scale data, and suggest improvements to the process.

The LCA is intended to assist in the development process of microalgae biofuel facilities, and allow for a fair comparison of these technologies with fossil fuels and first- and second-generation biofuels. By the end of this work, the LCA will have quantified the environmental impact of microalgae-derived biodiesel, and give recommendations for how this may be reduced by identification of the main environmental impact hotspots. It will also show how microalgae biofuel production compares with other pathways of fuel production.

The audience for this work is:

- The members of the Algae Cluster
- European Commission
- Peer-reviewed literature
- Financiers
- Public in general

This is to be disseminated to the public and to the scientific community through peer-reviewed journals.

4.1.1.3 Scope

The product system studied is a microalgae biofuel facility, where the function of the system is to produce biodiesel from microalgae.

In comparison, other facilities which produce transportation fuel are studied. These are:

1. Petroleum derived diesel or CNG
2. First Generation production of biodiesel

The data on petroleum derived biodiesel will be from the Ecoinvent database.

4.1.1.3.1 Consequential or attributional

This study will be an attributional study.

4.1.1.3.2 Functional Unit

Throughout this thesis, there are three different functional units, depending on the exact system being studied.

1) The functional unit used within the Algae Cluster, to allow us to compare with the All Gas and BIOFAT system is *"combustion of 1MJ (Lower Heating Value) of algal biofuel in a car engine"*.

This functional unit was selected as it is also used in many other LCA studies such as (Lardon *et al.*, 2009) and (Hou *et al.*, 2011), thus allowing a strong crossover. It is important to note it is "biofuel" not biodiesel, as this allows for the comparison with biogas and other technologies

2) ''1 kg of *Chlorella Protothecoides*'' in order to allow us to compare fermenter systems on a more basic level, without the addition of vehicle models
3) "1MJ of biological material" which also allows us to compare with food crops

4.1.1.3.3 Software

Within this work, two software packages were chosen. These were GaBi ('GaBi ts: Software-System and Database for Life Cycle Engineering, Professional Version [7.2],' 2016), and OpenLCA. In the early days of the thesis, GaBi was the best choice; however, as the thesis progressed, it became clear that OpenLCA was a more appropriate and transparent package. One of the reasons for this is that within OpenLCA it is possible to drill down through an Ecoinvent model into the individual sources of impacts, whereas GaBi aggregated or unit processes do not allow for this livel of investigation.

4.1.1.3.3.1 GaBi

GaBi is a specialist LCA package created by Sphera Solutions (which took over thinkstep, who were originally known as PE-International, a commercial spin-out from the University of Stuttgart). The software has many advantages in that it is a logical graphical based system to create LCA models, and is highly configurable and adaptable. It is capable of analysing multiple scenarios quickly, as it is easy to create new databases to analyse data. This is an industry-standard LCA package and was the original software used within this Thesis.

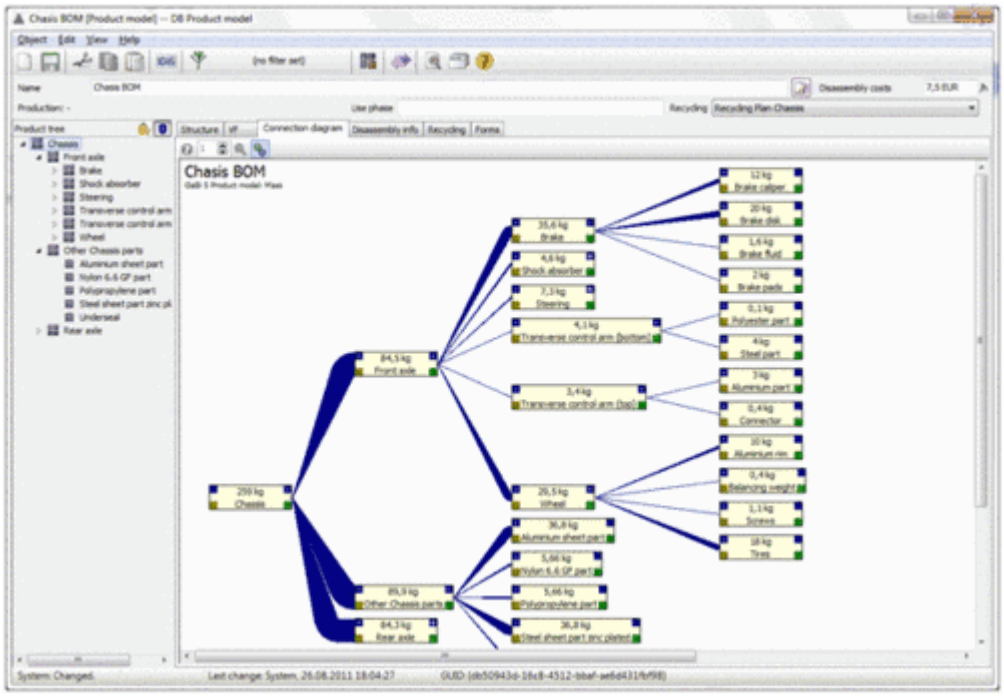

Figure 4-1: GaBi 8 – from Sphera Solutions website

4.1.1.3.3.2 OpenLCA

The original reason for choosing OpenLCA was because of various criticisms from a paper rejected by Nature Energy, this has been rewritten and resubmitted. This highlighted concerns regarding the statistical analysis, which GaBi simply would not be able to undertake, one of the reasons for this is that the Ecoinvent Integrated database within GaBi is stripped of all uncertainty data (both pedigree data andgeometric means). Many of the criticisms, whilst valid, were identifications of problems endemic throughout LCA in general. To tackle these problems, the decision was taken to use OpenLCA for the final models within this thesis, which would enable the trailing of different uncertainty methods. Additionally, OpenLCA presented a more transparent view of the way in which processes contribute to environmental impacts, allowing for the unfolding of individual Ecoinvent processes through their entire boundary conditions. OpenLCA is less intuitive to use, with a tab-based system as opposed to allowing the user to graphically draw the LCA process. It does have a graphical output of the models, which will show the tab-based model once finalised. OpenLCA is a scientific package, capable of various types of statistical analysis in advance of other packages. Additionally, OpenLCA is an Open Source package, with various add-ons and the capability to edit the software. All modules are written in Python, with JSON as the file exchange format. However, it is not easy to use unless the user is already experienced with LCA.

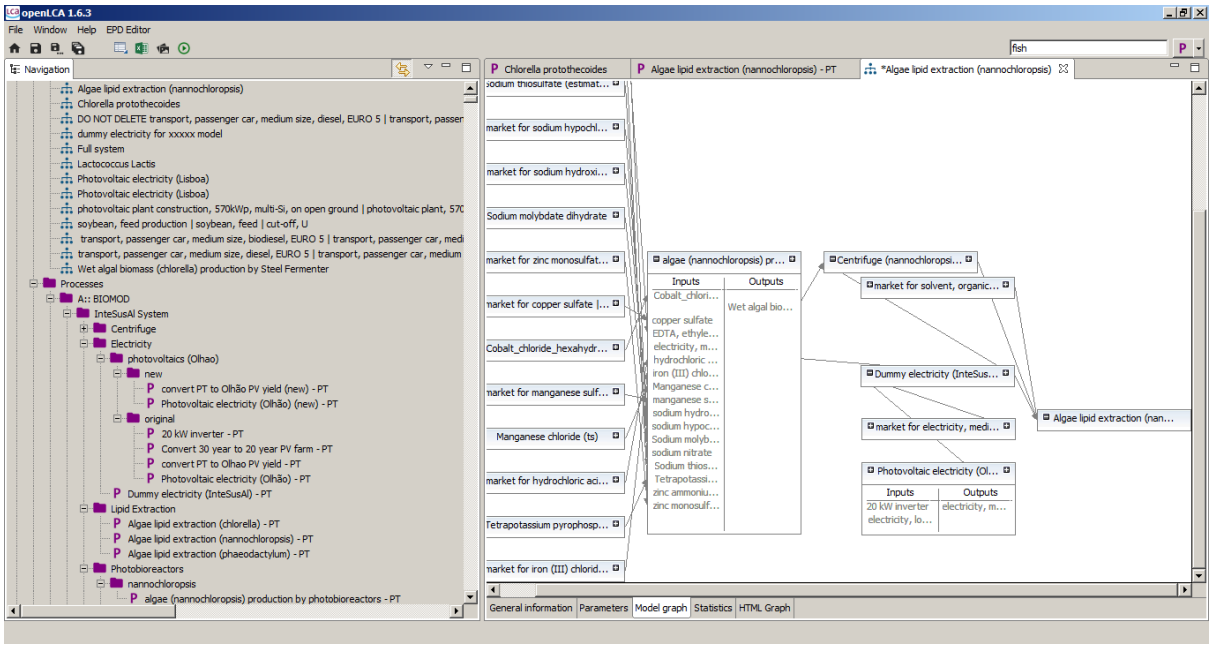

Figure 4-2: OpenLCA with part of the InteSusAl model

4.1.1.3.4 Impact Categories

Often with microalgae biofuel LCA, the only aspect considered is the Climate Change impact, usually based on the GWP100. This impact is clearly important; however, it means that other impacts are often overlooked and is not compliant with ISO 14040/44. Following (Rösch and Maga, 2012) it is clear that even apart from common impact categories used in LCA, there are many other relevant impacts not covered by LCA studies, which is due to the choices of the authors and availability of the data, not an issue with the overall method of LCA.

For the selection of the impact categories, the integrative concept of sustainable development (Batan *et al.*, 2010) (Kopfmüller *et al.*, 2001) was taken as a normative framework for identifying the sustainability criteria appropriate for microalgae production. Based on this concept and addressing the sustainable use of renewable and non-renewable resources, the following additional Mid Points (55eparation55 approach) from ReCiPe (Goedkoop *et al.*, 2013) were included:

- Ozone depletion (kg CFC-11 equivalent)
- Terrestrial acidification (kg SO2 equivalent to air)
- Freshwater eutrophication (kg P equivalent to freshwater)
- Marine eutrophication (kg N equivalent to freshwater)
- Human toxicity (kg 1,4 dichlorobenzene to urban air) and (DALY/PDF)
- Photochemical oxidant formation (kg NMVOC compound equivalent to air)
- Particulate matter formation (kg PM10 to air)

- Terrestrial ecotoxicity (kg 1,4 dichlorobenzene to industrial soil) and (DALY/PDF)
- Freshwater ecotoxicity (kg 1,4 dichlorobenzene to freshwater) and (DALY/PDF)
- Marine ecotoxicity (kg 1,4 dichlorobenzene to marine water) and (DALY/PDF)
- Agricultural land occupation (m^2 × year of agricultural land)
- Urban land occupation (m^2 × year of urban land)
- Natural land transformation (m^2 × year of natural land)
- Mineral resource depletion (kg Fe equivalent)
- Fossil resource depletion (kg oil equivalent)

Most impact category methods focus only on midpoint indicators. In contrast, the ReCiPe method developed by(Goedkoop *et al.*, 2013), which is a follow up of Eco-indicator 99 and CML 2002 methods, integrates and harmonises midpoint and endpoint approaches in a consistent framework(*An analysis of existing environmental impact assessment methodologies for use in life cycle assessment – background document*, 2010). Within this approach, nearly all impact categories have been redeveloped and updated in recent years. Midpoints have far greater certainty than endpoints, however, they can feel abstract, with units such as $kgCO_2eq$, whereas endpoints deal with the eventual result, in terms of species lost, or impacts on human life. By their very nature, endpoints have a greater level of uncertainty.

In addition, the following LCI indicators were selected:

- Primary energy consumption [MJ]
- Land occupation [m^2]
- Bluewater consumption [m^3] (Koehler and Thylmann, 2012)

Furthermore, the following impact categories were included:

- AR5 Climate Change over a 100-year period ($kgCO_{2eq}$)
- AR5 Climate Change over a 20-year period ($kgCO_{2eq}$)
- Land-use change (100-year and 20-year based $kgCO_{2eq}$)

The following subsections discuss blue water, climate change and land use criterion in more detail.

4.1.1.3.4.1 Blue Water Consumption

For impact assessments, in general, only blue water (groundwater + lake water + river water + fossil groundwater) is considered, excluding rainwater. Blue water consumption considers freshwater lost to the watershed due to water vapour to air, evapotranspiration, water incorporated into products, and

water release to the sea. Therefore, it can be calculated as an input of groundwater, lake water, river water, and fossil groundwater minus total blue water release from the technosphere into rivers or lakes (water outputs).

4.1.1.3.4.2 Global Warming Potential

Usually within LCA GWP100 is considered as the impact category for climate change. However, due to the differing rates that different gases are removed from the atmosphere through chemical and biogenic processes, the impacts can be quite different for short timescales. For example, non-fossil methane has a GWP of 28 kg CO_{2eq} over 100 years, but 84 kg CO_{2eq} over 20 years. This is because methane has a perturbation lifetime of 12.4 years in the atmosphere. This is important because these short bursts of heating could initiate "tipping points" in various feedback cycles within the climate, which could lead to runaway climate change(Howarth *et al.*, 2012). Feedback cycles utilised include albedo(Winton, 2008), methyl hydrates(Phrampus and Hornbach, 2012), permafrost(Walter *et al.*, 2006; Heimann and Reichstein, 2008), oceanic(Buesseler *et al.*, 2007), ecosystem(Heimann and Reichstein, 2008), rainforest drying, forest fires, and cloud feedback(Soden and Held, 2006; Shoemaker and Schrag, 2013a). However, it is important to stress that the GWP20 should not be considered more relevant than the GWP100. As shown in (Shoemaker and Schrag, 2013a), overvaluing the impacts of GWP20 above GWP100 could lead to decisions that lock the Earth's climate into a warmer temperature trajectory.

Through concentrating on short term impacts from methane the global temperature could be reduced by 0.5°C, however, this reduction would be the same if the reduction in methane production were delayed. However, through ignoring CO_2 due to the comparatively lower short-term impact, would allow for stocks of CO_2 in the atmosphere to increase, which due to the long perturbation lifetime of CO_2 in the atmosphere leads to a cumulative impact in temperatures. According to (Shoemaker and Schrag, 2013a), we as a society we were to delay CO2 mitigation due to concentrating on short term GHG such as methane, every 15 year delay would lead to an increase in the range of 3 to 4°C.

Essentially, the importance of GWP20 is due to the short term warming and concerns the global climatic system could be push into a situation where natural positive feedback cycles take the climate into a new state. However, the GWP100 metric matters when considering the cumulative impacts of gases which have long lifetimes in the atmosphere.

For the above reasons, both the GWP100 and GWP20 were included as impact categories for the Algae Cluster.

In order to keep this study in line with the latest knowledge on climate change impacts, instead of the ReCiPe characterisation value for the GWP100 and GWP20, values from the latest IPCC work, AR5, were used. The author worked with Sphera Solutions to create a validated, AR5 based LCA impact category database for GaBi.

4.1.1.3.4.3 Land Use Change

Land Use changes of first-generation biofuels are a large concern, as detailed in(Fargione *et al.*, 2008), (Gibbs *et al.*, 2008) and(Lapola *et al.*, 2010). The impacts of these changes vary, depending on the climate, original land use, and new land use. Both direct and indirect land-use changes can lead to various environmental impacts. One of the major positives of microalgae biofuels is that fertile cropland is not necessary.

There are a high number of uncertainties with Land Use Change, specifically the difficulty of indirect Land Use Change, which could result in crop farmers moving to a range of new lands. There are a high number of different methodologies for land-use changes, methods for direct, indirect, and both. These are described in (Djomo and Ceulemans, 2012).

The method used for this work is the IPCC Tier 1.(*Good practice guidance for land use, land-use change and forestry*, 2003) The reason for this choice was that although it can be considered the most basic method, it is also the most transparent, and very widely used. This means that in an area where there are a large number of uncertainties, the possibilities are kept as low as possible. Also, as this is a widely used methodology, results can be readily compared with those of other projects. An additional reason for using IPCC Tier 1 is that the use of standard values from the IPCC for land use calculations were recommended by paragraph 71 of the original EU Renewable Energy Directive(*Directive 2009/28/EC of the European parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing directives 2001/77/EC and 2003/30/EC*, 2009). There are some oversimplifications in the method; specifically, it assumes that N_2O emissions are solely a function of nitrogen inputs to the soil and does not 58eparatt for the carbon fluxes.

The IPCC Tier 1 method considers three areas:

1. Biomass carbon stock change
2. Soil organic carbon stock change
3. Incomplete combustion of biomass and dead organic matter (DOM) in the initial land-use category before conversion

All values were taken from default data from the IPCC guidelines, based on the land area changed, climate, type of vegetation and various other variables. Estimates are made of the biomass and organic

soil carbon stocks before and after conversion of land to new uses, and the sum of these changes added to the emissions from incomplete burning of biomass and dead organic material.

In the case of InteSusAl the facility was constructed on a mixture of brownfield wasteland (with existing buildings on) and former grassland in Mediterranean climates.

4.1.1.3.5 Boundary Conditions

As defined in ISO 14040/44, the system boundary defines the criteria specifying which unit processes are part of a product system. This line needs to be drawn around the system. The following sections explain the logic of where this boundary was placed and how a well-to-wheel study was decided upon.

4.1.1.3.5.1 Distribution and Transportation

The distribution of the microalgae-derived biodiesel is not included in the LCA. The logic for this is that this would apply to any form of diesel, be it petroleum or bio-derived. Therefore, the LCA would have become an LCA into the transportation network for fuel, and not show anything of particular differential relevance to microalgae-derived biodiesel. For the purpose of complying with the Renewable Energy Directive, it is assumed that the algal refinery will be 10km from the filling station used, and can therefore cut off the emissions of this transport, as they will contribute less than 1% to all impact categories.

4.1.1.3.5.2 Vehicles

Emissions from vehicles running biodiesel have been demonstrated to reduce levels of particulate matter (PM), CO and hydrocarbons by a substantial level in comparison to traditional petroleum-derived diesel. However, looking at the comprehensive 2002 review by the U.S. Environmental Protection Agency (EPA) (*A comprehensive analysis of biodiesel impacts on exhaust emissions*, 2002) NO_x levels were demonstrated to increase by up to 10% for B100[‡]. Other work has disputed this, such as research by the US National Renewable Energy Laboratory (NREL)(McCormick *et al.*, 2006), which showed the increase to be statistically insignificant. Further work carried out by the Desert Research Institute, and Marathon Petroleum (Robbins *et al.*, 2009) showed the increase to only be of the level of 2 to 3% increase for B100. Within the NREL work, there are criticisms over the ages of the vehicles used in the EPA study, which does not devalue the EPA study, but shows that modern vehicles have less NO_x issues with biofuels.

[‡] Pure 100% biodiesel

With regard to greenhouse gases, there are two major competing aspects for the CO_2 use phase emissions from biodiesel. Whilst the lower energy density of biodiesel will increase the CO_2 emissions per MJ, differences in the hydrogen/carbon ratio between biofuels and fossil fuel diesel reduce the CO_2 emissions. Overall, this leads to the biodiesel emissions being of the order of ~1% above petroleum-derived diesel. The reason to explain for the decrease in CO and increase in NO_x and CO_2 is the higher oxygen content of biodiesel compared with petroleum-derived diesel, however, as stressed earlier, not all work in the literature shows an increase in NO_x emissions from B100. The lower oxygen content also leads to higher levels of particulate matter (PM), non-methane volatile organic compounds (NMVOC) and volatile organic compounds (VOC), but higher ozone-forming potential. (Lopes *et al.*, 2014)

Looking in detail at mutagenic issues from NMVOCs,(Karavalakis *et al.*) investigated various emissions from biodiesel blends, including polycyclic aromatic hydrocarbons (PAHs), nitro-PAHs and carbonyls. This work showed increases in tailpipe emissions of some chemical compounds within these types with increasing biodiesel blends, whilst observing decreases in other compounds. Biodiesel did result in a definite reduction of nitro-PAHs and low molecular weight PAHs (the more toxic/carcinogenic types). The exact increase or decrease varied according to driving cycles.

Whilst biodiesel's climate change impacts are very similar to petroleum-derived diesel in the use phase; cancerous toxicity effects are different from conventional diesel; this, however, is an area currently under significant research. A further point to consider is that the Renewable Energy Directive requires the use phase to be included. Therefore, in order to give results comparable with RED, and to include the mutagenic issues of tailpipe emissions, the use phase is included in these Boundary Conditions.

For the purposes of including these impacts in the same way throughout those projects in the Algae Cluster that use biodiesel, data will be used from (Karavalakis *et al.*, 2010), based on the European certification driving cycle. This paper was chosen due to the substantial detail and depth, the use of EC driving cycles, and the use of B100. It is acknowledged that this is for soy-derived biodiesel; however, no published research was found for algal derived biodiesel on the above impacts.

4.1.1.3.5.3 Facility Construction

The models will include the major capital assets used in the cultivation and harvesting of the microalgae. Specifically, this will include:

- Photobioreactors/bioreactors
- Raceways
- Harvesting assets (including centrifuge)
- Disposable materials within the facility are also included in this LCA.

Assume that the facility has an operational lifetime of 20 years from commissioning.

4.1.1.3.6 Cut off

Following the ILCD handbook (M-A *et al.*, 2012), a 5% cut off will be applied for each of the impact categories to be included. This means, if an input contrubtes less than 5% of each individual environmental impact, it can be ignored. However, as recommended by the handbook, "The respective flows shall, however, be foreseen to be identified and stay in the inventory, but without stating an amount and being marked as "missing relevant" or "missing irrelevant", as applicable".

4.1.1.3.7 System Models

There have been two types of system models within this work. Initial modelling was undertaken with the Allocation at the point of substitution (APOS) model. This means the results are comparable with work on the All-Gas project. The reason both InteSusAl and All-Gas used this was that it was the only version of Ecoinvent available within GaBi.

Further modelling within this work, undertaken later utilised OpenLCA, which enabled more freedom to choose the system model. Hence, the work followed the "Allocation cut-off by classification" method. This method moves the recycling to the end of life, and does not reward the producer of the infrastructure for using recycled materials. This is sensible, as the levels of recycled content within the infrastructure is unknown, but can make reasonable assumptions on the recycling at the end of life.

4.1.1.3.8 Co-products

The allocation method should fit the question defined by the Goal. Since microalgae biorefineries are characterised by multiple final products (energetic and material ones), there is currently no objectively justifiable allocation method.

ISO 14040/44 suggest first avoiding allocation by dividing the unit process into two or more sub-processes or second by expanding system boundaries if possible. Since dividing the unit process is often impossible due to lacking information, system expansion is the most applied method in reviewed LCA biofuels studies. (Collet *et al.*, 2014) (Lardon *et al.*, 2009; Pandey *et al.*, 2011)

In this work, system expansion was initially the intended methodology. However, due to a significant lack of knowledge of the range of products from a full commercial algae biorefinery (which does not exist) then a more basic energy allocation methodology has been utilised.

Recycling processes in the Algae Cluster involved open and closed-loop recycling; these included recycling where changes in the inherent properties may occur. Both reuse and recycling of products were included in the LCA.

4.1.1.3.9 Data Considerations

4.1.1.3.9.1 Data Sources

Where possible, primary data is utilised. In some cases, high-quality foreground data is not available. In this case, in the first instance Ecoinvent database is utilised, as this is regularly used within microalgae biofuel studies (such as(Campbell *et al.*, 2010; Passell *et al.*, 2013; Handler *et al.*, 2014; Torres *et al.*, 2014)). Ecoinvent is an extremely widely used database generally within LCA and is available for all major LCA software tools (OpenLCA, GaBi, Simapro, AMEE, and Umberto). The database contains over 9000 unit processes.

If data is not available via primary sources or Ecoinvent, then other sources such as literature data is used.

For the InteSusAl models, Ecoinvent 3.2 was used. For the other models, in order to allow for computability with the SOCA database, for part of the Magnificent project not included within this PhD, the Ecoinvent 3.3 database was used.

4.1.1.3.9.2 Electricity

Multiple electricity models are created in order to compare with the All-Gas project and petroleum-derived references. These are based on various years for the electricity mix of the EU27+UK, as well as a mix for Portugal, and mixes which involve 80% or 100% photovoltaics onsite. These different options are detailed within the Life-Cycle Inventory.

4.1.1.3.10 Discussion

This chapter has presented the Goal and Scope used for this Thesis and the whole Algae Cluster, which is intended to ensure these three microalgae biofuel projects will return comparable LCA results. The facilities were all operating by late 2015, and so by mid-2016 had enough data to construct a full LCA of each facility.

Geographical issues played a major part in increasing the complexity of accurate comparisons between sites as irradiance and temperature both vary between sites. Another issue which affected the microalgae growth was the variation in water quality across different geographical locations.

4.2 Statistical Methods

With LCA, uncertainty analysis is an area which is often neglected; this is for several reasons. First, the individual processes which systems are made up of often do not contain uncertainty data themselves. For example, in the case of Sphera Solutions GaBi, the uncertainty data provided within the Ecoinvent

database is removed.

A further issue is that due to the way that LCA is often used for policy decisions, uncertainty is not something which a high priority is placed upon, and instead, simple, reproducible answers are required. For example, within the European Union Renewable Energy Directive.

4.2.1 *Sensitivity Analysis*

The traditional approach within LCA is to use a sensitivity analysis to form some level of quantification of the uncertainty.

A sensitivity analysis is essentially an assessment to understand which factors an assessment is most sensitive to, in terms of different impact categories. So, for example, it could be to test if the energy or chemicals used in a process have the largest impact on climate change.

In order to assess this, each factor is varied by a given percentage, to understand the impact that this has on the final model. For example, varying the amount of electricity used in a process by 5% might vary the climate change impacts by 15%, whilst the chemical inputs might only vary the climate change impacts by 1% when they are varied by 5%. Another area that might be investigated would be the comparison of primary data used in a project against the secondary data, to understand which had the greatest impact. This type of sensitivity analysis is known as a Local Sensitivity Analysis (LSA). This is, within the LCA literature, the most common form of uncertainty analysis. However, there are issues. Specifically, the correlation between different input flows is not considered. This means that not all inputs should be varied by a chosen percentage, but instead, groups of inputs should be varied. A more detailed, yet highly computationally intensive process is to undertake a Global Sensitivity Analysis (GSA) using Sobel Matrices, as described within (Wei *et al.*, 2015), which includes uncertainty within inputs in the sensitivity analysis. A modification of this method, through the use of modified Sobel Indices known as Multidimensional Indices, can include the issues of non-independent input parameters. However, as discussed in the supplementary materials of (Wei *et al.*, 2015) this more complex form of LCA sensitivity analysis is dependent on the methods used for the creation of a correlation matrix, resulting in results that are currently subjective and arbitrary. What is needed is guidelines for LCA practitioners on correlation matrices, and additional data introduced within the various LCI databases such as Ecoinvent.

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A sensitivity analysis is essentially an assessment to understand which factors an LCA is most sensitive to, in terms of different impact categories. So, for example, it could be to test if the energy or chemicals

used in a process have the largest impact on climate change. In order to assess this, each factor is varied by a given percentage, to understand the impact that this has on the final model. Models were created where the major impacts were varied by +5% and -5% to show their impacts.

4.2.2 *EcoInvent Approach*

In order to fit with the methodology undertaken within the Ecoinvent database, and utilise the statistical data within that database, this thesis used log-normal distributions. Within Ecoinvent, there are lognormal distributions which are based on the pedigree matrix; this is a semi qualitative/quantitative method for uncertainty analysis. Initially, data is marked according to the following matrix. This is used to generate a log-normal distribution. This methodology is described in detail within (Ciroth *et al.*, 2016)

The following will explain the methodology used to create the uncertainties within Ecoinvent. It is important to note, in terms of replication, that the log-normal distribution conversation undertaken within OpenLCA is very slightly different to that within Ecoinvent itself. This is one of many subtle differences between applications of Ecoinvent within various LCA software packages.

The uncertainties within Ecoinvent are usually based around the two-parameter version of the lognormal distribution, the log-normal distribution (be it the two or three-parameter version) is a distribution which is often found within the natural world, in distributions where there are low mean values, large variances and no negative value, examples include species abundance, lengths of latent periods of infectious diseases, and distribution of mineral resources in Earth's crust (Limpert *et al.*, 2001). Lognormal distributions do not have negative values and have a skewed distribution (the differences between normal and log-normal are shown in Figure 8). It is an important note to make that, as the uncertainty is based on a log-normal distribution, then this is independent of units, which could if the uncertainty was based on arithmetic means, cause issues.

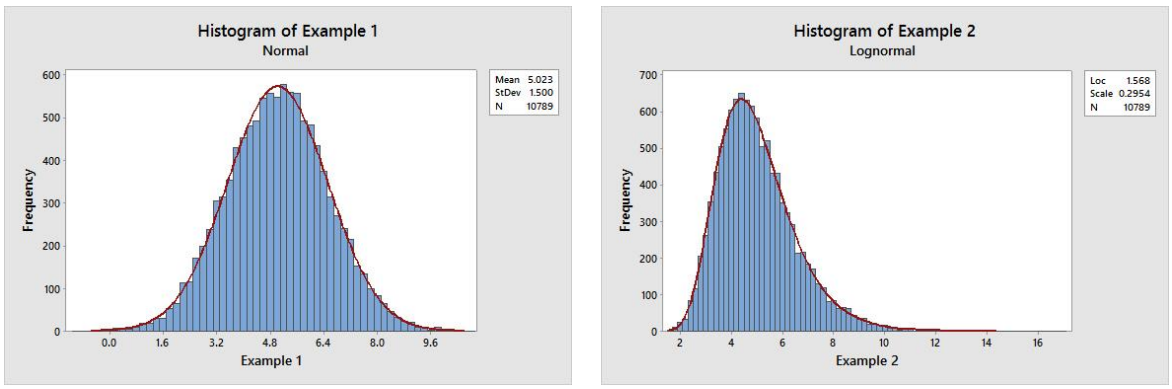

Figure 4-3: Normal and log-normal distribution – random data generated according to a normal and lognormal probability function with excel and plotted with Minitab

The Probability Density Function (PDF) of the log-normal distribution is given by;

$$f(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} exp\left(-\frac{(ln(x)-\mu)}{2\sigma^2}\right)$$

Where;

σ = geometric standard deviation

μ = geometric mean

The geometric standard deviation and geometric mean can be converted back to their more well-known arithmetic variants through; (from (Robinson, 1976))

$$\mu_{arithmetic} = exp\left(\mu + \frac{\sigma^2}{2}\right)$$

$$\sigma^2_{arithmetic} = (exp(\sigma^2) - 1)exp(2\mu + \sigma^2)$$

There are three inputs used by Ecoinvent to create this probability distribution, these are; 1) deterministic value (usually known in mathematics as the geometric mean), 2) the basic uncertainty and 3) the pedigree matrix.

The first stage is to calculate μ from the deterministic value (geometric mean).

$$\mu = ln(\mu^*)$$

Where;

μ^* = deterministic value (geometric mean)

The next stage is to calculate the basic uncertainty, which is the uncertainty from measurement inaccuracies. This figure is also referred to as the Variance of log-transformed data".

input / output group	c	p	a	input / output group	c	p	a
demand of:				**pollutants emitted to air:**			
thermal energy, electricity, semi-finished products, working material, waste treatment services	0.0006	0.0006	0.0006	CO_2	0.0006	0.0006	
transport services (tkm)	0.12	0.12	0.12	SO_2	0.0006		
Infrastructure	0.3	0.3	0.3	NMVOC total	0.04		
resources:				NO_X, N_2O	0.04		0.03
Primary energy carriers, metals, salts	0.0006	0.0006	0.0006	CH_4, NH_3	0.04		0.008
Land use, occupation	0.04	0.04	0.002	Individual hydrocarbons	0.04	0.12	
Land use, transformation	0.12	0.12	0.008	PM>10	0.04	0.04	
pollutants emitted to water:				PM10	0.12	0.12	
BOD, COD, DOC, TOC, inorganic compounds (NH_4, PO_4, NO_3, Cl, Na etc.)		0.04		PM2.5	0.3	0.3	
Individual hydrocarbons, PAH		0.3		Polycyclic aromatic hydrocarbons (PAH)	0.3		
Heavy metals		0.65	0.09	CO, heavy metals	0.65		
Pesticides			0.04	Inorganic emissions, others		0.04	
NO_3, PO_4			0.04	Radionuclides (e.g., Radon-222)		0.3	
pollutants emitted to soil:							
Oil, hydrocarbon total		0.04					
Heavy metals		0.04	0.04				
Pesticides			0.033				

Table 4-1: Default basic uncertainty (variance σ_b^2 of the log transformed data, i.e. the underlying normal distribution) applied to intermediate and elementary exchanges when no sampled data are available; c: combustion emissions ; p: process emissions; a: agricultural emissions. Taken from the Ecoinvent website (Ecoinvent).

Following this, the value of SD95 can be calculated as below;

$$\sigma 95 = exp\left(\sqrt{\sigma_b^2}\right)^2$$

Table 4-2: Pedigree Matrix as given on the Ecoinvent website (Ecoinvent).

	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
1	**Verified data based on measurements**	**Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations**	**Less than 3 years of difference to the time period of the data set**	**Data from area under study**	**Data from enterprises, processes and materials under study**
2	**Verified data partly based on assumptions or non-verified data based on measurements**	**Representative data from > 50% of the sites relevant for the market considered, over**	**Less than 6 years of difference to the time period of the data set**	**Average data from larger area in which the area under study is included**	**Data from processes and materials under study (i.e. identical technology) but**

		an adequate period to even out normal fluctuations			**from different enterprises**
3	**Non-verified data partly based on qualified estimates**	**Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods**	**Less than 10 years of difference to the time period of the data set**	**Data from area with similar production conditions**	**Data from processes and materials under study but from different technology**
4	**Qualified estimate (e.g. by industrial expert)**	**Representative data from only one site relevant for the market considered or some sites but from shorter periods**	**Less than 15 years of difference to the time period of the data set**	**Data from area with slightly similar production conditions**	**Data on related processes or materials**
5	**Non-qualified estimates**	**Representativeness unknown or data from a small number of sites and from shorter periods**	**Age of data unknown or more than 15 years of difference to the time period of the data set**	**Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)**	**Data on related processes on laboratory scale or from different technology**

The next phase is the pedigree matrix, which is a scorecard type methodology, where an LCA gives the data they are using a mark.

Based on the options selected, then the following figures are used to calculate the uncertainty from each element marked.

Table 4-3: Indicator score calculations within EcoInvent

Indicator Score	**1**	**2**	**3**	**4**	**5**
Reliability	0.000	0.0006	0.002	0.008	0.04
Completeness	0.000	0.0001	0.0006	0.002	0.008
Temporal correlation	0.000	0.0002	0.002	0.008	0.04
Geographical correlation	0.000	2.5×10^{-5}	0.0001	0.0006	0.002

Further technical correlation	0.000	0.006	0.008	0.04	0.12

From this, the variance of data with pedigree can be calculated, by summing the basic uncertainty and pedigree uncertainties. The half range of confidence interval is then calculated, giving

$$\sigma^* = exp\left(\sqrt{\sigma_b^2}\right)^2$$

At the end of this, the figures given by Ecoinvent are the geometric mean and the geometric standard deviation.

4.2.3 *Uncertainty within individual impact categories*

Further uncertainties can be found within the impact categories considered. For the sake of comparing two systems using the same impact category, the uncertainty will impact both processes equally, so it can be considered something to ignore in terms of comparative studies. However, in the broader sense of environmental research, then this uncertainty should be considered.

As discussed within the ILCD handbook, the uncertainties over chemical flows are less certain than energy flows. Thus the chemical-related impacts such as human toxicity and ecotoxicity have greater uncertainties than the energy-related impacts such as acidification, photochemical ozone formation or global warming impacts (Wold *et al.*, 2012). The only solution to these issues is to recreate various elements of the impact categories and LCI databases, which is beyond the remit of this thesis.

4.2.4 *Monte Carlo*

One issue of the log-normal distributions provided by Ecoinvent is that they are particularly hard to sum in order to understand the total uncertainty gathered from all the individual processes within a system. There are various proposed methods; however, the simplest approach is to use a Monte Carlo simulation, to try a number of values for each process following the probability distribution for that process (usually log-normal, although there may be some normal uncertainties and other distributions). A further issue is adding uncertainties with differing probability distributions is really complicated and time-consuming.

In terms of LCA packages, OpenLCA, which was chosen for the majority of analysis within this project, has the capability to run Monte Carlo simulations which take the lognormal distributions of individual processes into account. GaBi, which was used earlier within the project, has the issue that it is only

designed to deal with normal distributions, which if using Ecoinvent based statistical data and assumptions, are not likely to be the distribution of uncertainties for any given process.

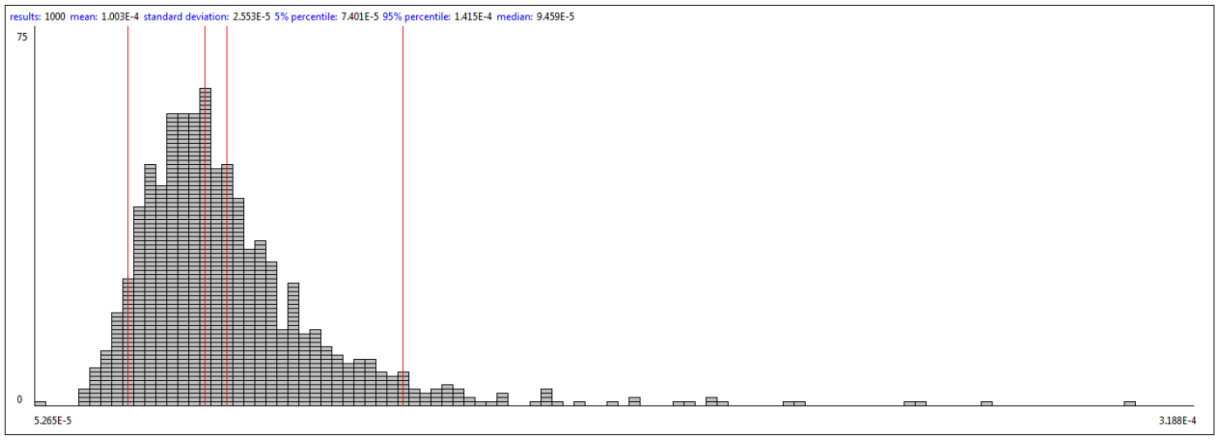

Figure 4-4: Result of a 1,000 run Monte Carlo simulation, based on the market for diesel, EU-CH, no inf | diesel | cut-off, U model, adapted by the author from an existing process. This graph shows the probability distribution of results for ReCiPe 2008 Marine Eutrophication

As can be seen within the above, the mean and standard deviation given are actually the arithmetic mean and standard deviation, which for this distribution, which is clearly not normal, is not appropriate. It will be discussed in the next section what probability distribution this figure represents (perhaps surprisingly, it is not a log-normal distribution, although it does share some characteristics with the aforementioned).

4.2.4.1 Probability Distributions

In addition to the normal and log-normal already discussed, there are a wide range of different distributions found within nature. Those considered within this work are;

Normal distribution

$$f(x)(x|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right), \sigma > 0$$

Lognormal,

$$f(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} exp\left(-\frac{(ln(x)-\mu)}{2\sigma^2}\right), x > 0, \sigma > 0$$

3-Parameter Lognormal,

$$f(x;\mu,\sigma,\theta,m)=\frac{1}{(x-\theta)\sigma\sqrt{2\pi}}exp\left(-\frac{\left(ln\left(\frac{x-\theta}{m}\right)\right)^2}{2\sigma^2}\right),x>0;m,\sigma>0$$

The distribution is applied to the frequency analysis of floods, annual flows, and monthly flows (reference http://onlinelibrary.wiley.com/doi/10.1029/WR006i002p00505/abstract)

Exponential

$$f(x;\theta)=\frac{1}{\theta}exp\left(-\frac{x}{\theta}\right),x>0,\theta>0$$

2-Parameter Exponential

$$f(x;\theta,\lambda)=\frac{1}{\theta}exp\left(-\frac{x-\lambda}{\theta}\right),x>0,\theta>0,-\infty<\lambda<\infty$$

Smallest Extreme Value

$$f(x;\lambda,\sigma)=\frac{1}{\sigma}exp\left(-\frac{x-\lambda}{\sigma}\right)exp\left(-exp\left(\frac{(x-\mu)}{\sigma}\right)\right)$$

Largest Extreme Value

$$f(x;\lambda,\sigma)=\frac{1}{\sigma}exp\left(-\frac{\mu-x}{\sigma}\right)exp\left(-exp\left(\frac{(\mu-x)}{\sigma}\right)\right)$$

Weibull

$$f(x;\beta,\sigma)=\frac{\beta}{\sigma^\beta}x^{\beta-1}exp\left(-\frac{x^\beta}{\alpha}\right),x\geq0,\alpha>0,\beta>0$$

3-Parameter Weibull

$$f(x;\alpha,\beta,\sigma)=\frac{\beta}{\sigma^\beta}(x-\lambda)^{\beta-1}exp\left(-\frac{(x-\lambda)^\beta}{\alpha}\right),x\geq\lambda,\alpha>0,\beta>0$$

Gamma

$$f(x;\alpha,\beta,\Gamma)=\frac{x^{\alpha-1}exp\left(-\frac{x}{\beta}\right)}{\Gamma(\alpha)\beta^\alpha},\alpha>0,\beta>0$$

3-Parameter Gamma

$$f(x;\alpha,\beta,\gamma,\Gamma) = \frac{(x-\gamma)^{\alpha-1} exp\left(-\frac{(x-\gamma)}{\beta}\right)}{\Gamma(\alpha)\beta^{\alpha}}, \alpha > 0, \beta > 0$$

Logistic

$$f(x;\sigma,\mu) = \left(\frac{1}{\sigma}\right)\frac{exp\left(\frac{(x-\mu)}{\sigma}\right)}{\left[1+exp\left(-\frac{(x-\mu)}{\sigma}\right)\right]^2}, -\infty < x < \infty, -\infty < \mu < \infty, \sigma > 0$$

Log logistic

$$f(x;\sigma,\mu) = \left(\frac{1}{x\sigma}\right)\frac{exp\left(\frac{(ln(x)-\mu)}{\sigma}\right)}{\left[1+exp\left(\frac{(ln(x)-\mu)}{\sigma}\right)\right]^2}, x > 0, \sigma > 0$$

3-parameter log logistic

$$f(x;\sigma,\lambda) = \left(\frac{1}{\sigma(x-\lambda)}\right)\frac{exp\left(\frac{(ln(x-\lambda)-\mu)}{\sigma}\right)}{\left[1+exp\left(\frac{(ln(x-\lambda)-\mu)}{\sigma}\right)\right]^2}$$

4.2.4.2 Identification of Distributions

A number of probability functions can be considered, within this work Minitab has been used, as this allows for a range of well-used probability functions to be used (all of those listed in the previous section). Minitab attempts to fit various probability distributions to histograms of the data, as well as allowing a visual assessment of the fit. The command within Minitab is: Stat > quality tools > individual distribution identification.

The factors considered by Minitab are:

Anderson-Darling statistic (AD): The Anderson Darling is used to test if a sample of data came from a specific probability distribution, it is a modification of the Kolmogorov-Smirnov test, but gives more weight to the tails. The test involves the assumption that the values within the probability distribution or in cumulative order ($x_1 \leq x_2 \leq \cdots \leq x_n$). The z statistic is calculated for each value of i, and from this, the AD statistic (A) is then calculated from;

$$A^2 = -\left\{\sum_{i=1}^{n}\frac{(2i-1)}{n}[ln(z_i) + ln(1-z_{n+1-i})]\right\} - n$$

The critical values for the Anderson-Darling test are dependent on the specific distribution that is being tested. Tables exist of the various values for different probability distributions, and the test rejects a particular probability distribution if the calculated value of A is greater than the critical value. For different types of probability distribution, the value of A must be multiplied by a particular factor before comparison with the critical value. Critical values are published within (Stephens, 1974; Stephens, 1976; Stephens, 1977a; Stephens, 1977b; Stephens, 1979). It is important to be aware that the Anderson-Darling statistic does suffer from a major issue with ties in data, which can lead to a rejection of a particular probability distribution(Machiwal and Jha, 2012).

P-value of the Anderson-Darling test: From the calculated values of A within the AD, the p-value can then be calculated. However, it is important to note that in terms of 3 parameter tests, the p-value is impossible to calculate. The formulae for the P-value of various values of A can be found within Chapter 4 of (D'Agostino and Stephen's, 1986), depending on the number of known variables.

Likelihood-Ratio Test P-Value (LRT P): For 3-parameter distributions only, this is a test of the ratio of the simple version of a probability function, against the 3-parameter version. For large samples, this ratio follows a chi-squared distribution. A low value suggests that the 3-parame4ter version provides a significant improvement over the 2-parameter version. A higher value suggests that the 3-parameter version is an unnecessary complication.

In addition, Minitab provides Probability Plots of the data, these are a transformed plot of the Cumulative Distributed Function (CDF) for each probability function, with the scales transformed to give the impression the CDF is a linear plot. The population data is then plotted against this to show how it compares. An example of this is given in Figure 10. Finally, Minitab can provide a fit against the histogram of data itself, such as in Figure 11.

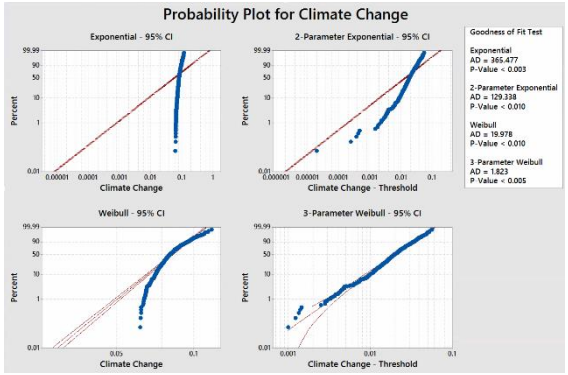

Figure 4-5: Probability plot for a process producing microalgae. The exponential and Weibull have been chosen for this graph, to show the range of different fits

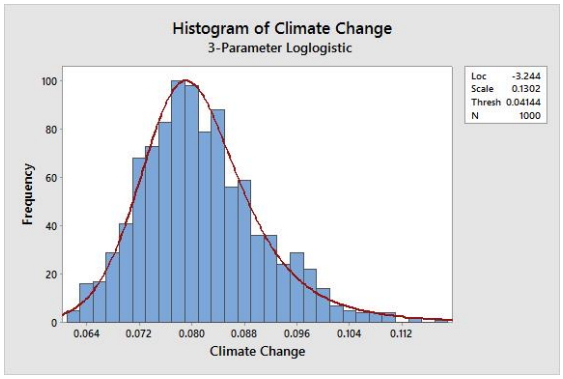

Figure 4-6: Histogram of the data for the climate change impacts of microalgae production, with a 3-parameter log-logistic distribution fitted to the data.

4.2.4.3 Significance testing

The usual method for measuring the significance of two unrelated value with normal distributions is the t-test. This is a test over if the means of two normally distributed populations are significantly different, or if the differences are just essentially statistical noise. The t-test is the ratio of the means against the variation of each population.

In terms of the significance of two independent log-normal distributions, then one approach is to log the two distributions (or use another type of Box-Cox transformation), creating normal distributions, and then undertaking a t-test on these. There are a number of issues with this, as comparing the means of log-transformed data is not the same as comparing the means of the original log-normal distributions. This is discussed in detail within (Feng *et al.*, 2013).

On the basis of this, a more suitable nonparametric method should be used on the data. Specifically, the Mann-Whitney U-Test (sometimes known as the Wilcoxon Rank Sum Test). This method provides a test of the null hypothesis, based on ranking each individual data point. It is a test of the null hypothesis that it is equally likely that a randomly selected value from one sample will be less than or greater than a randomly selected value from a second sample. The following description is from (Spence *et al.*, 1983; Weimer, 1993; Gravetter and Wallnau, 2000)There are a number of requirements for this test to be appropriate, specifically;

1. The dependent variables under consideration should be measures at the ordinal or continuous level
2. The independent variables should both be independent of each other
3. The populations within each group must be independent of each other; there must be no crossover.
4. The probability distributions of the two independent variables must not be normally distributed, but also must both have the same distribution, whatever distribution that happens to be.

To undertake the test, first, the two sets of data are ranked, and the values of the Mann-Whitney Statistic (U) calculated.

The values of U are;

$$U_A = W_A - n_A \frac{(n_A + 1)}{2}$$

Where;

n_A = number of variables in population A (the smallest population)

W_A = sum of the ranks in population A

In a case where the population sizes of n_A and n_B are the same, then try both to see which has the minimum value,U_A or U_B.

The mean of the sampling distribution of U is given by;

$$\mu_U = \frac{n_A n_B}{2}$$

Whilst the standard deviation of U is given by;

$$\sigma_U = \sqrt{\frac{n_A n_B (n_A + n_B + 1)}{12}}$$

However, if there are some tied ranks, then this should be adapted to;

$$\sigma_U = \sqrt{\frac{n_A n_B}{12}\left((n+1) - \sum_{i=1}^{k}\left(\frac{t_i^3 - t_i}{n(n-1)}\right)\right)}$$

Where;

$n = n_A + n_B$

t_i = number of subjects sharing rank i

k_i = number of (distinct) ranks

From these, the value of z-statistic can be calculated as;

$$z = \frac{U - \mu_U}{\sigma_U}$$

With z, this shows how far from the mean of the U value distribution the z-statistic lays. The p-value can then be calculated, either by formula or from tables, under the assumption that the distribution of U (not the distribution of the populations under study) is normal.

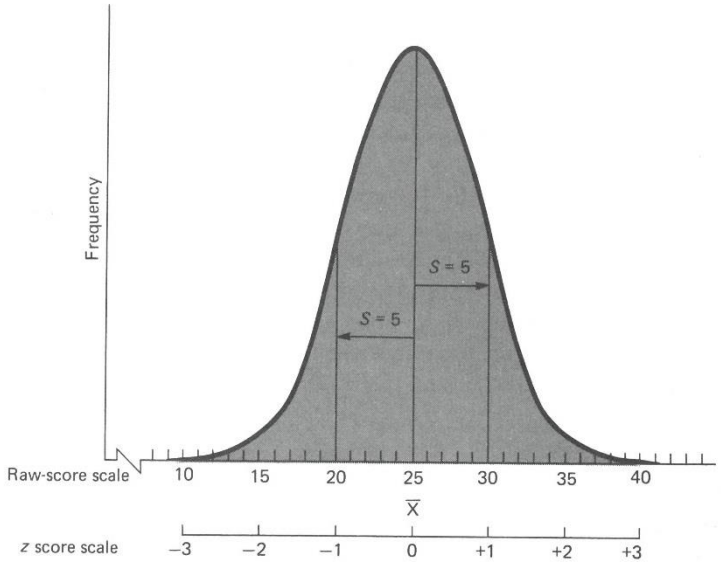

Figure 4-7: Example of z-scores, where z=1 is the value of σ_U, and this is a normal distribution. Taken from (Spence et al., 1983)

It is important to note that this is based on calculating the significance of the difference in the medians of the data, not geometric or other types of mean.

The best way to demonstrate the U-test is through a basic example, adapted from(Weimer, 1993)

Assume there are two groups of industrial processes, which produce a certain amount of dry microalgae per day. The totals produced per day are given below

Table 4-4: U-test example, data used

Process	Dry microalgae produced [kg/day]									
Process A	73	67	72	46	83	75	62	90	95	N/A
Process B	71	47	68	87	77	92	65	86	79	57

To understand if these two processes are significantly different, the Mann-Whitney test will be applied. First, rank the data;

Table 4-5: U-test example, ranked data

Value	Rank	Process
46	1	A
47	2	B
57	3	B
62	4	A
65	5	B

67	6	A
68	7	B
71	8	B
72	9	A
73	10	A
75	11	A
77	12	B
79	13	B
83	14	A
86	15	B
87	16	B
90	17	A
92	18	B
95	19	A

As Process A has the least samples, W_A as is calculated as follows for A;

This can be given by;

W = 1+4+6+9+10+11+14+17+19=91

$$W_A = 1 + 4 + 6 + 9 + 10 + 11 + 14 + 17 + 19 = 91$$

From this, U_A can be calculated

$$U_A = W_A - n_A \frac{(n_A+1)}{2} = 91 - 9\frac{(9+1)}{2} = 46$$

The mean is given as;

$$\mu_U = \frac{n_A n_B}{2} = \frac{9 \times 10}{2} = 45$$

Whilst the standard deviation of U is given by;

$$\sigma_U = \sqrt{\frac{n_A n_B (n_A+n_B+1)}{12}} = \sqrt{\frac{(9\times10)(9+10+1)}{12}} = \sqrt{150} = 12.25$$

On the basis that $n_A > 8$ then the sampling distribution of U can be taken as normal, and the z-statistic is given as;

$$z = \frac{U - \mu_U}{\sigma_U} = \frac{46 - 45}{12.25} = 0.08$$

In order for $p > 0.05$ (for the difference to be significant) then according to tables, the critical values are $\pm z_{0.05} = \pm 1.96$. As $-1.96 < z = 0.08 < 1.96$, then the null hypothesis can not be rejected. Furthermore, thus there are no significant differences between the processes.

4.2.5 *Summary*

Therefore, in summary, using the methods described in this chapter, the following methods are used to determine the uncertainty.

1. Sensitivity Analysis
2. Statistical analysis via Monte Carlo analysis

The Monte Carlo analysis based method following these steps:

1) Ensure Ecoinvent uncertainty is inputted
2) Add in further measurement uncertainties within data
3) Run a 1000n Monte Carlo Analysis
4) Export data from OpenLCA to Minitab
5) Identify Probability Distributed of new case and base case
6) Assuming the same probability function is within the new and base cases, run a U-test to quantify the significance of the difference between the two.

4.3 Land Use Methodology

An important element of the climate change impact of biofuels is land-use change, how does the greenhouse gas alleviation of the biofuel usage compare with that of the original environment the biofuels are grown on? Additionally, how much CO_{2eq} is released when the land changes use? This is known as direct Land Use Change (dLUC). Furthermore, there are indirect Land Use Change (iLUC) issues to consider, whereby biofuel production displaces existing land users, who then convert some other land elsewhere for their purposes, such as displaced farmers.

Various studies have highlighted these issues, such as (Fargione *et al.*, 2008) (Gibbs *et al.*, 2008) and (Lapola *et al.*, 2010). Additionally, in 2015 the European Commission GLOBIOM report (Valin *et al.*, 2015) presented comparisons of iLUC for EU and non-EU crops.

There are a high number of different methodologies for land-use changes, methods for direct, indirect, and both. These are described in Table 4-6 taken from(Djomo and Ceulemans, 2012):

Table 4-6: Methodologies for land-use change calculations taken from (Djomo and Ceulemans, 2012)

Name		dLUC	iLUC
2006 IPCC Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use	Tier 1	x	
	Tier 2	x	
	Tier 3	x	
DAYCENT		x	
The Global Trade Analysis Project (GTAP) model			x
Modelling International Relationship in Applied General Equilibrium (MIRAGE) model			x
The Food and Agricultural Policy Research Institute (FAPRI) model			x
International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model			x
Global Biomass Optimization (GLOBIOM) model			x
Emissions Prediction and Policy Analysis (EPPA) model merged with Terrestrial Ecosystem Model (TEM)		x	x
Forest and Agriculture Sector Optimization Model (FASOM) merged with The Food and Agricultural Policy Research Institute (FAPRI) model		x	x
Center for Agricultural and Rural Development (CARD) merged with Greenhouse gases from Agriculture Simulation (Green-AgSim) model.		X	x
Integrated Model to Assess the Global Environment (IMAGE)			x
Risk-Adder			x
Reduce-Form Model of iLUC (RFMI)			x

The method which has been used in this work is the *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use Tier 1* methodology(*2006 IPCC Guidelines for National Greenhouse Gas Inventories*, 2006). The reason for this is that although it can be considered the most basic, it is also the most transparent, and very widely used. This means that in an area where there are a large number of uncertainties, then the possibilities are kept as low as possible. Additionally, as this is a widely used methodology, results can be compared with those of other projects. The method is designed for national reporting of emissions from Land-Use Change; however, without turning this project into a detailed study of Land Use Change, it would be impractical to use the other models. It is accepted there are some oversimplifications in the method; specifically, it assumes that N_2O emissions are solely a function of nitrogen inputs to the soil and also does not account for the carbon fluxes.

The IPCC Tier 1 method considers three areas:

1. Biomass carbon stock change
2. Soil organic carbon stock change

3. Incomplete combustion of biomass and dead organic matter (DOM) in the initial land-use category before conversion

All values are taken from default data from the IPCC guidelines, based on the land area changed, climate, type of vegetation and various other variables. Estimates are made of the biomass and organic soil carbon stocks before and after conversion of land to new uses, and the sum of these changes added to the emissions from incomplete burning of biomass and dead organic material.

4.4 Climate Change Impacts

At the beginning of this research, an issue within LCA was the use of outdated climate change information, from the 2007 IPCC 4th Assessment (AR4) (Forster *et al.*, 2007a). Despite the release of updated figures within Chapter 8 of the WGI contribution to the Fifth Assessment (AR5)(Myhre *et al.*, 2013a) in 2013, most LCA practitioners were (and still are) unaware of the updated figures for GWP100[§], or the importance of considering other time horizons, such as GWP20. Through conversations at various conferences, it seems clear many LCA practitioners are unaware as to the scientifiec methods of Global Warming Potential and Global Temperature Potential. It is important to note that the differences between AR4 and AR5 can lead to an 80approx. 10% difference for the climate change impacts of some industrial systems, and using outdated data can lead to wrong choices in terms of sustainability. In addition to containing modified values for the radiative forcing impacts of greenhouse gases, AR5 also includes far more than AR4; 207 as opposed to 96[**].

As a result of this, the author created a new AR5 database for GaBi, which was implemented into the official release of the software by Sphera Solutions (at the time, PE International). This model includes both Global Warming Potentials and Global Temperature Potentials. A similar database has been created by the author for OpenLCA. With the coming release of AR6, post thesis publications using the final LCA models within this Thesis will use a newly created version of AR6 data within GaBi and OpenLCA, created using the same methodology as the AR5 data. This model, as with the AR5, will include GWP and GTP data for various time horizons.

In order to create the GaBi AR5 mode database, the author converted the data from Table 8.A.1 of AR5 into a GaBi format file. As this work was of interested to PE International, the producers of GaBi, the author worked with PE to validate this work. Morten Kokborg from PE International provided the author with a selection of additional flows to be included in the October 2014 update of GaBi. These flows were drafts, not having completed the full PE International Quality Assurance process.

Using Nitro PDF, the data from WGI-AR5 was converted into an Excel format spreadsheet. This conversion was not perfect, and so the data on each chemical was compared individually between

[§] Some examples, such as the European Commission's Renewable Energy Directive (2009) still use figures from the IPCC Third Assessment (2001) – although by 2020 the Commission intends to start using the 2007 figures from AR4.

[**] The full 96 chemicals are listed in an errata to the original WGI-AR4 report, the errata can be found at http://www.ipcc.ch/publications_and_data/ar4/wg1/en/erratataserrata-errata.html

table 8.A.1 and the spreadsheet.

One significant issue for using the GWP and GTP values in WGI-AR5 for GaBi is that the chemicals have many different names. Therefore GaBi would refer to a chemical by one name, whereas WGI-AR5 would use another. To give an example; Methylene bromide is also known as Dibromomethane.

The solution to this was to first catalogue all the chemicals within WGI-AR5 by their CAS Registry Numbers (CASRN). Each chemical has a unique numerical identifier under this methodology; the numbers are not related to properties; it is simply a catalogue. Data for the CASRN was gathered from (Hodnebrog *et al.*, 2013) and (US Government Printing Office, 2014), with the gaps filled in by using the NIST Chemistry Workbook (Technology, 2014)and the ChemIDplus database within TOXNET (U.S. National Library of Medicine, 2018).

Initially, the quantities file ***"IPCC global warming, incl biogenic carbon"*** within the GaBi ***"Impacts ILCD/PEF recommendation"*** impact categories were used. This file contains GWP100 data from the IPCC WGI-AR4 report converted into GaBi flows. The list of flows was compiled with the CASRN, and compared with the WGI-AR5 data. This showed that in WGI-AR5 the chemicals Dimethylether (CH_3OCH_3) and Trifluoroiodomethane (CF_3I) are not included in Table 8.A.1. In order to understand if this was a mistake within WGI-AR5, Working Group I of the IPCC were contacted to query these omissions, who replied that:

> "[T]his was not an oversight, but based on the IPCC authors' judgement of the quality of the available information for the assessment of the halocarbons. For both compounds, the WGI authors have concluded that an assessment of the metric values on the same level as for the rest of the compounds (>200 in Table 8.A.1) was not possible because of insufficient evidence."

Additionally, it was found that the GaBi ***"IPCC global warming, incl biogenic carbon"*** impact category used HFE-254cb2 instead of HFE-254cb1, and also included Halon 4204 instead of Halon 4202.

Following this, searches were carried out in GaBi for the corresponding flows to other chemicals in Table 8.A.1. Mainly this was carried out using the CASRN, however, in some cases, the CASRN recorded in GaBi was inaccurate or missing, and so synonyms of names were used to search. Comparisons of the GaBi WGI-AR4 data and WG1-AR5 data to find chemicals which had been misclassified, investigating each one with a GWP100 difference of over 10%.

The completed spreadsheet of WGI-AR5 chemical names was validated by PE International and then converted into GaBi quantity files. The files produced were:

- Global Warming Potential over 20 years (GWP20)
- Global Warming Potential of 100 years (GWP100)

- Global Temperature change over 20 years (GTP20)
- Global Temperature change over 50 years (GTP50)
- Global Temperature change over 100 years (GTP100)

The final validated files created by the author were included in the October 2014 update of GaBi. This helped enable other researchers to use the latest data for Climate Change impacts.

Whilst this thesis uses the AR5 data created by the author, there are now some other AR5 databases for LCA software, which will be reviewed below, and the model created within this Thesis;

4.4.1 *GaBi Sphera Solutions*

The GaBi Sphera Solutions AR5 database was the first application of AR5 within LCA. It was created by the author, working with Thinkstep, as described above in 2014. There are all 209 individual gases from Table 8.A.1 of AR5 included (as well as biogenic and non-biogenic versions of CO2 and CH4).

The figures within the database are based on table Table 8.A.1 within AR5 pages 731 to page 737.

Minor queries were answered by the IPCC WGI TSU with relation to Dimethylether and Trifluoroiodomethane GWP and GTP values.

Problems

- The data, being based on the main AR5 document, did not include precise figures, which ideally should come from http://cicero.uio.no/halocarbonmetrics/ , as detailed in section 8.SM.13 of the Supplementary Materials to Chapter 8 of AR5 (Myhre *et al.*, 2013c). This could have been avoided through a more detailed reading of AR5, or through AR5 being more clear.
- In cases where the figures were "<1" then a number of "0.9" was used within the GaBi database. Again, this could have been avoided by using the original source of the Cicero website.
- Gases not included within the main table 8.A.1 of AR5 are not included, such as Carbon Monoxide.
- Carbon-climate feedback (CCFB) systems are not included.

Positive notes

- This was the first application of AR5, released within months of the AR5 reports.
- It presents data for GWP20, GWP100, GTP20, GTP50 and GTP100, with versions included biogenic and non-biogenic, as well as Land Use Change, making it the most comprehensive
- It includes all AR5 emission factors.

- It includes all AR5 emission factors for gases names within Table 8.A.1 of AR5

4.4.2 *EcoInvent*

Ecoinvent released two versions of AR5, the first was acknowledge to include mistakes in terms of an inconsistent approach to including CCFB values, but the second contains the most accurate figures, having used the Cicero website. However, only 37 chemicals are considered (with biogenic and non-biogenic methane and carbon dioxide).

Problems

- Limited number of gases are included.
- GTP50 not included.

Positives

- Most accurate application of AR5 data for those gases that are included.
- Like Sphera Solutions, this includes GWP20 and GTP.
- It does include Carbon Monoxide.

4.4.3 *ReCiPe*

Within ReCiPe 2016, a version of AR5 was included. Due to the popularity of ReCiPe within academia, this will most probably be the most well-used version of AR5 within LCA. It contains 209 separate gases names within AR5 Table 8.A.1, but uses CCFB for GWP100 (within the ReCiPe Hierarchist model) but not for GWP20 (within the ReCiPe Individualist model). Although in terms of the way ReCiPe's Hierarchist and Individualist models work this makes sense, it is not helpful for someone considering climate change over different time horizons. The method uses data from AR5, not the Cicero website. It does not include any GTP data.

Problems

- Only GWP is considered within the Hierarchist model, with only GWP20 in the Individualist model, which can lead to confusion, as the Individualist model does not include CCFB impacts.
- GTP is not included within the ReCiPe model
- As with GaBi, this is not from the Cicero website, which has more precise figures.
- Gases listed as "<1" for GWP are set at "1" or "0" within the ReCiPe databases
- Gases not included within the main table 8.A.1 of AR5 are not included, such as Carbon Monoxide.

Positive Notes

- Due to the high use of ReCiPe, three years after the release of AR5 this finally brought up to date GWP figures into the LCA "mainstream".
- This is the only database to use the CCFB data from AR5.
- It includes all AR5 emission factors for gases names within Table 8.A.1 of AR5

4.4.4 *Summary*

Whilst three separate groups have created LCA databases of the AR5 data, none of them are perfect. Ecoinvent uses the most accurate figures, whilst Sphera Solutions includes more methods of measuring climate change. ReCiPe's model includes CCFB for GWP100, which is very important, but only considers GWP20 and GWP100, and the difference between Individualist and Hierarchist models lead to CCFB considered for GWP20 and not GWP100, which can lead to confusion. Sphera Solutions and ReCiPe both use all gases within Table 8.A.1 but ignore Carbon Monoxide. Ultimately, despite the existence of the AR5 data, the LCA community is still fixed on the GWP100 values from the AR4, published in 2007. This is, in the experience of the author, due to a lack of understanding by many LCA researchers of what the IPCC is, or what GWP is. There is inconsistency in the way AR5 is applied in the three databases used. In order for LCA to be used to lower the climate change impacts of all products, through identifying the hidden greenhouse gas emissions within complex supply chains, a consistent and accurate approach to climate change impacts must be implemented, working with the IPCC.

Table 4-7: Comparison of three main AR5 databases used within LCA

Climate Change Factors		GaBi Sphera Solutions	Ecoinvent	ReCiPe 2016
IPCC AR5 factors included	GWP20	X	X	X
	GWP100	X	X	X
	GTP20	X	X	
	GTP50	X		
	GTP100	X	X	
Additional Factors	Land Use Change	X		
	GWP1000			X
	Gases included	209	37	209
	CCFB Method	No CCFB	No CCFB	CCFB for GWP100, no CCFB for GWP20
	Date released	2014	2015	2016

As an additional output from this Thesis, in order to reduce these issues, it would make sense to form a small working group to ensure that:

1) All gases considered within AR5 are correctly mapped to the names used by LCA software
2) The full list of gases considered in AR6 is used in all LCA software
3) A consistent approach is taken to the inclusion of climate feedbacks
4) The release of AR6 LCA data within software is as quickly as possible
5) This is communicated to the LCA community, so it is understood that practitioners should, finally, stop using IPCC AR4 data for climate change calculations

This work is not particularly hard if there is good communication between the IPCC and all those involved in the various impact factors and software packages. There is limited software and/or research involved; it is more a process of organisation. This will ensure AR6 LCA data is released quickly, prevent various LCA groups replicating effort, and ensure that this is done in the most accurate way possible. That will ensure with the release of the Sixth Assessment (AR6), the approach of all LCA software and databases is to have an AR6 database released immediately, working with the IPCC to ensure that there are no mistakes or misunderstandings, and ensure a consistent approach is applied to carbon-climate feedback (CCFB) loops. Whilst not particularly difficult, this will be an output from this Thesis which will have an impact on all LCA studies.

Chapter 5. Data

Within this project, data has been taken from several different projects, funded by the European Commission and Innovate UK. The data for these has been used via the employment of the author by both Offshore Renewable Energy Catapult (ORE Catapult) and the commercial spin-out from ORE Catapult, Narec Distributed Energy (NDE). This section of the methodology will cover the detail of the projects, the databases, primary data, and the construction of metering equipment.

5.1 Projects Used

The LCA has used data from the InteSusAl, BIOMOD and MAGNIFICENT projects. The InteSusAl project was part of the Algae-Cluster, from which this thesis also takes comparative data from the All-Gas project.

5.1.1 *The Algae Cluster*

The Algae-Cluster was a major European Commission driven microalgae demonstration project, made up of three individual European Commission funded microalgae biofuel projects. Each of these originally aimed to construct a demonstration facility of size 10 hectares, to each demonstrate and optimise different approaches to the production of microalgae biofuels('Algae Cluster,' 2014). The three projects were: InteSusAl, BIOFAT and All-Gas.

5.1.1.1 InteSusAl (Demonstration of integrated and sustainable microalgae cultivation with biodiesel validation)

Partner organisations: Centre for Process Innovation (UK), Necton (PT), Royal Netherlands Institute for Sea Research (NL), Institute Food & Biobased Research (DLO-FBR) (NL), European Renewable Energy Centre (EU), National Renewable Energy Centre (UK).

The InteSusAl project designed, built and operated a 1-hectare microalgae production facility in Olhão, Portugal. The facility was constructed on the same site as Necton's existing microalgae production system. Figure 5-1 details the InteSusAl concept. Fermenters growing microalgae (*Chlorella protothecoides*) heterotrophically feed CO_2 into a system of photobioreactors growing the microalgae species, *phaeodactylum tricornutum* and *nannochloropsis salina*, separately. When the microalgae oil is recovered and converted to biodiesel through the process of transesterification, the waste glycerol produced is fed back to the fermenters. Additional glycerol is supplied as waste from other industrial producers. The author of this thesis was the Work Package leader for Work Package 7, wrote the major LCA reports, and also wrote numerous parts of the original funding bid related to LCA.

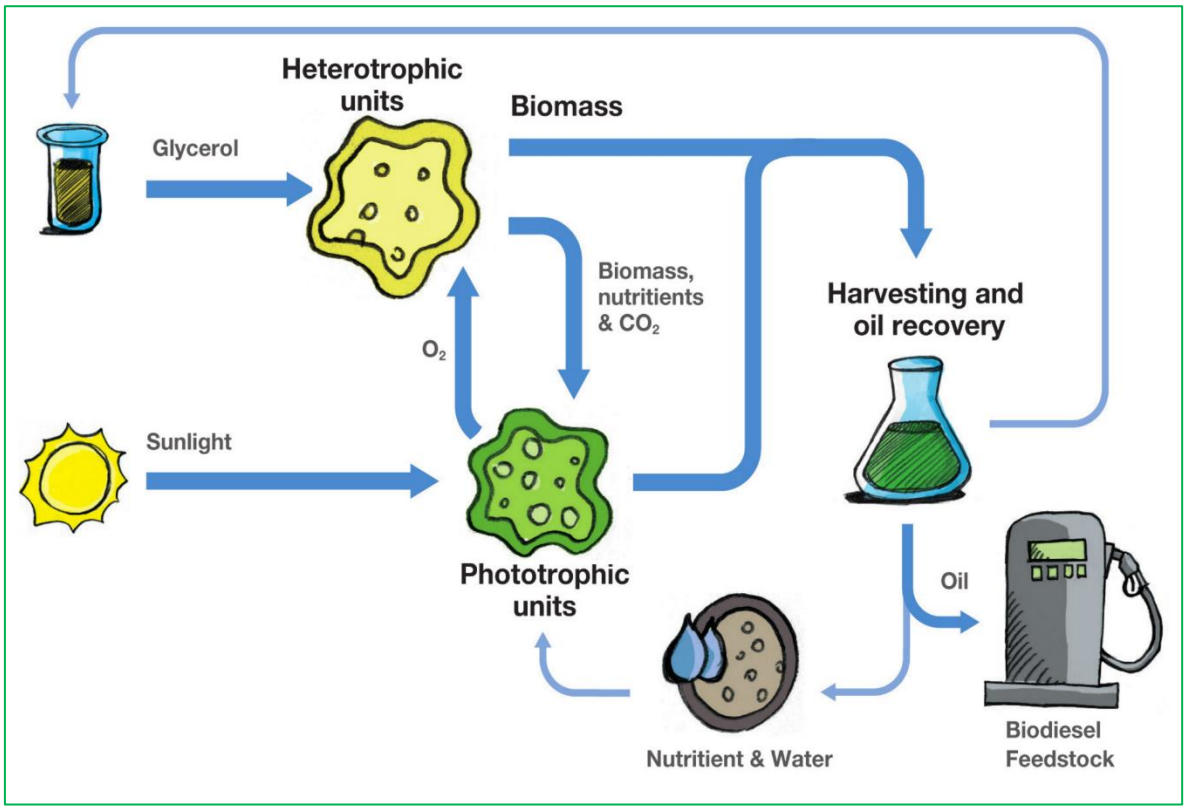

Figure 5-1: InteSusAl process diagram from ('InteSusAl,' 2014)

Figure 5-2: Photobioreactors at the Necton site in Olhão, photograph by author. The green photobioreactors (left) contain nannochloropsis salina, and the brown (right) contains phaeodactylum tricornutum.

5.1.1.2 BioMOD (Single Use Technology (SUT) systems for Bioprocessing in Industrial Biotechnology)

Partner organisations: Centre for Process Innovation (UK), BioProcess Engineering Services Ltd (UK), University of Bath (UK), GlaxoSmithKlien (UK), National Renewable Energy Centre (UK).

This AMSCI funded project (which is ultimately funded by Innovate UK) was based around the design, manufacture and operation of low-cost disposable plastic-based fermenters. Within this project, chlorella was grown (amongst other microorganisms not relevant to this thesis). The data from this project is used within the LCA to understand if bag-based fermenters instead of steel ones would reduce the impact of the InteSusAl facility. The data from this project has taken a minor part of this thesis, due to the poor results in terms of productivity.

The BoMODule is a bag based semi-continuous fermenter system. The concept was that through using disposable bags, the levels of cleaning and sterilisation would be reduced. Additionally, the system is a low power modular system, which reduced the need for the construction of large infrastructure. Single-Use Technology (SUT) itself is not novel, and the early beginnings of the approach were in the 1960s (Eibl *et al.*, 2010) , however, the approach of BioMOD to develop a system appropriate for large scale production is novel. The important question from an LCA perspective is if the use of disposable bags will be balanced out by the reduction in energy use, to give higher or lower environmental impacts.

Figure 5-3: BioMODule system within CPI

5.1.1.3 MAGNIFICENT (Microalgae as a Green source for Nutritional Ingredients for Food/Feed and Ingredients for Cosmetics by cost-Effective New Technologies)

Partner organisations: Wageningen University (NL), Stichting Wageningen Research (NL), Fraunhofer Gesellschaft Zur Foerderung Der Angewandten Forschung E.V. (DE), Necton – Companhia Portuguesa De Culturas Marinhas Sa (PT), AlgaFarm (PT), Sparos Lda (PT), Erdyn Consultants (FR), Alga Development Engineering And Services Sl (SP), Madebiotech – C R & D S.A. Zona Franca Da Madeira

(PT), Narec Distributed Energy Limited (UK), Algosource Technologies (FR), Kemin Industries (BE), Imenz Bioengineering Bv (NL), N-Zyme Biotec Gmbh (DE), Natac Biotech Sl (SP), Total Raffinage Chimie Sa (FR).

MAGNIFICENT is a Horizon 2020 funded project which is running from 2017 to 2021. It is funded via the BBI-RIA (Bio-based Industries Research and Innovation action) scheme under grant agreement ID: 745754. The project is a direct follow on to InteSusAl and is using the photobioreactor elements of the facilities. Additional facilities within Wageningen University and MadeBiotech are being used to grow microalgae. The purpose of this project is to look into all the various types of high-value products which can be created by microalgae. These include antioxidants, colourants, functional proteins, bioactive peptides, lipids, polysaccharides and antimicrobials, for use within the pharmaceutical, nutraceutical, food and feed markets. The data from this project is from the trials at the All Microalgae facility in Lisbon.

5.2 Models

The core model for this thesis was for the InteSusAl project, and this is the source of most of the research within this work. Supplementary models were made for the BioMODule system, and also for the MAGNIFICENT project. These were to understand if bag-based fermenters would be a good idea to improve the system, and in terms of MAGNIFICENT, the models were to provide an updated system based on a larger facility, which also enabled statistical analysis through the use of OpenLCA.

The models were as follows;

InteSusAl (GaBi)

1) A: 2012 Electricity – in order to compare with the All-Gas project
2) B: 2020 Electricity – a present-day system
3) C: 100% Photovoltaics – Based on modified versions of Ecoinvent photovoltaic models, utilising the software PVSyst

BIOMOD (OpenLCA)

1) Portuguese Grid Electricity (2016-2017)

MAGNIFICENT (OpenLCA)

1) Portuguese Grid Electricity (2016-2017)
2) 80% PV and 20% grid electricity

Whilst it may seem strange to use two different sets of modelling software; this was necessary due to

the length of the PhD. An issue with a part-time PhD is that the work undertaken at the beginning is significantly out of date by the end of the work. Therefore, with the third case study, a far more updated approach has been taken. This means that the thesis is still producing publishable work, and not simply work which is out of date. An additional difference, was, throughout the course of this project, the author has learned to speak Portuguese (to a very basic level). Hence, the number of sources available, especially on the Portuguese electricity grid, was increased.

5.3 Commercial Data

Within this work, commercial data has been used from organisations outside of the project. In particular, yeast data was gathered from a Chinese based manufacturer, who wished to remain anonymous within any documentation, which unfortunately includes this thesis.

5.4 Secondary Data

Secondary LCA databases were used, specifically EcoInvent. Further data is being used from Sphera Solutions (via their Data on Demand service), NREL and the literature. These are summarised below.

Ecoinvent | Ecoinvent Centre

The Ecoinvent database (Wernet *et al.*, 2016) was used as the primary source for secondary data and baselines. Whilst EcoInvent is now on version 3.6, the version used for this work was 3.2. Ecoinvent is produced by the EcoInvent Centre and is a major source of LCA data within Academia and Industry. The Ecoinvent data is supplied with probability distributions for all inputs and outputs, created via a pedigree matrix-based methodology (Ciroth *et al.*, 2016). Ecoinvent is an extensively used database within industry and academia and globally is the leading LCA database. It is independently maintained by the Ecoinvent Centre (originally known as the Swiss Centre for Life Cycle Inventories). (Wernet *et al.*, 2016) [4].

U.S. Life Cycle Inventory Database | NREL

The NREL database provides a large amount of information on downstream processes and competitive feedstocks which Ecoinvent does not have to an adequate level. It is important to note that these models are not aggregated, and contain a list of all inputs and outputs, enabling the models to then be replicated using the Ecoinvent database. (National Renewable Energy Laboratory, 2012)

GaBi Professional Database | Sphera Solutions

Sphera Solutions are the producers of GaBi, a major LCA package used throughout industry. They also produce substantial databases on a range of LCA topics. Some of the models within Sphera Solutions's

databases are not available within Ecoinvent.

GaBi professional is the standard database used within GaBi ('GaBi database, Service Pack [30],' 2016). However, there are various methodological differences between this and the Ecoinvent database, such as on recycling. Hence, when using this data, if possible, the database was simply used for LCI data which could then be recreated within Ecoinvent, as opposed to simply transferring models across, which could lead to inconsistencies within the models.

Data on Demand | Sphera Solutions

Data on Demand is a service offered by Sphera Solutions for additional, non-standard databases within GaBi. These have been used in cases where there was no other available data available from industry, the literature or any other sources.

5.5 Electricity LCI

There are several electricity scenarios used in this Thesis:

1) GaBi base models
    a. EU-27 grid mix in 2012
    b. EU-27+UK 2020 grid mix
    c. 100% Photovoltaic energy (Olhão)
2) OpenLCA based models
    a. Portuguese Electricity Model (2016-2017)
    b. Madeira Electricity Grid (2016-2017)
    c. 80% Photovoltaic energy (Lisbon/Olhão)

Additionally, for this work, electricity monitoring equipment was constructed for measuring the electricity use of fermenter systems.

5.5.1 *GaBi Models*

5.5.1.1 GaBi EU-27 grid mix in 2012

This was based on the GaBi model *"EU-27 Electricity grid mix (agg ts) (001b3cb7-b868-4061-8a91-3e6d7bcc90c6)"*

5.5.1.2 GaBi EU-27+UK 2020 grid mix

Electricity data for 2020 is not yet available, as the year had not completed when this thesis was submitted. Additionally, the original models for the InteSusAl and BIOMOD were undertaken part with

through this project, in 2017; hence the 2020 grid mix was not understood.

The EU 27+UK 2020 electricity grid mix was based on data from individual European countries' National Renewable Energy Action Plan (NREAPs) (via (Beurskens *et al.*, 2011) and (Beurskens, 2013)) and nuclear decommissioning.

The model began with the individual EU-27 country electricity mixes from the Sphera Solutions Professional Database. These were for the year 2010. The grid mix within this database is divided into several categories, as shown in Table 5-1, note that there is no (13) in any energy mix. This fitted with the NREAP categories for electricity mix, which are also shown in Table 5-1.

Table 5-1: Sphera Solutions Database and NREAP grid mix categories

Sphera Solutions Professional Database electricity grid mix categories	NREAP grid mix categories
• (01) [%] percentage power from nuclear power • (02) [%] percentage power from lignite • (03) [%] percentage power from hard coal • (04) [%] percentage power from coal gases • (05) [%] percentage power from natural gas • (06) [%] percentage power from fuel oil • (07) [%] percentage power from biomass (solid) • (08) [%] percentage power from biogas • (09) [%] percentage power from waste incineration (Waste-to-Energy) • (10) [%] percentage power from hydro power • (11) [%] percentage power from wind power • (12) [%] percentage power from photovoltaics • (14) [%] percentage power from geo thermal • (15) [%] percentage power from peat • (18) [%] power own consumption related to gross generation; for pump storage, heat pumps, electric b • (23) [%] grid losses/ distribution losses related to power supply	• Hydropower • Hydropower <1 MW • Hydropower 1 MW – 10 MW • Hydropower >10 MW • Pumped storage hydropower • Geothermal • Solar • Solar photovoltaic • Concentrated solar power • Tidal, wave and ocean energy • Wind power • Onshore wind • Offshore wind • Biomass • Solid biomass • Biogas • Bioliquids

Most of these align well. However, some of the NREAP categories were condensed as follows:

- ***"(07) [%] percentage power from biomass (solid)"*** covered both ***"Solid biomass"*** and ***"Bioliquids"***.
- ***"(10) [%] percentage power from hydro power"*** covered ***"Hydropower <1 MW", "Hydropower 1 MW – 10 MW"*** and ***"Hydropower >10 MW"***
- ***"(11) [%] percentage power from wind power"*** used ***"Onshore wind"*** and ***"Offshore wind"***

There is no concentrated solar power model within the Sphera Solutions Professional database or the Ecoinvent database. Therefore, a worst-case assumption was taken, and ***"(12) [%] percentage power from photovoltaics"*** used, which had the highest impacts.

With these assumptions, the NREAP 2010 data was then mapped to the Sphera Solutions Professional Database for individual EU-27 country grid mixes. These mostly agreed with the Sphera Solutions Database models. A few issues were highlighted within the existing Sphera Solutions databases, specifically that there are some issues with the classification of pumped storage. For example, with Luxembourg this appears to have been counted twice, including it in both: ***"(18) [%] power own consumption related to gross generation; for pump storage, heat pumps, electric b"*** and ***"(10) [%] percentage power from hydro power"***. Sphera Solutions have been alerted so that these issues will be fixed in future releases.

With the 2010 data mapped, the 2020 NREAP data was then mapped onto the modified Sphera Solutions grid mixes, taking into account the impacts of energy efficiency measures reported in the NREAP, as a percentage of total consumption. Following this, the nuclear plant capacities were also mapped. The percentage increase or decrease in renewable and nuclear generation was calculated, and mapped onto the remaining fossil generation, reducing or increasing the fossil generation balance with the expected demand, to take account of the renewable/nuclear generation increase or decrease. Finally, countries which export power (France and Sweden) were given credits according to the mean mix of the rest of the EU-27+UK. A new model was constructed for Croatia.

Finally, using these new grid mixes, the total expected energy production of each country was used to create a mean energy mix per kWh for the whole of the EU-27+UK.

An initial set of grid impacts were calculated for each individual country within the EU-27+UK, and the impacts calculated on a per MWh basis. Table 5-2 provides the ReCiPe impacts for the whole of the EU-27+UK in 2020 and compares this data to the Sphera Solutions EU-27 2010 and 2012 data. Clearly, this is not a perfect comparison, as this is comparing the EU-27 with the EU-27+UK, although the difference is Croatia, a comparatively low energy user.

Table 5-2: Comparison of Sphera Solutions 2010 grid data for the EU-27 and estimated 2020 grid data – colours range from high (red) to low (green)

Impact	InteSusAl Facility (2010 electricity)	InteSusAl Facility (2011 electricity)	InteSusAl Facility (2012 electricity)	InteSusAl Facility (EU 2020)
IPCC AR5				
GWP100, excl biogenic carbon [kg CO_{2eq}]	1.02×10^{0}	1.01×10^{0}	1.01×10^{0}	9.53×10^{-1}
GWP20, excl biogenic carbon [kg CO_{2eq}]	1.30×10^{0}	1.29×10^{0}	1.29×10^{0}	1.23×10^{0}
GWP100, incl biogenic carbon [kg CO_{2eq}]	7.99×10^{-1}	7.97×10^{-1}	7.91×10^{-1}	7.36×10^{-1}
GWP20, incl biogenic carbon [kg CO_{2eq}]	1.08×10^{0}	1.07×10^{0}	1.07×10^{0}	1.01×10^{0}
ReCiPe 1.08 Endpoint (H)				
Freshwater ecotoxicity [species.yr]	3.70×10^{-11}	3.70×10^{-11}	3.70×10^{-11}	3.70×10^{-11}
Human toxicity [DALY]	3.54×10^{-7}	3.54×10^{-7}	3.53×10^{-7}	3.53×10^{-7}
Marine ecotoxicity [species.yr]	6.13×10^{-12}	6.13×10^{-12}	6.13×10^{-12}	6.13×10^{-12}
Terrestrial ecotoxicity [species.yr]	5.06×10^{-11}	5.06×10^{-11}	5.04×10^{-11}	5.04×10^{-11}
ReCiPe 1.08 Midpoint (H)				
Agricultural land occupation [m^2a]	2.68×10^{-1}	2.68×10^{-1}	2.71×10^{-1}	2.74×10^{-1}
Climate change, default, excl biogenic carbon [kg CO_{2eq}]	9.97×10^{-1}	9.94×10^{-1}	9.87×10^{-1}	9.33×10^{-1}
Climate change, incl biogenic carbon [kg CO_{2eq}]	7.81×10^{-1}	7.78×10^{-1}	7.72×10^{-1}	7.18×10^{-1}
Fossil depletion [kg oil eq]	2.65×10^{-1}	2.63×10^{-1}	2.58×10^{-1}	2.50×10^{-1}
Freshwater ecotoxicity [kg 1,4-DB eq]	4.27×10^{-2}	4.27×10^{-2}	4.27×10^{-2}	4.27×10^{-2}
Freshwater eutrophication [kg P eq]	1.68×10^{-4}	1.69×10^{-4}	1.69×10^{-4}	1.69×10^{-4}
Human toxicity [kg 1,4-DB eq]	5.08×10^{-1}	5.08×10^{-1}	5.07×10^{-1}	5.08×10^{-1}
Ionising radiation [kg ^{235}U eq]	4.48×10^{1}	4.39×10^{1}	4.40×10^{1}	4.39×10^{1}
Marine ecotoxicity [kg 1,4-DB eq]	3.36×10^{-2}	3.36×10^{-2}	3.36×10^{-2}	3.36×10^{-2}
Marine eutrophication [kg N-Equiv.]	1.13×10^{-3}	1.13×10^{-3}	1.13×10^{-3}	1.14×10^{-3}
Metal depletion [kg Fe eq]	4.36×10^{-2}	4.35×10^{-2}	4.41×10^{-2}	4.47×10^{-2}
Ozone depletion [kg CFC-11 eq]	1.36×10^{-7}	1.36×10^{-7}	1.36×10^{-7}	1.36×10^{-7}
Particulate matter formation [kg PM10 eq]	1.80×10^{-3}	1.83×10^{-3}	1.64×10^{-3}	1.64×10^{-3}

Photochemical oxidant formation [kg NMVOC]	2.65×10^{-3}	2.67×10^{-3}	2.50×10^{-3}	2.48×10^{-3}
Terrestrial acidification [kg $SO_{2\ eq}$]	6.68×10^{-3}	6.78×10^{-3}	6.04×10^{-3}	6.04×10^{-3}
Terrestrial ecotoxicity [kg 1,4-DB eq]	3.35×10^{-4}	3.36×10^{-4}	3.34×10^{-4}	3.34×10^{-4}
Water depletion [m^3]	4.50×10^{0}	4.12×10^{0}	4.67×10^{0}	3.54×10^{0}

This can be better seen in Table 5-3 in which the impacts are ordered in order of reduction of impact to increase of impact.

Table 5-3: Reordered data from the previous table, showing the change from 2010 to 2020 in impacts for the European grid mix.

Impact	Change [%]
ReCiPe 1.08 Midpoint (H) Metal depletion [kg Fe eq]	2.50%
ReCiPe 1.08 Midpoint (H) Agricultural land occupation [m^2a]	2.30%
ReCiPe 1.08 Midpoint (H) Marine eutrophication [kg N-Equiv.]	0.60%
ReCiPe 1.08 Midpoint (H) Freshwater eutrophication [kg P eq]	0.50%
ReCiPe 1.08 Endpoint (H) Marine ecotoxicity [species.yr]	0.00%
ReCiPe 1.08 Midpoint (H) Marine ecotoxicity [kg 1,4-DB eq]	0.00%
ReCiPe 1.08 Endpoint (H) Freshwater ecotoxicity [species.yr]	0.00%
ReCiPe 1.08 Midpoint (H) Freshwater ecotoxicity [kg 1,4-DB eq]	0.00%
ReCiPe 1.08 Midpoint (H) Human toxicity [kg 1,4-DB eq]	-0.10%
ReCiPe 1.08 Endpoint (H) Human toxicity [DALY]	-0.10%
ReCiPe 1.08 Midpoint (H) Ozone depletion [kg CFC-11 eq]	-0.10%
ReCiPe 1.08 Endpoint (H) Terrestrial ecotoxicity [species.yr]	-0.30%
ReCiPe 1.08 Midpoint (H) Terrestrial ecotoxicity [kg 1,4-DB eq]	-0.30%
ReCiPe 1.08 Midpoint (H) Ionising radiation [kg ^{235}U eq]	-1.90%
IPCC AR5 GWP20, excl biogenic carbon [kg CO2-Equiv.]	-5.70%
ReCiPe 1.08 Midpoint (H) Fossil depletion [kg oil eq]	-5.70%
IPCC AR5 GWP100, excl biogenic carbon [kg CO_{2eq}]	-6.30%
ReCiPe 1.08 Midpoint (H) Photochemical oxidant formation [kg NMVOC]	-6.40%
ReCiPe 1.08 Midpoint (H) Climate change, default, excl biogenic carbon [kg CO_{2eq}]	-6.40%
IPCC AR5 GWP20, incl biogenic carbon [kg CO_{2eq}]	-6.70%
IPCC AR5 GWP100, incl biogenic carbon [kg CO_{2eq}]	-7.90%

ReCiPe 1.08 Midpoint (H) Climate change, incl biogenic carbon [kg CO_{2eq}]	-8.00%
ReCiPe 1.08 Midpoint (H) Particulate matter formation [kg PM10 eq]	-9.10%
ReCiPe 1.08 Midpoint (H) Terrestrial acidification [kg $SO_{2\ eq}$]	-9.60%
ReCiPe 1.08 Midpoint (H) Water depletion [m^3]	-21.50%

Interestingly, Table 5-2 shows that the major percentage improvement in the EU grid mix will be with regard to water depletion. The actual GWP impacts have been reduced by 6.3% (AR5 GWP100 excl. biogenic). Some impacts increased from 2010 to 2020, specifically Metal depletion [kg Fe eq], Agricultural land occupation [m2a], Marine eutrophication [kg N-Equiv.] and Freshwater eutrophication [kg P eq].

5.5.2 *GaBi 100% Photovoltaic energy (Olhão)*

Various renewable energy systems could be used within the InteSusAl facility. For example, the waste biomass could be burned in a CHP system (although economically this would not be a wise use of high-value products), or wind or solar could be used to generate electricity to power the equipment. The technology which makes the most sense for InteSusAl is photovoltaics, as the phototrophic system will use more electrical power for the pumping, harvesting and cooling during times of the day with high irradiance.

In order to create an LCA model of the array, the Ecoinvent Integrated 3.2 model for photovoltaics in Portugal (*PT: electricity production, photovoltaic, 570kWp open ground installation, multi-Si*) was modified, using data from a PVSyst designed solar farm for the InteSusAl project, with the following changes:

- The *"PT: electricity production, photovoltaic, 570kWp open ground installation, multi-Si"* model assumes an electricity production of 1216.2 kWh/kWp/year. This was corrected using the output of the solar farm model (including 0.6% annual degradation).
- The array has a size of 229 kWp, not 570kWp
- The inverter systems may require replacement after ten years. No LCA model existed for the Schneider Conext 20000 E within the databases used in this project; therefore a scaled model based on weight was created, scaled up from the *"RER: inverter production, 0.5kW"* model within Ecoinvent Integrated. This was chosen as the Ecoinvent Integrated 2.5kW model is only a scaled model from the 0.5kW version, and the 500kW version is too large compared to the Schneider Conext 20000 E for a reliable scale. The Schneider Conext 20000 E weighs 60kg

(3kg/kW), whilst the 0.5kW system weighs1.6kg (3.2kW/kg.). Therefore, in order to estimate the 20 kW Schneider Conext 20000 E, a factor of 18.75 was applied.

The environmental impacts of this PV system was compared with Portuguese grid electricity, the Sphera Solutions EU27 grid mix, Sphera Solutions Portuguese electricity grid mix, and Ecoinvent Integrated Portuguese low and medium electricity grid mixes.

Table 5-4: Various electricity mixes for the EU27 and Portugal – colours range from high (red) to low (green)

Impact Category		PV (Olhão)	EU-27: Electricity grid mix ts	PT: Electricity grid mix ts	PT: market for electricity, low voltage Ecoinvent	PT: market for electricity, medium voltage Ecoinvent
IPCC AR5	GWP100, excl biogenic carbon [kg CO_{2eq}]	6.94×10^{-2}	4.68×10^{-1}	5.06×10^{-1}	5.95×10^{-1}	5.72×10^{-1}
	GWP20, excl biogenic carbon [kg CO_{2eq}]	8.13×10^{-2}	5.15×10^{-1}	5.81×10^{-1}	6.74×10^{-1}	6.48×10^{-1}
	GWP100, incl biogenic carbon [kg CO_{2eq}]	6.95×10^{-2}	4.68×10^{-1}	5.06×10^{-1}	5.94×10^{-1}	5.71×10^{-1}
	GWP20, incl biogenic carbon [kg CO_{2eq}]	8.14×10^{-2}	5.15×10^{-1}	5.81×10^{-1}	6.73×10^{-1}	6.47×10^{-1}
ReCiPe 1.08 Endpoint (H)	Freshwater ecotoxicity [species.yr]	5.94×10^{-12}	1.53×10^{-13}	7.95×10^{-14}	1.63×10^{-11}	1.55×10^{-11}
	Human toxicity [DALY]	6.41×10^{-8}	7.08×10^{-9}	5.23×10^{-9}	1.51×10^{-7}	1.26×10^{-7}
	Marine ecotoxicity [species.yr]	1.08×10^{-12}	1.30×10^{-14}	1.10×10^{-14}	2.81×10^{-12}	2.65×10^{-11}
	Terrestrial ecotoxicity [species.yr]	1.53×10^{-11}	1.06×10^{-12}	8.56×10^{-13}	9.18×10^{-12}	7.65×10^{-11}
ReCiPe 1.08 Midpoint (H)	Agricultural land occupation [m^2a]	3.43×10^{-3}	8.42×10^{-3}	8.78×10^{-3}	4.15×10^{-2}	3.96×10^{-2}
	Climate change, excl biogenic carbon [kg CO_{2eq}]	6.85×10^{-2}	4.64×10^{-1}	4.99×10^{-1}	5.88×10^{-1}	5.65×10^{-1}
	Climate change, incl biogenic carbon [kg CO_{2eq}]	6.87×10^{-2}	4.64×10^{-1}	4.99×10^{-1}	5.88×10^{-1}	5.65×10^{-1}
	Fossil depletion [kg oil eq]	1.79×10^{-2}	1.20×10^{-1}	1.39×10^{-1}	1.70×10^{-1}	1.63×10^{-1}
	Freshwater ecotoxicity [kg 1,4-DB eq]	6.86×10^{-3}	1.78×10^{-4}	9.24×10^{-5}	1.89×10^{-2}	1.78×10^{-2}
	Freshwater eutrophication [kg P eq]	3.90×10^{-5}	9.70×10^{-7}	1.04×10^{-6}	1.26×10^{-4}	1.08×10^{-4}
	Human toxicity [kg 1,4-DB eq]	9.23×10^{-2}	1.01×10^{-2}	7.48×10^{-3}	2.17×10^{-1}	1.80×10^{-1}
	Ionising radiation [kg ^{235}U eq]	6.52×10^{0}	1.96×10^{-1}	1.72×10^{-2}	3.92×10^{1}	3.77×10^{1}
	Marine ecotoxicity [kg 1,4-DB eq]	5.95×10^{-3}	7.39×10^{-5}	6.25×10^{-5}	1.54×10^{-2}	1.45×10^{-2}
	Marine eutrophication [kg N-Equiv.]	2.82×10^{-5}	5.35×10^{-5}	5.46×10^{-5}	8.34×10^{-5}	7.70×10^{-5}
	Metal depletion [kg Fe eq]	1.90×10^{-2}	2.86×10^{-3}	3.36×10^{-3}	1.71×10^{-2}	7.60×10^{-3}
	Ozone depletion [kg CFC-11 eq]	1.13×10^{-8}	3.30×10^{-10}	3.59×10^{-11}	3.64×10^{-8}	3.49×10^{-8}
	Particulate matter formation [kg PM10 eq]	1.73×10^{-4}	3.29×10^{-4}	2.79×10^{-4}	1.07×10^{-3}	1.02×10^{-3}
	Photochemical oxidant formation [kg NMVOC]	2.86×10^{-4}	7.61×10^{-4}	8.06×10^{-4}	1.72×10^{-3}	1.64×10^{-3}
	Terrestrial acidification [kg $SO_{2\ eq}$]	4.53×10^{-4}	1.10×10^{-3}	8.56×10^{-4}	4.07×10^{-3}	3.87×10^{-3}
	Terrestrial ecotoxicity [kg 1,4-DB eq]	1.01×10^{-4}	7.06×10^{-6}	5.68×10^{-6}	6.06×10^{-5}	5.05×10^{-5}
	Water depletion [m^3]	1.02×10^{0}	3.87×10^{0}	1.47×10^{0}	5.23×10^{0}	5.03×10^{0}

This shows two interesting factors. Firstly, solar PV is a much lower source of climate change related impacts. However, there are significant differences between Sphera Solutions and Ecoinvent methodologies for electricity impacts.

5.5.3 *OpenLCA Models*

5.5.3.1 OpenLCA Portuguese Electricity Model (2016-2017)

A specialised model for electricity has been constructed within OpenLCA for the Portuguese electricity grid. This will be ported over to GaBi with the same figures. The electricity model in Ecoinvent for Portugal clearly needs to be updated, as it is based on 2012 data. The clearest evidence that it needs correction is the electricity import to Spain, which is set at 19%. Throughout 2017 and 2018 numerous news stories in the renewable energy industry press ran stories on how Portugal had moved from a net importer to a net exporter. To correct this, the existing Ecoinvent model "market for electricity, high voltage | electricity, high voltage | cut-off, U – PT" was duplicated, and then more up to date data used to create a new model. The data sources considered were Associação Portuguesa de Energias Renováveis (APREN) (Associação Portuguesa de Energias Renováveis (APREN), 2017; Associação Portuguesa de Energias Renováveis (APREN), 2018ª; Associação Portuguesa de Energias Renováveis (APREN), 2018b), the CIA World Factbook (Central Intelligence Agency, 2018), International Energy Agency country factsheet (International Energy Agency, 2018) and the Redes Energéticas Nacionais (Redes Energéticas Nacionais, 2018). Of these sources, the REN data was used for the final model, which provides detailed monthly data on the electricity mix in Portugal. Some of the technologies within the "market for electricity, high voltage | electricity, high voltage | cut-off, U – PT" original model were not mentioned within the REN data, such as biomass. Also, it was unclear which type of cogeneration is meant within the REN data.

Because Portugal suffered a major drought in 2017, the amount of hydroelectricity dropped significantly, and thus coal and oil output increased. Therefore, an average of 2016 and 2017 was taken, as hopefully, the 2017 drought is not representative of future years.

In the case of photovoltaics, which makes a surprisingly low contribution to the Portuguese electricity grid, the model *"electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | cut-off, U – PT"* was used. As already established in the discussion of the photovoltaic models, this model significantly underestimates the electricity generates and so will give a large impact than reality. An additional issue is that this produces low voltage electricity, so some conversion loses are within this model which would not occur if it were to output at high voltage.

The processes used within the model were;

Table 5-5: Models used for Portuguese electricity model for 2017

Technology	Model
Hydro – Run-of-river	electricity production, hydro, run-of-river | electricity, high voltage | cut-off, U – PT
Hydro – Reservoirs	electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | cut-off, U – PT
Coal	electricity production, hard coal | electricity, high voltage | cut-off, U – PT
CCGT natural gas	electricity production, natural gas, combined cycle power plant | electricity, high voltage | cut-off, U – PT
Cogen	heat and power co-generation, natural gas, conventional power plant, 100MW electrical | electricity, high voltage | cut-off, U – PT
Wind	electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | cut-off, U – PT
Photovoltaic	electricity production, photovoltaic, 570kWp open ground installation, multi-Si
Wave	None
Hydro – pumped	electricity production, hydro, pumped storage | electricity, high voltage | cut-off, U – PT

In addition to these, the existing non-generating flows within the REN data were kept; specifically these refer to the construction of the electricity network

- *"market for transmission network, electricity, high voltage \| transmission network, electricity, high voltage \| cut-off, U – GLO*
- *"market for transmission network, long-distance \| transmission network, long-distance \| cut-off, U – GLO"*

One issue from this was that as Portugal exports a large amount of electricity, this is offsetting the Spanish electricity grid, and therefore deserves a credit. However, the models for the Spanish electricity grid were also similarly out of data. Data was downloaded from the website of Red Eléctrica de España (Red Eléctrica de España, 2018a; Red Eléctrica de España, 2018b) to create a model in a similar way to the Portuguese models, but using "market for electricity, high voltage \| electricity, high voltage \| cut-off, U – ES"

Admittedly there are also flow to-and-from the French electricity system; however, this was considered negligible compared to the Portuguese/Spanish connection. These models were used as the original models are also used, and so connected via new versions of *"electricity voltage transformation from*

high to medium voltage | electricity, medium voltage | cut-off, U" through to *"market for electricity, medium voltage | electricity, medium voltage | cut-off, U"*, but with the municipal waste element removed as this does not show up within the REN data.

Comparing these electricity models gives;

Table 5-6: Comparison of electricity models

Impact category	Reference unit	2016-2017	Ecoinvent	% of Ecoinvent
agricultural land occupation – ALOP	m2a	1.97E-04	2.44E-04	80%
climate change – GWP100	kg CO2-Eq	6.04E-01	5.10E-01	119%
fossil depletion – FDP	kg oil-Eq	1.94E-01	1.46E-01	132%
freshwater ecotoxicity – FETPinf	kg 1,4-DCB-Eq	5.45E-03	3.24E-03	168%
freshwater eutrophication – FEP	kg P-Eq	1.27E-04	1.34E-04	95%
human toxicity – HTPinf	kg 1,4-DCB-Eq	9.63E-02	1.30E-01	74%
ionising radiation – IRP_HE	kg U235-Eq	6.14E-03	4.67E-02	13%
marine ecotoxicity – METPinf	kg 1,4-DCB-Eq	4.99E-03	3.16E-03	158%
marine eutrophication – MEP	kg N-Eq	4.21E-04	4.97E-04	85%
metal depletion – MDP	kg Fe-Eq	7.71E-03	5.92E-03	130%
natural land transformation – NLTP	m2	2.58E-05	1.81E-05	142%
ozone depletion – ODPinf	kg CFC-11-Eq	4.76E-08	3.98E-08	120%
particulate matter formation – PMFP	kg PM10-Eq	7.18E-04	9.20E-04	78%
photochemical oxidant formation – POFP	kg NMVOC	1.30E-03	1.50E-03	87%
terrestrial acidification – TAP100	kg SO2-Eq	2.42E-03	3.17E-03	76%
terrestrial ecotoxicity – TETPinf	kg 1,4-DCB-Eq	1.08E-05	2.37E-05	46%
urban land occupation – ULOP	m2a	2.30E-03	2.50E-03	92%
water depletion – WDP	m3	1.75E-03	1.46E-03	120%

As can be seen, the carbon impact of the Portuguese electricity grid has actually increased, this is because of the 2017 drought, which reduced the production of electricity from hydro from 15,195 TWh/year to 7,339 TWh/year. However, there have been environmental benefits from the increase of wind energy, and also the change from a net importer in 2012 (when the Ecoinvent model is based) through to being a net exporter as in 2016 and 2017.

5.5.3.2 OpenLCA 80% Photovoltaic energy (Lisbon)

In order to create an OpenLCA model of the array, the Ecoinvent model for photovoltaics in Portugal (*PT: electricity production, photovoltaic, 570kWp open ground installation, multi-Si*) was modified for Lisbon and Olhão. Accurate outputs for these sites were created using the Industry standard software PVSyst, with weather data from Metronorm 7.1.

The system modelled had the following characteristics:

- PV module Manufacturer: Panasonic
- PV module model: HIT Model VBHN240SJ25
- Number of PV modules
    - In series: 17 modules
    - In parallel: 140 strings
    - Total number of PV modules: 2,380 modules
- Array global power Nominal (STC) 571 kWp
- Inverter manufacturer: Schneider Electric
- Inverter Model: Conext Core XC-540-NA (540 kWac)
- Number of inverters: 1 unit
- Total output power: 540 kWac

The two sites were;

Lisboa

- Latitude 38.72° N Longitude -9.15° W
- Tilt of modules: 35°

Olhão

- Latitude 38.72° N Longitude -9.15° W
- Tilt of modules: 35°

The output from the two sites in year 1 was;

- **Lisboa:** 977.7 MWh (1,723 kWh/kWp/year)
- **Olhao:** 1084.6 MWh (1,899 kWh/kWp/year)

These are given within the Appendix for this report.

Based on these outputs, the *"PT: electricity production, photovoltaic, 570kWp open ground installation, multi-Si"* model was modified, including a correction for 0.8% annual degradation (to fit with 85% after 20 years).

The output of the *"PT: electricity production, photovoltaic, 570kWp open ground installation, multi-Si"* is given as 1216.2 kWh/kWp, based on a thirty-year lifetime. For the two models from PVSyst, the figures are for Lisboa 1523 kWh/kWp/year and for Olhão 1678 kWh/kWp/year.

The inverter systems may require replacement after ten years. No LCA model existed for the Schneider

Conext Core XC-540-NA within the databases used in this project; therefore a scaled model based on weight was created, scaled down from the *"market for inverter, 500kW | inverter, 500kW | cut-off, U – GLO"* model within Ecoinvent. The Conext Core XC-540-NA weighs 1,495kg, whereas the "market for inverter, 500kW | inverter, 500kW | cut-off, U – GLO" weighs 3,000kg.

The environmental impacts of these PV systems were compared with the standard Ecoinvent Portuguese grid electricity (*market for electricity, medium voltage | electricity, medium voltage | cut-off, U – PT*).

5.5.4 *Energy Metering*

In order to measure the environmental impacts of microalgae production, it was important to understand the energy requirements of the various pieces of equipment used within InteSusAl. For the smaller pieces of equipment, the rated output could be multiplied by the operational time. For larger systems, such as the media clarification unit and the Fermenter heater/chiller unit, unit-specific energy monitors were built.

5.5.4.1 System design

Three different bespoke energy monitors were constructed. These systems were designed to plug into a local power point, and then any large piece of equipment to be used could be plugged into the meters. The three monitors were:

- Monitor #1: three-phase 63A
- Monitor #2: three-phase 32A
- Monitor #3: single-phase 32A

Each monitor involves a male plug and connector, connected via a commercial electricity meter with pulse outputs.

Element	Meter #1	Meter #2	Meter #3
Meter	Landis Gyr E230	Landis Gyr E230	Elster A100C
Plugs	32A 400V 4P+E	63A 400V 4P+E	32A 230V 2P+E
Connector	32A 400V 4P+E	63A 400V 4P+E	32A 230V 2P+E

Figure 5-4: Specifications of each monitor

In order to record the output of each system, Gemini Tinytag TGPR-1201 pulse loggers were connected to the pulse outputs of each meter. Where there were two sets of pulse outputs (as in the three-phase

systems) the outputs of the left are the defaults, with all meters, the default pulse value was 1Wh.

Each TGPR-1201 was set to log the total energy per minute, giving a maximum sample program of 45 days, at which point the data needs to be downloaded before data memory was saturated. The batteries can last one year. The loggers were programmed using Tinytag Explorer 4.7 control software.

Figure 5-5: Monitor #1 (right) and monitor #2 (left)

5.5.4.2 Commissioning

The TGPR-1201 loggers were initially tested with an existing single-phase 16A monitor system, with a domestic water heater used as a load. The operational testing was carried out utilising a large industrial laser appliance within the Solar Capture Technologies industrial laboratory.

The data loggers were calibrated for meter and pulse rate accuracy at Offshore Renewable Energy Catapult's Charles Parsons High Voltage Laboratory, using a Cressall Resistors AC 30 load unit. This showed the three monitors to be working correctly and safely. The meter results were compared with the logger data, confirming that the systems were recording correctly and that they were recording at the expected Wh/pulse rate. Further checks were undertaken by CPI, with an additional safety case added to the single-phase meter.

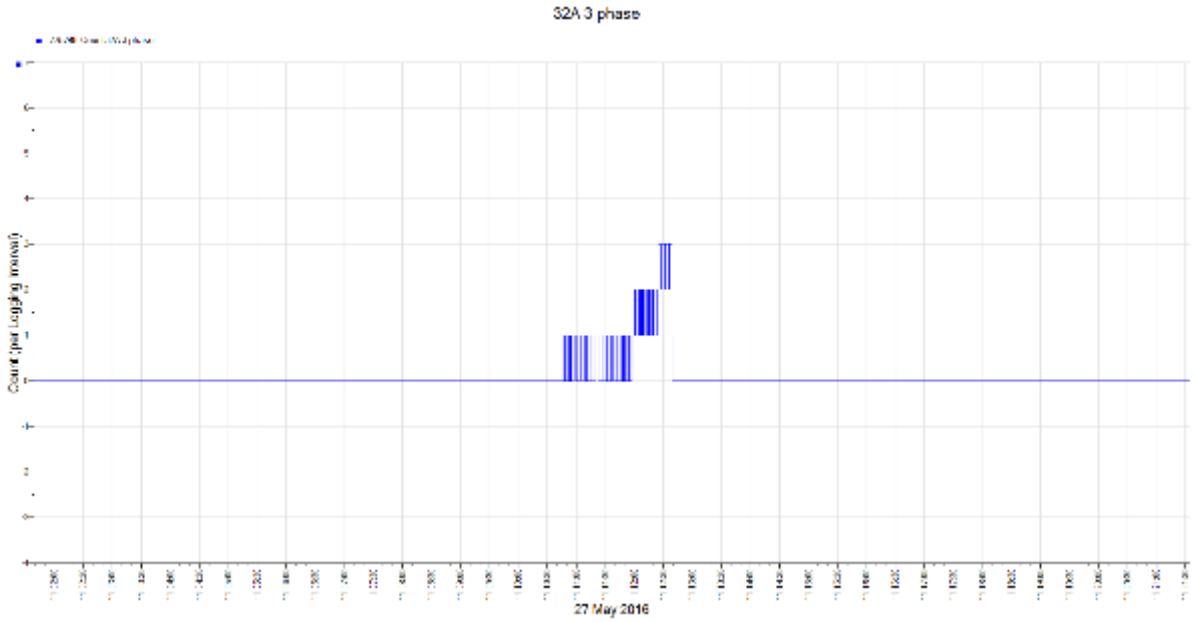

Figure 5-6: Three-phase 32A monitor data output from the commissioning test, as displayed on Tinytag Explorer 4.7

Figure 5-7: Cressall load bank

5.5.4.3 Electricity results

The electricity meters were used on the final run of the fermenter system in CPI on the three largest loads, these were:

Meter	System Measured	Rated [kW]
Monitor #1: three-phase 63A	Media Clarification Unit	6.5
Monitor #2: three-phase 32A	Feed Vessel Agitator	1.5
Monitor #3: single-phase 32A	Fermenter heater/chiller unit	6.5

Figure 5-8: Meters and units they were connected to

The results showed that the three systems did not run at their rated power. In the case of the agitator, this ran below rated input as the dissolved oxygen remained at acceptable levels within the fermenter.

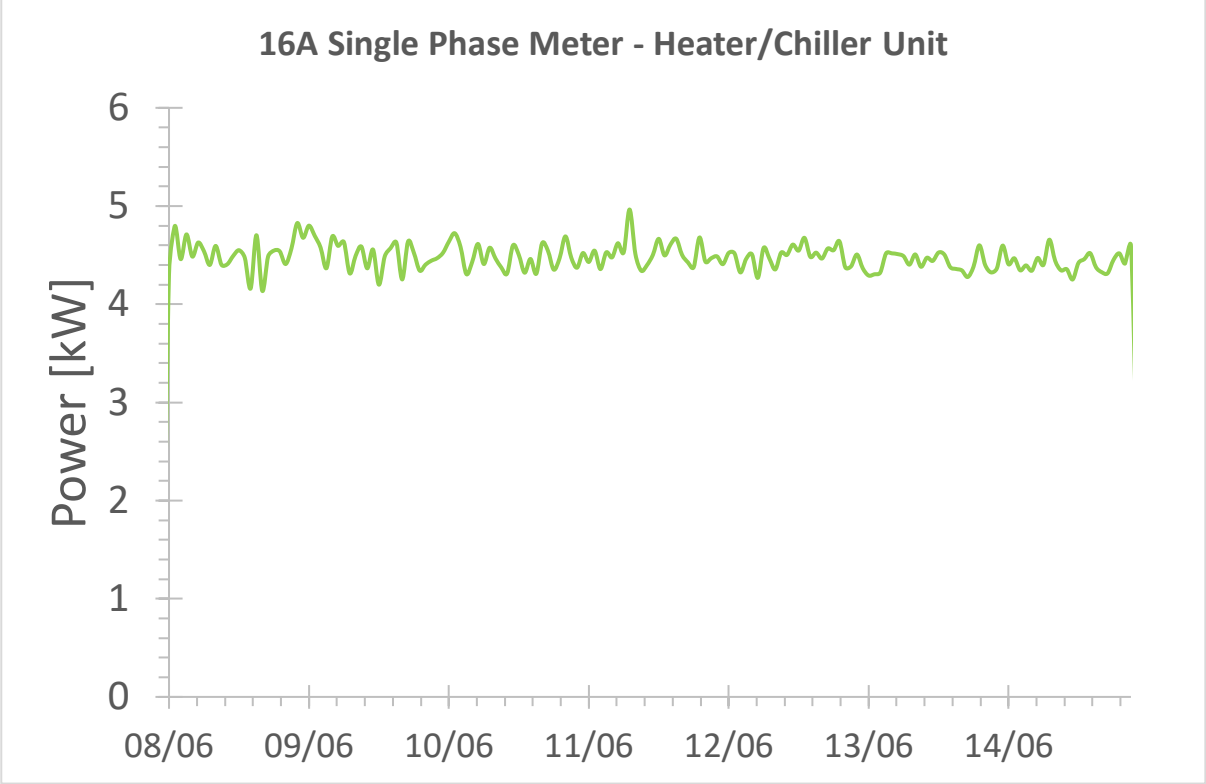

Figure 5-9: Data from Heater/Chiller unit, rebinned to 1-hour resolution

With regard to the Media Clarification Unit, a large amount of its operational time is spent using a low amount of power; therefore, it uses far less than expected.

Using this data, which was representative of any normal fermenter run, the following average power consumptions were calculated:

System	Rated [kW]	Average power draw [kW]
Media Clarification Unit	6.5	1.4505
Feed Vessel Agitator	1.5	0.5360
Fermenter heater/chiller unit	6.5	4.4806

Figure 5-10: Meters and units they were connected to

This data shows that the fermenter system utilised far less electricity than expected, which is a positive finding for this LCA study.

5.6 Yeast LCI

During the initial modelling of the InteSusAl system, yeast extract was identified as one of the major impacts for the facility. Initial models showed that the percentage contribution to ***AR5 GWP100 excl. biogenic*** was 25.6%, whilst over a 20-year period, it was as high as 34.8%. Therefore, it was considered important to check the accuracy of the yeast models used. Below follows a summary of these models.

5.6.1 *Ecoinvent 3.2 Model*

There are several yeast models from Ecoinvent Integrated 3.2. It is important to note that these were yeast models, not yeast extract models.

Table 5-7: Ecoinvent yeast models. Note protein feeds (measured in kg) have >20% protein, whereas energy feeds have <20% protein.

Name	Reference Product	Loc	Time Period
Undefined			
fodder yeast to generic market for protein feed	fodder yeast [kg]	GLO	01.01.2012 – 31.12.2012
market for fodder yeast	fodder yeast [kg]	GLO	01.01.2012 – 31.12.2012
Allocation, cut-off by classification			
fodder yeast to generic market for protein feed	energy feed, gross [MJ]	GLO	01.01.2012 – 31.12.2015
fodder yeast to generic market for protein feed	protein feed, 100% crude [kg]	GLO	01.01.2012 – 31.12.2015
Allocation at the point of substitution (APOS)			
fodder yeast to generic market for protein feed	protein feed, 100% crude [kg]	GLO	01.01.2012 – 31.12.2015
fodder yeast to generic market for protein feed	fodder yeast [kg]	GLO	01.01.2012 – 31.12.2015
fodder yeast to generic market for protein feed	energy feed, gross [MJ]	GLO	01.01.2012 – 31.12.2015
market for fodder yeast	fodder yeast [kg]	GLO	01.01.2012 – 31.12.2015
Substitution, consequential, long-term			
fodder yeast to generic market for protein feed	fodder yeast [kg]	GLO	01.01.2012 – 31.12.2015
market for fodder yeast	fodder yeast [kg]	GLO	01.01.2012 – 31.12.2015

Within the GaBi integrated database, the ***Allocation, cut-off by classification*** models are converted into the models provided in Table 5-8.

Table 5-8: Ecoinvent Integrated models within GaBi, note, all are Allocation, cut-off by classification.

Nation	Name	Type	Quantity	Code
GLO	fodder yeast to generic market for protein feed	agg	kg	85934148-cf66-43c6-9148-6bb8fd96a22ne
GLO	fodder yeast to generic market for protein feed	agg	MJ	df39cf5a-4968-4fc2-ba76-25f9829b6fc4
GLO	fodder yeast to generic market for protein feed	u-so	kg	9e83d993-386b-4865-96c6-5bdd6654b179
GLO	fodder yeast to generic market for protein feed	u-so	MJ	36612817-164d-4ee2-92c1-1a4afdcf99b2
GLO	market for fodder yeast	agg	kg	08b51b5c-425c-4856-a432-28674fcfe84f
GLO	market for fodder yeast	u-so	kg	7b4f631b-04f0-465f-97ff-295e72e2a7ca

5.6.2 *COFALEC Model*

There is a further analysis of the environmental impacts of yeast performed by PwC for COFALEC, the confederation of yeast producers that represents the EU yeast industry in Europe (*Carbon Footprint of Yeast produced in the European Union*, 2012). This analysis showed substantially lower impacts compared with Ecoinvent, giving 3.20 kg CO_2 eq. for 1kg of 95% dry yeast. Attempts were made to contact both COFALEC and PwC to discuss the differences between their analysis and that of Ecoinvent, but no response, or acknowledgement of attempts to communicate, has been forthcoming.

5.6.3 *Biofuel Processing Yeast Studies*

Yeast is sometimes considered with regard to biodiesel. For example (Dunn *et al.*, 2012) investigated the impacts of enzyme and yeast manufacture for ethanol produced from corn and cellulosic materials. However, this work showed a low overall impact from the yeast, quite different from the results within the microalgae biodiesel analysis. The paper created an estimate of the energy and ingredients for yeast production, based on data from (Humbird *et al.*, May 2011) and the yeast production process described within(Knauf and Kraus., 2006). However, analysis by Dunn et al. is based on assuming that production of *Saccharomyces Cerevisiae* has the same energy intensity as *Z.Mobilis.* The following data from (Humbird *et al.*, May 2011) and (Ingledew *et al.*) was used for the (Dunn *et al.*, 2012) model.

Table 5-9: Yeast data from the supplementary material of (Dunn et al., 2012)

Input	Unit	Value
NH_3	kg	0.08
Molasses	kg	3.90
P_2O_5	kg	0.03
Steam	MJ	13
Electricity	MJ	3.1

Table 5-10: Yeast ingredient transport data summarised within the supplementary material of (Dunn et al., 2012)

Component	Transportation Distance (km)
Sodium hydroxide	161
Molasses	80.5
Yeast	161

This data was used to construct a yeast LCA model, which is provided at the end of this section.

5.6.4 *Commercial Model*

After discussions with various firms, one company which produces yeast extract provided confidential data to the InteSusAl consortium on the inputs and outputs of their yeast production. The company cannot be named, and the underlying data cannot be shared. This data was used to construct an LCA model, which is also given at the end of this section.

5.6.5 *Yeast Summary*

The models presented within Table 5-11 show that the lowest impacts were from the (Dunn *et al.*, 2012) model. However, the confidential data does show a significantly lower level of emissions that the Ecoinvent data. There are a number of possibilities for this, the Ecoinvent data is a global average, which will cover a wide range of sustainable and unsustainable facilities. This is a good example of how it is important to consider real industrial data behind the feedstock chemicals and products used for the InteSusAl facility.

Table 5-11: Comparison of yeast and extract models for 1kg of material – conditional formatting used, red = high, green = low

Impact	Confidential Yeast Production	Yeast (Dunn et al.)	GLO: fodder yeast to generic market for protein feed Ecoinvent	GLO: market for fodder yeast Ecoinvent
IPCC AR5				
GWP100, excl biogenic carbon [kg CO_{2eq}]	1.02×10^{1}	2.65×10^{0}	1.83×10^{1}	1.77×10^{1}
GWP20, excl biogenic carbon [kg CO_{2eq}]	1.26×10^{1}	2.97×10^{0}	3.22×10^{1}	3.11×10^{1}
GWP100, incl biogenic carbon [kg CO_{2eq}]	8.95×10^{0}	2.44×10^{-1}	-4.41×10^{0}	-4.26×10^{0}
GWP20, incl biogenic carbon [kg CO_{2eq}]	1.13×10^{1}	5.59×10^{-1}	9.21×10^{0}	8.90×10^{0}
ReCiPe 1.08 Endpoint (H)				
Freshwater ecotoxicity [species.yr]	2.00×10^{-10}	7.20×10^{-11}	6.88×10^{-10}	6.65×10^{-10}
Human toxicity [DALY]	1.89×10^{-6}	6.10×10^{-7}	1.09×10^{-5}	1.05×10^{-5}
Marine ecotoxicity [species.yr]	3.41×10^{-11}	1.21×10^{-11}	1.02×10^{-10}	9.84×10^{-11}
Terrestrial ecotoxicity [species.yr]	1.57×10^{-10}	4.61×10^{-11}	3.02×10^{-9}	2.92×10^{-9}
ReCiPe 1.08 Midpoint (H)				
Agricultural land occupation [m^2a]	1.35×10^{0}	1.06×10^{0}	1.85×10^{1}	1.79×10^{1}
Climate change, excl biogenic carbon [kg CO_{2eq}]	9.98×10^{0}	2.65×10^{0}	1.73×10^{1}	1.68×10^{1}
Climate change, incl biogenic carbon [kg CO_{2eq}]	8.76×10^{0}	2.38×10^{-1}	-5.19×10^{0}	-5.02×10^{0}
Fossil depletion [kg oil eq]	2.37×10^{0}	7.50×10^{-1}	2.70×10^{0}	2.61×10^{0}
Freshwater ecotoxicity [kg 1,4-DB eq]	2.31×10^{-1}	8.31×10^{-2}	7.95×10^{-1}	7.68×10^{-1}
Freshwater eutrophication [kg P eq]	1.55×10^{-3}	4.15×10^{-4}	3.87×10^{-3}	3.74×10^{-3}
Human toxicity [kg 1,4-DB eq]	2.72×10^{0}	8.76×10^{-1}	1.56×10^{1}	1.51×10^{1}
Ionising radiation [kg ^{235}U eq]	3.11×10^{2}	9.93×10^{1}	6.57×10^{2}	6.34×10^{2}
Marine ecotoxicity [kg 1,4-DB eq]	1.87×10^{-1}	6.62×10^{-2}	5.58×10^{-1}	5.39×10^{-1}
Marine eutrophication [kg N-Equiv.]	7.42×10^{-3}	5.87×10^{-3}	7.68×10^{-2}	7.42×10^{-2}
Metal depletion [kg Fe eq]	1.68×10^{-1}	5.95×10^{-2}	8.75×10^{-1}	8.46×10^{-1}
Ozone depletion [kg CFC-11 eq]	6.81×10^{-7}	2.44×10^{-7}	9.33×10^{-7}	9.01×10^{-7}
Particulate matter formation [kg PM10 eq]	2.21×10^{-2}	3.77×10^{-3}	4.87×10^{-2}	4.70×10^{-2}
Photochemical oxidant formation [kg NMVOC]	3.20×10^{-2}	6.29×10^{-3}	4.96×10^{-2}	4.79×10^{-2}
Terrestrial acidification [kg $SO_{2\ eq}$]	7.14×10^{-2}	1.31×10^{-2}	2.45×10^{-1}	2.37×10^{-1}
Terrestrial ecotoxicity [kg 1,4-DB eq]	1.03×10^{-3}	3.03×10^{-4}	2.01×10^{-2}	1.94×10^{-2}
Water depletion [m^3]	2.55×10^{1}	6.37×10^{0}	2.26×10^{1}	2.18×10^{1}

5.7 Soybean LCI

In addition to biodiesel, the MAGNIFICENT based data will be compared with soy, for feed, to understand if there are better uses of microalgae than fuel. Therefore, a Soy model was adapted from Ecoinvent.

The soybean model is based on Ecoinvent 3.3 models. There were two different models available, one for Canada and one for the Rest of the World (RoW). The RoW model was used. Because the modelling is based around Ecoinvent data for the microalgae, only minor changes had to be made.

There were significant issues with data from Ecoinvent for Soy; specifically, the water use data did not appear to be correct. The irrigation data within the Ecoinvent database was compared with information from other Ecoinvent crop models and data within (Ercin *et al.*, 2011; Mekonnen and Hoekstra, 2011; Willaarts *et al.*, 2011; Gheewala *et al.*, 2014; Dalin *et al.*, 2019; Taherzadeh and Caro, 2019). These showed far greater use of blue, grey and green water than that reported within EcoInvent 3.3. Therefore, the models were modified to be in line with literature results.

The “soybean, feed production | soybean, feed | cut-off, U (inf) (RoW)” model was used from Ecoinvent 3.3. Two versions were created, one with infrastructure, one with the infrastructure impacts stripped out.

The water use figures have been taken from outside of OpenLCA, this is because the underlying water use figures within Ecoinvent appear to have some errors, inasmuch as they show zero irrigation for soy production, whilst most crop models show a significant amount of irrigation use. Additionally, the models for organic soy production do give irrigation data, which is strange as generally organic food production is thought to use lower amounts of water than large scale non-organic crop production. These differences between models are shown in Table 5-12.

Model	Country	Irrigation [kg water /kg product]
soybean production | soybean | cut-off, U	AR, BR, CA-QC, CH, RoW	0.000
	US	0.0506
soybean production, Swiss integrated production, intensive | soybean, Swiss integrated production | cut-off, U	CH	0.146
	RoW	0.146
soybean production, organic | soybean, organic | cut-off, U	CH	0.152
	RoW	0.152
sugar beet production | sugar beet | cut-off, U	RoW	0.000
sunflower production | sunflower seed | cut-off, U		0.463
sweet corn production | sweet corn | cut-off, U	US	0.0576
wheat production | wheat grain | cut-off, U	RoW	0.340
protein pea production | protein pea | cut-off, U	RoW	0.000
protein pea production, organic | protein pea, organic | cut-off, U	RoW	0.0740
wheat production | wheat grain | cut-off, U	FR	0.123
wheat production, organic | wheat grain, organic | cut-off, U	CH	0.126

Table 5-12: Irrigation data for various crops within Ecoinvent 3.3

It is important to note that these low soybean figures do not fit with the description from the irrigation model within Ecoinvent, which presumes for a generic crop there is a water use of 1,200m^3 per hectare. Based on soy productivity of 2660 kg soy/ha ((Willaarts *et al.*, 2011) Centre West Brazil), this would lead to 451kg water/kg of soy.

The values of water use for soy production within the literature are particularly high Table 5-13 shows the water use for various soy crops within the literature.

Source	Country	Region	water use [kg/kg soy]	Comments
(Ercin *et al.*, 2011)	Canada	-	3,172	-
	France	-	2,651	rainfed soybean
	France	-	2,144	irrigated soybean
(Mekonnen and Hoekstra, 2011)	Global Average	-	2112	Rain fed (Green: 2079 Blue: 0 Grey: 33)
		-	2600	Irrigated (Green: 1590 Blue: 926 Grey: 85)
		-	2145	Global (Green: 2037 Blue: 70 Grey: 37)
(Gheewala *et al.*, 2014)	Thailand	-	1,851	
(Dalin *et al.*, 2019)	Global Average	-	3,700	Taken from figure 2, right pane
(Willaarts *et al.*, 2011)	Brazil	Center West	2091	Table 3
		South	2424	
		South East	2033	
		North East	1724	
		North	1819	
	US	-	3941	
	Argentina	-	3891	
(Taherzadeh and Caro, 2019)	US	-	7251	Table 1, 2016 data
	Brazil	-	5544	
	Argentina	-	7270	
	Paraguay	-	6711	
	Uruguay	-	7204	

Table 5-13: Irrigation data for soybean from the literature

This shows that the figures vary widely for water use (Taherzadeh and Caro, 2019) gives the highest figures, whilst a figure closer to 3,000 kg water/ kg soy has more agreement. Therefore, the figures for water use are difficult. As this is a comparative study, a conservative figure for the water use of the soy baseline has been used, following (Mekonnen and Hoekstra, 2011) and using 2,600 kg water/kg soy. Of this, Blue: 926m^3 is from irrigation and Green: 1,590 from rainfall. The pedigree matrix has been adjusted to represent this huge variation in figures.

On this basis, the water depletion data from OpenLCA is not considered to be accurate, and instead, the data from the literature has been used. One clear concern is that if the irrigation data has been missed out from the soy data, perhaps it has been missed out from processes which contributed to the microalgae model. A review of the processes feeding into the microalgae model was undertaken, and none of the processes was found to have unusually low water use values; however, it is acknowledged that this is an additional source of uncertainty, and hence the water use values within this article should be considered very carefully. As such, within the pedigree matrix, the values for water use have been values at 4.3.3.5.3. The water use has been set with the standard irrigation model for Ecoinvent producing 926kg, and rainfall supplying 1,590kg of water.

5.8 InteSusAl LCI

5.8.1 *Operation*

Within the InteSusAl project, the majority of the microalgae production side of the overall concept was constructed and operated in Olhão, Portugal. The system comprised of four TPBR systems, each with 15,000 L capacity (total capacity 60,000 L). Three 1,000 L fermenters were operated in Portugal, with a fourth 1,000 L fermenter running in Wilton, UK. Growth productivity trials were conducted from October 2015 to June 2016 for *Chlorella protothecoides* (fermenters), *Phaeodactylum tricornutum* (TPBR) and Nanno*chloropsis salina* (TPBR). During these trials, the required chemicals, energy use and microalgae volume produced were measured. The CO_2/O2 gas exchange system, water recycling and glycerol recycling systems were not implemented within this facility. Growth productivity trials were run at the facility from October 2015 to June 2016. Within these, the input chemicals, energy use and microalgae volume produced were measured. Where necessary, existing databases and literature have been used to supplement the real data.

Where primary data could not be sourced from site, data was first acquired from the Ecoinvent Integrated 3.2 database(Wernet *et al.*, 2016), the literature, or if necessary from the producers of GaBi, Sphera Solutions. It is acknowledged that this is not ideal due to differences in the databases and underlying methodologies. A fossil fuel reference was used from existing Ecoinvent database models.

In the case of potassium dihydrogen phosphate (CAS: 7778-77-0), due to a lack of access to industrial data, a proxy from Sphera Solutions was used within the models. The proxy model was tetrapotassium pyrophosphate (CAS: 7320-34-5) based on the Sphera Solutions trisodium phosphate process. The logic for the use of this proxy was that both potassium dihydrogen phosphate and tetrapotassium pyrophosphate have similar methods of manufacturing.

The LCI data is provided below.

Table 5-14: Culture Media Phototrophic

Input	CAS	amount	unit
Sodium nitrate	7631-99-4	0.400000	kg / 1 kg DW biomass
Potassium hydrogen phosphate	7778-77-0	0.032000	kg / 1 kg DW biomass
Iron (III) chlorid	7705-08-0	0.007529	kg / 1 kg DW biomass
EDTA disodium dihydrate	6381-92-6	0.023059	kg / 1 kg DW biomass
Zinc Chloride	7646-85-7	0.000321	kg / 1 kg DW biomass
Zinc sulfate heptahydrate	7446-20-0	0.000676	kg / 1 kg DW biomass
Sodium molybdate dihydrate	10102-40-6	0.000569	kg / 1 kg DW biomass
Cobalt Chloride, 6-Hydrate	7791-13-1	0.000056	kg / 1 kg DW biomass
Copper (II) Sulfate Pentahydrate	7758-99-8	0.000059	kg / 1 kg DW biomass
Manganese(II) chloride tetrahydrate	13446-34-9	0.000465	kg / 1 kg DW biomass
Magnesium sulfate heptahydrate	10034-99-8	0.001158	kg / 1 kg DW biomass
Carbon Dioxide (*Nannochloropsis* sp.)	124-38-9	2.3	kg / 1 kg NAS DW biomass
Carbon Dioxide (*Phaeodactylum tricornutum*)	124-38-9	2.9	kg / 1 kg PHT DW biomass

Table 5-15: Culture Media Heterotrophic

Input	CAS	amount	unit
potassium hydrogen phosphate	7778-77-0	0.031500	kg / 1 kg algae
sodium dihydrogen phosphate	7558-80-7	0.013000	kg / 1 kg algae
ammonium sulphate	7783-20-2	0.003000	kg / 1 kg algae
magnesium sulphate	7487-88-9	0.003300	kg / 1 kg algae
iron III chloride hydrate	7705-08-0	0.000080	kg / 1 kg algae
copper sulphate	7758-98-7	0.000020	kg / 1 kg algae
manganese chloride	7773-01-5	0.000025	kg / 1 kg algae
zinc sulphate	7733-02-0	0.000002	kg / 1 kg algae
calcium chloride	7733-02-0	0.000040	kg / 1 kg algae
Water	7732-18-5	16.6	kg / 1 kg algae
sodium hydroxide	1310-73-2	0.0595	kg / 1 kg algae
technical grade glycerol	56-81-5	38.016	tonnes / year
glycerine (internal – from hetro)	56-81-5	3.811851506	tonnes / year
glycerine (internal – from photo)	56-81-5	1.20163164	tonnes / year

Table 5-16: Electricity (autotrophic)

Section	Energy	amount	unit
phototrophic (per TPBR)	Electricity	124.8	kWh / day
Green Walls (per Green Wall)	Electricity	4.8	kWh / day
Harvesting	Electricity	8.75	kWh / m^3

Table 5-17: Electricity (heterotrophic)

System	Rated [kW]	Average power draw [kW]
Media Clarification Unit	6.5	1.4505
Feed Vessel Agitator	1.5	0.536
Fermenter heater/chiller unit	6.5	4.4806

Table 5-18: Algae Lipid content

Species	Lipid content
Phaeodactylum tricornutum	14%
Nannochloropsis sp.	21%
Chlorella	40%

Table 5-19: Lipid extraction data, taken from CPI, for Nannochlorpsis

Name	Amount	Unit
Inputs		
Electricity	10	MJ
Organic solvent	0.01	kg
Microalgae	1	kg
Outputs		
Algal oil	0.21	kg
Waste	0.01	kg
Biomass	0.79	kg

Table 5-20: Lipid extraction data, taken from CPI, for Phaeodactylum

Name	Amount	Unit
Inputs		
Electricity	10	MJ
Organic solvent	0.01	kg
Microalgae	1	kg
Outputs		
Algal oil	0.14	kg
Waste	0.01	kg
Biomass	0.86	kg

Table 5-21: Lipid extraction data, taken from CPI, for Chlorella

Name	Amount	Unit
Inputs		
Electricity	10	MJ
Organic solvent	0.01	kg
Microalgae	1	kg
Outputs		
Algal oil	0.4	kg
Waste	0.01	kg
Biomass	0.6	kg

Table 5-22: Use phase, almost identical to the Ecoinvent model "transport, passenger car, medium size, diesel, EURO 3 (biodiesel)", except that fuel used modified to account for an estimate of 38MJ/kg energy density of microalgae-derived biodiesel.

Flow	Amount	Unit
Input		
brake wear emissions, passenger car [Waste]	-7.55E-06	kg
diesel, low-sulfur [allocatable product]	0.06062	kg
passenger car maintenance [allocatable product]	8.60E-06	pcs.
Road [allocatable product]	0.000911396	ma
road wear emissions, passenger car [Waste]	-1.66E-05	kg
tyre wear emissions, passenger car [Waste]	-9.72E-05	kg
Output		
RER: transport, passenger car, medium size, diesel, EURO 3 [allocatable product]	1000	m
Acetaldehyde (Ethanal) [Group NMVOC to air]	1.79E-06	kg
Acetone (dimethylcetone) [Group NMVOC to air]	8.11E-07	kg
Acrolein [Group NMVOC to air]	9.88E-07	kg
Ammonia [Inorganic emissions to air]	9.70E-07	kg
Benzaldehyde [Group NMVOC to air]	2.37E-07	kg
Benzene [Group NMVOC to air]	5.46E-07	kg
Butane [Group NMVOC to air]	3.04E-08	kg
Butanone (methyl ethyl ketone) [Group NMVOC to air]	3.31E-07	kg
Cadmium [Heavy metals to air]	6.06E-10	kg
Carbon dioxide (biotic) [Inorganic emissions to air]	0.18999	kg
Carbon monoxide [Inorganic emissions to air]	7.57E-05	kg
Chromium (unspecified) [Heavy metals to air]	3.03E-09	kg
Chromium IV [Heavy metals to air]	6.06E-12	kg
Copper [Heavy metals to air]	1.03E-07	kg
Cycloalkanes (unspec.) [Group NMVOC to air]	1.79E-07	kg
Dust (PM2.5) [Particles to air]	3.56E-05	kg
Ethane [Group NMVOC to air]	9.11E-08	kg
Ethylene oxide [Group NMVOC to air]	3.03E-06	kg
Formaldehyde (methanal) [Group NMVOC to air]	3.31E-06	kg
Heptane (isomers) [Group NMVOC to air]	5.52E-08	kg

Lead [Heavy metals to air]	5.00E-15	kg
Mercury [Heavy metals to air]	1.21E-12	kg
Methane [Organic emissions to air (group VOC)]	2.08E-06	kg
Nickel [Heavy metals to air]	4.25E-09	kg
Nitrogen oxides [Inorganic emissions to air]	0.000253	kg
Nitrous oxide (laughing gas) [Inorganic emissions to air]	3.03E-06	kg
NMVOC (unspecified) [Group NMVOC to air]	1.46E-05	kg
Pentane (n-pentane) [Group NMVOC to air]	1.10E-08	kg
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Group PAH to air]	1.12E-08	kg
Propane [Group NMVOC to air]	3.04E-08	kg
Propylene oxide [Group NMVOC to air]	9.93E-07	kg
Selenium [Heavy metals to air]	6.06E-10	kg
Styrene [Group NMVOC to air]	1.02E-07	kg
Sulphur dioxide [Inorganic emissions to air]	1.21E-06	kg
Toluene (methyl benzene) [Group NMVOC to air]	1.90E-07	kg
Xylene (meta-Xylene; 1,3-Dimethylbenzene) [Group NMVOC to air]	1.68E-07	kg
Xylene (ortho-Xylene; 1,2-Dimethylbenzene) [Group NMVOC to air]	7.45E-08	kg
Zinc [Heavy metals to air]	6.06E-08	kg

Table 5-23: Inputs and outputs of NREL model used for algae transesterification, modified from "RNA: Soy biodiesel, production, at plant USB/NREL USLCI <u-so>". Figures the same, just the names changed.

Flow	Amount	Unit
Input		
RNA: Electricity, at grid, U.S. [Products and Intermediates]	0.431996544	MJ
RNA: Methanol, at plant [Products and Intermediates]	0.305	kg
RNA: Natural gas, combusted in industrial boiler [Products and Intermediates]	0.0762	m3
RNA: Sodium hydroxide, production mix, at plant [Products and Intermediates]	0.00327	kg
RNA: Soybean oil, crude, degummed, at plant [Products and Intermediates]	3.32	kg
RNA: Transport, combination truck, diesel powered [Products and Intermediates]	1240	kgkm
RNA: Dummy, Citric Acid, at plant [Dummy Flows]	0.00245	kg
RNA: Dummy, Hydrochloric Acid, at plant [Dummy Flows]	0.146	kg
RNA: Dummy, Phosphoric Acid, at plant [Dummy Flows]	0.00213	kg
RNA: Dummy, Sodium Methylate, at plant [Dummy Flows]	0.0777	kg
Water (river water) [Water]	0.00114	kg
Output		
RNA: Glycerin, at biodiesel plant [Products and Intermediates]	0.403	kg
RNA: Algae biodiesel, production, at plant [Products and Intermediates]	3.36	kg
Fatty acids (calculated as total carbon) [Hydrocarbons to fresh water]	0.00694	kg

5.8.2 *Construction Model*

Detailed construction information was provided from the Necton and CPI sites on the construction of the facilities. Information on End-of-Life, where appropriate Ecoinvent models did not exist, was gathered from a range of sources. Specifically; polyethylene terephthalate (PET) and high-density polyethylene (HDPE) was based on (Franklin Associates, 2011), poly(methyl methacrylate) (PMMA) recycling was based on standard industry practices, and data within The Advanced Thermal AnalysiS laboratory (ATHAS)(Wunderlich, 1995), polypropylene (PP) data was from (Hardwick, 2015), and polyvinyl chloride (PVC) data was gathered from (Stichnothe and Azapagic, 2013) proxy Processes

Table 5-24: Summarised construction data for the InteSusAl facility in Olhão. (1 of 2)

Material	Mass [kg]
AGGREGATES	
Concrete	619,705.00
Crushed stone and stone dust	392,100.00
Graded aggregate	226,200.00
gravel and grit	924,740.00
Perforated clay bricks	280.80
Soil	1,944,800.00
Stone	45,256.70
stone dust	61,440.00
tout-venant	832,000.00
Ceramic tiles	7,595.00
METALS	
Aluminium parts	182.25
Cast Iron	1,153.80
Galvanized Steel screw	5.00
Galvanized Steel sheet	976.90
stainless Steel (304)	5,210.22
Stainless Steel (316)	182.61
stainless Steel (unspecified)	2,883.33
stainless Steel (1,449)	900.00
Steel (unspecified)	42.00
MIXED	
aluminium + glass	1.00
EPDM + Stainless Steel	7.56
Medium voltage cable	133.59
lamp	42.40
motor	1.00
ABAC B4900-270 FT4 FFO Piston Compressor	174.00

Table 5-25: Summarised construction data for the InteSusAl facility in Olhão. (2 of 2)

Material	Mass [kg]
PLASTICS	
FRP	12,494
HDPE	2,909
PMMA	13,440
Polyamide	13.34
Polyamide glass fibre	12
Polybutadiene	1.80
Polymer concrete	1,554
polyurethane	2,275
PP	442
PP – H	8,000
PVC	5,902
PVC cleaner	50
PVC Solvent Cement	50
PP Recycled	800
Styrene Acrylonitrile	34
Styrofoam	66
Polyethylene	153
WOOD	
Ceiling wood beam	48

Table 5-26: Construction of fermenter system, based on data from CPI

Material	Mass [kg]
Stainless Steel	1,435
Silicone tubing	17.69
EPDM	10.77

5.8.3 *Recycling and Disposal*

One area which always presents difficulty within LCA is that of the end-of-life scenarios. In short, there is no way to know the methods of disposal and recycling of products in ten or twenty years into the future. Although a method of recycling may be technically possible, that does not mean it will be adopted internationally, as both market forces and politics are strong drivers. Therefore, the best can be done is to calculate based on the current recycling practices. Where adequate recycling or disposal models were not available, new ones were created. These are detailed in the following sub sections.

5.8.3.1 Polyethylene terephthalate (PET) and High-density polyethylene (HDPE)

Information for the recycling process of these were gathered from(Franklin Associates, 2011). This

document includes detailed data on consumer waste recycling, including the chemical inputs, energy and emissions. Models were based upon this data (excluding the transport emissions from kerbside collections, which were not relevant for this case).

5.8.3.2 Poly(methyl methacrylate)

This is a good example of open-loop recycling, as the PMMA cannot be directly recycled into new PMMA; instead, it is recycled into methyl methacrylate (MMA). Little industrial data was found on the recycling process, but, from a chemistry point of view, it is known that the PMMA is heated up to a temperature of 400°C in order to convert it. The energy required to heat up 1 kg of substance by a certain temperature is:

$$E = mc\Delta T \qquad \textit{Equation 1}$$

m = mass [kg]

c = specific heat capacity

ΔT = Temperature change [K]

The specific heat capacity of PMMA varies with temperature, so for an increase in temperature from 20°C to 400°C (293.15K to 673.15K) the energy was calculated in steps. The range of specific heat capacities for PMMA was found from The Advanced Thermal AnalysiS laboratory (ATHAS)(Wunderlich, 1995). The data was found within the Internet Archive(Advanced THermal AnalysiS Laboratory, 1993) as it is no longer online. This data gives the specific heat capacity of PMMA from 0.1 K to 1000 K. Through a step model, the energy to heat 1kg of PMMA from 20°C to 400°C is 0.84MJ (0.23247 kWh) (assuming 1 mol of PMMA = 100.12 g/mol.).

Using this data, the model removed the impacts of the MMA input into the PMMA process and replaced it with collected recycled plastic heated with 0.23247 kWh using and industrial furnace.

5.8.3.3 Polypropylene (PP)

The best data found on the recycling of PP was from(Hardwick, 2015), which is a report by Sphera Solutions (the makers of GaBi) into the LCA of polymer banknotes. This report does include the energy required to mechanically recycle PP into new granulate.

5.8.3.4 Polyvinyl chloride (PVC)

The recycling data for PVC was gathered from(Stichnothe and Azapagic, 2013), which considers the recycling of PVC window frames. This paper considers the recycling of consumer and industrial window

frames into two qualities of PVC chips. For InteSusAl, data was considered for the recycling of industrial window frames into high-quality PVC to keep the system closed loop.

5.8.3.5 Other materials

In cases where there was limited information on recycling within the Ecoinvent database or the literature, this was a strong indication that the products were not recycled widely. In these cases, the impacts associated with the incineration of the products were considered. The option of including carbonation within the concrete models was considered; however, at present, there is no widespread practice of using this process to absorb CO_2 from the atmosphere.

5.8.4 *Transport Impacts*

Where possible, "Market" processes were used from Ecoinvent. These include data on the average transport impacts of the products. In some cases, such as the "Sphera Solutions data on-demand" processes, there was no "Market" data. In these cases, the transport used within Ecoinvent for fodder yeast was used. The motivation was that the yeast industry is primarily based in China, which provided an extreme case for the transport impacts for a microalgae production facility based within the EU.

5.9 LCI data from BIOMOD

Life Cycle Assessment was undertaken of production of *Chlorella Protothecoides* from the BioMODule system and compared with data for production of *Chlorella P.* from a steel fermenter system.

The data from BIOMOD was quite basic compared to that of InteSusAl. The models were for simple bag-based fermenters, and the data was compared with that from the fermenters from InteSusAl, but recreated with OpenLCA in order to allow for the use of pedigree matrices (detailed later within the sections on Uncertainty). As with InteSusAl, the microalgae was fed on yeast extract as the carbon source. The productivity of the steel fermenter was taken as biomass per year 1,203.84kg/year, in order to apply the infrastructure impacts correctly.

The LCI data is given below.

Table 5-27: Makeup of a bag based fermenter. Note, the energy to create one back is 0.13kWh.

Plastic	Width (micro m)	kg
PA	25	0.7447
ULDPE	50	1.4894
EVOH	10	0.2979
ULDPE	100	2.9787
ULDPE	50	1.4894

Table 5-28: Summary of all inputs for one batch run of the BioMODule system, which will produce 15kg of Chlorella Protothecoides

Flow	Amount	Unit
ammonium sulfate, as N	4.012	kg
boric acid, anhydrous, powder	0.012	g
calcium chloride	8.826	g
Cobalt_chloride_hexahydrate_estimation (ts)	0.04	g
copper chloride	0.004	g
Crystallin Dextrose Monohydrate	16	kg
EDTA, ethylenediaminetetraacetic acid	4.254	g
iron(III) sulfate, without water, in 12.5% iron solution state	0.4	g
manganese sulfate	0.016	g
nickel sulfate	0.008	g
Sodium molybdate dihydrate	1.6	g
Potassium hydrogen phosphate	2.56	kg
Yeast extract (industrial data) – CN	1.605	kg
zinc monosulfate	0.32	g

Table 5-29: Summary of all disposable inputs for one batch run of the BioMODule system, which will produce 15kg of Chlorella Protothecoides

Consumable	Number required for three batches
Silicone tubing for pump (0.5 inch ID) = Part code: 02-93-2447	3
Hose barbs	15
Cable ties	3
Air filter (0.2um) – Part code: MCY4440PFRPH4	6
Air filter (0.2um) – Part code: AB1 PFR 7PVH4	9
Air filter (0.2um) – Part code: AB2 PFR 7PVH4	6
Alkali filter (0.2um) – Part code: ZCMSA020TPEX	6
Post Acid filter (0.8um) – Part code: Sartopore PP2 8µ 5595301P9-SS	6
Post Acid filter (0.2um) – Part code: 16VPB002-05 JEAC or ALT220G23CDH4	6

5.10 LCI data from MAGNIFICENT

The facility under study is the 150m^3 photobioreactor based facility at AlgaFarm, close to Lisbon in Portugal. Data was recorded from 13/06/2017 to 11/08/2017. Additional data for a 100m^3 system at AlgaFarm was used for the period 17th Oct–15th Dec 2017. (Pereira *et al.*, 2018). Assuming a one-month downtime in late December to early Jan, the yearly output of the 150m^3 facility could be estimated, which was calculated to be 5,372 kgDW/year. Over a 15-year period, this would equate to 79,546 kgDW.

High levels of operational data were collected by Hugo Peira on the operation of the facility. The

detailed data from the InteSusAl facility has been simplified down for the PBRs, whilst sensible assumptions were used for the GRP tanks, spray drier and the pump. The air compressor was included within the impacts in the operational model. Together, this was used to create the LCI data as below.

Stage	Input	Amount	Unit
Processing	Electricity	10312.30	kWh
Harvesting	Electricity	407.37	kWh
Production	carbon dioxide, liquid	2397.49	kg
	compressed air, 600 kPa gauge	7747.20	m^3
	electricity	89.43	kWh
	electricity	12972.20	kWh
	f2 medium	4520	kg
	iron (3%)	12.60	kg
	potassium nitrate	14.95	kg
	tap water	416.90	kg

Table 5-30: Inputs to produce 1104.51kg of microalgae paste

Input	Amount	Unit
bisphenol A epoxy-based vinyl ester resin	371.67	kg
cable, three-conductor cable	128.45	m
extrusion, plastic pipes	0.23	kg
polybutadiene	3	kg
polyethylene pipe, DN 200, SDR 41	5006.96	m
polymethyl methacrylate, sheet	22400	kg
polypropylene, granulate	734.92	kg
polyvinylchloride, bulk polymerised	9836.73	kg
sheet rolling, aluminium	303.76	kg
steel, chromium steel 18/8	15934.94	kg

Table 5-31: Materials for 150m3 of photobioreactors, based on data from InteSusAl

Input	Amount	Unit
casting, steel, lost-wax	652	kg
integrated circuit, logic type	5	kg
polyethylene, high density, granulate	98	kg

Table 5-32: Materials for a spray drier, based on sensible assumptions on heavy equipment

Input	Amount	Unit
cast iron	98	kg
integrated circuit, logic type	2	kg
polyethylene, high density, granulate	5	kg

Table 5-33: Materials for a pump, based on sensible assumptions on heavy equipment

Input	Amount	Unit
glass fibre reinforced plastic	880	kg

Table 5-34: Materials for a 10m^3 GRP tank, based on a study of technical specifications of various products

Input	Amount	Unit
glass fibre reinforced plastic	2560.0	kg

Table 5-35: Materials for a 100m^3 GRP tank based on a study of technical specifications of various products.

Chapter 6. Validation of Software and Secondary Data

The validation of LCI data is extremely difficult, as it is highly methodology dependent, and simple changes can result in entirely different results.

The validation for the overall approach of the GaBi modelling within this work was undertaken by using the data from (Passell *et al.*, 2013), which considered a real-world microalgae production facility. The models from this paper were recreated within GaBi. This validated the general approach of this thesis.

Then, various processes were compared within GaBi, OpenLCA, and the EcoInvent online database, to find differences within different applications of the same version of EcoInvent. These were a root towards finding deeper issues within the software and Ecoinvent.

6.1 Validation of GaBi Methodology

6.1.1 *Introduction*

In order to validate the use of GaBi and associated databases within this project, and to understand how the InteSusAl process compares with other microalgae biofuel facilities, data was sourced from the literature which is based on commercial operating facilities. Specifically, data was sourced from(Passell *et al.*, 2013), which additional data gathered via personal communication with one of the co-authors, Harnoor Dhaliwal from EarthShift LLC.

(Passell *et al.*, 2013) used data from two industrial sources, Seambiotic (www.seambiotic.com) from

Israel and Solution Recovery Services (SRS) Inc. (now trading as Valicor) from the US. The biofuel production side was modelled using the GREET 1_2011 software.

6.1.2 *Methodology*

In order to compare the LCA methodology within this project with the work by Passel et al., (2013), , Harnoor Dhaliwal was approached for the full Life Cycle Inventory data, which she provided in detail. A model was constructed within GaBi to match the processes and flows of Seambiotic and Valicor. Where possible, as with(Passell *et al.*, 2013), EcoInvent 2.2 processes were used.

6.1.3 *Results*

Initially, the results for GWP100, photochemical ozone formation (kg NMVOC eq), particulate matter (kg PM10 eq), water depletion [m^3] and NER were compared between the (Passell *et al.*, 2013) data and models generated within GaBi. These are presented in Table 6-1.

Table 6-1: Comparison of the model from (Passell et al., 2013) with the model produced using GaBi

(Passell *et al.*, 2013)			ReCiPe 1.08 Midpoint (H)			% diff
Impact	**Unit**	**Value**	**Impact**	**Unit**	**Value**	
Climate Change (GWP100)	kg CO_{2eq}	2.88	Climate change, default, excl biogenic carbon (GWP100)	kg CO_{2eq}	2.82	1.93%
Photochemical Ozone Formation	kg $NMVOC_{eq}$	0.0074	Photochemical oxidant formation	kg $NMVOC_{eq}$	0.0071	3.84%
Particulate Matter	kg $PM10_{eq}$	0.0046	Particulate matter formation	kg $PM10_{eq}$	0.0044	3.55%
Water depletion	m^3	0.08	Water depletion	m^3	10.78	-13386.96%

As can be seen, for Climate Change, photochemical oxidant formation and particulate matter formation, there is strong agreement between (Passell *et al.*, 2013) and this work. However, for water depletion, there is a significant difference; this issue is addressed later within this chapter. The primary source of water use within the microalgae biodiesel model was electricity use, which totalled 10.7 kg/MJ. However, interestingly, the sum of all the other processes which contribute to the water depletion (excluding electricity) give an impact of 0.082 m^3/MJ. This suggested that the difference could be due to (Passell *et al.*, 2013) missing out the electricity contributions for water depletion; however, it is more likely to be issues within GaBi, as explained in the later sections of this chapter.

6.1.3.1 Additional Impact Categories

Following on from this, the full selection of ReCiPe Hierarchist mid-point categories were analysed for

the (Passell *et al.*, 2013) base case. These clearly showed that for all impact categories, the electricity demand was the major source of impacts. The next process which contributes to various impacts is the production of ammonium sulphate, which contributes 10.6% of the metal depletion, 4.1 % of Natural land transformation and Ozone depletion, and 4.8% of Terrestrial ecotoxicity. This analysis agrees strongly with papers in the literature, which identify the electricity requirements as the major issue for algal biofuels.

Table 6-2: Analysis of data from (Passell et al., 2013) using GaBi, impact categories are all calculated using ReCiPe 1.08 Midpoints (H). Figures are all % impact of each individual process on each individual impact category. Colour scale varies from 100% (green) to 0% (red).

Impact	Unit	Extraction and 128eparation (extra facility energy and the hexane leakage) <u-so>	GLO: methanol, at plant	GLO: sodium methoxide, at plant	RER: ammonium sulphate, as N, at regional storehouse	RER: heat, natural gas, at boiler modulating <100kW	RER: hexane, at plant	RER: hydrochloric acid, 30% in H2O, at plant	RER: single superphosphate, as P2O5, at regional storehouse	RER: sodium hydroxide, 50% in H2O, production mix, at plant	RER: tap water, at user	US: electricity, medium voltage, at grid	US: Natural gas, combusted in industrial boiler USLCI <u-so>
Agricultural land occupation	m^2	0	0	0	1.9	0	0.1	0	0.5	0	0	97.4	0
Climate change, default, excl biogen	kg CO_{2eq}	0	0	0	1	0.6	0.1	0	0.2	0	0	98.1	0
Fossil depletion	kg oil_{eq}	0	0	0	1.3	0.8	0.6	0	0.2	0	0	97.1	0
Freshwater ecotoxicity	kg 1,4-DB_{eq}	0	0	0	0.6	0	0.1	0	0.3	0	0	99	0
Freshwater eutrophication	kg P_{eq}	0	0	0	0.5	0	0.1	0	0.4	0	0	98.9	0
Human toxicity	kg 1,4-DB_{eq}	0	0	0	0.9	0	0.1	0	0.4	0	0	98.5	0
Ionising radiation	kg $U235_{eq}$	0	0	0	0.3	0	0.1	0	0.3	0	0	99.2	0
Marine ecotoxicity	kg 1,4-DB_{eq}	0	0	0	0.9	0.1	0.1	0	0.4	0	0	98.5	0
Marine eutrophication	kg N_{eq}	0	0	0	0.5	0.1	0.1	0	0.3	0	0	98.9	0
Metal depletion	kg Fe_{eq}	0	0	0.1	10.6	0.6	0.8	0.1	2.5	0	0	85.3	0
Natural land transformation	m^2	0	0.1	0	4.1	1.9	3.5	0	0.7	0	0	89.7	0
Ozone depletion	kg $CFC\text{-}11_{eq}$	0	0.1	0	4.1	2.8	2	0.2	0.5	0	0	90.3	0
Particulate matter formation	kg $PM10_{eq}$	0	0	0	0.7	0.1	0.1	0	0.6	0	0	98.4	0
Photochemical oxidant formation	kg NMVOC	0.1	0	0	0.9	0.2	0.4	0	0.5	0	0	97.9	0
Terrestrial acidification	kg $SO2_{eq}$	0	0	0	0.5	0.1	0.1	0	0.4	0	0	98.9	0
Terrestrial ecotoxicity	kg 1,4-DB_{eq}	0	0	0.1	4.8	0.4	1.5	0.1	4.9	0	0	88.2	0
Urban land occupation	m^2	0	0	0	0.8	0	0.1	0	0.4	0	0	98.6	0
Water depletion	m^3	0	0	0	0.4	0	0.1	0	0.2	0	0	99.2	0

6.1.4 *Conclusion*

As shown within Table 6-1, for Climate Change (GWP100), Photochemical Ozone Formation, and Particulate Matter this analysis has shown good agreement between the results in (Passell *et al.*, 2013) and those calculated by the author from the same data. This gives confidence in the LCA methodology to be used within this Thesis. There are concerns over the water depletion, which is addressed next. Additionally, further impact categories were analysed, showing electricity to be the major contributor

to all impact categories, although the manufacture of ammonium sulphate for the microalgae does also contribute to some categories.

6.2 Comparison of OpenLCA and GaBi

Whilst the GaBi methodology appeared to work when compared with published data, further validation was undertaken to compare GaBi with OpenLCA. This is because the similarities between the Seambiotic and GaBi data could be because both were making the same mistakes. Additionally, there was still the issue of water use inconsistencies.

Several models from the APOS EcoInvent databases were compared within GaBi, OpenLCA and using the original data from the EcoInvent database (on the Ecoinvent website). Differences were highlighted, as demonstrated within Table *6-3* and Table 6-4, which shows large differences within Terrestrial Toxicity, freshwater ecotoxicity, marine ecotoxicity, marine eutrophication, ionising radiation and human toxicity, and very significant differences for water depletion. Please note, these are all analysis of the same data so should, in theory, be identical.

Table 6-3*: Comparison of GaBi, OpenLCA, and the original Ecoinvent data for "diesel production, low-sulfur agg Ecoinvent 1920:Manufacture of refined petroleum products".*

Name	OpenLCA		GaBi		EcoInvent Website	
	CH	EU-CH	CH	EU-CH	CH	EU-CH
Agricultural land occupation	1.13×10^{-2}	1.03×10^{-2}	1.13×10^{-2}	1.03×10^{-2}	1.13×10^{-2}	1.03×10^{-2}
Photoch×10mical oxidant formation	3.04×10^{-3}	3.68×10^{-3}	3.04×10^{-3}	3.69×10^{-3}	3.04×10^{-3}	3.69×10^{-3}
Particulate matter formation	1.08×10^{-3}	1.50×10^{-3}	1.08×10^{-3}	1.50×10^{-3}	1.08×10^{-3}	1.50×10^{-3}
Ozone depletion	6.14×10^{-7}	6.92×10^{-7}	6.14×10^{-7}	6.92×10^{-7}	6.14×10^{-7}	6.92×10^{-7}
Terrestrial ecotoxicity	4.89×10^{-5}	6.20×10^{-5}	2.46×10^{-4}	2.59×10^{-4}	4.86×10^{-5}	6.17×10^{-5}
Freshwater ecotoxicity	3.00×10^{-3}	3.80×10^{-3}	1.82×10^{-2}	1.74×10^{-2}	3.32×10^{-3}	4.14×10^{-3}
Freshwater eutrophication	3.83×10^{-5}	6.31×10^{-5}	3.83×10^{-5}	6.31×10^{-5}	3.83×10^{-5}	6.33×10^{-5}
Natural land transformation	1.19×10^{-3}	1.35×10^{-3}	1.06×10^{-3}	1.21×10^{-3}	1.19×10^{-3}	1.35×10^{-3}
Marine ecotoxicity	2.37×10^{-3}	3.15×10^{-3}	1.44×10^{-2}	1.40×10^{-2}	2.40×10^{-3}	3.18×10^{-3}
Marine eutrophication	9.32×10^{-5}	1.20×10^{-4}	9.32×10^{-5}	1.18×10^{-4}	6.31×10^{-4}	7.80×10^{-4}
Ionising radiation	2.38×10^{-1}	2.67×10^{-1}	2.30×10^{1}	2.59×10^{1}	2.38×10^{-1}	2.67×10^{-1}
Metal depletion	1.42×10^{-2}	1.79×10^{-2}	1.41×10^{-2}	1.78×10^{-2}	1.42×10^{-2}	1.79×10^{-2}
Urban land occupation	5.84×10^{-3}	6.57×10^{-3}	5.71×10^{-3}	6.43×10^{-3}	5.84×10^{-3}	6.57×10^{-3}
Water depletion	6.24×10^{-1}	6.38×10^{-1}	6.24×10^{-1}	6.38×10^{-1}	1.03×10^{-3}	1.38×10^{-3}
Human toxicity	6.42×10^{-2}	9.08×10^{-2}	1.58×10^{-1}	1.77×10^{-1}	8.06×10^{-2}	1.07×10^{-1}
Fossil depletion	1.15×10^{0}	1.30×10^{0}	1.13×10^{0}	1.29×10^{0}	1.20×10^{0}	1.37×10^{0}
Climate Change	4.22×10^{-1}	5.92×10^{-1}	4.25×10^{-1}	5.93×10^{-1}	4.22×10^{-1}	5.92×10^{-1}
Terrestrial acidification	3.60×10^{-3}	5.15×10^{-3}	3.60×10^{-3}	5.15×10^{-3}	3.60×10^{-3}	5.15×10^{-3}

Table 6-4: Percentage comparison of GaBi, OpenLCA, and the original Ecoinvent data for "diesel production, low-sulfur agg Ecoinvent 1920:Manufacture of refined petroleum products".

Name	Comparison (OpenLCA with GaBi)		Comparison (OpenLCA with EocInvent)		Comparison (GaBi with EocInvent)	
	CH	EU-CH	CH	EU-CH	CH	EU-CH
Agricultural land occupation	100%	100%	100%	100%	100%	100%
Photochemical oxidant formation	100%	100%	100%	100%	100%	100%
Particulate matter formation	100%	100%	100%	100%	100%	100%
Ozone depletion	100%	100%	100%	100%	100%	100%
Terrestrial ecotoxicity	20%	24%	101%	101%	505%	420%
Freshwater ecotoxicity	17%	22%	90%	92%	547%	421%
Freshwater eutrophication	100%	100%	100%	100%	100%	100%
Natural land transformation	112%	112%	100%	100%	89%	90%
Marine ecotoxicity	16%	23%	99%	99%	602%	439%
Marine eutrophication	100%	102%	15%	15%	15%	15%
Ionising radiation	1%	1%	100%	100%	9638%	9672%
Metal depletion	101%	101%	100%	100%	100%	100%
Urban land occupation	102%	102%	100%	100%	98%	98%
Water depletion	100%	100%	60374%	46111%	60374%	46111%
Human toxicity	41%	51%	80%	85%	196%	165%
Fossil depletion	101%	101%	95%	95%	94%	94%
Climate Change	99%	100%	100%	100%	101%	100%
Terrestrial acidification	100%	100%	100%	100%	100%	100%

GaBi and OpenLCA were investigated to understand these differences and the author communicated with both Sphera Solutions (the makers of GaBi) and Greendelta (the makers of OpenLCA). Various other Ecoinvent models were analysed, and all found the same problems.

The reasons for these were as follows;

- Both GaBi and OpenLCA count inputted and outputted water as water consumption, leading to massive overestimates
- In numerous cases in terms of toxicity, inputs for water, ground and air were confused within GaBi. So, emissions to water would be included when only emissions to land were relevant, for example. This led to overestimations
- General transcription errors within the ReCiPe database within each software package or the process.

To overcome these issues within this Thesis, the issues were highlighted to Sphera and Greendelta, who made the appropriate corrections to their software. However, there is still the concern there may be further issues in the software which was not found.

In terms of water, it is clear that water use data is wrong for every model produced by GaBi and OpenLCA prior to the software developers being alerted from the work in this thesis. In terms of the literature, this essentially that as GaBi features in a significant number of published LCA papers, this means a significant number of published LCA studies provide the wrong data for water use. The issues over toxicity mean that there is no confidence in toxicity data reported from the GaBi models within this thesis (or any published piece of work that used GaBi).

As a side note, in general, water use impacts are not informative. For further work post-thesis, an option to improve water data would be to use local water impacts, as described within [12] using the water scarcity footprint (WSF) which is calculated according to Equation 2 and is based on the blue water consumption and the regional specific water stress index (WSI) as defined by [13].

$$WSF = \sum_{i} \frac{CWU_i * WSI_i}{WSI_{global}} \qquad \textit{Equation 2}$$

Where;

CWU_i = consumption of blue water in region i

WSI_i = regional water stress in region i

WSI_{global} = global average water stress index (value 0.602)

Chapter 7. Results

7.1 InteSusAl Models

As described within the Methods Section, the results from the analysis of the InteSusAl system within GaBi were compared with a petroleum-derived reference, as presented below. These difference scenarios, as described within Section 5.5, were:

- Scenario A: In this scenario, the average energy mix for the EU-27 countries on the year 2012 were considered, which was the year the InteSusAl project began and ensured that the work is comparable to previous reports (Maga, 2016).
- Scenario B: In this scenario, the average energy mix for the EU-27+UK for 2020 was considered.
- Scenario C: In this scenario, solar photovoltaic (PV) electricity from a PV farm (modelled using PVSyst (PVSyst, 2020)) were considered as the main source of electricity for microalgae production.

7.1.1 *Infrastructure Model*

Detailed information was provided from the Necton and CPI sites on the construction of the facilities, as detailed within Chapter 5 This information was then converted into LCA models. Information on End-of-Life (EoL), where appropriate Ecoinvent models did not exist, was gathered from a range of sources.

The top five sources of AR5 GWP100 impacts within the infrastructure models were PVC, PMMA, concrete, Fibreglass Reinforced Plastic (FRP), aluminium and stainless steel. In terms of climate change, the timescale considered is important, for example, over a 100-year period concrete is the third largest impact (14.4% of the GWP100 impact), whereas over 20 years the third largest impact is that of FRP (13.7%) whilst concrete is 11.9% of the GWP20 impact.

7.1.2 *Operational Model*

The results of the three scenarios compared with petroleum-derived diesel fuel is given in Table 7-1, with the figures presented as percentages within Table 12-1, Table 12-1 is then graphically partially represented in Figure 12-2.

Based on the results, it proved that within Scenario A and B, the main source of impacts for microalgae production was from the electricity generation. The use of photovoltaics, as recommended in (Taylor

et al., 2013) and (Tredici, 2010), decreases the non-infrastructure GWP100 impacts by 58% compared with Scenario A, so that they were 88% those of petroleum-derived diesel, however, the photovoltaics still contributed to all midpoint and endpoint impacts, due to the necessary construction of the PV arrays. Please note, we have included the construction of PV in the non-infrastructure model, as infrastructure is included in the grid electricity models.

When considering Climate Change impacts, the impacts increased with the smaller timescale considered (e.g., higher impacts for GWP20 compared with GWP100). This is due to the different global warming impact of the methane produced within a 100-year period. Most of the methane produced in the life cycle of microalgae biodiesel comes from the energy generation for both the operation of the facility in Olhão itself and for the production of the yeast. Due to its short lifetime in the atmosphere (12.4 years)(Myhre *et al.*, 2013b), biogenic methane has an impact of 84 times that of CO2 over 20 years reducing to 28 times over 100 years. This highlights the question of whether short- or long-term timescales should be considered for climate change based decision making, and their balance (Shoemaker and Schrag, 2013b; Pierrehumbert, 2014; Cooper *et al.*, 2019). A full breakdown of the contributors to GWP100 and GWP20 is given in the Table 12-9 and Table 12-10. The impacts of using previous GWP data from the IPCC 4th Assessment Report (AR4)(Forster *et al.*, 2007b) with the 5th Assessment report (AR5)(Myhre *et al.*, 2013b) was also considered.

With the new AR6 characterisation factors coming in 2021, it is important to be aware of the differences between different sets of GWP data. Within our modelling, we compared AR4 CFs with AR5 CFs. In the current work using AR4 CFs leads to an underestimate of the GWP100 impacts ranging from 0.9% to 1.4% across the microalgae scenarios, and an underestimate of petroleum diesel of 0.3%. In this particular case, considering the large uncertainties within LCA, these differences cannot be considered relevant. However, that is not to say that in other LCA studies, the differences between AR4 and AR5 will not be relevant. It is important to note that these minor differences across AR4 and AR5 proved inconsistent, and potentially leading to misleading results for other processes.

Table 7-1 Results of the three microalgae scenarios, with and without infrastructure, compared with petroleum diesel burned in an engine (including infrastructure). Graphical representations of elements of this includes Figure 12-2, Figure 12-3, Figure 12-4, and Figure 12-5*

Impact Category	Petroleum-derived Diesel fuel	Microalgae biodiesel (three scenarios based on electricity used)					
		Without infrastructure			With infrastructure		
		(A) 2012 EU grid	(B) 2020 EU grid	(C) PV only	(A) 2012 EU grid	(B) 2020 EU grid	(C) PV only
IPCC AR5 (excl. biogenic carbon)							
GWP100 [kg CO_2 eq]	8.84×10^{-2}	1.85×10^{-1}	1.68×10^{-1}	7.76×10^{-2}	2.56×10^{-1}	2.38×10^{-1}	1.48×10^{-1}
GWP20 [kg CO_2 eq]	9.13×10^{-2}	2.12×10^{-1}	1.92×10^{-1}	9.40×10^{-2}	3.02×10^{-1}	2.82×10^{-1}	1.84×10^{-1}
GTP100 [kg CO_2 eq]	8.70×10^{-2}	1.73×10^{-1}	1.57×10^{-1}	7.01×10^{-2}	2.36×10^{-1}	2.19×10^{-1}	1.33×10^{-1}
GTP50 [kg CO_2 eq]	8.76×10^{-2}	1.78×10^{-1}	1.61×10^{-1}	7.31×10^{-2}	2.43×10^{-1}	2.26×10^{-1}	1.38×10^{-1}
GTP20 [kg CO_2 eq]	9.04×10^{-2}	2.04×10^{-1}	1.85×10^{-1}	8.90×10^{-2}	2.84×10^{-1}	2.65×10^{-1}	1.70×10^{-1}
ReCiPe 1.08 Endpoint (H)							
Freshwater ecotoxicity [species.yr]	3.58×10^{-13}	1.54×10^{-12}	1.54×10^{-12}	2.55×10^{-12}	4.72×10^{-12}	4.72×10^{-12}	5.73×10^{-12}
Human toxicity [DALY]	5.68×10^{-9}	1.69×10^{-8}	1.72×10^{-8}	2.64×10^{-8}	4.03×10^{-8}	4.05×10^{-8}	4.97×10^{-8}
Marine ecotoxicity [species.yr]	7.66×10^{-14}	2.68×10^{-13}	2.68×10^{-13}	4.55×10^{-13}	7.59×10^{-13}	7.60×10^{-13}	9.47×10^{-13}
Terrestrial ecotoxicity [species.yr]	2.13×10^{-12}	1.91×10^{-12}	1.92×10^{-12}	4.33×10^{-12}	3.34×10^{-12}	3.34×10^{-12}	5.75×10^{-12}
ReCiPe 1.08 Midpoint (H)							
Agricultural land occupation [m^2a]	2.43×10^{-4}	9.44×10^{-3}	1.03×10^{-2}	7.88×10^{-3}	1.19×10^{-2}	1.28×10^{-2}	1.03×10^{-2}
Climate change, excl biogenic [kg CO_2 eq]	8.81×10^{-2}	1.83×10^{-1}	1.66×10^{-1}	7.63×10^{-2}	2.52×10^{-1}	2.35×10^{-1}	1.45×10^{-1}
Climate change, incl biogenic [kg CO_2 eq]	8.82×10^{-2}	2.10×10^{-1}	1.92×10^{-1}	1.03×10^{-1}	2.79×10^{-1}	2.62×10^{-1}	1.72×10^{-1}
Fossil depletion [kg oil eq]	3.02×10^{-2}	4.87×10^{-2}	4.60×10^{-2}	2.12×10^{-2}	6.92×10^{-2}	6.65×10^{-2}	4.17×10^{-2}
Freshwater ecotoxicity [kg 1,4-DB eq]	4.14×10^{-4}	1.79×10^{-3}	1.78×10^{-3}	2.95×10^{-3}	5.47×10^{-3}	5.46×10^{-3}	6.63×10^{-3}
Freshwater eutrophication [kg P eq]	1.48×10^{-6}	1.06×10^{-5}	1.07×10^{-5}	1.72×10^{-5}	2.37×10^{-5}	2.39×10^{-5}	3.04×10^{-5}
Human toxicity [kg 1,4-DB eq]	8.15×10^{-3}	2.43×10^{-2}	2.47×10^{-2}	3.80×10^{-2}	5.79×10^{-2}	5.82×10^{-2}	7.16×10^{-2}
Ionising radiation [kg U235 eq]	6.08×10^{-1}	2.23×10^{0}	2.20×10^{0}	3.33×10^{0}	5.23×10^{0}	5.20×10^{0}	6.33×10^{0}
Marine ecotoxicity [kg 1,4-DB eq]	4.24×10^{-4}	1.47×10^{-3}	1.47×10^{-3}	2.50×10^{-3}	4.18×10^{-3}	4.19×10^{-3}	5.21×10^{-3}
Marine eutrophication [kg N eq]	6.64×10^{-6}	5.73×10^{-5}	5.91×10^{-5}	4.85×10^{-5}	9.49×10^{-5}	9.67×10^{-5}	8.62×10^{-5}
Metal depletion [kg Fe eq]	4.17×10^{-4}	2.23×10^{-3}	2.42×10^{-3}	4.83×10^{-3}	2.25×10^{-2}	2.27×10^{-2}	2.51×10^{-2}
Ozone depletion [kg CFC-11 eq]	1.63×10^{-8}	5.56×10^{-9}	5.49×10^{-9}	7.45×10^{-9}	3.16×10^{-8}	3.16×10^{-8}	3.35×10^{-8}
Particulate matter formation [kg PM10 eq]	7.95×10^{-5}	2.47×10^{-4}	2.47×10^{-4}	1.93×10^{-4}	4.66×10^{-4}	4.66×10^{-4}	4.12×10^{-4}
Photochemical oxidant formation [kg NMVOC]	1.94×10^{-4}	4.53×10^{-4}	4.46×10^{-4}	3.08×10^{-4}	7.03×10^{-4}	6.97×10^{-4}	5.59×10^{-4}
Terrestrial acidification [kg SO_2 eq]	1.77×10^{-4}	7.63×10^{-4}	7.63×10^{-4}	5.60×10^{-4}	1.10×10^{-3}	1.10×10^{-3}	8.95×10^{-4}
Terrestrial ecotoxicity [kg 1,4-DB eq]	1.41×10^{-5}	1.26×10^{-5}	1.27×10^{-5}	2.87×10^{-5}	2.20×10^{-5}	2.20×10^{-5}	3.80×10^{-5}
Water depletion [m^3]	1.50×10^{-2}	1.16×10^{0}	7.95×10^{-1}	3.52×10^{-1}	1.43×10^{0}	1.06×10^{0}	6.21×10^{-1}

* Infrastructure for microalgae is scaled on the basis of a 20 year lifetime with a yearly production of 15.27 tonnes/hectare/year. A similar table based on percentages is provided in Table 12-1.

Global Temperature Potential (GTP) was also considered in this study. Unlike GWP, this metric accounts for the impact of the temperature of the planet normalised against CO2 (Cherubini *et al.*, 2016) rather than changes in levels of radiative forcing. For Scenario C's operational emission, the GTP varied from

7.02×10-2 (GTP 100-year) to 7.32×10-2 (GTP 50 year) and 8.91×10-2 (GTP 20 year), implying 26.9% reduction from GTP-100 to 20. Less detailed figures for the operational impacts, including GWP10, GWP50 and GTP 10 are presented in Figure 5, this uses the data for CH4 and N2O from Figure 8.SM.16 within the supplementary material of AR5 (Myhre *et al.*, 2013b), but does not include the GWP or GTP data of other minor contributing GHGs emitted.

The above shows that in order to interpret results correctly, it is important for there to be a dialogue between LCA practitioners and climate science. When simplifying the complexity of climate change for policymakers, it is understandable that GWP100 is used; however, the reality is more complex, hence for decisions around strategic investment into new technologies, a range of methods should be considered. In addition, there are further areas to consider, such as the interaction of chemicals (for example methane and aerosols)(Drew T. Shindell *et al.*, 2009) and the cumulative impacts of GHGs on the climatic system (Cherubini *et al.*, 2016) which are not counted within LCA. Data for all GHGs considered are provided in Table 7-2, to allow the reader to employ their own Climate Change CFs and also to find the other aspects of GHG emissions.

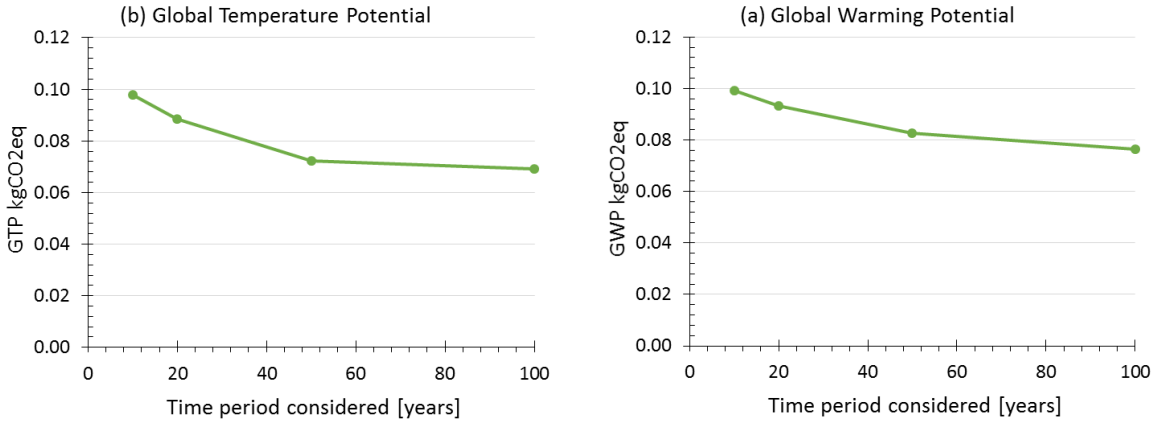

Figure 7-1 GWP (a) and GTP (b) of Scenario C. This uses data from Figure 8.SM.16 within the AR5 supplementary data (Myhre et al., 2013b). The plots only use data for CO2, CH4 and N2O. Comparing with the full LCA models, these GHG contributed to 99.46% (GWP20) and 99.32% (GWP100) of the GWP of Scenario C. Pulse assumed at year 0.

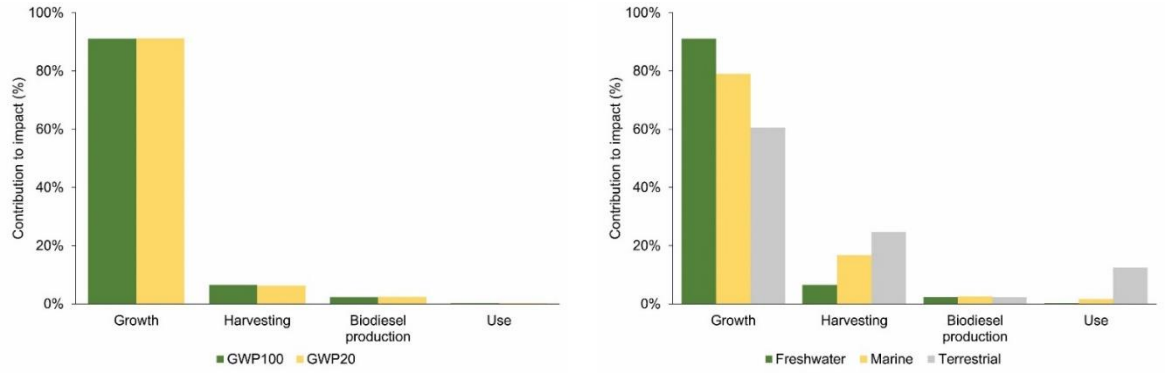

Figure 7-2 Comparison of impacts in the four main phases of microalgae biofuel production and use. Left GWP100 and GWP20, right, ecotoxicity.

Table 7-2: Breakdown of operational GHG emissions in kg to allow the reader to use their own climate change conversion factors.

	Volume [kg]			
	Petroleum-derived diesel fuel	Petroleum-derived diesel fuel		
		(A) 2012	(B) 2020	(A) 2012
Carbon dioxide	8.64×10^{-2}	1.68×10^{-1}	1.51×10^{-1}	6.60×10^{-2}
Carbon dioxide (aviation)	0	1.50×10^{-6}	2.20×10^{-6}	2.99×10^{-8}
Nitrogentriflouride	8.26×10^{-19}	2.83×10^{-12}	4.79×10^{-12}	5.66×10^{-14}
Nitrous oxide (laughing gas)	1.41×10^{-6}	1.02×10^{-5}	1.02×10^{-5}	7.43×10^{-6}
Sulphur hexafluoride	4.47×10^{-10}	1.02×10^{-8}	1.02×10^{-8}	1.16×10^{-8}
1,1,1-Trichloroethane	1.49×10^{-12}	7.50×10^{-12}	7.50×10^{-12}	1.33×10^{-11}
Carbon tetrachloride (tetrachloromethane)	9.36×10^{-12}	2.77×10^{-9}	2.77×10^{-9}	3.26×10^{-9}
Chloromethane (methyl chloride)	3.93×10^{-11}	1.99×10^{-10}	1.99×10^{-10}	3.51×10^{-10}
Dichloroethane (ethylene dichloride)	1.41×10^{-10}	7.12×10^{-9}	7.12×10^{-9}	7.29×10^{-9}
Dichloromethane (methylene chloride)	2.32×10^{-11}	3.76×10^{-10}	3.76×10^{-10}	5.64×10^{-10}
Halon (1211)	9.03×10^{-12}	1.35×10^{-10}	1.35×10^{-10}	1.58×10^{-10}
Halon (1301)	1.34×10^{-9}	1.29×10^{-10}	1.29×10^{-10}	1.61×10^{-10}
Methyl bromide	4.93×10^{-17}	9.50×10^{-16}	9.50×10^{-16}	1.15×10^{-15}
Perfluoropentane	3.13×10^{-12}	1.38×10^{-11}	1.38×10^{-11}	2.32×10^{-11}
R 11 (trichlorofluoromethane)	4.08×10^{-17}	7.83×10^{-15}	7.92×10^{-15}	3.88×10^{-12}
R 113 (trichlorotrifluoroethane)	6.62×10^{-12}	1.68×10^{-11}	1.68×10^{-11}	2.46×10^{-11}
R 114 (dichlorotetrafluoroethane)	7.93×10^{-11}	3.75×10^{-10}	3.08×10^{-10}	4.33×10^{-10}
R 116 (hexafluoroethane)	3.85×10^{-12}	6.03×10^{-11}	6.90×10^{-11}	5.07×10^{-9}
R 12 (dichlorodifluoromethane)	1.32×10^{-13}	6.45×10^{-11}	6.45×10^{-11}	3.50×10^{-10}
R 124 (chlorotetrafluoroethane)	6.62×10^{-12}	1.68×10^{-11}	1.68×10^{-11}	2.45×10^{-11}
R 125 (pentafluoroethane)	0	2.07×10^{-11}	3.53×10^{-11}	4.26×10^{-13}
R 13 (chlorotrifluoromethane)	0	3.21×10^{-16}	3.31×10^{-16}	6.41×10^{-18}
R 134a (tetrafluoroethane)	1.55×10^{-11}	6.21×10^{-11}	7.10×10^{-11}	1.29×10^{-9}
R 143 (trifluoroethane)	0.00×10^{0}	1.85×10^{-11}	3.14×10^{-11}	3.81×10^{-13}
R 152a (difluoroethane)	1.07×10^{-10}	4.03×10^{-10}	4.03×10^{-10}	1.14×10^{-7}
R 21 (Dichlorofluoromethane)	2.65×10^{-17}	3.37×10^{-15}	3.37×10^{-15}	2.39×10^{-12}
R 22 (chlorodifluoromethane)	1.93×10^{-10}	1.01×10^{-9}	1.01×10^{-9}	1.36×10^{-8}
R 23 (trifluoromethane)	8.47×10^{-15}	1.44×10^{-10}	2.43×10^{-10}	7.65×10^{-10}
R 245fa	0	3.68×10^{-10}	6.26×10^{-10}	7.59×10^{-12}
R32 (difluoromethane)	0	3.10×10^{-12}	5.29×10^{-12}	6.41×10^{-14}
Tetrafluoromethane	5.25×10^{-11}	7.18×10^{-10}	7.90×10^{-10}	1.98×10^{-8}
Trichloromethane (chloroform)	7.94×10^{-12}	7.81×10^{-9}	7.81×10^{-9}	1.13×10^{-8}
Methane	5.37×10^{-5}	4.67×10^{-4}	4.23×10^{-4}	2.97×10^{-4}
Methane (biotic)	2.82×10^{-7}	1.48×10^{-5}	2.00×10^{-5}	4.04×10^{-6}

All microalgae scenarios are the areas show greater impacts compared with petroleum-derived diesel.

For example, even without infrastructure, water depletion [m3] for PV-powered microalgae biodiesel were 2347% greater than for fossil-derived diesel. Using PV reduced 12 mid-point impact categories, whilst others such as ecotoxicity, toxicity, eutrophication, metal depletion and ozone depletion were increased. It is noted that Scenario C doubles ozone depletion from the operation. Within the Ecoinvent data used, the ozone depletion impact from PV was found to be from tetrafluoroethylene use in cell manufacturing. However, the PV models within the GaBi Professional database, show no tetrafluoroethylene use. As this is a major impact on the models, further investigation is necessary and further evidence from real industrial data required.

One important question to address is; is the Ecoinvent model an appropriate comparator? In terms of the general models, the GaBi models are constructed from the same Ecoinvent database, as the petroleum diesel model. It is true that all the electricity use within the petroleum diesel models are standard grid mixes, and hence it could be argued that if we want to consider PV in microalgae, we should also consider PV for the electricity demands of producing petroleum diesel, however, that is currently not something which is happening to the entire global fossil fuel industry, whereas microalgae production facilities, such as Necton, really are constructing solar farms. A review of the system boundaries showed them to be the same for both the microalgae models and the diesel models in most aspects, however, within the petroleum diesel models the transport of intermediate petrochemical products globally to refineries is included, whereas within the microalgae models the presumption was that it would be one large biorefinery, however, this seems fair as it is the intention of the microalgae industry to build full biorefineries.

In terms of the significance of the climate change and water values, even with PV there is 67% higher value for microalgae derived diesel compared with fossil derived diesel (for models including infrastructure). In terms of water, this value is 4040%. These values are outside of what could reasonably be attributed to errors within the models.

*The microalgae production process was divided into four sections, (a) cultivation, (b) harvesting, (c) processing and (d) use. The cultivation phase created a significantly greater climate change contribution and Ecotoxicity impact, as shown in Figure **7-2**. A larger set of impacts are detailed in*

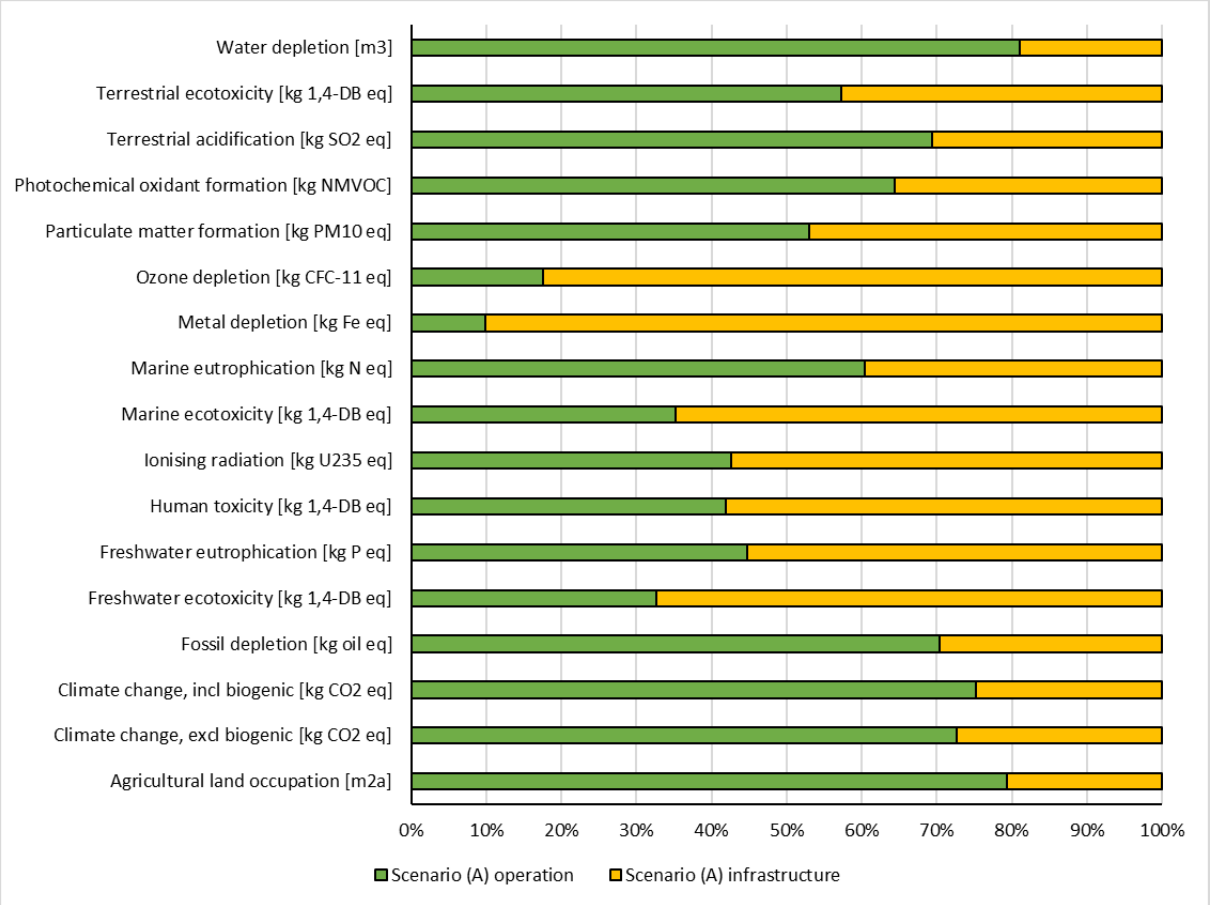

Figure 12-3: Mixture of operational and infrastructure ReCiPe 1.08 Hierarchist Mid Point impacts for Scenario A.

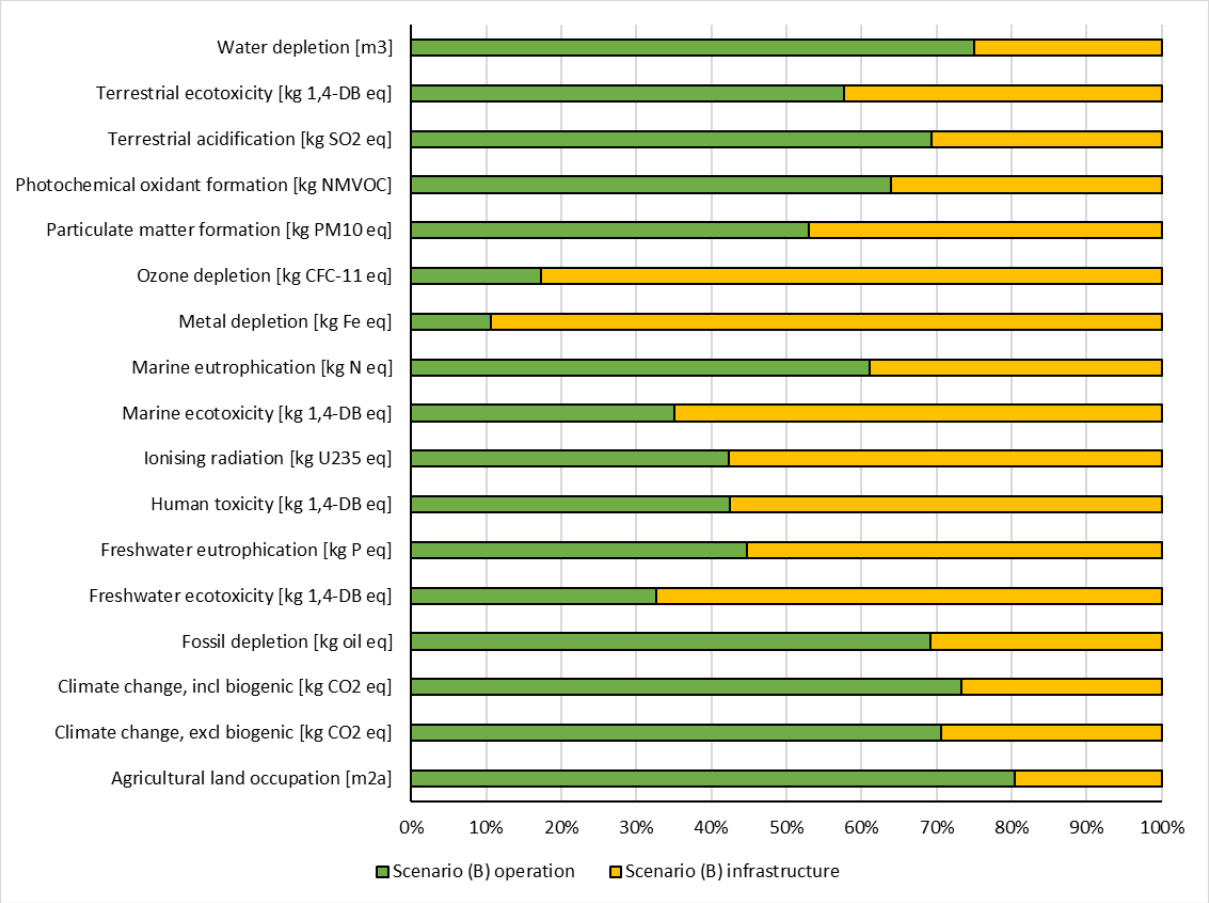

Figure 12-4: Mixture of operational and infrastructure ReCiPe 1.08 Hierarchist Mid Point impacts for Scenario B.

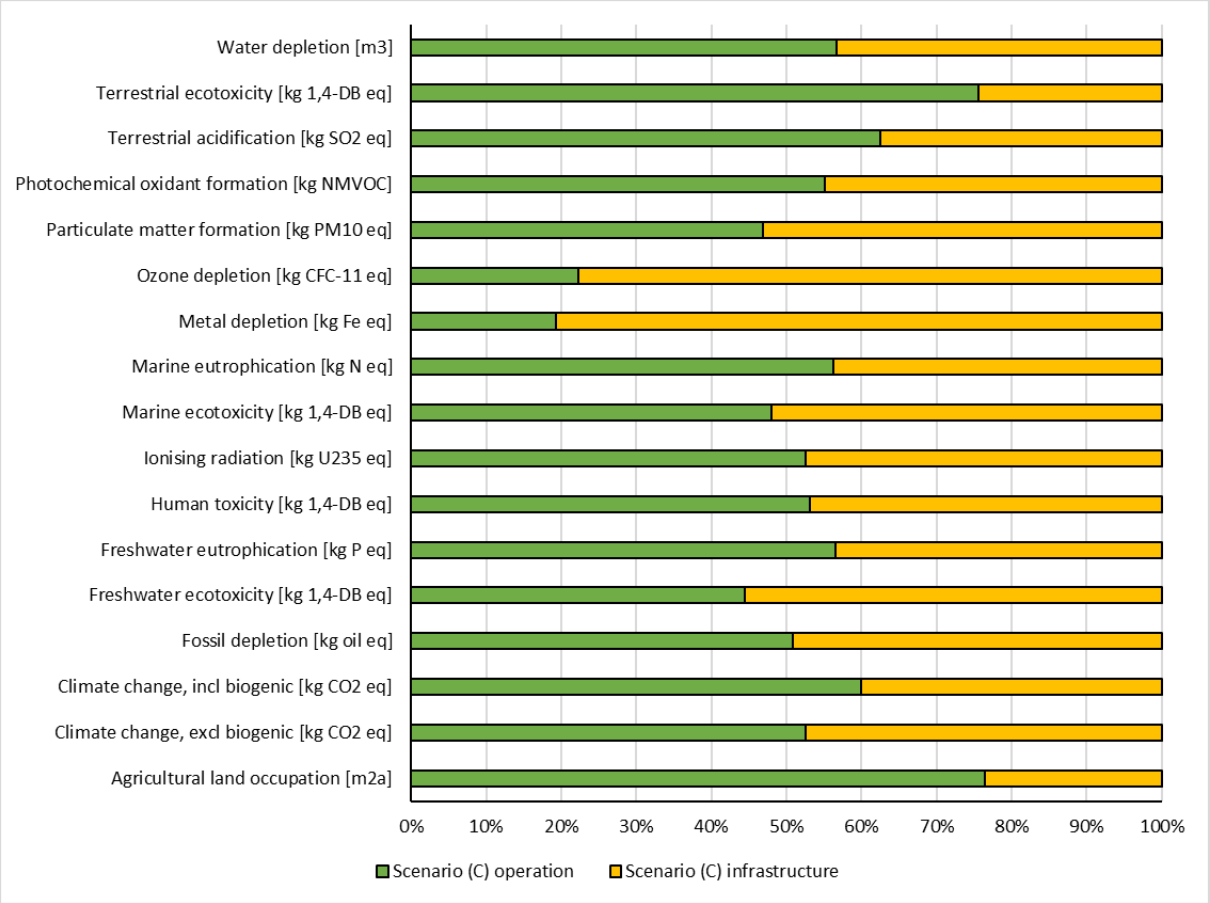

Figure 12-5 and Table 12-2.

For Scenarios A and B, electricity was the major source of operational impacts. If PV derived electricity is used (Scenario C), this reduces this source to the second-largest (or joint first source of impacts), with the major or joint source the production of yeast extract for the fermenters (except in the case of terrestrial ecotoxicity and metal depletion where electricity is still the most significant impact). After these two impact sources, other contributors to impacts were freshwater and potassium pyrophosphate. With regard to AR5 GWP100 impacts, yeast was responsible for 68.2%, PV electricity 15.7%, potassium pyrophosphate 8.9% and freshwater 2.7%.

In all the impacts considered, these were the most relevant inputs, with methanol, phosphoric acid, sodium hypochlorite, and hydrochloric acid are each minor contributors to most impacts. Natural gas and organic solvents used in the transesterification process yielded minor contributions to ozone depletion (full data in Table 12-14 to Table 12-16 for Scenario C). From this, it shows that engineers need to optimise the production systems as well as have a greater understanding of the impacts of feedstocks (particularly yeast extract if used). For example, could a microalgae biofuel facility use more sustainable yeast extract (potentially co-located on-site) and produced using electricity from renewable

energy? In this case, a further reduction of operational GWP100 in the region of 32% could be achieved. It is by taking a critical eye, and perhaps direct involvement, in production of the chemical feedstocks for microalgae biofuels that the industry can reduce impacts. For small systems this is impractical, but for the 10 - 100 hectares bio-refineries considered by industry in the near future, this could well be a viable option. Of course, yeast itself can produce a wide range of lipids (Parsons *et al.*, 2018), so one could question the very logic of using yeast as a feedstock instead of using the yeast directly. This question requires a comparative analysis of fuel from microalgae with fuel from yeast, and further work to answer that question.

It is important to note that this LCA is based on the assumption that the glycerol fed to the fermenters (in addition to the internally recycled glycerol) is industrial waste. Using fresh glycerol will give very different results, which would not be favourable for microalgae biofuels, suggesting that microalgae derived diesel is even less advisable as a replacement for fossil derived diesel.

7.1.3 *Sensitivity and Uncertainty*

A sensitivity analysis was undertaken for the operational model, varying input variables within the cultivation, harvesting and processing phases by 5%, of which the results model are given for all three Scenarios within Table 12-3 to and Table 12-8. This shows a similar pattern to the results previously given, with the system most sensitive to electricity and yeast extract.

For Scenario A, a change of 5% in the electricity use would result in a change of 3.2% of the GWP100. A change of 5% of the yeast input would result in a 1.45% change in AR5 GWP100. Within scenario C, the yeast input becomes the dominant factor, taking the example of AR5 GWP100 again, yeast will vary the final result by 3.42% if it is varied by 5%, whereas electricity will only cause a 0.77% change in the final result.

7.1.4 *Implications of the system modelling*

Clearly, both the operational and Infrastructure impacts must be combined when comparing with fossil fuels. In terms of InteSusAl, the Infrastructure impacts will be larger than an established biorefinery which is optimally set out. To merge the operational and infrastructure models of the InteSusAl system, the impacts of the Infrastructure were equally distributed, assuming 38 MJ energy content for microalgae biodiesel, 15.27 tonnes/hectare/year production of microalgae and 20 years lifetime. This showed, for all scenarios, that microalgae biofuels do not compare well with fossil fuels in such a production quantity. If a productivity of >25.6 tonnes/hectare/year were achieved, which is a reasonable level, then a PV powered system (Scenario C) would be on a par with fossil fuels in terms of climate change (GWP100), productivity of 31.4 tonnes/hectare/year would lead to equivalence in

terms of ozone depletion, but 313.2 tonnes/hectare/year would be needed for equivalence with petroleum diesel in terms of eutrophication. This shows that the InteSusAl system is within reach of petroleum diesel in some areas of sustainability, such as Ozone depletion, Terrestrial ecotoxicity, and climate change/ But not the majority of others especially impacts such as freshwater ecotoxicity, freshwater eutrophication, various types of depletion and land use.

In order to improve the productivity, there are a number of strategies that could be followed. First, improvements in bioreactor design could lead to higher productivities, through ensuring that the microalgae is under optimal conditions. Improvements in strains can improve productivities, this can be through natural mutagenesis, or through the production of better adapted strains through CRISPR, as is currently under research at Wageningen UR. {Naduthodi, 2021 #135}

In terms of comparators, this thesis has concentrated on liquid transport fuels. However, it is important to remember there are a wide range of products which can be produced from microalgae. These include fucoxanthin [1], polyphenols [2], DHA-EPA rich oils [3], β-carotene [4], astaxanthin [5], docosahexaenoic acid [6] and many others. One important piece of work to undertake post thesis is to understand how microalgae derived bioproducts compare with these.

7.1.5 *Land Use*

The initial calculation as detailed within Section 7.3., shows that in terms of direct land-use change (dLUC) per MJ, the InteSusAl process, throughout it's lifetime, would release 2.362×10^{-2} kg CO_{2eq}/MJ, or if at the productivity level of 100 tonnes/hectare dry mass, a capability proven within the project, then 2.119×10^{-3} kg CO_{2eq} /MJ. This compares with palm oil, which would emit 4.917×10^{-1} kg CO_{2eq}/MJ. This shows that microalgae biofuels would have a dLUC impact of between 0.4 and 4.8% that of palm oil-based biofuels.

Comparing this with the impacts of Ecoinvent models for Palm Oil shows that these dLUC change impacts outweigh the other LCA impacts calculated for palm oil, but in terms of InteSusAl are far less than the production impacts when including infrastructure. This showed microalgae-derived biodiesel to have an impact approximately three times that of palm oil.

Table 7-3: Comparison of dLUC data and LCA data, showing that when dLUC is taken into account, algal biofuels

have a lower climate change impact than palm oil

Model	IPCC AR5 GWP100 (excl. biogenic) [$kgCO_{2eq}$]	
	Biodiesel (palm, MY)	InteSusAl (Scenario C, InteSusAl pilot productivity)
LCA	1.580×10^{-2}	1.48×10^{1}
IPCC 2006 Tier 1 dLUC	4.917×10^{-1}	2.362×10^{-2}
Combined	5.075×10^{-1}	1.012×10^{-1}

It should be stressed that caution should be applied to this data, as the IPCC Tier 1 methodology is relatively simple. If the InteSusAl data could be used in more advanced land-use change models (direct and indirect), this would give more exact figures. An additional element to highlight is that the dLUC calculations have not taken account of coproducts.

This section has clearly shown even when land use is considered, there is now major advantage for microalgae-derived biofuels. It must be remembered that microalgae biofuels do not require fertile or even usable land, whereas other crops will always necessitate usable land to grow crops in. Furthermore, only an analysis with Palm Oil was conducted, and it must be remembered that different biofuels have different levels of land-use change, dependent on the original land, geography and the biofuel crop. Finally, this has not included iLUC, which is a subject that would involve study outside the scope of this sustainability analysis. Hopefully, the results of this project, within subsequent peer-reviewed papers, will allow for dedicated dLUC/iLUC researchers to compare microalgae with various biofuels.

7.2 Alternative material choices for facility build

In terms of the construction, the photobioreactors represent a major part of the construction. Therefore, this section will consider options for reducing the impacts of this element of a commercial system. A model has been constructed within OpenLCA of the Necton PBR system, which includes 4no 15,000 L systems, with large collection tanks constructed from FRP (Fiber Reinforced Plastic).

The outputs for the impacts were given as in Table 7-4,

Table 7-4: Impacts of Necton PBR system construction (including recycling and end of life)

ReCiPe 2016 Impacts		Impact result
Name	**Unit**	**Baseline**
climate change	kg CO2-Eq	5.21×10^{5}
agricultural land occupation	m2a	1.51×10^{2}
urban land occupation	m2a	3.80×10^{3}
natural land transformation	m2	-6.22×10^{0}
marine eutrophication	kg N-Eq	5.97×10^{2}
photochemical oxidant formation	kg NMVOC	1.93×10^{3}
freshwater ecotoxicity	kg 1,4-DCB-Eq	1.04×10^{4}
freshwater eutrophication	kg P-Eq	8.05×10^{1}
marine ecotoxicity	kg 1,4-DCB-Eq	9.78×10^{3}
water depletion	m3	7.16×10^{2}
fossil depletion	kg oil-Eq	1.74×10^{5}
terrestrial acidification	kg SO2-Eq	2.08×10^{3}
human toxicity	kg 1,4-DCB-Eq	1.39×10^{5}
ionising radiation	kg U235-Eq	1.84×10^{4}
terrestrial ecotoxicity	kg 1,4-DCB-Eq	3.47×10^{1}
metal depletion	kg Fe-Eq	1.60×10^{5}
ozone depletion	kg CFC-11-Eq	1.53×10^{-2}
particulate matter formation	kg PM10-Eq	1.11×10^{3}

In terms of the major sources of the impacts within the construction, these are the same for most impact categories. For climate change (GWP100) these are given as;

- 36% PMMA
- 17% Concrete
- 14% Steel
- 10% FRP
- 9% polyethylene pipe

The PMMA is purely from the clear tubes within the PBRs. PMMA is used because it is an easy to work with material, strong and cheap. However, PBRs can instead use a variety of materials, including glass. Whilst more expensive, the advantage of glass is that it does not degrade due to UV, giving it a longer lifespan. The concrete within the facility and steel are hard to remove, as they are needed for the ancillaries of the facility, and the hardstanding the facility is built upon. There are some alternatives for concrete, such as load bearing hempcrete from IsoHemp, however these were not available when the original InteSusAl system was constructed. This had not been investigated in detail within this thesis, as microalgae production systems could be built on former industrial areas with existing suitable hardstandings, and the purpose of this thesis is to show improvements relevant to new microalgae systems.

. However, the FRP can be replaced with steel. Two additional models have been created, one with the PMMA replaced with glass, and one with the FRP tanks additionally replaced with steel tanks. These are given in Table 12-18 and additionally given as percentages within Table 12-19.

The negative impact of the natural land transformation is a concern, which when looking in detail at the contribution trees within OpenLCA shows that it comes from the credit for recycling concrete at the end of the project. It is believed this value is due to an error within the software, as it is too high a credit.

In terms of the major contributors, for the glass model, the major sources of impacts for climate change were;

- 27.49% Glass
- 24.82% Steel
- 18.16% FRP
- 15.36% Polyethylene pipe
- 7.15% Polyvinylchloride

When the FRP is replaced with steel, the five major sources of impacts are;

- 34.17% Glass
- 30.86% Steel
- 19.10% Polyethylene pipe
- 8.90% Polyvinylchloride
- 4.69% Recycled plastic

It is clear that to reduce the environmental impacts of the construction of the facility, to reduce climate change impacts by 43%, glass should be used instead of PMMA, and the substitution of steel for FRP reduces impacts even further.

7.3 InteSusAl and Palm Oil Calculations

This section provides results from using the *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use Tier 1* methodology to investigate two options:

1) Palm Oil grown in deforested Indonesian rainforest land, which was burnt to remove the original forest

2) InteSusAl Project, based on the original mixture of grazing land and abandoned buildings in Olhão

To compare the dLUC impacts, the amount of energy produced per hectare for different fuels must be factored in. For palm oil, this thesis uses the productivity figure from page 63 of(Valin *et al.*, 2015), 88GJ/hectare, which equates to 1.136×10^{-5} hectare/MJ. For InteSusAl, there are two scenarios, one taking assumptions from the actual productivity figures[f], and the other from the predicted possible outputs[g]. This gives 1.381×10^{-5} hectare/MJ and 1.238×10^{-6} hectare/MJ, respectively. The InteSusAl land was approximately one third settlement land prior to conversion, so a factor of 0.66 is applied to the land/MJ values, giving 9.205×10^{-6} hectare/MJ and 8.255×10^{-7} hectare/MJ respectively. As the calculation is over 20 years, then the above figures are divided by 20 to give the land and impacts for 1MJ of energy. This gives:

Palm oil: 5.68182×10^{-7} ha/MJ

InteSusAl (actual project performance): 4.602×10^{-7} ha/MJ

InteSusAl (possible 100 tonnes/microalgae dry weight/year): 4.128×10^{-8} ha/MJ

Two sets of factors are used for this calculation. For the palm oil, consider *"Forest Land"* converted to *"Crop Land".* For the InteSusAl project, consider *"Grassland"* converted to *"Settlement Land"*.

7.3.1 *Palm oil calculation (per MJ)*

Annual change in carbon stocks in biomass

- Annual area of Land Converted to Cropland (ΔA_{TO_OTHER}) = 1.136×10^{-5} hectare
- Biomass stocks before the conversion (B_{BEFORE}) = 350 tonnes dm ha^{-1} *(Table 4.7 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Tropical rain forest, Asia (insular))*
- Carbon fraction of dry matter (CF) = 0.5 tonnes C (tonne dm)$^{-1}$ *(default)*
- Annual biomass carbon growth (ΔC_G) = 10 tonnes C yr^{-1} *(Table 5.9 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Tropical wet)*

[f] Productivity of 6.846 tonnes/hectare/year, lipid content of 21% (Nannochloropsis salina) and 40% (chlorella protothecoides), transesterification factor of 1.012, energy content of 38 MJ/kg

[g] Productivity of 100 tonnes/hectare/year, lipid content of 21% (worst case, as do not know ration of PBRs to fermenters), transesterification factor of 1.012, energy content of 38 MJ/kg

- Annual loss of biomass carbon (ΔC_L) = 50 tonnes C yr^{-1} *(Table 5.1 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Tropical wet)*

This gave a change in biomass from the forest clearing of:

$\Delta C_B = \Delta C_G + ((0 - B_{BEFORE}) * \Delta A_{TO\_OTHER}) * CF - \Delta C_L =$ **-1.22×10^{-4} tonnes C yr^{-1}**

Annual change in carbon stocks in dead organic matter due to land conversion

Not considered in Tier 1 calculations (but is considered in Tier 2 and Tier 3)

Annual change in carbon stocks in mineral soils (part 1)

- Reference carbon stock for the climate/soil combination (SOC_{ref}) = 66 tonnes C ha^{-1} *(Table 2.3 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Sandy soils, Tropical, wet)*
- Time dependence of stock change factors (D) or number of years over a single inventory time period (T) was set at: D = 20 years *(default)*
- Stock change factor for land-use system in the last year of an inventory time period set to tree crop value ($F_{LU(0)}$) = 1.00 *(Table 5.5 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Perennial/Tree Crop)*
- Stock change factor for land-use system due to management ($F_{MG(0)}$) = 1.00 *(Table 5.5 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Full)*
- Stock change factor for carbon input in the last year of the inventory period ($F_{I(0)}$) = 0.92 *(Table 5.5 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Low level, tropical, Moist/Wet)*
- Stock change factor for land-use system at the beginning of the inventory time period ($F_{LU(0-T)}$) = 1.00 *(Table 5.5 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Perennial/Tree Crop)*
- Stock change factor for land-use system due to management ($F_{MG(0)}$) = 1.22 *(Table 5.5 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), No-till, Tropical, Moist/Wet)*
- Stock change factor for carbon input at the beginning of the inventory time period: ($F_{I(0-T)}$) = 1

This gave an annual change in carbon stocks in mineral soils: $\Delta C_{Mineral}$ =

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D} = \textbf{-5.625×10}^{\textbf{-7}}\ \textbf{tonnes C yr}^{\textbf{-1}}$$

Where $SOC = \sum_{c,s,i}(SOC_{REF_{c,s,i}} F_{LU_{c,s,i}} F_{MG_{c,s,i}} F_{I_{c,s,i}} A_{c,s,i})$

Annual change in carbon stocks in mineral soils (part 2)

- Emission factor for climate type (EF) = 20 tonnes C ha^{-1} yr^{-1} (*(Table 5.6 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Tropical/Sub-Tropical)*

This gave an annual carbon loss from cultivated organic soils of:

$L_{organic} = A \times EF =$ **-2.273×10^{-4} tonnes C yr^{-1}**

Annual change in carbon stocks due to biomass burning

- Mass of fuel available for combustion (M_B)= 2.1 tonnes C ha^{-1} *(Table 2.2 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), tropical, broadleaf deciduous, litter carbon stocks)*
- Combustion factor for (C_f)= 0.50 *(Table 2.6 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), primary tropical moist forest)*
- CO_2 emission factor, g kg^{-1} dry matter burnt ($G_{EF\ CO2}$)= 1580 *(Table 2.5 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Tropical forest)*
- CH_4 emission factor, g kg^{-1} dry matter burnt ($G_{EF\ CH4}$) = 6.8 *(Table 2.5 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Tropical forest)*
- N_2O emission factor, g kg^{-1} dry matter burnt ($G_{EF\ N2O}$) = 0.2 *(Table 2.5 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Tropical forest)*
- Global warming potential of CH4: $GWP100_{CH4}$ = 28 CO_{2eq}
- Global warming potential of N2O: $GWP100_{N2O}$ = 298 CO_{2eq}

This gives the mass of greenhouse gas emissions from fire:

- $L_{fire\ CO_2} = AM_B C_f G_{ef\ CO_2} 10^{-3} =$ 9.426×10^{-6} kg
- $L_{fire\ CH_4} = AM_B C_f G_{ef\ CH_4} 10^{-3} =$ 1.014×10^{-6} kg
- $L_{fire\ N_2O} = AM_B C_f G_{ef\ N_2O} 10^{-3} =$ 3.556×10^{-7} kg

Therefore, the Greenhouse gas emissions are:

$GHG_{fire} = L_{fire\ CO_2} + \left(L_{fire\ CH_4} GWP100_{CH_4}\right) + \left(L_{fire\ N_2O} GWP100_{N_2O}\right) =$

1.080×10^{-5} kg $CO_{2eqGWP100}$

Greenhouse Gas Impact

Total greenhouse gas impact of land conversion =

$\left(\Delta C_B + \Delta C_{Mineral} + L_{organic}\right)\frac{44}{12} + GHG_{fire} =$ **4.479E×10^{-4} tonnes CO_{2eq}**

7.3.2 *InteSusAl Calculation (6.8 tonnes/ha/year dry mass) (per MJ)*

- Annual area of Land Converted to Cropland (ΔA_{TO_OTHER}) = 9.205×10^{-6} hectare
- Biomass stocks before the conversion (B_{BEFORE}) = 6.1 tonnes dm ha^{-1} *(Table 6.4 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Warm Temperate – Dry)*
- Carbon fraction of dry matter (CF) = 0.5 tonnes C (tonne dm)$^{-1}$ *(default)*
- Annual biomass carbon growth (ΔC_G) = 0 tonnes C yr^{-1} *(Settlement so all activity ceases)*
- Annual loss of biomass carbon (ΔC_L) = 0 tonnes C yr^{-1} *(Settlement so all activity ceases)*

This gave a change in biomass from the removal of grassland:

$\Delta C_B = \Delta C_G + ((0 - B_{BEFORE}) * \Delta A_{TO\_OTHER}) * CF - \Delta C_L =$ **-4.40×10^{-6} tonnes C yr^{-1}**

Annual change in carbon stocks in dead organic matter due to land conversion

Not considered in Tier 1 calculations (but is considered in Tier 2 and Tier 3)

Annual change in carbon stocks in mineral soils

- Reference carbon stock for the climate/soil combination (SOC_{ref}) = 19 tonnes C ha^{-1} *(Table 2.3 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Sandy soils, warm temperate, dry)*
- Time dependence of stock change factors (D) or number of years over a single inventory time period (T) was set at: D = 20 years *(default)*
- Stock change factor for land-use system in the last year of an inventory time period set to tree crop value ($F_{LU(0)}$) = 0 *(Settlement)*
- Tillage value for InteSusAl ($F_{MG(0)}$)= 0 *(Settlement so no till)*
- Stock change factor for land-use system in the last year of an inventory time period set to tree crop value ($F_{LU(0)}$) = 1.00 *(Settlement)*
- Stock change factor for land-use system at the beginning of the inventory time period ($F_{LU(0\text{-}T)}$) = 1.00 *(Table 6.2 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), All)*
- Stock change factor for land-use system at the beginning of the inventory time period ($F_{LU(0\text{-}T)}$) = 1.00 *(Table 6.2 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Nominally managed)*
- Stock change factor for carbon input at the beginning of the inventory time period: ($F_{I(0\text{-}T)}$)= 1.00 *(Table 6.2 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Medium)*

This gave an annual change in carbon stocks in mineral soils: $\Delta C_{Mineral}$ =

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D} =$$ **-4.372×10^{-7} tonnes C yr^{-1}**

Where $SOC = \sum_{c,s,i}(SOC_{REF_{c,s,i}} F_{LU_{c,s,i}} F_{MG_{c,s,i}} F_{I_{c,s,i}} A_{c,s,i})$

Annual change in carbon stocks in mineral soils (part 2)

- Emission factor for climate type (EF) = 10 tonnes C ha^{-1} yr^{-1} (*(Table 5.6 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Warm Temperate)*

This gave an annual carbon loss from cultivated organic soils of:

$L_{organic} = A \times EF =$ **4.602×10^{-6} tonnes C yr^{-1}**

Annual change in carbon stocks due to biomass burning

- No biomass burning occurred during land conversion

Greenhouse Gas Impact

Total greenhouse gas impact of land conversion =

$$\left(\Delta C_B + \Delta C_{Mineral} + L_{organic}\right)\frac{44}{12} + GHG_{fire} = \underline{\textbf{5.147E×10}^{\textbf{-6}}\textbf{ tonnes CO}_{\textbf{2eq}}}$$

7.3.3 *InteSusAl Calculation (100 tonnes/ha/year dry mass) (per MJ)*

- Annual area of Land Converted to Cropland (ΔA_{TO_OTHER}) = 8.255×10^{-7} hectare
- Biomass stocks before the conversion (B_{BEFORE}) = 6.1 tonnes dm ha^{-1} *(Table 6.4 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Warm Temperate – Dry)*
- Carbon fraction of dry matter (CF) = 0.5 tonnes C (tonne dm)$^{-1}$ *(default)*
- Annual biomass carbon growth (ΔC_G) = 0 tonnes C yr^{-1} *(Settlement so all activity ceases)*
- Annual loss of biomass carbon (ΔC_L) = 0 tonnes C yr^{-1} *(Settlement so all activity ceases)*

This gave a change in biomass from the removal of grassland:

$\Delta C_B = \Delta C_G + ((0 - B_{BEFORE}) * \Delta A_{TO\_OTHER}) * CF - \Delta C_L =$ -**$\underline{1.26\text{E}\times10^{-7}\text{ tonnes C yr}^{-1}}$**

Annual change in carbon stocks in dead organic matter due to land conversion

Not considered in Tier 1 calculations (but is considered in Tier 2 and Tier 3)

Annual change in carbon stocks in mineral soils

- Reference carbon stock for the climate/soil combination (SOC_{ref}) = 19 tonnes C ha^{-1} *(Table 2.3 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Sandy soils, warm temperate, dry)*
- Time dependence of stock change factors (D) or number of years over a single inventory time period (T) was set at: D = 20 years *(default)*
- Stock change factor for land-use system in the last year of an inventory time period set to tree crop value ($F_{LU(0)}$) = 0 *(Settlement)*
- Tillage value for InteSusAl ($F_{MG(0)}$)= 0 *(Settlement so no till)*
- Stock change factor for land-use system in the last year of an inventory time period set to tree crop value ($F_{LU(0)}$) = 1.00 *(Settlement)*
- Stock change factor for land-use system at the beginning of the inventory time period ($F_{LU(0\text{-}T)}$) = 1.00 *(Table 6.2 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), All)*

- Stock change factor for land-use system at the beginning of the inventory time period ($F_{LU(0-T)}$) = 1.00 *(Table 6.2 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Nominally managed)*
- Stock change factor for carbon input at the beginning of the inventory time period: ($F_{I(0-T)}$)= 1.00 *(Table 6.2 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Medium)*

This gave an annual change in carbon stocks in mineral soils: $\Delta C_{Mineral}$ =

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D} = \underline{\textbf{-3.921×10}^{\textbf{-8}}\ \textbf{tonnes C yr}^{\textbf{-1}}}$$

Where $SOC = \sum_{c,s,i}(SOC_{REF_{c,s,i}} F_{LU_{c,s,i}} F_{MG_{c,s,i}} F_{I_{c,s,i}} A_{c,s,i})$

Annual change in carbon stocks in mineral soils (part 2)

- Emission factor for climate type (EF) = 10 tonnes C ha^{-1} yr^{-1} (*(Table 5.6 of(2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006), Warm Temperate)*

This gave an annual carbon loss from cultivated organic soils of:

$$L_{organic} = A \times EF = \underline{\textbf{4.128×10}^{\textbf{-7}}\ \textbf{tonnes C yr}^{\textbf{-1}}}$$

Annual change in carbon stocks due to biomass burning

- No biomass burning occurred during land conversion

Greenhouse Gas Impact

Total greenhouse gas impact of land conversion =

$$(\Delta C_B + \Delta C_{Mineral} + L_{organic})\frac{44}{12} + GHG_{fire} = \underline{\textbf{2.119E×10}^{\textbf{-6}}\ \textbf{tonnes CO}_{\textbf{2eq}}}$$

7.4 Biomod results

Within Table 7-5 is the results of the BioMODule system, compared with a traditional steel fermenter, as taken from the InteSusAl models. This has been undertaken within OpenLCA. All impact categories show that the impacts of the bag-based system are at least one order of magnitude greater than the steel based fermenter comparison.

Table 7-5: Comparison of a BioMODule system and a steel fermenter, purely for the production of 1kg of chlorella

Impact category	Unit	BioMODule						Steel Fermenter						Percentage Difference
		Result	Pedigree					Result	Pedigree					
			R	C	T	G	F		R	C	T	G	F	
agricultural land occupation - ALOP	m2a	2.32E-04	1	1	3	2	1	9.84E-06	1	1	3	2	1	2360%
climate change - GWP100	kg CO2-Eq	4.11E+00	2	2	4	4	2	5.05E-02	3	3	4	4	2	8137%
fossil depletion - FDP	kg oil-Eq	4.41E-01	1	1	5	3	1	1.20E-02	1	1	5	4	1	3680%
freshwater ecotoxicity - FETPinf	kg 1,4-DCB-Eq	2.71E-02	1	1	4	2	1	8.40E-04	1	1	3	1	1	3231%
freshwater eutrophication - FEP	kg P-Eq	1.68E-03	1	1	3	1	1	2.49E-05	1	1	3	1	1	6752%
human toxicity - HTPinf	kg 1,4-DCB-Eq	8.53E-01	1	1	4	2	1	2.13E-02	1	1	4	2	1	4001%
ionising radiation - IRP_HE	kg U235-Eq	5.65E-01	1	1	5	2	1	2.99E-03	1	1	5	2	1	18883%
marine ecotoxicity - METPinf	kg 1,4-DCB-Eq	2.45E-02	1	1	4	2	1	7.91E-04	1	1	3	2	1	3095%
marine eutrophication - MEP	kg N-Eq	1.78E-02	3	3	4	3	2	7.23E-05	3	3	4	3	2	24652%
metal depletion - MDP	kg Fe-Eq	9.93E-02	2	2	5	2	1	1.69E-03	2	2	5	2	1	5859%
natural land transformation - NLTP	m2	4.79E-05	2	1	5	3	2	1.14E-06	1	1	4	3	1	4218%
ozone depletion - ODPinf	kg CFC-11-Eq	1.19E-07	2	3	5	4	2	3.71E-09	3	3	5	4	2	3195%
particulate matter formation - PMFP	kg PM10-Eq	1.59E-02	4	2	4	4	3	3.16E-04	4	2	4	4	3	5018%
photochemical oxidant formation - POFP	kg NMVOC	2.49E-01	3	4	5	4	2	1.55E-04	4	4	5	4	3	160664%
terrestrial acidification - TAP100	kg SO2-Eq	3.96E-02	3	3	4	3	2	3.44E-04	3	2	3	2	2	11497%
terrestrial ecotoxicity - TETPinf	kg 1,4-DCB-Eq	1.93E-04	2	2	4	4	1	1.08E-05	1	2	4	4	1	1794%
urban land occupation - ULOP	m2a	9.07E-03	1	1	5	4	2	3.82E-04	2	1	5	4	1	2373%
water depletion - WDP	m3	7.77E-01	3	2	3	2	1	1.07E-02	3	2	3	2	1	7276%

7.5 MAGNIFICENT Results

Within this section, are presented the MAGNIFICENT system results. As described previously, with this data, which is the most up to date within this thesis, the methodology has been advanced. Hence, the ReCiPe 2016 methodology was used for impact categories, in addition to the AR5 climate change impacts. The modelling has only been taken to the gate, not to the full biofuel route. To understand if food is a possible different route which microalgae production could go down, the models have been compared with soy on a per MJ basis.

The scenarios used were:

- Algae production Facility
    - With Infrastructure
        - Portuguese Grid Electricity
        - 80% PV and 20% grid electricity
    - Without Infrastructure
        - Portuguese Grid Electricity
        - 80% PV and 20% grid electricity
- Soy production
    - With infrastructure
    - Without Infrastructure

In terms of the mix of renewable energy and grid electricity, 80% was considered, based on the times

of operation of equipment, to be the absolute maximum energy which could be used from solar by the facility. Any higher and an energy storage system would be required, which would need to be modelled as part of the LCA, and the study would become a study into energy storage rather than of microalgae production.

Based on the results of the above, detailed within Appendix A, as with the InteSusAl modelling, "easy wins" were considered to reduce the environmental impacts. These were reducing the electricity use and using photobioreactors constructed from glass instead of PMMA (not replacing, as then PMMA photobioreactors would be sent for disposal/recycling before the end of their useful life). Work undertaken by Hugo Pereira at the AlgaFarm facility, for a forthcoming publication, showed that the pumps within the system could be turned off overnight, reducing energy use by 48%, without any impact on the growth of microalgae.

A model was created of glass photobioreactors versus PMMA. The glass data was adapted from publicly available datasheets from Schott, who produce glass photobioreactors. The PMMA photobioreactors had an inner diameter of 55mm with a wall thickness of 4mm and a density of 1.18g cm^{-3}. The hypothetical glass photobioreactor tubes had an inner diameter of 55mm with a wall thickness of 2.2mm and a density of 2.2 g cm^{-3}. This means the mass in kg of glass compared with PMMA is essentially equal.

First, the arithmetic calculations are addressed (Table 12-20 and Table 12-21. In terms of the environmental impacts of microalgae compared with soy on a per MJ basis, algae does not compare well. The areas where the impacts of microalgae were shown to be far lower were; agricultural land occupation, marine eutrophication, natural land transformation, terrestrial ecotoxicity and water depletion. The majority of these would be expected, considering the large amounts of land used for soy. When infrastructure was not considered within the modelling, there were positive outcomes in terms of freshwater ecotoxicity, particulate matter formation and photochemical oxidant formation. However, other impacts, such as climate change, currently shows that due to the extremely high energy use of microalgae production, microalgae do not compare well with soy. However, Land Use Change Impacts are not considered here, which is a major source of impacts for soy.

As with the InteSusAl models, steel, PMMA and electricity use were major sources of environmental impacts. Even when considering PV use, they were still major impacts, due to the admittedly small impact of producing photovoltaics. With the exception of ionising radiation, these three contribute from 34% to 89% of each ReCiPe and AR5 impact. The use of steel is unavoidable for many parts; however, the use of PMMA and electricity can be tackled to reduce the overall environmental impacts. Turning off the pumps at night or using glass instead of PMMA for photobioreactors both showed clear

reductions in the impacts. It is clear from this that these relatively easy changes in design and operation can reduce the environmental impacts. However, from the arithmetic calculations, this still shows that an improvement in productivity is necessary in order to bring the impacts of climate change down to those of soy. An improvement in productivity of four times, when combined with these measures, should leave microalgae as a more environmentally sustainable food source than soy on a per MJ basis.

In order to provide an uncertainty assessment, the pedigree matrix-based Monte Carlo method described within Chapter 4 is used, in order to produce probability distributions, with geometric standard deviations and also to calculate the significance via U-tests. The comparison between soy and microalgae models showed that all the differences were significant, which is unsurprising considering the level of difference between the figures, as can be seen within Table 12-20.

Of concern is the differences between the results from the basic arithmetic calculations, and the results from the more complex statistical analysis (Table 12-27 and Table *12-29*). The differences are such that, with the Monte-Carlo based method PMMA is a better choice in various environmental impacts than glass, the result of the arithmetic calculation. This difference is particularly interesting. Because of this, there are concerns with the way statistics are presented within LCA.

The issue appears to be the way that the same figures within the Ecoinvent database are sometimes treated as arithmetic means, and sometimes treated as gemetric means. The figures within the Ecoinvent database are arithmetic means, however, for the probability distributions created within Ecoinvent based on the pedigree matrix, the arithmetic means are then treated as geometric means.

The geometric mean is in most cases the median figure; hence LCA databases effectively redefine the arithmetic mean as the median, which then means issues occur due to this error. The differences between the arithmetic and MC methods are less pronounced within the soy models, as their pedigree matrices produce very tight probability distributions. However, in terms of the microalgae, due to this study being based on one site, this automatically means that the completeness level is scored low, which has a knock-on effect in terms of the probability distribution. This leads to larger differences between the arithmetic and MC method. The area where this is most pronounced in within the comparison of the PMMA and glass-based photobioreactors, where due to the high levels of uncertainty within the construction pedigree matrices, then PMMA is shown to be more sustainable than glass. This runs counter to the results of any modelling of the two materials separately.

Based on this, there are concerns with the use of MC based models and hope that other LCA practitioners will consider the issues, and preferably consult with a statistician before undertaking this to give an indication of uncertainty. Other uncertainty methods do exist, such as the work by (van der

Spek *et al.*, 2016) on expanding the pedigree matrix methodology whilst keeping it qualitative and not converting qualitative uncertainty into quantitative uncertainty.

Essentially, this difference can, as seen in the modelling within this thesis, make a large difference. Hence in order to deal with this situation, further work will be undertaken post thesis to understand this is more detail, and communicate with Ecoinvent and the makers of OpenLCA, GreenDelta, to find a possible solution.

Within this work, there were some issues with OpenLCA, in terms of the input flow and output flow of a process must not be the same, this is solved through splitting flows into two parts with an intermediate flow between. In terms of the analysis, there are concerns that the metal depletion calculations are inaccurate; this gave results one order of magnitude lower within the Monte Carlo than the arithmetic analysis. For example, under the scenario with 2016-2017 electricity, the arithmetic calculation for microalgae including infrastructure gives an impact of 8.1×10^{-2} as opposed the Monte Carlo model with 7.74×10^{-3} . This is suggestive that there is an error. The majority of impacts for the microalgae system infrastructure come from the "market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | cut-off, U – GLO" flow for the chromium steel. However, comparing the results for this between a Monte Carlo and arithmetic calculation showed similar results for an output of "1kg of steel, chromium steel 18/8". Specifically, arithmetic calculations provided 8.9 kg Fe-Eq whilst the Monte Carlo provided 9.0 Fe-Eq with a geometric standard deviation[h] of 1.02. Essentially, the results for the infrastructure under a Monte Carlo model do not add up from their component parts by approximately one order of magnitude. This suggests an issue with the mathematical processes undertaken by the software within a Monte Carlo analysis, and so it is suggested all values are treated with caution. The way to overcome this issue in terms of this work is to highlight issues when the arithmetic and Monte Carlo analysis differ by a significant amount, and in the longer term, as OpenLCA is open source software, the team behind OpenLCA need to be approached, and the author must work to help them find the source of the issues.

However, outside of this specific issue, through experience, it is important to note that all LCA and LCA databases have various issues, and it is not intended to highlight OpenLCA as a bad example of software, simply that when undertaking an MC analysis then there should also be an analysis calculation in order to compare the geometric and arithmetic methods, to ensure they are within one order of magnitude in order to give confidence that the MC has been undertaken correctly, and so has

[h] Geometric standard deviations are explained in Section 4.2

the following mathematical processes. Additionally, for further certainty, the calculations could be undertaken from the raw data within the Ecoinvent database, using a spreadsheet-based solution as opposed to LCA software, however this is a very time consuming process, and if this level of due diligence is used, then it could be aergued we should not use LCA software at all.

Chapter 8. Discussion

8.1 InteSusAl

The core work of this thesis has revolved around the InteSusAl project, with scenarios based on the 2012 electricity mix (scenario A), the 2020 electricity mix (Scenario B) and a PV powered facility (Scenario C). These scenarios were modelled using the software GaBi. Additional models were created using OpenLCA to investigate alternative material choices, and the IPCC 2006 LUC methodology was used to investigate land use.

As described within the results section, models within GaBi were created for both with and without infrastructure and compared with petroleum-derived diesel. The results of these are detailed in Table 7-1 and Table 12-1.

It is clear from these models that the approach used within InteSusAl does not, at present, compete with fossil fuels in any of the AR5 or ReCiPe midpoint impact factors.

The productivity of InteSusAl is too low, and if this were increased to >25.6 tonnes/hectare/year then this would radically change the impacts. There are a number of ways that this could be addressed. Genetic engineering of algae is a growing area, especially with the introduction of CRISPR technology {Naduthodi, 2018 #136}{Chang, 2020 #137}. Through this, the lipid content can be substantially increased. However, there would be consequences of this in terms of any possible by-products.

Another way that the LCA of the InteSusaL facility could be improved would be through a more intelligent use of the byproducts. Within these models, it was assumed that they would be used for another energy process, and an energy based allocation, following RED, was used. However, if some of the coproducts from the complex carbohydrates and proteins were used, then this could possibly replace current pharmaceutical, nutraceutical and food products which have higher environmental impacts. The work within the MAGNIFICENT models showed that the algae production in Allmicroalgae did not compare well with soy, and hence it is suggestive that using the InteSusAl waste product as a replacement for soy feed would not provide any environmental benefits. One product worthy of further investigation is Beta Glucan, as these reside in the cell wall, not the lipid. Generally these are produced

from oats, yeast or mushrooms. Further work of interest would be to investigate how Beta Glucans could be extracted from the waste material, and how this compares with baselines. One important consideration is, whatever the by-products are used for, there may be regulatory issues if the algae has experienced some form of genetic engineering, although it can be debated if such regulations should apply to CRISPR, in the same way that mutagenesis can be argued.

As initially mentioned within the results section, the major source of impacts for the InteSusAl facility was the yeast feed for the heterotrophic systems, bringing the yeast production to the algae facility would enable cleaner grid electricity to be used for the yeast production, and also reduce transport impacts (although these are not significant anyway). In essence, bringing everything together as a single biorefinery, with feed produced on the same site, is a logical way for the advancement of algae biodiesel.

Outside of the yeast, electricity is a major source of impacts, especially in Scenarios A and B. Even in Scenario C, the impacts of constructing the PV systems have a major impact in all environmental impact categories. Therefore, aside from increasing productivity, reductions must be made in the energy used. Within the growth phase, there are numerous pumps using energy. One obvious way to reduce these impacts is to use variable speed drive pumps. A further method is for photbioreactors to be optimised in a manner that reduces energy consumption, this could come at the cost of productivity, but if the energy and productivity are balanced correctly, then a system which is environmental and econmically more attractive could be created.

We can use the results to investigate the Net Energy Ratio. If the energy content of the coproducts is taken into account, NER will reach to 0.99, i.e. 0.99 MJ of electricity/gas was used for 1 MJ of biodiesel produced, however, if the energy through the whole value chain, including the feedstock chemical production, is considered then the NER is calculated as 1.03. These are not ideal results but should be viewed in comparison with other technologies. Work by (Brandt *et al.*, 2015) show that the NER can vary dramatically per oilfields (in terms of crude oil, not diesel) from 0.5 to 0.01, dependent on location and technology. In terms of actual petroleum diesel, the average NER for US petroleum diesel is 1.20, although with the increasing use of oil shale and tar sands, then this has increased within the US to 1.65 (Shirvani *et al.*, 2011). This shows the InteSusAl system NER is comparable with other poorly performing fossil fuel extraction/production methods.

In terms of infrastructure, the InteSusAl model showed that replacing PMMA with glass photobioreactors will reduce the impacts of the facility. There are further advantages of using glass. For example, PMMA will gradually break down due to UV, losing levels of transmittance and also becoming brittle. Glass will not change its characteristics over the 20 year lifetime of a microalgae

facility, and has an easy and established recycling supply chain.

In short, whilst these results do now show algae biodiesel in a good light, it still shows that there are possible improvements to the technology, which could enable algae biodiesel to be a useful future technology, if the correct improvements are made to the production systems.

8.2 BIOMOD

The impacts of the BIoMODule system were far greater than those of the steel fermenter system. This was because of the very low productivity within the experiments, and not clear evidence that disposable systems are a poor choice. However, data needs to be collected from larger, more commercial facilities. It is important to note that the results from the BioMODule directly contradict the literature from GE.

There is not much we can be written on this, in comparison to the InteSusAl and MAGNIFICENT facilities studied within this thesis, the BioMOD system was a very small prototype, not a pilot or demonstrator. Hence making firm conclusions from this system would not be representative of the technology at an industrial scale.

8.3 MAGNIFICENT

The results from the analysis under the MAGNIFCIENT data utilised more up to date data, databases and greater statistical analysis with OpenLCA.

As with the InteSusAl modelling, it showed that microalgae-derived diesel does not compare well, environmentally, with fossil-derived diesel. In this case the models compared microalgae to soy on a per MJ basis, without the final conversion to fuel. This was because the MAGNIFICENT project was focussed on by-products.

The most interesting aspect from this analysis was that it enabled for a good example for utilising the pedigree matrix data as log-normal distributions, and utilising Monte Carlo analysis to merge the data and use these distributions. It highlighted that, when there is a high level of uncertainty, such as with the particularly wide probability distributions of the algae models, then the results can be different to a basic arithmetic model.

This is something which warrants further investigation, as uncertainty is a growing area with LCA at present, and it is important to highlight where there may be issues from using uncertainty methods. As detailed within the results chapter, this difference may be due to how the arithmetic and geometric mean from Ecoinvent are treated when creating the lognormal distribution, in which the geometric

mean of the lognormal distribution may be simply the arithmetic mean, causing an issue with the final results.

Chapter 9. Conclusion

Overall, this thesis shows the issues that exist around microalgae-derived diesel fuels. Whilst commonly thought of as a possible future solution for liquid transport fuels, the reality is more complex, and mukti0ple improvements need to be undertaken in order to ensure that it truly is a low carbon fuel, and also to ensure that microalgae-derived fuels have lower environmental impacts in general.

There are improvements that could be undertaken, including reducing the energy use, utilising renewable energy, and increasing the productivity of microalgae production.

Whilst this thesis does not present a positive image of microalgae as a source of liquid biofuels, it does show a realistic view, and advise on possible methods for improvements.

The following presents a more in depth view from the results of each major datasource used within this thesis.

9.1 InteSusAl

The results of this LCA show the impacts of a functioning microalgae production facility, using a mixture of heterotrophic and autotrophic growth systems.

In terms of the energy put into the system, a NER of ~1 is found. This shows the facility NER was similar to that of the Sapphire HTL facility investigated by (Liu *et al.*, 2013). This, as mentioned before, compares with poorly performing oil fields. Hence, as these results are for a small pilot site, they are encouraging.

If comparing with biofuels, palm oil, well regarded as a very damaging source of environmental impacts, has a climate change impact one third of the InteSusAl facility even if including land use change.

The assessment shows that when infrastructure is included, microalgae-derived diesel, compared with petroleum-derived diesel, have higher GWP based climate change impacts over 100-years, but this becomes worse over shorter timescales. For AR5 based GWP over 100 years, the scenarios range from 0.256 $kgCO_2eq/MJ$ (Scenario A, 2012), 0.238 $kgCO_2eq/MJ$ (Scenario B, 2020), and 0.148 $kgCO_2eq/MJ$ (Scenario C, PV). This compares with petroleum-derived diesel, with an impact of 0.0884 $kgCO_2eq/MJ$. Additionally, when considering infrastructure, for all other environmental impacts, further

improvements are necessary. For example, for Scenario B, the impacts of freshwater ecotoxicity for microalgae-derived biodiesel were 1320% times that of petroleum-derived diesel. For freshwater eutrophication, the value was 1612%. Both of these are primarily due to the yeast used within the system. This is highly concerning. If these issues are shown to be common within other microalgae facilities with feedstocks such as yeast, then a serious rethink must be made on microalgae-derived fuels, and perhaps efforts should be focussed on high-value products and feed, should their LCAs provide better results.

The major sources of these impacts have been identified, and the recommendation of co-location of feedstock production could lead to a significant reduction in environmental impacts. Additionally, this example was a demonstration site, and at true industrial scales, it is reasonable to assume that infrastructure would become a far smaller part of the impacts. A larger facility should use glass photobioreactors, instead of PMMA, to improve the levels of sustainability. It is hoped these recommendations will be considered by microalgae biodiesel researchers and industry, in order to improve the environmental impacts of the microalgae supply chain, be it used for fuel or high-value products.

In hindsight, the fossil fuel baseline should have been created using a range of literature, and such an important part of the analysis should not have purely relied on Ecoinvent based data, as there could have been errors within Ecoinvent.

9.2 BioMOD

The BioMODule results, based on a small trial within CPI, showed that the bag-based fermenter did not compare well under any measure with a steel fermenter. However, as the BioMODule was such a small system, not of pilot scale, and the steel fermenter was a pilot-scale system. it cannot be considered to be a fair comparison. If it is indicative of real results, then it is highly concerning.

9.3 MAGNIFICENT

There are several areas highlighted within this work to focus on to improve the environmental sustainably of microalgae products

In the case of microalgae versus soy, on a per MJ basis, microalgae has generally higher environmental impacts, including in climate change, whilst some impacts are lower.

Electricity use can be reduced by 48% with no impact on the growth of microalgae, providing reductions in all environmental impacts. Whilst the PMMA tubes can be replaced with glass, providing an

environmental improvement, this leads to social impacts.

It is important to note that this assessment is based on generic data, with little site-specific data outside of the operational data. Sustainability choices in terms of suppliers of materials and energy can always improve the sustainability of a process. Generic glass models or photovoltaics models do not tell the full story, as every production site is different in terms of the environmental and social impacts.

This thesis attempted to consider uncertainty through the use of a pedigree matrix-based qualitative/quantitative method. Whilst there are many valid arguments against this method, it was used in order to utilise the uncertainty information which is provided within Ecoinvent. Through this process, new valid arguments against using this method have been discovered, specifically concerns over the fluidity of the definitions of the arithmetic mean and geometric mean within LCA databases.

Scaling up of the technology will have a clear impact. It is very important to remember that this article is based on a very small system compared with the global soy production supply chain.

This work shows that in this comparison of a small demonstrator with the global soy production supply chain, microalgae do not compare well with soy, but there are specific changes to systems which can be made in order to increase the sustainability. However, this must be undertaken in a holistic way which considers both environmental and social impacts.

9.4 Final Thoughts

The work has used a wide range of data, stretched from October 2015 to June 2016 for InteSusAl, and for MAGNIFICENT 13/06/2017 to 11/08/2017 and 17th Oct–15th Dec 2017. Various software packages and methodologies have been utilised, necessary as the field of LCA advanced throughout the length of this seven-year part time PhD.

The overall conclusions that can be made from this work are as follows.

- A comparison of microalgae-based biodiesel with petroleum-derived biodiesel showed that microalgae-derived fuels do not compare well
- If a productivity of >25.6 tonnes/hectare/year were achieved, which is a reasonable level, then a PV powered system (Scenario C) would be on a par with fossil fuels in terms of climate change (GWP100), productivity of 31.4 tonnes/hectare/year would lead to equivalence in terms of ozone depletion, but 313.2 tonnes/hectare/year would be needed for equivalence with petroleum diesel in terms of eutrophication
- Electricity is a major source of impacts, and photobioreactors need to be redesigned to be far more efficient

- Systems should utilise photovoltaics for the majority of their electricity demand
- Heterotrophic systems allow for greater productivity per hectare, but the feedstocks come with significant environmental impacts.
- Yeast was a major source of environmental impacts, and any microalgae production system that uses yeast as a feedstock must consider alternatives.
- Bag based fermenters has higher impacts than steel fermenters, but this was presumably due to the system analysed, which was not representative of commercial systems, and contradicts the limited literature that exists.
- Microalgae-derived biofuels have a dLUC impact of between 0.4 and 4.8% that of palm oil-based biofuels on a per MJ basis
- The small dLUC impact of microalgae-derived biodiesel still leaves microalgae-derived biodiesel with an impact three times that of palm-derived biodiesel.
- In terms of the MAGNIFICENT system, a comparison with soy showed that some impact categories (such as eutrophication) show an improvement per MJ over soy, for climate change, there is much work to do.
- Replacing materials within the facility, such as PMMA within glass, can improve the impacts of a system
- Uncertainty methods within LCA need to be considered carefully, as differences between arithmetic and geometric approaches give conflicting results
- LCA software has issues, such as with water use, which may impact a large amount of the literature. Validation is vital for LCA software.

In terms of the productivities, considering again the values within Section 2.4.8 on page 36, we can compare the proposed of >25.6 tonnes/hectare/year value with what is photosynthetically possible, as in *Table 2-2*, to show this is realistic. (Passell et al., 2013) show that 11 tonnes/ha/year was achieved in the facilities studied, whilst . (Pérez-López *et al.*, 2017) had areal productivities varying from 4.3 to 70 tonnes/ha/year depending on the time of year. Hence, whilst very different systems, it does show that the productivities suggested are not impossible.

To generalise these results, it is important to note that the LCAs within this work only give answers with regard to a specific methodology for producing microalgae-derived biodiesel. There are many other methods available, as mentioned in this thesis. The All-Gas project deserves special mention, as, using a similar (but not exactly the same) methodology to Scenario A, they found that micro-algae derived biofuels (gas and biodiesel) appeared a sustainable approach to utilising the waste in a water treatment works. Clearly though, the options for bioproducts are severely limited due to health grounds.

Therefore, this work shows that at present, the systems investigated within this thesis do not offer a sustainable solution to petroleum-derived diesel, and that further work must be undertaken, or different avenues for fuel production investigated.

Microalgae is an interesting product, which may have possibilities in the future for fuel or food. However, there is much work to do. It is important to always be realistic about technologies. Until it can be shown otherwise, microalgae biofuels are not part of the answer for combating climate change.

Chapter 10. Impact

This work presented a comprehensive LCA, based on strong datasets from a variety of real-life algae production systems,

The overriding narrative from all of these analyses is that microalgae derived diesel has a higher environmental impact than that of fossil derived diesel in all of the ReCiPe Hierarchist Mid Points. Multiple scenarios based on energy sources, bioreactor types, and material choices show a consistent story.

This thesis contains models and data that challenge the current optimism within the literature concerning microalgae-derived diesel and contains options on how to reduce these environmental impacts to a point where miscroalgae-derived biodiesel could possibly, at some point in the future, become a sustainable fuel.

The models within this work contribute to the slowly growing set of data within the literature on real facilities, which ios extremely important to grow, in order to allow academia, commercial entities, and policy makers to have a realistic view of the encironmental impacts of produced microalgae-derived diesel.

Importantly, the thesis shows that perhaps microalgae production should target alternative products, such as high value products, instead of fuels. However, this is further research that will be undertaken post thesis, and as described in the Future Research section, funding for commercial research projects within which there are elements continuing the work of this thesis has already been granted via EEA Grants and Horizon Europe.

As described in the Future Research section, new papers are under development which continue the work, methodologies, and models of this thesis, with more advanced versions of the models utilised in this thesis reconstructed within OpenLCA.

Chapter 11. Future Research

There are a number of areas where the results and models from this work could be advanced.

This data and models from this work are being used within the AlgaCycle project, which involves by Necton, the project partner who built and operates the photobioreactor systems which were originally constructed for InteSusAl. Within AlgaCycle, the photobioreactor systems are utilising recycled nutrients from traditional crop production for the growth of microalgae. More information on the project can be found at https://www.algacycle.com, and the project is funded under the EEA Grants.

As a follow on from the AlgaCycle project, the data and models from this thesis will also utilised as the initial foundations for the LCA work within the Horizon Europe REALM project (Reusing Effluents from Agriculture to unLock the potential of Microalgae). The project gained funding in February 2022.

There are a further two funded project applications for research into increasing the sustainability of the Necton photobioreactors, on which Necton are waiting to hear, and will also utilise the work from this thesis.

Following on from this thesis, the author is working with GreenCoLab in Portugal on three papers on the LCA of the Allmicroalgae system, as studied within this thesis. The first paper is a highly modified version of the comparison of *Tetraselmis* and soy. Two further papers will consider various species at Allmicroalgae, based on more real data. The first of these is due to be submitted in April 2022, with the other two intended to be submitted in summer 2022.

The author wishes to undertake more work on climate change indicators; however this has been delayed due to work commitments.

Further work that this thesis suggests is important is related to the optimisation of photobioreactor design, and it is the author's hope to secure funding to allow for work in this direction.

Issues such as the geometric mean / arithmetic mean problem within Ecoinvent will be investigated in more detail, and Ecoinvent and software providers communicated with when this is understood in more detail

Ultimately, the work of this thesis is to be used in a number of projects and publications, involving a strong research collaboration between the companies Necton and Narec Distributed Energy, for which some funding is already now guarantied.

Chapter 12. Appendix A - Results Tables

12.1 InteSusAl Models

Table 12-1: Impacts per Scenario, percentage figures.

Impact Category	Petroleum-derived Diesel fuel	Algae biodiesel (three scenarios based on electricity used)					
		Without infrastructure			With infrastructure		
		(A) 2012 EU grid	(B) 2020 EU grid	(C) PV only	(A) 2012 EU grid	(B) 2020 EU grid	(C) PV only
IPCC AR5							
IPCC AR5 GWP100, excl biogenic carbon [kg CO_2 eq]	100%	210%	190%	88%	289%	270%	168%
IPCC AR5 GWP20, excl biogenic carbon [kg CO_2 eq]	100%	232%	210%	103%	331%	309%	202%
IPCC AR5 GTP100, excl biogenic carbon [kg CO_2 eq]	100%	199%	180%	81%	271%	252%	152%
IPCC AR5 GTP50, excl biogenic carbon [kg CO_2 eq]	100%	204%	184%	84%	278%	258%	158%
IPCC AR5 GTP20, excl biogenic carbon [kg CO_2 eq]	100%	225%	204%	99%	315%	293%	188%
ReCiPe 1.08 Endpoint (H)							
Freshwater ecotoxicity [species.yr]	100%	431%	431%	712%	1319%	1318%	1600%
Human toxicity [DALY]	100%	298%	302%	465%	709%	713%	875%
Marine ecotoxicity [species.yr]	100%	349%	350%	594%	992%	992%	1236%
Terrestrial ecotoxicity [species.yr]	100%	90%	90%	203%	157%	157%	270%
ReCiPe 1.08 Midpoint (H)							
Agricultural land occupation [m^2a]	100%	3883%	4256%	3245%	4877%	5250%	4239%
Climate change, excl biogenic carbon [kg CO_2 eq]	100%	208%	188%	87%	286%	266%	165%
Climate change, incl biogenic carbon [kg CO_2 eq]	100%	238%	218%	117%	317%	297%	195%
Fossil depletion [kg oil eq]	100%	161%	152%	70%	229%	220%	138%
Freshwater ecotoxicity [kg 1,4-DB eq]	100%	431%	431%	712%	1320%	1320%	1601%
Freshwater eutrophication [kg P eq]	100%	717%	724%	1164%	1604%	1612%	2051%
Human toxicity [kg 1,4-DB eq]	100%	299%	303%	466%	711%	714%	878%
Ionising radiation [kg U235 eq]	100%	367%	362%	547%	860%	856%	1041%
Marine ecotoxicity [kg 1,4-DB eq]	100%	347%	348%	590%	987%	988%	1230%
Marine eutrophication [kg N eq]	100%	863%	890%	731%	1430%	1457%	1298%
Metal depletion [kg Fe eq]	100%	535%	582%	1158%	5396%	5442%	6019%
Ozone depletion [kg CFC-11 eq]	100%	34%	34%	46%	194%	194%	206%
Particulate matter formation [kg PM10 eq]	100%	310%	310%	242%	586%	586%	519%
Photochemical oxidant formation [kg NMVOC]	100%	233%	230%	159%	363%	359%	288%
Terrestrial acidification [kg SO_2 eq]	100%	431%	431%	316%	620%	620%	506%
Terrestrial ecotoxicity [kg 1,4-DB eq]	100%	90%	90%	203%	156%	156%	270%
ReCiPe 1.08 Midpoint (H) - Water depletion [m3]	100%	7748%	5302%	2347%	9541%	7095%	4140%

Figure 12-1: Contribution of each stage (Growth, Harvesting, Processing and Use) to the total operational impact of each category. Data for IPCC AR5 GWP and selected ReCiPe 1.08 Hierarchist Mid Points for Scenario C.

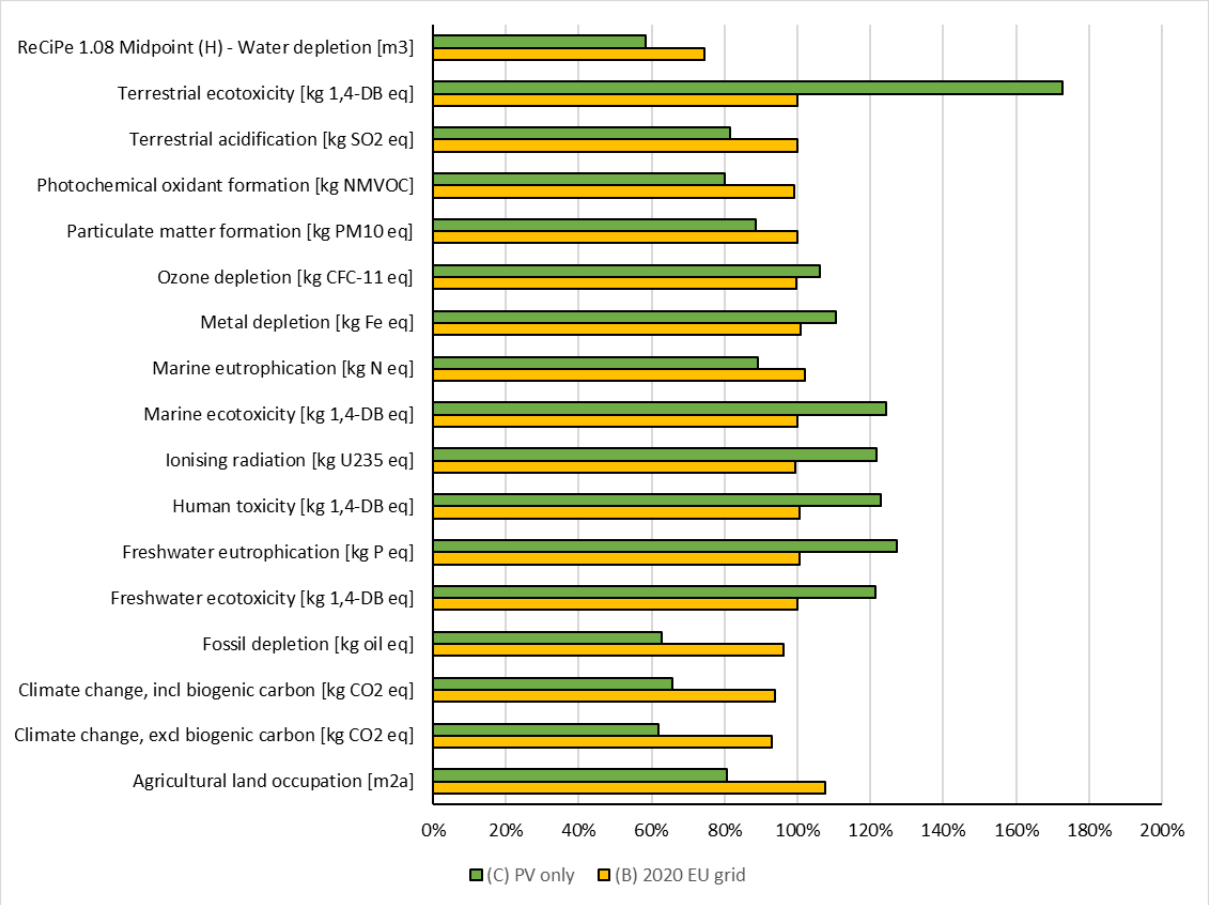

Figure 12-2: Percentage of impacts from scenario B and C when compared with Scenario A

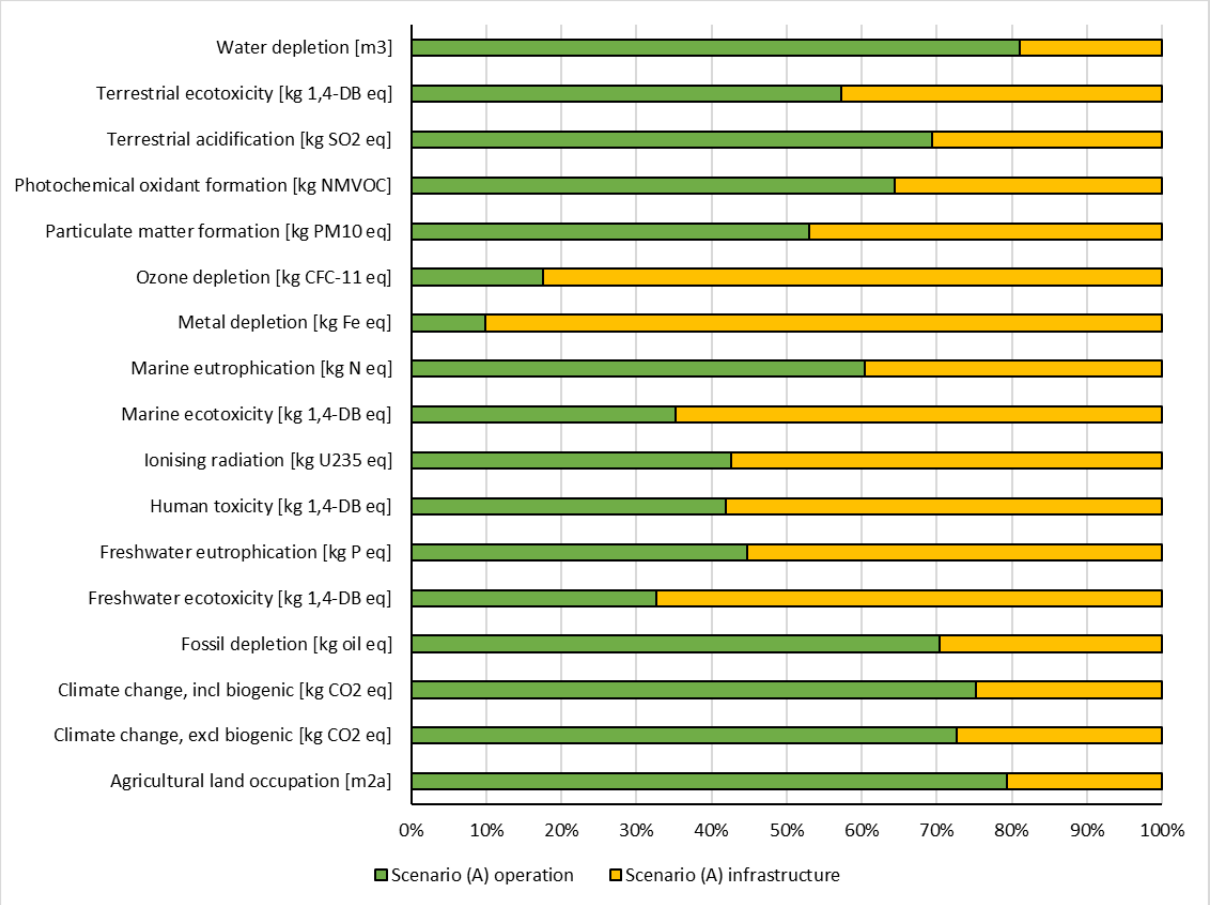

Figure 12-3: Mixture of operational and infrastructure ReCiPe 1.08 Hierarchist Mid Point impacts for Scenario A.

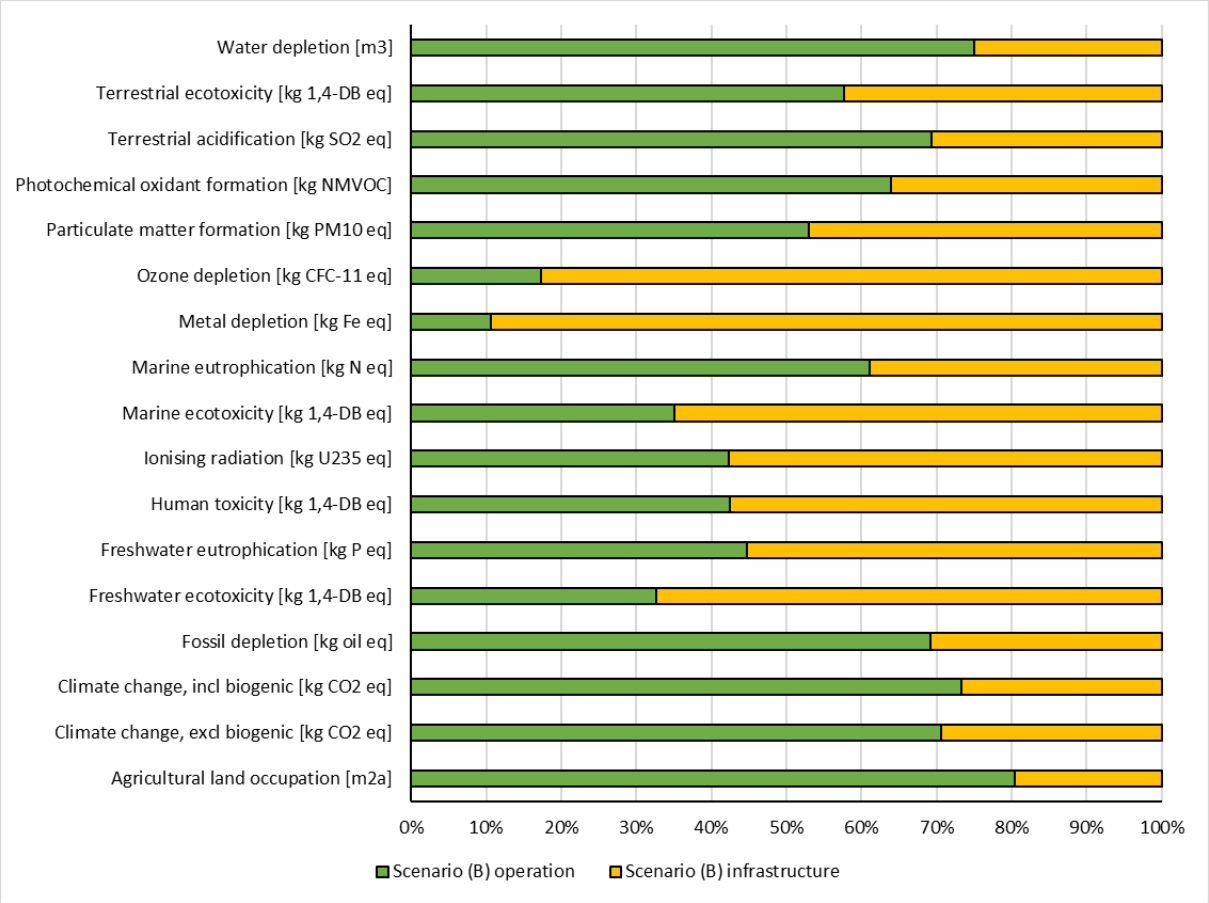

Figure 12-4: Mixture of operational and infrastructure ReCiPe 1.08 Hierarchist Mid Point impacts for Scenario B.

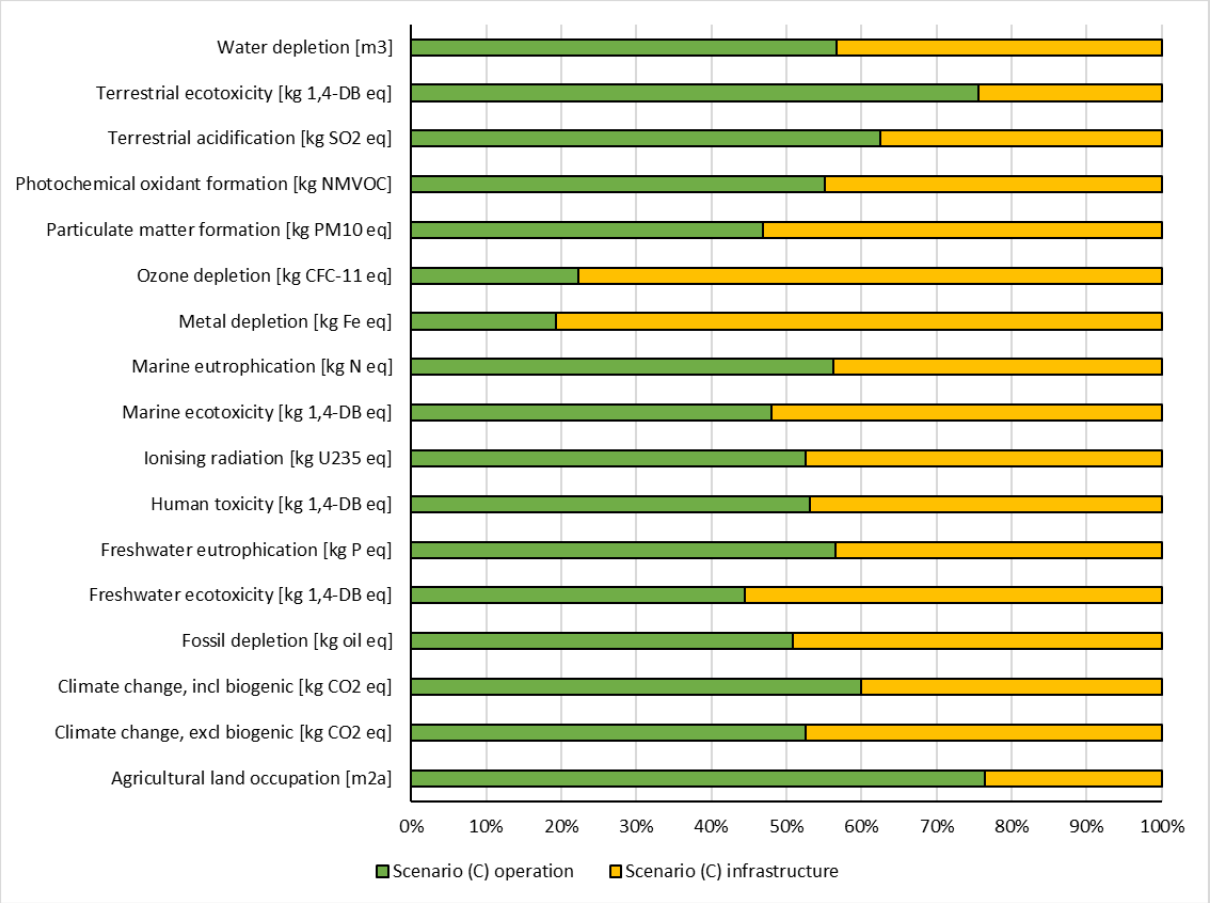

Figure 12-5: Mixture of operational and infrastructure ReCiPe 1.08 Hierarchist Mid Point impacts for Scenario C.

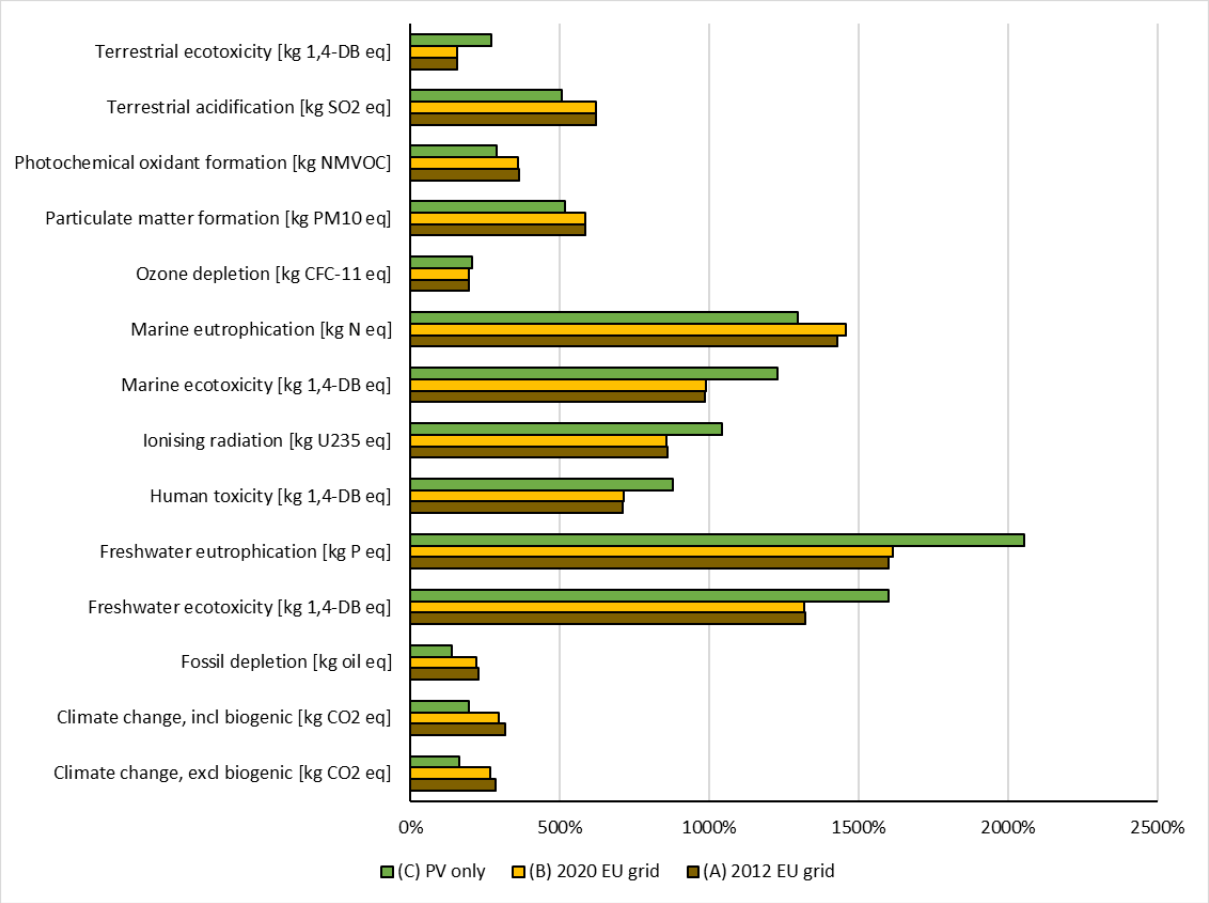

Figure 12-6: Selected ReCiPe 1.08 Hierarchist Mid Points for Scenario A, B and C with infrastructure, as a percentage of fossil derived deisel's impacts, where fossil diesel has an impact of 100%. Not all impacts shown due to the significant differences between them.

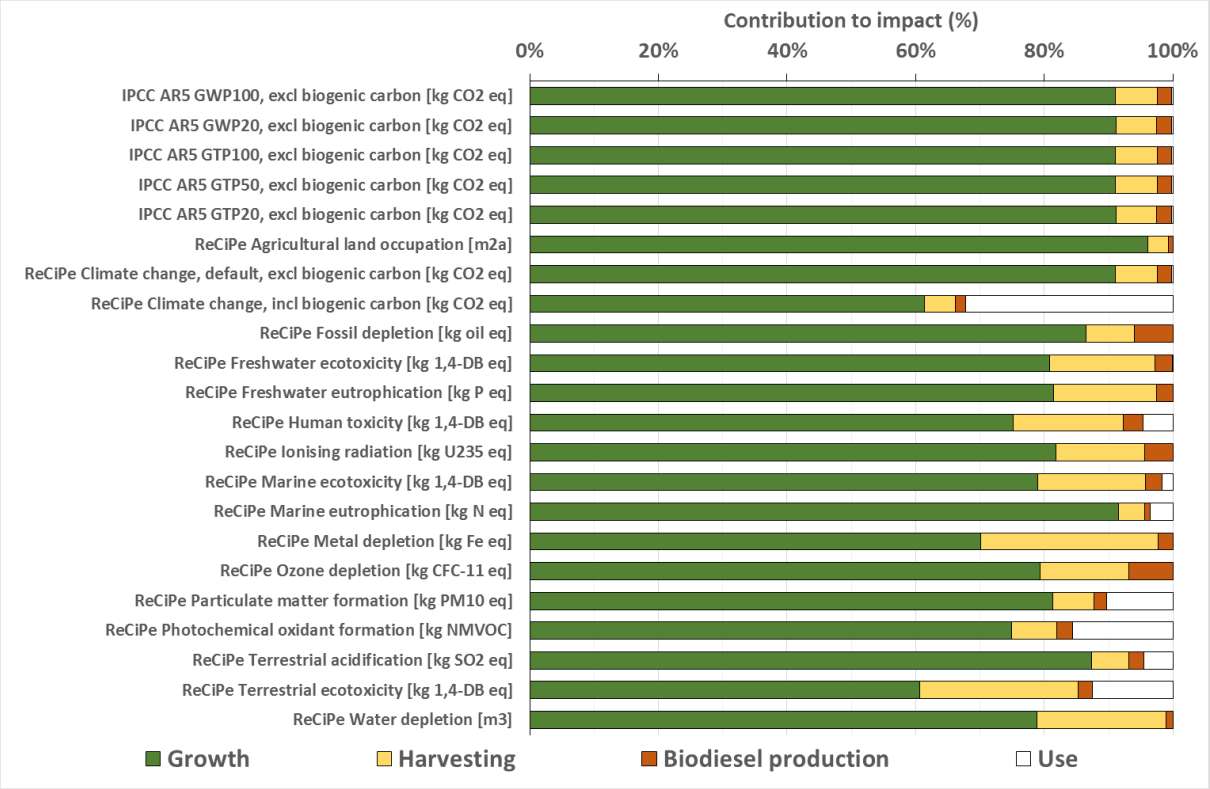

Figure 12-7: Contribution of each stage (Growth, Harvesting, Processing and Use) to the total operational impact of each category. Data for IPCC AR5 GWP and selected ReCiPe 1.08 Hierarchist Mid Points for Scenario C.

Table 12-2: Impacts per operational phase for Scenario C.

Impact Category	Phase			
	Growth	Harvesting	Biodiesel production	Use
IPCC AR5				
GWP100, excl biogenic carbon [kg CO_{2eq}]	4.40×10^{-3}	1.77×10^{-1}	1.26×10^{-2}	3.76×10^{-4}
GWP20, excl biogenic carbon [kg CO_{2eq}]	5.65×10^{-3}	2.14×10^{-1}	1.47×10^{-2}	4.24×10^{-4}
GTP100, excl biogenic carbon [kg CO_{2eq}]	3.85×10^{-3}	1.60×10^{-1}	1.16×10^{-2}	3.13×10^{-4}
GTP50, excl biogenic carbon [kg CO_{2eq}]	4.06×10^{-3}	1.66×10^{-1}	1.20×10^{-2}	3.85×10^{-4}
GTP20, excl biogenic carbon [kg CO_{2eq}]	5.26×10^{-3}	2.03×10^{-1}	1.41×10^{-2}	4.26×10^{-4}
ReCiPe 1.08 Endpoint (H)				
Freshwater ecotoxicity [species.yr]	6.38×10^{-12}	1.76×10^{-13}	5.15×10^{-12}	1.04×10^{-12}
Human toxicity [DALY]	6.60×10^{-8}	2.03×10^{-9}	4.96×10^{-8}	1.13×10^{-8}
Marine ecotoxicity [species.yr]	1.14×10^{-12}	2.89×10^{-14}	8.99×10^{-13}	1.90×10^{-13}
Terrestrial ecotoxicity [species.yr]	1.08×10^{-11}	2.38×10^{-13}	6.57×10^{-12}	2.66×10^{-12}
ReCiPe 1.08 Midpoint (H)				
Agricultural land occupation [m^2a]	1.97×10^{-2}	1.40×10^{-4}	1.90×10^{-2}	6.24×10^{-4}
Climate change, excl biogenic carbon [kg CO_2 eq]	1.91×10^{-1}	4.29×10^{-3}	1.74×10^{-1}	1.24×10^{-2}
Climate change, incl biogenic carbon [kg CO_2 eq]	2.57×10^{-1}	4.23×10^{-3}	1.58×10^{-1}	1.24×10^{-2}
Fossil depletion [kg oil eq]	5.30×10^{-2}	3.17×10^{-3}	4.58×10^{-2}	3.96×10^{-3}
Freshwater ecotoxicity [kg 1,4-DB eq]	7.36×10^{-3}	2.04×10^{-4}	5.95×10^{-3}	1.21×10^{-3}
Freshwater eutrophication [kg P eq]	4.31×10^{-5}	1.12×10^{-6}	3.51×10^{-5}	6.85×10^{-6}
Human toxicity [kg 1,4-DB eq]	9.49×10^{-2}	2.92×10^{-3}	7.13×10^{-2}	1.62×10^{-2}
Ionising radiation [kg U235 eq]	8.31×10^{0}	3.62×10^{-1}	6.80×10^{0}	1.15×10^{0}
Marine ecotoxicity [kg 1,4-DB eq]	6.24×10^{-3}	1.59×10^{-4}	4.93×10^{-3}	1.04×10^{-3}
Marine eutrophication [kg N eq]	1.21×10^{-4}	1.00×10^{-6}	1.11×10^{-4}	4.97×10^{-6}
Metal depletion [kg Fe eq]	1.21×10^{-2}	2.85×10^{-4}	8.48×10^{-3}	3.32×10^{-3}
Ozone depletion [kg CFC-11 eq]	1.86×10^{-8}	1.28×10^{-9}	1.48×10^{-8}	2.56×10^{-9}
Particulate matter formation [kg PM10 eq]	4.82×10^{-4}	9.36×10^{-6}	3.92×10^{-4}	3.13×10^{-5}
Photochemical oxidant formation [kg NMVOC]	7.71×10^{-4}	1.91×10^{-5}	5.77×10^{-4}	5.42×10^{-5}
Terrestrial acidification [kg SO_2 eq]	1.40×10^{-3}	3.23×10^{-5}	1.23×10^{-3}	8.25×10^{-5}
Terrestrial ecotoxicity [kg 1,4-DB eq]	7.16×10^{-5}	1.58×10^{-6}	4.34×10^{-5}	1.77×10^{-5}
Water depletion [m^3]	8.80×10^{-1}	9.35×10^{-3}	6.94×10^{-1}	1.77×10^{-1}

Table 12-3: Sensitivity Analysis on Scenario A, a variation of all variables by 5%, with the table showing resultant percentage variation in the total operational impact categories. Impact Categories considered are AR5 IPCC excl. Biogenic.

Variable	GTP100	GTP50	GTP20	GWP100	GWP20
	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq
electricity	3.27	3.24	3.11	3.20	3.08
yeast extract	1.39	1.42	1.54	1.45	1.57
potassium hydrogen phosphate	0.19	0.19	0.19	0.19	0.19
water	0.06	0.06	0.06	0.06	0.06
phosphoric acid	0.01	0.01	0.01	0.01	0.01
sodium nitrate	0.01	0.01	0.01	0.01	0.01
sodium hypochlorite	0.01	0.01	0.01	0.01	0.01
solvent, organic	0.01	0.01	0.01	0.01	0.01
sodium hydroxide	0.00	0.00	0.00	0.00	0.00
hydrochloric acid	0.00	0.00	0.00	0.00	0.00
EDTA	0.00	0.00	0.00	0.00	0.00
copper sulfate	0.00	0.00	0.00	0.00	0.00
calcium chloride	0.00	0.00	0.00	0.00	0.00
iron (III) chloride	0.00	0.00	0.00	0.00	0.00
sodium molybdate dihydrate	0.00	0.00	0.00	0.00	0.00
zinc monosulfate	0.00	0.00	0.00	0.00	0.00
zinc sulfate heptahydrate	0.00	0.00	0.00	0.00	0.00
zinc chloride	0.00	0.00	0.00	0.00	0.00
magnesium sulfate	0.00	0.00	0.00	0.00	0.00
cobalt chloride, 6-hydrate	0.00	0.00	0.00	0.00	0.00
copper (II) sulfate pentahydrate	0.00	0.00	0.00	0.00	0.00
manganese(II) chloride tetrahydrate	0.00	0.00	0.00	0.00	0.00
glycerol	0.00	0.00	0.00	0.00	0.00
sodium thiosulfate	0.00	0.00	0.00	0.00	0.00

Table 12-4: Sensitivity Analysis on Scenario A, variation of all variables by 5%, with table showing resultant variation in the percentage total operational impact categories. Impact Categories considered are ReCiPe(H) (2008) Midpoints.

Variable	Agricultural land	Climate change, excl	Fossil depletion	Freshwater ecotoxicity	Freshwater eutrophicatio	Human toxicity	Ionising radiation	Marine ecotoxicity	Marine eutrophicatio	Metal depletion	Ozone depletion	Particulate matter	Photochemical oxidant	Terrestrial acidification	Terrestrial ecotoxicity	Water depletion	Water depletion
	m2*a	kg CO2 eq	kg oil eq	kg 1,4-DB eq	kg P eq	kg 1,4-DB eq	kg U235 eq	kg 1,4-DB eq	kg N eq	kg Fe eq	kg CFC-11 eq	kg PM10 eq	kg NMVOC	kg SO2 eq	kg 1,4-DB eq	m2*a	m3
electricity	1.12	3.21	3.11	0.12	0.11	0.52	0.11	0.06	1.17	1.61	0.07	1.68	2.11	1.81	0.70	4.89	3.73
yeast extract	3.74	1.44	1.29	3.37	3.79	2.91	3.63	3.31	3.39	1.98	3.20	2.35	1.86	2.46	2.14	0.00	1.03
potassium hydrogen phosphate	0.03	0.19	0.33	0.01	0.02	0.09	0.00	0.01	0.10	0.08	0.00	0.30	0.24	0.31	0.06	0.10	0.08
water	0.04	0.06	0.06	0.93	0.41	0.53	0.70	0.92	0.04	0.42	0.79	0.10	0.08	0.08	0.20	0.00	0.09
phosphoric acid	0.02	0.01	0.02	0.12	0.30	0.17	0.06	0.13	0.01	0.20	0.08	0.05	0.03	0.04	0.13	0.00	0.01
sodium nitrate	0.00	0.01	0.01	0.03	0.03	0.03	0.03	0.03	0.08	0.05	0.02	0.01	0.01	0.01	0.02	0.00	0.00
sodium hypochlorite	0.01	0.01	0.01	0.11	0.06	0.07	0.08	0.11	0.01	0.08	0.11	0.01	0.01	0.01	0.02	0.00	0.01
solvent, organic	0.01	0.01	0.04	0.03	0.03	0.03	0.02	0.03	0.00	0.05	0.23	0.01	0.02	0.01	0.04	0.00	0.00
sodium hydroxide	0.00	0.00	0.00	0.02	0.01	0.01	0.01	0.02	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00
hydrochloric acid	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00
EDTA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
copper sulfate	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.01	0.00	0.00
calcium chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
iron (III) chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium molybdate dihydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
zinc monosulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
zinc sulfate heptahydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
zinc chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
magnesium sulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cobalt chloride, 6-hydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
copper (II) sulfate pentahydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
manganese(II) chloride tetrahydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
glycerol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium thiosulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 12-5: Sensitivity Analysis on Scenario B, variation of all variables by 5%, with table showing resultant percentage variation in the total operational impact categories. Impact Categories considered are AR5 IPCC excl. Biogenic.

Variable	GTP100	GTP50	GTP20	GWP100	GWP20
	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq
electricity	3.08	3.06	2.88	3.01	2.88
yeast extract	1.53	1.56	1.73	1.60	1.73
potassium hydrogen phosphate	0.21	0.21	0.21	0.21	0.21
water	0.06	0.06	0.06	0.06	0.06
phosphoric acid	0.02	0.02	0.01	0.01	0.01
sodium nitrate	0.01	0.01	0.01	0.01	0.01
sodium hypochlorite	0.01	0.01	0.01	0.01	0.01
solvent, organic	0.01	0.01	0.01	0.01	0.01
sodium hydroxide	0.00	0.00	0.00	0.00	0.00
hydrochloric acid	0.00	0.00	0.00	0.00	0.00
EDTA	0.00	0.00	0.00	0.00	0.00
copper sulfate	0.00	0.00	0.00	0.00	0.00
calcium chloride	0.00	0.00	0.00	0.00	0.00
iron (III) chloride	0.00	0.00	0.00	0.00	0.00
sodium molybdate dihydrate	0.00	0.00	0.00	0.00	0.00
zinc monosulfate	0.00	0.00	0.00	0.00	0.00
zinc sulfate heptahydrate	0.00	0.00	0.00	0.00	0.00
zinc chloride	0.00	0.00	0.00	0.00	0.00
magnesium sulfate	0.00	0.00	0.00	0.00	0.00
cobalt chloride, 6-hydrate	0.00	0.00	0.00	0.00	0.00
copper (II) sulfate pentahydrate	0.00	0.00	0.00	0.00	0.00
manganese(II) chloride tetrahydrate	0.00	0.00	0.00	0.00	0.00
glycerol	0.00	0.00	0.00	0.00	0.00
sodium thiosulfate	0.00	0.00	0.00	0.00	0.00

Table 12-6: Sensitivity Analysis on Scenario B, variation of all variables by 5%, with table showing resultant variation in the percentage total operational impact categories. Impact Categories considered are ReCiPe(H) (2008) Midpoints.

Variable	Agricultural land	Climate change, excl	Fossil depletion	Freshwater ecotoxicity	Freshwater eutrophicatio	Human toxicity	Ionising radiation	Marine ecotoxicity	Marine eutrophicatio	Metal depletion	Ozone depletion	Particulate matter	Photochemical oxidant	Terrestrial acidification	Terrestrial ecotoxicity	Water depletion	Water depletion
	m2*a	kg CO2 eq	kg oil eq	kg 1,4-DB eq	kg P eq	kg 1,4-DB eq	kg U235 eq	kg 1,4-DB eq	kg N eq	kg Fe eq	kg CFC-11 eq	kg PM10 eq	kg NMVOC	kg SO2 eq	kg 1,4-DB eq	m2*a	m3
electricity	0.00	3.03	0.00	0.12	0.16	0.57	0.05	0.07	0.00	0.02	1.68	2.08	1.81	0.71	0.00	4.84	0.00
yeast extract	0.00	1.59	0.00	3.38	3.75	2.88	3.67	3.31	0.00	3.23	2.35	1.89	2.45	2.13	0.00	0.00	0.00
potassium hydrogen phosphate	0.00	0.21	0.00	0.01	0.02	0.09	0.00	0.01	0.00	0.00	0.30	0.24	0.31	0.06	0.00	0.16	0.00
water	0.00	0.06	0.00	0.93	0.41	0.52	0.71	0.92	0.00	0.80	0.10	0.08	0.08	0.20	0.00	0.00	0.00
phosphoric acid	0.00	0.01	0.00	0.12	0.30	0.17	0.07	0.13	0.00	0.08	0.05	0.03	0.04	0.13	0.00	0.00	0.00
sodium nitrate	0.00	0.01	0.00	0.03	0.03	0.03	0.03	0.03	0.00	0.02	0.01	0.01	0.01	0.02	0.00	0.00	0.00
sodium hypochlorite	0.00	0.01	0.00	0.11	0.06	0.07	0.08	0.11	0.00	0.12	0.01	0.01	0.01	0.02	0.00	0.00	0.00
solvent, organic	0.00	0.01	0.00	0.03	0.03	0.03	0.02	0.03	0.00	0.23	0.01	0.02	0.01	0.04	0.00	0.00	0.00
sodium hydroxide	0.00	0.00	0.00	0.02	0.01	0.01	0.01	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
hydrochloric acid	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00
EDTA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
copper sulfate	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
calcium chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
iron (III) chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium molybdate dihydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
zinc monosulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
zinc sulfate heptahydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
zinc chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
magnesium sulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cobalt chloride, 6-hydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
copper (II) sulfate pentahydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
manganese(II) chloride tetrahydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
glycerol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium thiosulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 12-7: Sensitivity Analysis on Scenario C, variation of all variables by 5%, with table showing resultant percentage variation in the total operational impact categories. Impact Categories considered are AR5 IPCC excl. Biogenic.

Variable	GTP100	GTP50	GTP20	GWP100	GWP20
	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq
electricity	0.79	0.78	0.75	0.77	0.74
yeast extract	3.39	3.40	3.47	3.42	3.49
potassium hydrogen phosphate	0.60	0.59	0.56	0.58	0.55
water	0.00	0.00	0.00	0.00	0.00
phosphoric acid	0.03	0.03	0.03	0.03	0.03
sodium nitrate	0.02	0.02	0.02	0.02	0.02
sodium hypochlorite	0.02	0.02	0.02	0.02	0.02
solvent, organic	0.00	0.00	0.00	0.00	0.00
sodium hydroxide	0.00	0.00	0.00	0.00	0.00
hydrochloric acid	0.00	0.00	0.00	0.00	0.00
EDTA	0.00	0.00	0.00	0.00	0.00
copper sulfate	0.00	0.00	0.00	0.00	0.00
calcium chloride	0.00	0.00	0.00	0.00	0.00
iron (III) chloride	0.00	0.00	0.00	0.00	0.00
sodium molybdate dihydrate	0.00	0.00	0.00	0.00	0.00
zinc monosulfate	0.00	0.00	0.00	0.00	0.00
zinc sulfate heptahydrate	0.00	0.00	0.00	0.00	0.00
zinc chloride	0.00	0.00	0.00	0.00	0.00
magnesium sulfate	0.00	0.00	0.00	0.00	0.00
cobalt chloride, 6-hydrate	0.00	0.00	0.00	0.00	0.00
copper (II) sulfate pentahydrate	0.00	0.00	0.00	0.00	0.00
manganese(II) chloride tetrahydrate	0.00	0.00	0.00	0.00	0.00
glycerol	0.00	0.00	0.00	0.00	0.00
sodium thiosulfate	0.02	0.02	0.02	0.02	0.02

Table 12-8: Sensitivity Analysis on Scenario C, variation of all variables by 5%, with table showing resultant variation in the percentage total operational impact categories. Impact Categories considered are ReCiPe(H) (2008) Midpoints.

Variable	Agricultural land	Climate change, excl	Fossil depletion	Freshwater ecotoxicity	Freshwater eutrophicatio	Human toxicity	Ionising radiation	Marine ecotoxicity	Marine eutrophicatio	Metal depletion	Ozone depletion	Particulate matter	Photochemical oxidant	Terrestrial acidification	Terrestrial ecotoxicity	Water depletion	Water depletion
	m2*a	kg CO2 eq	kg oil eq	kg 1,4-DB eq	kg P eq	kg 1,4-DB eq	kg U235 eq	kg 1,4-DB eq	kg N eq	kg Fe eq	kg CFC-11 eq	kg PM10 eq	kg NMVOC	kg SO2 eq	kg 1,4-DB eq	m2*a	m3
electricity	0.00	0.77	0.00	2.01	1.96	2.11	1.69	2.06	0.50	0.00	0.00	1.30	0.77	0.80	0.69	3.08	0.00
yeast extract	0.00	3.42	0.00	2.06	2.36	1.88	2.45	1.97	3.99	0.00	0.00	2.40	2.99	2.72	3.32	0.95	0.00
potassium hydrogen phosphate	0.00	0.58	0.00	0.56	0.26	0.39	0.46	0.54	0.16	0.00	0.00	0.57	0.51	0.46	0.52	0.12	0.00
water	0.00	0.00	0.00	0.02	0.01	0.01	0.02	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
phosphoric acid	0.00	0.03	0.00	0.08	0.19	0.11	0.04	0.07	0.02	0.00	0.00	0.06	0.06	0.04	0.06	0.06	0.00
sodium nitrate	0.00	0.02	0.00	0.02	0.02	0.02	0.02	0.02	0.10	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00
sodium hypochlorite	0.00	0.02	0.00	0.07	0.04	0.05	0.06	0.06	0.01	0.00	0.00	0.09	0.02	0.02	0.02	0.01	0.00
solvent, organic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium hydroxide	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
hydrochloric acid	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
EDTA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
copper sulfate	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
calcium chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
iron (III) chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium molybdate dihydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
zinc monosulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
zinc sulfate heptahydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
zinc chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
magnesium sulfate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cobalt chloride, 6-hydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
copper (II) sulfate pentahydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
manganese(II) chloride tetrahydrate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
glycerol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium thiosulfate	0.00	0.02	0.00	0.02	0.02	0.02	0.02	0.02	0.01	0.00	0.00	0.17	0.01	0.03	0.02	0.02	0.00

Table 12-9: Breakdown of operational emissions for IPCC AR5 GWP100, excl biogenic carbon [kg CO_2-eq].

Chemical			IPCC AR5 GWP100, excl biogenic carbon [kg CO_2-eq]			
			Petroleum-derived diesel fuel	Algae biodiesel		
				(A) 2012 EU	(B) 2020 EU	(C) PV only
Inorganic emissions to air		Carbon dioxide	8.64×10^{-2}	1.68×10^{-1}	1.51×10^{-1}	6.60×10^{-2}
		Carbon dioxide (aviation)	0.00×10^{0}	1.50×10^{-6}	2.20×10^{-6}	2.99×10^{-8}
		Nitrogentriflouride	1.33×10-^{14}	4.56×10^{-8}	7.71×10^{-8}	9.11×10^{-10}
		Nitrous oxide (laughing gas)	3.73×10^{-4}	2.70×10^{-3}	2.71×10^{-3}	1.97×10^{-3}
		Sulphur hexafluoride	1.05×10^{-5}	2.40×10^{-4}	2.40×10^{-4}	2.73×10^{-4}
Organic emissions to air (group VOC)	Halogenated organic emissions to air	1,1,1-Trichloroethane	2.38×10^{-10}	1.20×10^{-9}	1.20×10^{-9}	2.12×10^{-9}
		Carbon tetrachloride (tetrachloromethane)	1.62×10^{-8}	4.79×10^{-6}	4.79×10^{-6}	5.64×10^{-6}
		Chloromethane (methyl chloride)	4.72×10^{-10}	2.39×10^{-9}	2.39×10^{-9}	4.21×10^{-9}
		Dichloroethane (ethylene dichloride)	1.27×10^{-10}	6.41×10^{-9}	6.41×10^{-9}	6.56×10^{-9}
		Dichloromethane (methylene chloride)	2.09×10^{-10}	3.38×10^{-9}	3.38×10^{-9}	5.08×10^{-9}
		Halon (1211)	1.58×10^{-8}	2.37×10^{-7}	2.37×10^{-7}	2.76×10^{-7}
		Halon (1301)	8.45×10^{-6}	8.12×10^{-7}	8.12×10^{-7}	1.01×10^{-6}
		Methyl bromide	9.86×10^{-17}	1.90×10^{-15}	1.90×10^{-15}	2.30×10^{-15}
		Perfluoropentane	2.68×10^{-8}	1.18×10^{-7}	1.18×10^{-7}	1.98×10^{-7}
		R 11 (trichlorofluoromethane)	1.90×10^{-13}	3.65×10^{-11}	3.69×10^{-11}	1.81×10^{-8}
		R 113 (trichlorotrifluoroethane)	3.85×10^{-8}	9.80×10^{-8}	9.80×10^{-8}	1.43×10^{-7}
		R 114 (dichlorotetrafluoroethane)	6.81×10^{-7}	3.22×10^{-6}	2.65×10^{-6}	3.72×10^{-6}
		R 116 (hexafluoroethane)	4.27×10^{-8}	6.69×10^{-7}	7.66×10^{-7}	5.63×10^{-5}
		R 12 (dichlorodifluoromethane)	1.35×10^{-9}	6.58×10^{-7}	6.58×10^{-7}	3.57×10^{-6}
		R 124 (chlorotetrafluoroethane)	3.49×10^{-9}	8.87×10^{-9}	8.87×10^{-9}	1.29×10^{-8}
		R 125 (pentafluoroethane)	0.00×10^{0}	6.56×10^{-8}	1.12×10^{-7}	1.35×10^{-9}
		R 13 (chlorotrifluoromethane)	0.00×10^{0}	4.46×10^{-12}	4.60×10^{-12}	8.91×10^{-14}
		R 134a (tetrafluoroethane)	2.02×10^{-8}	8.07×10^{-8}	9.23×10^{-8}	1.68×10^{-6}
		R 143 (trifluoroethane)	0.00×10^{0}	6.06×10^{-9}	1.03×10^{-8}	1.25×10^{-10}
		R 152a (difluoroethane)	1.47×10^{-8}	5.56×10^{-8}	5.56×10^{-8}	1.58×10^{-5}
		R 21 (Dichlorofluoromethane)	3.92×10^{-15}	4.99×10^{-13}	4.99×10^{-13}	3.54×10^{-10}
		R 22 (chlorodifluoromethane)	3.39×10^{-7}	1.78×10^{-6}	1.78×10^{-6}	2.39×10^{-5}
		R 23 (trifluoromethane)	1.05×10^{-10}	1.78×10^{-6}	3.01×10^{-6}	9.48×10^{-6}
		R 245fa	0.00×10^{0}	3.16×10^{-7}	5.37×10^{-7}	6.51×10^{-9}
		R32 (difluoromethane)	0.00×10^{0}	2.10×10^{-9}	3.58×10^{-9}	4.34×10^{-11}
		Tetrafluoromethane	3.48×10^{-7}	4.76×10^{-6}	5.24×10^{-6}	1.31×10^{-4}
		Trichloromethane (chloroform)	1.27×10^{-10}	1.25×10^{-7}	1.25×10^{-7}	1.81×10^{-7}
	Methane	Methane	1.61×10^{-3}	1.40×10^{-2}	1.27×10^{-2}	8.92×10^{-3}
		Methane (biotic)	7.90×10^{-6}	4.15×10^{-4}	5.60×10^{-4}	1.13×10^{-4}

Table 12-10: Breakdown of operational emissions for IPCC AR5 GWP20, excl biogenic carbon [kg CO_2-eq].

Chemical			IPCC AR5 GWP100, excl biogenic carbon [kg CO_2-eq]			
			Petroleum-derived diesel fuel	Petroleum-derived diesel fuel		
				(A) 2012	(B) 2020	(C) PV
Inorganic emissions to air	Carbon dioxide		8.64×10^{-2}	1.68×10^{-1}	1.51×10^{-1}	6.60×10^{-2}
	Carbon dioxide (aviation)		0.00×10^{0}	1.50×10^{-6}	2.20×10^{-6}	2.99×10^{-8}
	Nitrogentriflouride		1.05×10^{-14}	3.63×10^{-8}	6.13×10^{-8}	7.25×10^{-10}
	Nitrous oxide (laughing gas)		3.72×10^{-4}	2.69×10^{-3}	2.70×10^{-3}	1.97×10^{-3}
	Sulphur hexafluoride		7.84×10^{-6}	1.79×10^{-4}	1.79×10^{-4}	2.03×10^{-4}
Organic emissions to air (group VOC)	Halogenated organic emissions to air	1,1,1-Trichloroethane	8.59×10^{-10}	4.34×10^{-9}	4.34×10^{-9}	7.66×10^{-9}
		Carbon tetrachloride (tetrachloromethane)	3.26×10^{-8}	9.63×10^{-6}	9.63×10^{-6}	1.13×10^{-5}
		Chloromethane (methyl chloride)	1.77×10^{-9}	8.95×10^{-9}	8.95×10^{-9}	1.58×10^{-8}
		Dichloroethane (ethylene dichloride)	4.22×10^{-10}	2.14×10^{-8}	2.14×10^{-8}	2.19×10^{-8}
		Dichloromethane (methylene chloride)	7.67×10^{-10}	1.24×10^{-8}	1.24×10^{-8}	1.86×10^{-8}
		Halon (1211)	4.16×10^{-8}	6.21×10^{-7}	6.21×10^{-7}	7.23×10^{-7}
		Halon (1301)	1.05×10^{-5}	1.01×10^{-6}	1.01×10^{-6}	1.26×10^{-6}
		Methyl bromide	4.44×10^{-16}	8.54×10^{-15}	8.57×10^{-15}	1.04×10^{-14}
		Perfluoropentane	1.99×10^{-8}	8.73×10^{-8}	8.73×10^{-8}	1.47×10^{-7}
		R 11 (trichlorofluoromethane)	2.81×10^{-13}	5.41×10^{-11}	5.46×10^{-11}	2.68×10^{-8}
		R 113 (trichlorotrifluoroethane)	4.30×10^{-8}	1.09×10^{-7}	1.09×10^{-7}	1.59×10^{-7}
		R 114 (dichlorotetrafluoroethane)	6.12×10^{-7}	2.89×10^{-6}	2.38×10^{-6}	3.34×10^{-6}
		R 116 (hexafluoroethane)	3.16×10^{-8}	4.95×10^{-7}	5.67×10^{-7}	4.17×10^{-5}
		R 12 (dichlorodifluoromethane)	1.43×10^{-9}	6.97×10^{-7}	6.97×10^{-7}	3.78×10^{-6}
		R 124 (chlorotetrafluoroethane)	1.24×10^{-8}	3.15×10^{-8}	3.15×10^{-8}	4.59×10^{-8}
		R 125 (pentafluoroethane)	0.00×10^{0}	1.26×10^{-7}	2.14×10^{-7}	2.60×10^{-9}
		R 13 (chlorotrifluoromethane)	0.00×10^{0}	3.50×10^{-12}	3.61×10^{-12}	6.99×10^{-14}
		R 134a (tetrafluoroethane)	5.77×10^{-8}	2.30×10^{-7}	2.64×10^{-7}	4.80×10^{-6}
		R 143 (trifluoroethane)	0.00×10^{0}	2.22×10^{-8}	3.77×10^{-8}	4.58×10^{-10}
		R 152a (difluoroethane)	5.38×10^{-8}	2.04×10^{-7}	2.04×10^{-7}	5.79×10^{-5}
		R 21 (Dichlorofluoromethane)	1.44×10^{-14}	1.83×10^{-12}	1.83×10^{-12}	1.30×10^{-9}
		R 22 (chlorodifluoromethane)	1.02×10^{-6}	5.34×10^{-6}	5.34×10^{-6}	7.16×10^{-5}
		R 23 (trifluoromethane)	9.11×10^{-11}	1.55×10^{-6}	2.62×10^{-6}	8.26×10^{-6}
		R 245fa	0.00×10^{0}	1.07×10^{-6}	1.83×10^{-6}	2.22×10^{-8}
		R32 (difluoromethane)	0.00×10^{0}	7.54×10^{-9}	1.28×10^{-8}	1.56×10^{-10}
		Tetrafluoromethane	2.56×10^{-7}	3.51×10^{-6}	3.85×10^{-6}	9.63×10^{-5}
		Trichloromethane (chloroform)	4.74×10^{-10}	4.68×10^{-7}	4.68×10^{-7}	6.80×10^{-7}
	Methane	Methane	4.56×10^{-3}	3.97×10^{-2}	3.60×10^{-2}	2.53×10^{-2}
		Methane (biotic)	2.37×10^{-5}	1.24×10^{-3}	1.68×10^{-3}	3.38×10^{-4}

Table 12-11: Contribution of each input to each impact category (purely operational) (IPCC AR5).

Process	IPCC AR5				
	GWP100, excl biogenic carbon [kg $CO_{2\ eq}$]	GWP20, excl biogenic carbon [kg $CO_{2\ eq}$]	GTP100, excl biogenic carbon [kg $CO_{2\ eq}$]	GTP50, excl biogenic carbon [kg $CO_{2\ eq}$]	GTP20, excl biogenic carbon [kg $CO_{2\ eq}$]
Yeast extract	68.20%	69.43%	68.20%	67.43%	69.43%
Cobalt Chloride, 6-Hydrate	0.00%	0.00%	0.00%	0.00%	0.00%
Manganese(II) chloride tetrahydrate	0.00%	0.00%	0.00%	0.00%	0.00%
Natural gas	0.21%	0.28%	0.21%	0.18%	0.28%
Sodium molybdate dihydrate	0.00%	0.00%	0.00%	0.00%	0.00%
Sodium thiosulfate	0.04%	0.04%	0.04%	0.04%	0.04%
Potassium hydrogen phosphate	8.93%	8.38%	8.93%	9.27%	8.38%
Zinc Chloride	0.00%	0.00%	0.00%	0.00%	0.00%
diesel, low-sulfur	0.07%	0.07%	0.07%	0.07%	0.07%
calcium chloride	0.00%	0.00%	0.00%	0.00%	0.00%
citric acid	0.09%	0.08%	0.09%	0.09%	0.08%
copper sulfate	0.00%	0.00%	0.00%	0.00%	0.00%
EDTA	0.02%	0.03%	0.02%	0.02%	0.03%
iron (III) chloride	0.01%	0.01%	0.01%	0.01%	0.01%
magnesium sulfate	0.00%	0.00%	0.00%	0.00%	0.00%
methanol	0.95%	1.13%	0.95%	0.85%	1.13%
phosphoric acid	0.65%	0.60%	0.65%	0.68%	0.60%
sodium hydroxide	0.07%	0.07%	0.07%	0.07%	0.07%
sodium hypochlorite	0.37%	0.35%	0.37%	0.38%	0.35%
sodium nitrate	0.44%	0.40%	0.44%	0.45%	0.40%
solvent, organic	0.33%	0.33%	0.33%	0.34%	0.33%
water, deionised	2.73%	2.61%	2.73%	2.81%	2.61%
zinc monosulfate	0.00%	0.00%	0.00%	0.00%	0.00%
Photovoltaic electricity	15.74%	15.19%	15.74%	16.12%	15.19%
hydrochloric acid	0.53%	0.50%	0.53%	0.55%	0.50%
passenger car use	0.19%	0.18%	0.19%	0.18%	0.18%
treatment of brake wear emissions	0.00%	0.00%	0.00%	0.00%	0.00%
treatment of tyre wear emissions	0.00%	0.00%	0.00%	0.00%	0.00%
treatment of road wear emissions	0.00%	0.00%	0.00%	0.00%	0.00%
Transport, combination truck	0.40%	0.33%	0.40%	0.44%	0.33%

Table 12-12: Contribution of each input to each impact category (purely operational) (IPCC AR5).

Process	ReCiPe 1.08 Endpoint (H)			
	Freshwater ecotoxicity [species.yr]	Human toxicity [DALY]	Marine ecotoxicity [species.yr]	Terrestrial ecotoxicity [species.yr]
Yeast extract	40.82%	37.26%	39.04%	18.91%
Cobalt Chloride, 6-Hydrate	0.00%	0.00%	0.00%	0.00%
Manganese(II) chloride tetrahydrate	0.00%	0.00%	0.00%	0.00%
Natural gas	0.37%	0.21%	0.33%	0.12%
Sodium molybdate dihydrate	0.00%	0.00%	0.00%	0.00%
Sodium thiosulfate	0.00%	0.01%	0.00%	0.00%
Potassium hydrogen phosphate	0.15%	1.21%	0.11%	0.55%
Zinc Chloride	0.00%	0.00%	0.00%	0.00%
diesel, low-sulfur	0.06%	0.05%	0.06%	0.08%
calcium chloride	0.01%	0.01%	0.01%	0.01%
citric acid	0.16%	0.16%	0.15%	0.35%
copper sulfate	0.04%	0.26%	0.05%	0.05%
EDTA	0.05%	0.04%	0.04%	0.02%
iron (III) chloride	0.05%	0.03%	0.04%	0.01%
magnesium sulfate	0.00%	0.00%	0.00%	0.00%
methanol	0.94%	1.10%	0.73%	0.62%
phosphoric acid	1.53%	2.18%	1.50%	1.21%
sodium hydroxide	0.30%	0.18%	0.29%	0.03%
sodium hypochlorite	1.33%	0.90%	1.28%	0.19%
sodium nitrate	0.42%	0.36%	0.41%	0.13%
solvent, organic	0.34%	0.35%	0.33%	0.33%
water, deionised	11.27%	6.75%	10.89%	1.79%
zinc monosulfate	0.00%	0.00%	0.00%	0.01%
Photovoltaic electricity	40.97%	42.71%	41.89%	62.05%
hydrochloric acid	1.15%	1.52%	1.20%	0.98%
passenger car use	0.01%	1.61%	0.27%	2.00%
treatment of brake wear emissions	0.02%	2.99%	1.30%	7.90%
treatment of tyre wear emissions	0.03%	0.12%	0.07%	2.65%
treatment of road wear emissions	0.00%	0.00%	0.00%	0.00%
Transport, combination truck	0.00%	0.00%	0.00%	0.00%

Table 12-13: Contribution of each input to each impact category (purely operational) (ReCiPe 1.08 Midpoint (H)) (first 8).

Process	ReCiPe 1.08 Midpoint (H)							
	Agricultural land occupation [m2a]	Climate change, excl biogenic carbon [kg CO2 eq]	Fossil depletion [kg oil eq]	Freshwater ecotoxicity [kg 1,4-DB eq]	Freshwater eutrophication [kg P eq]	Human toxicity [kg 1,4-DB eq]	Ionising radiation [kg U235 eq]	Marine ecotoxicity [kg 1,4-DB eq]
Yeast extract	88.87%	68.06%	58.20%	40.82%	46.67%	37.25%	48.63%	38.99%
Cobalt Chloride, 6-Hydrate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Manganese(II) chloride tetrahydrate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Natural gas	0.02%	0.21%	1.25%	0.37%	0.13%	0.21%	0.23%	0.33%
Sodium molybdate dihydrate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Sodium thiosulfate	0.00%	0.04%	0.08%	0.00%	0.00%	0.01%	0.00%	0.00%
Potassium hydrogen phosphate	0.83%	8.97%	14.87%	0.15%	0.19%	1.21%	0.04%	0.11%
Zinc Chloride	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
diesel, low-sulfur	0.01%	0.07%	0.54%	0.06%	0.04%	0.05%	0.08%	0.06%
calcium chloride	0.01%	0.00%	0.00%	0.01%	0.01%	0.01%	0.01%	0.01%
citric acid	0.21%	0.09%	0.08%	0.16%	0.12%	0.16%	0.11%	0.15%
copper sulfate	0.00%	0.00%	0.00%	0.04%	0.26%	0.26%	0.01%	0.05%
EDTA	0.01%	0.02%	0.03%	0.05%	0.03%	0.04%	0.04%	0.04%
iron (III) chloride	0.01%	0.01%	0.01%	0.05%	0.03%	0.03%	0.03%	0.04%
magnesium sulfate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
methanol	0.05%	0.93%	3.51%	0.94%	0.64%	1.09%	0.55%	0.73%
phosphoric acid	0.41%	0.65%	0.98%	1.54%	3.74%	2.18%	0.88%	1.51%
sodium hydroxide	0.03%	0.07%	0.07%	0.30%	0.14%	0.18%	0.25%	0.29%
sodium hypochlorite	0.23%	0.37%	0.36%	1.32%	0.76%	0.90%	1.10%	1.27%
sodium nitrate	0.09%	0.47%	0.27%	0.42%	0.33%	0.36%	0.38%	0.41%
solvent, organic	0.17%	0.33%	1.66%	0.34%	0.32%	0.35%	0.31%	0.33%
water, deionised	0.98%	2.74%	2.63%	11.26%	5.08%	6.75%	9.36%	10.85%
zinc monosulfate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Photovoltaic electricity	7.65%	15.80%	14.85%	40.97%	39.87%	42.75%	34.47%	41.92%
hydrochloric acid	0.42%	0.53%	0.60%	1.15%	1.62%	1.52%	3.52%	1.20%
passenger car use	0.00%	0.22%	0.00%	0.01%	0.00%	1.60%	0.00%	0.28%
treatment of brake wear emissions	0.00%	0.00%	0.00%	0.02%	0.00%	2.98%	0.00%	1.35%
treatment of tyre wear emissions	0.00%	0.00%	0.00%	0.03%	0.00%	0.12%	0.00%	0.07%
treatment of road wear emissions	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Transport, combination truck	0.00%	0.41%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 12-14: Contribution of each input to each impact category (purely operational) (ReCiPe 1.08 Midpoint (H)) (second 8).

Process	ReCiPe 1.08 Midpoint (H)							
	Marine eutrophication [kg N eq]	Metal depletion [kg Fe eq]	Ozone depletion [kg CFC-11 eq]	Particulate matter formation [kg PM10 eq]	Photochemical oxidant formation [kg NMVOC]	Terrestrial acidification [kg SO2 eq]	Terrestrial ecotoxicity [kg 1,4-DB eq]	Water depletion [m3]
Yeast extract	79.50%	18.05%	47.61%	59.54%	54.14%	66.19%	18.76%	37.69%
Cobalt Chloride, 6-Hydrate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Manganese(II) chloride tetrahydrate	0.00%	0.13%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Natural gas	0.03%	0.12%	1.48%	0.17%	0.17%	0.21%	0.12%	0.09%
Sodium molybdate dihydrate	0.00%	1.60%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Sodium thiosulfate	0.01%	0.00%	0.00%	0.02%	0.02%	0.02%	0.00%	0.03%
Potassium hydrogen phosphate	2.23%	0.73%	0.04%	7.57%	6.95%	8.31%	0.55%	5.71%
Zinc Chloride	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
diesel, low-sulfur	0.02%	0.04%	0.83%	0.07%	0.11%	0.08%	0.08%	0.02%
calcium chloride	0.00%	0.01%	0.00%	0.00%	0.00%	0.01%	0.01%	0.00%
citric acid	0.15%	0.09%	0.15%	0.08%	0.07%	0.08%	0.36%	0.05%
copper sulfate	0.02%	0.61%	0.00%	0.03%	0.01%	0.03%	0.05%	0.01%
EDTA	0.11%	0.03%	0.05%	0.02%	0.02%	0.02%	0.02%	0.01%
iron (III) chloride	0.00%	0.04%	0.05%	0.01%	0.01%	0.01%	0.01%	0.01%
magnesium sulfate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
methanol	0.17%	0.70%	1.75%	0.89%	0.98%	1.22%	0.62%	0.19%
phosphoric acid	0.31%	1.87%	1.19%	1.21%	0.90%	1.23%	1.20%	0.44%
sodium hydroxide	0.03%	0.08%	0.42%	0.07%	0.06%	0.06%	0.03%	0.08%
sodium hypochlorite	0.15%	0.76%	1.72%	0.35%	0.33%	0.32%	0.19%	0.36%
sodium nitrate	1.94%	0.47%	0.25%	0.24%	0.26%	0.27%	0.13%	0.13%
solvent, organic	0.10%	0.50%	3.37%	0.30%	0.66%	0.33%	0.33%	0.10%
water, deionised	0.98%	3.84%	11.74%	2.60%	2.25%	2.23%	1.79%	3.35%
zinc monosulfate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%
Photovoltaic electricity	10.21%	68.96%	26.61%	15.83%	16.30%	14.18%	62.26%	51.05%
hydrochloric acid	0.27%	1.36%	2.72%	0.44%	0.44%	0.45%	0.98%	0.66%
passenger car use	3.56%	0.00%	0.00%	8.27%	15.62%	4.50%	1.99%	0.00%
treatment of brake wear emissions	0.00%	0.00%	0.00%	0.67%	0.00%	0.01%	7.85%	0.00%
treatment of tyre wear emissions	0.01%	0.00%	0.00%	0.62%	0.00%	0.00%	2.66%	0.00%
treatment of road wear emissions	0.00%	0.00%	0.00%	0.75%	0.00%	0.00%	0.00%	0.00%
Transport, combination truck	0.17%	0.00%	0.00%	0.26%	0.68%	0.22%	0.00%	0.00%

Table 12-15: Inputs and outputs of NREL model used for microalgae transesterification, modified from "RNA: Soy biodiesel, production, at plant USB/NREL USLCI <u-so>". Figures the same, just the names changed.

Flow	Amount	Unit
Input		
RNA: Electricity, at grid, U.S. [Products and Intermediates]	0.431996544	MJ
RNA: Methanol, at plant [Products and Intermediates]	0.305	kg
RNA: Natural gas, combusted in industrial boiler [Products and Intermediates]	0.0762	m3
RNA: Sodium hydroxide, production mix, at plant [Products and Intermediates]	0.00327	kg
RNA: Soybean oil, crude, degummed, at plant [Products and Intermediates]	3.32	kg
RNA: Transport, combination truck, diesel powered [Products and Intermediates]	1240	kgkm
RNA: Dummy, Citric Acid, at plant [Dummy Flows]	0.00245	kg
RNA: Dummy, Hydrochloric Acid, at plant [Dummy Flows]	0.146	kg
RNA: Dummy, Phosphoric Acid, at plant [Dummy Flows]	0.00213	kg
RNA: Dummy, Sodium Methylate, at plant [Dummy Flows]	0.0777	kg
Water (river water) [Water]	0.00114	kg
Output		
RNA: Glycerin, at biodiesel plant [Products and Intermediates]	0.403	kg
RNA: Algae biodiesel, production, at plant [Products and Intermediates]	3.36	kg
Fatty acids (calculated as total carbon) [Hydrocarbons to fresh water]	0.00694	kg

Table 12-16: Use phase, almost identical to the Ecoinvent model "transport, passenger car, medium size, diesel, EURO 3 (biodiesel)", except that fuel used modified to account for an estimate of 38MJ/kg energy density of microalgae-derived biodiesel.

Flow	Amount	Unit
Input		
brake wear emissions, passenger car [Waste]	-7.55E-06	kg
diesel, low-sulfur [allocatable product]	0.06062	kg
passenger car maintenance [allocatable product]	8.60E-06	pcs.
road [allocatable product]	0.000911396	ma
road wear emissions, passenger car [Waste]	-1.66E-05	kg
tyre wear emissions, passenger car [Waste]	-9.72E-05	kg
Output		
RER: transport, passenger car, medium size, diesel, EURO 3 [allocatable product]	1000	m
Acetaldehyde (Ethanal) [Group NMVOC to air]	1.79E-06	kg
Acetone (dimethylcetone) [Group NMVOC to air]	8.11E-07	kg
Acrolein [Group NMVOC to air]	9.88E-07	kg
Ammonia [Inorganic emissions to air]	9.70E-07	kg
Benzaldehyde [Group NMVOC to air]	2.37E-07	kg
Benzene [Group NMVOC to air]	5.46E-07	kg
Butane [Group NMVOC to air]	3.04E-08	kg
Butanone (methyl ethyl ketone) [Group NMVOC to air]	3.31E-07	kg
Cadmium [Heavy metals to air]	6.06E-10	kg
Carbon dioxide (biotic) [Inorganic emissions to air]	0.18999	kg
Carbon monoxide [Inorganic emissions to air]	7.57E-05	kg
Chromium (unspecified) [Heavy metals to air]	3.03E-09	kg
Chromium IV [Heavy metals to air]	6.06E-12	kg
Copper [Heavy metals to air]	1.03E-07	kg
Cycloalkanes (unspec.) [Group NMVOC to air]	1.79E-07	kg
Dust (PM2.5) [Particles to air]	3.56E-05	kg
Ethane [Group NMVOC to air]	9.11E-08	kg
Ethylene oxide [Group NMVOC to air]	3.03E-06	kg
Formaldehyde (methanal) [Group NMVOC to air]	3.31E-06	kg
Heptane (isomers) [Group NMVOC to air]	5.52E-08	kg
Lead [Heavy metals to air]	5.00E-15	kg
Mercury [Heavy metals to air]	1.21E-12	kg
Methane [Organic emissions to air (group VOC)]	2.08E-06	kg
Nickel [Heavy metals to air]	4.25E-09	kg
Nitrogen oxides [Inorganic emissions to air]	0.000253	kg
Nitrous oxide (laughing gas) [Inorganic emissions to air]	3.03E-06	kg
NMVOC (unspecified) [Group NMVOC to air]	1.46E-05	kg
Pentane (n-pentane) [Group NMVOC to air]	1.10E-08	kg
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Group PAH to air]	1.12E-08	kg
Propane [Group NMVOC to air]	3.04E-08	kg
Propylene oxide [Group NMVOC to air]	9.93E-07	kg
Selenium [Heavy metals to air]	6.06E-10	kg
Styrene [Group NMVOC to air]	1.02E-07	kg
Sulphur dioxide [Inorganic emissions to air]	1.21E-06	kg
Toluene (methyl benzene) [Group NMVOC to air]	1.90E-07	kg
Xylene (meta-Xylene; 1,3-Dimethylbenzene) [Group NMVOC to air]	1.68E-07	kg
Xylene (ortho-Xylene; 1,2-Dimethylbenzene) [Group NMVOC to air]	7.45E-08	kg
Zinc [Heavy metals to air]	6.06E-08	kg

12.2 Alternative material choices for facility build

Table 12-17: Impacts of Necton PBR system construction (including recycling and end of life)

ReCiPe 2016 Impacts		Impact result
Name	**Unit**	**Baseline**
climate change	kg CO2-Eq	5.21×10^{5}
agricultural land occupation	m2a	1.51×10^{2}
urban land occupation	m2a	3.80×10^{3}
natural land transformation	m2	-6.22×10^{0}
marine eutrophication	kg N-Eq	5.97×10^{2}
photochemical oxidant formation	kg NMVOC	1.93×10^{3}
freshwater ecotoxicity	kg 1,4-DCB-Eq	1.04×10^{4}
freshwater eutrophication	kg P-Eq	8.05×10^{1}
marine ecotoxicity	kg 1,4-DCB-Eq	9.78×10^{3}
water depletion	m3	7.16×10^{2}
fossil depletion	kg oil-Eq	1.74×10^{5}
terrestrial acidification	kg SO2-Eq	2.08×10^{3}
human toxicity	kg 1,4-DCB-Eq	1.39×10^{5}
ionising radiation	kg U235-Eq	1.84×10^{4}
terrestrial ecotoxicity	kg 1,4-DCB-Eq	3.47×10^{1}
metal depletion	kg Fe-Eq	1.60×10^{5}
ozone depletion	kg CFC-11-Eq	1.53×10^{-2}
particulate matter formation	kg PM10-Eq	1.11×10^{3}

Table 12-18: Impacts of Necton PBR system construction compared with a version with glass PBR and with tanks from FRP

ReCiPe 2016 Impacts		Impact result		
Name	**Unit**	**Baseline**	**With glass PBRs**	**Glass PBRs + steel tanks (no FRP)**
climate change	kg CO2-Eq	5.21×10^{5}	2.95×10^{5}	2.37×10^{5}
agricultural land occupation	m2a	1.51×10^{2}	6.91×10^{1}	6.57×10^{1}
urban land occupation	m2a	3.80×10^{3}	2.04×10^{3}	1.94×10^{3}
natural land transformation	m2	-6.22×10^{0}	2.13×10^{1}	2.13×10^{1}
marine eutrophication	kg N-Eq	5.97×10^{2}	4.22×10^{2}	3.39×10^{2}
photochemical oxidant formation	kg NMVOC	1.93×10^{3}	1.21×10^{3}	1.07×10^{3}
freshwater ecotoxicity	kg 1,4-DCB-Eq	1.04×10^{4}	8.65×10^{3}	8.30×10^{3}
freshwater eutrophication	kg P-Eq	8.05×10^{1}	7.96×10^{1}	7.45×10^{1}
marine ecotoxicity	kg 1,4-DCB-Eq	9.78×10^{3}	8.55×10^{3}	8.26×10^{3}
water depletion	m3	7.16×10^{2}	6.44×10^{2}	6.03×10^{2}
fossil depletion	kg oil-Eq	1.74×10^{5}	1.05×10^{5}	8.69×10^{4}
terrestrial acidification	kg SO2-Eq	2.08×10^{3}	1.45×10^{3}	1.26×10^{3}
human toxicity	kg 1,4-DCB-Eq	1.39×10^{5}	1.11×10^{5}	1.06×10^{5}
ionising radiation	kg U235-Eq	1.84×10^{4}	1.33×10^{4}	1.19×10^{4}
terrestrial ecotoxicity	kg 1,4-DCB-Eq	3.47×10^{1}	2.33×10^{1}	2.21×10^{1}
metal depletion	kg Fe-Eq	1.60×10^{5}	1.51×10^{5}	1.50×10^{5}
ozone depletion	kg CFC-11-Eq	1.53×10^{-2}	1.16×10^{-2}	1.06×10^{-2}
particulate matter formation	kg PM10-Eq	1.11×10^{3}	8.69×10^{2}	7.93×10^{2}

Table 12-19: Impacts of Necton PBR system construction compared with a version with glass PBR and with additionally tanks from FRP in terms of percentage of impacts.

ReCiPe 2016 Impacts		Impact result as a percentage of the baseline	
Name	**Unit**	**With glass PBRs**	**Glass PBRs + steel tanks (no FRP)**
climate change	kg CO2-Eq	57%	45%
agricultural land occupation	m2a	46%	43%
urban land occupation	m2a	54%	51%
natural land transformation	m2	-343%	-342%
marine eutrophication	kg N-Eq	71%	57%
photochemical oxidant formation	kg NMVOC	62%	55%
freshwater ecotoxicity	kg 1,4-DCB-Eq	83%	80%
freshwater eutrophication	kg P-Eq	99%	93%
marine ecotoxicity	kg 1,4-DCB-Eq	87%	84%
water depletion	m3	90%	84%
fossil depletion	kg oil-Eq	60%	50%
terrestrial acidification	kg SO2-Eq	70%	61%
human toxicity	kg 1,4-DCB-Eq	80%	76%
ionising radiation	kg U235-Eq	72%	65%
terrestrial ecotoxicity	kg 1,4-DCB-Eq	67%	64%
metal depletion	kg Fe-Eq	94%	94%
ozone depletion	kg CFC-11-Eq	76%	70%
particulate matter formation	kg PM10-Eq	78%	71%

12.3 Magnificent Results

Table 12-20: Basic arithmetic analysis. The LCA AR5 and ReCiPe impacts of soy and microalgae, on a per MJ basis. The MJ content of microalgae is taken as 38MJ/kg, and soy is 15MJ/kg.

Impact Category	Soybean (RoW)		Algae			
	Standard Electricity		2016-2017		80% PV	
	With inf	No inf	With inf	No inf	With inf	No inf
AR 5						
GTP 100 year	4.85×10^{-2}	3.51×10^{-2}	3.04×10^{-1}	1.30×10^{-1}	2.55×10^{-1}	8.03×10^{-2}
GTP 20 year	7.50×10^{-2}	5.75×10^{-2}	4.33×10^{-1}	1.92×10^{-1}	3.74×10^{-1}	1.33×10^{-1}
GWP 100 year	6.02×10^{-2}	4.52×10^{-2}	3.54×10^{-1}	1.54×10^{-1}	3.00×10^{-1}	1.00×10^{-1}
GWP 20 year	8.41×10^{-2}	6.52×10^{-2}	4.67×10^{-1}	2.08×10^{-1}	4.05×10^{-1}	1.46×10^{-1}
ReCiPe						
agricultural land occupation	6.20×10^{-3}	6.19×10^{-3}	6.83×10^{-5}	4.43×10^{-5}	5.10×10^{-5}	2.70×10^{-5}
climate change	5.18×10^{-2}	3.78×10^{-2}	3.42×10^{-1}	1.49×10^{-1}	2.90×10^{-1}	9.62×10^{-2}
fossil depletion	1.13×10^{-2}	5.98×10^{-3}	1.18×10^{-1}	4.24×10^{-2}	9.94×10-2	2.42×10^{-2}
freshwater ecotoxicity	2.71×10^{-3}	2.51×10^{-3}	9.61×10^{-3}	1.99×10^{-3}	1.08×10-2	3.15×10^{-3}
freshwater eutrophication	2.78×10^{-5}	2.21×10^{-5}	9.41×10^{-5}	4.93×10^{-5}	9.34×10-5	4.86×10^{-5}
human toxicity	1.72×10^{-2}	1.00×10^{-2}	1.13×10^{-1}	4.47×10^{-2}	1.23×10-1	5.52×10^{-2}
ionising radiation	3.29×10^{-3}	2.52×10^{-3}	1.76×10^{-2}	1.32×10^{-2}	1.89×10-2	1.44×10^{-2}
marine ecotoxicity	8.10×10^{-4}	6.09×10^{-4}	8.78×10^{-3}	1.85×10^{-3}	9.89×10-3	2.96×10^{-3}
marine eutrophication	5.78×10^{-4}	5.58×10^{-4}	3.02×10^{-4}	1.05×10^{-4}	2.76×10-4	7.97×10^{-5}
metal depletion	4.72×10^{-3}	8.12×10^{-4}	8.06×10^{-2}	5.06×10^{-3}	8.42×10-2	8.68×10^{-3}
natural land transformation	1.99×10^{-3}	1.99×10^{-3}	6.37×10^{-6}	5.48×10^{-6}	4.32×10-6	3.42×10^{-6}
ozone depletion	3.51×10^{-9}	2.65×10^{-9}	1.50×10^{-8}	1.14×10^{-8}	1.27×10-8	9.09×10^{-9}
particulate matter formation	4.62×10^{-4}	4.20×10^{-4}	6.08×10^{-4}	1.76×10^{-4}	5.90×10-4	1.58×10^{-4}
photochemical oxidant formation	5.02×10^{-4}	4.15×10^{-4}	1.05×10^{-3}	2.99×10^{-4}	9.74×10-4	2.23×10^{-4}
terrestrial acidification	3.12×10^{-4}	2.41×10^{-4}	1.42×10^{-3}	5.52×10^{-4}	1.24×10-3	3.77×10^{-4}
terrestrial ecotoxicity	4.12×10^{-3}	4.11×10^{-3}	2.45×10^{-5}	1.50×10^{-5}	6.17×10-5	5.22×10^{-5}
urban land occupation	1.22×10^{-3}	6.84×10^{-4}	1.36×10^{-3}	5.30×10^{-4}	1.23×10-3	4.03×10^{-4}
water depletion	1.74×10^{-1}	1.74×10^{-1}	8.62×10^{-4}	6.00×10^{-4}	7.43×10-4	4.81×10^{-4}

Table 12-21: Arithmetic calculation of the percentage impact of microalgae when compared with soy, on a per MJ basis.

Impact Category	2016-2017		80% PV	
	With inf	No inf	With inf	No inf
AR 5				
GTP 100 year	627%	369%	525%	229%
GTP 20 year	578%	334%	498%	231%
GWP 100 year	587%	340%	499%	222%
GWP 20 year	555%	320%	482%	224%
ReCiPe				
agricultural land occupation	1%	1%	1%	0%
climate change	559%	393%	559%	254%
fossil depletion	877%	709%	877%	406%
freshwater ecotoxicity	397%	79%	397%	126%
freshwater eutrophication	336%	223%	336%	220%
human toxicity	715%	445%	715%	549%
ionising radiation	574%	523%	574%	573%
marine ecotoxicity	1221%	303%	1221%	485%
marine eutrophication	48%	19%	48%	14%
metal depletion	1783%	624%	1783%	1070%
natural land transformation	0%	0%	0%	0%
ozone depletion	360%	430%	360%	343%
particulate matter formation	128%	42%	128%	38%
photochemical oxidant formation	194%	72%	194%	54%
terrestrial acidification	398%	229%	398%	156%
terrestrial ecotoxicity	1%	0%	1%	1%
urban land occupation	101%	78%	101%	59%
water depletion	0%	0%	0%	0%

Table 12-22: The LCA AR5 and ReCiPe impacts of soy and microalgae, on a per MJ basis. The MJ content of microalgae is taken as 38MJ/kg, and soy is 15MJ/kg. The Geometric mean and geometric standard deviation are calculated using the pedigree method as described within the methodology.

	Soyabean (RoW)				Algae							
	Standard electricity				2016-2017				80% PV			
	With Infrastructure		Without Infrastructure		With Infrastructure		Without Infrastructure		With Infrastructure		Without Infrastructure	
Impact Category	Geomean	Geostd	Geomean	Geostd	Geomean	Geostd	Geomean	Geostd	Geomean	Geostd	Geomean	Geostd
AR 5												
GTP 100 year	5.21×10^{-2}	1.14	3.70×10^{-2}	1.13	1.61×10^{-1}	1.2	1.36×10^{-1}	1.18	1.11×10^{-1}	1.19	6.99×10^{-2}	1.17
GTP 20 year	8.03×10^{-2}	1.14	5.99×10^{-2}	1.12	2.37×10^{-1}	1.21	2.03×10^{-1}	1.19	1.75×10^{-1}	1.2	1.22×10^{-1}	1.21
GWP 100 year	6.45×10^{-2}	1.14	4.73×10^{-2}	1.12	1.91×10^{-1}	1.2	1.62×10^{-1}	1.18	1.36×10^{-1}	1.19	9.00×10^{-2}	1.18
GWP 20 year	8.99×10^{-2}	1.14	6.78×10^{-2}	1.12	2.57×10^{-1}	1.21	2.20×10^{-1}	1.19	1.91×10^{-1}	1.21	1.35×10^{-1}	1.22
ReCiPe												
agricultural land occupation	6.22×10^{-3}	1.12	6.22×10^{-3}	1.12	4.87×10^{-5}	1.27	4.67×10^{-5}	1.26	3.21×10^{-5}	1.19	2.39×10^{-5}	1.19
climate change	5.63×10^{-2}	1.17	4.00×10^{-2}	1.12	1.85×10^{-1}	1.19	1.58×10^{-1}	1.17	1.32×10^{-1}	1.18	8.50×10^{-2}	1.16
fossil depletion	1.26×10^{-2}	1.18	6.54×10^{-3}	1.14	5.25×10^{-2}	1.18	4.42×10^{-2}	1.16	3.46×10^{-2}	1.18	2.10×10^{-2}	1.15
freshwater ecotoxicity	3.29×10^{-3}	1.33	2.81×10^{-3}	1.16	4.01×10^{-3}	1.42	3.29×10^{-3}	1.41	5.34×10^{-3}	1.41	2.94×10^{-3}	1.39
freshwater eutrophication	3.50×10^{-5}	1.34	2.61×10^{-5}	1.29	8.20×10^{-5}	1.61	6.63×10^{-5}	1.61	7.69×10^{-5}	1.58	5.21×10^{-5}	1.62
human toxicity	3.70×10^{-2}	1.69	1.97×10^{-2}	1.65	1.40×10^{-1}	1.99	1.08×10^{-1}	1.98	1.47×10^{-1}	1.78	8.98×10^{-2}	1.84
ionising radiation	4.49×10^{-3}	1.77	3.40×10^{-3}	1.79	1.78×10^{-2}	2.02	1.63×10^{-2}	2.05	1.97×10^{-2}	2.01	1.60×10^{-2}	2.01
marine ecotoxicity	1.27×10^{-3}	1.47	8.43×10^{-4}	1.28	3.73×10^{-3}	1.42	3.09×10^{-3}	1.41	5.03×10^{-3}	1.4	2.78×10^{-3}	1.39
marine eutrophication	6.08×10^{-4}	1.2	5.84×10^{-4}	1.2	1.60×10^{-4}	1.22	1.18×10^{-4}	1.28	1.33×10^{-4}	1.19	6.91×10^{-5}	1.18
metal depletion	5.39×10^{-3}	1.19	1.02×10^{-3}	1.19	7.74×10^{-3}	1.47	6.17×10^{-3}	1.54	1.16×10^{-2}	1.33	6.71×10^{-3}	1.49
natural land transformation	2.00×10^{-3}	1.14	2.00×10^{-3}	1.13	7.46×10^{-6}	1.49	7.28×10^{-6}	1.49	4.98×10^{-6}	1.42	3.52×10^{-6}	1.42
ozone depletion	4.47×10^{-9}	1.36	3.30×10^{-9}	1.33	1.33×10^{-8}	1.21	1.27×10^{-8}	1.18	1.09×10^{-8}	1.2	7.41×10^{-9}	1.17
particulate matter formation	4.83×10^{-4}	1.13	4.32×10^{-4}	1.12	2.42×10^{-4}	1.24	2.02×10^{-4}	1.24	2.25×10^{-4}	1.2	1.27×10^{-4}	1.21
photochem oxidant formation	5.38×10^{-4}	1.13	4.33×10^{-4}	1.12	4.08×10^{-4}	1.23	3.40×10^{-4}	1.23	3.29×10-4	1.19	1.87×10-4	1.18
terrestrial acidification	3.47×10^{-4}	1.17	2.62×10^{-4}	1.13	7.07×10^{-4}	1.26	6.12×10^{-4}	1.28	5.29×10-4	1.19	3.27×10-4	1.2
terrestrial ecotoxicity	4.16×10^{-3}	1.23	4.12×10^{-3}	1.23	1.82×10^{-5}	1.33	1.77×10^{-5}	1.32	6.25×10-5	1.59	3.05×10-5	1.42
urban land occupation	1.42×10^{-3}	1.21	7.91×10^{-4}	1.2	8.11×10^{-4}	1.59	7.09×10^{-4}	1.64	6.69×10-4	1.37	4.07×10-4	1.43
water depletion	1.85×10^{-1}	1.16	1.84×10^{-1}	1.16	6.81×10^{-4}	1.21	6.44×10-4	1.19	5.53×10-4	1.19	4.27×10-4	1.17

Table 12-23: The percentage impact of microalgae when compared with soy, on a per MJ basis. The Geometric standard deviation is calculated from that within Table 14-24 using $\sigma_x = exp\sqrt{(ln\sigma_a)^2 + (ln\sigma_b)^2}$.

Impact Category	2016-2017				80% PV			
	With Infrastructure		Without Infrastructure		With Infrastructure		Without Infrastructure	
	Percentage	Geostd	Percentage	Geostd	Percentage	Geostd	Percentage	Geostd
AR 5								
GTP 100 year	310%	1.05	368%	1.04	214%	1.05	189%	1.04
GTP 20 year	295%	1.05	339%	1.04	218%	1.05	204%	1.05
GWP 100 year	295%	1.05	342%	1.04	211%	1.05	190%	1.04
GWP 20 year	285%	1.05	325%	1.04	213%	1.05	199%	1.05
ReCiPe								
agricultural land occupation	1%	1.07	1%	1.07	1%	1.05	0%	1.04
climate change	328%	1.06	393%	1.04	235%	1.05	212%	1.04
fossil depletion	418%	1.06	676%	1.04	275%	1.06	321%	1.04
freshwater ecotoxicity	122%	1.23	117%	1.15	162%	1.22	104%	1.14
freshwater eutrophication	234%	1.36	254%	1.34	220%	1.34	200%	1.34
human toxicity	378%	2.12	548%	2.05	398%	1.84	456%	1.86
ionising radiation	397%	2.26	478%	2.34	438%	2.26	471%	2.28
marine ecotoxicity	295%	1.31	366%	1.2	398%	1.3	330%	1.18
marine eutrophication	26%	1.08	20%	1.1	22%	1.07	12%	1.06
metal depletion	144%	1.2	606%	1.25	215%	1.12	658%	1.21
natural land transformation	0%	1.19	0%	1.19	0%	1.15	0%	1.15
ozone depletion	298%	1.14	384%	1.11	245%	1.14	224%	1.11
particulate matter formation	50%	1.06	47%	1.06	46%	1.05	29%	1.05
photochem oxidant formation	76%	1.06	78%	1.06	61%	1.05	43%	1.04
terrestrial acidification	204%	1.08	233%	1.08	153%	1.06	125%	1.05
terrestrial ecotoxicity	0%	1.13	0%	1.12	2%	1.29	1%	1.18
urban land occupation	57%	1.28	90%	1.32	47%	1.14	51%	1.17
water depletion	0%	1.06	0%	1.06	0%	1.05	0%	1.05

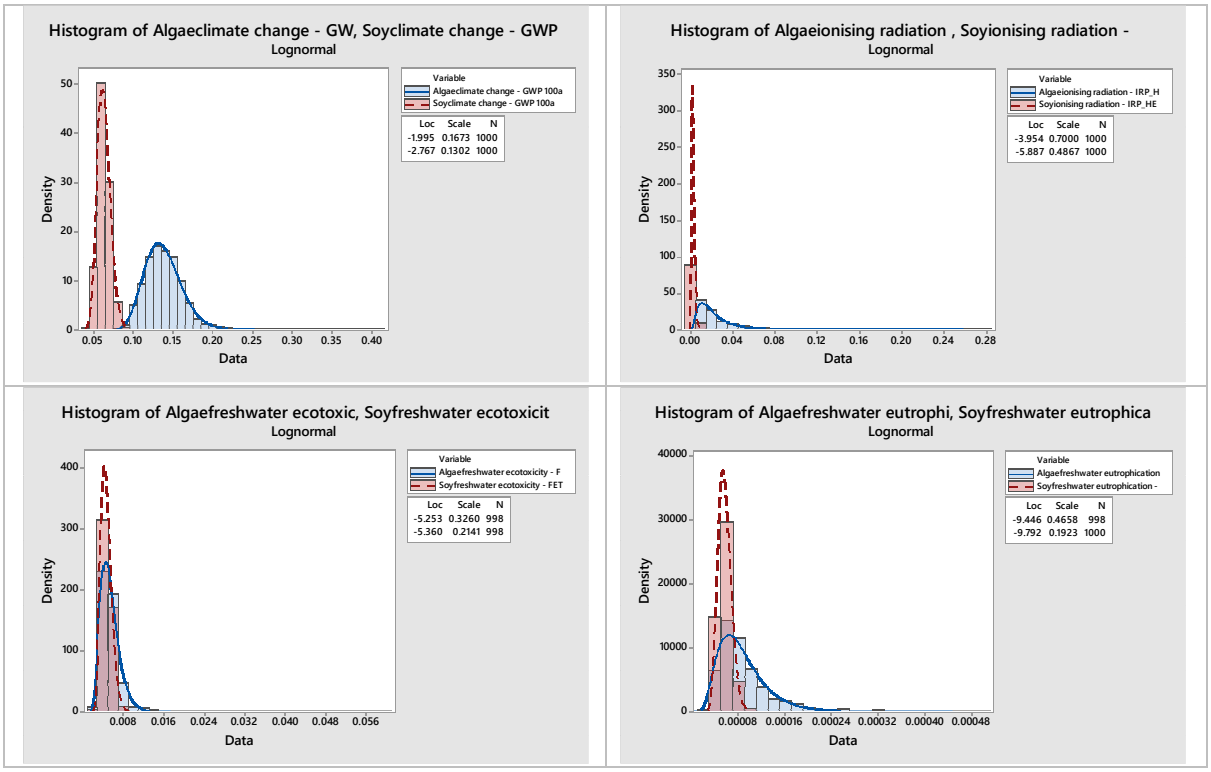

Figure 12-8: Examples of the lognormal distributions from the pedigree matrix-based uncertainty assessment. Four examples of various distributions are provided. These are all for the 80% PV scenario, with infrastructure.

Table 12-24: Sensitivity Analysis, each of the major impacts has been varied by +/-5%. Results from a basic arithmetic calculation, hence, no geometric standard deviations included. These are based on a grid electricity-based microalgae model, including infrastructure.

Impact category	Reference unit	Steel+	PMMA+	el+	Steel-	PMMA-	el-
AR5							
GTP 100 year	kg CO2-Eq	0.57%	1.35%	1.47%	-0.57%	-1.35%	-1.47%
GTP 20 year	kg CO2-Eq	0.49%	1.41%	1.26%	-0.49%	-1.41%	-1.26%
GWP 100 year	kg CO2-Eq	0.53%	1.38%	1.37%	-0.53%	-1.38%	-1.37%
GWP 20 year	kg CO2-Eq	0.48%	1.42%	1.22%	-0.48%	-1.42%	-1.22%
ReCiPe							
agricultural land occupation	m2a	1.32%	0.05%	2.27%	-1.32%	-0.05%	-2.27%
climate change	kg CO2-Eq	0.53%	1.38%	1.39%	-0.53%	-1.38%	-1.39%
fossil depletion	kg oil-Eq	0.39%	1.49%	1.30%	-0.39%	-1.49%	-1.30%
freshwater ecotoxicity	kg 1,4-DCB-Eq	3.16%	0.24%	0.45%	-3.16%	-0.24%	-0.45%
freshwater eutrophication	kg P-Eq	0.79%	0.21%	1.06%	-0.79%	-0.21%	-1.06%
human toxicity	kg 1,4-DCB-Eq	1.16%	0.07%	0.67%	-1.16%	-0.07%	-0.67%
ionising radiation	kg U235-Eq	0.57%	0.03%	0.27%	-0.57%	-0.03%	-0.27%
marine ecotoxicity	kg 1,4-DCB-Eq	3.27%	0.11%	0.45%	-3.27%	-0.11%	-0.45%
marine eutrophication	kg N-Eq	0.68%	1.41%	1.10%	-0.68%	-1.41%	-1.10%
metal depletion	kg Fe-Eq	4.39%	0.01%	0.08%	-4.39%	-0.01%	-0.08%
natural land transformation	m2	-0.19%	-0.03%	3.20%	0.19%	0.03%	-3.20%
ozone depletion	kg CFC-11-Eq	0.60%	0.07%	2.50%	-0.60%	-0.07%	-2.50%
particulate matter formation	kg PM10-Eq	1.69%	1.00%	0.93%	-1.69%	-1.00%	-0.93%
photochem oxidant formation	kg NMVOC	0.67%	1.80%	0.98%	-0.67%	-1.80%	-0.98%
terrestrial acidification	kg SO2-Eq	0.70%	1.49%	1.34%	-0.70%	-1.49%	-1.34%
terrestrial ecotoxicity	kg 1,4-DCB-Eq	1.19%	0.16%	0.35%	-1.19%	-0.16%	-0.35%
urban land occupation	m2a	1.80%	0.17%	1.33%	-1.80%	-0.17%	-1.33%
water depletion	m3	0.66%	0.07%	1.61%	-0.66%	-0.07%	-1.61%

Table 12-25*: Total contribution to impacts by major sources. Based on a grid electricity-based microalgae model, including infrastructure.*

Impact category	Reference unit	Steel	PMMA	El	Total
AR5					
GTP 100 year	kg CO2-Eq	11%	27%	29%	68%
GTP 20 year	kg CO2-Eq	10%	28%	25%	63%
GWP 100 year	kg CO2-Eq	11%	28%	27%	66%
GWP 20 year	kg CO2-Eq	10%	28%	24%	63%
ReCiPe					
agricultural land occupation	m2a	26%	1%	45%	73%
climate change	kg CO2-Eq	11%	28%	28%	66%
fossil depletion	kg oil-Eq	8%	30%	26%	64%
freshwater ecotoxicity	kg 1,4-DCB-Eq	63%	5%	9%	77%
freshwater eutrophication	kg P-Eq	16%	4%	21%	41%
human toxicity	kg 1,4-DCB-Eq	23%	1%	13%	38%
ionising radiation	kg U235-Eq	11%	1%	6%	18%
marine ecotoxicity	kg 1,4-DCB-Eq	65%	2%	9%	77%
marine eutrophication	kg N-Eq	14%	28%	22%	64%
metal depletion	kg Fe-Eq	88%	0%	2%	89%
natural land transformation	m2	-4%	-1%	64%	59%
ozone depletion	kg CFC-11-Eq	12%	1%	50%	64%
particulate matter formation	kg PM10-Eq	34%	20%	19%	72%
photochem oxidant formation	kg NMVOC	13%	36%	20%	69%
terrestrial acidification	kg SO2-Eq	14%	30%	27%	71%
terrestrial ecotoxicity	kg 1,4-DCB-Eq	24%	3%	7%	34%
urban land occupation	m2a	36%	3%	27%	66%
water depletion	m3	13%	1%	32%	47%

Table 12-26*: Comparison of three different scenarios with the soy production. These are the baseline electricity output, using glass photobioreactors instead of PMMA, and turning the pumps off at night.*

Impact Category	Soyabean (RoW)	2016-2017	Glass	48% el reduction
AR 5				
GTP 100 year	4.85×10^{-2}	3.04×10^{-1}	2.34×10^{-1}	2.80×10^{-1}
GTP 20 year	7.50×10^{-2}	4.33×10^{-1}	3.26×10^{-1}	4.05×10^{-1}
GWP 100 year	6.02×10^{-2}	3.54×10^{-1}	2.70×10^{-1}	3.28×10^{-1}
GWP 20 year	8.41×10^{-2}	4.67×10^{-1}	3.50×10^{-1}	4.37×10^{-1}
ReCiPe				
agricultural land occupation	6.20×10^{-3}	6.82×10^{-5}	7.16×10^{-5}	6.01×10^{-5}
climate change	5.18×10^{-2}	3.42×10^{-1}	2.62×10^{-1}	3.17×10^{-1}
fossil depletion	1.13×10^{-2}	1.18×10^{-1}	8.63×10^{-2}	1.10×10^{-1}
freshwater ecotoxicity	2.71×10^{-3}	9.61×10^{-3}	9.30×10^{-3}	9.38×10^{-3}
freshwater eutrophication	2.78×10^{-5}	9.42×10^{-5}	9.50×10^{-5}	8.89×10^{-5}
human toxicity	1.72×10^{-2}	1.13×10^{-1}	1.16×10^{-1}	1.09×10^{-1}
ionising radiation	3.29×10^{-3}	1.76×10^{-2}	1.85×10^{-2}	1.74×10^{-2}
marine ecotoxicity	8.10×10^{-4}	8.78×10^{-3}	8.73×10^{-3}	8.57×10^{-3}
marine eutrophication	5.78×10^{-4}	3.02×10^{-4}	2.45×10^{-4}	2.85×10^{-4}
metal depletion	4.72×10^{-3}	8.06×10^{-2}	8.11×10^{-2}	8.03×10^{-2}
natural land transformation	1.99×10^{-3}	6.32×10^{-6}	9.76×10^{-6}	5.30×10^{-6}
ozone depletion	3.51×10^{-9}	1.50×10^{-8}	1.57×10^{-8}	1.30×10^{-8}
particulate matter formation	4.62×10^{-4}	6.08×10^{-4}	5.32×10^{-4}	5.79×10^{-4}
photochem oxidant formation	5.02×10^{-4}	1.05×10^{-3}	7.49×10^{-4}	9.96×10^{-4}
terrestrial acidification	3.12×10^{-4}	1.42×10^{-3}	1.09×10^{-3}	1.32×10^{-3}
terrestrial ecotoxicity	4.12×10^{-3}	2.45×10^{-5}	2.47×10^{-5}	2.40×10^{-5}
urban land occupation	1.22×10^{-3}	1.36×10^{-3}	1.43×10^{-3}	1.27×10^{-3}
water depletion	1.74×10^{-1}	8.62×10^{-4}	8.91×10^{-4}	7.90×10^{-4}

Table 12-27: The percentage impact of microalgae when compared with soy, on a per MJ basis. Highlighted cells have impacts lower than soy.

Impact Category	Baseline	Glass	48% el reduction
AR 5			
GTP 100 year	627%	484%	579%
GTP 20 year	578%	435%	539%
GWP 100 year	587%	448%	545%
GWP 20 year	555%	416%	520%
ReCiPe			
agricultural land occupation	1%	1%	1%
climate change	660%	505%	612%
fossil depletion	1037%	762%	966%
freshwater ecotoxicity	354%	343%	346%
freshwater eutrophication	339%	342%	320%
human toxicity	654%	672%	631%
ionising radiation	536%	563%	528%
marine ecotoxicity	1084%	1077%	1058%
marine eutrophication	52%	42%	49%
metal depletion	1707%	1717%	1700%
natural land transformation	0%	0%	0%
ozone depletion	426%	446%	370%
particulate matter formation	132%	115%	125%
photochem oxidant formation	209%	149%	198%
terrestrial acidification	454%	350%	422%
terrestrial ecotoxicity	1%	1%	1%
urban land occupation	112%	117%	104%
water depletion	0%	1%	0%

Table 12-28: Comparison of three different scenarios with the soy production. These are the baseline electricity output, using glass photobioreactors instead of PMMA, and turning the pumps off at night. Model undertaking including uncertainty assessment, as detailed earlier

Impact Category	Soyabean (RoW)		Algae					
	Standard electricity		2016-2017		Glass		48% el reduction	
	Geomean	Geostd	Geomean	Geostd	Geomean	Geostd	Geomean	Geostd
AR 5								
GTP 100 year	5.21×10^{-2}	1.14	1.61×10^{-1}	1.20	1.78×10^{-1}	1.18	1.37×10^{-1}	1.19
GTP 20 year	8.03×10^{-2}	1.14	2.37×10^{-1}	1.21	2.57×10^{-1}	1.19	2.06×10^{-1}	1.21
GWP 100 year	6.45×10^{-2}	1.14	1.91×10^{-1}	1.20	2.08×10^{-1}	1.18	1.64×10^{-1}	1.20
GWP 20 year	8.99×10^{-2}	1.14	2.57×10^{-1}	1.21	2.78×10^{-1}	1.19	2.24×10^{-1}	1.21
ReCiPe								
agricultural land occupation	6.22×10^{-3}	1.12	4.87×10^{-5}	1.27	5.38×10^{-5}	1.24	4.03×10^{-5}	1.27
climate change	5.63×10^{-2}	1.17	1.85×10^{-1}	1.19	2.01×10^{-1}	1.17	1.59×10^{-1}	1.22
fossil depletion	1.26×10^{-2}	1.18	5.25×10^{-2}	1.18	5.74×10^{-2}	1.17	4.48×10^{-2}	1.21
freshwater ecotoxicity	3.29×10^{-3}	1.33	4.01×10^{-3}	1.42	4.34×10^{-3}	1.52	3.64×10^{-3}	1.52
freshwater eutrophication	3.50×10^{-5}	1.34	8.20×10^{-5}	1.61	8.46×10^{-5}	1.60	7.37×10^{-5}	1.63
human toxicity	3.70×10^{-2}	1.69	1.40×10^{-1}	1.99	1.52×10^{-1}	1.99	1.26×10^{-1}	1.97
ionising radiation	4.49×10^{-3}	1.77	1.78×10^{-2}	2.02	1.95×10^{-2}	1.98	1.74×10^{-2}	2.00
marine ecotoxicity	1.27×10^{-3}	1.47	3.73×10^{-3}	1.42	4.03×10^{-3}	1.52	3.39×10^{-3}	1.52
marine eutrophication	6.08×10^{-4}	1.20	1.60×10^{-4}	1.22	1.93×10^{-4}	1.19	1.42×10^{-4}	1.25
metal depletion	5.39×10^{-3}	1.19	7.74×10^{-3}	1.47	8.57×10^{-3}	1.43	7.45×10^{-3}	1.52
natural land transformation	2.00×10^{-3}	1.14	7.46×10^{-6}	1.49	1.15×10^{-5}	1.47	6.02×10^{-6}	1.52
ozone depletion	4.47×10^{-9}	1.36	1.33×10^{-8}	1.21	1.47×10^{-8}	1.20	1.12×10^{-8}	1.24
particulate matter formation	4.83×10^{-4}	1.13	2.42×10^{-4}	1.24	2.98×10^{-4}	1.20	2.11×10^{-4}	1.27
photochemical oxidant formation	5.38×10^{-4}	1.13	4.08×10^{-4}	1.23	5.03×10^{-4}	1.20	3.51×10^{-4}	1.25
terrestrial acidification	3.47×10^{-4}	1.17	7.07×10^{-4}	1.26	8.31×10^{-4}	1.22	6.02×10^{-4}	1.27
terrestrial ecotoxicity	4.16×10^{-3}	1.23	1.82×10^{-5}	1.33	2.00×10^{-5}	1.30	1.76×10^{-5}	1.35
urban land occupation	1.42×10^{-3}	1.21	8.11×10^{-4}	1.59	9.80×10^{-4}	1.50	7.16×10^{-4}	1.54
water depletion	1.85×10^{-1}	1.16	6.81×10^{-4}	1.21	7.35×10^{-4}	1.20	5.99×10^{-4}	1.23

Table 12-29*: The percentage impact of microalgae when compared with soy, on a per MJ basis. Highlighted cells have impacts lower than soy. The Geometric standard deviation is calculated from that within Table 14-30 using* $\sigma_x = exp\sqrt{(ln\sigma_a)^2 + (ln\sigma_b)^2}$.

Impact Category	Basline		Glass		48% el reduction	
	Percentage	Geostd	Percentage	Geostd	Percentage	Geostd
AR 5						
GTP 100 year	310%	1.05	341%	1.05	263%	1.05
GTP 20 year	295%	1.05	320%	1.05	257%	1.05
GWP 100 year	295%	1.05	323%	1.05	254%	1.05
GWP 20 year	285%	1.05	309%	1.05	249%	1.05
ReCiPe						
agricultural land occupation	1%	1.07	1%	1.06	1%	1.08
climate change	328%	1.06	357%	1.05	283%	1.06
fossil depletion	418%	1.06	456%	1.05	356%	1.07
freshwater ecotoxicity	122%	1.23	132%	1.29	111%	1.29
freshwater eutrophication	234%	1.36	242%	1.35	211%	1.38
human toxicity	378%	2.12	411%	2.11	340%	2.08
ionising radiation	397%	2.26	434%	2.2	386%	2.23
marine ecotoxicity	295%	1.31	319%	1.38	268%	1.38
marine eutrophication	26%	1.08	32%	1.07	23%	1.08
metal depletion	144%	1.2	159%	1.17	138%	1.22
natural land transformation	0%	1.19	1%	1.18	0%	1.21
ozone depletion	298%	1.14	330%	1.14	251%	1.15
particulate matter formation	50%	1.06	62%	1.05	44%	1.08
Photochem oxidant formation	76%	1.06	94%	1.05	65%	1.07
terrestrial acidification	204%	1.08	240%	1.06	174%	1.08
terrestrial ecotoxicity	0%	1.13	0%	1.12	0%	1.14
urban land occupation	57%	1.28	69%	1.22	50%	1.25
water depletion	0%	1.06	0%	1.06	0%	1.07

Chapter 13. Works Cited

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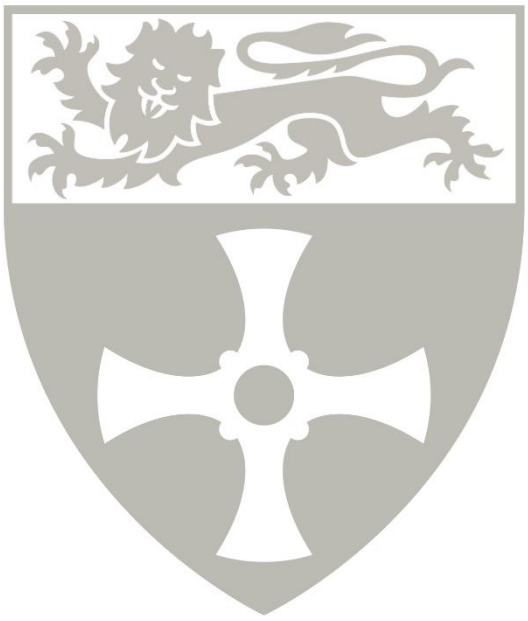

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