MODELING A BIOREFINERY - AN ECOTECHNOLOGICAL APPROACH TO ENERGY PRODUCTION USING MICROALGAE AND ANAEROBIC DIGESTION

MODELLERING AV EIT BIORAFFINERI - KRETSLØPSBASERT ENERGIPRODUKSJON VED BRUK AV MIKROALGER OG ANAEROBISK NEDBRYTING

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MASTER THESIS 30 CREDITS 2010

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Usipoziba ufa utajenga ukuta.

Methali

If you ignore the crack, you must rebuild the wall.

Swahili Proverb

Preface

This thesis is the fulfillment of my Master degree in Technology at the Norwegian University of Life Sciences (Universitetet for Miljø- og Biovitenskap, UMB) at Ås. With a strong interest in renewable energy resources together with an academic background from Industrial Economics and Water- and Environmental Sciences, the concept presented in this thesis was a 'hole-in-one' for me.

There are many people who deserves my thanks and gratitude for the help and support during the work leading to this thesis. First, I would like to thank my supervisor Associate Professor John Morken at the Department of Mathematical Sciences and Technology (IMT) for always having time to discuss the different aspects of the thesis. My thank goes also to Dr. Zehra Zengin at MST for reading and commenting on the thesis.

I would like to thank Professor Hans Ragnar Gislerød and Research Fellow Anette Åkerstrøm at Department of Plant and Environmental Science (IPM) for giving me an introduction to the field of microalgae. My friend Kristian Fjørtoft also deserves a thank for productive discussions on the engineering of the system flows. Appreciations also go to Researcher Espen Govasmark at IPM, Associate Professor Lasse Vråle at IMT and Senior Researcher Tormod Briseid and Dr. Roald Sørheim at Bioforsk, whom all have made contributions to the final results presented in this thesis.

A great thank goes to the classmates whom I have shared office with in Fløy 5. Having this common workplace has done the writing process easier and much more social and fun. I would also like to thank Eivind Norheim and Kari Horgen Skjønsberg for their hospitality and encouragements.

Finally, a great appreciation goes to my wonderful wife for being supportive, understanding and patient throughout this period. I look forward to eventually be able to spend more time with you and our wonderful daughter.

Ås, May 2010

Jon Eivind Tululu Strømme

Samandrag

Fyrste generasjons biodrivstoff har fått hard kritikk for konkurransen med matproduksjon. Utvikling av andre generasjon biodrivstoff, eksempelvis mikroalgar, som ikkje nyttar matjord har difor i aukande grad vorte framheva som ei mogleg løysing. Masseproduksjon av algediesel vil krevja store mengder kunstgjødsel, og gjev difor algediesel ei stor miljøbyrde. I denne oppgåva er ein kretsløpsteknologi som kombinerer algedyrking og anaerobisk nedbryting vorte modellert. Ved å nytte livssyklusmetodar har biodieselen som vert produsert vorte analysert med omsyn på bidraget til global oppvarming og utarminga av fossile energireservar. Sidan anlegget gjer om organisk avfall til biodiesel, straum og organisk gjødsel, har ein valt å kalle det for eit bioraffineri.

Modellen har vore eit nyttig reiskap for å skjønne symbioseegenskapane og dynamikken i systemet, men har óg gjeve nødvendig informasjon for å kunne undersøkje i kva grad biodieselen er fornybar og karbonnøytral. Energiutrekningar syner at meir energi vert produsert dersom prosessane vert kombinert i same kretsløpsteknologi. For kvar energieining som kjem inn gjennom det organiske avfallet, vert 1.77 energieiningar eksportert ut av systemet anten som straum eller biodiesel. Modellen syner at bioraffineriet kan vere sjølvforsynt med energi, og vert difor heilt uavhenig av eksterne energikjelder. Miljøbelastninga til biodieselen kjem difor utelukkande frå oppstraumsbelastningane frå innsatsfaktorane. Fossil CO_2 og metanol er dei absolutt største bidragsytarane, og gjer at den fossile energiandelen av biodieselen er på ca 23%. Dersom fornybare kjelder vert nytta for å framskaffe CO_2 og metanol, kan ein senka det fossile energibehovet og drivhusgassutsleppet med høvesvis 96% og 98%. Den fossile energibalansen for biodieselen vert då heva til 50, noko som betyr at for kvar eining fossil energi nytta får ein 50 einingar fornybar energi tilbake. Samanlikna med fossil diesel vil drivhusgassutsleppa kunne reduserast med 99%, noko som tilsvarar ca 3 kg CO_2 for kvar liter drivstoff.

Avslutningsvis vert moglege forbetringar for konseptet presentert og diskutert. Modelleringa og livssyklusanalysane har synt at konseptet kan vere ei mogleg løysing for produksjon av bioenergi utan å korkje konkurrere med matproduksjon over landjord, eller vere avhengig av nitrogenbasert kunstgjødsel.

Abstract

The sustainability of first generation biofuels is hotly debated. Development of second generation biofuels produced from non-food sources such as microalgae, has therefore increasingly gained attention. Mass production of algal biodiesel require large amounts of chemical fertilizers which contributes to a large environmental burden. In this thesis an ecotechnology combining algae cultivation with anaerobic digestion (ACAD) has been modeled and it's output been evaluated with regard to global warming potential and fossil energy resource depletion using a life cycle approach. Due to the concept's capacity to convert organic wastes into bioenergy and organic fertilizer, the concept has been labeled the ACAD biorefinery.

The model of the ACAD biorefinery proved itself as a powerful tool for understanding the symbiosis and the dynamics of the system, and it provided the information needed to evaluate the degree of renewability and carbon neutrality for the biodiesel produced. Energy estimations showed that the system produces more energy combined than the stand alone processes. For every unit of feedstock energy entering the system, 1.77 units of energy exits the system either as biodiesel or as electricity. The biorefinery is completely independent of external energy supply, and the fossil burden of the biodiesel produced comes solely from the upstream burdens of the inputs to the system. The primary burden drivers are fossil CO_2 and methanol. With these burdens the fossil energy ratio of the ACAD biodiesel is approximately 23%. If renewable resources are used to produce the needed CO_2 and methanol, the required fossil energy input and the fossil greenhouse gas (GHG) output could be reduced with 96% and 98% respectively. The net energy balance will then increase to 50, meaning that for every unit fossil energy used; 50 units of renewable energy are produced. Compared to conventional diesel the GHG output could be reduced with 99%, equal to approximately 3 kg CO_2-eq per liter fuel.

At the end, opportunities for the ACAD concept are discussed. The modeling and the life cycle assessments made in this thesis have showed that the ACAD concept could be a solution for bioenergy production without competing with food production for arable land and without depending on chemical nitrogen fertilizer.

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Chapter 1

Introduction

1.1 Challenges facing the World

How can the world manage to supply an increasing demand for energy, while fossil-fuels reserves are declining and global climate changes are threatening the livelihoods of millions of already poor and vulnerable people?

1.1.1 Climate, energy and poverty crisis

Storms, floods, droughts, irregular seasons, forest fires and heat waves have all hit the headlines in recent years. Are we facing the start of the Global Climate Change? What we do know is that the atmospheric CO_2 and the average air temperatures have risen since the Industrial Revolution. Every year combustion of fossil fuels is adding about 6 gigatons per year of carbon (in the form of CO_2) to the atmosphere (**?**). In just a few hundred years, humans have released the organic carbon accumulated over hundreds of millions of years. Without a change in policy the world is on a path for a rise in global temperature by up to 6°C, with catastrophic consequences for our climate (**?**). Continued greenhouse-gas (GHG) emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century (**?**). To avoid the most severe weather and sea-level rise and limit the temperature increase to about 2°C, the GHG concentration needs to be stabilised at around 450 ppm CO_2-equivalent.

Although they have contributed the least to the global climate change, developing countries and their poor population, are those who must bear the heaviest burdens of the climate change. At the same time they are in desperate need of access to affordable and improved energy services in order to reach their growth and development targets.

Conservation and energy efficiency will be needed in order to keep the total energy demand from growing to unmanageable levels, but in order to lower the emissions, renewable energy resources must substitute for fossil fuels. Alternatives to fossil fuels must be renewable, carbon-neutral and be able to be implemented on large scale without severely negative impacts.

1.1.2 Bioenergy - A part of the solution

Renewable energy

The development of CO_2-neutral energy is one of the most urgent challenges facing our society. The global energy market can essentially be divided into the electricity and the fuel sector. Both sectors will have to achieve significant emission reductions to meet planned international targets agreements. Currently the electricity sector accounts for approximately 33% of global energy and is developing a range of low CO_2-emission approaches for electricity production (e.g. nuclear, solar, wind, geothermal, hydroelectric, clean-coal technology) (**?**). Fuels account for a much larger market share (67%) of the global energy consumption (approximately 15,5 TW in 2005) (**?**). Despite the obvious importance of fuels, CO_2-neutral (e.g. biodiesel, bioethanol, biomethane, BTL-diesel) fuel production systems are far less developed than electrical CO_2-neutral production technology.

Bioenergy

Common for all bioenergy is that the ultimate source of energy is sunlight, making it a renewable source. Photosynthesis captures the sun's energy and binds it in organic molecules, which are carriers of the electrons and their energy (**?**). Bioenergy is carbon neutral, because the time from photosynthesis to humans' energy use is short - days or years - not hundreds of millions of years, as with fossil fuels (**?**). Renewable and carbon neutral are related, but distinct features. Renewable means that the energy comes from a source that was produced recently, and that can continue to be produced. Carbon neutral means that any CO_2 released was taken from the atmosphere recently, creating a short-term carbon cycle, not a net addition of CO_2 (**?**).

Problems of first generation biofuels

? asks the question whether biomass energy can meet the human demand of fuel energy (approximately 10 TW) now derived from fossil fuels. His conclusion is that for biomass to be a major renewable, carbon neutral source, photosynthetic energy capture must be expanded to produce some "new biomass". This is due to the fact that the large amount of biomass needed cannot simply be diverted from the natural flow of high-energy electrons through biomass, without affecting the balance of the earth's ecosystems.

Another, and the most common, concern with first generation production systems is that as production capacities increase, so does their competition with agriculture for arable land used for food production. A scenario drawn by **?** shows that if the current oil-producing crops would be grown on all arable land (assuming 29,2% of the Earth is land, of which 13% is arable, energy conversion efficiencies of 1% from sunlight to biomass, 20% of yield as oil and approximately 170 W m^{-2} of solar energy on the surface of the world on average) these would be able to cover less than half of our energy demand today. Evidently, first generation bioenergy production systems cannot contribute in a major way to global fuel requirements (**?**).

Non-arable energy production systems

The problems of first generation biofuels have paved the road for second generation bioenergy systems. They have the potential of having much higher Net Energy Balance (NEB), can be more water-efficient and require much less arable land (**?**). Two different approaches for production of second generation bioenergy are lignocellulosic technologies and the use of microorganisms. The focus of this thesis will be on the second approach.

Microorganisms

Two different methods of energy production using microbial microorganism are combined in the concept presented in this thesis; methanogenesis microorganisms and microalgae. Methanogenesis is the name for the production of methane (CH_4) using anaerobic microbial communities (**?**), while microalgae cultivation in this thesis refers to the microalgae ability to convert sunlight into biomass.

Organic waste

A potential large and untapped source of biomass for making useful energy is residual biomass from normal human activity, such as agriculture, food-producing industry, and municipal and industrial wastewaters. These residual biomasses contain enough energy to meet a significant fraction of the world's entire energy demand, if they could be collected and converted into useful energy forms (**?**). Wastes often creates serious environmental harm and are expensive to handle. Their collecton and conversion to energy could provide a giant benefit to environmental quality and improve the economy of energy producing technologies.

This thesis investigates an ecotechnological concept which produce bioenergy from organic waste using microorganisms.

1.2 Introduction to the elements of the concept

1.2.1 Wastewater treatment

Sludge treatment The purpose of water treatment is to separate undesirable substances from the water. In conventional wastewater treatment plants (WWTP) this is usually done by using chemical precipitation to encourage dissolved substances and particles to form larger particles that are more easily separated from the water. The particles that are separated form a sludge. Sludge generally contains both useful, useless and harmful components and is often classified as waste. Opportunities to how one can utilize the useful component of the sludge must be investigated in order to achieve a more sustainable wastewater handling. One challenge with sewage sludge is that it consists of a matrix of components that might jeopardize the processes set to handle the sludge. Efforts should therefore be made to prevent harmful substances from entering the sewage works. In a WWTP the sludge usually goes through at least three main processes; thickening, stabilization and dewatering. The costs of processing sludge at a WWTP are often considerable, and it can also be difficult to find good methods of final disposal. According to reference (**?**) 40-60% of the total cost of a treatment plant go toward processing sludge, despite the fact that the volume of sludge is only around 1% of that of the incoming wastewater. Thickening is therefore essential in order to reduce the volume and the cost of processing sludge, and is often done by either sedimentation or flotation before stabilisation and dewatering. Raw sludge contains biodegradable compounds that remains biologically active until it has been stabilised. One of the methods for stabilisation are anaerobic digestion (AD). Together with the energy production, a major advantage of the AD process is that it greatly reduces the volume of the sludge. The AD process is described more in detail in the following section.

1.2.2 Anaerobic digestion

Anaerobic digestion (AD) or methanogenesis is a waste management process for organic waste materials producing biogas and a stabilized residue called digestate. The digestate can under certain conditions be used as organic fertilizer. Today the most common use of AD-technology is in farm-based manure facilities. In the far East family-sized low-technology digesters are used to provide biogas for cooking and lighting. According to **?** a total of about 3.4 million family size biogas plants were by Dec. 2002 installed all over India. The potential number of family size biogas plants in India is according to the same reference as much as 12 million.

Anaerobic digestion is also used to stabilize and thicken sewage sludge (also called biosolids) in wastewater treatment plants (WWTP). More than 1.000 high-rate anaerobic digesters are operated world-wide to treat organic polluted industrial wastewater (**?**). Biogas produced in the AD-process is primarily composed of methane (CH_4) and carbon dioxide (CO_2) with smaller amounts of hydrogen sulphide(H_2S) and ammonia (NH_3). Biogas can be used for all applications designed for natural gas, using post-treatment processes to obtain appropriate quality standards for the different applications.

Since low temperatures restricts the anaerobic sewage treatment, tropical and sub-tropical countries constitute a privileged niche for the advantageous application of anaerobic digestion for treatment of organic wastes (**?**). Using anaerobic processes for the treatment of high-strength industrial wastewater have become very popular since expensive equipment used for aerobic processes are not needed, resulting in lower energy and investments costs. The production of methane also improves the net energy balance of the treatment process and the net production of excess sludge is lower than for aerobic processes (**?**). Recovery of the resources also improves the sustainability of the treatment system.

After the AD process the digested slurry, the digestate, goes through a dewatering process separating solids from the liquid. The solids can be used as soil amendment, but the liquid is harder to handle due to its volume and state. In WWTP the reject water(liquid) is many times pumped back to the inlet of the wastewater adding a substantial load to the following treatment processes. Alternative usage of this reject water is a key issue in this thesis.

1.2.3 Microalgae

Microalgae are sunlight-driven cell factories that can convert inorganic carbon dioxide to potential biofuels, foods, feeds and high-value bioactives (**?**). They are a diverse group of eukaryotic and prokaryotic(cyanobacteria) photosynthetic microorganisms that grow rapidly due to their simple structure. The biodiversity of photosynthetic microbes is enormous. **?** estimates their being more than 100,000 species, and yet most of it remains biochemically and metabolically unexplored. According to **?** only four species had been cultivated at industrial scale in 2007. On top of the natural variety comes the possibility to change the properties of the microalgae by genetical modification.

In this paper I will focus on the microorganisms ability to capture sunlight and concentrate it in organic matter that can be anaerobic digested to produce methane and biodiesel.

1.2.4 Introduction to ecotechnology

Ecological engineering or ecotechnology is defined as the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both. In order to reach the goal of sustainability it is therefore important that energy production systems are converted from to natural cycle oriented. In natural cycles there are not waste, but products at different stages of the cycle. In order to reach a sustainable energy production, the technologies involved must be based on ecological engineering.

1.2.5 Biorefinery - Nature's analogue

The anaerobic process produces both CO_2 and a liquid fertilizer (digestate) with high amounts of macro nutrients such as nitrogen and phosphorous. Microalgae needs nutrients, CO_2 and sunlight to grow. By integrating these processes into one ecotechnology, one can hopefully maximize the total efficiency, lower the production costs, recycle the nutrients and lower the carbon footprint of the energy production system, resulting in sustainable and low-carbon production of renewable energy. The production of biogas by methanogenesis from wastewater sludge, production of biomass by algae and cyanobacteria, and the combination of these microbial processes in an ecotechnological symbiosis can potentially improve the sustainability of all the technologies involved.

In this thesis the virtual facility using anaerobic digestion, microalgal cultivation, scrubbing, oil extraction, transesterification and heat and power production leading to the production of power and biodiesel, is referred to either as a the 'Algae Cultivation with Anaerobic Digestion (ACAD) Biorefinery', or simply just the 'Biorefinery'. The biodiesel and the power produced will be referred to as ACAD Biodiesel and ACAD Power. Although these names do not cover all the aspects of the concept, they distinguish themselves from energy produced using the stand-alone processes of anaerobic digestion or algae cultivation.

1.3 The objective of this thesis

In this thesis a virtual ACAD Biorefinery is sought constructed by using estimates and figures derived from literature on the different processes involved. When such a model is constructed, the Global Warming Potential and the Fossil Energy Resource Depletion is estimated by using Life Cycle Assessments. This would hopefully lead to:

a) a greater understanding of the combined processes,

b) a foundation for evaluating the sustainability and the renewability of the ACAD concept and it's products,

d) reveal challenges and opportunities for the ACAD energy production system.

Although the virtual ACAD biorefinery primarily will be based on aggregated and statical figures, the goal is to manage to capture the most important features of the concept. It is also worth mentioning that this thesis tries to asses the life cycle of a process which does not exist at industrial scale, and for which many technological challenges are still unsolved. We have tried to use reasonable assumptions in order to outline the potential of a ACAD-based production system for bioenergy. The results will therefore neither be conclusive nor very detailed, but hopefully indicate the environmental impact of the concept and be a contribution to the development of a sustainable microbial energy production system.

Chapter 2

Theory

In this chapter former research on the different parts of the ACAD concept will be presented, outlining the theoretical framework for building the virtual ACAD Biorefinery and to perform a life cycle evaluation of the outputs of the ACAD biorefinery.

2.1 Former research on the concept

The idea of combining anaerobic digestion with microalgae cultivation was proposed and proven to be technically feasible in the laboratory by **?**. A broader evaluation of a tentative microbiological process which converts solar energy to electrical power through algal photosynthesis, methane fermentation of algae and thermal combustion of methane was proposed in 1960 (**?**).

More recently, a revival of the biological sunlight-to-biogas energy conversion system has been proposed by **?**. A study by **?** investigated why anaerobic digestion of microalgae might be a necessary step to make microalgal biodiesel sustainable. This study also outlined the potential of feeding all of the algal material into the anaerobic digester, without the production of biodiesel from the lipid part of the algae. In his study **?** predicted that the promising integration process coupling anaerobic digestion with microalgal culture will re-emerge in the coming years either as a mandatory step to support large scale microalgal cultures or as a stand alone bioenergy producing process.

2.2 Related Environmental Studies

According to **?** there are no industrial facility producing biodiesel from microalgae. The same reference also states that, by them, no thorough Life Cycle Assessment of the production chain from microalgae culture for biodiesel were currently available, with the exception of LCA studies about co-firing of microalgae with coal. The aim of the study of **?** was therefore to assess the environmental impact of the technologically immature process of producing biodiesel from microalgae. The outcome of his study confirmed the potential of microalgae as an energy source, but highlighted the imperative necessity of decreasing the energy and fertilizer consumption. **?** also suggested anaerobic digestion of oilcakes (residue after oil extraction) as a way to reduce external energy demand and to recycle a part of the mineral fertilizer.

According to a study by **?** work by **?** summarizes the life cycle implications of algae-to-fuel conversions without detailing the cultivation burdens. The study by **?** compared the environmental life cycle burdens of algae to other bioenergy feedstock. The results of this study indicated that conventional crops have lower environmental impact than algae in energy use, greenhouse gas emissions and water usage. The large environmental footprint of algae cultivation was found to be driven predominately by upstreams impacts, such as the demand for CO_2 and fertilizer. **?** therefore suggested that in order to reduce these impacts, flue gas, and to a greater extent, wastewater could be used to offset most of the environmental burdens associated with the algae cultivation.

The work by **?** and **?** with the supporting information to their publications, will be extensively used as a reference in this thesis.

2.3 Explanation of the Concept

Following comes a short explanation on the concept.

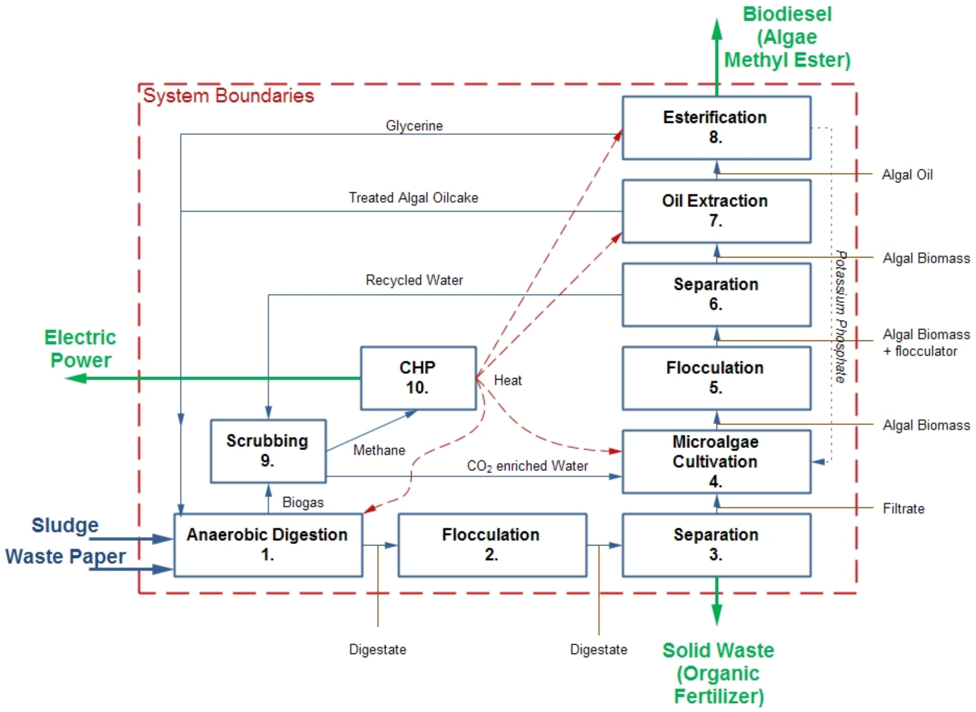

Figure 2.1: Overview of the ACAD Biorefinery

1. Organic substances (sludge, waste paper, algal oilcake and glycerine) are fed into the anaerobic digester (AD).
2. The nutritious effluent from the AD, referred to as digestate, is flocculated with the aid of a coagulant.
3. The solids and the liquid are separated through a dewatering process. The solids are a co-product of the process and can be used as soil conditioner or an organic fertilizer.
4. The remaining filtrate is pumped to an high rate algal pond where it acts as a fertilizer. Algal biomass is grown and harvested from the pond.
5. The harvested algal matter is treated with a coagulant..
6. ..before the solids and the water are separated.

7. The algal sludge is then treated in order to extract the lipids(oil), but also to make the residue (oilcake) more easily available for the microorganisms in the anaerobic digester. The oilcake is recycled back into the AD-reactor.

8. The algal oil undergoes an esterification process with the aid of methanol and a base (NaOH). This process produces biodiesel and a residue called glycerine. The glycerine fraction is also routed back to the AD-reactor.

9. The overflow from the dewatering prosess in process 6, is used to purify the biogas by a scrubbing process in order to increasing the methane content of the biogas. The carbon-rich effluent from the scrubbing is then pumped back to the algae pond to stimulate the growth of more algae.

10. The methane produced is combusted in a combined heat and power(CHP) gas engine to produce electricity and heat. The heat is used in various processes in the system; extraction of oil, pre-treatment of biomass prior to the AD, heat to the algae pond and to ensure optimal temperature within the AD reactor. The CO_2 produced during the combustion in the CHP is pumped back to the algal pond where it acts as a carbon source for the algae.

During the entire process the nutrients and the carbon is recycled, resulting in a loop for converting sunlight to bioenergy. The system is design so that no additional nitrogen fertilizer is necessary. The theoretical parameters used to build the virtual facility are presented in the next section.

2.3.1 Theoretical Parameters

A list of all the parameters, with its respective references, presented in this section is found in the Appendix A. Figure 2.3.1 shows the flow of inputs and output from and to the system.

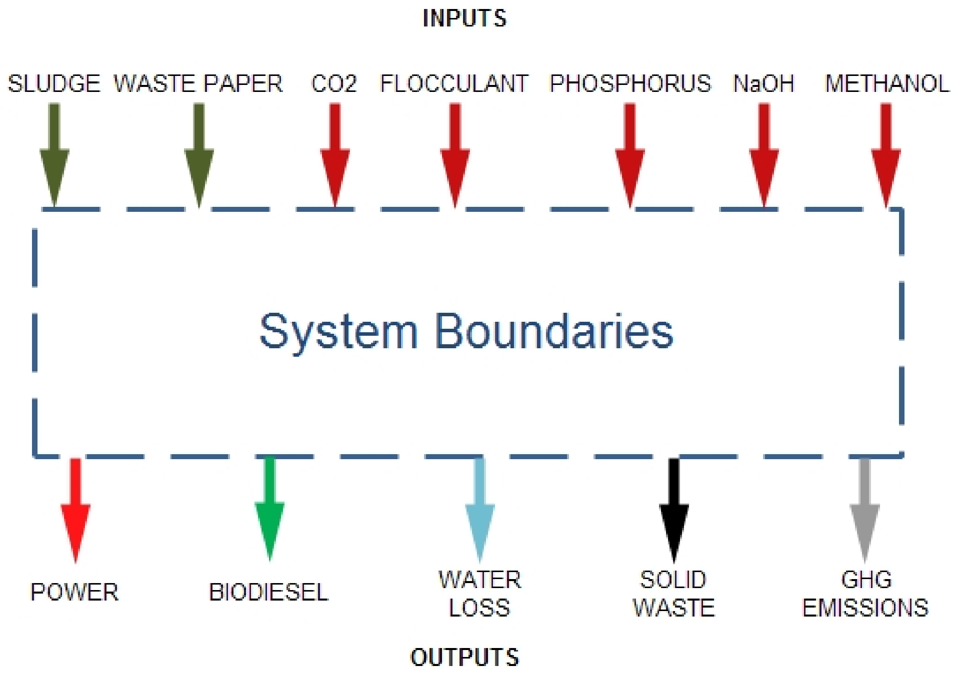

Figure 2.2: Flows in and out of the System Boundaries

Organic Matter

The mixture of the organic matter is very important for several reasons. The mixture must reach the optimal ratio between carbon and nitrogen (C/N-ratio) and to supply enough nitrogen for the algae production. In the ACAD model four different organic matters enters the AD; wastewater sludge, waste paper, algal olicake and glycerine (residue from biodiesel production).

Table 2.1: Characteristics of the different feedstock entering the AD-reactor

Type	**DM (%)**	**VS of DM (%)**	**N (%)**	**P (%)**	**C/N**
Oilcake	20	90	13.0	3.17	4.2
Sludge	1	72	7.1	2.78	7.2
Waste paper	48.6	92	0.39	None	126
Glycerine	50	100	None	0.15	50

The references for the different characteristics are given in the Appendix.

C/N-ratio

Together with the resistant to biodegradation of algae cells, the low C/N-ratio of algal sludge is also a factor that must be considered. Low C/N-ratio could result in high total ammonium nitrogen (TAN) released and high volatile fatty acids (VFAs) accumulated in the digester (**?**). High concentrations of TAN and VFAs in the digester disturbs the methanogen activity and in high concentrations it could fail the anaerobic digestion. One method to avoid the unwanted levels of ammonia is to lower the C/N-ratio by co-digesting with high carbon content and thereby improve the digestion performance. According to **?** this practice has been used for co-digestion of sewage sludge and municipal solid waste (MSW). Most MSW concists of paper material which has a C/N-ratio ranging from 173/1 to greater than 1000/1, while typical sewage sludge has a C/N-ratio ranging from 6/1 to 16/1. Co-digestion could not only reduce the problems with excess amounts of ammonia, but also increase the methane production yield.

By mixing algal sludge with waste paper **?** found that the optimal C/N-ratio for co-digestion was in the range of 20-25/1. This range will be used in order to calculate the mixture of the organic matter entering the AD in our model.

Anaerobic Digestion

Anaerobic digestion is a biological process which converts organic material into energy-rich biogas (contains CO_2 and CH_4), but it also mineralize some of the organic nitrogen and phosphorus into ammonium and phosphate that can be used to produce more organic matter (e.g. algae). The products of the AD-process are biogas and digestate. The biogas is mainly composed of methane and carbon dioxide, but also in a smaller fraction, of hydrogen sulphide, dinitrogen, dihydrogen and other volatile compounds (**?**). AD plants have different design, but usually consist of the following main stages: a) pre-treatment of the waste, b) digestion of the waste including feeding and mixing in the reactor, c) gas handling (collection, treatment, storage and utilization) and d)management of the digestate.

An AD facility can be characterized according to the following digestion options (**?**): a) Dry vs wet, b) Thermophilic vs mesophilic c) One stage vs two-stage and d) One phase vs two phase. According to **?** two stage and two-phase systems are few due to technical and economical reasons. Most AD systems are therefore one-stage, in which the whole process takes place in the same reactor. Consequently, the majority of AD facilities are described as dry or wet, and thermophilic or mesophilic AD facilities. This thesis will focus on wet digestion under mesophilic conditions. The heat produced in the CHP is used for oil-extraction and to pre-treat the oilcake, but might also be used to increase the process heat in the AD-reactor to reach thermophilic conditions. This might increase the methane yield.

In order to simplify the model, the biogas is assumed to only consist of methane and CO_2, and that there are no emissions from the AD-reactor.

Biogas production

Destruction of Organic Matter:
The rate of the destruction of the organic matter, referred to as volatile solids (VS) or organic matter (OM), is of major importance for the overall performance of the AD-process. According to **?**, the maximum VS destruction was about 45% for algae, compared to about 60% for wastewater sludge. The relatively low digestibility and thus yield of microalgal biomass was the because of cell wall resisting the degradation by the bacteria in the AD. Cell wall disruption is therefore a strategy for increasing the digestibility. **?** evaluated thermochemical pretreatment of green micoalgae biomass, finding that methane production rates increased by one third when the biomass was preheated for a period. Co-digestion of algal matter with high-carbon, low-nitrogen substrates has the potential to increas the biogas production per unit volume of the digester tank. In the ACAD model the VS destruction rate of the organic matter is set equal to destruction rate of wastewater sludge, i.e. 60%.

Production of biogas:
Since the feeding described in the work of **?** is closest to the feeding material in the ACAD concept, the productivity yields presented in their work are used for the ACAD model. Their maximum yield came when they mixed 2 g VS/l day algal sludge with 3 g VS l^{-1} day waste paper, giving an algae fraction in the feedstock of 40%. At this feeding rate (5 g VS l^{-1} day^{-1}) they achieved a CH_4 yield of 1607 ml l^{-1} day^{-1} which equals to a production yield of 0.324 m3 CH_4 kg^{-1} VS and a total biogas yield of 0.537 m^3 kg^{-1} VS. The quality of the biogas, i.e. methane fraction, is therefore approximately 60%.

In addition to the mentioned figures, different material properties are also included in the model: For methane, CH_4:

Specific volume (1.013 bar and 21 °C) : 1.48 m^3 kg^{-1}

Gas density (1.013 bar and 15 °C) : 0.68 kg m^{-3}

Higher Heating Value: 55.54 MJ/kg, which with the gas density above gives 10.49 kWh m^{-3}.

For CO_2:

Gas density (1.013 bar and 15 °C) : 1.87 kg m^{-3}

Specific volume (1.013 bar and 21 °C) : 0.547 m^3 kg^{-1}.

All of the energy in the biogas is assumed to come from the methane fraction, i.e. the energy in the biogas is equal to the energy in the methane fraction. All the figures above can be found in the appendix, together with its references.

Nitrogen content

One challenge in determining the flow of the concept is regarding how much of the nutrients in the feedstock that becomes algae available through the anaerobic process. The literature reports little about the chemical and biological characteristics of the digestate and the changes of the organic matter that occurs during the AD-process. General figures of the composition of the digestate is hard to find, since the composition is highly dependent on the properties of the feedstock and the condition in the AD-reactor. Work by **?** shows that the AD results in a strong reduction of the easily degradable fraction of the organic matter and an accumulation of recalcitrant molecules, and that the high mineralization of nitrogen and phosphorus may point to the digestate as a readily available liquid fertilizer for agronomic use.

In the same reference the fate of nutrients through the AD-process is evaluated. In literature, they say, macro nutrients total content tends not to be influenced or is only slightly decreased during the AD processes. They found that as degradable organic matter was transformed into biogas, the relative content of ammonia in the TS increased proportionally to the biological stability. These findings are interpreted so that the mineralization of ammonia is greater than the destruction of VS, since destruction of VS leads to a greater biological stability.

In the ACAD model the conversion rate of organic nitrogen to ammonia is therefore set equal to the VS destruction rate (i.e. 60% of the nitrogen entering the AD-reactor is converted to ammonia in liquid phase). All of this ammonia is also assumed to be algae available. The nitrogen not transferred into ammonia (40%), leaves the system boundaries together with the solid waste. In order to keep the nitrogen balance within the system, the amount of nitrogen leaving the system must enter the system either through the co-digestion material or as fertilizer. Since one of the goals for the ACAD concept is to eliminate the need for nitrogen fertilizer, the first strategy is chosen.

By co-digesting sewage sludge, waste paper, oilcake and glycerine in a designed mixture both the nitrogen balance and the optimal C/N-ratio is maintained.

Algae Cultivation

As showed in chapter 1 the field of microalgae is vast, and overall data on productivity, nutrient requirements, composition and energy content, will always be coupled with uncertainties and can always be criticized for being too general. But in order to investigate the potential of the ACAD concept, general data and rough assumptions will be used. The parameters used are derived from literature and are described in the following sections.

Productivity

Productivity is a measure of how much algal biomass that is produced per area per time. **?** considered a scenario where productions up to 127 tons ha^{-1} yr^{-1} can be achieved in high-rate raceway ponds. According to **?** productivity rate between 20 and 30 g m^{-2} day^{-1} (73-109 tons ha^{-1} yr^{-1}) are in the range of usual performances of open raceways. In the work by **?** the productivity is estimated as a function of photosynthetically active radiation and coupled with data for insulation and radiation. This approach is too detailed and time-demanding for this thesis. In the ACAD model, fixed figures for algae productivity will be implemented.

For the ACAD model the algae figures showed by **?** for the growth of *Chlorella Emersonii* grown under limited nitrogen conditions are chosen.

Table 2.2: Properties of *Chlorella emersonii* grown in low-nitrogen media (**?**)

Description	**C.em. Low-N**
Growth rate, μ (d^{-1})	0.46
Dry weight, g l^{-1}	1.11
Productivity, mg dry wt.l^{-1} day^{-1}	25
Protein (%)	28
Carbohydrate(%)	11
Lipid(%)	63
Calorific value (MJ kg^{-1})	29

Although Table 1 in **?** shows a productivity of 79 mg dry wt. l^{-1} day^{-1} for the *C.emersonii* cultivated in low-N medium, the text states that the productivity was 25 mg l^{-1} d^{-1} in the low nitrogen medium. This value is assumed to be the right one. In order to add up to 100% the distribution of protein, carbohydrates and lipids is adjusted to: 28%, 11% and 61% respectively. Consistent with the the work by **?**, the photosynthesis potential of a pond is assumed of being equivalent to a 5-cm depth photobioreactor. By using the growth rate and the dry weight per volume shown in tabel 2.2, the productivity per area is estimated to be 25.53 g dry wt.m^{-2} day^{-1}. This gives an annual productivity of $\approx$ 90 ton dry wt.ha^{-1} year^{-1}.

Algae concentration

Algae concentration is an important parameter since it governs the volumes of algal water to be pumped out of the pond. Consistent with the findings of **?**, the algae concentration in the pond is set to 1.11 g l^{-1}.

Nutrient requirements

On the basis of the algal biomass fraction on protein, carbohydrate and lipids and the molecular formula for these compounds the nitrogen requirements can be estimated. Phosphorus is more closely associated to the metabolic functions (e.g., photosynthesis) than to storage function (**?**). The quota of phosphorus in the algae is therefore assumed to be proportional to the protein content, and then indirectly to the nitrogen fraction of the biomass. The needed levels of the different nutrients (N, P, K, Mg and S) are calculated using the figures for C.vulgaris low-N, estimated in the work of **?**, and calculated proportional to the protein content.

It is assumed that the total amount of nutrients is used with a perfect efficiency. Other nutrients than nitrogen and phosphorus, are assumed to be in sufficient quantities in the pond or from the digested sludge. By the properties given in table 2.2, the nitrogen and phosphorus content of the algae matter is calculated to approximately 4.5% and 1% respectively.

CO_2 requirements

According to **?** the consumption of CO_2 per kg algae is 1.6 kg kg^{-1}. This means that in order to cultivate 1 kg of algal matter, 1.6 kg of CO_2 is needed. The supply of CO_2 to the algae comes from three sources. The first source comes from the overflow used to scrub the biogas, the second source is from the combustion of the methane in the gas engine (CHP) while the last source is CO_2 derived externally. During the anaerobic process the CO_2 content of the digestate is raised, the algae will therefore also have a supply of CO_2 through the digestate. This supply is not included the ACAD model.

Evaporation

? calculated the evaporation from algae production with regard to a Mediterranean context, with annual balance between rainfall and evaporation results in a water loss of 300 mm. Their calculations showed a a total water need around 4 liter per kg of dry algae. This estimate is implemented as evaporation in the ACAD model.

Water Scrubbing

Water scrubbing is used to remove carbon dioxide and hydrogen sulphide from biogas since these gases are more soluble in water than methane. The absorption process is purely physical. The biogas is pressurized and fed to the bottom of a packed column where water is fed on the top and so the absorption process is operated counter-currently (**?**).

Carbon dioxide solubility in water is assumed to be 1.45 g L^{-1} at 25°C and 100 kPa. A scrubbing efficiency of 0.75 is used, i.e. that 1 liter water can reach 75% of the maximum carbon dioxide bound in water. In the ACAD model the overflow from the settling basin of algal sludge is used for scrubbing before the CO_2-enriched water is pumped back to the pond acting as a carbon supply.

Combined Heat and Power (CHP) Gas Engine

The utilization of biogas in internal combustion engines is a long established and extremely reliable technology. A diesel engine can be rebuilt into a spark ignited gas engine or dual engine fuel (8-10% diesel). The dual fuel engine has a higher electricity efficiency (**?**). According to the same reference a small CHP can achieve practical electric efficiencies of 29% (spark ignition) and 31% (dual fuel). Larger engines have efficiencies up to 38%.

In the ACAD model figures in line with the technical characteristics of the gains and losses as outlined in reference (**?**) are used. The characteristics are summarized in table 2.3. The CHP derives all its energy from the methane.

Table 2.3: The distribution of the energy through the CHP combustion

Output	**% of energy**
Power	32
Heat	55
Loss	13

The second overflow, from rotary press of algal sludge, is used as cooling water for the CHP. The energy in the heated water is then utilized for oil-extraction, esterification, biomass pre-treatment and for maintaining an optimal process temperature in the AD-reactor. The overflow is ultimately pumped back to the pond.

Combustion of Biogas

In the combustion process, methane and oxygen is converted to carbon dioxide and water as shown in the total chemical equation 2.1:

$$CH_4(g) + 2O_2(g) \rightarrow CO2(g) + 2H_2O(l) + Heat \tag{2.1}$$

where bracketed *g* and *l* stands for gaseous and liquid form respectively. The combustion within the CHP is assumed to be perfect, meaning that all of the carbon in the methane finally end up as CO_2. The weight ratio between methane and

CO_2 in the formula is estimated to 2.56 kg kg^{-1}, meaning that the combustion of one kilo methane result in 2.56 kg of CO_2.

Algal Sludge Thickening

The algae concentration in the open raceway pond is set to 1.11 g l^{-1} (**?**). Water from the algae pond is pumped out of the pond and coagulated/flocculated with the aid of aluminum sulfate. The algae sludge and the water is separated in a settling tank. After the settling tank the sludge is assumed to have reached a concentration of 20 kg m^{-3} (2% dry weight)(**?**). The seperated algae matter is then processed through a rotary press producing a algal sludge with a dry weight concentration of 200 kg m^{-3} (20% dry weight)(**?**).

Oil Extraction

Autoclaving, microwaves, sonication, chemical methods, steam explosion, mechanical friction are among the methods that have been used for oil extracting in the literature. This thesis does not go into the details of the oil extraction. According to one study, oil extraction by the use of microwave oven method was identified as the most simple, easy and effective method among the test methods (**?**). But since the ACAD process has excess heat, this heat can be utilized for thermomechanical oil extraction methods. 55% og the energy in the methane is converted to heat through the CHP process, this heat is assumed to be enough to extract the oil and at the same time pre-treat the algal oilcake making it more bioavailable for the fermentation in the AD-reactor. The pre-treatment using heat will also raise the temperature of the feedstock and then contribute to a higher process temperature in the AD-reactor. Through the oil extraction process, algal oil is separated from the oilcake and the water which is fed back to the AD.

Esterification

A description of the esterification process of rape oil is given in reference (**?**). The same processes and inputs are assumed to be valid for the production of biodiesel from algae oil. A short description of the process is therefore given. Before starting the esterification the water must be removed from the oil since its presence causes the triglycerides to hydrolyze producing soaps instead of undergoing transesterification to give biodiesel. The algal oil is heated, and gradually brought into contact with a mixture of sodium hydroxide (NaOH) and methanol. Small amount of phosphoric acid and smectite is also used. After an hour of agitation, the mixture is seperated into two main components; methyl esters and glycerine. The glycerine phase is much denser than biodiesel phase (methyl esters or FAME) and the two can be separated through a settling vessel or a decanter. Once the biodiesel is separated from the glycerine, the biodiesel can be purified by washing gently with warm water to remove residual catalyst or soaps.

Potassium hydroxide (KOH) could be used instead of NaOH. Although KOH is more expensive and require larger amounts than NaOH, it may be a better option for the ACAD process. Cultivation of algae could be limited by the supply of potassium, and KOH might then be a better option than NaOH since the potassium phosphate produced as a by-product from the esterification could be transferred back to the algae pond acting as a K-fertilizer. Despite this, NaOH is used in the ACAD model.

The glycerine produced in the process is also fed into the anaerobic digester. The glycerine could have been further processed to produce pure glycerine, but in order to simplify the concept, it is recycle back to the AD. Energetic and economical comparisons of this usage to other have not been done in this thesis.

2.4 Life Cycle Assessments

2.4.1 Life Cycle Energy Balance

Energy and Greenhouse Gas Balance

One goal of the ACAD concept is to be totally independent on external energy and heat supply (except sunlight). This independence might improve the flexibility of the ACAD biorefinery regarding location, but it also make it easier to evaluate the environmental burdens related to the production of the outputs. Figure 2.4.1 shows how the energy consumption and GHG emissions from the inputs are related to the biorefinery in a life cycle setting. By using figure 2.4.1, the grade of renewability and the net GHG emissions are sought explained in the following sections.

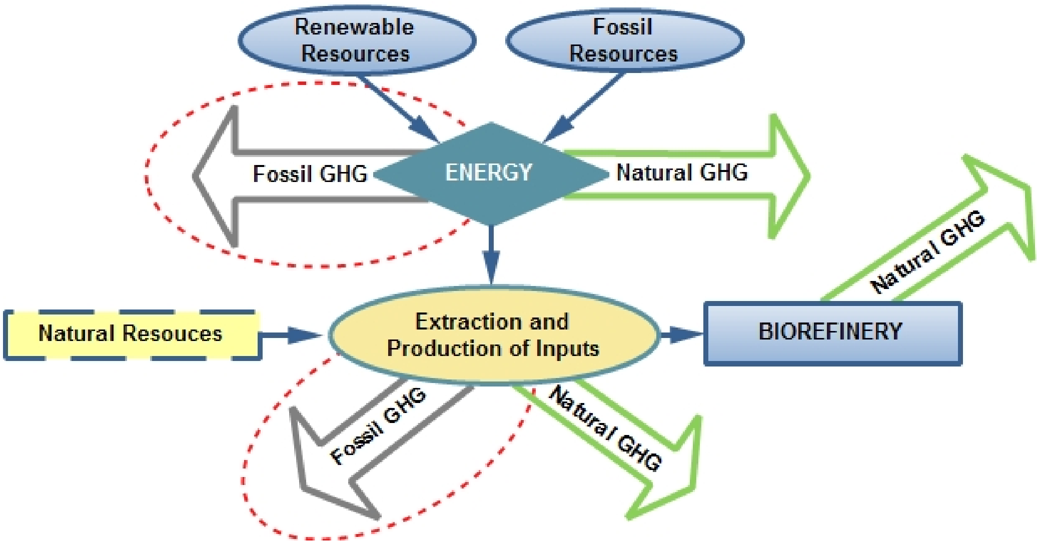

Figure 2.3: Life Cycle of Inputs

Energy - Renewability

The term renewable relates to the time since the energy was produced. Fossil energy sources were accumulated over hundreds of millions of years and cannot renew itself a short period of time. These sources are therefore labeled; non-renewable or fossil. Renewable energy means that the energy comes from a source that was produced recently, and that this source can continue to produce. Since no energy with fossil origin is used directly in the ACAD process, one might argue that the production of the output energy is completely renewable. But some of the inputs have been extracted with and from fossil resources (figure 2.4.1). In a life cycle perspective this energy consumption must be accounted for in the end product,e.g. the ACAD biodiesel. As long as the inputs are completely or partially produced with or from fossil resources, the end product cannot be completely renewable.

Another aspect of renewability is related to other fossil natural resources than energy sources. The source of phosphorus in fertilizer is fossilized remains of ancient marine life found in rock deposits, and is therefore not renewable and the source will eventually be depleted. Phosphorus scarcity could have large impacts on global food security(**?**). Since renewability regarding energy is the focus of this thesis, only fossil energy consumption in the production of phosphorus is included. In a total sustainability evaluation of the ACAD process, fossil phosphorus must be included. Anyway, phosphorus recycling through the ACAD process reduces the need for fossil phosphorus in the algae cultivation. If all the phosphorus needed could be supplied through the digestate, the sustainability of the ACAD concept will be improved.

Greenhouse Gases - Carbon Neutrality

Carbon neutral means that any CO_2 released was taken from the atmosphere recently, creating a short term carbon-cycle, not a net addition of CO_2. Renewable and carbon neutral are closely related, but are distinct features.

The calculation of CO_2 emissions from the provision of product or service is based, principally, on the evaluation of emissions from the use of fuels and electricity. Carbon coefficients indicates the CO_2 emissions produced per unit of direct and indirect energy requirements (kg CO_2/MJ). Whether any CO_2 emissions arise from feedstock which store carbon originally derived from fossil fuels, depends on the ultimate fate of this carbon. In the ACAD biorefinery this issue arise regarding the fate of the carbon in the methanol used in the esterification process and the external CO_2 used to stimulate algae growth. Conventional production of methanol and CO_2 (by-product of ammonium nitrate fertilizer production) uses natural gas as resource, making its origin fossil. Although some of the carbon in the methanol and the external CO_2 is stored in the carbon cycle of the ACAD biorefinery, the ultimate destination of the carbon is assumed to be the atmosphere. The carbon from the natural gas feedstock is therefore included in the greenhouse gas (GHG) burdens of the methanol and the CO_2 input.

The ACAD biorefinery has no direct fossil emissions or energy consumptions, but due to the indirectly contribution from the production of the inputs, the system is neither totally carbon-neutral nor totally renewable. In the following section different energy measures for the degree of renewability and efficiency are presented, together with definition of

Total Fossil Energy

The definition of Total Primary Energy is not equal in the literature. **?** defines total primary energy as the cumulative energy content of all resources extracted from the environment, while **?** defines primary energy as the amount of energy available in fossil energy resources in their natural state, such as coal, natural gas and oil deposits in the ground. The point of deviation is on what to include; energy from all resources or only the energy originating from fossil resources? Instead of using the word 'Primary' this thesis will use 'Fossil' and 'Life Cycle Energy' with the following definitions:

> Total Fossil Energy is equal to the sum of:
>
> > the direct external energy use, originating from fossil energy resources
> >
> > $+$ indirect energy associated the production of the inputs originated from fossil resources
> >
> > $+$ the energy contained in the feedstock derived from fossil fuels.
>
> Total Life Cycle Energy is equal to the sum of:
>
> > Total Fossil Energy
> >
> > the direct external energy use, originating from non-fossil energy resources
> >
> > $+$ the energy content of all the inputs of non-fossil origin

From the above definitions, total fossil energy relates to the sum of the fossil energy requirements, while life cycle energy also include the non-fossil calorific energy content of the other inputs. By the definition above Total Fossil Energy is a measure of fossil fuel resource depletion.

Product Energy

Product energy is a measure of the energy delivered to the consumer. In the ACAD concept this is the energy in the electricity and biodiesel produced. Since product energy is the valuable contribution of an energy carrier, the required fossil energy and greenhouse gas is measured with regard to product energy. The product energy of the biodiesel is assumed to be the same as the energy density of the fuel.

2.4.2 Energy Parameters

Life Cycle Energy Efficiency

Life Cycle Energy Efficiency (LCEE) compares the total amount of energy that goes into a fuel cycle compared to the energy contained in the fuel product. The efficiency accounts for the losses of feedstock energy and additional energy needed to make the product energy, and is therefore an overall energy efficiency measure.

$$LCEE = ProductEnergy/TotalLifeCycleEnergy \tag{2.2}$$

Fossil Energy Ratio

Fossil energy ratio (FER) gives a measure of the degree of renewability or sustainability.

$$FER = TotalFossilEnergy/ProductEnergy \tag{2.3}$$

If the product energy is in the form of a fuel, the fuel approaches "complete" renewability when the FER is zero. That is, a completely renewable fuel has no fossil energy requirements throughout its life cycle. A FER of 1 indicates that an equal amounts of fossil fuels is needed to produce the output energy, i.e. completely non-renewable. Due to the consumption of fossil energy in the production of the inputs to the system, the energy produced with this concept will never be completely renewable.

Fossil Energy Balance

Fossil Energy Balance (FEB) is a measure of how many units of delivered energy one gets per unit fossil energy.

$$FEB = ProductEnergy/TotalFossilEnergy \tag{2.4}$$

As the energy carrier approaches "complete"' renewability the FEB reach 'infinity'.

2.4.3 Comparisons

Conventional fossil diesel

The primary energy and the greenhouse gas requirements for the conventional fossil diesel is taken from the report by **?**. Both 'low sulphur' and 'ultra low sulfur' diesel will be included in the comparison.

Oilseed rape biodiesel

Biodiesel can be made from various types of biomass. One common type is biodiesel from oilseed rape (OSR), which has been proposed as the main possible future source of biodiesel because of its ability to be cultivated on a fairly wide range of agricultural land (**?**). The work of **?** will be used as reference for the fossil energy and GHG requirements for both the rapeseed biodiesel and conventional diesel.

Algal biodiesel without anaerobic digestion

A version where algae is cultivated with the use of chemical fertilizer and all the energy needed for the production is from external sources. In this scenario all the fertilizer, CO_2 and methanol is of fossil origin, and all the energy required for running and treating the algae matter comes from an external electricity supply. In this scenario, the oilcake is regarded as waste and the whole burden is therefore allocated to the algal biodiesel.

ACAD biodiesel

We have decided to label the biodiesel produced by the ACAD concept as 'ACAD Biodiesel'. Four different scenarios for the ACAD Biodiesel are used in the comparison.

ACAD biodiesel with CO_2 and methanol of fossil origin

In the first production scenario all of the needed CO_2 and methanol is derived from and with fossil resources. Both of these inputs have a high environmental burden in regard to both fossil energy consumption and to fossil greenhouse gas emissions. In the comparison this scenario will be referred to as just 'ACAD Biodiesel'.

ACAD biodiesel without fossil CO_2

In the second scenario, the CO_2 could be obtained as flue gas, from burning of renewable biomass or from plant producing methanol from biomass via gasification. Since the CO_2 in this scenario is regarded as either waste (no allocated burden) or comes from renewable resources there are assumed no environmental burden attached to it.

ACAD biodiesel without fossil CO_2 and methanol

The third scenario outlined is when both the CO_2 and the methanol is produced from renewable resources, and no fossil energy burden are associated with these inputs. This is a rough assumption since although the CO_2 and the methanol might be made from renewable resources (such as wood), the energy used to produce and process them might be of fossil origin. Assuming that the inputs have no fossil energy or fossil GHG burden at gate, means that no fossil resources has been used to produce the inputs.

ACAD biodiesel with wastewater trade-offs

In many Wastewater Treatment Plants(WWTP) using anaerobic digestion to stabilize the sludge, the reject water after the AD-process is pumped back to the incoming wastewater stream and undergoes treatment processes for nutrient removal in order to reach quality standards on the treated water. Since the anaerobic digestion process mineralize much of the organically bound nutrients (especially nitrogen) and make it more water soluble , the levels of nutrients that has to be removed from the water stream is actually higher for a WWTP with AD than a WWTP without. By directing the reject water to an algae pond, the treatment plant could be saved from a heavily polluted wastewater stream. Some 60-80% of the energy consumption during WWT is associated with nutrient removal.

? investigated the energetic aspect of removal and recovery of nutrients in WWTP. When only considering the running electricity and fossil energy requirements for the traditional way of WWT and fertilizer production they estimated these specific energy requirements;

- 45 MJ kg^{-1} N for denitrification in a WWTP
- 49 MJ kg^{-1} P for P-precipitation in a WWTP
- 45 MJ kg^{-1} N for N-fertilizer production
- 29 MJ kg^{-1} P for P-fertilizer production

From a life cycle perspective also the burdens of the inputs to the system should be regarded. If methanol is used as a carbon source for the denitrification process a ratio of 3.4 kg methanol per 1 kg N removed can be used to estimate the mass of methanol required (**?**). The impact factor for methanol production is 37.5 MJ kg^{-1} methanol (**?**). If phosphorus removal proceed via chemical precipitation with ferrous sulfate, a ratio of 1.8 kg Fe per kg P removed can be used to calculate the mass of ferrous sulfate can be calculated (**?**). Impact factor for iron(III) sulfate production is 1.95 MJ kg^{-1} $Fe(II)SO_4$ (**?**).These figures gives an upstream energy burden of 127 MJ kg^{-1} N removed, and 3.51 MJ kg^{-1} P removed. Including the running electricity and fossil requirements listed above gives a total figure of **172 MJ kg^{-1} N removed, and 52.51 MJ kg^{-1} P removed**.

The last ACAD biodiesel scenario for the ACAD biodiesel uses this situation as a reference system and includes this offset as a energy gain. Only the energy requirements are compared with this option.

2.4.4 Fuel specifications for biodiesel and conventional diesel

In order to have a clear basis for subsequent comparison, it is necessary to establish some main characteristics of biodiesel and conventional diesel. The ACAD biodiesel or algae diesel is therefore assumed having the same characteristics as biodiesel produced from oilseed rape. Another name for biodiesel is FAME (fatty acid methyl ester). The characteristics of the fuels are summarized in table 2.4.

Table 2.4: Fuel specifications for biodiesel and conventional diesel (Source: (**?**))

Specification	**Biodiesel (FAME)**	**Conventional Low Sulphur Diesel**	**Conventional Ultra Low Sulfur Diesel**
Density (kg/l)	0.88	0.85	0.83
Net Calorific value (MJ/kg)	37.27	42.38	42.38
Gross Calorific Value (MJ/kg)	37.84	45.60	45.60

Chapter 3

Methods

3.1 Life Cycle Assesment

As environmental awareness increases, industries and businesses are assessing how their activities affect the environment. The environmental performance of products and processes has become a key issue in promoting "greener" products and processes. Life Cycle Assessment (LCA) is a tool for assessing the environmental performance of industrial systems.

LCA is a systematic approach to measure the potential environmental impacts of a product, process or a service throughout its life cycle. The International Organization for Standardization (ISO) have created two LCA standards; the ISO14040 and the ISO14044. LCA is by these standards defined as

> *'the compiling and evaluation of the inputs and outputs and the potential environmental impacts of a product system during a product's lifetime.'*

LCA is a technique where the inputs and the outputs of an activity are systematically identified and quantified from the extraction of raw materials from the environment to their eventual assimilation back into the environment; raw material acquisition - production - use - disposal(Figure 3.1). These flows are then assessed in terms of their potential to contribute to specific environmental impacts (Impact assessment, Figure 3.2). While a complete 'cradle-to-grave' LCA includes all the stages, example of other versions are 'cradle-to-gate' and 'cradle-to-combustion'.

The LCA concept is not new, but have recently gained more interest due to increased concern for environmentally aspects and a need for a more holistic and systematical method for assessing the environmental impact of products, processes and services. The early LCA studies focused on the use of energy and

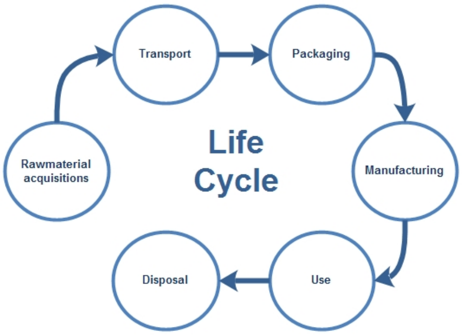

Figure 3.1: Life cycle of a product

materials in the manufacture of products in order for product and process development. More recently, the focus of researches has broadened to include a wide variety of environmental concerns including global warming, acidification, ozone depletion and eutrophication. By taking the comprehensive life cycle approach, one can characterize the environmental advantages and disadvantages of alternatives by taking into account upstream and downstream consequences. The system approach of LCA requires assessment of a process in terms of a ’functional unit’. Based on the purpose of the LCA study the goal definition, the scope, the system boundaries and the ’functional unit’ is chosen. This gives the framework for the collection of data and for the interpretation of the results. LCA can be combined with Life Cycle Costing (LCC) and risk analysis. LCA methodology is increasingly being used to support environmental sound strategic planning, public policy making and to compare the environmental burdens of products and processes.

Three tasks are conducted in the LCA:

1. Compiling an inventory of relevant energy and material inputs to the system and environmental releases from the system.
2. Evaluating the potential environmental impact associated to the identified inputs and environmental releases
3. Interpreting the results in light of the goal for the study

The mentioned tasks are being conducted in a systematic and phased based LCA process involving four components (as shown in 3.2).

1. *Goal Definition and Scoping* - Defining and describing the product, process or activity to be investigated. The context of which the assessment is to be made, the boundaries, the assumptions and the environmental effects to be reviewed in the assessment must be identified.

2. *Inventory Analysis* - All of the energy, water and resource usage and the environmental releases (to air, water and land) must be identified and quantified related to a chosen functional unit.
3. *Impact Assessment* - Assessing the potential human and ecological effect of the flows identified in the inventory analysis.
4. *Interpretation* - Evaluate the results of the inventory with its impact assessment with a clear understanding of the uncertainty and the assumptions used to generate the results.

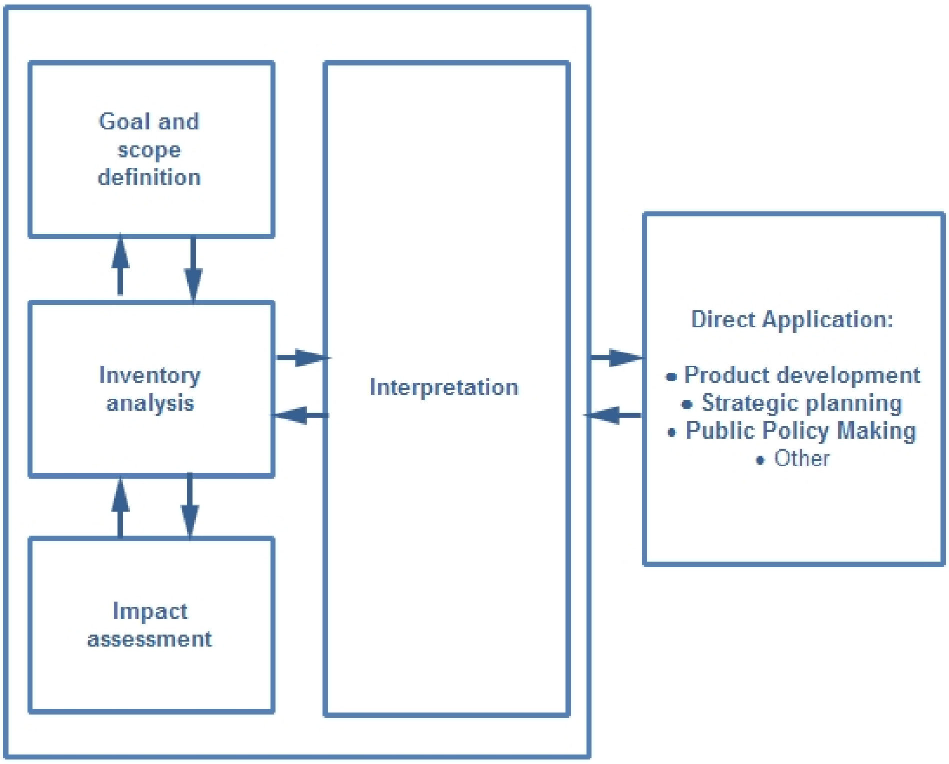

Figure 3.2: Methodologic framework for LCA

Performing an LCA can be resource and time intensive. Most of the time available for this thesis will be used on gaining insight into the different parts of the system, and constructing a model based on published material. The design of the ACAD facility with its inventory is kept as simple as as possible, trying to highlight the factors that affect the chosen impact categories the most. Since this is a LCA of a virtual concept and that there are, to our knowledge, no industrial scale facilities using this concept at present time, this LCA should be seen as a sketch of the environmental issues related to the concept.

3.1.1 Goal definition and scoping

The aim of this LCA is to quantify the fossil energy and GHG requirements of the biodiesel produced in the ACAD Biorefinery. The environmental impacts factors investigated are; *Global Warming Potential, Fossil Energy Resource Depletion*. Global warming potential is linked to the total fossil greenhouse gas outputs, while the fossil energy resource depletion is linked to the total fossil energy requirement. The impacts of the ACAD Biodiesel will then be discussed and compared to other types of diesel. The overall goal of the LCA is to gain sufficient information to evaluate and conclude regarding the potential of the ACAD Biodiesel, and to identify areas of further improvements.

In order to this the following questions needs to be answered:

- *How does the system look like?*
- *How is the energy balance of the system?*
- *What are the inputs to the system?*
- *What are the indirect upstreams contribution of the inputs?*

Since this LCA is of a vitual product, the required level of data accuracy is therefore set to generic and estimated values. The ACAD concept involves many different processes and all of the processes have a been extensively studied earlier, a general approach is therefore necessary.

As far as possible, all of the data used in building the ACAD model are based on published scientific papers. All of the data derived from external sources should be presented with a reference. All calculations should either be explained in the paper or enclosed in the Appendix. All of the measuring units used are based on the metric system.

The engineering calculation software MathCad is used to build the system flow of the ACAD model. The calculations for the ACAD model are found in the Appendix B.

3.1.2 Functional unit

All of the data will be organized in the terms of a *functional unit* that appropriately describe the function of the process being investigated. A functional unit should be defined so that an equal amount of product or equivalent service is delivered to the consumer. In this LCA the functional unit is set to the energy content of one ton of biodiesel. This functional unit is chosen because it allows a comparison to other types of diesel on the basis of energy.

3.1.3 Scope of the study

An LCA includes all four stages of a product or process life cycle: raw material acquisition, manufacturing, use/reuse/maintenance, and recycle/waste management. By combining anaerobic digestion and algae cultivation one seeks to build a closed loop system. Due to losses of nutrients and the fact that not all of the organic matter is turned into biogas, indicates that a totally closed system will be nutrient limited after a while. The focus of this LCA will therefore be to identify and quantify the supporting flows into the system and energy and waste flows out of the system. Due to limited time and resources the system being analyzed has been been simplified extensively.

These are some of the assumptions defining the system boundaries:

1. *Inputs* The co-substrates sludge and waste paper are characterized as wastes, and has no environmental burden when entering the system boundaries. The upstream environmental burdens for the other input materials will be accounted for by linking the consumption of these materials to the cradle-to-gate data acquired from the literature.

2. *Nitrogen* Since all the needed nitrogen comes from the digestate, no external nitrogen fertilizer is needed for the algae cultivation.

3. *Outputs* Valuable products leaving the system are biodiesel and electricity. The allocation of the total burdens will be based on their energy content. The solid waste (organic fertilizer) is characterized as a waste product and has therefore no environmental burden.

4. *Energy* Except for solar energy, no external energy is entering the system. All of the energy needed for running the system (process heat and electricity) is derived from the produced electricity and heat energy from the CHP. Excess electricity leaves the system boundaries as one of the valuable products. This means that the heat from the CHP is enough for both oil extraction, esterification, pre-treating the algal sludge and to obtain an optimal process temperature within the AD reactor.

5. *Water loss* The water losses out of the system comes from evaporation from the pond and from the water leaving the system together with the solid waste.

6. *Infrastructure* Environmental burdens related to the infrastructure, maintainance and distribution are taken directly from reference (**?**).

7. *Downstream* The downstream environmental consequences from the usage of the solid waste is not included in this LCA.

8. *Emissions* It is assumed that all of the CO_2 produced either in the biogas or from the combustion of the methane in the CHP, is consumed by the algae. As long as the algae's need for CO2 is greater than the production of CO_2, no CO_2 will therefore emit to the atmosphere from the system. No other GHG emissions are assumed from the system (e.g. from AD reactor, scrubbing, algae pond, CHP). If the CO_2 consumption of the algae exceeds the internal production, the additional CO_2 will be derived from external sources.

9. *Nutrients* The total amount of nutrients are used with a perfect efficiency.

3.1.4 Allocation

Two valuable products leave the system; biodiesel(algal methyl ester) and power. The direct and indirect environmental burdens must therefore be allocated between these products. Since both of the products are energy carriers the allocation is done with regard to energy content. Although electricity has a greater exergy, this has not been taken into account when measuring the allocation factor. The biodiesel produced bears therefore a greater burden than if exergy allocation method would have been used.

3.1.5 Impact categories

Fossil Energy Resource Depletion

Fossil Energy Requirement is a measure of how much fossil energy the product has used to through its life cycle, and is therefore a measure of the fossil energy resource depletion of the product. Energy is reported here in terms mega joules (MJ).

Global Warming Potential

Global warming potential is quantified in terms of kilograms equivalents of CO2. For a fair comparison, the same global warming potential values as in reference (**?**) are used.

Table 3.1: Global Warming Potential

Gas	GWP
Carbon dioxide, CO_2	1
Methane, CH_4	24.5
Nitrous Oxide, NO_2	320

3.2 Building the system flow

In this section the assumptions, figures and calculations used to find the system flow are presented. The calculations and a list of parameters are showed in the appendix. The flow chart of the model is shown in figure 3.3.

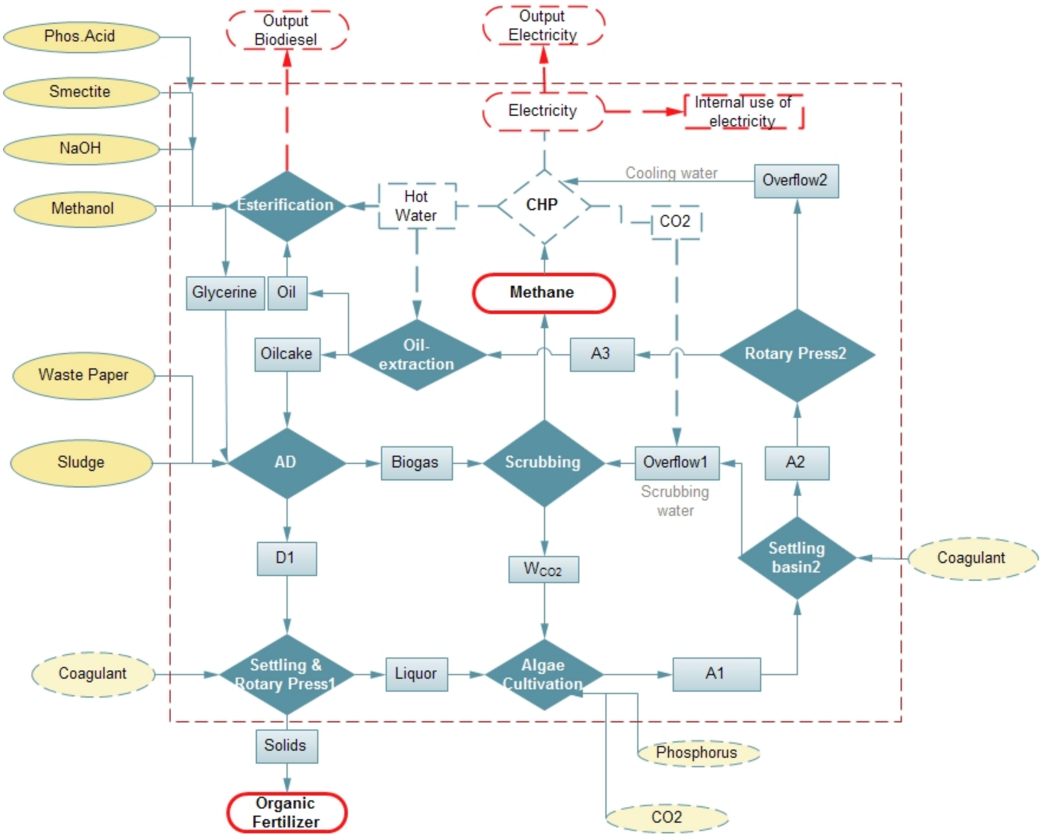

Figure 3.3: System overview

Functional unit

The functional unit for the system flow is one ton of biodiesel.

Methane

The methane production is a central feature in the ACAD model, this was therefore chosen as the reference for the rest of the calculations. Knowing the amount of methane to produce the amount of organic matter (in kg VS) feed into the anaerobic digester is calculated by using formula 3.1:

$$B_2G * \%CH_4 * (X_{OC} + X_S + X_C + X_G) = M \tag{3.1}$$

Where B_2G is the amount of biogas produced per kg VS feed, $\%CH_4$ is the amount of methane in the biogas, and $X_{OC...G}$ are the mass of oilcake, sludge, wastepaper and glycerine respectively. M is the volume of methane produced. In order to scale the model to fit the functional unit, the methane production is set to the level where the system yields 1 ton of biodiesel.

C/N-ratio

As mentioned in chapter 2 the C/N-ratio of the organic matter in the AD reactor is an important process parameter. The optimal ratio of carbon and nitrogen is set to C/N = 20-30/1 (**?**). Since the algal matter has a low C/N it must be mixed with more carbon rich material in order to reach the optimal C/N-ratio. The mix between algal and co-digestion matter is limited to be in the optimal C/N range by using the following equations:

$$CN_{min} \leq (a * CN_{OC} + b * CN_S + d * CN_C + k * CN_G) \leq CN_{max} \tag{3.2}$$

$$\sum(a, b, d, k) = 1 \tag{3.3}$$

$$0 \leq a, b, d, k \leq 1 \tag{3.4}$$

Subscript OC, S, C and G stands for oilcake, sludge, waste paper and glycerine respectively. While a, b, d, k are the different feedstock percentage contribution to the total weight entering the AD-reactor (kg VS).

Nitrogen balance

One of the key goals of ACAD concept is to eliminate the use of external supply of nitrogen fertilizer. Production of nitrogen fertilizer is energy demanding and the use of artificial fertilizer contributes greatly to the environmental burden associated with production of energy from microalgae (**??**). By altering the type of co-digestion material and the mix between co-digestion material and algal matter, the nitrogen is sought to be balanced trough the system, i.e. the nitrogen leaving the system is equal to the nitrogen entering the system.

'Production' of algae-available nitrogen :

$$\beta_{VS} * (x * N_{OC} + y * N_S + z * N_C + j * N_G) \tag{3.5}$$

β_{VS} is the mineralization factor of the nitrogen in the AD. N indicates the percentage of total nitrogen in the feedstock, while subscript OC, S, C and G stands for oilcake, sludge, waste paper and glycerine respectively. The symbols x, y, z, j are the weight of the different feedstock (kg VS). As mentioned earlier, the production of nitrogen must equal to the algae's consumption of nitrogen.

Carbon balance

Carbon balance can be calculated using these equations:

Production of CO_2 in the biogas:

$$W_{CO_2} * B_2G * \%CO_2 * M \tag{3.6}$$

Production of CO_2 from combustion in CHP:

$$\beta_{CO_2} * W_{CH_4} * B_2G * \%CH_4 * M \tag{3.7}$$

CO_2 consumed by algae:

$$A_{CO_2} * X_A \tag{3.8}$$

where W_{CO_2} W_{CH_4} are the weights of CO_2 and CH_4, B_2G is the production of biogas (m^3) per kg VS, $\%CO_2$ and $\%CH_4$ are the % of CO_2 and CH_4, β_{CO_2} is the weight ratio between CO_2 and CH_4 and M is the total mass of the feedstock entering the AD-reactor. If the consumption of CO_2 is greater than the productions, CO_2 must be derived from external sources.

3.2.1 Energy

Energy produced

There are two energy products leaving the system; electric power and biodiesel. The produced biogas is after scrubbing combusted in a combined heat and power

(CHP) gas engine. The heat produced is utilized in the different processes within the system, and the power needed for running the processes within the system, is subtracted before the excess power is exported. The calculations leading to the power and heat need for the different processes in the system are explained under.

3.2.2 Lower Heating Values feedstock

Figure 3.2 shows the lower heating values for the different feedstock involved in the process.

Table 3.2: Lower Heating Values of various feedstock

Feedstock	**Energy (MJ/kg)**
Algae	29.00
Sludge	16.56
Waste Paper	19.23
Methanol	20.09

Mixing in AD

Power needed to run the AD-reactor:

$$El_{AD} = X_{biogas} * \delta_{AD_{El}} \tag{3.9}$$

Heat needed in the AD-reactor

$$Heat_{AD} = X_{biogas} * \delta_{AD_{Heat}} \tag{3.10}$$

where El_{AD} and $Heat_{AD}$ are the power and heat needed, X_{biogas} is the volume of biogas produced, and $\delta_{AD_{El}}$ and $\delta_{AD_{Heat}}$ are the factor for electricity and heat respectively.

According to **?**, the energy consumption for biogas production from raw sludge fermentation were 10200 kWh/1000 PCE in heat consumption and 2300 kWh/1000 PCE in electrical consumption. PCE (Per-capita equivalent) is a measure which relates to the average production of waste per capita. By using the figure for biogas production of 9125 Nm3/1000 PCE, factors for electricity and heat consumption per Nm3 biogas produced were estimated: $\delta_{AD_{El}} = 0.25$ and $\delta_{AD_{Heat}} = 1.118$. Both the electricity and the heat needed comes from the CHP.

Scrubbing

According to reference (**?**) the electricity consumption for biogas purification has a factor of 0.5 kWh per m3 product gas purified. The electric energy needed is then found simply by multiplying this factor with the volume of the product gas.

Pumping

Power needed for pumping:

$$El_{pump} = (\rho_W * g * h * \sum(Q))/\eta_{pump} \tag{3.11}$$

where ρ_W is the density of water, g is the gravitational acceleration, h is the height of which the water must be raised, $\sum(Q)$ is the sum of all the flows and η_{pump} is the efficiency of the pump.

Mixing in pond

Power needed to circulate the ponds:

$$El_{mix} = Area * \theta mix \tag{3.12}$$

where $Area$ is the pond area needed to be circulated, and θmix is the power consumption per area. Consistent with the work of **?** θmix=11668 MJ ha^{-1} yr^{-1}.

Rotary press

Power needed in the rotary presses:

$$El_{rotary} = Q * \theta rotary \tag{3.13}$$

where Q is the volume of water needed to be dewatered, and $\theta rotary$ is the power consumption per m^3. Calculated from the specification of a rotary press given by a producer[1]: $\theta rotary$=0.01449 kWh m^{-3}.

CO2 injection

Power needed for the CO_2 injection:

$$El_{injection} = X_{CO_2} * \theta injection \tag{3.14}$$

where X_{CO_2} is the weight of the CO_2 to be injected, and $\theta injection$ is the power consumption per kg CO_2. According to **?**: $\theta injection$=0.022 kWh kg^{-1} CO_2.

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[1] metsopaper.com

Oil extraction

Reference (**?**) explains and quantifies the energy consumption for the production of rape oil from rape seed. By using the LCI of 'Rape seeds, in oil mill, RER' these figures were estimated:

Electricity (press) = 0.1 kWh kg^{-1} oil produced

Electricity (refining) = 0.0061 kWh kg^{-1} oil produced

Steam = 1.7889 MJ kg^{-1} oil produced

Oil extraction from algal sludge (80% water) and oil extraction from rape seeds (12% water (**?**)) are quite different and may differ significantly regarding the energy consumption. Despite this the figures for the energy consumption for the extraction of rape seed oil is used as a reference for the oil extraction in the ACAD concept. The energy consumption related to the oil extraction will will be discussed in chapter 5.

Esterification

We assume that the esterification of algal oil is similar to the esterification of rape seed oil. From reference (**?**), the LCI of 'Rape oil, in esterification plant, RER' is used to estimate these values for energy consumption:

Electricity = 0.0422 kWh kg^{-1} methyl ester (biodiesel) produced

Steam = 0.9238 MJ kg^{-1} methyl ester (biodiesel) produced

3.3 Life Cycle Inventory

3.3.1 Allocation

As mentioned earlier, the allocation between the power and the biodiesel produced biodiesel by the virtual facility, is based on the energy content of the products. The allocation factor for the ACAD diesel is calculated according to equation 3.15.

$$Allocation_{bd} = \frac{Energy_{bd}}{Energy_{bd} + Energy_{P}} \tag{3.15}$$

where bd and P stands for biodiesel and power respectively.

3.3.2 Basis for comparison

In order to make a fair comparison between the fuels, many of the life cycle inventories (LCI) used to assess the fossil energy and the greenhouse gas requirements for biodiesel production from oilseed rape in reference (**?**) are used. Life cycle inventories not found in this reference, are derived from (**?**). The LCI used to calculate the fossil energy and the greenhouse gas requirements for the ACAD biodiesel examined in this thesis, are summarized in 3.3.

Table 3.3: Life Cycle Inventory for different compounds

Item *Inputs*	**Functional Unit**	**Energy Req (MJ)**	**CO_2-eq Req (kg)**	**CO_2 (kg)**	**CH_4 (kg)**	**NO_2 (kg)**
Electricity	1 MJ	3.083	0.16	0.15	4.04E-4	5.58E-6
Nitrogen fertilizer	1 kg N	40.608	6.693	-	-	-
Aluminum sulfate	1 kg $Al_2(SO_4)_3$	5.7	0.51	-	-	-
Super phosphate	1 kg P_2O_5	15.8	0.71	0.7	2.3E-5	4.2E-5
CO_2	1 kg CO_2	3.06	0.50	-	-	-
Methanol	1 kg CH_4OH	38.08	2.76	2.72	1.3E-3	1.5E-5
Sodium oxide	1 kg NaOH	19.87	1.2	1.12	3.25E-3	-
Hexane	1 kg	52.05	0.56	0.543	6.73E-4	1.3E-5
Phosphoric acid	1 kg	11.4	0.8	0.768	1.23E-3	2E-5
Smectite	1 kg	2.55	0.2	0.197	3.7E-5	6.5E-6
Others						
Plant Construction*	per ton bd	106	5	-	-	-
Plant Maintenance*	per ton bd	66	2	-	-	-
Distribution*	per ton bd	498	32	-	-	-

Source: (**??**)
*= per ton biodiesel produced taken for 'Modified Production of Biodiesel from Oilseed Rape'(**?**).

The results for the CO_2 and the nitrogen fertilizer used here comes from the joint production of ammonium nitrate and the recovery of CO_2 as an industrial gas from natural gas feedstock. Although ammonium nitrate is the main product, the CO_2 is also used for industrial purposes and must therefore share some of the burdens related to energy inputs and GHG outputs. Since the results for the ACAD biodiesel will be compared to the results for the conventional diesel and rapeseed biodiesel in reference (**?**), the same allocation procedure for ammonium nitrate and CO_2 used in their report. The allocation was based on market price leading to a share of 93% for ammonium nitrate and 7% for CO_2. All the CO_2 is assumed to ultimately be released into the atmosphere, and therefore included in the GHG requirements of the nitrogen fertilizer and the CO_2. Since no industrial CO_2 is used in rapeseed cultivation, the values for nitrogen fertilizer are found by calculating backwards to find the values for fossil energy requirements and GHG requirements per kilo CO_2.

3.3.3 Comment on the different scenarios

Conventional Diesel and Rapeseed Biodiesel

The energy requirements and the greenhouse gas requirements for the two conventional diesel types, low and ultra low sulphur diesel, and for the two rapeseed biodiesel types, conventional and modified, are taken directly from reference (**?**).

The goal of this study was to *provide an independent, comprehensive and rigorous evaluation of the comparative energy, global warming and socio-economic costs and benefits of producing biodiesel from Oilseed Rape (OSR) in the UK.*

The functional unit of their study were 1 tonne of biodiesel produced from OSR and distributed to relevant sales points. All the comparisons in the study is by the unit of energy delivered or saved (MJ). These are their two scenarios:

1. Conventional production of biodiesel from oilseed rape by solvent extraction.
2. Modified production of biodiesel from oilseed rape with low-nitrogen cultivation, straw replacing heating fuel and biodiesel replacing diesel fuel.

In the comparison, this scenario is added:

1. Modified production of biodiesel from oilseed rape with low-nitrogen cultivation, straw replacing heating fuel, biodiesel replacing diesel fuel and renewable methanol replacing methanol produced from natural gas.

On the basis of the parameters and the assumptions made in the reference (**?**), the life cycle inventory for the ACAD biodiesel investigated in this study has been contructed.

Algal biodiesel without AD

In the inventory for the algal diesel without AD, the nitrogen and phosphorus requirement are supplied completely externally. The electricity needed for the mixing, pumping, CO_2-injection, rotary press, extraction, esterification and to produce the needed heat for the extraction and esterification is supplied externally.

ACAD biodiesel

The life cycle inventory for the ACAD biodiesel is constructed by multiplying the life cycle coefficients in table 3.3, with the input needed to produce one functional unit. The life cycle energy requirements and GHG requirements are then summarized and allocated to the biodiesel on the basis of its relative energy content. Since the biorefinery produces its own electricity and steam, these figures are not inputs to the system and therefore not included in the inventory. In the LCI for the ACAD Biodiesel the life cycle burdens related to plant construction and maintenance have not been estimated. These figures are therefore included as they are for the modified production of biodiesel from oilseed rape. The distribution of the biodiesel is assumed to be equal for the ACAD biodiesel as distribution for the conventional rapeseed biodiesel, meaning that fossil fuel is used for this distribution. If the biodiesel produced is used the direct contribution of distribution will fall out. Different scenarios for the ACAD biodiesel are:

1. ACAD biodiesel with industrial CO_2 and fossil methanol.
2. ACAD biodiesel with 'burden-free'- CO_2 but with fossil methanol.
3. ACAD biodiesel with 'burden-free'- CO_2 and methanol.
4. ACAD biodiesel with 'burden-free'- CO_2 and including avoided burdens from WWT.

For the two last scenarios the burden associated with the CO_2 and methanol is excluded. For the last scenario this might not give a completely correct picture of the total life cycle burden. Although the methanol is produced from renewable resources, fossil energy might have been used in the production. The methanol in the last scenario must therefore also be interpreted as 'burden-free'.

Reference system

When using wastewater treatment with flocculants and fossil methanol as a reference system, the offset is simply added as a energy gain for the ACAD biodiesel. In the last ACAD biodiesel scenario these offsets are included.

Chapter 4

Results

4.1 System flows

4.1.1 Overview the ACAD biorefinery

Given the system inputs and the constraints the system flows have been calculated. The calculations leading to the results presented in this chapter and a summarized flowchart with quantified flows are found in Appendix B, while the inputs and parameters used are listed with there corresponding reference in Appendix A.

4.1.2 Producing one functional unit

Biomass

The table 4.1 shows the amount of the different biomass needed to produce 1 functional unit from the system. The functional unit is set to 1 ton biodiesel. This equals to 1136 liters or 19 full tanks if your car's fuel tank takes 60 liters. In order to produce this quantity, the anaerobic digester needs following feeding:

Table 4.1: Amount and fraction of the different feedstock entering the AD

Type	Quantity (kg TS)	Fraction of total VS
Oilcake	657	36%
Sludge	983	44%
Waste Paper	238	13%
Glycerine	109	7%
Total	**1987**	**100%**

The mixture between the feedstock is calculated on the basis of C/N-ratio and the nitrogen cycle of the concept. Figure 4.1 shows that for each ton of biodiesel produced, approximately 1987 kg of feedstock must enter the AD-reactor, only about 60% of this comes from the external sources; sludge and waste paper. Per ton of external organic waste sources 930 l biodiesel are produced. Using the same volume of a diesel tank, this is equal to approximately 15 tanks of biodiesel per ton of organic waste.

Biogas production

Given the biomass outlined in table 4.1, the amount of biogas produced is shown in table 4.2.

Table 4.2: Volume and energy of biogas and methane produced for each functional unit

Description	**Volume biogas (m^3)**	**Volume methane (m^3)**	**Energy content (MJ)**
Biogas produced	525	875	19 820

The biogas production is estimated based on the total amount of volatile solids entering the AD. A function of 0.537 m^3 kg^{-1} of VS (**?**) and a methane content of 60% is used (**?**). The energy content of the methane is calculated to 55.54 MJ kg^{-1}.

Algae cultivation

The figures on algae cultivation in order to produce one functional unit are summarized in table 4.3.

Table 4.3: Algae biomass produced, productivity, evaporation and total pond area needed to support this production

Description	**Quantity**
Algal biomass cultivated, kg	1685
Total evaporation, liter	6745
Needed area, ha day	7
Productivity ton/ha/day	93

The productivity in 4.3 is based on the parameters for *Chlorella emersonii* taken from **?**. Evaporation is calculated as a function of algae biomass produced (**?**).

One of the factors that governs the productivity of the algae is the solar radiation. Assuming that sufficient nutrients are available for the algae, the sunlight needed to support the photosynthetic process might be the limiting factor. The algae's need for sunlight and the fact that anaerobic digestions works better in warmer climates, indicates that the ACAD concept could be suitable in a tropical context. Tanzania is therefore used as example for a location for the ACAD biorefinery in this thesis.

Fertilizer and CO_2 requirements

The fertilizer and carbon dioxide requirements to produce the algal biomass outlined in table 4.3 are summarized in table 4.4

Table 4.4: Fertilizer and CO_2 requirements

Description	**Needed**	**Supplied within the system**	**External supply**
Nitrogen, kg	77	88	None
Phosphorus, kg	17	9	8
Carbon dioxide, kg	2697	1568	1129

Nutrients requirements are based on stoichometric estimations and the work by **??**. Nutrient supply is estimated by multiplying the organis N an P in the feedstock, with the mineralization factor in the AD. CO_2 is supplied from both the biogas and the CHP.

Outputs

There are two outputs from the ACAD biorefinery; energy and solid waste. Using the functional unit as a reference the outputs have been calculated and are summarized in 4.5.

Table 4.5: Outputs from the ACAD biorefinery

	Output	**Mass**	**Energy**
		(kg)	**(MJ)**
Products			
	Biodiesel	1000	37270
	Power		3640
Waste			
	Organic Fertilizer	1505	

The organic fertilizer is calculated from the mass balance of the system, and is therefore the theoretical balance. When calculating exclusively on the flows in and out of the anaerobic digester the solid waste in the digestate adds up to approximately one tonne, equal in weight to the biodiesel out of the system.

The power exported per functional is enough to support the annual electricity consumption of approximately 18 Tanzanians, but one would need to produce 27 times more in order to provide the annual electricity consumption of one Norwegian (**?**).

4.2 Energy

4.2.1 Energy in feedstock

By multiplying the amount of feedstock with its calorific gross value, the energy content of the biomass were calculated. The results are summarized in table 4.6.

Table 4.6: Energy content of the biomass involved

Feedstock	Energy (GJ)	Fraction of total Energy (%)
Algae	49	68%
Sludge	16	23%
Waste Paper	4	6%
Methanol	2	3%
Total	**72**	**100**%

The total biomass energy entering the system: sludge, waste paper and methanol (other inputs are not included due to their low contribution) equal to 23140 MJ. Since the system produces a total of 40910 MJ of useful energy (biodiesel and power) the factor between total feedstock energy inn and out becomes 1.77.

4.2.2 Energy produced

From table 4.6 we saw that the total energy into the system and energy of algae summarized to 72 GJ. How is this energy distributed through the system? The energy produced in the system have different forms. Related to the total energy in the biomass, the distribution of the different forms are presented in table 4.7.

From table 4.7 we can conclude that 68% of the energy in the feedstock are used, and that 57% of the energy in the feedstock is exported as either biodiesel or power. The energy lost is either heat to air or the energy leaving the system

Table 4.7: Distribution of energy

Description	Energy (GJ)	Fraction of total energy
Biodiesel	37	52%
Power	4	5%
Heat	11	15%
Loss	20	28%
Total	**72**	**100%**

together with the solid waste. Given the algae productivity of the model, the energy production adds up to a total of 2263 GJ ha^{-1} $year^{-1}$.

Of the total exported energy of 40.9 GJ, the distribution between diesel and power are shown in table 4.8. This distribution will be used to allocate the life cycle environmental burden of the production system to the ouput products; biodiesel and electric power.

Table 4.8: Export of energy

Description	Energy (GJ)	Fraction of Exported Energy
Biodiesel	37.3	91.1%
Power	3.6	8.9%
Total	**40.9**	**100%**

4.2.3 Energy consumed in the system

Through the combustion of the methane in a combined heat and power gas engine the system produces its own electric power. About 43% of the power produced is consumed within the system boundaries, the rest is assumed to be exported to a power grid. The representative power consumption is shown in table 4.9. The heat from the CHP is used in different processes within the system. From table 4.9, we can see that scrubbing is the process that consumes most power, followed by the anaerobic digester, oil extraction, esterificaion and mixing. The rest of the processes account for approximately 1% of the power consumption. The power which is not consumed is exported. Some CHP gas engines are able to utilize the biogas prior to the upgrading. By using such an engine, the power needed for scrubbing might be eliminated, but this would also increase the energy used for the CO_2 injection to the pond. In the ACAD biorefinery presented in this thesis, scrubbing of the biogas has been included together with it's power consumption.

Table 4.9: Consumption of electricity

Process	**Power consumption, MJ**	**Fraction**
Anaerobic Digestion	787	12.4 %
Mixing in Pond	211	3.3 %
Scrubbing	945	14.9 %
Pumping	72	1.1 %
CO_2 Injection in Pond	72	1.1 %
Rotary Presses	72	1.1 %
Oil Extraction	393	6.2 %
Esterification	152	2.4 %
Total	**2704**	**42.5** %

4.3 Life Cycle Inventory

4.3.1 Impact quantities

When the ACAD model is constructed, the flows in and out of the system, the energy consumption and the waste can be quantified with regard to one ton biodiesel. These figures are summarized in table 4.10.

Table 4.10: Inputs, outputs and power consumption for the ACAD biorefinery producing 1 ton biodiesel

	Description	**Quantity**
Inputs		
	Aluminium Coagulant, kg	6.9
	Phosphorus, kg	7.6
	CO2, kg	1129.0
	Methanol, kg	113.6
	NaOH, kg	12.3
	Phosphoric Acid, kg	5.7
	Smectite, kg	6.2
Waste		
	Organic Fertilizer, kg	1505.0
Power Consumption		
	Power Consumption, kWh	751

By multiplying these flows with its respective energy and GHG requirements, their contribution can be assessed. Since this system produces its own power, no external power supply is needed. The life cycle assessments in this thesis focus on the fossil energy and greenhous gas requirements, the power consumptions outlined in 4.9 are therefore not included in the life cycle inventory. Downstream energy and GHG requirements for the organic fertilizer are not included either.

4.3.2 Inventory data

As shown earlier in this chapter, the allocation factor for the biodiesel is estimated to 91.1%, meaning that 91.1% of the total life cycle environmental burden should be allocated the biodiesel. In this case the total fossil energy requirement and the total fossil GHG burden needs to be allocated. The burden for each input is calculated by multiplying the allocated weight with the burden parameters listen in table 3.3 in chapter 3. The results are summarized in table 4.11.

Table 4.11: Life Cycle Inventory when producing 1 functional unit

Item *Inputs*	**Functional Unit**	**Allocated Weight (kg)**	**Energy Req (MJ)**	**CO_2-eq Req (kg)**
Aluminum sulfate	1 kg $Al_2(SO_4)_3$	6.28	35.82	3.20
Super phosphate	1 kg P_2O_5	6.97	110.17	4.98
CO_2	1 kg CO_2	1029.87	4273.98	422.25
Methanol	1 kg CH_4OH	103.63	3946.11	285.87
Sodium oxide	1 kg NaOH	11.25	223.61	13.50
Hexane	1 kg	2.34	122.02	1.32
Phosphoric acid	1 kg	5.16	58.8	4.15
Smectite	1 kg	5.63	14.35	1.13
Others				
Plant Construction	per ton bd*		106	5
Plant Maintenance	per ton bd*		66	2
Distribution	per ton bd*		498	32
Sum	per functional unit	1171	9455	775.40

* = per tonnes biodiesel produced

The sum of the required energy and CO_2-eq refers to the fossil life cycle energy and greenhouse gas needed to produce one functional unit in the ACAD biorefinery.

4.3.3 Life Cycle Energy Balance

Different energy parameters are summarized in table 4.12.

Table 4.12: Life Cycle Energy Figures for the total ACAD energy

	Name	**Quantity**
Sum of energy	Total Primary Energy, GJ	9.384
	Total Primary Energy, GJ	9.384
	Total Life Cycle Energy, GJ	72.131
	Fossil Energy, GJ	9.384
	Product Energy, GJ	40.929
Energy measures		
	Life Cycle Energy Efficiency	36.3%
	Fossil Energy Ratio	22.9%
	Net Fossil Energy Balance	4.37

In table 4.12 all of the exported energy is included, not only the biodiesel. These figures means that 36.3% of the total energy involved (total primary energy + internal and input feedstock energy) is exported as usefull energy either as biodiesel or power. Per unit of fossil energy used to extract resources, transport, produce and distribute the product energy, 4.37 units of energy is supplied by the ACAD biodiesel and electricity.

It is with noting that these figures are based on fossil CO_2 and methanol, and that the fossil energy ratio will decrease substantially if these inputs where non-fossil, i.e. have no fossil burden at gate.

Chapter 5

Discussion

As a reminder, this thesis investigates the life cycle of a concept which does not exist at industrial scale, and rough estimates and assumptions have been made in order to construct a model of the virtual facility. Many technological challenges are still unsolved, and some are probably not even been identified yet. Although limited by time, one have tried to make reasonable assumptions in order to design the best waste-biogas-microalgal system for production of bioenergy, on which life cycle assessments then have been conducted. The results from these assessments must therefore not be interpreted as a thoroughly, real and stable assessment of the combination of anaerobic digestion and microalgae cultivation, but more as a preliminary study to identify opportunities and challenges regarding such a concept.

5.1 Results

Although **?** argues that the whole algal biomass should be digested when the cell lipid content is below 40%, the ADAC calculations have found that the two phase approach, both biodiesel and biogas, yields more energy in the ACAD concept than digesting the whole biomass even for levels below 40%. Since the oil extraction process is also a pre-treatment for the oilcake, the biogas yield might be higher than projected in the ACAD model(se figure 4.2). With regard to environmental issues, biodiesel is a very important energy source since it can substitute for fossil diesel directly without major changes in the infrastructure. There are many renewable and low-carbon solutions for production of power, but not as many for fuels. Because of the mentioned reasons, the two-output version has been chosen for the ACAD concept.

5.1.1 Overall energy comments

In order to make the figures for the ACAD biorefinery more understandable, the following sections explain the energy output of the ACAD biorefinery with regard to different features.

- Per 1 ton of ACAD biodiesel, the system produces 40.9 GJ energy.
- For every 1 GJ entering the system in net calorific value of the feedstock, 1.768 GJ leaves the system as either biodiesel or power. Due to the algae ability to convert sunlight to biomass energy, the energgy output is higher than the input.
- Of all the feedstock energy in the system (including the algal biomass) about 57% of the energy is exported as either biodiesel or electricity.
- Given the algae productivities of the model, the energy production per ha per year is 2.26 TJ or 71.7 kW.

Figure 4.6 showed that for every unit of feedstock energy entering the system boundaries, 1.77 units of energy exits the system? How can this be possible? Where does the energy come from? It comes from the algae's ability to combine CO_2, nutrients and sunlight into energy-rich biomass. One way to interpret the numbers in table 4.6 is to say that the nutrients of yesterdays anaerobic digestion has contributed to 68% of todays energy in internal feedstock. The energy content of the algae outnumbers the energy content of the other biomass sources, suggesting that the ACAD concept is more of a sunlight-to-bioenergy, than waste-to-bioenergy system. Actually, the energy content of the algae is more than twice the energy content of the inputs to the system. The role of the anaerobic digester is therefore primarily that of supplying nutrient to the algae, and secondly produce biogas for heat and electricity production.

Given an annual fossil energy consumption of the world of 10.4 TW (**?**), a pond area of 1450000 km^2 is needed for the ACAD concept to supply energy equal to the world's annual fossil energy consumption. This area is 3.76 times the total area of Norway, and approximately 16% of the area covered by Sahara. In order to produce this amount of energy one would need approximately 8 billion tons of sludge and 2 billion tons of waste paper. These are extremely large quantities. Anaerobic digestion is a very robust technology, and a diverse range of organic materials could be digested. Other organic sources than sludge and waste paper could therefore be inputs to the ACAD biorefinery.

5.1.2 Power

Following are some short comments regarding the power production of the concept.

- Approximately 1 MWh of power is produced per functional unit in the ACAD biorefinery
- The power only accounts for about 9% of the total exported energy
- 43% of the energy produced in the system is also consumed by internal processes
- Approximately 18% of the initial energy in the methane is eventually exported as power.
- The system produces about 2.3 times the energy it consumes

Although it do not contribute in large quantity, the power fraction is very important in many ways. First, the electricity production makes the system less dependent on external energy sources, making it more robust and flexible regarding location. Another benefit with the electricity production is that since electricity has a higher energy quality, it can be used in many applications not suitable for liquid fuels.

5.2 Concept evaluation

5.2.1 Comparison with other ACAD-concepts

Although the ACAD biorefinery model build in this thesis differ from the model used by **?**, the results from their research could indicate the viability of the figures for the ACAD biorefinery. **?** also combined algae cultivation with anaerobic digestion, but they included a microbial fuel cell (MFC) as well. The technology of the MFC was still in the development phase when their report was written. The closed-loop-system they presented had methane and electricity as the final outputs. In table 5.1, values for the closed-loop-system and the ACAD biorefinery are compared.

Compared to the closed-loop-system many of the parameters for the ACAD biorefinery are high, especially regarding algae productivities, which the results in higher energy production. If more moderate algae productivities are implemented in the ACAD model (average algae productivity achieved by **?**(38 ton ha^{-1} yr^{-1} and 25% oil content) the energy production decreases to 15 kW ha^{-1}. The productivity is the parameter that differ the most between the closed-loop-system and

Table 5.1: Comparison with the Closed-Loop-Concept

Description	**Closed-loop-Concept**	**ACAD Biorefinery**
Productivity, ton VS ha^{-1} yr^{-1}	24-65	84
Concentration in pond, mg VS l^{-1}	256-703	1000
Biogas production, m^3 kg VS^{-1}	0.38-0.63	0.54
Biogas quality, %	40-65	60
VS destruction, %	49-64	60
C/N-ratio	10-17	25
Calorific value of algae, kJ g^{-1}	25	29
Energy production prospects, kW ha^{-1}	9-23	71

the ACAD biorefinery. This question then arise: Is the productivity used in the ACAD model unreasonably high? In order to answer this question productivity and oil yiels are discussed in more detail in the following section.

5.2.2 Viability of some key assumptions

The assumptions with the highest degree of uncertainty and most profound impact on the total efficiency of the concept are algal productivity, lipid content and energy needed for the oil extraction. These assumptions are therefore discussed in more detail in the following sections.

Oil yield

The rate of algal oil yield is a factor of two parameters; general productivity and the content of lipids in the algae. Increasing the oil yield has been one of the main focuses for research since microalgae was suggested as a source of lipids for bioenergy production. It is a well establish truth within the algae research that nitrogen-limiting conditions increases the lipid content of a number of algae, but at the same time the productivity decreases. High percentage of lipids and high rates of productivity has therefore been found to be mutually exclusive (**?**).

Two major government-sponsored research programs in Japan and USA concluded that algae technology was not yet feasible, and the programs were terminated after investing millions of US dollars. In contrast to these failures, **?** report on the results of a privately initiative that has engineered, built and successfully operated a commercial-scale (2 ha), modular, production system for photosynthetic microbes on Hawaii. Their approach is to combine photobioreactor and open ponds in a two-stage process, shifting between nutrient-sufficient conditions and nutrient-limiting conditions. The first stage (nutrient-sufficient conditions) takes place in a photobioreactor that favors a continuous cell division and prevent contamination, the goal of the second stage is to expose the cells to nutrient deprivation and other environmental stressed that leads to synthesis of the product of interest; oil. Environmental stresses are applied by transferring the culture from the photobioreactor to an open pond. By this method they have managed to achieved microbial oil production from *Haematococcus pluvialis* in equivalent to > 420 GJ ha^{-1} yr^{-1} with a prospect of producing 3200 GJ ha^{-1} yr^{-1}.

The figures behind the production of 420 GJ ha^{-1} yr^{-1} are oil productivities ranging from a mean of 3.78 g(oil) m^{-2} d^{-1} to a maximum of 9.09 g(oil) m^{-2} d^{-1}. The average annual rate of dry weight biomass production from *H.pluvialis* in the pond was 15.1 g m^{-2} d^{-1}, adding up to an annual basis of 38.1 tonnes dry wt. ha^{-1} yr^{-1}, and a maximum of 91.8 tonnes dry wt. ha^{-1} yr^{-1} (**?**). The average oil content in the open pond culture was 25% of dry weight. In their prospects they project yield of 56.5 g dry wt. m^{-2} d^{-1} at a 35% oil content resulting in an oil production rate from the total system of 19.8 g oil m^{-2} d^{-1}.

Given the numbers listed above, are the oil productivity rates used in the ACAD biorefinery model reasonable? The productivities used in the ACAD model are compared to the obtained and the projected productivities by **?** in table 5.2.

Table 5.2: Algae productivities

Description	**Oil content**	**Oil productivity**	**Biomass production**	**Energy production**
	(%)	**(g m^{-2} d^{-1})**	**(g m^{-2} d^{-1})**	**(kW ha^{-1})**
Average achieved open pond*	25	3.78	15.1	24
Maximum achieved pond*	25	9.09	36.4	58
Projected values*	35	19.8	56.5	101
ACAD Biorefinery**	61	15.6	25.5	71

* Values derived from (**?**).

** Parameters used in the ACAD model

According to **?**, evidence for the projected value listed in table 5.2 can be demonstrated using species with known performance characteristics under conditions that prevail in their existing production system. As we see from table 5.2, the oil productivity used in the ACAD biorefinery is higher than the achieved values, but lower than their projected value. We also see that compared to the maximum achieved value derived from **?**, the oil percentage for the ACAD model is much higher, but the productivity in general is lower. If we assume that the development in the algae productivities are improved as projected by **?**, the oil productivity of the ACAD biorefinery of around 15 g oil m^{-2} d^{-1} might not be unrealistic, but compared to the already achieved values the oil productivity of the ACAD model is very high. A lipid content of 61% is definetly questionable, and is discussed further later in this section.

An increase in productivity and a decrease in lipid content for the algae in the ACAD model, will shift the production of energy from biodiesel into biogas, which again is converted to power and heat. If biodiesel is to be the main output of the ACAD biorefinery, the lipid production must be a major focus. As mentioned earlier, the oil productivity depends on both the oil content and the productivity of algal biomass in general. While the first parameter affects the ratio between ACAD biodiesel and power, the second parameter governs the pond area needed to produce the energy. Changes in algae productivity will not affect the conclusions regarding the sustainability of the biodiesel produced significantly, but has a great impact on the figures for the overall energy productivity per area. Since pond area is not a main focus of this thesis, the general productivity is not commented furter. On the other hand, lipid content is more vital and is therefore discussed further.

Lipid content

While **?** cultivated *Haematococcus pluvialis*, the figures used in the ACAD Biorefinery model are based on the yield for *Chlorella emersonii* taken from **?**. A lipid content of around 60% for *C.emersonii* might be easier to attain than for *Haematococcus pluvialis*? In table 5.3, lipid content for different algae strains are summarized (**?**).

As one can see from 5.3, the lipid content of the algae varies a lot. High lipid productivity has a profound effect on the total energy production of the ACAD biorefinery. Algae with high oil productivities should therefore be used to optimize the concept. The '*C.emersonii* Low-N' was chosen for the ACAD model because of it's high lipid content. According to **?** oil content in microalgae can exceed 80% by weight, and that oil levels of 20-50% are quite common. But, as mentioned earlier, high oil levels often means low productivity. An alternative way to improve oil productivities is the use of photosynthetic bacteria, such as the cyanobacteria *Synechocystis*. According to **?**, cyanobacteria accumulate lipids in thylakoid membranes, which is associated with high levels of photosynthesis and a rapid growth rate. **?** have, according to **?**, managed to genetic improve a single-gene mutant of *Synechocystis* that accumulates up to 50% of its dry weight in lipids. The lipid level of 61% used in the ACAD biorefinery model is in the upper level, but by using suitable microalgae or cyanobacteria, this oil content or at least the oil productivity of the ACAD model are assumed to be achieveable.

As a comparison; if the ACAD biorefinery had reached the projected algae

Table 5.3: Average lipid content of different *Chlorella*strains from (**?**)

Microalgae	**Lipid (%)**
C.vulgaris control	18
C.vulgaris Low-N	40
C.emersonii control	29
C.emersonii Low-N	63*
C.protothecoides control	11
C.protothecoides Low-N	23
C.sorokiniana control	20
C.sorokiniana Low-N	22
C.minutissima control	31
C.minutissima Low-N	57

*this is the lipid content used in the ACAD biorefinery, but it is adjusted to 61% in order to make the fractions of lipid, carbohydrates and protein equal to 100%

productivity rate given in **?** of 56.5 g dry wt. m^{-2} d^{-1} at a 35% oil content giving a oil production rate of 19.8 g oil m^{-2} d^{-1} it would have resulted in these figures for the ACAD biorefinery:

- The power fraction of the exported energy rises to 23%. Which means that a larger fraction of the environmental burden must be allocated to the electricity output.
- Annual energy production increases to 3386 GJ ha^{-1} yr^{-1} or 107 kW ha^{-1} yr^{-1}.
- For each functional unit approximately 3 MWh of power is produced together with approximately 1100 liters of ACAD biodiesel.

As one can see, the energy production of ACAD biorefinery compares well with the projected energy production of 3200 GJ ha^{-1} yr^{-1} (**?**) indicating that the ACAD concept could be more efficient than the stand-alone algae cultivation.

Is there enough energy in the heat?

Using the numbers from oil extraction and esterification of rapeseed oil into biodiesel and adding the heat needed for optimal process temperatures in the AD-reactor, the energy consumption sums up to 6.3 GJ. Since the energy content of the heat from the CHP is 10.9 GJ, only 58% of the heat is consumed within the biorefinery.

The excess heat (42%) is assumed to be necessary, but also sufficient, for the oil extraction and the pre-treatment of the oilcake prior to the anaerobic digestion. If the system needs more power to perform the oil extraction, the electricity consumption for the oil extraction can increase substancially (900%) before making the system dependent on external power supply. Since the electricity exported only accounts for about 9% of the total exported energy, an increase in the power consumption for oil extraction will therefore not lead to a significantly decrease in the overall efficiency of the ACAD biorefinery. Based on the presented figures we find the assumptions regarding energy for oil extraction are valid, and that if more power is needed this could most likely be supplied within the system without affecting the overall energy production significantly.

5.3 Life Cycle Impact Analysis

In the following section the sustainability of producing biodiesel using the ACAD bhiorefinery are addressed. As mentioned earlier, this thesis focuses on the required fossil energy inputs and greenhouse gas outputs through the life cycle of the biodiesel. Required in this context means the accumulated fossil energy and fossil GHG needed to extract, process and distribute the inputs, the energy needed for production and distribution of the product to the user, and finally the demolition of the product in an engine converting it to delivered energy and CO_2. Following comes a presentation of the fossil energy and the GHG requirements of the ACAD biodiesel, before these numbers then are compared to other types of diesel fuels.

5.3.1 Representative fossil energy inputs

Figure 5.1 shows how the different input contributes to the total fossil energy required. As we can see from the figure, the fossil energy requirement are dominated completely by the input of CO_2 and methanol, and to some extent distribution. The reason for this is both the large quantities needed of these inputs, but also their relatively large fossil energy burdens. If CO_2 and methanol are produced from renewable resources, the fossil fuel resource depletion of the energy outputs could be reduced substancially. This would have a profound effect on the fossil energy requirement of the ACAD biodiesel.

Since fossil diesel is used for the distribution of the ACAD biodiesel, distribution also increases the fossil energy requirement. This contribution is easily reduced by exchanging the fossil diesel used with some of the ACAD biodiesel it distributes.

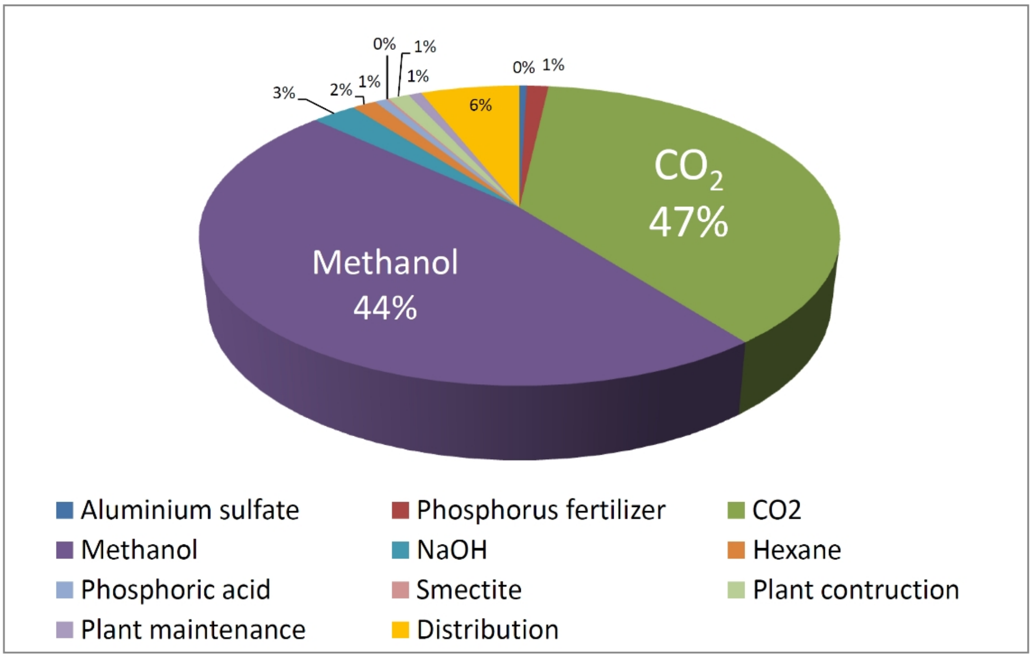


Figure 5.1: Representative energy requirements inputs for the ACAD biodiesel using CO_2 and methanol of fossil origin

If one manage to replace all the mentioned inputs; CO_2, methanol and fossil diesel for distribution, with renewable resources, the fossil energy requirement could be reduced with 96%. The ACAD biodiesel would then reach a life cycle renewability of 98% and a net energy balance of 50, meaning that for each unit fossil energy used 50 units of fuel energy is delivered. For this reason sources of non-fossil CO_2 and methanol should be identified and used in the ACAD ecotechnology concept. Analogue to the fossil energy contribution for distribution, the greenhouse gas outputs could be reduced by exchanging fossil diesel with ACAD diesel. As mentioned in chapter 4, the driving forces with regard to fossil energy and greenhouse gas requirements, are CO_2 and methanol, and to some extent distribution. By using renewable resources as input the fossil greenhouse gas requirements could be lowered with up to 98%.

In the next section the performance of the ACAD biodiesel is compared to the performance of other types of diesel fuels; fossil and renewable.

5.3.2 Representative greenhouse gas outputs

As seen in figure 5.2, the contribution of CO_2 and methanol is even greater for GHG requirements than for the fossil energy requirements. These two inputs stands for 94% of the total life cycle greenhouse gas outputs.

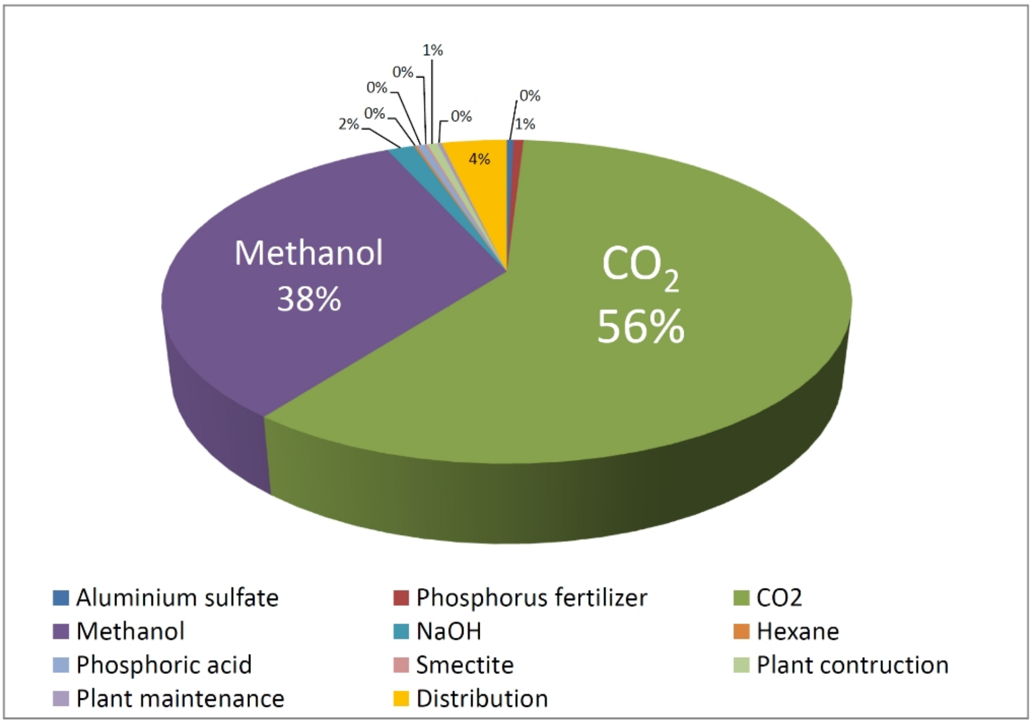


Figure 5.2: Representative greenhouse gas requirements outputs for the ACAD biodiesel using CO_2 and methanol of fossil origin

5.4 Comparisons

Before the comparison of the fossil energy requirements and the GHG requirements between the different fuels, a presentation of the representative requirements for conventional and modified rapeseed oil biodiesel production is given. All of the presented numbers have been taken directly from reference (**?**).

5.4.1 Requirements for rapeseed oil biodiesel production

Conventional production

In conventional production of rapeseed oil biodiesel, the esterification process stands for 35% of the fossil energy requirements, and 25% of the representative fossil GHG outputs. This is caused mainly by the consumption of methanol, but also the direct energy consumption in the esterification process. The production of the nitrogen fertilizer stands for 24% of the fossil energy requirements, and just above half of the representative fossil GHG outputs.

Modified production

The conventional biodiesel production from oilseed rape was by **?** considered with these modifications; low-nitrogen cultivation of oilseed rape, the use of rape straw as an alternative heating fuel in the processing of the biodiesel, and the replacement of conventional diesel by biodiesel in the agricultural operations and road transport vehicles. Assuming that these modified production can be achieved in practice, representative requirements were calculated.

Compared to the figures from the conventional production, the representative contribution for the esterification and the production of the nitrogen fertilizer is magnified even further, with values of 55% and 22% for the representative energy requirements, and 47% and 43% for the representative fossil GHG requirements. Compared to the values for the ACAD biodiesel, both the conventional and the modified rapeseed biodiesel has a great contribution from the production of nitrogen fertilizer, but the do not have a contribution from CO_2 production since the CO_2 needed for the growth of oilseed rape is taken directly from the atmosphere. ACAD biodiesel gets its nitrogen from the digestate, but uses concentrated CO_2 to stimulate the growth of the microalgae. Values for solvent extraction and esterification is also higher for the rapeseed biodiesel compared to ACAD biodiesel, since both external supply of electricity and natural gas are used.

5.4.2 Comparisons of energy requirements

All the measures in the following comparisons are given as "per MJ", which shows the measured relative to the energy output, calculated as the net calorific value of the diesel/biodiesel.

As seen in figure 5.3, the fossil diesel has a higher fossil energy requirement than it delivers. This is due to the energy needed to extract, manufacture and distribute the diesel to the costumers. All of the alternative energy resources compares well with the conventional diesel with regard to fossil energy requirement (see figure 5.3).

The biodiesel with the highest fossil energy requirement is the algal biodiesel without nutrient recycling through an AD-process. This biodiesel gets the upstream burdens for the nitrogen fertilizer production, the production of CO_2, the production of fossil methanol and the burden related to the energy consumption at the production site. The biodiesel with the second highest fossil energy requirement is the conventional production of rapeseed biodiesel. Modified rapeseed oil biodiesel and the ACAD biodiesel using industrial fossil CO_2 and methanol,

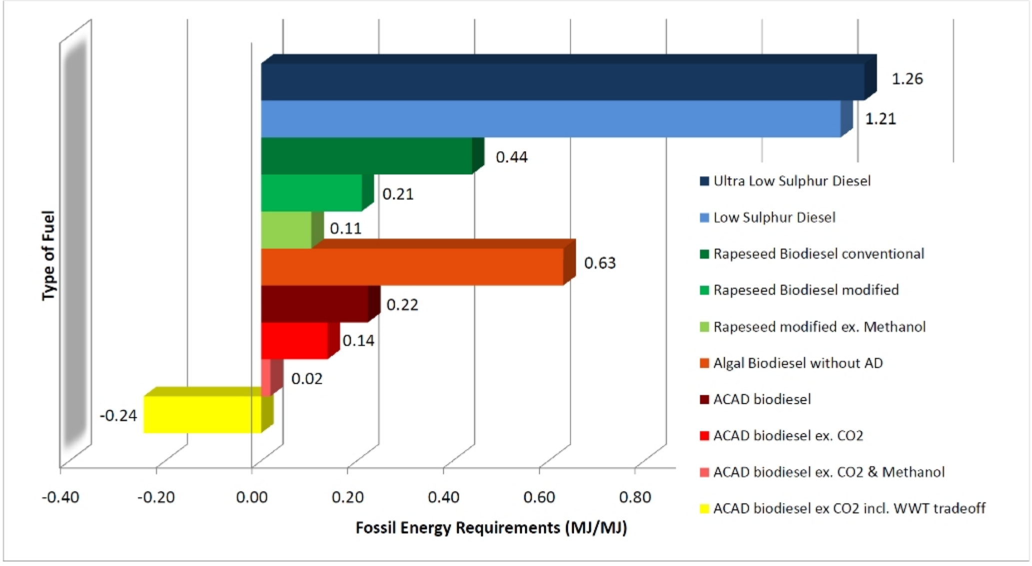


Figure 5.3: Comparative fossil energy requirements

require approximately the same amount of fossil energy throughout it's life cycle. Great improvements, with regard to fossil energy requirements, can be made for both the production of rapeseed oil biodiesel and the ACAD biodiesel if the methanol used is produced from and with non-fossil resources. In addition to this, ACAD biodiesel can lower it's fossil energy requirement even further by using non-fossil CO_2.

The figures for both the conventional and the modified production of biodiesel from rapeseed oil (**?**), are given with a reference system. The reference system determine credits for alternative activities that are avoided or displaced by the main process under investigation. The reference system used for the production of biodiesel from rapeseed oil consisted of fallow set-aside with diesel fuel consumption of 922 MJ ha^{-1} for mowing, and a gross energy requirement of 1.110 MJ MJ^{-1} for diesel fuel in the UK in 1996.

For the first three ACAD biodiesel scenarios no reference system has been used, but for the last scenario avoided burdens related to wastewater treatment are included. The reference system used are chemical precipitation of phosphorus and use of methanol as a carbon source for the denitrification process in a wastewater treatment plant. Since 'fossil' methanol is used in the wastewater treatment process, this type of methanol is also used in the production of ACAD biodiesel. By including this reference system the energy requirement actually becomes negative, meaning that the avoided fossil energy requirements are greater than the required fossil energy needed for the biodiesel production. Compared to the reference system the fossil energy depletion rate is negative, even before the avoided burdens related to using conventional fossil diesel are included. The sustainability of the diesel fuel sector could therefore be substancially improved if consumption where shifted from conventional fossil diesel to ACAD biodiesel.

5.4.3 Comparisons of greenhouse gas emissions

In the following section the fossil greenhouse gas outputs for different fuel are compared. Since figures outlining the fossil greenhouse gas emissions for wastewater treatment are not included, the last scenario in figure 5.3 is not included in figure 5.4. But, since fossil energy requirements and GHG requirements are usually strongly related, it is reasonable to assume that the production of ACAD biodiesel would result in avoided fossil GHG burdens for the WWT as well.

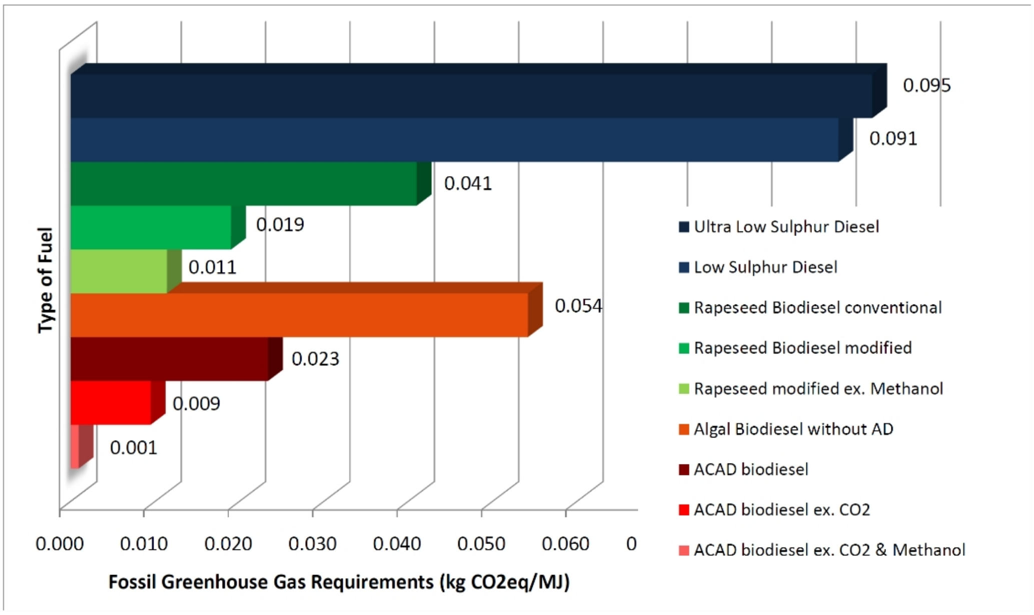


Figure 5.4: Comparative fossil greenhouse gas outputs

Figure 5.4 shows how many kilos of fossil CO_2-equivalents that are being emitted per MJ of energy delivered by the fuel. A comparison between the extrems (ultra low sulphur diesel vs ACAD biodiesel ex. CO_2 & methanol) shows that the required fossil greenhouse gas requirements can be reduced with approximately 99% by shifting from conventional to ACAD biodiesel. Algal biodiesel without anaerobic digestion, would only gives a decrease of 43%, while the best rapeseed oil biodiesel (modified, without fossil methanol) gives a 88% decrease.

Shifting from using ultra low sulphur diesel to ACAD biodiesel(with fossil CO_2 and methanol) would save 2.7 ton CO_2-equivalents per functional unit compared to Ultra low sulphur diesel. For the best case scenario (ACAD biodiesel with renewable CO_2 and methanol) 3.5 ton CO_2-equivalents emitted to the atmosphere could be reduced per ton ACAD biodiesel produced.

Knowing that the production of ACAD biodiesel does not need arable land like the production of biodiesel from rapeseed oil, indicates that ACAD biodiesel production is superior to rapeseed oil biodiesel in regard to required fossil energy, greenhouse gas emissions and with regard to land use.

As shown in the previous two sections, the ACAD biodiesel compare well with other types of diesel fuels, both in regard to global warming potential and fossil energy resource depletion. By relatively simple modification, the ACAD biodiesel could reach nearly complete renewability and carbon neutrality. The ecotechnology of producing biodiesel using microorganisms such as methanogenesis and microalgae, should therefore be investigated and developed further.

5.4.4 Comments on the energy offsets from WWT

The last ACAD biodiesel scenario compared in figure 5.3 showed a negative fossil energy requirement if wastewater treatment(WWT) was used as a reference system. The representativ contribution for this trade off is shown in figure 5.5.

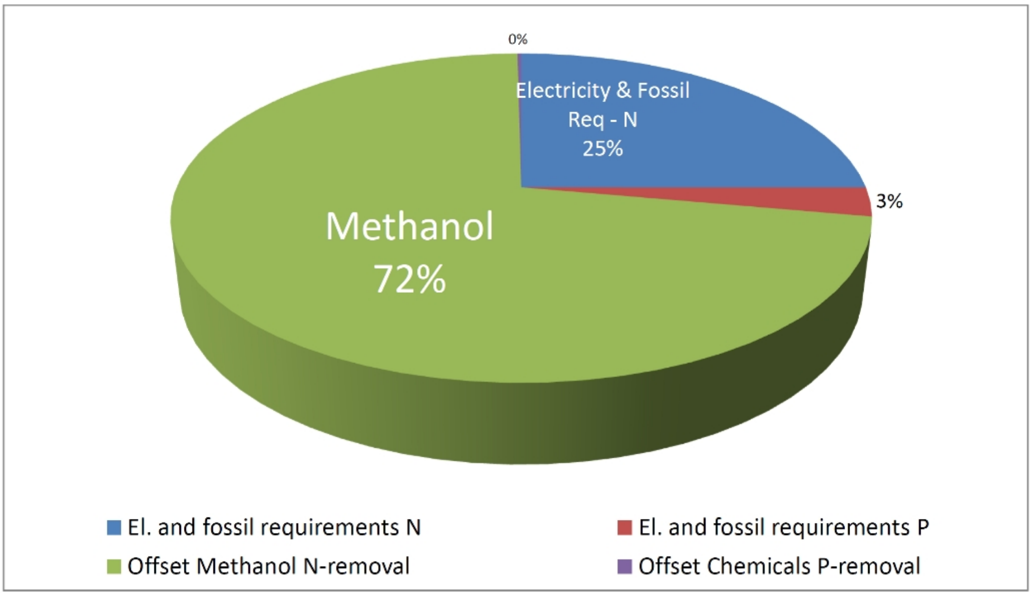


Figure 5.5: WWT trade offs using ACAD biorefinery

The offset is highly dominated by the methanol consumption needed for the denitrification process. Nitrogen removal stands for 93% of the total fossil energy offset and is the major burden driver for the wastewater treatment process. It is worth mentioning that many wastewater treatment plants uses returned sludge as the carbon source (activated sludge process) instead of industrial methanol. This would lower the burden associated with methanol use, but it could also increase the energy consumption within the treatment plant since large volumes of sludge need to be pumped through the system. Avoided burdens regarding treatment of the digestate is an important consideration when evaluating the total sustainability of the ACAD concept.

5.5 Chemical fertilizer offset

Another avoided burden is regard to the production of chemical fertilizer. These offsets could be included if production with chemical fertilizer are used as a reference system.

5.5.1 Production of chemical fertilizer

Large scale production of biomass from microalgae will require large amounts of fertilizer. If chemical fertilizer is used for algae production processes the production of the chemical fertilizer is the principal burden driver (**?**). The energy requirements for production of fertilizer are found in the work by **?**:

- 45 MJ kg^{-1} N for N-fertilizer production
- 29 MJ kg^{-1} P for P-fertilizer production

If the algae gets its nutrients from the digestate this will exclude the need for chemical fertilizer and its associated life cycle burdens. The fossil energy requirement for production of ammonium nitrate fertilizer are by **?**, estimated to 40.6 MJ kg^{-1} N. The difference from the energy requirements as seen in the list above (4.4 MJ kg^{-1} N) can be interpreted as the non-fossil contribution of the overall energy requirement.

5.5.2 Summarized burden offsets

When the nutrients in the effluent water from an AD is pumped to an algae pond instead of to the water treatment process, it reduces the need for chemical fertilizer for the algae cultivation. By summarizing the burdens related to the production of chemical fertilizer (as listed in section 5.5.1) and the offset from wastewater treatment, (as described in chapter 2), the total offset adds up to 217 MJ kg^{-1} N removed, and 81.51 MJ kg^{-1} P removed.

Compared to this scenario; *algae cultivation with use of chemical fertilizer, wastewater treatment of effluent from AD, nitrogen removal via nitrification and denitrification (with methanol) and phosphorus removal with chemical precipitation by ferrous sulfate;*

the ACAD concept contributes to an offset of 18.7 GJ due to nitrogen removal, and 0.97 GJ due to phosphorus per functional unit. These offsets accumulates to a total of 19.6 GJ or 16.8 MWh. This offset is equal to 48% of the total energy produced from the concept, and is a important consideration when evaluating the ACAD concept.

Use of wastewater effluent (digestate) as pond medium could significantly reduce not only the need for chemical fertilizer in algae cultivation and its associated life cycle burdens, but also reduce the consumption of freshwater during algae cultivation and the costs of wastewater treatment. The needed freshwater could be reduced to practically zero if the digestate, and perhaps other wastewater streams, are routed through a raceway pond prior to disinfection and discharge.

5.6 Scenario in a Tanzanian setting

In order to visualize the usefulness of the concept the ACAD biorefinery is in this section coupled with a real-case scenario. According to **?** the most serious solid waste management problem in Tanzania is disposal of organic waste. According to the the same reference, a pilot biogas plant project, named Taka Gas Project (TGP), have been carried out in Dar Es Salaam city, the largest urban centre in Tanzania, in response to energy and solid waste management problems. The main objective of the TGP is to obtain biogas through anaerobic digestion of Municipal Solid Waste (MSW). The biogas generated from the plant will be used for thermal generation of electricity, and the generated electricity will be sold to the Tanzanian Electric Supply Company Ltd. (TANESCO). The processed organic waste material will be sold to farmers as organic fertilizer. The market waste, which is one of the major contributers to the total MSW collected, has a C/N ratio ranging between 18.4 and 26. As mentioned earlier, the optimal C/N ratio for the AD lies between 20 - 25 (**?**).

Could the ACAD concept be combined with the Taka Gas Project? Firs issue to answer is; could this location support the algae productivity? Given a production rate of 93 ton ha^{-1} year^{-1} and a calorific value of 29 MJ kg^{-1}, the energy in the algae matter adds up to a total of 75 kWh m^{-2} year^{-1} or 0.75 MJ m^{-2} day^{-1}. According to **?** the annual average radiation value in Tanzania ranged from lowest 15 MJ m^{-2} day^{-1} to highest 25 m^{-2} day^{-1}. Given these values the ACAD biorefinery needs solar efficiency between 3-5% in order to reach the productivity of 75 kWh m^{-2} year^{-1}. This solar efficiency is approximately one third to a half of 9% which is generally adopted as the maximum theoretical efficiency for the photosynthetic conversion of solar energy to biomass (**?**). The Taka Gas Project is in Dar Es Salaam, which lies in a sunny area of Tanzania. The algal productivity of the ACAD biorefinery are therefore assumed to be possible in this area.

According to **?** a total quantity of 61.67 ton day^{-1} organic waste could be collected for the Taka Gas Project. By making a rather general assumption saying that this waste equals the sum of wastewater sludge and waste paper needed for the ACAD biorefinery (regard to both quality and quantity), the following outputs can be estimated for the Taka Gas Project if it where converted to a ACAD Biorefinery.

Table 5.4: Potential outputs of a Taka ACAD biorefinery

Output	**Quantum**
Products	
Biodiesel, ton/d	50
Biodiesel, MWh/d	523
Power, MWh/d	51
Waste	
Organic Fertilizer, ton/d	51

The figures listed in table 5.4 cannot be compared directly with the estimated expected outputs described in the Taka Gas Project (**?**) since their estimations are based on very concervative projections. It should also be mentioned that the TS level of the MSW is much higher than the inputs used in the ACAD Biorefinery so the feedstock cannot be compared directly. Nevertheless, an ACAD approach to the Taka Gas Project might improve the total energy production of the project, but also be a means of utilizing the produced digestate.

If the ACAD biorefinery is placed in a tropical area such as Tanzania, the use of natural coagulants/flocculants might be an interesting option to chemical coagulants such as the aluminum used in the ACAD model. Moringa oleifera Lam is a natural polymer that has become an important alternative in water treatment in developing countries (**?**). Opportunities regarding the use of Moringa oleifera in an ACAD concept is presented in chapter 7.

Chapter 6

Conclusion

The object of this thesis was to attain a greater understanding of the ecotechnology combining algae cultivation with anaerobic digestion (ACAD), use a life cycle approach to evaluate the global warming potential and the fossil energy resource depletion of the energy produced by such a system, and finally highlight challenges and opportunities for the ACAD concept.

The construction of the ACAD model, has outlined both challenges and opportunities of the ACAD concept. Many different operation factors and processes are combined, and they have to function together in order for the concept to be balanced. Setting the methane production as the key reference parameter, the flows of the system were calculated using parameters and figures derived from the literature. By altering the mixture of the feedstock entering the anaerobic digester, optimal carbon/nitrogen-ratio of the feedstock and the nitrogen balance of the system were reached. The model proved itselves to be a powerful tool for understanding the symbiosis and the dynamics of the ACAD concept, and it provided the information needed to evaluate the global warming potential and the fossil energy resource depletion of the ACAD biodiesel. Many symbiotic features were identified; nutrient removal from the digestate & the nutrient supply for the algae cultivation, excess heat & need for heat in different processes and production & consumption of electric power.

Energy calculations on the ACAD concept showed that more energy can be produced by combining the processes. For every unit of feedstock energy entering the system, 1.77 units of energy is exported as either biodiesel or electricity. The energy content of the algae outnumbers the energy content of all the other biomass sources, suggesting that the ACAD concept is more of a sunlight-to-bioenergy, than waste-to-bioenergy system. Actually, the energy content of the algae is more than twice the energy content of the inputs to the system. The role of the anaerobic digester in the ACAD concept is therefore primarily that of supplying nutrient to the algae, and secondly produce biogas for heat and electricity production.

The model showed that the ACAD biorefinery could be totally independent on external energy supply. Approximately half of the electricity produced in the system is used to run the different processes within the system, the other half is exported. The exported power accounts for approximately 9% of the total exported energy, while the remaining 91% is biodiesel energy. By using Life Cycle Assessments (LCA) the global warming potential and the fossil energy resource depletion of the ACAD biodiesel were estimated and compared to other diesel types. Since the ACAD biorefinery has no direct fossil energy requirements or fossil greenhouse gas outputs, the fossil burden of the biodiesel comes solely from the upstream burdens of the inputs to the system. The primary burden drivers are the fossil methanol and the CO_2 used in the production of the ACAD biodiesel. With these contributions the fossil energy ratio of the ACAD biodiesel is approximately 23% and the life cycle energy efficiency 36%. If renewable resources are used to produce the methanol and the CO_2 needed, the fossil energy and the greenhouse gas requirements could be reduced with 96% and 98% respectively. The net energy balance of the biodiesel will then increase to 50, meaning that for every unit of fossil energy used 50 units of renewable energy is produced. Compared to conventional diesel (ultra low sulphur diesel) the GHG emissions could be reduced with 99%, equal to approximately 3 kg CO_2 per liter of fuel.

If wastewater treatment is used as a reference system for the ACAD biodiesel, the fossil energy requirement actually end up being negative meaning that more fossil energy are avoided than the needed fossil energy. This is mainly due to the large consumption of fossil methanol used for the denitrification in the WWTP. If one manage to design the ACAD biorefinery so that all of the nutrient needed for the algae cultivation is made available through the anaerobic digestion process, the biorefinery could be nearly independent of fossil inputs and the biodiesel be nearly completely renewable and carbon neutral.

Although the algae-productivity parametres used in this thesis are in the upper level, they are still below productivity rates projected by others and are only, based on solar radiation in Tanzania, 1/3 to 1/2 of the maximum theoretical efficiency for the photosynthetic conversion of solar energy to biomass. Given the assumptions and parametres outlined in this thesis the ACAD biorefinery can reach a energy productivity of 71.7 kW hectare^{-1}. By building the model of the ACAD biorefinery the viability of combining anaerobic digestion and algae cultivation have been strengthen.

There are many questions needed to be addressed before the ACAD biorefinery can be implemented. How will the unwanted substances in the wastewater affect the growth of the algae? How can the productivities and the oil content be maximized? Which strain of algae or cyano-bacteria is most suitable? Should one use open ponds or photobioreactors or both? Are the assumptions made in this thesis viable in the real life? Despite all the questions listed above one thing is sure; if the cultivation of microalgae is to be implemented on a large scale for energy production it cannot rely on chemical fertiliser using todays methods for production without having a large environmental burden on the energy produced.

Among the possible improvements of the ACAD biorefinery are purification of the biogas by the algae, co-location with a methanol producing plant, use of cyanobacteria to increase the oil productivity, use of moringa oleifera as a natural coagulant. These improvements are commented in chapter 7. By constructing a system dynamic model of the ACAD biorefinery more detailed information could be fed into the model making it more useful in prediction the efficiencies, and the inputs and outputs of the system. An interesting follow-up of this thesis could be to investigate the possibility of implementing the ACAD concept on the Taka Gas Project in Dar Es Salaam, Tanzania.

This thesis has detailed some of the parametres involved when combining algae cultivation with anaerobic digeston, and has showed that such bioenergy concept could produce substantial amounts of energy without using arable land, and without the need for chemical nitrogen fertilizer. By using inputs of renewable origin the sustainability of the biodiesel could be increased further. Using an ecotechnological approach seems as a key component when building sustainable energy production systems.

Chapter 7

Perspectives and Opportunities

Biogas purification by microalgae
Instead of removing the CO_2 by scrubbing the biogas in a scrubbing tower, the algae pond might be used for CO_2 fixation. In one study the CO_2 content of the biogas was reduced from 40% to less than 5% by scrubbing in a high rate pond (**?**). **?** investigated the purification process of biogas by using intensive microalgae cultures.

Biomethanol production
One interesting opportunity for the ACAD concept is co-location with a plant producing methanol from biomass via gasification. Since the algae in the biorefinery needs CO_2 and the methanol plant needs to remove some of the CO_2 in order to get the ratio $(H_2\text{-}CO_2)/(CO + CO_2)$ to the value desired for methanol synthesis (**?**), the co-location could create a win-win situation for both the biorefinery and the methanol plant.

In order to produce methanol a syngas (a mixture of CO and H_2) is needed (**?**). Today, syngas is most commonly produced from the methane component in natural gas. Syngas could also be produced through biomass gasification, which has the methanol and CO_2 as products. Since the ACAD biorefinery exports electricity, some of the methane could be used for methanol production without making the biorefinery dependent on external electricity. Co-location of a methanol production site and the ACAD biorefinery could create synergies, since the methanol plant might have excess CO_2, the ACAD biorefinery needs methanol and CO_2 and finally that the ACAD biorefinery could supply the methane needed for the methanol production. Such a co-location will improve the sustainability of the products, but could also improve the economics of the productions. One challenge lies in handling and optimizing different technologies together.

Phytoremediation by using *Moringa oleifera*

Moringa oleifera is a tropical plant belonging to the *Moringaceae* family. Because of its many uses (food, feed, medicine, oil and water treatment) and it's high nutrient level it has been referred to as 'the miracle tree'. Since the seeds from this plant contain catiotic proteins which could act as active coagulating agents, an water extraction of the seeds have been used as a natural low-cost coagulant for treating drinking water **?**. **?** continuous supplied an anaerobic digester with extracts of *Moringa oleifera* seeds (WEMOS), and registered an increase in the diversity of hydrolytic bacteria, and therefore enhanced the biological start-up of the reactor. As a coagulant, Moringa is non-toxic and biodegradable. It is environmental friendly, and does not affect the pH and conductivity of the water after treatment (**?**). According to the same reference the sludge produced by coagulation with *Moringa* is not only harmless, but also four to five times less in volume than the chemical sludge produced by alum coagulant. In a study by **?** they found that when wastewater was treated with *Moringa oleifera* seeds, the removal of suspended solid was good, but an extra chemical oxygen demand (COD) was released in the treated water. Studies investigated *Moringa oleifera* ability to remove unwanted substances from the wastewater has also been conducted (**????**). Production of biodiesel from *Moringa oleifera* has been studied (**?**).

In an ACAD biorefinery *Moringa oleifera* could be used at different stages in the process. *Moringa* could be used for the coagulation of the sludge in the wastewater treatment plant, resulting in lower volumes, but the *Moringa* could also stimulate the anaerobic digestion. The digestate could also be coagulated by the use of *Moringa*. The nutrients added by *Moringa* might stimulate to an increase in the algae growth. Coagulant such as alum and iron binds phosphorus hard, making it less available for the algae. The study by **?** showed that the WEMOS consisted of both the macro and many of the micro-nutrients, together with organic matter which could act as a carbon source for the algae. If *Moringa oleifera* is used as a coagulant, this would also probably increase the value of the organic fertilizer, due to *Moringa*'s nutrient level and that the phosphorus is not bounded as hard as with chemical coagulants.

If the ACAD biorefinery is situated in a tropical area, the *Moringa oleifera* could probably be a low-cost alternative to aluminum within the biorefinery. Therefore, the application of this plant or other similar plants species should be investigated to see how they could improve the overall productivity and sustainability of the ACAD concept.

Bibliography

Akhtar M., Hasany S. M., Bhanger M. & Iqbal S. (2007). 'Sorption potential of Moringa oleifera pods for the removal of organic pollutants from aqueous solutions'. *Journal of Hazardous Materials* **141**(3):546 – 556.

Alfayo R. & Uiso C. B. S. (2002). 'Global solar radiation distribution and available solar energy potential in Tanzania'. *Phys. Scr.* **T97**. Anglais.

Beltran-Heredia J. & Sanchez-Martin J. (2008). 'Heavy Metals Removal from Surface Water with Moringa Oleifera Seed Extract as Flocculant Agent'. *Fresenius Environgmental Bulletin* **17**(12A):2134–2140.

Cardoso K. C., Bergamasco R., Cossich E. S. & Konradt Moraes L. C. (2008). 'Optimizing mixture and decantation times in the process of coagulation/flocculation of raw water using Moringa oleifera Lam'. *Acta Scientiarum-Technology* **30**(2):193–198.

Chen P. H. & Oswald W. J. (1998). 'Thermochemical treatment for algal fermentation'. *Environment International* **24**(8):889 – 897.

Chisti Y. (2007). 'Biodiesel from microalgae'. *Biotechnology Advances* **25**(3):294–306.

CIA (2009). 'The World Factbook 2009'. *Washington, DC: Central Intelligence Agency, 2009* .

Clarens A. F., Resurreccion E. P., White M. A. & Colosi L. M. (2010). 'Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks'. *Environmental Science & Technology* **44**(5):1813–1819.

Conde J., Moro L., Travieso L., Sanchez E., Leiva A., Dupeiron R. & Escobedo R. (1993). 'Biogas Purification Process Using Intensive Microalgae Cultures'. *Biotechnology Letters* **15**(3):317–320.

Cordell D., Drangert J.-O. & White S. (2009). ‘The story of phosphorus: Global food security and food for thought’. *Global Environmental Change* **19**(2):292–305.

Foresti E., Zaiat M. & Vallero M. (2006). ‘Anaerobic Processes as the Core Technology for Sustainable Domestic Wastewater Treatment: Consolidated Applications, New Trends, Perspectives, and Challenges’. *Reviews in Environmental Science and Biotechnology* **5**(1):3–19.

Gilberg L., Hansen B., Karlsson N. E. A., Ingemar and & Pålsson A. (2003). *About Water Treatment*. Kemira Kemwater.

Golueke C. & Oswald W. (1959). ‘Biological conversion of light energy to the chemical energy of methane’. *Appl. Environ. Microbiol.* **7 (4)**:219–227.

Hamelinck C. N. & Faaij A. P. C. (2002). ‘Future prospects for production of methanol and hydrogen from biomass’. *Journal of Power Sources* **111**(1):1 – 22.

Huntley , Mark , Redalje & Donald (2007). ‘CO2 Mitigation and Renewable Oil from Photosynthetic Microbes: A New Appraisal’. *Mitigation and Adaptation Strategies for Global Change* **12**(4):573–608.

Illman A. M., Scragg A. H. & Shales S. W. (2000). ‘Increase in Chlorella strains calorific values when grown in low nitrogen medium’. *Enzyme and Microbial Technology* **27**(8):631 – 635.

IPCC (2007). ‘Climate Change 2007: Synthesis Report. Summary for Policymakers.’. Tech. rep., Intergovernmental Panel on Climate Change,.

Jungbluth N., et al. (2007). ‘Life Cycle Inventories of Bioenergy. Final report ecoinvent data v2.0 No. 17.’. Tech. rep., Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

Kalavathy M. H. & Miranda L. R. (2010). ‘Moringa oleifera–A solid phase extractant for the removal of copper, nickel and zinc from aqueous solutions’. *Chemical Engineering Journal* **158**(2):188 – 199.

Kalogo Y., M’Bassiguié Séka A. & Verstraete W. (2001). ‘Enhancing the start-up of a UASB reactor treating domestic wastewater by adding a water extract of Moringa oleifera seeds’. *Applied Microbiology and Biotechnology* **55**(5):644–651.

Kapdi S., Vijay V., Rajesh S. & Prasad R. (2005). 'Biogas scrubbing, compression and storage: perspective and prospectus in Indian context'. *Renewable Energy* **30**(8):1195 – 1202.

Lardon L., Hélias A., Sialve B., Steyer J.-P. & Bernard O. (2009). 'Life-Cycle Assessment of Biodiesel Production from Microalgae'. *Environmental Science & Technology* **43**(17):6475–6481.

Lee J.-Y., Yoo C., Jun S.-Y., Ahn C.-Y. & Oh H.-M. (2010). 'Comparison of several methods for effective lipid extraction from microalgae'. *Bioresource Technology* **101**(1, Supplement 1):S75 – S77. Supplement Issue on Recent Developments of Biomass Conversion Technologies.

Mandeno G., Craggs R., Tanner C., Sukias J. & Webster-Brown J. (2005). 'Potential biogas scrubbing using a high rate pond'. *Water Science and Technology* **51**(12):253–256.

Maurer M., Schwegler P. & Larsen T. (2002). 'Nutrients in urine: Energetic aspects of removal and recovery'. *Water Science and Technology* **48**(1):37–46.

Mbuligwe S. E. & Kassenga G. R. (2004). 'Feasibility and strategies for anaerobic digestion of solid waste for energy production in Dar es Salaam city, Tanzania'. *Resources, Conservation and Recycling* **42**(2):183 – 203.

Moller J., Boldrin A. & Christensen T. H. (2009). 'Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution'. *Waste Management & Research* **27**(8):813–824.

Mortimer N. D., Cormack P., Elsayed M. A. & Horne R. (2003). 'Evaluation of the comparative energy, global warming and socio-economic costs and benefits of biodiesel.'. Final Report 20/1 1-64., Department for Environment, Food and Rural Affairs. Resources Research Unit, School of Environment and Development, Sheffield Hallam University.

Ndabigengesere A. & Narasiah K. S. (1998). 'Quality of water treated by coagulation using moringa oleifera seeds'. *Water Research* **32**(3):781 – 791.

Ndabigengesere A., Narasiah K. S. & Talbot B. G. (1995). 'Active agents and mechanism of coagulation of turbid waters using Moringa oleifera'. *Water Research* **29**(2):703 – 710.

Oswald W. & Golueke C. (1960). 'Biological transformation of solar energy'. *Adv. Appl Microbiol.* **4**:223–262.

Purtschert I., Siegrist H. & Gujer W. (1996). ‘Enhanced denitrification with methanol at WWTP Zürich-Werdhölzli’. *Water Science and Technology* **33**(12):117 – 126. Design and Operation of Large Wastewater Treatment Plants VII.

Rashid U., Anwar F., Moser B. R. & Knothe G. (2008). ‘Moringa oleifera oil: A possible source of biodiesel’. *Bioresource Technology* **99**(17):8175 – 8179.

Rasi S., Veijanen A. & Rintala J. (2007). ‘Trace compounds of biogas from different biogas production plants’. *Energy* **32**(8):1375 – 1380.

Rittmann B. E. (2008). ‘Opportunities for renewable bioenergy using microorganisms’. *Biotechnology and Bioengineering* **100**(2):203–212.

Salerno M., Nurdogan Y. & Lundquist T. J. (2009). ‘Biogas Production from Algae Biomass Harvested at Wastewater Treatment Ponds’. *Bioenergy Engineering Conference 11-14 October 2009* **BIO-098023**.

Schamphelaire L. D. & Verstraete W. (2009). ‘Revival of the biological sunlight-to-biogas energy conversion system’. *Biotechnology and Bioengineering* **103**(2):296–304.

Schenk P., Thomas-Hall S., Stephens E., Marx U., Mussgnug J., Posten C., Kruse O. & Hankamer B. (2008). ‘Second Generation Biofuels: High-Efficiency Microalgae for Biodiesel Production’. *BioEnergy Research* **1**(1):20–43.

Schievano A., Pognani M., D’Imporzano G. & Adani F. (2008). ‘Predicting anaerobic biogasification potential of ingestates and digestates of a full-scale biogas plant using chemical and biological parameters’. *Bioresource Technology* **99**(17):8112 – 8117.

Sharma P., Kumari P., Srivastava M. & Srivastava S. (2006). ‘Removal of cadmium from aqueous system by shelled Moringa oleifera Lam. seed powder’. *Bioresource Technology* **97**(2):299 – 305.

Sheehan J., Dunahay T., Benemann J. & Roessler P. (1998). *A Look Back at the U.S. Department of Energy’s Aquatic Species Program: Biodiesel from Algae*. U.S. Department of Energy’s Office of Fuels Development.

Sialve B., Bernet N. & Bernard O. (2009). ‘Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable’. *Biotechnology Advances* **27**(4):409 – 416.

Vermaas W. F. J. (1998). ‘Gene modifications and mutation mapping to study the function of photosystem II’. In L. McIntosh (ed.), *Photosynthesis: Molecular Biology of Energy Capture*, vol. 297 of *Methods in Enzymology*, pp. 293 – 310. Academic Press.

Weidema B. (2006). ‘Ecoinvent Data v2.0’. *Swiss Centre for Life Cycle Inventories* .

Wheeler P. & Lindberg A. (1999). ‘Biogas upgrading and utilisation.’. *IEA Bioenergy - Task 24: Energy from biological conversion of organic waste* pp. 1–19.

Wijffels R. H. (2008). ‘Potential of sponges and microalgae for marine biotechnology’. *Trends in Biotechnology* **26**(1):26–31.

Yen H.-W. & Brune D. E. (2007). ‘Anaerobic co-digestion of algal sludge and waste paper to produce methane’. *Bioresource Technology* **98**(1):130 – 134.

Appendix A

Inputs to the Model

Overview - Parametres used in the ACAD Biorefinery Model

Description	Value	Units	Reference or Comment
Algae Biomass			
Carbon in proteins	53.16	%	Calculated from biomass fraction in Table 1 Lardon(2009)
Nitrogen in proteins	16.24	%	Calculated from biomass fraction in Table 1 Lardon(2009)
Carbon in carbohydrates	40	%	Calculated from biomass fraction in Table 1 Lardon(2009)
Carbon in lipids	75.71	%	Calculated from biomass fraction in Table 1 Lardon(2009)
Fraction of protein	28	%	Illmann(2000)
Fraction of carbohydrates	11	%	Illmann(2000)
Fraction of lipids	61	%	Illmann(2000)
Calorific value	29	kJ/g	Illmann(2000)
Phosphorus in algae	1	%	Calculated on basis of protein content and table 2 Lardon(2009)
Algae cultivation			
Growth rate	0.46	per day	Illmann(2000)
Dry weight per volume	1.11	g/l	Illmann(2000)
Depth of pond	5	cm	Lardon(2009)
Productivity	25.53	g/m2/day	Calculated from Illmann(2000) and Lardon(2009)
CO2 requirements	1.6	kg/kg	Clarens(2010) - Supporting Information
Evaporation	4	l/kg	Lardon(2009)
Flocculation efficiency	0.9		Lardon(2009)
Glycerine			
C/N-ratio	50		Assumed value
Fraction of volatile solids of total solids	100	%	Assumed value
Dry weight per volume	500	g/l	Assumed value
Nitrogen in glycerine	0	%	Assumed value
Phosphorus in glycerine	0	%	Assumed value
Calorific value	19	MJ/kg	University of Strathclyde Scotland
Oilcake			
Fraction of volatile solids of total solids	90	%	Assumed value
Sludge			
C/N-ratio	7.2		Table 1: composition mixed sludge. EU DG Environment -96, B/2(2001),
Fraction of volatile solids of total solids	72	%	Table 1: composition mixed sludge. EU DG Environment -96, B/2(2001),
Dry weight per volume	10	g/l	Table 1: composition mixed sludge. EU DG Environment -96, B/2(2001),
Nitrogen in sludge	7.1	%	Table 1: composition mixed sludge. EU DG Environment -96, B/2(2001),
Phosphorus in sludge	2.78	%	Table 1: composition mixed sludge. EU DG Environment -96, B/2(2001),
Calorific value	16.56	MJ/kg	Table 1: composition mixed sludge. EU DG Environment -96, B/2(2001),
Waste paper			
C/N-ratio	126		BIOBIB-Database, University of Technology Vienna
Fraction of volatile solids of total solids	92	%	BIOBIB-Database, University of Technology Vienna
Dry weight per volume	486	g/l	BIOBIB-Database, University of Technology Vienna
Nitrogen in waste paper	0.39	%	BIOBIB-Database, University of Technology Vienna
Phosphorus in waste paper	0	%	BIOBIB-Database, University of Technology Vienna
Gross calorific value	21368	kJ/kg	BIOBIB-Database, University of Technology Vienna, Assume LHV=90%HHV.
Anaerobic Digestion			
Production of biogas per kg VS	0.537	m3/kg	Calculated from Yen & Brune(2007)
Fraction of methane in biogas	60	%	Calculated from Yen & Brune(2007)
VS destruction in AD	60	%	Assumed value
Mineralisation of nitrogen in AD	60	%	Assumed value
Mineralisation of phosphorus in AD	20	%	Assumed value
Optimal C/N min	20		Yen & Brune(2007)
Optimal C/N max	25		Yen & Brune(2007)
Weights and ratios			
Density of CO2	1.87	kg/m3	at 1.013 bar and 15°C, CO2 gas properties, Air Liquide, airliquide.com
Solubility of CO2 in water	1.45	g/l	at 25°C and 100 kPa, wikipedia
Densite of CH4	0.68	kg/m3	at 1.013 bar and 15C, CH4 gas properties, Air Liquide, airliquide.com
Weight ratio of CH4 and CO2 in combustion	2.56		Calculated from chemical combustion formula
Higher heating value CH4	55.5	MJ/kg	Bossel(2003), European Fuel Cell Forum
Flows			
Concentration after flocculation	20	kg/m3	Lardon(2009)
Concentration after rotary press	200	kg/m3	Lardon(2009)
Flocculater consumption	5	g/m3	Lardon(2009)
Scrubbing efficiencies	0.75		Assumed value
Oil Extraction			
Phosphoric Acid per kg oil	1	g/kg	Mortimer(2003)
Smectite per kg oil	6	g/kg	Mortimer(2003)
Hexane per kg oil	2.5	g/kg	Mortimer(2003)
Esterification			
Phosphoric acid per kg oil	4.5	g/kg	Mortimer(2003)
Methanol per kg oil	110.5	g/kg	Mortimer(2003)
Sodium hydroxide per kg oil	12	g/kg	Mortimer(2003)
Net calorific value of biodiesel	37.27	MJ/kg	Mortimer(2003)
Net calorific value methanol	23	MJ/kg	Kaye & Laby, Tables of Physical & Chemical constants. (kayelaby.npl.co.uk)
Energy			
El. comsuption AD	0.25	kWh/m3	Ecoinvent report nr. 17
Heat consumption AD	1.118	kWh/m3	Ecoinvent report nr. 17
El. consumption mixing	11668	MJ/ha/yr	Clarens(2010)
El.consumption scrubbing	0.5	kWh/m3	Ecoinvent report nr. 17
Pump efficiency	0.8		Assumed
Head loss water	2	m	Assumed
El. CO2 injection per kg CO2	0.022	kWh/kg	Lardon(2009)
El. Rotary press	0.01449	kWh/m3	Calculated from RST-HCS630x3000L, metsopaper.com
El. Extraction press	0.1	kWh/kg	Ecoinvent report nr. 17
El. Extraction refining	0.0061	kWh/kg	Ecoinvent report nr. 17
Heat consumption oil extraction	1.7889	MJ/kg	Ecoinvent report nr. 17
El. Esterification	0.0422	kWh/kg	Ecoinvent report nr. 17
Heat esterification	0.9238	MJ/kg	Ecoinvent report nr. 17

Appendix B

System Flow Calculations

ACAD BIOREFINERY

- System Flow Calculations

Jon Eivind T. Strømme - 2010

LEGEND

Figure	the figure or constant is derived from literature, not calculated
Figure	calculated figure
Figure	definition of a new unit

Figures from literature

BIOMASS

COMPOSITION

ALGAE (A) (from Illmann(2000))

$A_P := 28\%$ Protein

$A_C := 11\%$ Carbohydrates

$A_L := 61\%$ Lipids

$LHV_A := 29 \frac{MJ}{kg}$

$A_P + A_L + A_C = 1$

$\%N_A := (NitrogenInP \cdot A_P) = 4.547 \cdot \%$ Amount of nitrogen in Algae

$\%P_A := 1\%$ Amount of phosphorus in Algae

$$CN_A := \left[\frac{(A_P \cdot CarbonInP + A_L \cdot CarbonInL + A_C \cdot CarbonInC)}{A_P \cdot NitrogenInP} \right] = 14.397$$

$\%VS_A := 90\%$

CULTIVATION

$\mu := 0.46 \cdot day^{-1}$ $depth := 5cm$ Growth rate and depth of pond.

$C_{A1} := 1.11 \frac{gm}{l}$ $Volum := depth \cdot 1000l \cdot m^{-3} = 50 \cdot \frac{1}{m^2}$ Concentration in Pond (Illmann2000)

$p := \mu \cdot C_{A1} \cdot Volum = 25.53 \cdot gm \cdot m^{-2} \cdot day^{-1}$ Productivity (Illmann2000)

$N_A := \%N_A \cdot \frac{1000gm}{kg} = 45.472 \cdot \frac{gm}{kg}$ Nitrogen requirements

$P_A := \%P_A \cdot \frac{1000gm}{kg} = 10 \cdot \frac{gm}{kg}$ Phosphorus requirements

$CO2_A := 1.6kg \cdot kg^{-1}$ CO2 requirements Clarens(2010)

$\eta_F := 0.9$ Flocculation efficiency of algal matter (Lardon2009)

$\sigma_E := 4 \frac{l}{kg}$ Evaporation: 4 l/kg algal matter (Lardon2009)

GLYCERINE (G) (Residue from biodiesel production)

$CN_G := 50$

$\%VS_G := 100\%$

$DM_G := 500 \frac{gm}{L}$

$\%N_G := 0\%$

$\%P_G := 0\%$

$\omega_{Oil.Diesel} := 0.9727$

$\beta_{Glyseride} := 10.9\%$

Theoretically: 1 kg of oil results in 0.9727 kg biodiesel, and per kg biodiesel 106.1 gm of glycerine is produced..Ecoinvent rape seed oil esterification report no. 17

Substances in the biomass fraction. Lardon(2009):

$CarbonInP := \frac{(4.43 \cdot 12)}{100} = 53.16 \cdot \%$

$NitrogenInP := \frac{(1.16 \cdot 14)}{100} = 16.24 \cdot \%$

$CarbonInC := \frac{(6 \cdot 12)}{180} = 40 \cdot \%$

$CarbonInL := \frac{(40 \cdot 12)}{634} = 75.71 \cdot \%$

Protein: $C_{4.43}H_7O_{1.44}N_{1.6}$

Carbohydrates: $C_6H_{12}O_6$

Lipids: $C_{40}H_{74}O_5$

FEEDSTOCK INTO THE AD

OILCAKE

$OC_P := \frac{A_P}{(A_P + A_C)} = 71.795 \cdot \%$

$OC_C := \frac{A_C}{(A_P + A_C)} = 28.205 \cdot \%$

$\%VS_{OC} := 90\%$

$\%N_{OC} := \frac{(NitrogenInP \cdot OC_P)}{\%VS_{OC}} = 12.955 \cdot \%$

$\%P_{OC} := \left[\frac{\%P_A}{\%VS_{OC}} \cdot \left(\frac{\%N_{OC}}{\%N_A} \right) \right] = 3.166 \cdot \%$

$CN_{OC} := \frac{(OC_P \cdot CarbonInP + OC_C \cdot CarbonInC)}{OC_P \cdot NitrogenInP} = 4.241$

SLUDGE (S) (from EU DG Enivronment -96 B/2(2001)
Table 1: C - Composition Mixed Sludge

$DM_S := 10 \frac{gm}{L}$

$\%VS_S := 72\%$

$\%N_S := 7.1\%$

$\%P_S := 2.78\%$

$CN_S := 7.2$

WASTE PAPER (C) (University of Technology Vienna)

$CN_C := 126$

$DM_C := 486 \frac{gm}{L}$

$\%VS_C := 92\%$

$\%N_C := 0.39\%$

Produced methane(m3):

$M := 525m^3$

From Yen & Brune(2007)

$YB_{CH4} := \frac{1620ml}{5gm} = 0.324 \frac{m^3}{kg}$

$YB_{\%CH4} := \frac{1620ml}{(1620 + 1080)ml} = 60 \cdot \%$

$YB_{\%CO2} := 1 - YB_{\%CH4} = 40 \cdot \%$

$$YB_{2G} := \frac{\left(1607 \frac{ml}{l \cdot day} + 1080 \frac{ml}{l \cdot day}\right)}{5 \frac{gm}{l \cdot day}} = 0.537 \frac{m^3}{kg}$$

ANAEROBIC DIGESTION

$B2G := YB_{2G} = 0.537 \frac{m^3}{kg}$ Production of biogas per kg VS feedstock

$\%CH4 := YB_{\%CH4} = 0.6$ Biogas quality, methane fraction of biogas

$\%CO2 := 1 - \%CH4 = 0.4$ CO2 fraction og biogas

$\beta_{VS} := 60\%$ Percentage VS destruction in AD

$\alpha_N := \beta_{VS} = 60 \cdot \%$ Percentage mineralisation of N in AD

$\alpha_P := 20\%$ Percentage of mineralisation of P in the AD

Calculated from Miljøstyrelsen 2007 and Jordforsk rt 127/04

Weights and ratios:

$W_{CO2} := 1.87 \frac{kg}{m^3}$ Weight of CO2

$W_{CH4} := 0.68 \frac{kg}{m^3}$ Weight of methane, kg per m3, 1.013 bar 15*C

$\beta_{CO2} := 2.56 \frac{kg}{kg}$ According to chemical fomula of combustion of methane, this is the mass ratio between methane and CO2

$CN_{min} := 20$

$CN_{max} := 25$ Optimal CN ratio (Yen&Brune2007)

$\rho_W := 1 \frac{kg}{L}$ Weight of water

Energy in the methane:

$HHV_{CH4} := 55.54 \frac{MJ}{kg}$ energy per m3 methane. Since all energy is in the methane this is also the energy content of the biogas.

$E_{CH4.u} := HHV_{CH4} \cdot W_{CH4} = 37.767 \cdot \frac{MJ}{m^3}$ Pimentel 2002

Query

This Query finds the amount of algal matter and other feedstock by balancing the C/N ratio of the feedstock and the nitrogen balance of the system.

Guess values — Determining the mixture of the feedstocks

$x := 1kg \quad y := 1kg \quad z := 1kg \quad a := 1 \quad b := 1 \quad d := 1 \quad f := 0 \quad j := 1kg \quad k := 1$

Given

$$j = \beta_{Glyseride}\cdot\left[\omega_{Oil.Diesel}\cdot A_L\cdot\left[\frac{x}{\left[\%VS_{OC}\cdot\left(A_P + A_C\right)\right]}\right]\right]$$

Calclutating the amount of glycerine

$$CN_{min} \le \left(a\cdot CN_{OC} + b\cdot CN_S + d\cdot CN_C + k\cdot CN_G\right) \le CN_{max}$$

Ensuring the CN ratio is within the optimal range

$$(B2G\cdot\%CH4)\cdot(x + y + z + j) = M$$

Adjusting the volume of biogas produced to the functional unit

$$\left[W_{CO2}\cdot[(x + y + z + j)\cdot(B2G\cdot\%CO2)]\right] + \left[\beta_{CO2}\cdot W_{CH4}\cdot[(x + y + z + j)\cdot(B2G\cdot\%CH4)]\right] + f = CO2_A\cdot\frac{x}{\%VS_{OC}\cdot\left(A_P + A_C\right)}$$

Determining the Carbon Balance

$$\beta_{VS}\cdot\left(x\cdot\%N_{OC} + y\cdot\%N_S + z\cdot\%N_C + j\cdot\%N_G\right) = \left(N_A\right)\cdot\left[\frac{x}{\%VS_{OC}\cdot\left(A_P + A_C\right)}\right]$$

Ensuring the nitrogen balance

$$x \ge 0 \quad y \ge 0 \quad z \ge 0 \quad j \ge 0$$

Ensuring all of the feedstock are positive

$$a = \frac{x}{(x + y + z + j)} \qquad b = \left[\frac{y}{(x + y + z + j)}\right] \qquad d = \left[\frac{z}{(x + y + z + j)}\right] \qquad k = \left[\frac{j}{(x + y + z + j)}\right]$$

Fractions of feedstocks

$$a + b + d + k = 1$$

Ensuring that the fractions of feedstocks adds up to 1

$$\begin{pmatrix} X_{OC.VS} \\ X_{S.VS} \\ X_{C.VS} \\ \eta_{OC} \\ \eta_S \\ \eta_C \\ CO2_X \\ X_{G.VS} \\ \eta_G \end{pmatrix} := Find(x, y, z, a, b, d, f, j, k)$$

Returned values from the Query

RESULTS

$X_{OC.VS} = 591.852\,kg \quad \eta_{OC} = 36.35\cdot\%$ — needed amount of oilcake (kg VS) and fraction

$X_{S.VS} = 707.894\,kg \quad \eta_S = 43.477\cdot\%$ — needed amount of sludge (kg VS) and fraction

$X_{C.VS} = 219.41\,kg \quad \eta_C = 13.476\cdot\%$ — needed amount of waste paper (kg VS) and fraction

$X_{G.VS} = 109.054\,kg \quad \eta_G = 6.698\cdot\%$ — the amount of glycerine produced (kg VS) and fraction

$$X_{T.VS} := X_{OC.VS} + X_{S.VS} + X_{C.VS} + X_{G.VS} = 1.628 \times 10^3\,kg$$

Total weight VS

$$CN_T := \left(\eta_{OC}\cdot CN_{OC}\right) + \left(\eta_S\cdot CN_S\right) + \left(\eta_C\cdot CN_C\right) + \left(\eta_G\cdot CN_G\right) = 25$$

Total CN-ratio

PRODUCED BIOGAS:

$$Biogas := \left(X_{OC.VS} + X_{S.VS} + X_{C.VS} + X_{G.VS}\right)\cdot B2G = 875\cdot m^3$$

the amount of biogas produced with the given feeding.

$$V_{CH4} := (Biogas\cdot\%CH4) = 525\cdot m^3$$

volume of methane produced

$$E_{CH4} := E_{CH4.u}\cdot V_{CH4} = 1.983 \times 10^4\cdot MJ$$

Energy in the methane produced

TOTAL MASSES

$$X_A := \frac{X_{OC.VS}}{\left[\%VS_{OC}\cdot\left(A_P + A_C\right)\right]} = 1.686 \times 10^3\,kg \qquad X_S := \frac{X_{S.VS}}{\%VS_S} = 983.187\,kg \qquad X_C := \frac{X_{C.VS}}{\%VS_C} = 238.489\,kg$$

$$X_{OC} := X_A\cdot\left(A_P + A_C\right) = 657.613\,kg \qquad X_{Oil} := X_A\cdot\left(A_L\right) = 1.029 \times 10^3\,kg \qquad X_G := \frac{X_{G.VS}}{\%VS_G} = 109.054\,kg$$

$$X_T := \left(X_{OC} + X_S + X_C + X_G\right) = 1.988 \times 10^3\,kg$$

Total mass entering the AD

Production system

Pond

$X_A = 1.686 \times 10^3 \mathrm{kg}$ Needed production of algae material, kg

$Q_e := \sigma_E \cdot X_A = 6.745 \times 10^3 \cdot \mathrm{l}$ Evaporation total

$\mathrm{year} := p = 93.246 \cdot \mathrm{tonne} \cdot \mathrm{hectare}^{-1} \cdot \mathrm{yr}^{-1}$ Productivity (ton/ha/yr)

$LHV_{total.A} := \mathrm{year} \cdot LHV_A = 0.74 \cdot \dfrac{\mathrm{MJ}}{\mathrm{m}^2 \cdot \mathrm{day}}$

$\alpha_{Rad} := \dfrac{LHV_{total.A}}{Low_{Rad.TZ}} = 4.936 \cdot \%$

$\mathrm{Area} := \dfrac{X_A}{p} = 6.605 \times 10^4 \cdot \mathrm{m}^2 \cdot \mathrm{day}$

$\mathrm{Area}_{ha} := \mathrm{Area} = 6.605 \cdot \mathrm{hectare} \cdot \mathrm{day}$

$Low_{Rad.TZ} := 15\mathrm{MJ} \cdot \mathrm{m}^{-2} \cdot \mathrm{day}^{-1}$ Alfayo(2002)

$High_{Rad.TZ} := 24\mathrm{MJ} \cdot \mathrm{m}^{-2} \cdot \mathrm{day}^{-1}$ Alfayo(2002)

$\alpha_{Rad.low.TZ} := \dfrac{LHV_{total.A}}{Low_{Rad.TZ}} = 4.936 \cdot \%$

$\alpha_{Rad.high.TZ} := \dfrac{LHV_{total.A}}{High_{Rad.TZ}} = 3.085 \cdot \%$

Fertilizer and CO2 requirements

Nutrients:

$N_{Need} := N_A \cdot X_A = 76.674 \mathrm{kg}$ Needed nitrogen

$P_{Need} := P_A \cdot X_A = 16.862 \mathrm{kg}$ Needed phosphorus

$N_{Inn} := (X_{OC.VS} \cdot \%N_{OC}) + (X_S \cdot \%N_S) + (X_C \cdot \%N_C) + (X_G \cdot \%N_G) = 147.411 \mathrm{kg}$ Nitrogen in feedstock entering AD

$P_{Inn} := (X_{OC.VS} \cdot \%P_{OC}) + (X_S \cdot \%P_S) + (X_G \cdot \%P_G) = 46.068 \mathrm{kg}$ Phosphorus in feedstock entering AD

$N_{Supply} := N_{Inn} \cdot \alpha_N = 88.446 \mathrm{kg}$ Supply of ammonia to the pond

$P_{Supply} := P_{Inn} \cdot \alpha_P = 9.214 \mathrm{kg}$ Supply of phosphorus to the pond

$N_X := N_{Need} - N_{Supply} = -11.772 \mathrm{kg}$ Excess nitrogen if neg. $\dfrac{N_X}{N_{Need}} = -15.353 \cdot \%$

$P_X := P_{Need} - P_{Supply} = 7.648 \mathrm{kg}$ Need phosphorus $\dfrac{P_X}{P_{Need}} = 45.358 \cdot \%$

CO2:

$CO2_{Need} := X_A \cdot CO2_A = 2.698 \times 10^3 \mathrm{kg}$ Needed CO2

$CO2_{biogas} := W_{CO2} \cdot \left[X_{T.VS} \cdot (B2G \cdot \%CO2)\right] = 654.5 \mathrm{kg}$ CO2 in the biogas

$CO2_{CHP} := \beta_{CO2} \cdot V_{CH4} \cdot W_{CH4} = 913.92 \mathrm{kg}$ CO2 produced if all the methane is combusted

$CO2_{prod} := CO2_{biogas} + CO2_{CHP} = 1.568 \times 10^3 \mathrm{kg}$ Total production of CO2 in the system

$CO2_X = 1.129 \times 10^3 \mathrm{kg}$ CO2 needed to supplied externally

$\alpha_{CO2.ex} := \left(\dfrac{-CO2_X}{CO2_{Need}}\right) = -41.865 \cdot \%$ Percentage of CO2 supplied externally

NB: CO2 supplied from the digestate....

Water Balance in Pond

$\Lambda Pond := (Q_{AD} + Q_O + Q_{A3}) - Q_{A1} - Q_e = 4.551 \times 10^3 \mathrm{L}$ Water balance if all the overflow is returned to the pond

Volumes and Water balance

$C_{A1} = 1.11 \cdot \mathrm{kg} \cdot \mathrm{m}^{-3}$

$Q_{A1} := \dfrac{(X_A \cdot \eta_F)}{C_{A1}} = 1.367 \times 10^3 \cdot \mathrm{m}^3$ Volume pumped out of the pond given

Flocculation

$C_{A2} := 20\mathrm{kg} \cdot \mathrm{m}^{-3}$ Concentration after flocculation (Lardon2009)

$Q_{A2} := \dfrac{(X_A)}{C_{A2}} = 84.309 \cdot \mathrm{m}^3$ Flow

$Q_{O1} := Q_{A1} - Q_{A2} = 1.283 \times 10^3 \cdot \mathrm{m}^3$ Overflow 1

Rotary press

$C_{A3} := 200\mathrm{gm} \cdot \mathrm{l}^{-1}$ Concentration after rotary press (Lardon2009)

$Q_{A3} := \dfrac{X_A}{C_{A3}} = 8.431 \times 10^3 \cdot \mathrm{l}$ Flow

$Q_{O2} := Q_{A2} - Q_{A3} = 7.588 \times 10^4 \cdot \mathrm{l}$ Overflow 2

$Q_O := Q_{O1} + Q_{O2} = 1.359 \times 10^3 \cdot \mathrm{m}^3$ Total overflow

Volume entering the AD column

$Q_S := \left(\dfrac{X_S}{DM_S}\right) = 9.832 \times 10^4 \mathrm{L}$

$C_{AD} := (\eta_{OC} \cdot C_{A3}) + (\eta_S \cdot DM_S) + (\eta_C \cdot DM_C) + (\eta_G \cdot DM_G) = 176.027 \dfrac{\mathrm{kg}}{\mathrm{m}^3}$ Concentration into the AD

$Q_{AD} := \dfrac{X_T}{C_{AD}} = 1.13 \times 10^4 \mathrm{L}$ Volume into the AD - reactor

Volumes after the Anaerobic digestion

$X_{T.AD.X} := \left[X_T - (\beta_{VS} \cdot X_{T.VS})\right] = 1.011 \times 10^3 \mathrm{kg}$ Dry matter out of the AD

$C_{AD.X} := \left(\dfrac{X_{T.AD.X}}{Q_{AD}}\right) = 89.54 \dfrac{\mathrm{kg}}{\mathrm{m}^3}$ Concentration out of the AD

Concentration og nutrients in the digestate:

$N_D := \dfrac{N_{Supply}}{Q_{AD}} = 7.83 \cdot \dfrac{\mathrm{gm}}{\mathrm{l}}$ Ammonia(dissolved nitrogen) concentration in the digestate.
NB Inhibiting concentration vary in the wide range from 1.7 - 14 g/l (Sialve 2009)

$P_D := \dfrac{P_{Supply}}{Q_{AD}} = 0.816 \cdot \dfrac{\mathrm{gm}}{\mathrm{l}}$ Dissolved phosphorus in the digestate

$NP_{ratio} := \left(\dfrac{N_{Supply}}{P_{Supply}}\right) = 9.6$ Ammonia to phosphorus ratio in the digestate

Scrubbing

$CO2_{biogas} = 654.5\,kg$	CO2 needed to be scrubbed
$Q_O = 1.359 \times 10^3 \cdot m^3$	Water available for scrubbing
$S_{CO2} := 1.45gm \cdot l^{-1}$	Solubility of CO2 g/L at 25 °C, 100 kPa
$\eta_{Scrub} := 0.75$	Scrubbing efficiency,
$Q_{Scrub} := \frac{(CO2_{biogas})}{S_{CO2} \cdot \eta_{Scrub}} = 601.839 \cdot m^3$	Water needed for scrubbing,
$Q_{difference} := Q_{O1} - Q_{Scrub} = 681.03 \cdot m^3$	Difference in Overflow and Scrubb water. Not enough if negative.

Oil Extraction

Out

$X_{Oil} = 1.029 \times 10^3\,kg$	Amount of oil produced

Inn

$X_{OC} = 657.613\,kg$	Phosphoric acid, bentonite and hexane used in oil extraction From ecoinvent, LCI of 'Rape seeds, in oil mill, RER'. report nr 17.
$X_A = 1.686 \times 10^3\,kg$	
$X_{1.p.a.kg} := 1gm \cdot kg^{-1}$ $\quad X_{smectite.kg} := 6gm \cdot kg^{-1}$	Mortimer(2003)
$X_{hexane.kg} := 2.5gm \cdot kg^{-1}$	

$X_{1.p.a} := X_{1.p.a.kg} \cdot X_{Oil} = 1.029 \cdot kg$

$X_{smectite} := X_{smectite.kg} \cdot X_{Oil} = 6.171\,kg$

$X_{hexane} := X_{hexane.kg} \cdot X_{Oil} = 2.571\,kg$

$X_{E.Oil} := (X_A + X_{1.p.a} + X_{smectite} + X_{hexane}) - (X_{Oil} + X_{OC} + X_{hexane}) = 7.2\,kg$

Esterification

Inn

$\beta_{Methanol} := 110.5gm \cdot kg^{-1}$ $\quad NaOH_{kg} := 12gm \cdot kg^{-1}$

$X_{2.p.a.kg} := 4.5gm \cdot kg^{-1}$ $\quad X_{PP.kg} := 16.4gm \cdot kg^{-1}$

Phosphoric acid, bentonite and hexane used, and sodium phosphate (Mortimer2003) produced in oil extraction per kg oil. From ecoinvent, LCI of 'Rape seeds, in esterification plant, RER'.
report nr 17.

$X_{Oil} = 1.029 \times 10^3\,kg$

$X_{Methanol} := \beta_{Methanol} \cdot X_{Oil} = 113.657\,kg$

$X_{2.p.a} := X_{2.p.a.kg} \cdot X_{Oil} = 4.629\,kg$ $\qquad X_{p.a} := X_{1.p.a} + X_{2.p.a} = 5.657\,kg$

$X_{NaOH} := NaOH_{kg} \cdot X_{Oil} = 12.343\,kg$

Out

$X_{Diesel} := X_{Oil} \cdot \omega_{Oil.Diesel} = 1 \times 10^3\,kg$	Amount of biodiesel produced
$X_G = 109.054\,kg$	Amount of glycerine produced
$X_{PP} := X_{PP.kg} \cdot X_{Oil} = 16.869\,kg$	Amount of potassium phosphate produced

Mass Balance (residue):

$X_{E.Ester} := (X_{Oil} + X_{Methanol} + X_{2.p.a} + X_{NaOH}) - (X_{Diesel} + X_G + X_{PP}) = 32.787\,kg$

Biodiesel

$Factor := \frac{1000kg}{X_{Diesel}} = 1$

$D_{Biodiesel} := 880kg \cdot m^{-3}$	Density of Biodiesel (Wikipedia)
$E_{Biodiesel.kg} := 37.27 \frac{MJ}{kg}$	Net calorific value. Mortimer(2003)
$E_{Biodiesel} := E_{Biodiesel.kg} \cdot X_{Diesel} = 3.729 \times 10^4 \cdot MJ$	Energy content of the biodiesel produced
$Q_{Diesel} := \left(\frac{X_{Diesel}}{D_{Biodiesel}}\right) = 1.137 \times 10^3\,L$	Volume of the biodiesel produced

Combined Heat and Power (CHP)

$El_{CHP} := 0.32$	Electrical conversion efficiency. Ref. econinvent report nr 17.
$El_{prod} := (E_{CH4} \cdot El_{CHP}) = 1.762 \times 10^3 \cdot kWh$	Electricity produced from biogas
$Heat_{CHP} := 0.55$	Heat conversion coefficient
$Heat_{prod} := (E_{CH4} \cdot Heat_{CHP}) = 1.091 \times 10^4 \cdot MJ$	Heat produced from biogas,
$Loss_{CHP} := 1 - El_{CHP} - Heat_{CHP} = 0.13$	Energy loss coefficient
$Energy_{Loss} := (E_{CH4} \cdot Loss_{CHP}) = 2.578 \times 10^3 \cdot MJ$	Loss of energy during CHP
$El_{area} := \left(\frac{El_{prod}}{Area_{ha}}\right) = 97.465 \cdot MWh \cdot hectare^{-1} \cdot yr^{-1}$	Assuming linear propotions on all involved figures. This is the electric production capacity of the biorefinery. Energy usage at the plant is not subtracted.

Energy In Feedstock

Algae

$E_{Algae.kg} := 29MJ \cdot kg^{-1}$	Low-N Ch.emersonii Illmann(2000)
$E_{Algae} := E_{Algae.kg} \cdot X_A = 4.89 \times 10^4 \cdot MJ$	Energy in Algae matter

Sludge

$E_{Sludge.ton} := 16.56 \frac{MJ}{kg}$	from EU DG Enivronment -96 B/2(2001) Table 1: C - Composition Mixed Sludge
$E_{Sludge} := E_{Sludge.ton} \cdot X_S = 1.628 \times 10^4 \cdot MJ$	Energy in sludge

Waste Paper

$E_{C.kg} := 19.231MJ \cdot kg^{-1}\,231$	Calorific value waste paper (University of Technology Vienna) Assume 90%HHV=LHV
$E_C := E_{C.kg} \cdot X_C = 1.059 \times 10^6 \cdot MJ$	Energy in waste paper

Glycerine

$E_{G.kg} := 19.0MJ \cdot kg^{-1}$	Calorific value of glycerine, University of Strathclyde, Scotland
$E_G := E_{G.kg} \cdot X_G = 2.072 \times 10^3 \cdot MJ$	Energy in glycerine

Methanol

$E_{M.kg} := 23MJ \cdot kg^{-1}$	Calorific value of methanol, Kaye & Laby, Tables of Physical & Chemical constants. National Physical Laboratory. www.kayelaby.npl.co.uk
$E_M := E_{M.kg} \cdot X_{Methanol} = 2.614 \times 10 \; \frac{(E_M - E_G)}{E_M} = 20.737 \cdot \%$	

ENERGY CONSUMPTION

Anaerobic digestion

$E_{AD.Heat.m3} := 1.118\,kWh \cdot m^{-3}$ $\quad El_{AD.m3} := 0.25\,kWh \cdot m^{-3}$

Heat: 1.118 kWh per m3 biogas, Electricity: 0.25 kWh per m3 biogas.
From ecoinvent, LCI of Raw Sewage Fermentation. report nr 17

$Heat_{AD} := E_{AD.Heat.m3} \cdot Biogas = 3.522 \times 10^{3} \cdot MJ$ $\quad El_{AD} := El_{AD.m3} \cdot Biogas = 218.75 \cdot kWh$

Heat and electricty consumption in AD

Mixing

$El_{mixing} := 11668\,MJ \cdot hectare^{-1} \cdot yr^{-1}$

Energy consumption of mixing pond. Eq.S10 in Clarens(2009)

$El_{mix} := \left(El_{mixing} \cdot Area_{ha}\right) = 58.609 \cdot kWh$

Energy consumption of mixing the pond area.

Scrubbing

$El_{scrub.m3} := 0.5 \cdot kWh \cdot m^{-3}$

0.5 kWh per m3 biogas. From ecoinvent, Electricity consumption for biogas purification.
Ecoinvent report nr 17

$El_{scrub} := El_{scrub.m3} \cdot V_{CH4} = 262.5 \cdot kWh$

Pumping

$\eta_{pump} := 0.8$ $\quad h := 2m$

All of the flows in the system are assumed to be lifted $h = 2 \cdot m$ and the pump efficiency is set to $\eta_{pump} = 80 \cdot \%$

$$El_{pump} := \frac{\left[\rho_W \cdot g \cdot h \cdot \left(2 \cdot Q_{AD} + Q_{A1} + Q_O + Q_{A2} + Q_{A3} + Q_S\right)\right]}{\eta_{pump}} = 20.019 \cdot kWh$$

CO2 injection

$El_{CO2.injection} := 0.022\ kWh \cdot kg^{-1}$

Energy use per mass CO2 Ref 5 in Lardon(2009)

$CO2_{CHP} = 913.92\,kg$

mass of CO2 from the CHP

$El_{injection} := \left(El_{CO2.injection} \cdot CO2_{CHP}\right) = 20.106 \cdot kWh$

kWh if all the CO2 from the CHP is injected into the pond.

Rotary Press

$El_{rotary.ref} := 0.01449\,kWh \cdot m^{-3}$

Power consumption per volume in Rotary Press. Calculated from www.metsopaper.com.
RST-HCS630x3000L Installed power(kW): 3.7 + 1.5, max flow(LPM) 1,150.

$El_{rotary.1} := \left(Q_{AD} \cdot El_{rotary.ref}\right) = 0.164 \cdot kWh$

$El_{rotary.2} := Q_{A1} \cdot El_{rotary.ref} = 19.81 \cdot kWh$

El if Algae Biodiesel without AD:

$El_{rotary} := El_{rotary.1} + El_{rotary.2} = 19.974 \cdot kWh$

Oil Extraction

$El_{Extraction.press..kg} := 0.1\,kWh \cdot kg^{-1}$ $\quad El_{Extraction.refining..kg} := 0.0061\,kWh \cdot kg^{-1}$

Electricity: Press 0.1 kWh/kg oil and Refining 0.0061 kWh/kg oil, Steam: 1.7890 MJ/kg oil.
From ecoinvent, LCI of 'Rape seeds, in oil mill, RER'. report nr 17.

$El_{extraction.press} := El_{Extraction.press..kg} \cdot X_{Oil} = 102.857 \cdot kWh$ $\quad Heat_{Extraction.kg} := 1.7889\,MJ \cdot kg^{-1}$

$El_{extraction.refining} := El_{Extraction.refining..kg} \cdot X_{Oil} = 6.274 \cdot kWh$

$El_{extraction} := El_{extraction.press} + El_{extraction.refining} = 109.132 \cdot kWh$

$Heat_{extraction} := Heat_{Extraction.kg} \cdot X_{Oil} = 1.84 \times 10^{3} \cdot MJ$

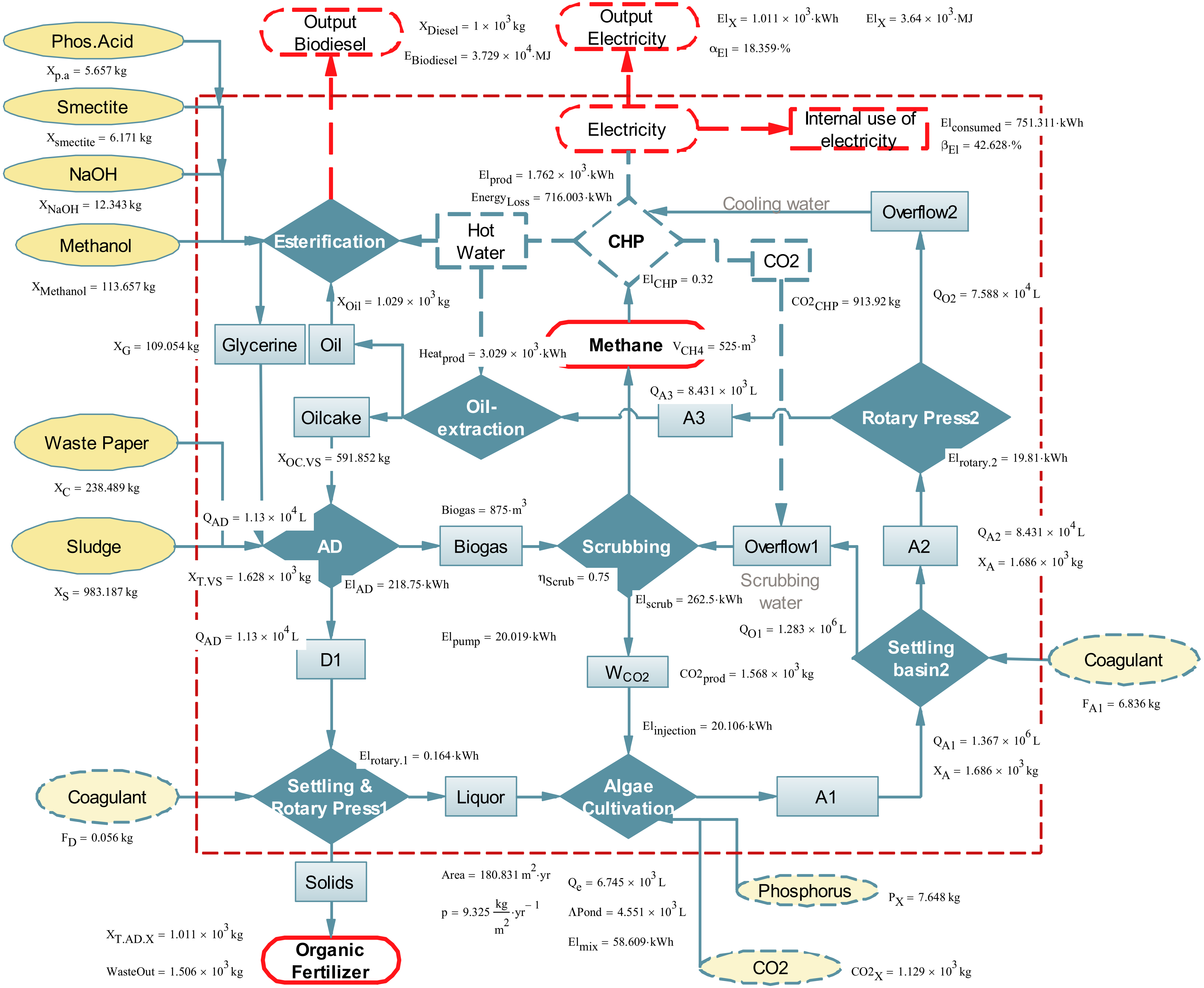
Oil Esterification

$El_{trans.kg} := 0.0422\,kWh \cdot kg^{-1}$ $\quad Heat_{Trans.kg} := 0.9238\,MJ \cdot kg^{-1}$

Electricity: 0.0422 kWh per kg methyl ester (biodiesel) produced. Steam: 0.9238 MJ per kg methyl ester (biodiesel) produced From ecoinvent, LCI of 'Rape seeds, in esterification plant, RER'. report nr 17

$El_{trans} := El_{trans.kg} \cdot X_{Diesel} = 42.221 \cdot kWh$

$Heat_{trans} := Heat_{Trans.kg} \cdot X_{Diesel} = 924.256 \cdot MJ$


Phos.Acid
$X_{p.a} = 5.657$ kg
Smectite
$X_{smectite} = 6.171$ kg
NaOH
$X_{NaOH} = 12.343$ kg
Methanol
$X_{Methanol} = 113.657$ kg
Output Biodiesel
$X_{Diesel} = 1 \times 10^3$ kg
$E_{Biodiesel} = 3.729 \times 10^4 \cdot$MJ
Output Electricity
$El_X = 1.011 \times 10^3 \cdot$kWh
$El_X = 3.64 \times 10^3 \cdot$MJ
$\alpha_{El} = 18.359 \cdot \%$
Electricity
Internal use of electricity
$El_{consumed} = 751.311 \cdot$kWh
$\beta_{El} = 42.628 \cdot \%$
$El_{prod} = 1.762 \times 10^3 \cdot$kWh
$Energy_{Loss} = 716.003 \cdot$kWh
Cooling water
Overflow2
Esterification
Hot Water
CHP
CO2
$El_{CHP} = 0.32$
$CO2_{CHP} = 913.92$ kg
$Q_{O2} = 7.588 \times 10^4$ L
$X_{Oil} = 1.029 \times 10^3$ kg
$X_G = 109.054$ kg
Glycerine
Oil
$Heat_{prod} = 3.029 \times 10^3 \cdot$kWh
Methane
$V_{CH4} = 525 \cdot m^3$
$Q_{A3} = 8.431 \times 10^3$ L
Oilcake
Oil-extraction
A3
Rotary Press2
$El_{rotary.2} = 19.81 \cdot$kWh
Waste Paper
$X_C = 238.489$ kg
$X_{OC.VS} = 591.852$ kg
$Q_{AD} = 1.13 \times 10^4$ L
Biogas = $875 \cdot m^3$
Sludge
AD
Biogas
Scrubbing
Overflow1
A2
$Q_{A2} = 8.431 \times 10^4$ L
$X_A = 1.686 \times 10^3$ kg
$X_S = 983.187$ kg
$X_{T.VS} = 1.628 \times 10^3$ kg
$El_{AD} = 218.75 \cdot$kWh
$\eta_{Scrub} = 0.75$
$El_{scrub} = 262.5 \cdot$kWh
Scrubbing water
$Q_{O1} = 1.283 \times 10^6$ L
Settling basin2
Coagulant
$F_{A1} = 6.836$ kg
$Q_{AD} = 1.13 \times 10^4$ L
$El_{pump} = 20.019 \cdot$kWh
D1
W_{CO2}
$CO2_{prod} = 1.568 \times 10^3$ kg
$El_{injection} = 20.106 \cdot$kWh
$El_{rotary.1} = 0.164 \cdot$kWh
$Q_{A1} = 1.367 \times 10^6$ L
$X_A = 1.686 \times 10^3$ kg
Coagulant
Settling & Rotary Press1
Liquor
Algae Cultivation
A1
$F_D = 0.056$ kg
Solids
Area = $180.831 \ m^2 \cdot yr$
$p = 9.325 \frac{kg}{m^2} \cdot yr^{-1}$
$Q_e = 6.745 \times 10^3$ L
$\Lambda Pond = 4.551 \times 10^3$ L
$El_{mix} = 58.609 \cdot$kWh
Phosphorus
$P_X = 7.648$ kg
$X_{T.AD.X} = 1.011 \times 10^3$ kg
$WasteOut = 1.506 \times 10^3$ kg
Organic Fertilizer
CO2
$CO2_X = 1.129 \times 10^3$ kg

Appendix C

Life Cycle Calculations

Life Cycle Inventory: ACAD Biodiesel

							Life Cycle Coefficients					Allocation factor =		91.22%			Life Cycle Inventory			
						Energy req.	CO2e.req	CO2	CH4	N20		Total consume		Per unit allocated	(MJ)	kg	kg	kg	kg	
Contribution	Contribution	FU		Unit		(MJ)	kg	kg	kg	kg		kg		1 tbd	Energy req.	CO2eq	CO2	CH4	N2O	
Input	Aluminium sulfate		1	kg Al2(SO4)2		5.7	0.51					6.89		6.28	35.82	3.20	0.00	0.00	0.00	Clarens(2010)
	Phosphorus fertilizer		1	kg P2O5		15.8	0.71	7.00E-01	2.30E-05	4.20E-05		7.64		6.97	110.17	4.98	4.88	0.00	0.00	Mortimer(2003)
	CO2		1	kg		3.06	0.50					1129.00		1029.87	3147.83	518.82	0.00	0.00	0.00	Calculated from Mortimer(2003)
	Methanol		1	kg methanol		38.08	2.76	2.72E+00	1.30E-03	1.50E-05		113.60		103.63	3946.11	285.87	282.07	0.13	0.00	Mortimer(2003)
	NaOH		1	kg NaOH		19.87	1.20	1.12E+00	3.25E-03	0.00E+00		12.34		11.25	223.61	13.50	12.60	0.04	0.00	Mortimer(2003)
	Hexane		1	kg hexane		52.05	0.56	5.43E-01	6.73E-04	1.35E-05		2.57		2.34	122.02	1.32	1.27	0.00	0.00	Mortimer(2003)
	Phosphoric acid		1	kg phos.acid		11.4	0.80	7.68E-01	1.23E-03	2.00E-05		5.65		5.16	58.80	4.15	3.96	0.01	0.00	Mortimer(2003)
	Smectite		1	kg smectite		2.55	0.20	1.97E-01	3.70E-05	6.50E-06		6.17		5.63	14.35	1.13	1.11	0.00	0.00	Mortimer(2003)
	Plant contruction														106.00	5.00	5.00	0.00	0.00	Taken directly from Mortimer(2003)
	Plant maintenance														66.00	2.00	2.00	0.00	0.00	requirement for production of biodiesel from
	Distribution														498	32	8	0.008	0	oilseed rape.
SUM	**Totals**											**1284**	**0**	**1171**	**8329**	**871.97**	**320.90**	**0.19**	**0.00**	
														1171.139829						
Reference System	**Diesel Fuel**																			
End Balance	**Total Balance**														**8329**	**871.97**	**320.90**	**0.19**	**0.00**	
CO2 burdens	CO2		1	kg		3.056516129	0.503774194	0	0	0	0	1129	0	1029.8738	3147.825881	518.8238431	0	0	0	
Algal Biodiesel without CO2 burden															**5181**	**353.15**	**320.90**	**0.19**	**0.00**	
Methanol burdens	Methanol		1	kg methanol		38.08	2.75865	2.722	0.0013	0.000015	0	113.601	0	103.6268322	3946.10977	285.8701606	282.0722372	0.134714882	0.001554402	
Distribution	Distribution		0		0	0	0	0	0	0	0	0	0	0	498	32	8	0.008	0	
Algal Biodiesel without CO2, methanol and distribution burdens															**737**	**35**	**31**	**0**	**0**	
Trade off percipitation	Phosphorus		1			52.51						9.21		8.40	441.11					
	Nitrogen		1			172						88.40		80.64	13870.29					
Algal Biodiesel without CO2 burden including tradeoffs from Wastewater treatment															**-9131**					
	+ Nitrogen Fertilizer		1	kg N		40.608	6.69					76.64		76.64	3112.03	512.92	0.00	0.00	0.00	
	+ Power		1	MJ		3.083	0.16	1.50E-01	4.04E-04	5.58E-06		1113.00		1113.00	3431.38	180.41	167.40	0.45	0.01	
	+ Heat		1	MJ		3.083	0.16208999	0.1504	0.0004043	5.577E-06				2763.00	8518.33	447.85	415.56	1.12	0.02	
	+ phosphorus		1	kg P		15.8	0.7140035	0.7	0.000023	0.000042				9.21	145.50	6.58	6.45	0.00	0.00	
Algal Biodiesel without AD w CO2 and Methanol															**23536**	**2020**				

Comparison: ACAD Biodiesel vs Other Types of Diesel

Specification	Biodiesel
	(FAME)
Density (kg/l)	0.88
Net Calorific Value (MJ/kg)	37.27
Gross Calorific Value (MJ/kg)	37.84

	Energy content (MJ)	
Functional Unit	**Net**	**Gross**
1 ton biodiesel fuel	37270	37840

Fuel	**Total Primary Energy Requirements**	**GHG requirement**	**Net Energy Gain**	**Fossil Energy Ratio**
Algae Biodiesel w CO2	8329	872	28941	4.474884211
Algae Biodiesel x CO2	5181	353	32089	7.193756865
Algae Biodiesel x CO2 w tradeoff	-9131		46401	-4.081916236
Algae without AD	23536	2020	13734	1.58353484
Conventional Rapeseed Diesel	16269	1516	21001	2.290859918
Modified Rapeseed Diesel	7750	702	29520	4.809032258
Modified Rapeseed Diesel ex. Methanol	3929	425		

	Energy requirements		**GHG requirements**	
Fuel	**Net**	**Gross**	**Net**	**Gross**
Algae Biodiesel w CO2	0.2235	0.2201	0.0234	0.0230
Algae Biodiesel x CO2	0.1390	0.1369	0.0095	0.0093
Algae Biodiesel x CO2 & Methanol	0.0198	0.0195	0.0009	0.0009
Algae Biodiesel x CO2 w tradeoff	-0.2450	-0.2413	0.0000	0.0000
Algae without AD	0.6315	0.6220	0.0542	0.0534
Conventional Rapeseed Diesel	0.4365	0.4299	0.0407	0.0401
Modified Rapeseed Diesel	0.2079	0.2048	0.0188	0.0186
Modified Rapeseed Diesel ex. Methanol	0.1054	0.1038	0.0114	0.0112

	Sum Values			
	Energy requirements (MJ/MJ)		**GHG req. (kg CO2eq/MJ)**	
Fuel	**Net**	**Gross**	**Net**	**Gross**
ACAD biodiesel ex CO2 incl. WWT tradeoff	-0.24	-0.24	0.023	0.02
ACAD biodiesel ex. CO2 & Methanol	0.02	0.02	0.001	0.000932356
ACAD biodiesel ex. CO2	0.14	0.14	0.009	0.01
ACAD biodiesel	0.22	0.22	0.023	0.04
Algal Biodiesel without AD	0.63	0.62	0.054	0.05
Rapeseed modified ex. Methanol	0.11	0.10	0.011	0.01
Rapeseed Biodiesel modified	0.21	0.20	0.019	0.00
Rapeseed Biodiesel conventional	0.44	0.43	0.041	0.02
Low Sulphur Diesel	1.21	1.13	0.091	0.09
Ultra Low Sulphur Diesel	1.26	1.17	0.095	0.09

			3.4	1.8
	(MJ/kg)		MJ/kg	1.95
Trade off	El. and fossil requirements N	El. and fossil requirements P	Offset Methanol	Offset Chemical precipitant
Nitrogen	45		129.472	
Phosphorus		49		3.51
	El. and fossil requirements N	El. and fossil requirements P	Offset Methanol N-removal	Offset Chemicals P-removal
Nitrogen	3629		10441	
Phosphorus		412		29.4855788
Total Offset	**3629**	**412**	**10441**	**29**

Metanol for esterification	113.60
Metanol for N-removal	274.18
Difference	**160.58**
Percentage more	241%