Modelling Energy Flows in a Microalgae-to-Biogas Production System

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Abstract

The aim of this study was to create a top-down model of a theoretical, full-scale microalgae-to-biogas production system with the help of the life cycle software GREET. The model was created for the purpose of calculating the energy balance and evaluate the energy performance of a defined algae product system, and the software and its applicability to the needs of the project employer was further evaluated.

The approach of a life cycle inventory study (LCI) was taken, and the inventory data was obtained from the literature as well as from previous findings within the project. The functional unit was defined as "the production of 1 MWh of biogas in a microalgae-to-biogas system" and the product system included the processes of microalgae cultivation, harvesting and biogas production through anaerobic digestion.

Findings of the LCI study indicated that for the given set of process criteria, the energy going in to the system was higher than the energy coming out, hence causing the energy balance to be negative. However, further work with modelling different scenarios should be done in order to better understand and optimize the system.

Language: English Key words: microalgae, system analysis, LCI, energy balance

EXAMENSARBETE

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Abstrakt

Målet med denna studie var att skapa en top-down modell av ett teoretiskt, fullskaligt mikroalg-till-biogas produktionssystem med hjälp av livcykelprogramvaran GREET. Ändamålet med modellen var att beräkna energibalanser och utvärdera ett definierat algproduktionssystems energiprestanda. Programvaran GREETs ändamålsenlighet för uppdragsgivarens behov granskades även.

Metodologiskt sett, utfördes arbetet som en livscykel- inventeringsstudie (LCI), där inventariedatan erhölls från litteraturstudier såväl som från tidigare projektresultat. Den funktionella enheten definierades som ”produktionen av 1 MWh biogas inom ett mikroalg-till-biogas produktionssystem”, och det studerade systemet innehöll processer av mikroalgsodling, skördning samt biogasproduktion genom anaerob rötning.

Resultaten av LCI-studien påvisade att energiströmmarna in i systemet var större än energiströmmarna ut ur systemet för de studerade processkriterierna, vilket resulterade i en negativ energibalans. För att bättre förstå och kunna optimera systemet behöver mera arbete läggas på att modellera olika processer och scenarion.

Språk: engelska Nyckelord: mikroalger, systemanalys, LCI, energibalans

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1 Introduction

With problems such as global warming, increasing energy demands among ever-increasing populations and the depletion of fossil fuels, the global energy system stands in front of many challenges. In order to provide energy and energy security while simultaneously cutting down on greenhouse gases and emissions, new sustainable solutions are needed. Biofuels, among others, have therefore received much attention.

Biofuels are fuels produced out of renewable resources and they can be considered more sustainable due to their neutral carbon balance. The first generation of biofuels were created from terrestrial plant crops, and these energy crops were either combusted or converted into other fuels such as ethanol, hydrogen or methane. Criticism was however raised as valuable food stock came to be used for fuel production (Ward, Lewis & Green, 2014) and this caused the second generation of biofuels to focus on the nonedible parts of the plants, lignocellulosic feedstocks and municipal solid wastes (Lee & Lavoie, 2013). However, when terrestrial plants exhibit a photosynthetic efficiency of 1–2 %, the efficiencies obtained by microalgae can reach 4–5 %, causing them to outperform the productivities achieved by the previous generation's biofuels (Ward, Lewis & Green, 2014). The third generation of biofuels does therefore relate to algal biomass and the converting of the algal biomass into a wide range of fuels and co-products.

The research and development of algae based fuels is a fairly young discipline with the first pioneering small-scale laboratory experiments on microalgae cultivation being conducted some 140 years ago. The idea that microalgae could be used for fuel production was however not expressed until the 1940s (Borowitzka, 2013, pp. 1-2). Golueke and Oswald were the first authors to publish studies on the anaerobic digestion of microalgal biomass in the late 1950s, after which further studies of the role of microalgae in sewage treatment followed (Ward, Lewis & Green, 2014, p. 206). Since then, the field has flourished and sprouted into many different research areas, and in addition to biofuel production, there is an interest for using algae in wastewater treatment, for carbon dioxide (CO_2) capture, as nutrition and as a source for high value chemicals. (Borowitzka, 2013, p. 10)

Even though the biofuel production from algae shows a great potential, the technology is not yet mature. The Technology Readiness Level (TRL) describes the technology maturity of a process or system on a scale from 1 to 9, where 1 is very basic research and 9 is a technology ready for commercialization. As assessed by Murphy et al. (2015), the TRL of seaweed fuels is around 5 whereas the TRL for microalgae and microalgal biogas is below 4. This means that there still exists several technical challenges and bottlenecks that need to be addressed before the algae derived biofuels successfully and in an economically feasible way will be able to hit the commercial markets.

This report will focus on the microalgae-to-biogas production system, and the aim is to create a top-down model of a theoretical biogas production system in order to evaluated the energy performance of the different processes and technologies. The model created will be developed in the LCA software GREET, and the applicability of the software when it comes to the modelling of different algae pathways and scenarios will be further investigated and evaluated.

1.1 Background and purpose

This report is written within the project TransAlgae, a cross-border Botnia-Atlantica project with project partners located in Finland, Sweden and Norway. TransAlgae focuses upon finding new solutions for renewable energy and products from algae grown in a Nordic climate (Biofuel region), and one of the main goals of the project is to create a continuous dialogue between the academia and the industry in order to reach an increased implementation of innovation within the region (TransAlgae, 2015).

As a part of the project, a system analysis will be conducted in order to evaluate and improve the performance of the algal biofuel system. As this system is of a highly complex nature with many different technologies and processes that can be integrated into the design, a system analytical approach is needed in order to evaluate the functionality and outcomes of different setups. By following all the system inputs, flows and outputs, accurate assessments of the performance can be done, enabling further development and pushing the innovations even further (National Research Council of the National Academies, 2012, pp. 17-18).

This report will be focusing on energy and the tracing of energy flows inside the system's borders, which will be located in a Nordic climate. The cultivation and harvesting of algae include several energy intensive steps and the purpose of this report is to collect data about these different stages in order to create a top-down model that calculates the energy balance of the whole system. An energy balance can be seen as "*a consideration of the energy input, output, and consumption or generation in a process or stage*" (Collins English Dictionary), and the energy balance can be either negative or positive depending on whether the amount of energy required to produce a product or a service is larger or smaller than the energy gained from it (TransAlgae, 2015).

The model for calculation the energy balance will be created in the life cycle software GREET, which is a software focusing on the simulations of energy use and emission outputs of different vehicle and fuel combination (Argonne National Laboratory, 2011). In addition to creating the model, an evaluation will be done of the software.

1.2 Methodology and structure

As the energy balance will be executed as a life cycle inventory study (LCI), a life cycle software will be used for the task. GREET, a shortening for *Greenhouse gases, Regulated Emissions and Energy use in Transportation* is a life-cycle model developed by Argonne National Laboratory and sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE). The GREET model simulates the energy use and emission outputs of various vehicle and fuel combination and makes it possible to analyse technologies and their energy and environmental impacts over an entire life cycle, from well to wheel or from the mining of raw material to vehicle disposal (Argonne National Laboratory, 2011).

As the focus point of the project is on energy balances and energy flows rather than on general environmental impacts, the goals of the study can be fulfilled by taking the approach of a life cycle inventory study (LCI) instead of conducting a full life cycle assessment study (LCA). The LCI differs from the LCA by excluding the impact assessment phase (ISO 14040:2006), and more about the LCA methodology can be found in Chapter 4.

The data used in this study will be gathered from the literature as well as from laboratory trials and previous findings of the project. As the field of algal expertise is still growing rapidly due to technological advances and the emerging of new knowledge, as recent data as possible will be used. However, as the focus of this report lies on modelling the energy balances of a large-scaled algal production system whereas much of the figures available come from small-scaled pilot experiments, process data from larger experiments will be favoured regardless of publication date. If no applicable large-scale data for a process can be found, the extrapolation of data from smaller setups will have to do.

The structure of the report is the following. Firstly, introductions will be given to algae and algae cultivation, after which the processes involved in the biogas production will be described as well as the general guidelines and practices involved in a life cycle study. Having provided the reader with a general background to the topics, the fifth chapter will define the studied product system and the scope of the report whereas all the inventory data gathered for the processes, the calculations and the assumptions made will be described in chapter six. Having compiled the necessary data, chapter seven provides a summary of the findings and some general thoughts on the results. The GREET software and the created model will be further described and evaluated in the eight chapter, after which the final conclusions and recommendations based on the findings will be provided.

1.3 Limitations and assumptions

Assumptions made in the data collection will be based on as well literature as previous findings in the project. However, it is important to bear in mind that most of the data originates from pilot- or small-scaled production, and that the data focusing on bigger production facilities often are based on theoretical extrapolation from small-scaled studies rather than actual results and measurements. As the algae cultivation and harvesting system is highly complex, the extrapolated data do not necessarily reflect the real conditions. In addition to this, the energy consumptions reported in the literature are generally based on the assumption of 100 % operation, and do not take into account down-time that might be occur due to e.g. contamination build-ups, culture collapses or equipment failure and maintenance. They might therefore be overly optimistic.

In the model, the energy and material related to the manufacturing of equipment, to the construction of facilities as well as the energy required for operating greenhouses in a Nordic setting will not be included in the study. More about this is found in Chapter 5. The included processes as well as the dimensioning of the pond for the baseline scenario has been defined by previous project activities as likely scenarios for microalgae-to-biogas production.

2 Introduction to algae and microalgae cultivation

Algae is an umbrella term for a wide range of photosynthetic organisms exhibiting no shared common origins (polyphyletic organisms) and which include both prokaryote and eukaryote species. Estimates of the number of algae species have been placed around 72 500, and these species display a wide array of diversity when it comes to e.g. size, ecology, cellular structures and levels of organization. Furthermore, different species thrive in highly different environments, and they can be both aquatic and subaerial (Barsanti & Gualtieri, 2014, pp. 1-2).

Most of the algae depend on photosynthesis, utilizing the suns light as their energy source and carbon in the form of CO_2 to produce biomass (Barsanti & Gualtieri, 2014, p. 16). They exhibit high photosynthetic yields, and about 3–8 % of the solar energy can be converted into biomass (Lardon et al. 2009). Due to this, they grow rapidly. Microalgae commonly double their biomass within 24 hours (during exponential growth, even in as short time periods as 3.5 hours) (Chisti, 2007), which in combination with them generally having high oil contents, being able to grow in brackish or even wastewater and their ability to utilize waste CO_2 for their growth (Brennan & Owende, 2010) make them an interesting biofuel alternative.

Sheehan et al (1998, pp. 5-6), considered three main options for fuel production from algal biomass, namely the (1) production of methane gas via biological or thermal gasification, (2) production of ethanol via fermentation and (3) the production of biodiesel. However, in addition to biofuels, algal biomass can also be converted into a range of other products such as food, pharmaceuticals and other chemicals (López-Contreras et al. 2017, p. 130).

Algae can be divided into two larger subgroups; macroalgae and microalgae. Even though this report will focus mainly on microalgae, a short introduction will be given to macroalgae too, as these are also studied within the TransAlgae project. Furthermore, will the biorefinery approach be shortly explained before diving in to the cultivation parameters and the selected cultivation pathway for the microalgae-to-biogas production system studied in this report.

2.1 Macroalgae

Macroalgae, also known as seaweeds, are multicellular algae with plant-like structural features (National Algal Biofuels Technology Review 2016, p. 35) which are fast growing and can reach a length of up to 60 metres (Sheehan et al. 1998, p. 2).

They are classified according to their predominant pigments into the categories brown, green and red algae (National Algal Biofuels Technology Review 2016, p. 35) and the macroalgae can either be obtained by harvesting natural stocks in coastal areas, by gathering drift seaweeds from shorelines or by cultivation. Depending on the species, the chemical composition of the seaweed varies. The composition is also affected by seasonality, harvesting location and age of the plant. Generally, the macroalgae are however high in water content, carbohydrates and minerals whereas the protein and lipid contents remain low. (López-Contreras et al. 2017, pp. 103-108)

2.2 Microalgae

Microalgae on the other hand are microscopic photosynthetic organism that can be divided further into the groups diatoms, green algae, blue-green algae and golden algae. Due to their simple cellular structure and their access to water and nutrients, they efficiently convert the solar energy (Sheehan et al. 1998, pp. 2-3), and with oil contents in the range 20 – 50 % dry weight (Chisti, 2007, p. 296) microalgae can produce more than 300 times more oil per acre than other terrestrial plants (Katiyar, Kumar & Gurjar, 2017, pp. 157, 164) which make them an interesting option for biodiesel production (see Table 1).

Table 1. Comparison of oil yield in some sources of biodiesel (Chisti, 2007, p. 296)

Crop	Oil yield (L/ha)	Land area needed (M ha)[a]	Percent of existing US cropping area[a]
Corn	172	1540	846
Soybean	446	594	326
Canola	1190	223	122
Jatropha	1892	140	77
Coconut	2689	99	54
Oil palm	5950	45	24
Microalgae[b]	136,900	2	1.1
Microalgae[c]	58,700	4.5	2.5

[a] For meeting 50% of all transport fuel needs of the United States.
[b] 70% oil (by wt) in biomass.
[c] 30% oil (by wt) in biomass.

Biodiesel production does however require a high energy consumption, which makes Murphy et al (2015, p. 10) suggest that there is a strong potential for microalgae-to-biogas systems having a superior energy balance than microalgae biodiesel.

2.3 The biorefinery concept

A biorefinery can be defined as a facility that converts biomass into numerous products such as fuels, chemicals, power, materials, foods etc. with minimal waste as a result (Das, 2015, p. 2), and both macro and microalgae can be considered ideal for a biorefinery approach as they, in addition to the lipids and carbohydrate utilized in the biofuel production, also contain high-value products such as pigments, proteins, vitamins, antioxidants and minerals which can find further applications in the pharmaceutical, cosmetical, and nutritional industries (López-Contreras et al. 2017, p. 111; Chew et al. 2017). As it is hard to reach economic feasibility by purely producing biofuels, high-value products can add much needed value to the production, hence making the production more economically viable (López-Contreras et al. 2017, pp. 111, 131), however, this will not be further expanded on in this report.

2.4 Cultivation parameters

When selecting which algae species to grow, there are a number of strains to choose between. As pointed out by Sheehan et al. (cited in Borowitzka, 2013, p. 8) the local conditions will affect which species that are the most ideal for a particular site, and tests even showed that the best way to reach successful outdoor cultivation was to allow a contaminant native to the area to take over. This as the algae tested in the laboratories not necessarily were robust enough to endure in the field.

Algae are grown in a cultivation medium, and this media can be either seawater, artificial seawater enriched with nutrients, synthetic cultivation media or wastewater. The media should provide the nutrients needed by the algae, and depending on the particular specie grown, the growing conditions must be adjusted accordingly. (Murphy et al. 2015, p. 19)

There are several parameters influencing algal growth, and the main ones can be listed as nutrient availability, light, temperature and pH of the culture, and cultivation pathway (Gonçalves et al. 2017, p. 32). Furthermore will mixing be important for the growth as the mixing ensures that all algae cells are equally exposed to light and nutrients (Barsanti & Gualtieri, 2014, pp. 227-228).

2.4.1 Nutrients

Carbon, nitrogen and phosphorous can be considered as the most important nutrients for the algal growth, and the ratios in which they are provided in the growth medium are important.

According to the Redfield ratio, photosynthetic aquatic organisms benefit from ratios of the size C:N:P = 106:16:1, but these need to be further adjusted according to the specific specie. Too little of a nutrient will be limiting for the growth. (Gonçalves et al. pp. 34-35, 37). Apart from the primary nutrients, algae do also require essential micronutrients such as silica, calcium, magnesium, potassium, iron, manganese, sulphur, zinc, copper and cobalt (Christenson & Sims, 2011).

Carbon can be utilized by the algae in the form of carbon dioxide and bicarbonate (Christenson & Sims, 2011), and as about 40% of the dry weight of the algal biomass is made up by carbon, a minimum of 183 tons of CO_2 is required to produce 100 tons of microalgae biomass. The algae can fix CO_2 directly from the atmosphere, but as the concentrations are low, additional CO_2 is required for microalgae cultures as they otherwise become carbon limited. This additional CO_2 can be provided in the form of flue gases, and be supplied to the culture through continuous bubbling or by on-demand injection. (Fernández et al. 2012) Due to their ability to utilize CO_2 emissions, algae based fuels can be considered carbon neutral (Ward, Lewis & Green, 2013), as the carbon released while combusting the fuel do not increase the carbon amounts in the atmosphere (Katiyar, Kumar & Gurjar, 2017, p. 168).

2.4.2 Light

The providing of sufficient light is vital as light is the source of energy for photosynthetic algae. The light can be both naturally and artificially provided, and depending on the density and depth of the algae culture, the light intensity needs to be adjusted in order to penetrate through the whole culture and reach all the algae cells. At the same time, too high light intensities may cause photo-inhibition and can also lead to overheating. All microalgae do not thrive in constant illumination (Barsanti & Gualtiere, 2014, p. 227), which makes it necessary to adjust the lightning according to the needs of the cultivated species.

2.4.3 Temperature and pH

The temperature kept in the cultivation media should ideally be as close to the temperature at which the organisms were collected, however, most of the commonly cultivated species will tolerate temperatures within the range 16–27°C. Often, temperatures in the range 18–20°C are used. (Barsanti & Gualtiere, 2014, p. 227). The temperature affects the growth rate, the cell size, the biochemical composition of the algae and hence the nutrient requirements, and too high or too low temperatures will therefore affect the cultivation negatively (Gonçalves et al. 2017, p. 37).

pH wise, values between 7 and 9 should be kept, and the optimum range for many species are 8.2-8.7 (Barsanti & Gualtiere 2014, p. 227). The pH is affected by the addition of CO_2, as the carbon dioxide increases the amount of inorganic carbon in the medium and hence reduces the pH (Borowitzka & Moheimani, 2013, p. 137).

2.4.4 Mixing

In order for all the microalgae to be equally exposed to light and nutrients, mixing is required and it prevents the sedimentation of the algae, avoids thermal stratification and improves the gas exchange between air and culture medium. The mixing can be obtained by mechanical means or by bubbling the culture with air, and it should be gentle in order not to damage the algae cells. (Barsanti & Gualtiere, 2014, p. 228)

2.5 Cultivation pathway

The algal biofuel production chain is highly complex. In order to visualize this, a high-level multi-pathway biofuel process flow diagram obtained from the National Algae Biofuels Technology Review (2016, p. 176) can be found in Figure 1.

As seen in the picture, the main stages in the biofuel process chain can be considered as (1) input of materials, (2) cultivation, (3) harvesting, (4) drying, (5) extraction and separation, (6) fuel conservation and (7) co-products conservation. However, depending on the preferred outputs of the system, some of the stages can be entirely bypassed whereas several technologies from one stage, such as the harvesting step, can be combined and used together.

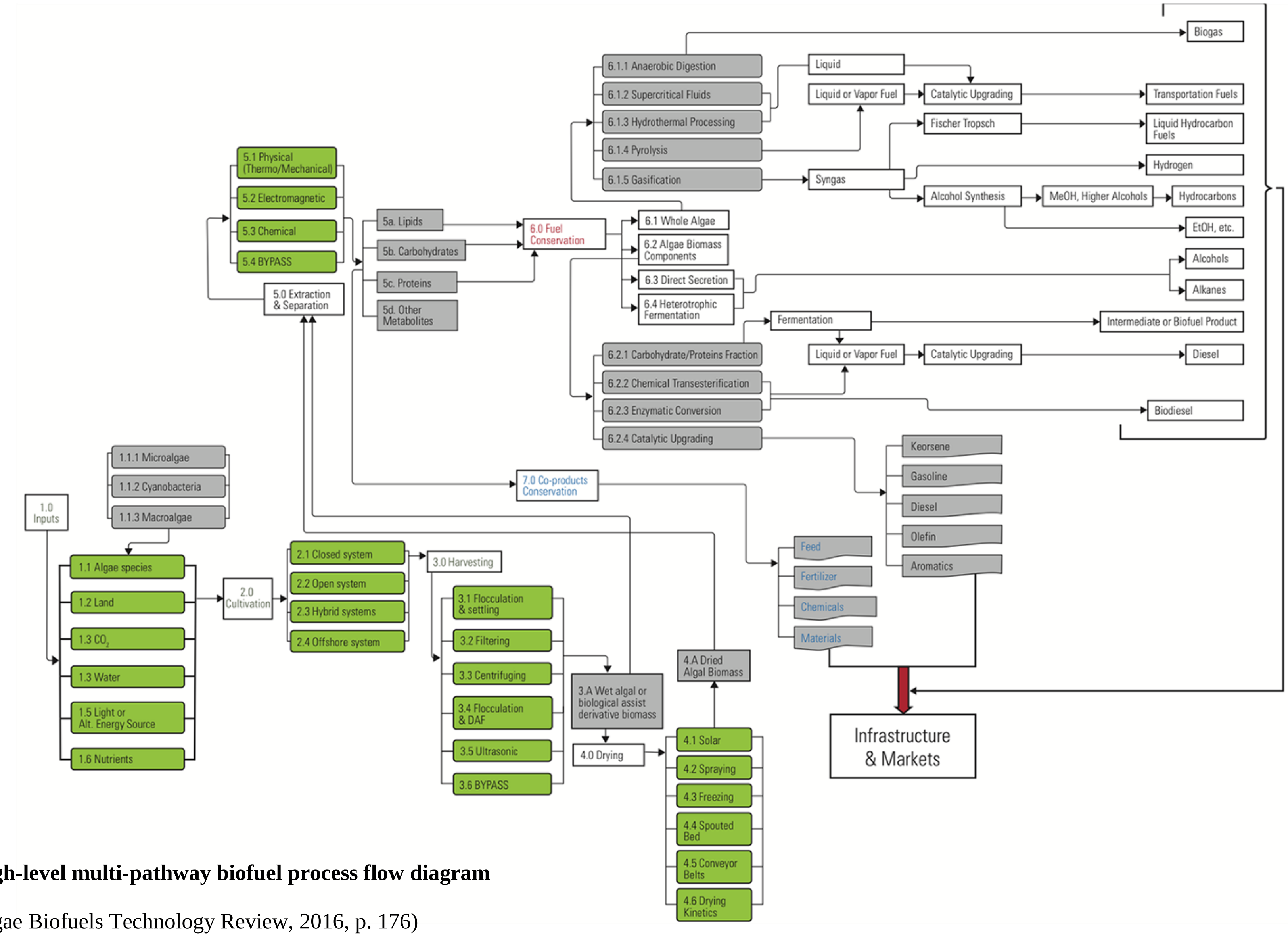

Figure 1. High-level multi-pathway biofuel process flow diagram

(National Algae Biofuels Technology Review, 2016, p. 176)

As the aim of this report was to create a top-down model of an algae production system where the outputs, processes and technologies had already been defined, the focus in this subchapter will not lie on comparing different technologies and their pros and cons but rather to provide the reader with relevant and sufficient background information in order to understand the specific pathway selected for the task. Namely, producing biogas and fertilizers out of whole microalgae through anaerobic digestion. This will be done in an open raceway pond system where the microalgae will be harvested through gravity sedimentation and centrifugation before they enter the anaerobic digester (see Figure 2).

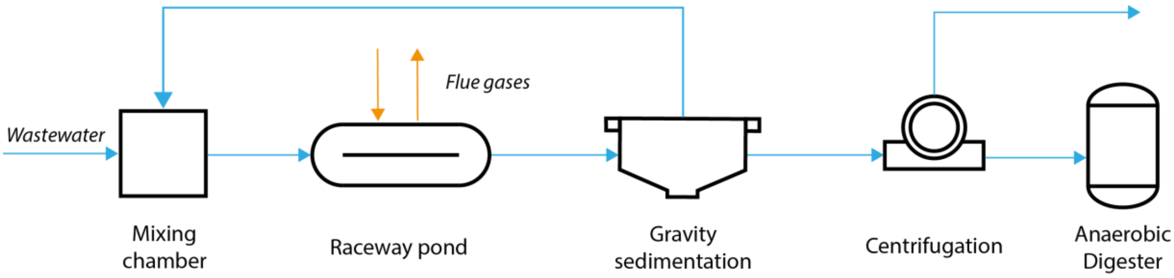

Figure 2. Flowchart of processes included in the studied pathway

2.5.1 Material inputs to the cultivation system

As mentioned in previous chapters, microalgae need light, CO_2 and nutrients for their growth. They also require a cultivation media which, in this case, will be wastewater retrieved from a nearby municipal wastewater treatment plant.

In addition to the inputs required by the algae, energy will also be needed in order to operate the processes and the machinery (e.g. pumping, mixing, centrifugation), for heating (e.g. of the cultivation media, of the anaerobic digester) and in order to provide light to the microalgae.

2.5.2 Cultivation

The cultivation will take place in an open raceway pond, and as the microalgae system is set in a Nordic climate, the pond will be located in a greenhouse in order to ensure access to enough light and suitable temperatures. Municipal wastewater will provide the nutrients required by the algae whereas CO_2 will be added to the raceway pond in the form of flue gases. The mixing of the raceway pond will be done with the help of a paddlewheel.

2.5.3 Harvesting

Harvesting is the step in which the algal biomass is concentrated and/or separated from the cultivation medium, and because of dilute algal suspensions and small sized algae cells, energy- and cost-efficient harvesting are considered to be two major challenges for the commercializing of biofuels from algae. This as the harvesting costs now accounts for a significant portion of the overall production costs. (Show & Lee, 2014, p. 104)

Microalgae are commonly harvested with the help of mechanical, chemical, electrical or biological based methods, and there is so far no single best method for the harvesting (Christensson & Sims, 2011, p. 692). In this report, the mechanical based methods of gravity sedimentation and centrifugation will be used.

Gravity sedimentation is a process where the particles are allowed to settle into a slurry in the bottom of a sedimentation tank. The slurry is then withdrawn and the media, also called effluent, will be pumped back to the inlet (Show & Lee, 2014, p. 96). The settlement behaviour varies both between algae species and within the specie itself, and settlement rates are affected by light intensity, nutrient deficiency, age of the algae cells and lipid content. Generally, the concentration of total solids after the sedimentation step is between 0.5 and 3 % (Milledge, 2013, p. 50, 52), and the recovery of the biomass is in the range 10–90 % (Christensson & Sims, 2011, p. 693). One type of gravity settler is the gravity thickener illustrated in Figure 3.

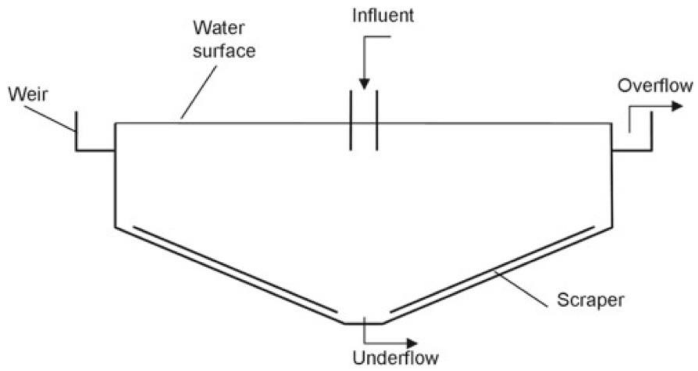

Figure 3. Example of gravity settler (Pahl el al. 2013, p. 172)

Whereas the sedimentation depends on the gravity and the natural tendency for higher density particles to settle, the centrifugation speeds up the process by utilizing centrifugal forces (Pahl et al, 2013, pp. 172-173). The suspension is fed into a centrifugal bowl where it is rotated. This causes the solids to gather at the bowl walls, from where they can then be removed. (Show & Lee, 2014, p. 101) There are several types of centrifuges in operation, and in this study, a Evodos dynamic settler will be used. The dynamic settler uses spiral plate technology and generates a high separation efficiency at the same time as the energy requirements are being kept low (Go-dove, 2018). As summarized by Christensson & Sims

(2011, p. 693), the centrifugation gives a solid concentration of 12–22 % whereas the recovery rate is >90 %.

2.5.4 Anaerobic digestion

Anaerobic digestion is the process in which bacteria breaks down organic wastes in the absence of free oxygen (Abbasi et al. 2012, p. 1), and the end products are a gas rich in methane (CH_4) and a slurry containing the non-biodegradable material (Igoni et al. 2008). The digestion can be operated either under thermophilic (50–65 °C), mesophilic (20–40 °C) or psychrophilic (< 10 °C) operation conditions, and depending on the temperature, different microorganisms and bacteria participate in the degradation (Abbasi et al. 2012, p. 7). Generally, a higher digester temperature causes a more rapid decomposition and gas production (Igoni et al. 2008, p. 434), however, it also leads to higher heating requirements in order to sustain the process. Conventionally, the produced biogas is therefore used in a combined heat and power (CHP) unit for production of energy, and the waste heat generated from the CHP unit is used for heating the digestion process (Zupančič & Roš, 2003, p. 2257).

3 Introduction to biogas

Biogas is produced as organic matter undergoes an anaerobic decomposition process, and the gas consists normally of 40–70 % methane (CH_4) (Abbasi et al. 2012, p. 1), 25–50 % CO_2 and some minor impurities such as hydrogen sulphide (H_2S), ammonia (NH_3), nitrogen gas (N_2), water vapour and dust (Dublein & Steinhauser, 2008, p. 52).

The ratio of methane to CO_2 in the gas depends on many factors, and as summarized by Dublein & Steinhauser (2008, pp. 53-54), some of these factors are exposure time in the digester (retention time), presence of long-chain hydrocarbon compounds, mixing and the liquid content, temperature and pressure in the digester. As methane is the energy carrier dictating the energy content of the biogas, a high ratio of methane to CO_2 is desired.

3.1 Biogas formation

The breakdown of biodegradable, organic matter into biogas and slurry can be divided into four phases, namely hydrolysis, acidogenesis, acetogenises and methanogenesis (see Figure 4), and each phase is carried out by a different group of microorganisms (Dublein & Steinhauser, 2008, p. 93).

In the hydrolysis phase, the large proteins, fats and carbohydrate polymers entering the digester are broken down into long-chain fatty acids, sugars and amino acids, which in the acidogenetic phase are turned into volatile fatty acids, alcohols, hydrogen (H_2) and carbon dioxide. In the third step, acetogenesis, the volatile fatty acids are further broken down by the acetogenic microorganisms into acetic acid, CO_2 and H_2, which are consumed by the mehanogenic microorganisms in the fourth step with methane and CO_2 as end products (Abbasi et al. 2012, pp. 2-3; Dublein & Steinhauser, 2008, pp. 93-98).

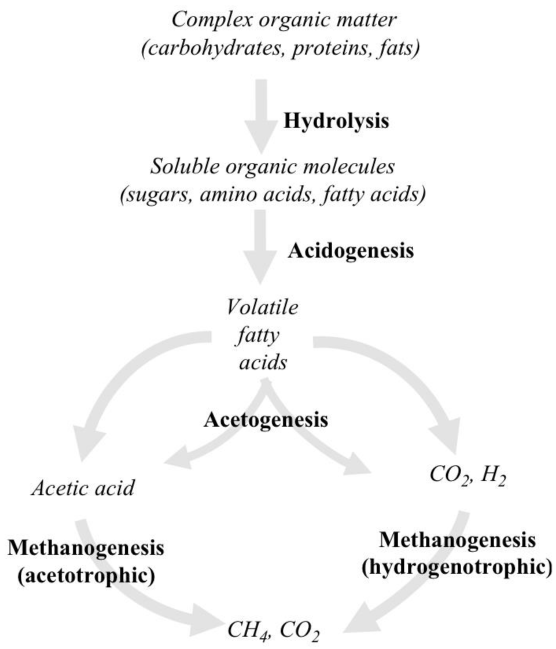

Figure 4. The phases included in the anaerobic digestion (Abbasi et al. 2012, p. 3)

3.2 Microalgae and anaerobic digestion

As summarized by Murphy et al. (2015, pp. 23-34), microalgae can be seen as an advantageous substrate for anaerobic digestion due to their high biomass productivity and low ash content, and depending on the microalgae strain, the biomethane potential (BMP) ranges from 100 to 450 L kg^{-1} volatile solids (VS). The volatile solids (VS), also called the organic dry matter (ODM), are determined by the drying of a sample to constant weight in a drying chamber operating at 103–105 °C (which gives the amount of total solids (TS) in the sample). After this, the sample is further ignited in a muffle furnace at 550 °C until it reaches constant weight again. When subtracting the remaining ashes of the sample from the total solids, the VS can be calculated. (Murphy et al. 2015, p. 38)

When digesting microalgae anaerobically, several things need to be considered. Ward, Lewis & Green (2014, pp. 207-209), discusses the problems with anaerobic digestion of microalgae and divide the topic into four separate problems, namely (1) low concentration of digestible substrate, (2) cell wall degradability and pre-treatment of microalgae biomass, (3) the carbon/nitrogen ratio associated with the microalgae biomass and (4) lipids and microalgae.

3.2.1 Low concentrations

The low concentrations of the microalgae biomass in large volumes of water can be considered an engineering issue as the microalgae suspension need to be further dewatered and harvested before being loaded into the anaerobic digester. This is because too dilute suspensions lead to a washout of the anaerobic bacteria community. (Ward, Lewis & Green, 2014, p. 209). There is therefore a need for efficient concentration and harvesting methods.

3.2.2 Cell wall degradability and pre-treatment of microalgae biomass

Depending on the specific algae strain, some species may have a very thick cell wall, which make the digestion difficult. To improve the biogas production rate, a pre-treatment step might hence be needed (Murphy et al. 2015, p. 25) in order to disrupt the cell wall. The pre-treatment methods can be mechanical, physical, thermal and chemical, and studies referred to by Ward, Lewis & Green (2014, pp. 208-209) showed that all tested pre-treatment methods produced better results than the untreated control comparison. However, as the methods can have a high energy consumption, the pre-treatment of the algal biomass could also be found to have an equal or higher energy consumption than the energy gained from the microalgal cell.

3.2.3 Carbon to nitrogen ratio

The carbon to nitrogen ratio in microalgae is generally low, with reported C/N ratios of between 4.16 to 7.82. C/N ratios of under 20 negatively affects the anaerobic digestion by creating an imbalance between the carbon and nitrogen requirements for the microorganisms, which causes an ammonia release that eventually leads to an inhibitory environment for the methanogenic bacteria. Different ways of co-digesting microalgae with other waste streams or biomasses in order to increase the C/N ratio has therefore been studied, with the co-digestion of e.g. paper waste showing good results. (Ward, Lewis & Green, 2014, p. 209)

3.2.4 Lipids and microalgae

Even though lipids increase the methane potential of the biogas, too high amounts of lipids may cause inhibition. Extracting the lipids from the biomass for liquid biofuel production before the step of anaerobic digestion can therefore be beneficial for the processes. (Ward, Lewis & Green, 2014, p. 209)

4 Introduction to LCA

Life cycle assessments (LCAs) are part of the environmental management standards found in the ISO 14000 family (ISO, 2018), and by conducting a life cycle assessment, a better understanding of the environmental aspects and potential impacts of a specific product or service can be acquired. By taking a cradle-to-grave approach, the environmental impacts occurring over the products whole life cycle are included, from raw material acquisition to production, use and end-of-life treatment (ISO 14040:2006, p. v), and the results of the LCA can help in identifying improvement possibilities for the production system as well as function as an aid in decision making and marketing (Baumann & Tillman, 2004, pp. 21-22).

As seen in Figure 5, an LCA can be divided into four phases, namely (1) goal and scope definition phase, (2) inventory analysis phase, (3) impact assessment phase and (4) interpretation phase (ISO 14040:2006, p. 8), where the goal and scope of the study determines the outlook and the results of the LCA. However, as the LCA is an iterative approach, the scope may have to be refined and revised during the studies (ISO 14044:2006, p. 7) as new data is gained and more knowledge acquired about the studied production system (Baumann & Tillman, 2004, p. 97).

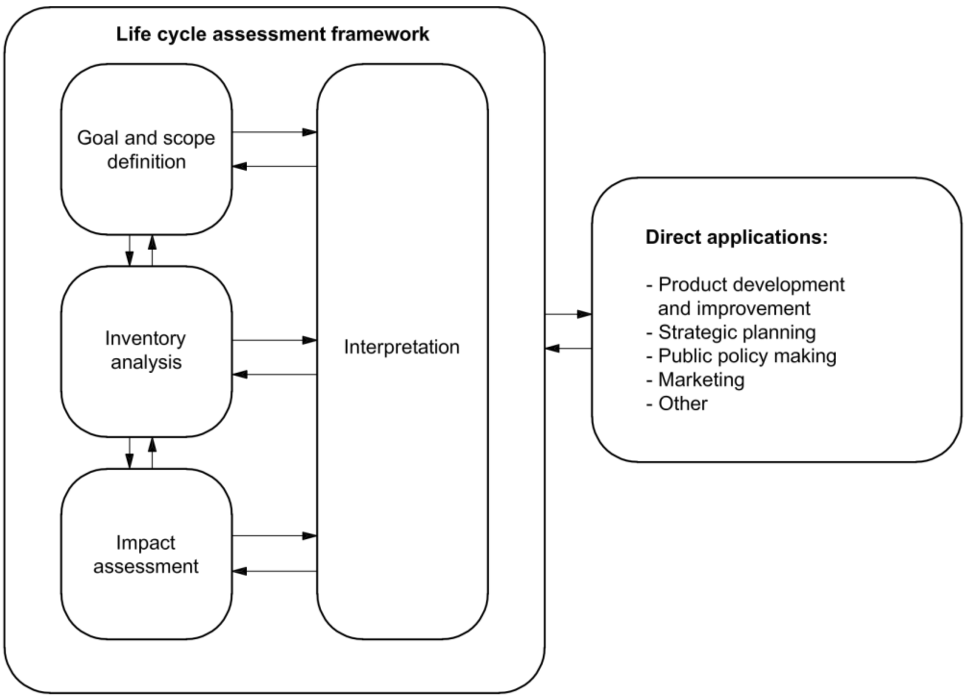

Figure 5. Stages of an LCA (ISO 14040:2006, p. 8)

As previously mentioned, the goals of this report will be fulfilled by taking the approach of a life cycle inventory study (LCI) instead of conducting a full LCA, meaning that the third phase, impact assessment, will be excluded. The impact assessment phase involves the selection of environmental impact categories and category indicators which the inventory data will be associated to, making it possible to evaluate the significance of the potential environmental impacts (ISO 14040:2006, p. 14). As the focus in this case is not on environmental impacts but on energy flows and balances, an LCI will be suitable for the task.

In the following subchapters, the methodology of the LCI will be further described.

4.1 Goal and scope

The goal of an LCI defines the purpose, application and target audience of the study whereas the scope defines what to analyse and how the analysis will be carried out (ILCD, 2010, p. 29, 51). The ISO standards stresses that the goal and scope should be clearly defined and consistent with the intended application (ISO 14044:2006), and the methodological choices done in the scope should be adjusted in accordance with the goals of the study (ILCD, 2010, p. 51) in order to ensure that the breadth, depth and detail of the study are sufficient enough to address said goal (ISO 14040:2006, p.11).

According to ISO 14044:2006, the following items should be considered and clearly defined within the scope: the product system, the functions of the product system, the functional unit, the system boundary, allocation procedures, life cycle impact assessment methodology, interpretation to be used, data and data quality requirements, value choices, assumptions, limitations, type of critical review and type and format of the produced report. Some of these aspects will be further described in the following subchapters, however, for a more detailed picture of the life cycle methodology the reader is recommended to seek advice from the ISO standards 14040:2006 and 14044:2006.

4.1.1 Product system

As the life cycle approach is concerned with technical systems and the environmental impacts occurring during a products whole life cycle, from raw material acquisition to final disposal, the understanding of the product system and its different processes and flows is important. A process can be defined as "*a set of interrelated or interacting activities that* *transform inputs into outputs*" (ISO 14040:2006, p. 3), and an example of process inputs and outputs (also known as flows) can be found in Figure 6.

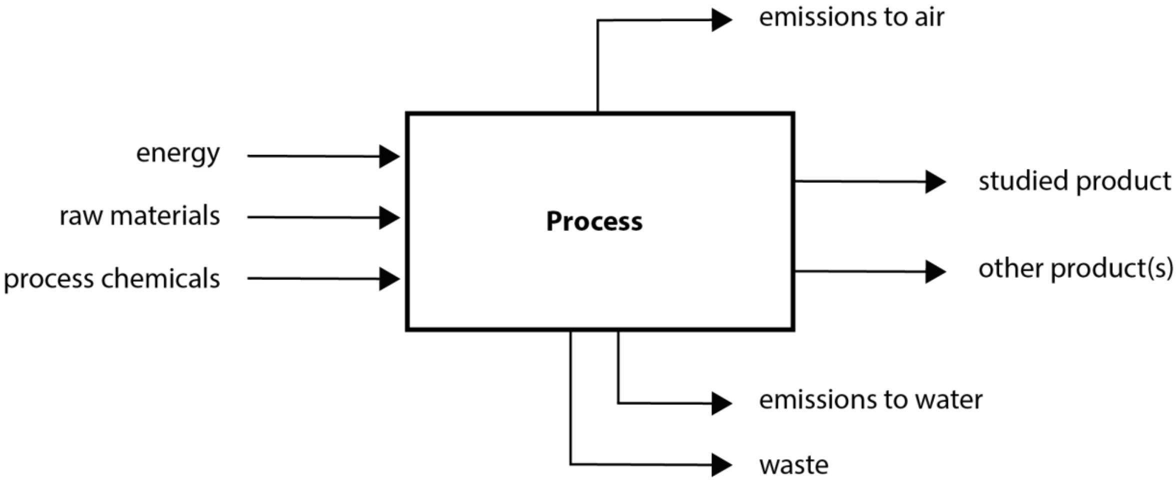

Figure 6. Example of process inputs and outputs (Baumann & Tillman, 2004, p. 103)

The product system is made up of several processes, each of which are connected to one another, to other product systems and to the environment by flows of material and/or energy (Figure 7). Depending on whether the flows originate from another system or from the environment, they can be divided further into product flows or elementary flows. (ISO 14040:2006, pp. 9-10).

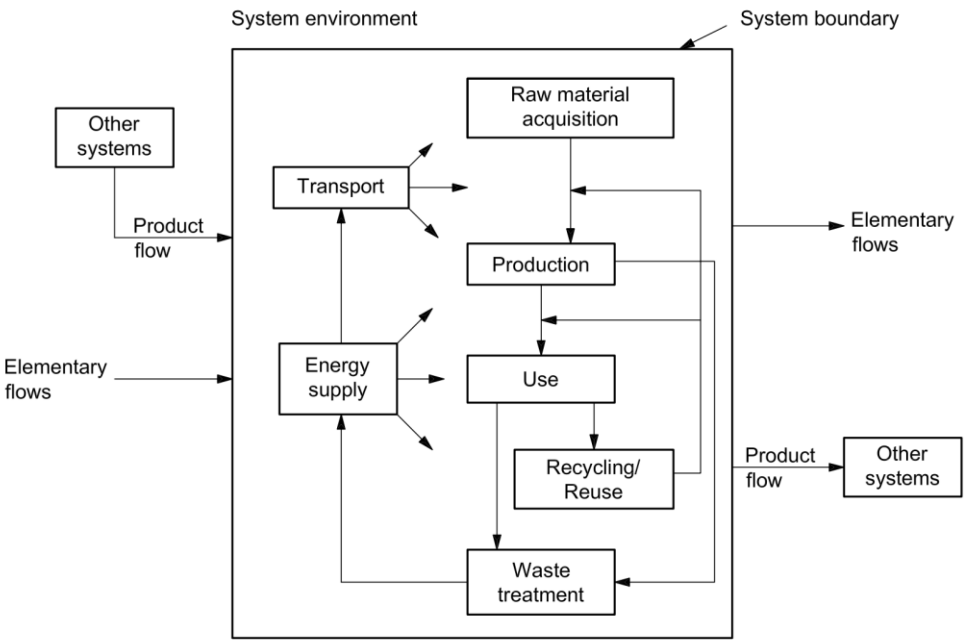

Figure 7. Example of product system (ISO 14040:2006)

4.1.2 Functional unit

A life cycle study is structured around a functional unit, and the task of the functional unit is to provide a reference to which the input and output data in a product system can be related and hence to define what is being studied (ISO 14040:2006). The product system can often perform several functions, and the functional unit should reflect the function that is chosen in a quantitative way (Baumann & Tillman, 2004, p. 176), by which it is possible to compare two or more product system to each other. Functions of an algae production system can for example be water cleaning, energy production or the producing of nutritional products. Depending on the goal of the life cycle study, the chosen functional unit should quantify the flows of the studied function, and in the examples above, m^3 of cleaned water, MJ of fuel produced or grams of dietary supplement could all work as functional units for their systems.

4.1.3 System boundary

As seen in Figure 7, the system boundary determines which processes that are included in the study, and the level of detail should be clearly stated and consistent with the goal of the life cycle study. Exclusion of life cycle stages, processes, inputs and outputs is only permitted if the removal does not significantly change the overall conclusions of the study, and any potential omissions need to be clearly stated and explained (ISO 14044:2006, p. 8). The processes and flows which are not quantitatively relevant for the study can be cut-off, and the cut-off criteria is defined by the level of completeness the study should exhibit (ILCD, 2010, pp. 102-104).

Ideally, the system boundary should be placed so that the inputs and outputs of the studied product system consist of elementary and product flows. (ISO 14044:2006, p. 8).

4.1.4 Allocation procedures

Allocation is needed when a product system produces multiple products, and the allocating partitions the input or output flows of a process or a system between the product system studied and one or more other product systems. As described in ISO 14040:2006 (p. 14) allocation should if possible be avoided by expanding the product system or dividing the unit processes.

4.2 Inventory analysis

The inventory analysis phase of a life cycle study can be divided into data collection, data calculating and allocation, and the aim is to quantify relevant inputs and outputs of the studied product system (ISO 14040:2006, p. 13).

In the data collection phase, quantitative and qualitative data is collected for all the processes included within the system boundaries, and as described in the ISO standards, the data can be classified under the major headings:

- energy inputs, raw material inputs, ancillary inputs, other physical inputs
- products, co-products and waste
- emissions to air, discharges to water and soil
- other environmental aspects (ISO 14040:2006, p. 13)

The aim of the data collection is to reach an understanding of the modelled product system and the relationship between the processes, and each process and its inputs and outputs should be described in detail (ISO 14044:2006, p. 11) and a detailed flow chart should be created (Baumann & Tillman, 2004, p. 98). As the life cycle approach stresses transparency, the data collected should be clearly referenced.

After having collected the data, a data validation should be done, for example by establishing mass and energy balances in order to check that every process follows the laws of conservation of mass and energy (ISO 14044:2006). The data should then be recalculated so that it relates to the selected functional unit, linking all the flows to this functional unit (Baumann & Tillman, 2004, p. 107). The allocation will then be performed in accordance with goal and scope.

4.3 Interpretation

The interpretation phase is the last step of a life cycle study, and the purpose is to identify the significant issues brought up by the results of the study, to evaluate the study and to draw conclusions, point out limitations and provide recommendations based on the obtained results. The results should be interpreted according to the goal and scope of the study. (ISO 14044:2006)

The evaluation of the study is done in order to enhance confidence and reliability in the results, and this can be done with the help of a completeness check, a sensitivity check and/or a consistency check. As the completeness check focuses on ensuring that all relevant data is included, the sensitivity check looks at how the results are affected by uncertainties in the data. The purpose of the consistency check is to make sure that the assumptions, methods and data are in accordance with the goal and scope of the study. (ISO 14044:2006)

5 Goal and scope definition of the report

The goal of this life cycle inventory study is to create a model of a theoretical, full-scale algae-to-biogas production system with the help of the life cycle software GREET. The model will be created for the project *TransAlgae,* and it aims to support the project activities by providing a way to analyse the energy performance of different process setups which are of particular interest for the project. An evaluation of the GREET software will also be made in order to determine whether it suits the needs of the project and whether its use can be further recommended.

The studied system is a microalgae-to-biogas product system with biogas being the main output. The system processes included are processes of microalgae cultivation, harvesting and anaerobic digestion, as well as transportation processes. Figure 8 demonstrates these processes, the material flows occurring between the processes and the system boundaries for the studied product system. The process of converting the biogas to electricity and heat will be situated outside the system boundaries.

In the studied product system, the focus lies on the energy required to operate the processes and the machinery in each step. Energy and material related to the manufacturing of equipment and to the construction of production facilities will hence fall outside the scope of the study. The cultivation will occur in a greenhouse, however, as the heat and light requirements for operating an algae cultivation in a greenhouse in a Nordic setting is a complex question, more data and information needs to be collected in order to correctly evaluate the energy requirements for the greenhouse operation. As of now, this step will hence be left outside the scope of the report. This is unfortunate as the energy flows for heating and adding light significantly will affect the energy balance of the whole system. However, as the model is further worked upon and expanded, the energy associated with maintaining stable heat and light conditions in the greenhouse will be further studied and included.

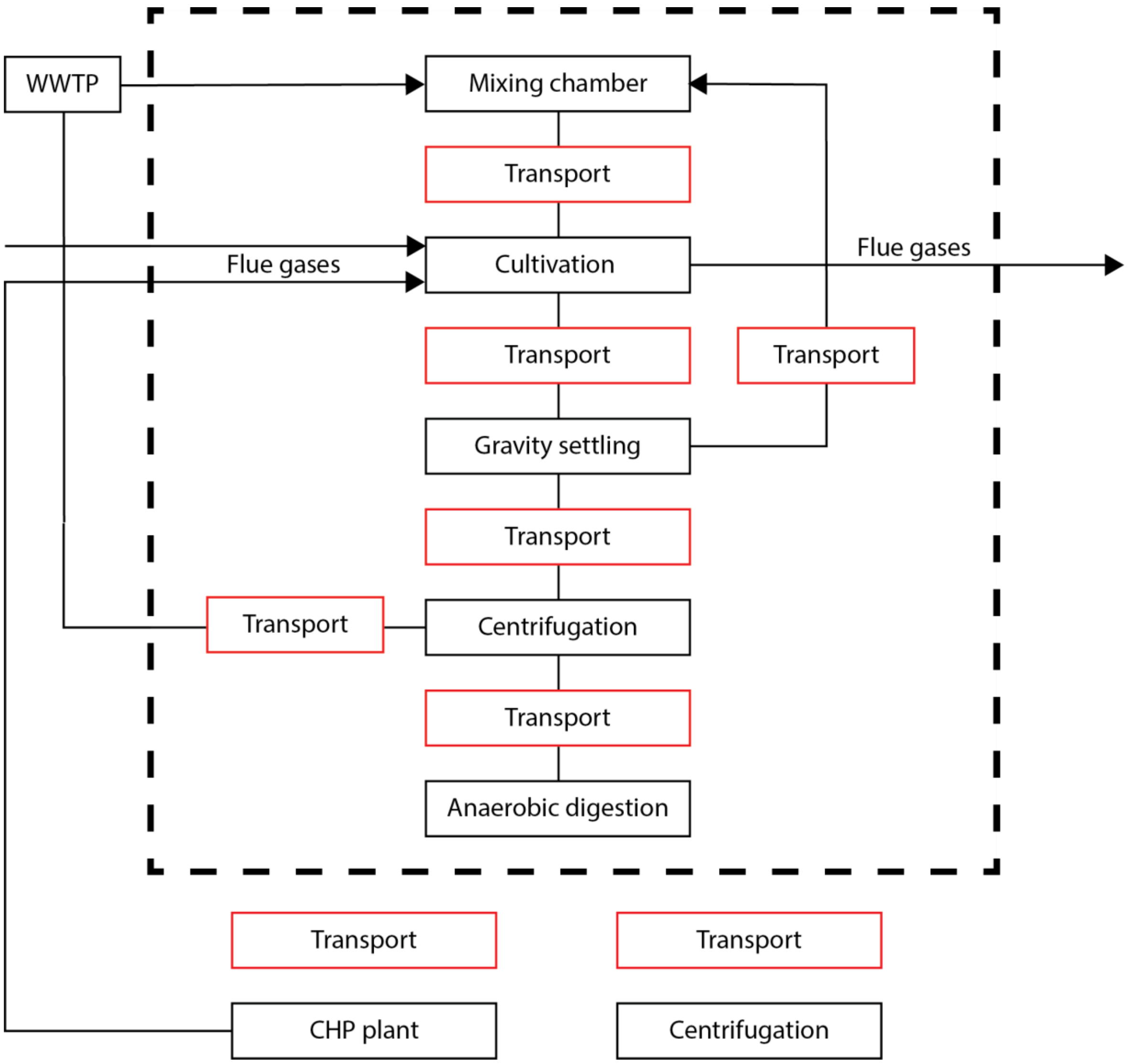

Figure 8. System boundaries of the studied algae-to-biogas system

The functional unit of the studied system is selected as "the production of 1 MWh of biogas in a microalgae-to-biogas system". As energy balances is of interest in the project, the overarching goal is to calculate the input energy required to produce an output of 1 MWh worth of energy within the selected product system. Optimally, this energy balance should be positive. Displacement will be used as an allocation method within the study.

In order to conclude how much different input values affect the overall energy performance of the system, a sensitivity analysis will be performed, and a couple of different scenarios will be compared to the baseline scenario.

6 Inventory data for baseline scenario

In order to create a model of the selected microalgae-to-biogas system in software GREET, a collection of data for the inventory have been performed. This data has been collected both from the literature as well as from the field and include the processes of cultivation, harvesting and anaerobic digestion as well as all the flows of material and energy occurring between these processes. The combustion of the biogas will not be included within the system boundaries. However, it is assumed that the biogas will be used in a combined heat and power (CHP) plant onsite, which will provide heat and electricity to the production facilities. The energy consumption associated with monitoring equipment will not be included in the study.

6.1 Cultivation data

As previously mentioned, the cultivation of the microalgae will occur in a raceway pond in an open system, located in a Nordic climate. The cultivation is semi-continuous and due to restrictions put by the climate, the cultivation will take place between April and September. Even though these are the months with the most favourable temperatures (see weather data in Appendix 1), extra light and heat will still be needed, which means that the cultivation pond needs to be situated in a greenhouse. At this point, the energy required to provide light and heat to the greenhouse will be left out of the model as this matter needs to be further studied within the project.

6.1.1 Pond dimensions

Raceway ponds of one hectare has previously been assessed as a likely size for commercial-scale operations (Milledge & Heaven, 2015), and for the baseline scenario, a pond size of about 1 hectare (10 017 m^2) has been selected in accordance with previous project findings. As there do not seem to be any energy balance advantages of having raceways deeper than 0.3 m and typical numbers used in other studies are pond depths of 0.2-0.3 m (Milledge & Heaven, 2015, p. 13), the depth has been further chosen as 0.3 m.

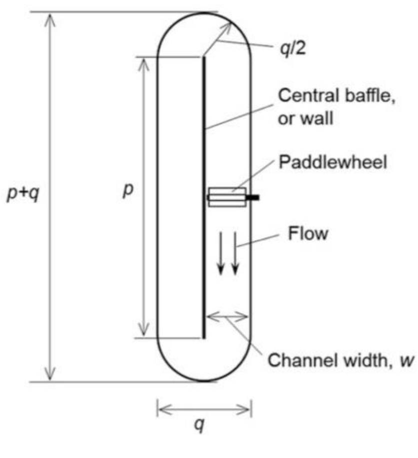

Figure 9. Illustration of raceway pond design (Chisti, 2016)

The pond dimensions can be found in Table 2, and based on a surface area of 1 ha, the volume of the pond can be calculated as 3005 m^3. Figure 9 includes a schematic picture of a typical raceway pond design obtained from Chisti (2016).

Table 2. Pond dimensions (values of channel length and width obtained from Milledge & Heaven, 2015)

	Unit	Value
Channel length	m	219
Channel width	m	20
Channel depth	m	0.3
Surface area	m^2	10017
Volume	m^3	3005

6.1.2 Paddlewheel mixing

As the flow in a raceway pond needs to be turbulent (Chisti, 2016), mixing is required. Craggs, Sutherland & Campell (2011), demonstrated that a single paddlewheel was enough to provide sufficient mixing in ponds of the size 1.25 ha. Hence, in the baseline scenario, one paddlewheel will be responsible for keeping the algae suspension properly mixed.

Generally, the paddlewheel velocities used range between 0.2 and 0.3 m s^{-1}, and 8-blade paddlewheels are often considered as optimal (Borowitzka & Moheimani, 2013, pp. 135-136). In the baseline scenario, a velocity of 0.3 m s^{-1} is selected, and the mixing will occur at the same speed during both day and night. Milledge (2013) calculated the energy requirements of a paddlewheel operating at 0.3 m s^{-1} in a 1 ha raceway pond as 21.8 kWh d^{-1}. However, this was while assuming a 100 % paddlewheel efficiency. As the efficiencies in reality are between 10–20 %, with efficiencies of 40–75 % being suggested for optimised paddlewheel and pond designs (Milledge & Heaven, 2017, p. 5), higher energy values are required. In the baseline scenario, a rather optimistic paddlewheel efficiency of 50 % is assumed, and when adapting the power consumption to this, the daily energy requirement of the paddlewheel reaches 43.7 kWh.

6.1.3 Microalgae species and characteristics

The microalgae species cultivated within the project are a diversified and natural mix of *Scenedesmus sp., Scenedesmus opoliensis* and *Scenedesmus quadricauda* as well as *Ankistrodesmus sp., Chlorella sp.* and *Coelastrum sp.* When grown in municipal wastewater, Olsson et al. (2017) obtained the composition data found in Table 3. Based on the carbohydrate, protein and lipid contents of the sample, they further calculated the theoretical methane potential as 446 NmL gVS^{-1} (Olsson et al, 2017).

Table 3. Composition data of microalgae used as substrate in Olsson et al. (2017)

	Unit	Value
VS	% of TS	59.2 ± 0.9
Lipids	% of TS	3.02
Protein	% of TS	33.2
Carbohydrates	% of TS	34.9
C- total	g kg TS^{-1}	377
N- total	g kg TS^{-1}	59.5
P- total	g kg TS^{-1}	4.6

The daily biomass productivity yield for this specific microalgae mix has not been stated. Borowitzka & Moheimani (2013, p. 147) compiled the reported biomass productivities for algae grown outdoors in open pond systems for a time period of 3 months or greater found in the literature, and the results display large variations. Depending on culture volumes, culture systems, locations, seasons and species cultivated, the productivities range from 1.6 g to 40 g dry weight m^{-2} day^{-1}. Due to little information being available from commercial-scale algae production, almost all of the reported values were from small-scale systems. According to Borowitzka & Moheimani (2013, p. 146), there is however no reason to assume that the annual average productivities of commercial algae companies exceed 20 g ash-free dry weight m^{-2} day^{-1}, and the productivities are likely to be less. In the baseline scenario, a conservative biomass production yield of 12 g m^{-2} day^{-1} is selected, which leads to daily productivities of 120 kg d^{-1} for a pond of the size 1 ha.

In order to maximise productivity, part of the culture should be regularly harvested while nutrients are provided at a constant level (i.e. semi-continuous culture), as this keeps the culture in the stage of exponential growth (Borowitzka & Moheimani, 2013, p. 137). According to studies summarized by Lundquist et al. (2010), the dilution rate, which can be described as the rate of influent addition and biomass removal from the raceway, should be kept between 20–50 % of the total raceway volume per day. For the baseline scenario, a low dilution rate of 20 % was assumed in the 3005 m^3 raceway pond, which equals an inflow of wastewater respective outflow of harvested algae suspension of 601 m^3 d^{-1} each.

Even though 120 kg of algal biomass is produced daily, the volumes harvested will be bigger due to the algae recycled from the harvesting re-entering the raceway pond. In order to determine the algal biomass proportion in the daily harvested suspension of 601 m^3, back counting is hence needed. Counting with 120 kg of biomass entering the final process of anaerobic digestion, and recovery rates of 95 % and 60 % in the dewatering steps found in the harvesting phase, gives a value of 211 kg of algae biomass being harvested on a daily basis. This equals to 0.35 kg m^{-3} of microalgae, and a harvested algae concentration of 0.035 %. The flows are further visualized in Table 4 and Figure 10.

Table 4. Raceway pond productivities, flows and concentrations

	Unit	Value
Biomass production yield	g m^{-2} d^{-1}	12
Pond productivity	kg ha^{-1} d^{-1}	120
Dilution rate	%	20
In- and outflow of pond	m^3 d^{-1}	601
Algae concentration in harvested suspension	kg m^{-3}	0.35

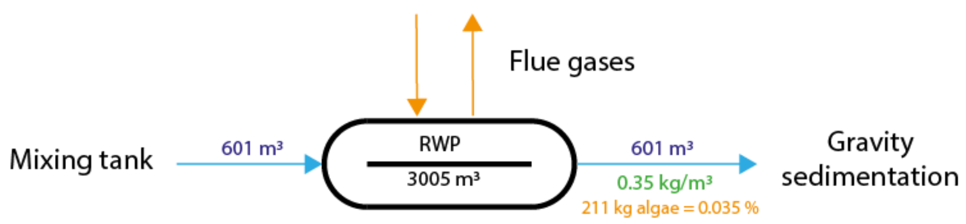

Figure 10. Culture flows in 1 ha raceway pond with selected parameters

6.1.4 Cultivation media

The modelled raceway pond is assumed to be situated in the immediate vicinity of a local municipal wastewater treatment plant, and the wastewater will provide the microalgae with the nitrogen, phosphorous and micronutrients needed. The wastewater is assumed to be gravity fed into the pond, hence requiring no energy for pumping. Olsson et al. (2017) report total nitrogen concentrations of 21.4 ± 5.4 mg L^{-1} and total phosphorous concentration of 2.5 ± 0.7 mg L^{-1} in the wastewater used in their study, and similar values will be assumed for this model.

Optimally, the cultivation media should provide nitrogen to phosphorous ratios (N:P) that match the stoichiometric ratio of the algae biomass, which according to the Redfield ratio exhibits an average of 16:1. Depending on the ratios found in the wastewater, it may hence be necessary to provide additional nutrients (Christenson & Sims, 2011). The ratio in Olsson et al.'s wastewater can be calculated as an average of 8.6:1 whereas the ratio obtained from the analysis of the algae biomass in Table 3 is 13:1. In the baseline scenario, no extra nutrients will however be added to the system.

The movement of liquids in the system and the required pumps are visualized in Figure 11. Water losses and evaporation are not accounted for in the model. The water from the sedimentation pond will be recycled back to the mixing chamber whereas the water separated in the centrifugation step will exit the system boundaries and be lead back to the waste water treatment plant.

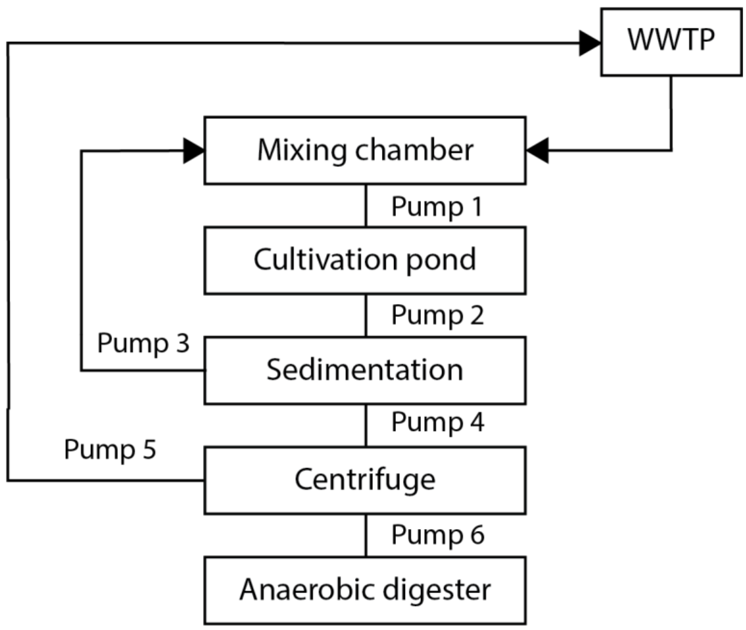

Figure 11. Water movements and pumps

6.1.5 Pumping power

The algae suspension needs to be moved around the system and this is done with the help of six pumps (see Figure 11). As described by Frank et al. (2011a, p. 21), solids below 2% can be treated as water. The pumping power depends on the pumping velocity and pump efficiency, but also on elevation changes and the characteristics of the pipeline (Frank et al, 2011a, p. 21). In this case, the first five pumps will handle liquids with under 2% solids, whereas the solid content will be higher in the sixth.

As the pumping power depends on the actual design and dimensions of the facility, general pumping values obtained from Frank et al (2011a, p. 21) will in this case be used for the five initial pumps, giving an approximate energy consumption of 2.4 x 10^{-5} kWh L^{-1} pumped liquid. In order to move the daily flow of 601 m^3 from the mixing chamber to the raceway pond, and from the raceway pond to the gravity sedimentation, a pumping power of 28.8 kWh d^{-1} is needed.

6.1.6 CO_2 addition

CO_2 will be added to the cultivation pond in the form of flue gases, and the flue gases derive both from the burning of the produced biogas on site as well as from nearby industry. The gases are transported by blowers through pipelines, and they are sparged into the pond through a CO_2 addition sump located near the paddlewheel (see Figure 12)

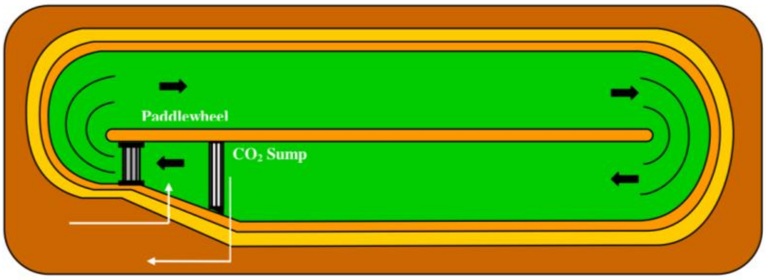

Figure 12. Schematic diagram of CO_2 addition sump (Craggs et al. 2011)

According to the data of the algae mix presented in Table 3, there is 377 g of carbon per kg of TS (total solids), and this is in line with literature values approximating the carbon content in the biomass to be about 40 % of the dry weight (Fernández et al., 2012). As previously mentioned, the ratio of carbon dioxide to dry algal biomass is 1.83, meaning that 1.83 kg of CO_2 is required to produce 1 kg of dry microalgae. However, due to outgassing the needs will in reality be several times higher than this. When the theoretical efficiency of the CO_2 use ranges between 20 and 90% depending on the operational conditions, the actual CO_2 fixation in raceway ponds can be less than 10 % (Slade & Bauen, 2013), making it necessary to provide CO_2 in surplus. Studies referred to by Maga (2017) on the other hand point to experimental data where a new injection system at 1 m depth and with small bubbles have shown to have a transfer efficiency of 95 %. An optimistic CO_2 utilization efficiency of 90% will therefore be assumed in the baseline scenario.

The daily production of 120 kg of algae biomass require 220 kg of CO_2, and with a utilization efficiency of 90 %, 244 kg of CO_2 should be added to the raceway pond. The CO_2 will be added in the form of flue gases with an assumed CO_2 concentration of 12 %, hence a daily injection of 2037 kg flue gases is needed in the pond in order to fill the carbon requirements of the algae. The ratio of carbon dioxide not taken up by the algae, and the rest of the flue gases will leave the system as air emissions.

Based on GREET calculations, Maga (2017) concludes that the average energy requirement for pumping the flue gases is 0.0027 kWh kg^{-1} for a sump depth of 1.2 m. Assuming the same setup gives a daily flue gas pumping energy requirement of 5.5 kWh.

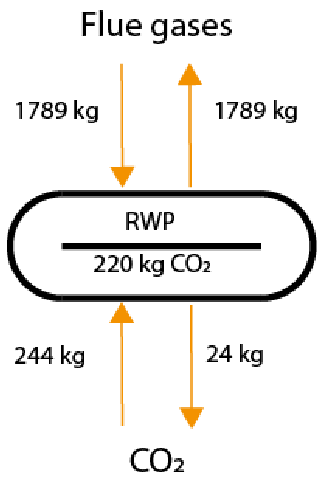

Figure 13. Schematic picture of gas flows in the cultivation system

6.2 Harvesting

The harvesting is carried out in two steps with a gravity sedimentation process followed by centrifugation, and the purpose is to dewater the algae in order to increase the proportion of algae to water, from 0.035 % to a selected output of 10 % of solid matter. The overflow water will be recycled back from the gravity settler to the mixing chamber where it will be joined by incoming wastewater. The water removed in the centrifugation step will exit the system.

6.2.1 Gravity sedimentation

The sedimentation velocity for spherical shapes can be calculated with Stoke's Law, which is defined as

$$Settling\ velocity = \frac{2}{9} g \frac{r_c^2}{\mu} (\rho_s - \rho_l) \qquad (1)$$

where r_c is the cell radius, μ the fluid viscosity and ρ_s and ρ_l the solid respective liquid densities (Milledge, 2013, p. 51). As the microalgae mix consists of algae cells of different sizes and forms, and no specific settling velocity is available for the mix, settling values have to be taken from the literature. Milledge (2013, p. 51) refers to studies were the average settling velocity for green microalgae was found to be 0.1 m day^{-1}, whereas studies conducted by Choi et al (2006) points to values of <0.24 m day^{-1} for smaller microalgae such as *Scenedesmus* and *Ankistrodesmus*.

In the baseline scenario, a sinking rate of 0.20 m d^{-1} will be used, and the settling will occur in a settling tank with inclined plates, also known as a lamella settler (Pahl et al, 2013). The output solid concentration of a lamella separator is 0.1–1.5 % dry micro-algal biomass (Milledge & Heaven, 2013, p. 167), and based on these values, a solid concentration of 1 % will be used in the model. As the recovery efficiency of the gravity sedimentation is between 10 and 90 % (Christensson & Sims, 2011, p. 693), an intermediate recovery value of 60 % will be applied.

The daily flow from the cultivation pond to the settler is 601 m^3 of suspension containing 0.035 % solids. When calculating with a recovery efficiency of 60 % and a solid concentration of 1 %, a dewatered output flow of 12.6 m^3 is obtained, containing 10 kg m^{-3} algae. As seen in Figure 14, 588 m^3 d^{-1} of suspension is transported back to the mixing chamber.

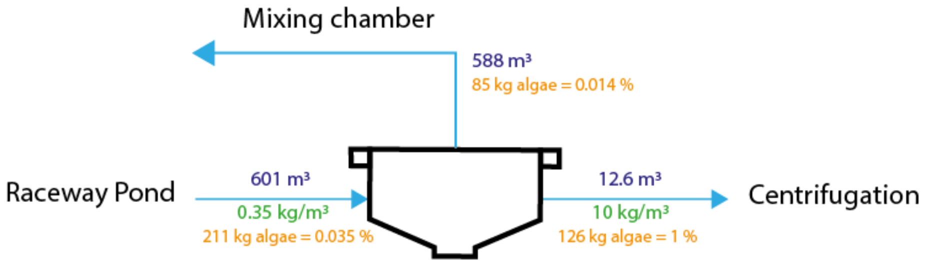

Figure 14. Mass balances of gravity sedimentation

The energy consumption of the lamella settler is generally low, with 0.1 kWh per m^3 being reported by the literature. However, as pointed out by Milledge & Heaven (2017, p. 6) the values reported by the manufacturers of the lamella settlers are closer to 0.05 kWh m^{-3}, which indicates that the actual energy requirements could be lower. In the baseline scenario, an intermediate value of 0.075 kWh m^{-3} will be used. With a daily outflow of 12.6 m^3 from the separator, the energy consumption can be calculated as 0.95 kWh.

6.2.2 Pumping power required by pump 3 and 4

As the solid content after the gravity sedimentation is <2% both for the recycled liquid and for the liquid transported to the centrifuge, the liquid can still be treated as water. As the energy consumption for the pumping is 2.4 x 10^{-5} kWh L^{-1}, the pumping of 12.6 m^3 to the centrifuge consumes 0.3 kWh whereas the recycling of 588.4 m^3 to the mixing chamber causes a required pumping power of 14.1 kWh per day.

6.2.3 Centrifugation

In order to handle the daily incoming flows of 12.6 m^3 (12600 L), an Evodos type 25 dynamic settler will be used. The dynamic settler uses a spiral plate technology, and is suitable for processing flows of 1000–3500 L h^{-1}. The settler has a separation efficiency of >95 % (Commercial Algae, 2018). The technical data can be found in Appendix 2, and the energy requirements of the separation and the pumping is in total 1.20 kWh m^{-3}, which, for a daily input of 12.6 m^3 of suspension, equals 15.1 kWh.

Evodos' dynamic settler generally concentrates the algal biomass to a slurry of 30 % total solids (Skorupskaite & Makareviciene, 2014). The production of biogas in anaerobic digesters is however negatively affected by high solid concentrations, with a TS content of more than 12 % impairing the gas production (Dublein & Steinhauser, 2008, p.112). A solid concentration of above 10 % may also make the microalgal suspension problematic to pump (Milledge & Heaven, 2017, p. 7). Because of this, a solid output of 10 % is strived for in the model. By using a recovery rate of 95 %, 120 kg of the incoming algae biomass is recovered. As this in turn equals 10 % of the total solids in the suspension, the total output flow can be calculated as 1.2 m^3 whereas 11.4 m^3 is transported back to the waste water treatment plant.

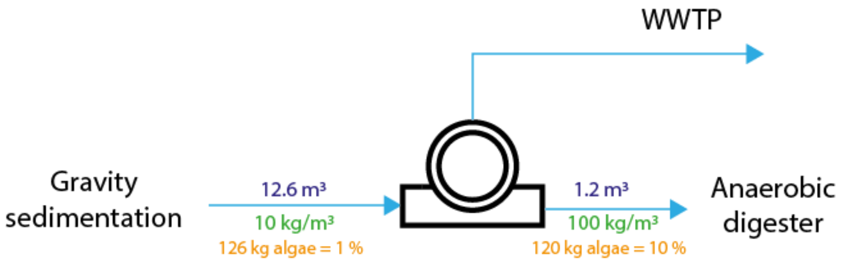

Figure 15. Daily liquid mass flows of the centrifuge

6.2.4 Pumping power required by pump 5 and 6

Having dewatered the suspension to 10 % solids, more power is needed to transport the suspension after the centrifugation step. As described by Deublin & Steinhauser (2008, pp. 210-211) centrifugal pumps are found in 50 % of all biogas plants and aids in transporting substrate with a dry matter of up to 12 % with a throughput of 2–6 m^3 min^{-1}. The power consumption is between 3 and 15 kW. Considering that the flow that needs pumping is of the size 1.2 m^3, the lowest power consumption will be applied for 2 min d^{-1}. This equals a power consumption of 0.1 kWh d^{-1}.

6.3 Anaerobic digestion

The harvested microalgae will undergo a thermophilic digestion process where the biomass is converted into biogas and digestate. The anaerobic digester operates at a temperature of 55°C with a hydraulic retention time of 20 days, and the produced biogas is assumed to have a composition of 60 % CH_4 and 4 0% CO_2. In accordance with previous findings in the project, the actual methane production is assumed to be 120 L CH_4 kg^{-1} VS, and these values will be used in the baseline scenario.

6.3.1 Digester dimensioning

As the digester will have to handle an incoming daily flow of 1.2 m^3 while having a hydraulic retention time of 20 days, a digester volume of at least 24 m^3 is needed. The design of the digester is usually cylindrical (Samer, 2012), and in this case, the dimensioning has been geometrically done by searching for suitable numbers that fulfil the equation of a cylinder's volume, $V = \pi r^2 h$. However, further optimizations should be done. An extra headspace of 10 % should be given to the internal tank volume (Samer, 2012), which leads to the acquiring of the tank dimensions found in Table 5.

Table 5. Assumed dimensions of digester tank

	Unit	Value
Internal tank volume	m^3	26.4
Tank height	m	4
Tank radius	m	1.45

6.3.2 Heating of digester

As summarized by Igoni et al (2008, p. 436), the heat requirements in the digester comes from (1) raising the temperature of the incoming flow to the temperature of the digester, (2) compensating for heat losses from the digester walls, floor and roof, and (3) making up for losses occurring in the piping between heat source and digestion tank. Assuming proper construction, the heat losses associated with the piping can be neglected.

As described by Zupančič & Roš (2003), The heat required to raise the temperature of the incoming suspension can be calculated as

$$Q_{sus} = \rho_{sus} * \dot{V}_{sus} * c_{psus} * (t_{sus} - t_{susO}) \qquad (2)$$

whereas the heat required for compensating for the losses is calculated by the formula

$$Q_c = k_{cout} * A_{out} * (55°C - t_{out}) + k_{cgrs} * A_{gr} * (55°C - t_{grs}) + k_{cgrw} * A_{gr} * (55°C - t_{grw}) \qquad (3)$$

The result of these calculations (see Appendix 3 and 4 for calculations and assumptions done) is that the heat required to heat the incoming suspension is 2.04 kW whereas the heat required to compensate for the losses is 0.67 kW. Assuming 24 hours of temperature rising and 24 hours of heat loss compensation per day gives a total heat requirement of Q = 65.04 kWh d^{-1}.

6.3.3 Daily biogas production

The methane production is calculated in terms of kg^{-1} VS, and as given by Table 3, the proportion of volatile solids (VS) in the microalgae is about 59.2 % of the total solids (TS). In the baseline scenario, the daily incoming rates of 120 kg microalgae do hence contain 71 kg VS, which multiplied with the methane production of 120 L CH_4 kg^{-1} VS gives a daily output of 8520 L CH_4. As 1 m^3 of methane equals 9.38 kWh (Craggs et al, 2011), and the daily methane output can be rewritten as 8.52 m^3 CH_4, the total daily energy output of the anaerobic digester is 79.9 kWh for the baseline scenario.

6.3.4 Mixing

Even though small biogas plants can operate without agitators (Deublein & Steinhauser, 2008, p. 254) and the need to provide agitation emerge first with digester capacities higher than 100 m^3 (Samer, 2012, p. 361), mixing is important in order to achieve an optimal anaerobic digestion. This as a uniformity in substrate concentration, temperature and other environmental factors is desirable. (Igony et al. 2008, p. 436)

As the reactor volume in the baseline scenario (26.4 m^3) however can be considered as small, agitation will not be considered at this point.

7 Summary of baseline data

The inventory data found in the baseline scenario has been summarized in Table 6. As the functional unit of the study is “the production of 1 MWh of biogas in a microalgae-to-biogas system”, Table 7 provides a summary of the energy flows related to the output of 1 MWh of biogas, whereas Table 8 has been used when modelling the processes in the GREET software. In Table 8, it is important to note that the flue gases and CO_2 emitted from the cultivation pond comes from recycled flue gases, which would have been emitted to the atmosphere in any case. The CO_2 utilized by the microalgae in their growth can hence be regarded as a negative emission.

When summing up the energy flows of the system, 2.17 MWh of energy was seen to be needed in order to produce 1 MWh worth of biogas. As this is more than twice as much, the energy balance for this set of process criteria can be considered negative.

Table 6. Summary of inventory data based on daily flows for a cultivated area of 1 ha

	Unit	Value
General		
Pond volume	m^3	3005
Surface area	m^2	10017
Daily biomass production yield	$g\ m^{-2}$	12
Daily productivity	kg	120
Dilution rate	%	20
Methane yield in biogas	$L\ CH_4\ kg^{-1}$	120
Retention time in anaerobic digester	d	20
Cultivation		
Solids concentration in pond	%	0.035
Flow out of pond	m^3	601
Pumping power (to cultivation)	kWh	14.4
CO_2 consumption	kg	220
Flue gases need (12% CO_2), 90% utilization	kg	2037
Flue gas pumping	kWh	5.5
Paddlewheel velocity	$m\ s^{-1}$	0.3
Power for paddlewheel mixing [1 ha]	kWh	43.7
Gravity sedimentation		
Pumping power (to settler)	kWh	14.4
Lamella separator	kWh	0.95
Recovery efficiency	%	60
Output flow of settler	m^3	12.6
Solids output concentration	%	1
Pumping power for recycled water (to mixing chamber)	kWh	14.1
Centrifugation		
Pumping power (to centrifuge)	kWh	0.3
Power consumption of dynamic settler	kWh	15.1
Flow out of centrifuge	m^3	1.2
Solids output concentration	%	10
Anaerobic digestion		
Pumping power (to reactor)	kWh	0.1
Digester volume	m^3	26.4
Heating power requirements	kWh	65.0
Biomass (in VS) added to the reactor	kg	71.0
Energy content in the biogas	kWh	79.9

Table 7. Energy flows involved in the production of 1 MWh of biogas in the selected production system

	Unit	Value	% of total energy input
Cultivation			
Pumping power (to cultivation)	MWh	0.180	8.3 %
Flue gas pumping	MWh	0.069	3.2 %
Power for paddlewheel mixing	MWh	0.547	25.2%
Gravity sedimentation			
Pumping power (to settler)	MWh	0.180	8.3 %
Lamella separator	MWh	0.012	0.6 %
Pumping power for recycled water (to mixing chamber)	MWh	0.176	8.1 %
Centrifugation			
Pumping power (to centrifuge)	MWh	0.004	0.2 %
Power consumption of dynamic settler	MWh	0.189	8.7 %
Anaerobic digestion			
Pumping power (to reactor)	MWh	0.001	0.06 %
Heating power	MWh	0.814	37.5 %
Energy content in the biogas	MWh	1	
Total energy output of system	MWh	1	
Total energy input to system	MWh	2.172	

Table 8. Material flows used for creating the GREET model

	Unit	Value	For 1 MWh
Cultivation			
Flow to sedimentation	m^3	601	7522
Flue gases need (12% CO_2), 90% utilization	kg	2037	25494
Flue gases emitted	kg	1789	22390
CO_2 emitted	kg	24	300
CO_2 absorbed by the algae	kg	220	2753
Gravity sedimentation			
Dewatered flow to centrifuge	m^3	12.6	158
Recycled flow	m^3	588.4	7364
Centrifugation			
Dewatered flow to AD	m^3	1.2	15
Discarded flow	m^3	11.4	143

The energy flows of the system have been further visualized in Figure 16, and the energy consumption can be described as:

- Paddlewheel mixing: 25.2 %
- Flue gas injection: 3.2 %
- Pumping power: 24.96 %
- Sedimentation and centrifuging: 9.3 %
- Anaerobic digester: 37.5 %

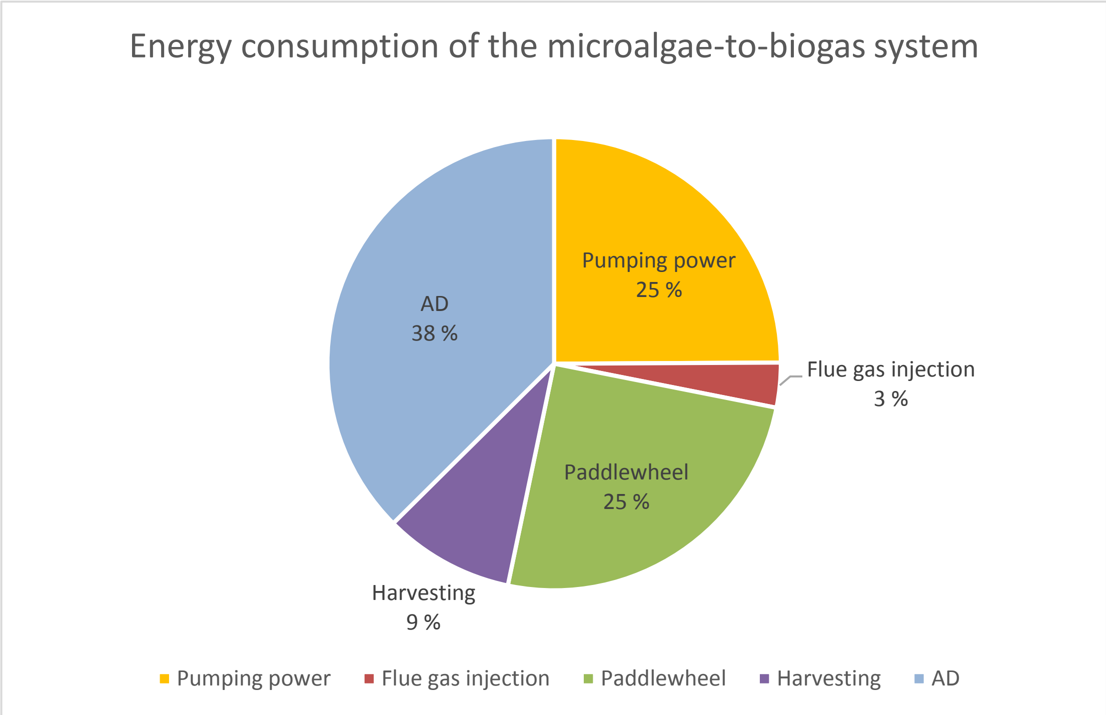

Figure 16. Percentage of total energy required by different processes

As seen, the anaerobic digester contributes to the largest share of the energy consumption, and the rising of the heat of the incoming algae suspension to a thermophilic temperature of 55 °C is energy consuming. In this study, the combustion of the biogas in a combined heat and power (CHP) unit is located outside the system boundaries, and as concluded by Zupančič & Roš (2003), the heat produced in the CHP unit would not on its own satisfy all the heat requirements of a thermophilic system. However, the introduction of heat regeneration was thought to solve the problem, which could make this an important aspect to look further into and to include within the system boundary.

The paddlewheel mixing power is seen to account for roughly 25% of the energy demand. As studies suggest that the paddlewheel velocity could be lowered at night times, this is a scenario that needs further investigation. The effect of differently sized cultivation ponds should also be further looked in to.

One way of positively affecting the system's energy balance is by increasing the amounts of produced biogas. In the baseline scenario, the actual methane production based on previous project findings was set as 120 L CH_4 kg^{-1} VS. However, this is quite low, and in similar systems, outputs in the size 280 L CH_4 kg^{-1} VS has been reached (All-gas.eu). This points to the potential of further system optimizations, and the effects of co-digestion in the digester, the using of pre-treatment methods on the algae biomass and further examination of optimal digester retention times and temperatures should therefore be looked into.

An important number not included in this study is the energy required in order to heat the greenhouse as well as the electricity needed to provide the extra light to the microalgae. These aspects need to be further investigated and included in order to obtain a realistic energy balance of a microalgae-to-biogas production facility situated in a Nordic climate.

8 GREET modelling

GREET is life-cycle model developed by Argonne National Laboratory that simulates the energy use and emission outputs of various vehicle and fuel combination and makes it possible to analyse technologies and their energy and environmental impacts over an entire life cycle, from well to wheel or from the mining of raw material to vehicle disposal (Argonne National Laboratory, 2011).

The GREET model consists of both a downloadable software (GREET.net) as well as an extensive Excel spreadsheet model including roughly 50 sheets, allowing for the simulations of more than 100 fuel production pathways (Frank et al. 2011a). One of these sheets is the Algae Process Description (APD) sheet, which makes it possible to systematically explore different algae biofuel production options (Frank et al, 2011b). In this report, the focus lies on the GREET software, which is a more graphical way of analysing different transportation fuels and vehicle technologies. The software builds on the data from the Excel model, however, it lets the user build the model by dragging and dropping elements and processes (greet.es.anl.gov/net), creating a more visual representation of the studied fuel pathway.

In the following, a brief introduction to the structure of the GREET.net software will be given. The inventory data in Tables 6-8 functions as the base for the created algae-to-biogas pathway model, and this will be further presented. Lastly, the findings and experiences of working with the GREET software will be reported, and recommendations and conclusions will be drawn regarding the software and its applicability for the project needs.

8.1 The GREET software

The GREET software is structured around five main panes, namely WTP (well-to-pump), WTW (well-to-wheels), data editors, simulation parameters and mapping (see Figure 17). Whereas the WTP allows for the immediate selection of a product and the analysis of its emissions, flow properties and resources, the WTW include specific vehicles technologies and allows the user to simulate energy and emission outputs of a specific fuel and vehicle combination according to a selected functional unit.

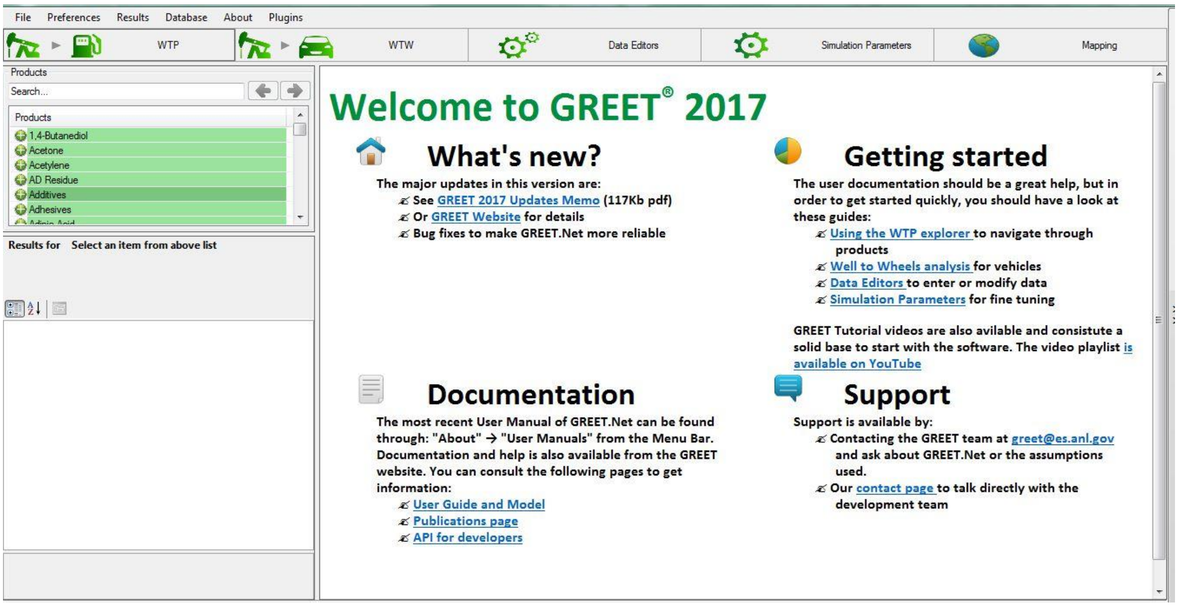

Figure 17. Landing page in the GREET.net software

The editing of the processes is done in the data editors pane (see Figure 18), and new resources, technologies, processes and pathways can also be added to the software. The processes are both stationary and transportation processes, and the editing is done by dragging and dropping resources, technologies and special items from the left-hand panes (see Figure 19) and quantifying these inputs and outputs in terms of mass or volume.

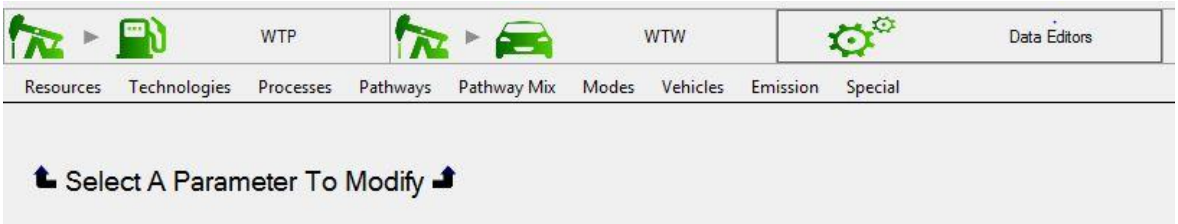

Figure 18. Editable data parameters in the GREET.net software

The simulation parameters found in the fourth pane, allows for further editing and adding of different parameters such as for example lower and higher heating values, ratios and yields which are used in the model, whereas the mapping pane enables the mapping and simulation of different user-defined scenarios of interest.

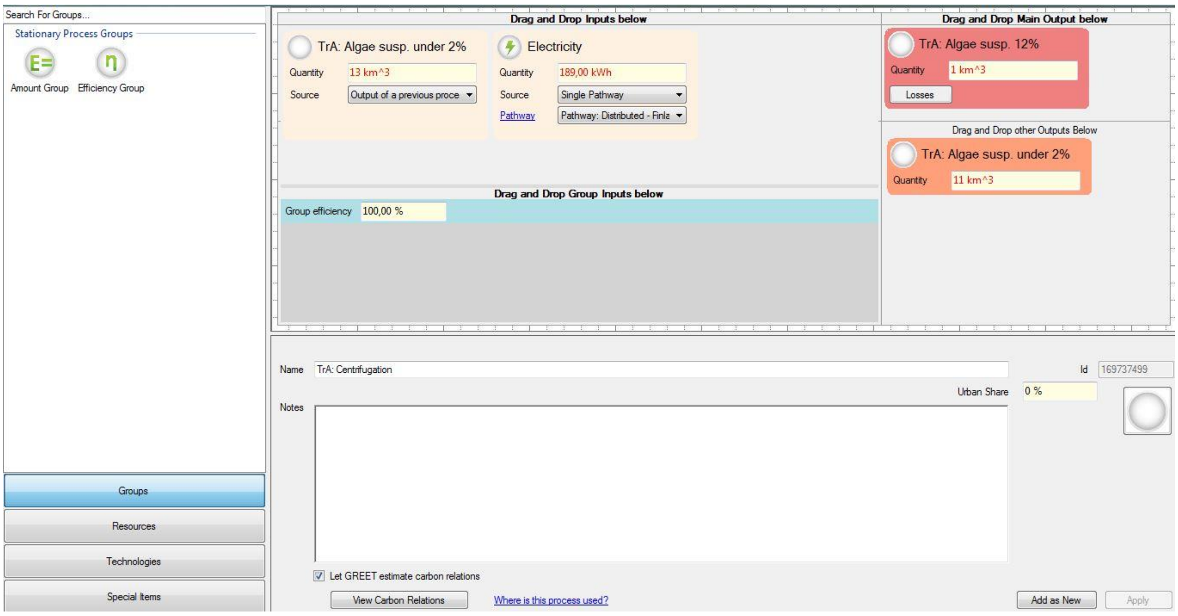

Figure 19. Process editing in GREET.net

When creating a pathway, different processes and pathways will be combined in order to recreate the process flow chart of the studied product. Figure 20 visualize part of an algae-to-renewable diesel pathway included in the GREET software, where the blue boxes stand for stationary processes and the pink for transportation. The emissions, flow properties and resources can be seen in the lower left corner for either a single process or for the whole pathway. The functional unit can be chosen, and this affects which values will be obtained.

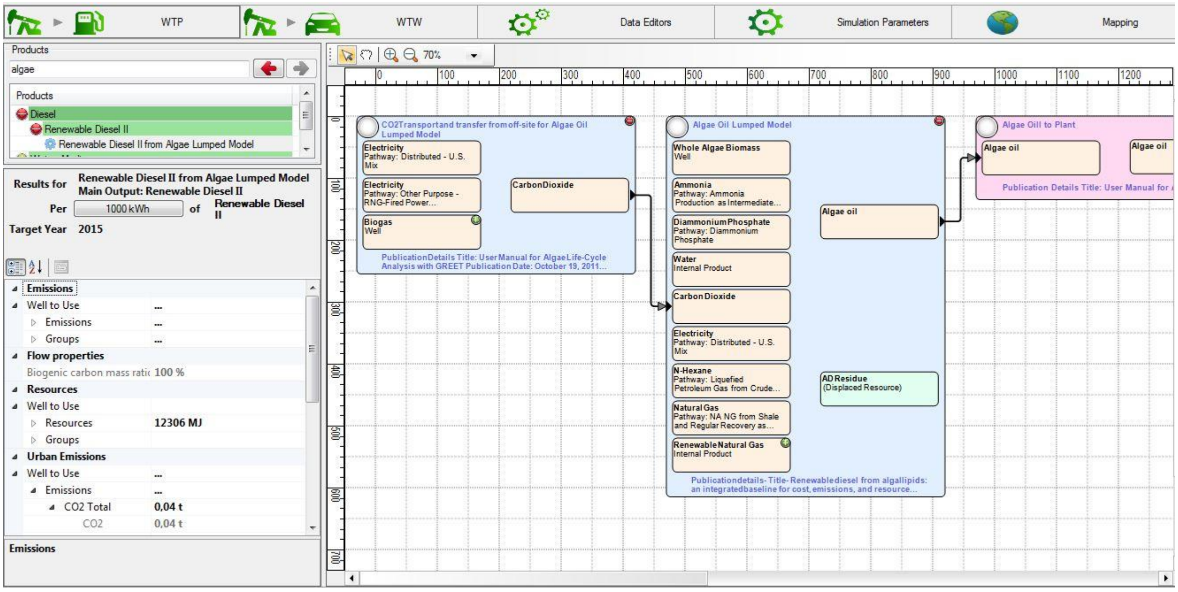

Figure 20. Parts of an algae fuel pathway included in the GREET software

8.2 Modelling of the microalgae-to-biogas production system

Originally, the thought was to mostly modify the already existing algal fuel pathway found in GREET ("Renewable diesel II from Algae Lumped model"), altering it to more suitable conditions with an output of biogas instead of diesel. However, this was easier said than done. Even though the process had references to publications from which the data had been obtained, the lumped algae oil model was complex to break down. As the inputs did differ much from the conditions defined by the project, a completely new pathway had to be created.

The inventory data obtained through the literature analysis and field examples (visualized in Table 8) stood as a base for the model, and in order to make it more transparent and easy to modify, all the process steps included within the system boundary was included as single processes in the modelled system (see Figure 21). The pathway hence included the stationary processes of cultivation, gravity settling, centrifugation and anaerobic digestion as well as the transportation processes occurring in-between.

The values were fed into the model according to the functional unit "the production of 1 MWh of biogas in a microalgae-to-biogas system".

8.3 Modelling results and conclusions

Although several attempts were made, it appears that the GREET.net software was not optimal for the modelling of the selected pathway and for handling the complex steps of the algae cultivation and harvesting. Each created process had to be manually defined according to a locked set of process and resource parameters, which did not always allow for the inserting of wished parameters. Furthermore, were there no general values for e.g. flue gas and biogas compositions to start off with and alter, which made emissions complicated to work with.

In the modelled system, water is assumed to be recycled between the sedimentation tank and the mixing chamber, this did however prove to be hard to model in the software. As the combustion of the biogas was not included within the system boundary, the opportunity to utilize the different combustion technologies was not widely used. However, as the software seem to excel when it comes to conversion technologies, the modelling of only the anaerobic digestion and the combustion of the generated biogas could be more fruitful.

As a way to compare different process options when it comes to the cultivation and harvesting, the Algae Process Description (APD) sheet found in the GREET Excel model seems like a more promising option. Even though work has not been done in the Excel model, there seem to be vast opportunities for defining single parameters, and the model includes a lot of predefined data related to the cultivation and harvesting of algae. Utilizing the outputs of the Excel model when modelling in the GREET.net software by compiling the cultivation and harvesting steps into a lumped model as seen in the "Renewable diesel II from Algae Lumped model", could therefore be a possibility. In any case is the overall recommendation of this study that the Algae Process Description (APD) sheet found in the GREET Excel should be further investigated and tried out with the inventory data obtained for the selected production system.

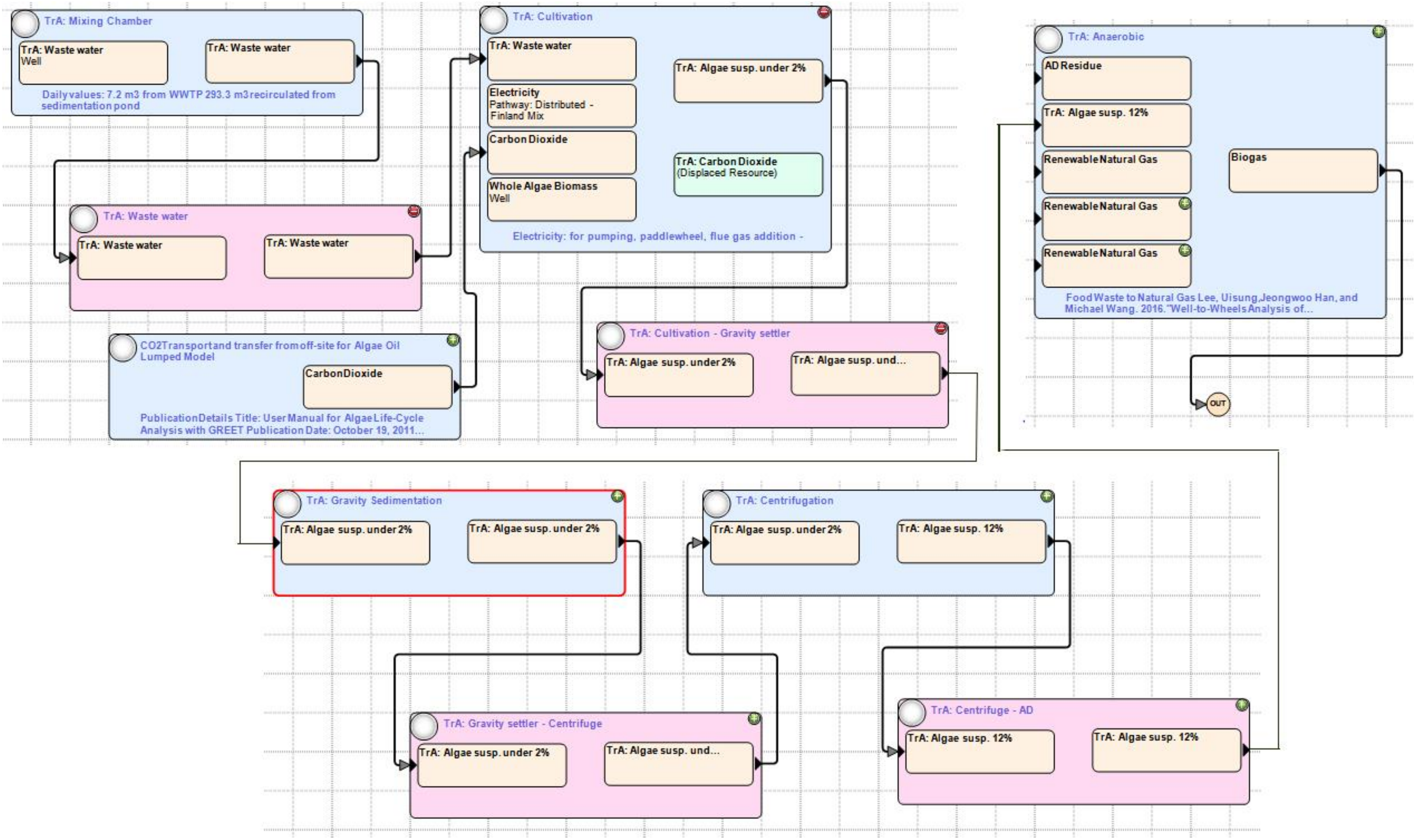

Figure 21. The microalgae-to-biogas pathway created in the GREET software

9 Discussion and conclusions

The goal of this study has been to create a model of a theoretical, full-scale algae-to-biogas production system with the help of the life cycle software GREET. This in order to provide a way in which the energy performance of different process setups can be easier analysed and understood.

Even though the software itself might not have been the most suitable for the task, the gathering of system data and the assessing of flows between the processes will still be useful for the overall understanding of the energy balance of the system. The GREET Excel sheet focusing on the modelling of algae-to-fuel processes has not been worked with in this report, but at an initial look, the model looks promising. Having already collected the inventory data for the studied system, trying out the Excel model should therefore not be too complicated and this should be the next step taken.

In this case, the microalgae will be cultivated in a Nordic environment, which requires extra heat and light inputs to the system. These energy inputs will significantly affect the overall energy balance, however, they have not been included in the baseline scenario of this study. Understanding and including these energy requirements is therefore important in order to correctly assess the energy needs of a Nordic microalgae-to-biogas system.

One way of positively affecting the system's energy balance is by increasing the amounts of produced biogas. In this report, low values have been assumed for the methane production, with 120 L of methane being produced per kg VS. For similar systems, values of more than double the size has however been reached (All-gas.eu), which points to the potential of further system optimizations. The effects of co-digestion in the digester, the using of pre-treatment methods on the algae biomass and further investigation of optimal retention times and temperatures could all be aspects contributing to this, as well as the adaption of the cultivation environment in order to meet the needs of the cultivated microalgae even better. The energy balance could also be positively affected by the integration with existing biogas plants and waste water treatment facilities.

As little data is available from large-scale algae fuel production systems, this inventory study depends on results coming from mainly pilot and small-scale systems which have been extrapolated to pond sizes and cultivations of larger scale. This extrapolate data might however not necessarily reflect the reality due to the complexity of the system and its many processes. More data from actual, large-scale models is therefore vital for the continued development of the algae-to-biofuel systems in order to overcome technical challenges and bottlenecks and make algae derived biofuels an economically feasible option on the markets.

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Appendices

Appendix 1. Weather statistics from Vaasa, Finland (63.0951° N, 21.6165° E)

	Temperature		
Months	**Normal**	**Warmest**	**Coldest**
January	-4.8°C	-2.5°C	-7.4°C
February	-5.8°C	-3.4°C	-8.6°C
March	-3.3°C	-1.0°C	-5.9°C
April	0.5°C	2.8°C	-1.8°C
May	5.4°C	8.5°C	3.0°C
June	11.0°C	14.0°C	8.5°C
July	14.9°C	17.4°C	12.6°C
August	14.4°C	16.7°C	12.3°C
September	10.1°C	12.1°C	8.2°C
October	5.4°C	7.0°C	3.7°C
November	0.9°C	2.6°C	-0.9°C
December	-2.4°C	-0.4°C	-4.5°C

Source: Yr.no (http://www.yr.no/place/Finland/Western_Finland/Vaasa/statistics.html)

Appendix 2. Technical data for gravity settler

Technical data

Evodos type 25

High separation effectiveness through Spiral Plate Technology. Separates many types of solids (abrasive, non-permeable, soft, grease). Low shear through smooth discharge mechanism. Designed for 24/7 processing and includes remote monitoring.

Capacity

- The feed pump is operated from the PLC and can be run from 250 to 4.000 liters/hour.
- The unit can discharge up to 50 liters of compressed solids per hour.

Dimensions

Dimensions of the unit, excluding the sub frame:

	Unit	Box
Height	2.179 mm	2.560 mm
Width	1.208 mm	1.570 mm
Length	1.195 mm	1.570 mm
Weight	1.600 kg	2.000 kg

Power requirements

- Evodos delivers units which are compliant to local voltage and frequency requirements.
- Standard power is 380V-480V, 50-60 Hz, 32A.
- Control voltage: 24 Volts DC.
- Drive motor: 5.5 kW (7.5 HP).

Energy requirements

- Separation: 0.95 kWh per m^3.
- Pump: 0.25 kWh per m^3.
- Discharge: 0.2 kWh with a maximum of 5 discharges per hour.

Security class

- IP55 and CE certification.

Process fluids

- The equipment is a two-phase separator, and also available as a three-phase separator.
- The standard equipment can process fluids from 5°C to 45°C.
  Optional: Capable to process fluids up to 95ºC.
- All fluid connections are 1" BSP.

Feed pump

- The feedpump is a monotype pump.
- The pump discharge pressure is max 0.2 bar.
- The feed pump is placed externally.
- The feed pump is controlled from the controlcabinet.
- The electrical wiring remains connected during transport, so it is "ready to go" upon arrival.

Construction materials

- Wet surfaces: 316L Stainless steel.
- Other metal surfaces: 304L stainless steel.
- Drum construction: Wound carbon with 316L interior.
- Siemens PLC, integrated, touch screen operated.
- External contacts for automatic start / stop and alarm.
- All seals and gaskets are made of NBR. If NBR cannot be used because of the products specifications, please contact our sales department.

Compressed air

- Pressurized air requirement: 6 bar.
- Air consumption: < 5 liter / hour.
- Connection: $^1/_4$".

Discharge

- The discharge method is electromechanical.
- The discharge time is 3 $^1/_2$ minutes.
- The discharged solids are compressed and almost free of process liquid.

Solids disposal

- The compressed solids are disposed downwards to the bottom of the machine. Optionally, the solids can be transported on a third party supplied conveyor, dropped into a container or a bin or it can be pumped.

Operations

- The process is PLC controlled.
- Remote monitoring functionality via internet.

Delivery

The standard delivery includes:

- Evodos type 25 two-phase separator, e.g. water and solids, packed in crate.
  Optional: three-phase separator e.g. water, oil and solids.
- Feed pump, which is attached with a 3 meter cable to the Evodos dynamic settler.
- 90/90 SPT vane package.
  Optional: 60/120 SPT vane package.
  Optional: Lower G-force adjustment ring.
- Power cable, 9 meter.
- One set of wear parts.

Optional delivery

- Air compressor.
- Sub frame to be placed under the Evodos.

evodos
Separation Excellence

Source:

http://www.commercialalgae.com/wpcontent/uploads/2015/06/Brochure_Type_25.pdf

Appendix 3. Heat requirements for anaerobic digester performing at 55°C. All calculations based on Zupančič & Roš (2003)

The heat required to raise the temperature of the incoming suspension can be calculated as

$$Q_{sus} = \rho_{sus} * \dot{V}_{sus} * c_{psus} * (t_{sus} - t_{susO}) \qquad (2)$$

where

	Unit	Description
Q_{sus}	kW	Heat required to heat the suspension
ρ_{sus}	kg/m^3	Density of suspension
$\dot{V}_{sus}$	m^3/s	Volume flow of suspension
c_{psus}	kJ/kgK	Specific heat of suspension, equals to the specific heat of water
t_{sus}	°C	Temperature of suspension in the digester
t_{susO}	°C	Minimum suspension temperature before entering the digester on monthly basis

As microalgae have a density close to water, water's density of ρ = 1000 kg/m^3 will be used. The volume flow of the suspension is further converted from $\dot{V}_{sus}$= 1.2 m^3/d to $\dot{V}_{sus}$= 1.39 x 10^{-5} m^3/s. The suspension is assumed to be stored indoors until pumped into the digester. A suspension temperature of t_{sus0} = 20°C is therefore used. Inserting these values into Equation 2 gives

$$Q_{sus} = 1000 \frac{kg}{m^3} * 1.39 * 10^{-5} \frac{m^3}{s} * 4.187 \frac{kJ}{kgK} * (55°C - 20°C) = 2.04 \, kW$$

Appendix 4. Heat required for compensating heat losses to air, soil and groundwater in anaerobic digester performing at 55°C. All calculations based on Zupančič & Roš (2003)

The heat required for compensating heat losses are calculated with the formula

$$Q_c = k_{cout} * A_{out} * (55°C - t_{out}) + k_{cgrs} * A_{gr} * (55°C - t_{grs}) + k_{cgrw} * A_{gr} * (55°C - t_{grw}) \quad (3)$$

where

	Unit	Description
Q_c	W	Heat loss
k_{cout}	W/m^2K	Heat transfer coefficient through walls from inside suspension to outside air
A_{out}	m^2	Digester surface from suspension to outside air
t_{out}	°C	Minimum outside air temperature
k_{cgrs}	W/m^2K	Heat transfer coefficient through ground walls from inside suspension to soil
A_{gr}	m^2	Digester surface in contact with the ground
t_{grs}	°C	Standard calculation temperature of soil (0°C)
k_{cgrw}	W/m^2K	Heat transfer coefficient from inside suspension to groundwater
A_{gr}	m^2	Digester surface in contact with the ground
t_{grw}	°C	Standard calculation temperature of groundwater (10°C)

The heat transfer coefficients are further calculated by Zupančič & Roš (2003) and follows the assumptions of digester wall structures listed in Table 9. Based on the weather statistics for Vaasa, Finland in Appendix 1, the average temperature between April and September under normal conditions has been calculated as 8.75°C, hence t_{out} = 8.75°C.

Table 9. Digester structures used by Zupančič & Roš (2003)

	From sludge to air		From sludge to soil		From sludge to groundwater	
	Thickness	λ_i or α	Thickness	λ_i or α	Thickness	λ_i or α
Inside α_{in}	–	245	–	245	–	245
Water insulation	0.005	0.6	0.005	0.6	0.005	0.6
Inside mortar	0.007	1.4	0.007	1.4	0.007	1.4
Concrete	0.3	2.33	0.6	2.33	0.6	2.33
Heat insulation	0.1	0.028	0.1	0.028	0.1	0.028
Aluminum plates	0.002	229	–	–	–	–
Outside α_{out}, α_{grs}, λ_{grw}	–	23.3	–	2.5	2	1.2
	k_{cout} = 0.265		k_{cgrs} = 0.235		k_{cgrw} = 0.181	

[a] Thickness is in (m); λ_i is in (W/mK); α is in (W/m^{2}K).

Applying area equations of the cylinder on the digester and its given dimensions (r = 1.45m, h = 4 m) results in values of A_{gr} = 3.80 m^2 and A_{out} = 26.61 m^2 (see Table 10)

Table 10. Area calculations for cylindrical tank

	Equation		**Value**
$\mathbf{A_{gr}}$	πr^2	π (1.45 m)^2	6.6 m^2
$\mathbf{A_{out}}$	$2\pi rh + \pi r^2$	2π * 1.45 m * 4 m + π (1.45 m)^2	43.0 m^2

Inserting all the given values into Equation 3 gives

$Q_c = 0.265 * 43.0 * (55 - 8.75) + 0.235 * 6.6 * (55 - 0) + 0.181 * 6.6 * (55 - 10) =$

Q_c = 666.1 W = 0.666 kW.

Hence, an average of 0.666 kW per day is required in order to compensate for the heat losses.