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ALGAE ENERGY
Final report

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Preface

This report was written during the EPS 2017 spring semester in Vaasa, Finland. The project this report was written for is Algae Energy, which is part of TransAlgae, and is executed by five international students participating in the EPS spring semester at Novia University of Applied Sciences.

This report will shortly discuss the approach, scope and management of the project. Furthermore, it will show the results of the research and calculations executed by the team about the energy balance for producing bioenergy and high value products from algae grown in a Nordic climate.

Before beginning with the report, a word of thanks goes to Andreas Willfors, who has been the supervisor of this project. Without his feedback, resources and advice this report would not have been what it is now. Other gratitude should be expressed to TransAlgae and Novia University of Applied Sciences, for providing this project and giving the facilities needed to come to these results.

Table of contents

1 Introduction

In April 2016, Interreg Botnia-Atlantica started with the project TransAlgae, a cross-border project with partners in Sweden, Finland and Norway. This project focuses on looking for solutions to include algae in a bio-based economy, striving for a fossil free future. The focus in this project is on the cultivation of algae in a Nordic climate.
Algae are considered having great potential reducing the impacts of climate change, since they can grow under conditions in which other plants might not survive, whilst still giving high yields. Also, algae can be used for many different purposes, such as food, feed, cosmetics, energy and more.

This project, Algae Energy, is part of the TransAlgae project. The aim is to give insights into the energy balance and feasibility of using algae grown in waste streams for biogas and high value products such as biodiesel or pigments for pharmaceutical applications. By investigating the state of the art, doing a systems analysis and using this research to dimension and calculate the energetic inputs, losses and outputs, an energy balance can be made which can be used for making a sensitivity analysis of the entire process. Altogether, these activities will result in conclusions about the energy efficiency of using algae for several applications in Nordic climates.

This final report was written to give insights into the results of the investigations and calculations about the complete process and the energy balance of getting energy out of algae grown in waste streams in Nordic climates. The report starts with explaining the project approach in Chapter 2 and a brief introduction of the team in Chapter 3. The basics of project management are addressed In Chapter 4, with the time management and the corporate identity. From Chapter 5 on, the results of the investigations and research will be given, starting with a literature study about the Nordic climate and a systems analysis of the process. In Chapter 6 the dimensions of the plant are calculated and the chosen system will be explained. After that, different energy balances will be given in Chapter 7, looking at different scenarios. After that, these energy balances will be improved by implementing solar panels. The final research and investigation are about the sensitivity analysis, which is done in Chapter 8. The report ends with the results and discussion in Chapter 9 and the conclusions and recommendations in Chapter 10.

1.1 System boundaries and limitations

In this section, the system boundaries of the process will be described. Also, the limitations will be mentioned that have come up during the realisation of this project.

First, the boundaries of the process of extracting biogas and high value products out of microalgae will be defined. This process starts with the cultivation part. Six ponds were placed in a greenhouse for every pond to ensure the growing of the algae. Afterwards, microalgae go to the harvesting part where it is separated from water. Devices such as a sedimentation tank and a centrifuge are used, respectively, in this step. Two different processes are possible after the harvesting part. First, if all the mass goes to the extraction step, only high value products will be obtained. If, on the other hand, all the mass goes to the transformation part, only biogas will be produced. A third scenario where half of the initial mass is converted in high value products and the other half in biogas, has also been considered. Moreover, it should be mentioned that the device for obtaining biogas is an anaerobic digester.

Finally, no other processes such as storage and transport of the biogas, or specific utilisation of the high value products were considered in this project.

Secondly, the limitations will be explained in detail. Initially, it should be commented that as the entire project is based on calculations, several assumptions have been adopted.

The region where this project is based on, being Botnia-Atlantica, must deal with the Nordic climate, specifically in Västerbotten, Nordland, Västernorrland, Nordanstig, Österbotten, Mellersta Österbotten and Södra Österbotten. For the calculations of this project, not all these regions have been considered. In the heat losses of the cultivation part, for example, the radiation has been taken from Tampere as a representative location for the Nordic climates. For a more accurate approach, the radiation of all these regions should have been measured. As not data was found for all the regions, this action has not been done.

It is relevant also that pipes during the entire process should have been considered. Due to difficulty of the calculations and the lack of data obtained in the results for each step, this part has been omitted. The result of taking these into account would have been the increase of the power input to compensate the heat losses.

In the cultivation part, the time takes for the water to cool down have also been assumed. All the calculations for the heat losses are based on this assumption. However, this reasoning will be discussed later in the report.

Another assumption is the density of the mixture of algae and water in the extraction part, as the algae concentration in the water is relatively low (0,05%). This assumption will be irrelevant for further calculations. Besides, in this part, due to the lack of similar models founded, the time the mixture of algae and water is in the centrifuge have been assumed to be one hour.

As for the extraction step, the model chosen is not specifically designed for microalgae. This assumption will be relevant if it finally cannot be used for this type of biomass.

Finally, in the transformation part where the anaerobic digester is placed, it should be considered the mixing or agitation of the biomass. Nevertheless, this has not been considered due to the uncertain shape of the digester. Besides, there are also parameters as the excessive foaming that could not be measured and therefore, considered.

2 Project approach

The overall aim of the project is to provide the client TransAlgae with an extensive, well-documented report about the production of energy and high value products out of algae grown in waste streams. After the spring semester, the project team will provide this report to TransAlgae and present it to several supervisors at Novia University with the outcome of the research and calculations about the central problem and sub-issues.

In this case, the main problem that will be addressed is:

> *What is the energy balance for the production of bioenergy and high value products from microalgae grown in Nordic climates?*

To get the answers to the main problem, several sub-issues will be addressed:

- *What could a production plant for algal biofuels in a Nordic climate look like?*
- *What is the production process for algal biogas and how does it work?*
- *What parameters have impact on the production process and how?*
- *How to calculate the energy balance?*

2.1 Project activities

To come to a complete and comprehensive report, various steps should be taken. First, desktop research about the Nordic climate and a systems analysis will be executed. This is done to get insights in what the complete process looks like and how it works. Furthermore, the insights from this research will be used in dimensioning and calculating the energy balance for the complete process. After that, energy balances can be made with the inputs from the calculations and dimensioning steps. Finally, with these outcomes a basic sensitivity analysis can be executed to give insights about which parameters have impact in the process and how big this impact is.

Every week, a meeting with supervisor Andreas Willfors will take place to discuss the progress and issues that occurred, and to give updates on the progress made.

The main deliverables for this project will be the midterm report and presentation, and the final report and presentation. For the midterm, the process and management of the project are the main focus. This will describe which obstacles occurred during the project work and how they were addressed, and what the progress of the project is until that moment. For the final report and presentation, the outcomes of the research and calculations will be presented.

2.2 Project organisation

This project has been executed by Michiel Boeren, Saskia van de Kerkhof, Alba Maqueda Mateos, Jelle Milbou and Lisette Spiering, participants of the European Project Semester at Novia University of Applied Sciences in Vaasa, Finland. The project has been supervised by Andreas Willfors, connected to Novia University and TransAlgae.

3 The team

The Algae Energy EPS group consists of five exchange students from different nationalities: Belgian, Dutch and Spanish. All the members have different skills and backgrounds. A Belbin test was executed to determine the team roles and the outcome of this test can be found in Appendix I. The team members are presented below.

Michiel Boeren
Nationality: Belgian
Age: 21
Home University: University of Antwerp
Degree Study: Civil Engineering Technology

Saskia van de Kerkhof
Nationality: Dutch
Age: 22
Home University: HAS University of Applied Sciences
Degree Study: International Food and Agribusiness

Alba Maqueda Mateos
Nationality: Spanish
Age: 22
Home University: University King Juan Carlos
Degree Study: Energy Engineering

Jelle Milbou
Nationality: Belgian
Age: 20
Home University: AP University College Antwerp
Degree Study: Energy Management

Lisette Spiering
Nationality: Dutch
Age: 23
Home University: Saxion Applied University
Degree Study: Applied Physics

Figure 1 The team members

4 Project management

Project management is a method to control a project in a successful way. A project needs structure and organisation to achieve success. That is why a successful project can be recognised by good time management, risk management and cost management. In this project, cost management was not considered because this is a research project for educational purposes.

In the next paragraphs time management and the corporate identity are discussed. MS-project was used to create a planning for this project and a brief overview of the project planning is given by a small table. Also, the work load of every team member is visualised in a graph. Second, the corporate identity of the project is given by creating a logo, a business card and a website. Finally, a movie was also made to present the project and to make publicity for the European Project Semester in general.

4.1 Time management

Time management is an important aspect when executing a project, since appropriate time management can contribute to efficient and easier (group)work. In this report, the planning of the project and the logbooks of the team will be discussed. This will give general insights in the approach, the executed work and the work load of the group.

4.1.1 Planning

For an efficient process during the project, a planning is needed to give guidance to all the team members to their activities. The planning will give an overview of which activities must be done at what time. The table below contains a shot and general overview of the activities that will be executed.

A more elaborate planning can be found in Appendix II, where the MS project planning and the Gantt-chart are given. In this, the red text represents milestones, both intern and extern.

Table 1 Planning

Date	Task	Resources
06/03/2017	Research done	JM; MB; AM; LS; SvdK
08/03/2017	Reading all other process steps	JM; MB; AM; LS; SvdK
09/03/2017	Energy Balance: general discussion of approach	JM; MB; AM; LS; SvdK
20/03/2017	Dimensioning of all devices and components	JM; MB; AM; LS
27/03/2017	Energy Balance: First EB with all parts of process + heat losses	JM; MB; AM
20/03/2017	Start writing report and conclusions	SvdK
31/03/2017	PowerPoint presentation finished	JM; MB; AM; LS; SvdK
03/04/2017	*Midterm presentation*	JM; MB; AM; LS; SvdK
04/04/2017	Discussion about feedback	JM; MB; AM; LS; SvdK
18/04/2017	Dimensioning of the other devices finished	JM; MB; AM; LS; SvdK
24/04/2017	Energy balances: All different scenarios chosen	JM; AM; LS
05/05/2017	Sensitivity analysis done	LS
05/05/2017	Energy balances calculated for the three scenarios	JM; MB
12/05/2017	PowerPoint presentation for final presentation	JM; MB; AM; LS; SvdK
16/05/2017	*Final presentation*	JM; MB; AM; LS; SvdK

During the first half of this semester, the planning was followed well. However, difficulties occurred during the dimensioning of the production plant. This resulted in a delay of this part, so it was not possible to finish a first energy balance before the midterm report. On the other hand, a buffer week was planned in the week before the midterm report, so a possibility of delay was anticipated. After the midterm report, the last dimensioning parts were finished to start with the energy balances. These parts were the lighting system, carbon dioxide supply, the extraction system, the heat losses and the anaerobic digester. The decision was made to calculate an energy balance for three different scenarios. During the second half, all the tasks where finished before the milestones, except the heat losses. There were several issues with the required values for the calculations, but these issues were solved in time. The energy consumption of the lighting system resulted in a high value, so a solution was required to cover this. Solar panels were dimensioned to cover this large energy consumption. Finally, the project was finished before the deadline according to the expectations.

4.1.2 Logbooks

Every team member should keep track of their working hours in the form of a logbook. In this logbook, there is aimed for an average of 37,5 h working hours during the semester. An overview of the hours spent on the project per team member can be seen in the graph and table below.

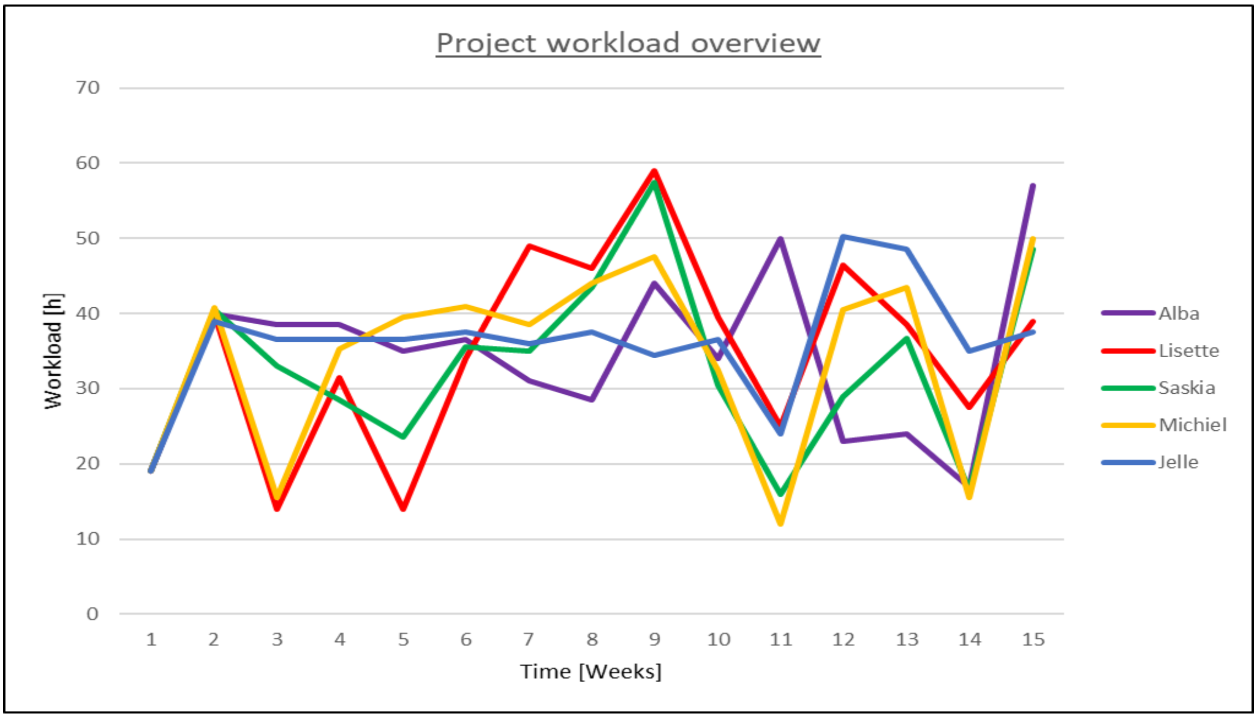

Figure 2 Project workload overview

In general can be said that the team reached their average work load this semester. Also, the team members had some inconsistencies during the semester due to traveling. To compensate these relative low working hours during these trips, extra working hours were spent during other weeks to achieve the advised average.

In general, the group work for this project has been effective and the working flow has been fluent. The midterm feedback was to improve the internal communication, which was done by discussing our findings and planning frequently. All of the group members have had an equal contribution to this project.

Table 2 Overview of time spent per week for each member

Week	Alba	Lisette	Saskia	Michiel	Jelle
1	19	19	19	19	19
2	40	40	40,5	40,75	39
3	38,5	14	33	15,5	36,5
4	38,5	31,5	28,5	35,25	36,5
5	35	14	23,5	39,5	36,5
6	36,5	34	35,5	41	37,5
7	31	49	35	38,5	36
8	28,5	46	43,5	44	37,5
9	44	59	57,5	47,5	34,5
10	34	39,5	30,5	32,5	36,5
11	50	25	16	12	24
12	23	46,5	29	40,5	50,25
13	24	38,5	36,75	43,5	48,5
14	17	27,5	16,5	15,5	35
15	57	39	48,5	50	37,5

The tables with the complete logbooks are presented as supporting material for this project. Therefore they will not be included in this report, but are provided to the supervisor.

4.2 Corporate identity

Creating a corporate identity can contribute to a complete and professional image towards the client and other parties. Therefore, a logo, business card, website and movie were created.

4.2.1 Logo

The logo includes bubbles or droplets that can be seen as algae particles, water or oil droplets, or air bubbles. This can refer to the microalgae, the oil (energy) extracted from it, or the cultivation method, being in ponds with wastewater streams. They are positioned like a stream in the shape of a half drop, that can also be considered a drop of oil. Also, the initials of Algae Energy are incorporated. Including the whole name might have been too long, and the version with only the initials could be more useful for different applications. It was agreed that this design was useful for the project. Also, some green is incorporated in the logo, referring to the algae particles.

Figure 3 Logo Algae Energy

4.2.2 Business card

The business card gives basic information about the project and the team. The colour green comes back which is in line with the green algae colour. The name of the project and the names of the team members are the most important aspects of the business card. Also, the name of the institution is mentioned as well as the location and course.

Figure 4 Business card Algae Energy

4.2.3 Website

Using wordpress.com, a website was created to keep others updated on the progress and activities of the team. On a regular basis, short blogs were posted with updates on several topics, such as the progress with midterm achievements, dimensioning and the making of the video.

The algae theme is incorporated in the style of the website, so readers easily get an idea what the project is about. The front page consists of an introduction to the team and the project, a contact page and a blog page. At the blog page, the different posts as mentioned above can be found.

The URL of the webpage is www.algaeenergyblog.wordpress.com

The front page looks as follows:

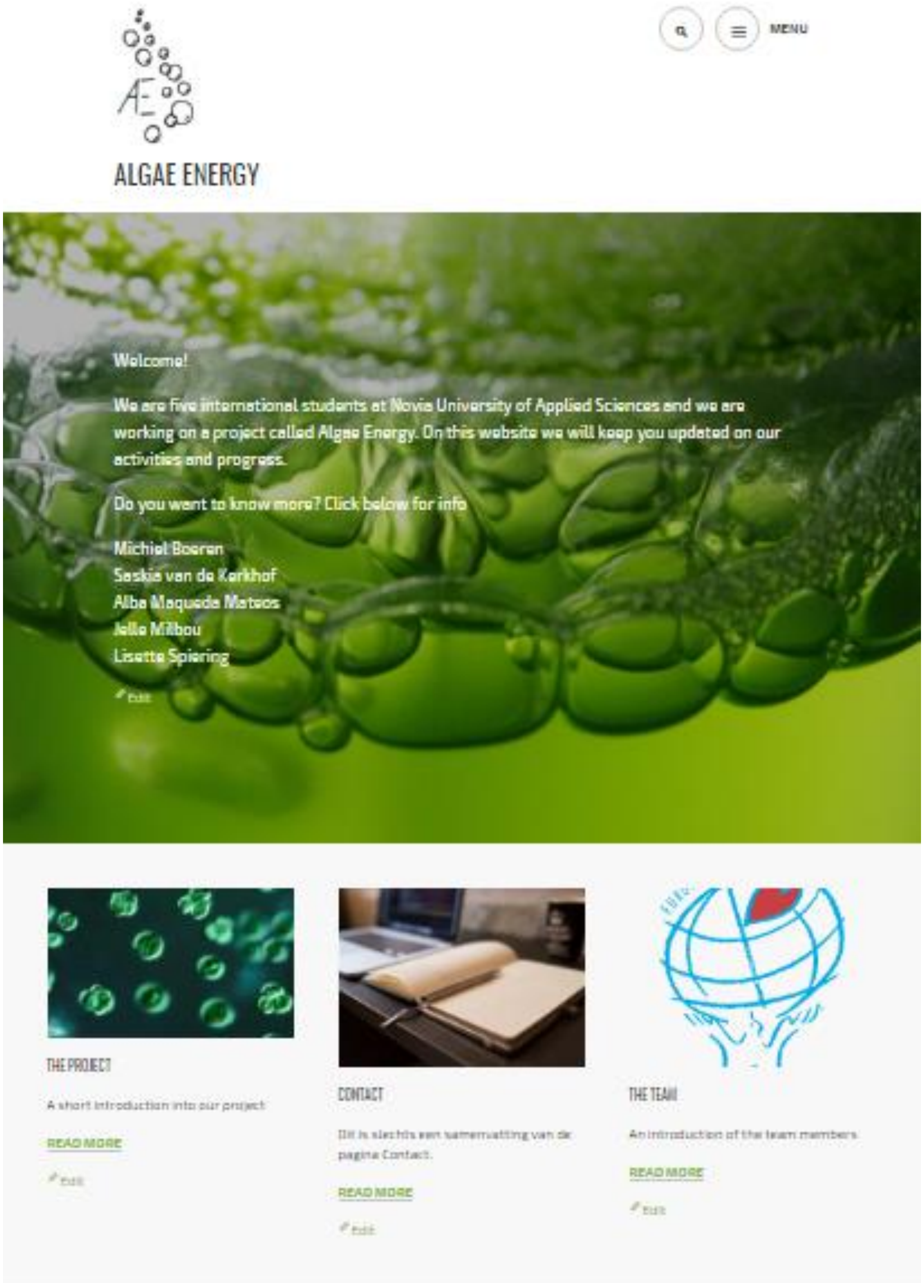

Figure 5 Website Algae Energy

4.2.4 Movie

Finally, a short movie was made about the EPS spring term which can be used by Novia to show to potential new students to market Novia-EPS. In this, the team is introduced shortly and the project is explained. Furthermore, some views of Vaasa and its surroundings are given and several photos and clips about activities in Finland are included.

5 Literature study

To get a grasp of the topic and gain knowledge that is needed for the dimensioning and calculations, a literature study was executed by the team. First, the Nordic climate was investigated since a requirement of the project is to implement the system in this climate. After that, the complete process from production, harvesting, extraction and transformation up to the upgrading was studied.

5.1 Nordic climate

The goal of this research is to get insights in the Nordic climate and to get to know the values for parameters that are important for the cultivation of algae, being the temperature and amount of light during a day.

Botnia-Atlantica, where TransAlgae is active, is a cross-border cooperation. Even though the whole area should be considered, in order to find specific data, for this research one city from each region was investigated. Below are the regions with the cities that were used.

- Västerbotten: Umeå and Storuman
- Nordland: Bodø
- Västernorrland: Sundsvall
- Nordanstig: Bergsjö
- Österbotten: Vasa (the Finnish name Vaasa will be used in the report)
- Mellersta Österbotten: Karleby (the Finnish name Kokkola will be used in the report)
- Södra Österbotten: Alavus

Figure 6 Botnia-Atlantica region (Interreg Botnia-Atlantica, n.d.)

Knowing the maximum and minimum temperature and daylight hours in this region is important for this project since these are important parameters for the cultivation. They can also have a significant influence on the final energy balance of the system.

To do the research, different climatograms were used. After the data was gathered, an overview was created using graphs to visualise the findings and draw conclusions.

5.1.1 Results

The results of the analysis of the temperature and amount of daylight in different cities in the Nordic countries will be given below. These results were used for the dimensioning of the system and calculating of the energy balance.

5.1.1.1 Temperature

The following graphs give an overview of the maximum and minimum temperatures in the cities mentioned above. The first graph shows the average maximum temperatures measured during a year in the different cities and the second graph visualises the average minimum temperatures.

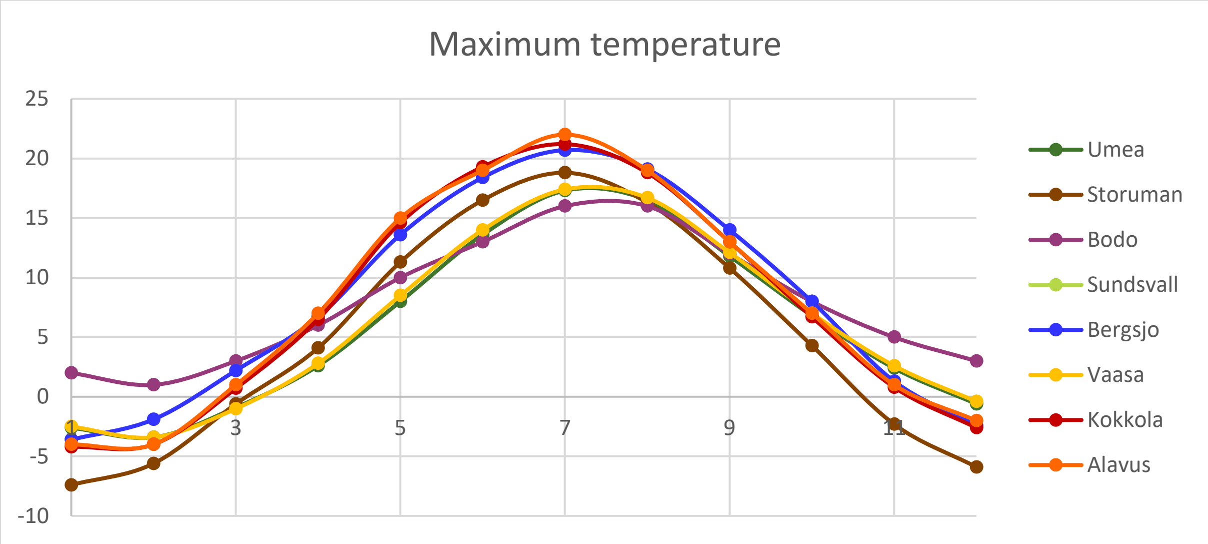

Figure 7 Maximum temperatures (Norwegian Meteorological Institute, Norwegian Broadcasting Corporation, 2017)

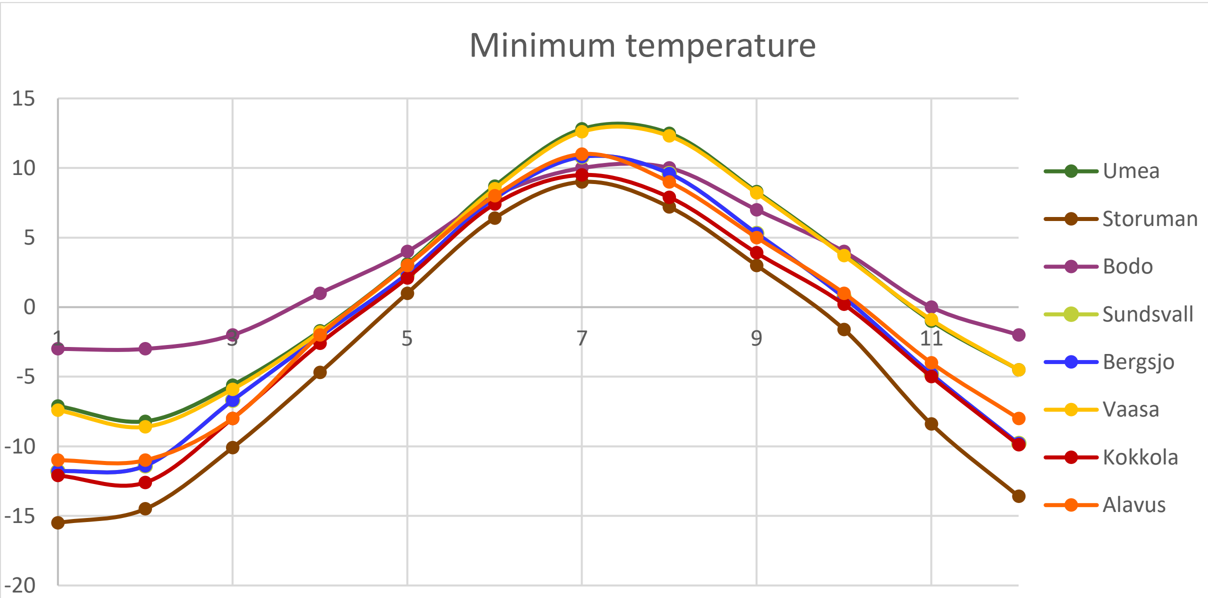

Figure 8 Minimum temperatures (Norwegian Meteorological Institute, Norwegian Broadcasting Corporation, 2017)

What can be concluded from these graphs is that the temperatures in these cities are quite the same during fall and spring, with a range of about five degrees. The differences are somewhat larger in winter and summer.

The temperature in Bodø, Vaasa and Umeå is higher than the other places during winter. The reason for this is that they are located near the sea or ocean and thus the climate is milder than in inland regions. In summer time, the sea is still cold from the winter, and since water does not heat up very fast, the spring and summer in these cities are colder. The opposite occurs in the winter, when the residual heat from the seas provides warm air in the cities, making the fall and winter slightly warmer than inland areas.

There are also differences between the cities located near the sea. The temperatures in Vaasa and Umeå are almost the same but in comparison with Bodø, they differ. Bodø is located near the ocean where there is a warm gulf stream so during sinter the temperature is higher. In the summer the temperature is somewhat lower because it is situated more northern than Vaasa and Umeå.

Storuman is a good example for a city that is situated in the outback. There are significant differences between winter and summer. Here, the temperature during winter is the lowest and during summer the temperature is the highest compared to the other cities.

In all the cities July and August are the warmest months with maximum temperatures between 15 and 20°C. Generally, the temperature in this region is below freezing point between October or November until March or April. The coldest months differ for the location each city but in general, February is the coldest for the cities close to the sea whereas January is the coldest month for inland cities.

5.1.1.2 Amount of daylight

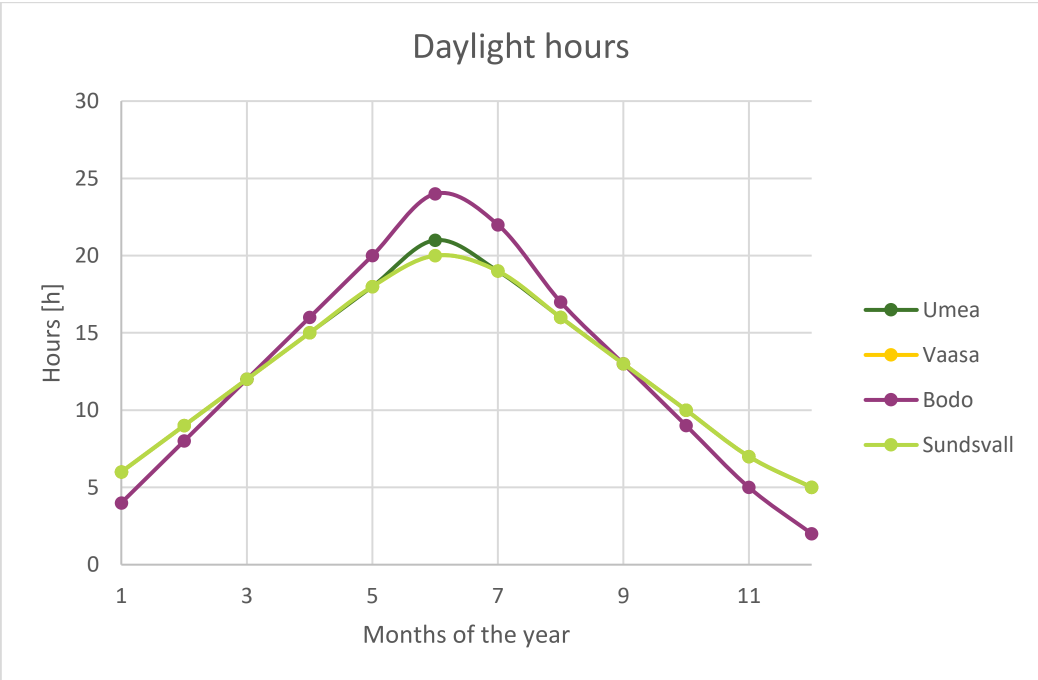

Figure 9 Daylight hours (Climate guides, 2017)

In Vaasa and Umeå the hours of daylight are almost the same because both cities are situated on the same northern latitude. Bodø has the lowest amount of daylight during winter but during summer it is light almost 24 hours per day. Sundsvall, Vaasa and Umeå have almost the same amount of daylight but only in June Umeå and Vaasa have one more hour of daylight.

5.2 Systems analysis

A systems analysis was done to study an algae biorefinery plant as a system and identify its component parts and processes. This analysis also provides information on how these parts and processes work to get to a result. The system was divided in the following processes: cultivation, harvesting, extraction and transformation. Every step has its own techniques and a choice must be made which technique is going to be used. Therefore, this systems analysis also gives insights in the pros and cons of every technique.

5.2.1 Cultivation

The next paragraphs show how a cultivation system works and which systems can be used to cultivate algae. The most important parameters for the cultivation of algae are also described.

5.2.1.1 Cultivation process

Algae is the collective name for microorganisms which consume nutrients, carbon dioxide and light and convert it into oxygen and chemical energy in the form of carbohydrates through photosynthesis. This is called autotrophic growth. These carbohydrates can further be extracted and used to produce for example algal biogas or high valuable products. Most of the algae naturally grows in water and the cultivation is often sustainable because the land on which it is produced does not compete with agricultural land. Also, it can be cultivated in poor waters.

Algae can be split up in microalgae and macroalgae. Microalgae is the most common type for cultivation and is most of the time referred as plankton while macroalgae is well known as seaweed.

In this project, the calculations are based on one specific type of algae, namely *Chlorella Vulgaris*. This was chosen because as told by the supervisor, *Chlorella Vulgaris* is one of the most commonly used types of algae. The properties of this type of algae are also suitable for the Nordic climate.

5.2.1.2 Cultivation systems

There are many existing solutions for algae cultivation systems. Each of these systems has their own advantages and disadvantages depending on the application, climate and purpose for that case. Cultivation systems can be split up in open systems and closed systems. An overview of these cultivation methods and a comparison table between open and closed systems is provided below.

Table 3 Comparison between open and closed cultivation systems

Cultivation system	Advantages	Disadvantages
Open	Low operating costs Easy maintenance Low investment cost Low risk for overheating Easy for cleaning Easy to scale up	Insufficient parameter control Large area land required High evaporation of water Low cell density in culture
Closed	High cell density in culture Low evaporation of water Good parameter control Medium/high cell density variable land is required	Expensive High maintenance cost High operating cost Cooling required Hard to scale up

As said before, algae cultivation systems can be split up in open and closed systems. The open systems can be subdivided in four frequently used techniques: open raceway ponds, shallow large ponds, tanks and circular ponds. The open raceway ponds are the most used type of cultivation. The closed systems can be subdivided in photobioreactors and fermenters. There are three types of photobioreactors: airlift, tubular and vertical column. (Barry, Wolfe, & English, 2016)

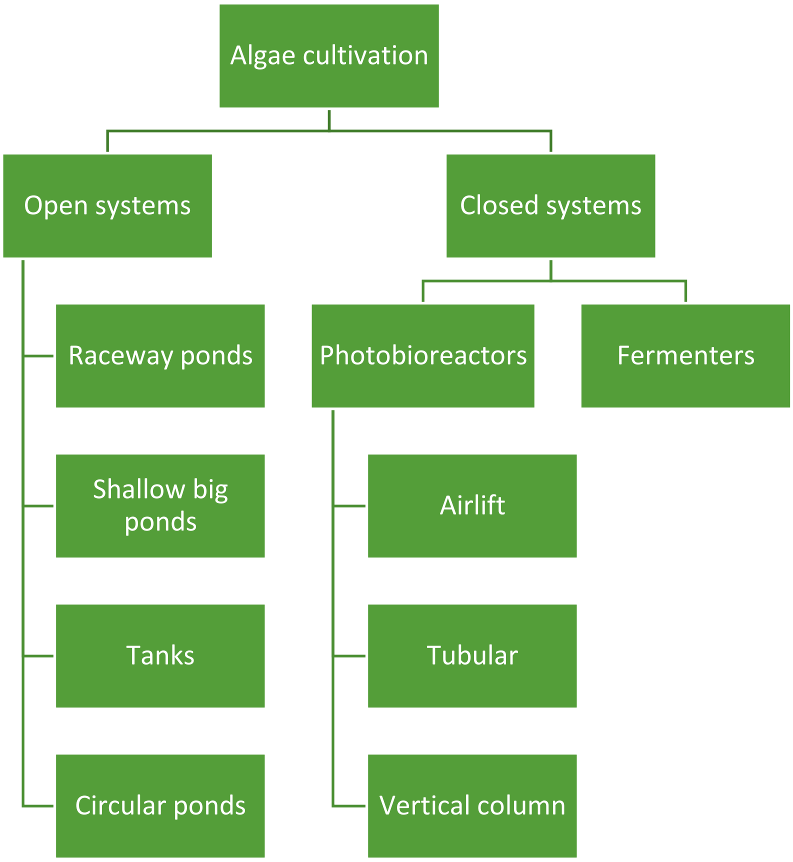

Figure 10 Overview of different algal cultivation systems

For this project, the choice was made for open raceway ponds to cultivate the algae because of their simplicity which is also supported by several scientific articles about algae cultivation. (T.J. Lundquist, 2010). They are very easy to scale up for a larger production and they have financial advantages over the other cultivation systems. The main disadvantage is the insufficient parameter control. Especially light and temperature are the bottleneck of this type of cultivation system. (Barry, Wolfe, & English, 2016) To take control over these parameters, the choice was made to make use of a greenhouses to protect the ponds. More about these greenhouses is explained in paragraph 6.1.1.6, heat fluxes in the greenhouse.

5.2.1.3 *Important cultivation parameters*

The growth of algae depends on many different parameters which can be split up into biotic and abiotic parameters. These parameters are provided below.

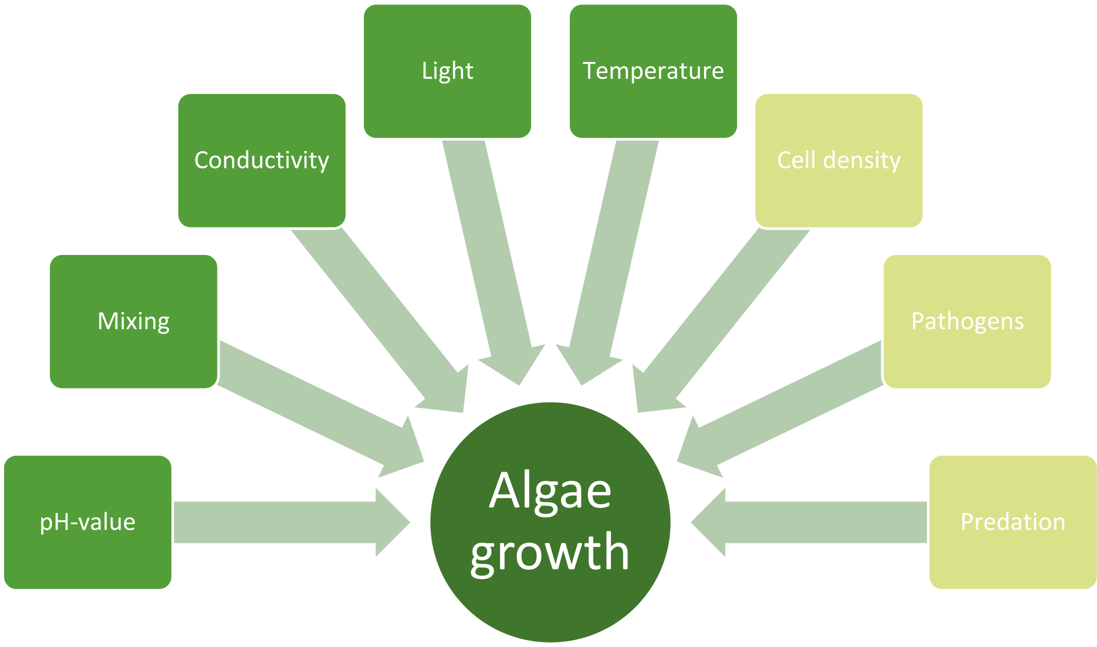

Figure 11 Important parameters that have influence on the growth of algae

The most relevant parameters are temperature and light. In general, the range temperature for algae production is between 16-27°C with an optimum between 18-24°C. The required temperature also depends on the type of algae culture. In this project, *Chlorella Vulgaris* is the used variety and 25°C is the optimum temperature for growth in fresh water. (S.P.Singh, 2015)

For light the range is between 1000 and 10000 lux. The optima are between 2500 and 5000 lux. (Barry, Wolfe, & English, 2016) Most scientific papers use another unit, namely micromole per square metre second ($\mu mol/m^2s$). The optimum range here is 100-300 $\mu mol/m^2s$. (Larissa K.P. Schultze, 2015)

Another important parameter is the pH-value which should be between 7 and 9. The optima is between 8,2–8,7. (Barry, Wolfe, & English, 2016) This parameter will not be considered further in this report.

5.2.2 Harvesting

Harvesting is the second step in the systems analysis and the aim is to separate most of the algae from the water. The process depends on the size and properties of algae strain. Harvesting can be difficult because of the small particle size of the algae. Also, a lot of energy is required to separate the algae from its medium. (Oilgae, n.d.)

Harvesting can be done in different ways with different methods. Every method has its advantages and disadvantages. It is difficult to say which method is best because it depends on the purpose of the system. The methods that can be used are flocculation, gravity sedimentation, flotation, dewatering (centrifugation) and drying. It is possible to use every method separately or combined.

When the methods are combined, the energy that is required is lower than when a single method is used.

For the project, it is chosen to combine gravity sedimentation and centrifugation as harvesting method. A disadvantage of this combination is that the centrifugation requires a lot of energy. It is important to try and improve the energy balance for this after the balance is determined. This can be done by combining other methods. (Barry, Wolfe, & English, 2016) (Mphil, August 2013) (Shelef, Sukenik, & Green, August 1984)

5.2.2.1 Gravity sedimentation

Gravity sedimentation is a process of a solid-liquid separation. This method separates the algae suspension into a slurry with a higher concentration of algae and an effluent. When the aim is to remove the particles from the suspension, there should always be a reasonable settling velocity. This settling velocity depends on the diameter of the particles, the density of the particles, density of the medium and the dynamic viscosity of the algae. The settling speed for a suspension is different for every type of algae and can be calculated with the Stokes equation. (Shelef, Sukenik, & Green, August 1984)

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

Equation 1

Where: g = Gravitational acceleration (m/s^2)

r_c = Cell radius (µm)

µ = Dynamic viscosity (Pa.s)

ρ_s = Density from the suspension (kg/m^3)

ρ_l = Density from the medium (kg/m^3)

(Weisstein, n.d.)

When the density difference between the suspension and the medium is small it is possible to have a long retention time. A solution to decrease the retention time of the sedimentation is to use inclined channels, plates or tubes. (Shelef, Sukenik, & Green, August 1984)

5.2.2.2 Centrifugation

Centrifugation is a method to separate the particles in a suspension - like with gravitational sedimentation - but the gravity is replaced by a much greater centrifugal force. This will reduce the separation time. Almost every type of algae can be separated with centrifugation.

Centrifugation can be done with different methods like a tubular centrifuge, multi-chamber centrifuges, imperforate basket centrifuge and a spiral plate centrifuge.

The spiral plate centrifuge will be used in the project calculations because it is commonly used on industrial scale.

5.2.2.3 Working spiral plate centrifuge

First, it is important to know that for a static (gravitational) settler the channel looks like the cross-section of a long shoe-box. The particles will move to bottom of the tank and the fluid moves in a continuous laminar flow through the channel. The dimensions from the tank are very important because the length of the particles' path depends on it. The longer the particles' path is, the less efficient the settler will work.

There are a few options to improve the efficiency of the settling process, for example to tilt or curve the channels so the particles will settle in one corner. As mentioned before, it is important to get a small settling distance to reach a high efficiency.

The spiral plate centrifuge has different curved channels and these channels are connected by hinges to a shaft. They form the heart of the plate centrifuge and there are many of these installed in the drum. This reduces the settling distance to 5-7mm.

To separate the particles the mass has to be rotated in the machine. All the machine parts rotate at the same speed so there is no friction between the different curved channels. In this centrifuge, it is possible to reach a centrifugal force up to 4500G. (Evodos, sd) The suspension rotates and the fluids move through the drum parallel to the main shaft, where it will flow in a laminar flow.

Under influence of the centrifugal forces the ultra-fine particles are moving towards the drum wall. After some time, the particles slurry gets thicker. This process can go further on until the bowl is half full. After this point, the machine switches to discharge mode.

In the discharge mode, the remaining fluid is pumped out and the drum slides to the 'upward' position. The drum will rotate in the opposite way as in the centrifuge mode. Under influence of this rotation the curved plates open up slightly. By an increasing counter rotation, the space between the curved plates expands so the slurry can get taken out of the bowl.

The slurry is taken out of the bowl with the drum. The drum carries a scraper and as it moves down the scraper takes the slurry off the splash screen. Then the slurry drops into a bin or on a conveyor belt under the machine that takes the slurry to another part of the system. The last step in the discharge mode is that the drum locks the curved plates back in their starting position, ready to resume the separation. This discharge cycle takes 6-8 minutes and it is fully automatic.
All from (Evodos, sd)

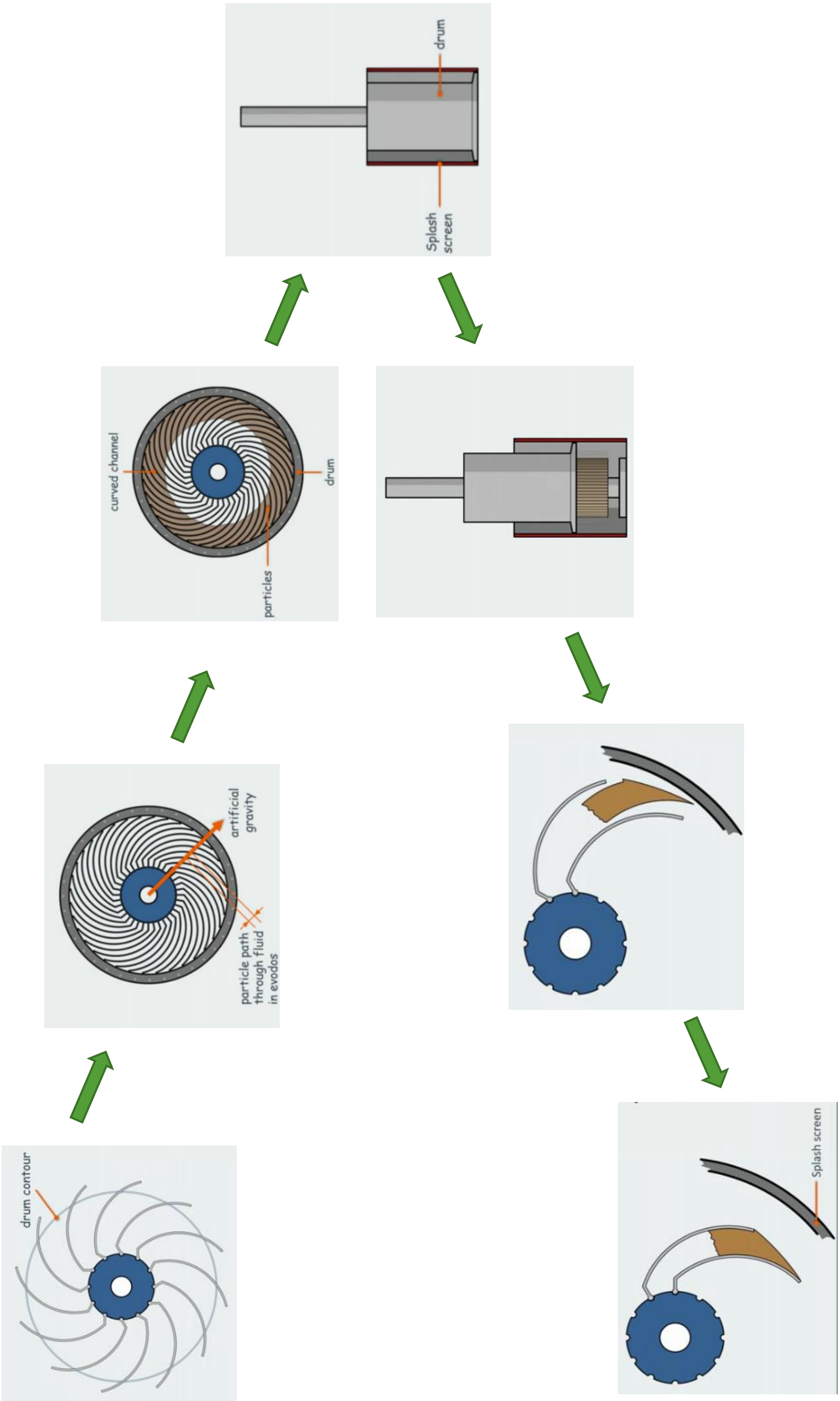

Figure 12 Centrifugation harvesting process (Evodos, sd)

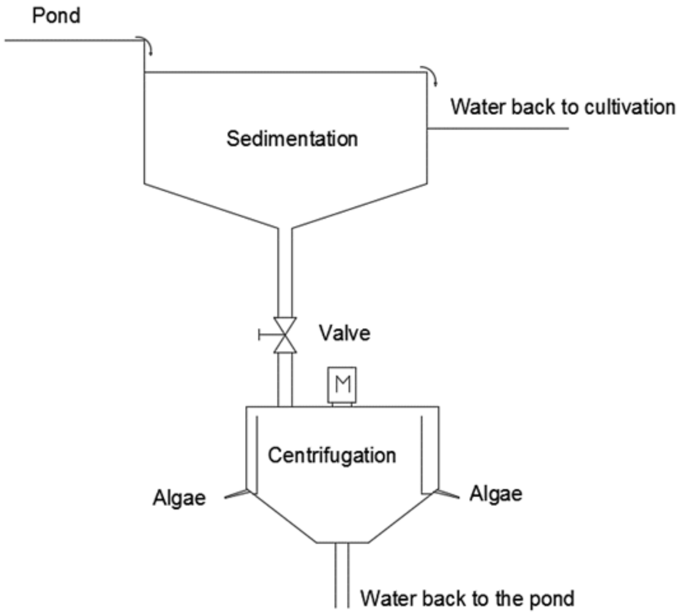

Figure 13 Option for harvesting system

The drawing above gives an option for the harvesting system. The algae suspension is pumped from the cultivation pond to the sedimentation pond. The sedimentation pond must be large enough because the whole cultivation pond is pumped in one time in the sedimentation pond and otherwise the algae would not sink easily in the water. There are two reasons that the algae do not sink easily. Firstly, the difference in density between the algae (1070 kg/m^3) and water (1000 kg/m^3) is small. Secondly, the algae need to stay close to the surface, so they can absorb more sunlight.
A solution to accelerate the sedimentation process is to add flocculants. In first instance, this method will not be used for this project but later, if needed, it might be included.

When the algae are settled down in the tank, the valve can be opened and the algae can flow into the centrifugation tank. When all the algae are in the centrifugation tank, the valve can be closed and the sedimentation can start again.

The inflow and outflow in the sedimentation tank is not continuous but it in batches. Firstly, the algae are pumped away to the centrifugation, secondly the recycled water is pumped back to a mixing tank. Finally, the sedimentation tank is filled again and the sedimentation cycle starts over. A remark for the recycled water flow is that it is not necessary to put a filter in the outflow. It is no problem if there is a number of particles and nutrients in the water because the water will be reused.

During centrifugation, the heavy particles will rotate to the border of the tank and the water will fall down in the tank. This water will flow back to the cultivation pond and the algae are captured. When the centrifugation process is finished, the slurry is removed from the centrifugation tank and transferred to the extraction and transformation.

5.2.3 Extraction

To get high value products, many components can be extracted from the algae. An overview of these components and some examples of extraction methods are given below. The practice of lipid extraction will be explained in Chapter 6.1.3.

5.2.3.1 Extraction of high value products from biomass

Many components can be extracted from algae. The major components to extract from algae are lipids, proteins and carbohydrates. (Chew, 2017)

a) Lipids

Microalgae contain a high amount of lipids. The percentage of lipids depend upon culture conditions, which can be the carbon to nitrogen (C/N) ratio. Usually, 30 to 50% of the algae will be lipids. Lipids can be extracted with solvent extraction, ultrasonic extraction, microwave assisted extraction, electroporation, osmotic pressure, isotonic extraction and enzyme extraction. Every method has its benefits and downsides. (Chew, 2017)

b) Proteins

Microalgae contain 50-70% protein, making this the largest component. Proteins can be used for human or animal nutrition. It can be extracted by centrifugation, filtration or solvent extraction. (Chew, 2017)

c) Carbohydrates

Algal carbohydrates consist of glucose, starch, cellulose and various kinds of polysaccharides. Glucose and starch can be used for bioethanol and hydrogen production. Polysaccharides are sources for biologically active molecules such as cosmetic additives, food ingredients and natural therapeutic agents. They are extracted with chemical hydrolysis. (Chew, 2017)

d) Vitamins

Algae contains high levels of vitamins. One vitamin called riboflavin can be recovered by filtering the algae under vacuum and extracting under subdued light. (Chew, 2017)

e) Polyunsaturated fatty acids (PUFA)

This component can help prevent various cardiac disorders and is becoming more attractive because marine resources for PUFA get depleted fast. There are several methods such as Bligh and dryer extraction, solvent extraction, sonication, direct saponification, supercritical fluid extraction, SC-CO_2 and SFE. (Chew, 2017)

f) Pigments

There are three basic classes of pigments: carotenoids, chlorophylls and phycobiliproteins. These are used in vitamins, cosmetics, pharmaceutical industries, food colouring agents and biomaterials. (Chew, 2017)

- Carotenoids give colour. They can be extracted using organic solvents, soxhlet extraction, supercritical CO_2 (SC-CO_2) and supercritical fluid extraction.
- Chlorophyll can also be extracted with several extraction steps with organic solvents. The use of methanol and ethanol showed to be more efficient than acetone. SC-CO_2 can be used because chlorophyll and carotenoids have a low polarity.
- Phycobiliproteins have antioxidant, antiviral, anticancer, anti-allergic, anti-inflammatory and neuro protective properties. They can be extracted with centrifugation, drying, homogenization, aqueous two phase extraction (ATPE) and repeated freeze thaw process.
- Astaxanthin are anti-aging, sun proofing, anti-inflammatory and immune system boosting. This pigment can be extracted by SC-CO_2 with a solvent such as vegetable oil.

An overview of the different products that can be extracted and the techniques is given below.

Table 4 Overview of extraction products and methods

Product	Extraction techniques	Notes
Lipids	Extraction techniques with high energy requirements, high temperatures and organic solvents	Simple, easy and environmentally friendly lipids extraction methods
Protein	Protein can be extracted using centrifugation, filtration and solvent extraction	Extraction with organic solvents maintains properties.
Carbo-hydrate	Usually extraction via chemical hydrolysis/chemical based extraction has low energy consumption,	Potential to be scaled-up and issues such as bio-toxicity, chemical cost and lipid degradation
Carotenoids	Extracted with organic solvent or supercritical fluid extraction (SFE), ultrasonication process got the highest yield	Low selectivity and excessive solvent requirements lead to SFE, anti-solvent precipitation can enhance the amount and light-related processes can promote the production
Chlorophylls	Several steps with organic solvents and the SC-CO_2 method	The SC-CO_2 method requires a temperature of 50-60°C and a pressure of 300-500 bar
Phycobiliproteins	Centrifugation, drying, homogenization and repeated freeze thaw process, a potential alternative is ATPE	
Astaxanthin	Organic solvent,	Cell disruption techniques show higher pigment production
Vitamins	Filtered under vacuum, followed by extraction of riboflavin under subdued light	Production depends on nitrogen source and concentration in the culture
Polyunsaturated fatty acids	Bligh and Dryer extraction, solvent extraction and sonication, direct saponification and supercritical fluid extraction (SFE), SC-CO_2 method yields the highest values of fatty acids, SFE technique was most effective for EPA and DHA extraction	Photobioreactors with optimal light source arrangement can enhance the production of EPA

5.2.4 Transformation

Anaerobic digestion is the process used to produce methane from microalgae. This process eliminates several of the obstacles that are responsible for the high costs associated with algal biofuels. Although, compared to the high cost of growing algae, methane production is a low-value product. Thus, an energy balance has to be calculated for this process to ensure the feasibility of it.

Co-digestion of microalgae with other feedstocks has several advantages, one of these is the increasing of the carbon to nitrogen ratio, which increases the amount of final methane produced. Another one is that proteins can be extracted to use as co-products prior to digesting. (Ramos-suárez & Carreras, 2013)

Before the anaerobic digestion process a pre-treatment step is usually done to enhance the maximum methane production. Different pre-treatments have been studied and tested. However, no pre-treatment will be done in this project. This decision will be explained in paragraph 5.2.4.2.

5.2.4.1 Microalgae in anaerobic digestion

One of the problems with the current cultivation practices is the small quantity of biomass that they are capable to produce. Microalgae, conversely, have a photosynthetic efficiency of 4-5% compared to 1-2% presented in terrestrial plants.

The following Table 5 presents an overview of the data that has been extracted for *Chlorella Vulgaris* and highlights the potential of them as a viable process for the production of biogas. This data is taken from an overview of different microalgae species, which can be found in Appendix III.

The specie used in this project and for this energy balance has been chosen to be *Chlorella Vulgaris*. They have a gas production of respectively 180-400 mL g^{-1} VS and 280-350 mL g^{-1} VS. The reason for this broad range is that same type of microalgae might have different cell compositions as well as different cell wall characteristics of the strains. (A.J. Ward, 2013)

Table 5 Methane production from the anaerobic digestion of microalgae biomass reported in scientific literature (Ward, Lewis, & Green, 2014)

Microalgae species	C/N ratio	Methane yield	Loading rate
Chlorella Vulgaris	N/R	403 mL g^{-1} VS	2 g/VS/L
Chlorella Vulgaris	N/R	286 mL g^{-1} VS	5000 mg/VS/L
Chlorella Vulgaris	6	240 mL g^{-1} VS	1000 mg/VS/L
Chlorella Vulgaris	N/R	189 mL g^{-1} VS	N/R
Chlorella Vulgaris	N/R	0,40-0,50 L	2667-6714 mg (COD)

Two different significant concepts (total solids and volatiles solids) have to be explained for a better understanding of this process. The total solids are the mass of material remaining after heating the substrate to 105ºC for one hour expressed as a percentage of the mass of the starting wet material. As for the volatile solids, they can be defined as mass of solids lost during ignition at 550ºC for two hours in a covered crucible expressed as a percentage of total solids. The matter remaining, also called substrate, results to be the organic part of the initial mass. (A.J. Ward, 2013)

Units range from gas production per grams of chemical oxygen demand (COD) destroyed, gas produced per gram of volatile solids loaded and gas produced per gram of total solids loaded.

When reporting microalgae biomass, the ash free dry weight (AFDW) or the volatile solids (VS) (digestible component) of the microalgae biomass is a percentage of the total solids and varies between species. The variation in AFDW and VS can vary up to 50% between species and can significantly affect predicting the theoretical biogas production potential for the anaerobic digestion of microalgae.

In this case, *Chlorella Vulgaris* has a percentage of AFDW and VS of respectively 90-93%. (A.J. Ward, 2013)

5.2.4.2 Problems with anaerobic digestion of microalgae

a) Low concentration of digestible substrate

For an optimal performance of the anaerobic digestion process a concentrating step is needed as it might be that the concentration of microalgae biomass is too low compared to the large volume of water. In the digester, a too diluted compound can lead to the washout of the anaerobic bacteria community.

A settling tank is often disposed after the digester, allowing a complete digestion of solids by reducing the bacterial washout when the hydraulic retention time (HTR) is lower than the solid retention time (STR) of the substrate. This tank allows bacteria and solids to settle via gravity resulting in higher conversions of biogas. (A.J. Ward, 2013)

b) Cell wall degradability and pre-treatment of algae biomass

Studies indicate that the degradation of the cell wall is strongly correlated to the amount of gas produced during anaerobic digestion. If the cell wall is not degraded enough, the microalgae may pass through the anaerobic digester without being digested hence having detrimental effects for the resulting biogas production.

Thus, a pre-treatment step is usually needed to disrupt the cell wall and increase bacterial hydrolysis before the compound enters the digester.

As for the pre-treatment step it must be said that the energy input for this process must be highly taken into account as several authors have found that the energy consumption for the pre-treatment of microalgae biomass is equal or higher than the energy gained from the microalgae in this project. Therefore, as mentioned before, no pre-treatment step will be considered for this project. (Zhang, Hu, & Lee, 2016)

c) The carbon/nitrogen ratio associated with microalgae biomass

Data reported shows the carbon/nitrogen ratio for different species of microalgae varies from 4,16 to 7,82 for microalgae species that have been investigated for anaerobic digestion.

When the C/N ratio is below 20, nitrogen is released in the form of ammonia during digestion. This leads to an inhibition in the methanogenic bacteria process and a volatile fatty acids accumulation in the digester. To overcome the low C/N ratios several studies have concluded to use co-digestion with microalgae. Waste streams or biomass can be used for this co-digestion process to increase the C/N ratio. Furthermore, the seasonal availability of the feedstock and location of production should be considered as the seasonal growth of microalgae limits anaerobic digestion to only six months of the year.

d) Lipids and microalgae

Lipids compared to proteins and carbohydrates are an attractive substrate since they have a high theoretical methane potential. However, high concentrations can also cause inhibition due to their intermediate products.

Crine et al. reported inhibition was observed for lipid concentrations of 31, 40 and 47%. (Ward, Lewis, & Green, 2014)

e) Theoretical methane production

To estimate the theoretical methane composition, Buswell and Boruff created a stoichiometric relationship that allows an approximate composition on a percentage molar basis of methane. (A.J. Ward, 2013) For this relationship, only the Carbon (C), Hydrogen (H), Oxygen (O) and Nitrogen (N) composition of a wastewater or substrate need to be known.

$$
\begin{aligned}
(C_aH_bO_cN_d) + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 \\
+ \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3
\end{aligned}
$$

Equation 2

Where a, b, c and d respectively equal the carbon content, hydrogen content, oxygen content and nitrogen molar composition.

$$\text{Methane yield (litres/g (VS) destroyed)} = \left(\frac{4a + b - 2c - 3d}{12a + b + 16c + 14d}\right) * V_m$$

Equation 3

Where V_m is the molar volume of methane or 22,14 L at 0°C and 1 atm. This Equation 3 is used to calculate the volume of methane gas depending on the number of volatile solids (VS) available in the substrate being digested.

The data shown in Table 6 illustrate the theoretical methane potential for *Chlorella Vulgaris,* utilising Equation 3 and values from literature. For comparison, the complete table with other microalgae species can be found in Appendix IV. However, Equation 3 overestimates the gas production as it assumes 100% conversion of the volatile solids to biogas and also does not consider the needs for bacterial cell maintenance and anabolism. (A.J. Ward, 2013)

Table 6 Biochemical analysis of Chlorella Vulgaris *and its theoretical methane potentials calculated from the mean carbon, nitrogen, hydrogen and oxygen values (Ward, Lewis, & Green, 2014)*

Specie	Carbon	Hydrogen	Nitrogen	Oxygen	Calculated methane potential (ml/g/VS)
Chlorella Vulgaris	52,6 ± 0,8	7,1 ± 0,1	8,2 ± 0,2	32,2	283

5.2.4.3 Inhibition of anaerobic digestion

a) Ammonia-nitrogen toxicity

Ammonia-nitrogen appears because of the biological breakdown of nitrogenous matter. Some of this nitrogen forms molecules with hydrogen which can raise the temperature or change the pH within the anaerobic digester. Those changes can lead to a drop in the gas production.

A solution to this problem can be solved by utilising a two-stage anaerobic digestion process. However, due to the lack of studies with this device and the unavailable data it will not be used in this project. (A.J. Ward, 2013)

b) Sulphur and its role in anaerobic digestion

Freshwater microalgae biomass contains low levels of sulphated amino acids and their digestion releases lower amounts of hydrogen sulphide. This hydrogen sulphide presented in gas form can be corrosive and can cause damage to machinery, such as gas engine power generators and piping. (A.J. Ward, 2013)

c) Digestion process

The whole process of digestion takes place in four steps represented in the following image. In this process, every step is done by different microorganisms. First, through hydrolysis the complex organic compounds are broken down into simpler compounds like sugars, amino acids and fatty acids. These compounds are fermented to a mixture of volatile organic acids. These chains are converted by acetogenesis to methane. Hydrogen and carbon dioxide are also liberated during fermentation and acetogenesis. Finally, methane is formed during a step called methanogenesis. An overview of the process is given in Figure 14. (R.Diltz & Pullammanappallil, 2016)

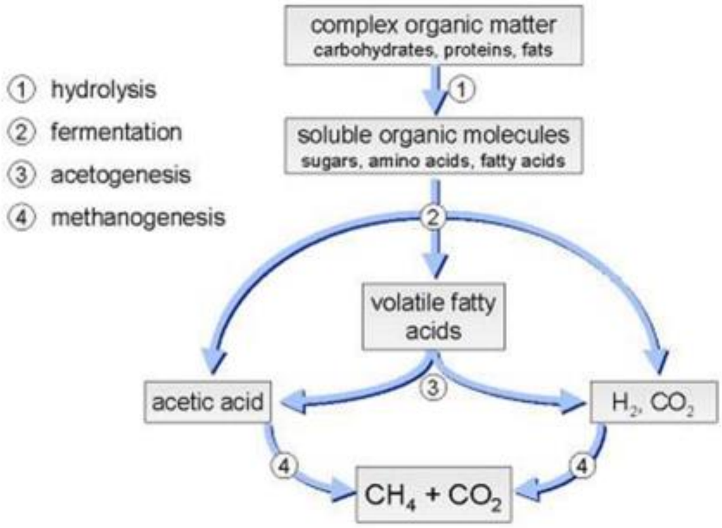

Figure 14 Pathways for mineralization of organic matter to biogas in an anaerobic digestion process (R.Diltz & Pullammanappallil, 2016)

Several factors affect the performance of the digester, but the most important one is the temperature. Biogas can be formed in the digester at different temperatures: temperature range 45–60°C is referred to as 'thermophilic,' whereas that carried out at temperature range 20–45°C is known as 'mesophilic' and at low temperatures (<20ºC) is referred to as 'psychrophilic' digestion.

5.2.4.4 Biogas

Biogas is a gas lighter than air with an ignition point of 700°C (diesel oil 350°C; petrol and propane about 500°C). The produced amount of biogas depends on many different factors during the cultivation, harvesting and transformation of the feed material, thus not a specific result of the different components can be stated. However, a rough approximation of the final biogas compositions is about 60 % methane (CH_4), 40 % carbon dioxide (CO_2) and small proportions, less than 1%, of other substances such as hydrogen sulphide (H_2S).

The methane content for different materials are: (Steffen & Szolar, 1998)

- Cattle manure ±65%
- Pig manure ±70%
- Straw ±60%
- Grass ±70%
- Leaves ±60%
- Kitchen waste ±50%
- Algae ±60%

5.2.4.5 Biogas plants

a) Integrated process

In the concentration step the supernatant is sent to the cultivation. The concentrated algae and the co-digestion material if needed, instead, go to the existing biogas plant. After that, the raw biogas is upgraded to biomethane. Finally, the CO_2 is recycled to the cultivation step as a feed material for the microalgae. (Wang, Nordlander, Thorin, & Yan, 2012)

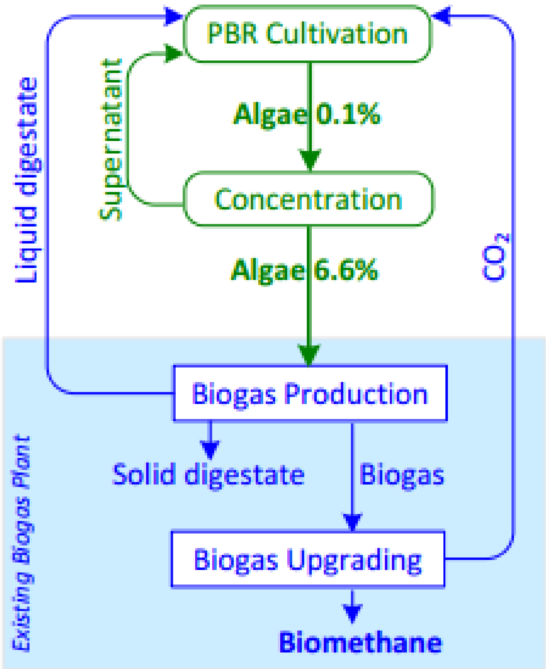

Figure 15 Process of the biogas production (Wang, Nordlander, Thorin, & Yan, 2012)

b) Feed methods

There are two different methods for feeding the digester: batch and continuous. Batch processes are filled and emptied completely after a fixed retention time. Instead, continuous processes are designed to be filled and emptied automatically and continuously through the overflow.

In this project, a batch plant will be used due to the facility of the energy balance and the current technology that presents available data only for this type of plants.

5.2.5 Upgrading

Raw biogas contains about 55-65% methane (CH_4), 30-45% carbon dioxide (CO_2), traces of hydrogen sulphide (H_2S) and fractions of water vapours. Removing CO_2 and H_2S will upgrade the biogas to natural gas quality. This will make it possible to use the biogas in the gas grid or compress it in cylinders to use it as vehicle fuel. (Kapdi, 2014)

5.2.5.1 Scrubbing CO_2 from biogas

There are a few different processes to remove carbon dioxide from gas. Separating gas components involves methods such as physical or chemical absorption, adsorption on a solid surface, membrane separation, cryogenic separation and chemical conversion. (Kapdi, 2014)

a) **Physical absorption method**
The physical absorption method is often applied because it is effective even at low flow rates that biogas plants operate at. Pressurized water is often used as an absorbent. (Kapdi, 2014)

b) **Chemical absorption method**
The chemical absorption method uses a solvent to bond chemically with the solute that is to be absorbed. It requires relatively much energy to regenerate the solvent because the chemical bonds have to be broken. (Kapdi, 2014)

c) **Adsorption on a solid surface**
Adsorption is the process where a gas component sticks to the surface of a solid material because of physical or van der Waal forces. It is performed at high temperatures and pressure. (Kapdi, 2014)

d) **Membrane separation**
Membranes are selective barriers. The gas is pressurised in this method to push it through the barrier. (Kapdi, 2014)

e) **Cryogenic separation**
Components can be separated pure and in liquid form which can be transported conveniently. The gas is cooled and compressed to a pressure around 80 bar. (Kapdi, 2014)

f) **Chemical conversion method**
Undesirable gas concentrations will be reduced to trace levels. CO_2 and H_2S are catalytically converted to methane and water. (Kapdi, 2014)

The scrubbing system will have advantages and disadvantages in its complexity and cost depending on the chosen method. The pros and cons for each method are listed below in Table 7.

Table 7 Separating CO_2 from gas techniques

Technique	What does it do?	Pros and cons
Physical absorption	Extracts CO_2 and H_2S with pressurised water	One of the easiest/cheapest methods
Chemical absorption	Reduce CO_2 from 40 to 0.5-1% with mono-ethanolamine (MEA)	regenerating
Adsorption on a solid surface	Removes CO_2, H_2S, moisture and other impurities with solids	Simple design, easy to operate, costly
Membrane separation	Extract CO_2 and H_2S with a membrane	Life time up to three years, high pressure
Cryogenic separation	Remove CO_2 by condensation and distillation	Pure liquid component, no cost information
Chemical conversion method	Convert CO_2 and H_2S to methane and water with methanation	Extremely high purity in the gas, needs much hydrogen, expensive

5.2.5.2 Scrubbing H_2S from biogas

H_2S is generally present in biogas, and concentrations vary with the feedstock. It should be removed to avoid corrosion in compressors, gas storage tanks and engines. H_2S is poisonous and corrosive as well as environmentally hazardous since it is converted to sulphur dioxide by combustion. It also contaminates the upgrading process. There are several methods to separate the H_2S from biogas. (Kapdi, 2014)

a) **Dry oxidation process**
This process is used when gas has a low sulphur content and a high purity is required. (Kapdi, 2014)

b) **Introduction of air/oxygen into the biogas system**
Sulphide is oxidised into sulphur. It is a simple and low cost process without special chemicals or equipment. (Kapdi, 2014)

c) **Adsorption using iron oxide**
H_2S reacts with iron hydro-oxides or oxides to form iron sulphide. The biogas goes through

iron oxide pellets to remove H_2S. The method is simple but regeneration releases a lot of heat. (Kapdi, 2014)

d) **Liquid phase oxidation process**
This is mainly used when a gas contains a low concentration of H_2S. It could be a physical absorption process or a chemical absorption process. (Kapdi, 2014)

e) **Using steel wool**
Biogas reacts with steel wool, creating black iron sulphide. The wool can be reused after exposure to air. (Shah Divyang R, 2016)

These scrubbing methods have their pros and cons listed below.

Table 8 Scrubbing techniques

Technique	What does it do?	Pros and cons
Dry oxidation process	Convert low contents of H_2S to (oxides of) sulphur	High quality gas
Introduction of air/oxygen into the system	Oxidise sulphide into sulphur with oxygen	Simple, low cost, overdose of air can make it explosive
Adsorption using iron oxide	Turn H_2S into iron sulphide with iron oxide pellets	Simple, lots of heat release, toxic component, sensitive to high water content
Liquid phase oxidation process	Absorb H_2S with water	High water consumption to absorb a small amount
Liquid phase oxidation process	Absorb H_2S with iron chloride	Extremely effective, most suitable in a small system
Using steel wool	Turn H_2S into iron sulphide with steel wool	Simple, low cost

6 Dimensioning

One of the aims of the project is to make an energy balance for a system that produces bioenergy and other high value products out of algae. Before the energy balance can be made, it is necessary to dimension all the different aspects of the system. This chapter will give all the calculations to dimension such a system. For this, all necessary devices and components of the processes were investigated. A system was designed and the devices and components were chosen. The dimensions of these parts were calculated in electrical power and working hours.

The calculations are divided in two main parts. First, all the process steps will be dimensioned for one pond. The process steps are divided in cultivation, harvesting, upgrading of biogas, transformation and extraction. Second, the chosen system will be explained. This paragraph will describe how the production plant works for this project. This paragraph is divided in the explanation and the argumentation of the system, and the flows that occur in this system.

6.1 Process steps

In the next paragraphs, the dimensioning is done for cultivation, harvesting, extraction and transformation. This dimensioning will determine all the aspects and size of the plant.

6.1.1 Cultivation

The cultivation system in this project contains the following parts that were dimensioned:

- Open ponds
- Flow in the ponds
- Paddle wheel
- Carbon dioxide supply
- Lighting system

6.1.1.1 Open ponds

The dimensions that are chosen for the ponds are provided below. The length, width and depth are based on the ratio of a larger pond of a study in the National Biosciences Institute in Berkeley, California. (T.J. Lundquist, 2010) In this project, the ratio of the dimensions of a larger pond was used to determine the measurements of the open raceway pond.

Table 9 Pond dimensions

Pond dimensions		Parameter
Length [m]	63	p
Channel width [m]	3	w
Pond width [m]	6	q
Depth [m]	0,3	d
Channel surface [m²]	0,9	A_c
Pond surface [m²]	406,27	A_p
Pond volume [m³]	121,88	V_p

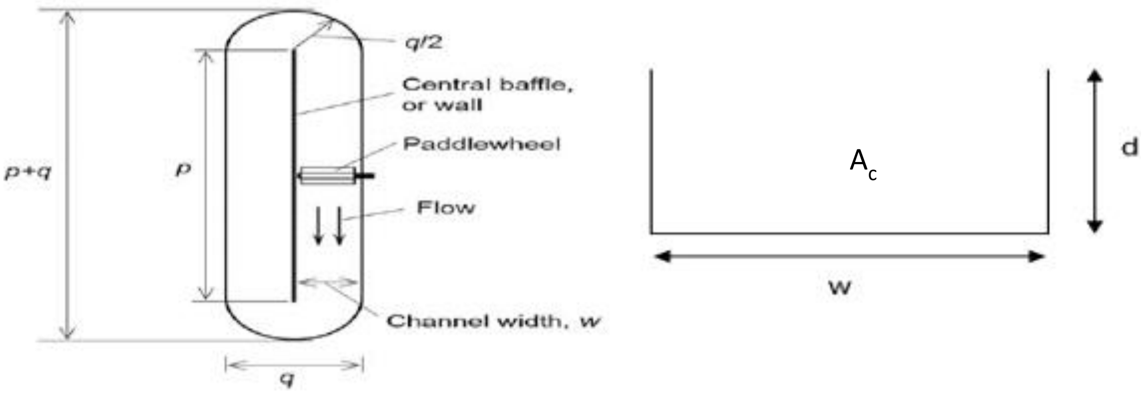

Figure 16 Technical drawing of an open pond (Chisti, 2016)

The surface of the pond is oval shaped and can be simplified as a rectangle with two circle halves. Figure 16 can be used to follow the next calculations. The calculation was done with the following equation:

$$A_p = p * q + \frac{\pi * d^2}{4}$$

Equation 4

When all values are filled out in the equation, the formula gives:

$A_p = 63m * 6m + \frac{\pi * (0.3m)^2}{4} = 406{,}27m^2$

For the volume of the pond the next equation is used:

$$V_p = A_p * d$$

Equation 5

Which gives:
$V_p = 406{,}27m^2 * 0{,}3m = 121{,}88m^3$

These results mean that one open raceway pond contains 121880 litres of water. (ρ=1000 kg/m³)

6.1.1.2 Flow in the open ponds

The flow velocity of the suspension inside the raceway pond is provided by a paddle wheel. The calculations are based on a doctoral thesis at the University of Southampton. The values for this are given in table 10. (Milledge, 2013)

The volume flow of the suspension inside the raceway ponds is calculated with the following equation:

$$q_v = v * A_c$$

Equation 6

$q_V = 0{,}2m/s * 0{,}9m^2 = 0{,}18\ m^3/s$

The next table gives an overview of the properties of this flow:

Table 10 Parameters for flows in open ponds (Milledge, 2013)

Flow		Parameter
Flow velocity [m/s]	0,2	v
Flow [m³/s]	0,18	q_v
Flow [l/s]	180	q_m

6.1.1.3 Reynolds number in raceway ponds

To determine whether the flow is laminar of turbulent, the Reynolds number must be calculated. The condition of the flow depends on the type of system and the environment. The following conditions can be used for open systems:

1. Laminar flow: Reynolds number < 500
2. Transitional flow: 500 < Reynolds number < 12500
3. Turbulent flow: 12500 < Reynolds number

The next equation is used for calculating the Reynolds number:

$$Re = \frac{v * \rho * R_H}{\eta}$$

Equation 7

With:

- Re is the Reynolds number
- v is the velocity from the suspension in the raceway ponds [m/s]
- ρ is the density of water [kg/m³]
- R_H is the hydraulic radius [m]
- η is the kinematic viscosity of water [Pa.s]

So,

$$Re = \frac{0{,}2m/s * 1000kg/m^3 * 0{,}25m}{0{,}89 * 10^{-3}Pa.s} = 56180$$

This implicates a turbulent flow, which an open raceway pond should have. The validity of the formula for an open pond is not sure and has to be assessed critically.

To guarantee that the flow velocity inside the raceway ponds remains constant, an electrically driven paddle wheel will be used. The calculation of the power of the paddle wheel is based on a paper in the Energy Biosciences Institute. (T.J. Lundquist, 2010)

The next equation is used:

$$P = \frac{9{,}8 * q_v * \rho * h_{tot}}{e}$$

Equation 8

Where:

- P is the power of a paddle wheel [W]
- 9,8 is the conversion factor [W.s/kg.m]
- q_v is the volume flow of the suspension inside the raceway ponds [m³/s]
- ρ is the density of water [kg/m³]
- h_{tot} is the total head loss in de raceway pond [m]
- e is the efficiency of the paddle wheel [%]

First, the total head loss will be calculated. This is the summation of the head loss in the bends and the friction loss. To calculate the friction loss the following equation is used:

$$h_c = v^2 * {f_M}^2 * \left(\frac{L}{{R_H}^{\frac{4}{3}}}\right)$$

Equation 9

Where:

- h_c is the friction loss [m]
- v is the velocity of the suspension in the raceway ponds [m/s]
- f_M is Manning's channel roughness factor [s/m³]
- L is the total length of the pond [m]
- R_H is the channel hydraulic radius [m]

To calculate this equation, the hydraulic radius is needed. This can be calculated with the next equation:

$$R_H = \frac{A_C}{(2 * d) + w}$$

Equation 10

When all values are filled out in the equation, next result is obtained:

$$R_H = \frac{0{,}9m^2}{(2 * 0{,}3m) + 3m} = 0{,}25m$$

With this, it is possible to calculate the friction loss in the open raceway ponds. The friction loss will be:

$$h_c = (0{,}2m)^2 * \left(\frac{0{,}015s}{m^3}\right)^2 * \left(\frac{2 * 63m}{(0{,}25m)^{\frac{4}{3}}}\right) = 0{,}0072$$

The next table gives an overview of the friction loss.

Table 11 Friction loss in the raceway pond

Friction loss		Parameter
Manning channel roughness factor [s/m³]	0,015	f_M
Friction loss [m]	0,00720	h_c

After this, the head loss in the bends needs to be calculated. The head loss in the bends can be calculated with the next equation:

$$h_b = \frac{K * v^2}{2g}$$

Equation 11

With:

- h_b the head loss in the bends [m]
- K the kinetic loss coefficient
- v the velocity of the suspension in the raceway ponds [m/s]
- g the gravitational acceleration [m/s²]

So,

$$h_b = \frac{2 * (0{,}2m/s)^2}{2 * 9{,}81m/s^2} = 0{,}00815m$$

Table 12 Head loss in the bends of the raceway ponds

Head loss in the bends		Parameter
Kinetic loss coefficient	2	K
Gravitational acceleration [m/s²]	9,81	g
Head loss in the bends [m]	0,00815	h_b

Finally, the total head loss in the raceway ponds is the summation of the losses:

$$h_{tot} = h_c + h_b$$

Equation 12

Then,

$$h_{tot} = 0{,}0072m + 0{,}00815m = 0{,}01536m$$

With the total head loss determined, the paddle wheel can be calculated:

$$P = \frac{9{,}8 * 0{,}18m^3/s * 1000kg/m^3 * 0{,}01536m}{0{,}40} = 67{,}7W$$

The paddle wheel has also the following properties:

Table 13 Technical properties of the paddle wheel

Paddle speed		Parameter
Angular speed [rad/s]	0,67	ω
Rotational speed [rpm]	6,37	n

The angular speed is calculated with the next equation:

$$\omega = \frac{v}{d}$$

Equation 13

Where:

- ω is the angular speed [rad/s]
- v is the velocity of the suspension in the raceway ponds [m/s]
- d is the depth of the pond [m]

So,

$$\omega = \frac{0{,}2\mathrm{m/s}}{0{,}3m} = 0{,}67\ \mathrm{rad/s}$$

The rotational speed is calculated with the following equation:

$$n = \frac{60 * \omega}{2\pi} = \frac{60 * 0{,}67rad/s}{2\pi} = 6{,}37\ rpm$$

The next table gives an overview of the specifications of the paddle wheel:

Table 14 Overview paddle wheel

Specifications paddle wheel	
Diameter wheel [m]	0,6
Angular speed [rad/s]	0,67
Rotational speed [rpm]	6,37
Electrical power [W]	67,7

As a conclusion of the calculations it turns out that the electrical power of the paddle wheel is very low. However, comparing the power of this paddle wheel to similar calculations of other open raceway ponds shows that the result is in line with the others. (T.J. Lundquist, 2010)

6.1.1.4 Lighting system

Lighting is a very important parameter for a steady growth of the algae culture. This light can be provided by the sun or artificial light. From an energetic perspective, it is important to use as much light from the sun as possible. According to the Nordic climate analysis in Chapter 5.1, the next table gives the amount of sunlight available in Vaasa for every month of the year. These values are based on the average hours of daylight per month.

Table 15 Hours of daylight during the year in Vaasa

Amount of daylight in Vaasa												
Months of the year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Hours of daylight [h]	6	9	12	15	18	20	19	16	13	10	7	5
Days per month	31	28	31	30	31	30	31	31	30	31	30	31
Total light per month [h]	186	252	372	450	558	600	589	496	390	310	210	155

Typical for the Nordic climate is the little number of hours of daylight during the winter months November until February. The summation of all the months gives next result:

$$Total\ number\ of\ sunlight\ per\ year = \sum total\ light\ per\ month = 4568\ h$$

If this amount is compared to the total number of hours in a year, being 8760 hours, a percentage of sunlight throughout the year can be calculated:

$$Sunlight\ per\ year\ [\%] = \frac{Total\ number\ of\ sunlight\ per\ year}{Hours\ per\ year} = \frac{4568\ h}{8760\ h} = 52\%$$

This would mean that of the total time, the system needs 48% artificial light. This is a significant number of time that the lighting system should operate. It can be about 15% more efficient to choose for less months to operate the production plant. The months March until September were chosen, because their number of sunlight per month is higher than 300 hours. Also, during the months October until February maintenance must be done to ensure a well-working system. Because maintenance can be done during the darkest months of the year, this is a good opportunity to revise the whole production system. The percentage of sunlight from March until September is:

$$Sunlight\ per\ period\ [\%] = \frac{3765\ h}{5140\ h} = 67\%$$

With a percentage of 67% sunlight during this period, the system only needs 33% artificial light of the time. The greenhouse ponds will be provided with LED lamps on the sides of the ponds. Typical for algae cultures is that they need a light irradiance between 100-300 µmol/m²s. (Larissa K.P. Schultze, 2015) In paragraph 6.1.1.1, the surface of one pond is calculated. With this surface, the total required light irradiance per pond can be calculated:

$$Total\ irradiance = 100\ \frac{\mu mol}{m^2.s} * 406{,}3m^2 = 40627\mu mol/s$$

Algae cultures need a special type of lighting, called assimilation lighting. (Bruce, 1990) This type of light is specifically used to grow plants. Especially during the winter months this type of lighting provides a steady grow for the algae culture. A choice was made for the Greenpower LED production module of the manufacturer Philips. This LED module has all the requirements which are necessary for a steady cultivation of the algae culture. The following table gives a compact overview of the properties of the LED. (Philips, 2017) The full datasheet can be found in Appendix VII.

Table 16 Lighting properties of the Philips Greenpower LED module

Lighting specifications	
Product Name	GP LED production DR/B 120 LB
Type	LED
Power [W]	23
Photon flux [µmol/s]	50
Dimensions [mm]	123x4x4
Lifetime/lamp [h]	25000

With the required amount of irradiance, being 40627 µmol/s and the Photon flux per LED module, being 50 µmol/s the number of LED modules can be calculated:

$$Number\ of\ LED\ modules = \frac{Total\ irradiance}{\frac{Photon\ flux}{LED\ module}} = \frac{40627\ \mu mol/s}{\frac{50\ \mu mol/s}{LED\ module}} = 813$$

At first sight, it can be concluded that the ponds require a very high number of LED modules. However, the result is reasonable because of the high irradiance per square metre. The power required per pond is then:

$$Power = \frac{Power}{LED\ module} * number\ of\ LED\ modules = \frac{23\ W}{LED\ module} * 813\ = 18{,}7\ kW$$

This 18,7kW needs to be multiplied by six ponds for a total of 112,2 kW for the whole production plant. The total energy consumption on yearly basis can now be calculated. The operating hours of the lighting system, which are calculated on the previous page, are 1685 hours.

$$Energy\ consumption = Total\ power * operating\ hours = 112{,}2\ kW * 1685\ h = 189047\ kWh$$

A very high amount energy is needed for operating the lighting system. This accounts for the largest part of the energy balance and can thus be the cause of a negative energy balance. Although this number of lamps is required, the energy consumption needs to be reduced. An innovative solution can be to place solar panels next to the cultivation ponds. The panels will produce electrical energy that can be used for the lighting system. In this way, the energy consumption of the lighting system can be reduced and in an environmental friendly way with the use of solar panels. To approve this solution, calculations are required to know if this is feasible or not.

6.1.1.5 Flue gases

Global warming is a widely-discussed topic nowadays. Fossil fuel combustion, transport and heating are the major factors which cause CO_2 emission on the planet. There are several solutions for this climate issue and cultivating algae can be one of them. An important advantage of algae is that they use carbon dioxide to grow. This makes a favourable impact on the climate. Algae can be transformed into biogas, or other biofuels by distillation out of the cultivated algae particles. Biofuels are essentially carbon-neutral because the carbon emitted during combustion had just recently been absorbed by the algae. This means that the net CO_2 emission is the same as if the algae had never been grown. That is why biofuels can replace fossil fuels to reduce the fossil CO_2-emission to the atmosphere.

In this project, a choice was made for the carbon dioxide delivery. There were two options available:

- CO_2 delivery from the industry, in the form of flue gases
- Making use of the carbon dioxide from the upgrading of the biogas plant

The decision was made to make use of flue gases to provide the raceway ponds with carbon dioxide. These flue gases can come from the industry, for example by a CHP-plant outside the system boundaries. The reason for making use of flue gases is based on both an environmental and an economic perspective, which could thus be a sustainable option.

First, the CO_2 emission of the industry in the form of flue gases is one of the main causes of global warming. If this emission can be used for cultivating algae, air pollution can be decreased. Second, companies must pay for every kilogram of carbon dioxide emission due to the carbon credit system. This system gives countries or companies the right to emit certain greenhouse gases or other harmful gases. It deals with the emission of gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and nitrogen oxides (NO_x). If the number of rights is limited, it becomes expensive for companies to emit these gases, which should lead to greening of the production process and investments in renewable energy. (European commission , 2017) So, when the raceway ponds in this project can be provided by these flue gasses, the emission of a certain company is reduced. This means that this company must pay less compared to when they do not provide these cultivation ponds with CO_2.

6.1.1.6 Heat fluxes in the greenhouse

For the energy balance of the cultivation part some heat calculations have to be done. First of all, it must be said that due to the complexity of the energy balance and the lack of data available for this specific scenario some assumptions have been made. Those assumptions and its correspondent justification will be explained in this section.

For a complete and an exhaustive energy balance all the flows represented in the next image must be taken into account. However, as it was mentioned before some fluxes will be omitted.

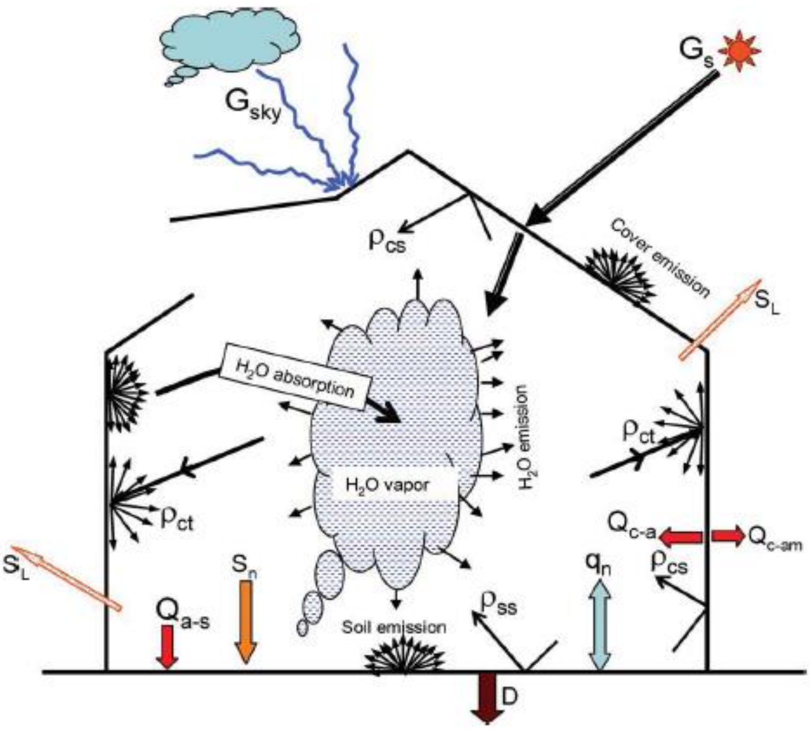

Figure 17 Schematic diagram of different modes of energy exchanges in a greenhouse (Ahmed M. Abdel-Ghany, 2005)

Starting with the energy balance of the greenhouse in the cultivation part, only three fluxes will be included. The energy of the rest of them is negligible and thus they will not make a significant difference in the final result. Those three fluxes have been chosen to be:

- The heat from the heater. The water where the microalgae are cultivated needs to be heated. Therefore, a heater is disposed on the bottom of the pond.
- The heat from the sun, including both heat transfer mechanisms, radiation and convection. The radiation flux is the result of the energy given to the surface of the greenhouse from the sun. The convection flux, instead, is the result of the heat transfer from the outside air to the exterior surface of the greenhouse.
- The heat losses from the greenhouse to the outside. As the inside of the greenhouse is warmer than the outside, some energy will be lost in this process. This energy is calculated

by the sum of the energy transfer through the water to the inside of the greenhouse (air) plus the energy lost on the convection from the greenhouse to the glass plus the heat transfer through the glass to the outside air.

The system in which the energy balance will be done was chosen to be the greenhouse, a closed system. The boundaries of the greenhouse are the glass that isolates the cultivation of the microalgae from the outside and the heater in the bottom of the pond.

The aim of this section is to calculate the energy losses during the cultivation of *Chlorella Vulgaris*. Also, it is needed to know how much power the heater needs in order to get a suitable temperature for growing the algae.

For the calculation of the energy losses an approach through resistances has been chosen. This analysis is a simple but accurate way of measuring the flux lost during the cultivation of the algae in a greenhouse.

For the first part then, it must be said that five resistances should be defined: (A.Çengel, 2003)

- $\mathrm{R_{out,air}}$ is the thermal resistance from the outside air to the outside surface of the glass
- $\mathrm{R_{glass}}$ is referred to the thermal resistance through the glass
- $\mathrm{R_{in,air,gl}}$is the thermal resistance from the inside surface of the glass to the inside air
- $\mathrm{R_{in,air,wt}}$ is the thermal resistance from the inside air to the water
- $\mathrm{R_{water}}$ is referred to the thermal resistance of the water

Heat loss is quantified by the thermal resistances. The thermal resistance, usually expressed in S.I. units of W/m^2.K, measures the opposition of the heat flux density through a given structure divided by the difference in environmental temperatures on either side of the structure in steady state conditions. (Yunus A. Çengel, 2011)

4 of the 5 previous resistances are calculated similarly. Starting with those, they are defined as:

$$\mathrm{R_{out,air}} = \frac{1}{h_{out,air}}$$

$$\mathrm{R_{in,air,gl}} = \frac{1}{h_{in,air}}$$

$$\mathrm{R_{in,air,wt}} = \frac{1}{h_{in,air}}$$

$$\mathrm{R_{water}} = \frac{1}{h_{wt}}$$

Where:

- $\mathrm{h_{out,air}}$ is the convection coefficient of the outside air [W/m^2.K]
- $\mathrm{h_{in,air}}$ is the convection coefficient of the insideair [W/m^2.K]
- $\mathrm{h_{wt}}$ is the convection coefficient of the water [W/m^2.K]

The convection coefficients above have been determined based on Fundamentals of Thermal-Fluid Sciences. (Yunus A. Çengel, 2011) Also, an average of the values was calculated due to the wide range of each coefficient. Therefore,

$$h_{out,air}\ (\text{summer}) = 75 \frac{W}{m^2.K}$$

$$h_{out,air}\ (\text{winter}) = 200\ \frac{W}{m^2.K}$$

$$h_{in,air} = 12\ \frac{W}{m^2.K}$$

$$h_{wt} = 500\ \frac{W}{m^2 \cdot K}$$

According to the research done in this project about the Nordic climates at least two scenarios have to be considered for the energy balance. These scenarios represent the changes in the coefficient factor outside the greenhouse in summer and in winter.

Replacing the values in the missing parameters, the solution values for each resistance are:

$$R_{out,air,summer} = \frac{1}{h_{out,air}} = \frac{1}{75\ \frac{W}{m^2 \cdot K}} = 0{,}0133\ \frac{m^2 \cdot K}{W}$$

$$R_{out,air,winter} = \frac{1}{h_{out,air}} = \frac{1}{200\ \frac{W}{m^2 \cdot K}} = 0{,}005 \frac{m^2 \cdot K}{W}$$

$$R_{in,air,gl} = \frac{1}{12\ \frac{W}{m^2 \cdot K}} = 0{,}0833\ \frac{m^2 \cdot K}{W}$$

$$R_{in,air,wt} = \frac{1}{12\ \frac{W}{m^2 \cdot K}} = 0{,}0833\ \frac{m^2 \cdot K}{W}$$

$$R_{water} = \frac{1}{500\ \frac{W}{m^2 \cdot K}} = 0{,}002 \frac{m^2 \cdot K}{W}$$

As can be seen, both thermal inside air resistance factors ($R_{in,air,gl}$ and $R_{in,air,wt}$), are the same. That is because these resistances depend on the coefficient factor of the inside air, which is the same for both. The coefficient factor, at the same time, depends on the amount of movement of this gas which is the same for both. However, both resistances should be considered.

For the resistance of the glass a different approach has to be done. That is because the heat transfer method through this material is not convection, like the others. The heat transfer through solids is called conduction. For this specific mechanism, the resistance is found as follows: (Yunus A. Çengel, 2011)

$$R_{glass} = \frac{d}{k} = \frac{1}{U}$$

Equation 14

Where:

- d is the thickness of the glass [m]
- k is the thermal conductivity of the glass [W/m.K]
- U is the heat flux density [W/m^2.K]

For obtaining the U-value several data have been researched. First of all, in heat transfer analysis through solids some factors have been taken into account. For the facility of the description the next image by Pilkington Co. was used:

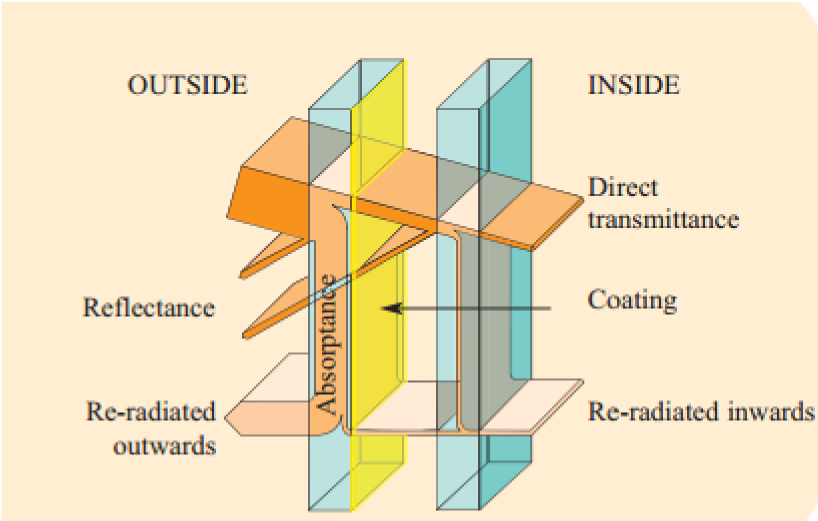

Figure 18 Insulating glass unit incorporating coated solar control glass (Pilkington, 2010)

Thus, parameters like the reflectance, the absorbance and the transmission are significant to determine the amount of energy the glass can transmit inside the greenhouse, and thus the amount energy lost or stored in this structure.

The glass that has been chosen has a thickness of 6mm. It is a double glass and it is called K Glass. According to Pilkington Co., this glass has the following properties:

glass configuration				performance code			light				energy						
II	II	II	III	W/m²K	%	%	%	%	%	–	%	%	%	%	–	–	–
				U	LT	g	LT	LRo	LRi	Ra	ET	ER	EA	TET	SSC	LSC	TSC
insulating glass unit, primary product outside #2	insulating glass unit, Pilkington K Glass™ #3	insulating glass unit, Pilkington K Glass™ #2+3	triple insulating glass unit, Pilkington K Glass™ #2+5	U value	light	energy	transmittance	reflectance outside	reflectance inside	colour rendering index	direct transmittance	reflectance	absorptance	total transmittance	shortwave shading coeff.	longwave shading coeff.	total shading coefficient
⇨				1,5	75	67	75	16	18	99	60	14	26	67	0,69	0,08	0,77
	⇨			1,5	75	72	74	18	16	99	60	16	24	72	0,69	0,14	0,83
		⇨		1,3	69	64	69	19	19	98	54	16	30	64	0,62	0,12	0,74
			⇨	1,0	63	58	63	23	23	98	46	19	35	58	0,53	0,14	0,67

Figure 19 Energy and light properties of K Glass (Pilkington, 2010)

The main parameter valuable for this analysis is, as said before, the U-value. Therefore, as can be seen, for a thickness of 6mm the U-value results to be 1,5 W/m^2.K. This table already considers all the factors needed for the analysis, which facilitates the approach taken.

As a result, the resistance needed through the glass is:

$$\mathrm{R_{glass}} = \frac{1}{1{,}5\ \frac{W}{m^2 \cdot K}} = 0{,}667\,\frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}$$

The total is needed for the energy balance. This total resistance is the sum of each resistances previously calculated. Both scenarios, summer and winter, will also be considered. Therefore:

$$\mathrm{R_{total}} = \mathrm{R_{out,air,summer}} + \mathrm{R_{glass}} + \mathrm{R_{in,air,gl}} + \mathrm{R_{in,air,wt}} + \mathrm{R_{water}}$$

Equation 15

$$\mathrm{R_{total}} = \mathrm{R_{out,air,winter}} + \mathrm{R_{glass}} + \mathrm{R_{in,air,gl}} + \mathrm{R_{in,air,wt}} + \mathrm{R_{water}}$$

Equation 16

Substituting:

$$\mathrm{R_{total,summer}} = 0{,}0133\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}} + 0{,}0833\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}} + 0{,}0833\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}} + 0{,}002\,\frac{\mathrm{m^2 \cdot K}}{\mathrm{W}} + 0{,}667\,\frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}$$

$$\mathrm{R_{total,winter}} = 0{,}005\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}} + 0{,}0833\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}} + 0{,}0833\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}} + 0{,}002\,\frac{\mathrm{m^2 \cdot K}}{\mathrm{W}} + 0{,}667\,\frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}$$

$$\mathrm{R_{total,summer}} = 0{,}849\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}$$

$$\mathrm{R_{total,winter}} = 0{,}840\,\frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}$$

Because the cultivation of the algae will be done from March to September, an average of the total resistance needs to be calculated. As the convection factors for each month for specific locations have not been found, it can be assumed without much error that the average for these seven months can be calculated from the average of when the temperature is the highest and the lowest, that is, respectively, for summer and winter. Therefore,

$$\mathrm{R_{total,average}} = \frac{0{,}849 + 0{,}840}{2} = 0{,}844\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}$$

According to the equation of heat transfer which can be found in any heat transfer book, the heat flux through a structure like a greenhouse is the following: (Yunus A. Çengel, 2011)

$$Q = \frac{A}{R} \cdot \Delta T$$

Equation 17

Specifying for this case:

$$Q_{losses} = \frac{A_{greenhouse}}{R_{total}} \cdot (T_{water} - T_{out,air})$$

Equation 18

It is needed then to determine the area of the greenhouse glass. On the cultivation section this area was calculated. Thus, taking this value:

$A_{glass} = 650{,}305\ m^2$

The shape of the glass of the greenhouse is visualised in the next figure.

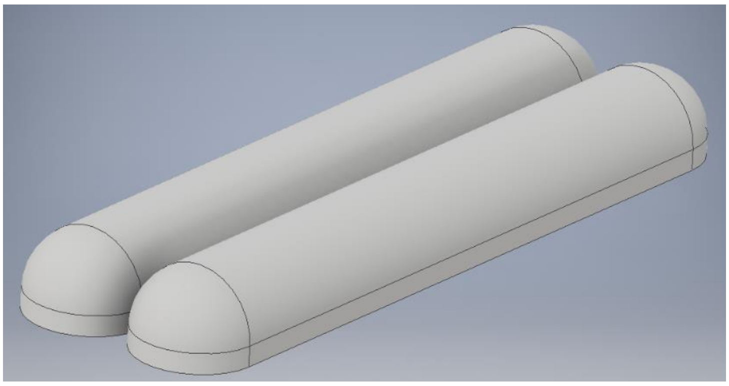

Figure 20 Shape of the greenhouses

Moreover, the wide range of the temperatures outside the greenhouse due to the seasonal changes will influence the final result of the heat power needed in the heater. That is because this power will be less in summer as the temperature difference between the inside and the outside of the greenhouse will not be as large as in winter, and thus the energy losses will also be less.

Therefore, an average of the temperatures of each season will be used for determining the heat losses in these different four periods. The next table shows the temperature average of all of them. These values were taken from the Nordic climate analysis.

Table 17 Average temperatures of the seasons

Average temperatures	
Temperature, inside [°C]	25
Temperature, summer [°C]	15
Temperature spring [°C]	0,5
Temperature, winter [°C]	-4,95
Temperature, autumn [°C]	7

On the other hand, the temperature of the water has been defined as 25 °C, as this temperature has been found to be the most suitable for the growth of microalgae as was explained in Chapter 5.2.1.

As a result, replacing the values for each season:

$$Q_{losses,summer} = \frac{650{,}305 m^2 * (25 - 15) K}{0{,}844\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}} = 7705{,}03\ W <> 7{,}705\ kW$$

$$Q_{losses,spring} = \frac{650{,}305m^2 * (25 - 0{,}5)K}{0{,}844\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}} = 18877{,}3\ W <> 18{,}877\ kW$$

$$Q_{losses,winter} = \frac{650{,}305m^2 * (25 - (-4{,}95))K}{0{,}844\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}} = 23076{,}6\ W <> 23{,}076\ kW$$

$$Q_{losses,autumn} = \frac{650{,}305m^2 * (25 - 7)K}{0{,}844\ \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}} = 13869\ W <> 13{,}869\ kW$$

In conclusion, the heat losses in kW through the greenhouse structure result to be for every season:

$$\mathrm{Q_{losses,summer}} = 7{,}71\ \mathrm{kW}$$

$$\mathrm{Q_{losses,spring}} = 18{,}88\ \mathrm{kW}$$

$$\mathrm{Q_{losses,winter}} = 23{,}08\ \mathrm{kW}$$

$$\mathrm{Q_{losses,autumn}} = 13{,}88\ \mathrm{kW}$$

Besides, the algae will be cultivated for 210 days distributed from March to September. Then the amount of energy to cultivate the algae in one pond for every period will be:

$$\mathrm{Q_{losses,summer}} = 7{,}71\ \mathrm{kW} * 93\ \mathrm{days} * 24\ \mathrm{h/day} = 17208{,}7\ kWh$$

$$\mathrm{Q_{losses,spring}} = 18{,}88\ \mathrm{kW} * 93\ \mathrm{days} * 24\ \mathrm{h/day} = 42140\ kWh$$

$$\mathrm{Q_{losses,winter}} = 23{,}08\ \mathrm{kW} * 16\ \mathrm{days} * 24\ \mathrm{h/day} = 8863\ kWh$$

$$\mathrm{Q_{losses,autumn}} = 13{,}88\ \mathrm{kW} * 8\ \mathrm{days} * 24\ \mathrm{h/day} = 2665\ kWh$$

Summing all these previous energy values, the total amount of heat losses during the period from March to September then results to be 70877 kWh.

According to the main question defined at the beginning of this section one more unknown parameter must be found to determine the power needed for the heater. That is, the energy needed to maintain water at 25ºC.

It is necessary to say that first, the heater needs to supply energy to achieve a proper temperature for the cultivation of the microalgae. After that, the heater will only need to supply enough energy to compensate the heat losses. Thus, the first energy will be needed once per cultivation cycle. The second one will be running continuously.

Beginning with the first energy, the power in kWh is required for the system to increase the temperature of the water from 20ºC (the temperature the water enters into the cultivation part) to 25ºC (the most suitable temperature the algae needs to grow) is calculated as follows:

$$Q_{stored} = m * C_P * \Delta T$$

Equation 19

Where:

- m is the mass in kg of the amount of water needed to heat [kg]
- C_P is the specific heat of water [J/kg.K]
- ΔT is the temperature gradient [K]

The mass required to heat is 121880 kg for one open pond as was determined in the cultivation part.

The specific heat of water, according to Fundamentals of manufacturing, is 4190 J/kg.K. (Rufe, 2002)

The temperature difference as was explained in the last paragraph results to be:

$$\Delta T = 25ºC - 20ºC = 5ºC$$

Consequently:

$$Q_{stored} = 121880\text{kg} * 4{,}190\frac{\text{kJ}}{\text{kg. K}} * (25-20)\text{K} = 2553386\text{ kJ} <> 2553{,}386\text{ MJ}$$

Knowing that:

$1\ kWh = 3600\ kJ$

The previous calculation in kWh is:

$Q_{stored} = 2553386\text{ kJ} * 0{,}000278\text{ kWh/kJ} = 709{,}84\text{ kWh}$

Thus, the energy needed in kWh the heater needs to supply the water to increase the temperature in 5ºC at the beginning of the cultivation process, results to be 709,84 kWh.

The next calculation is about finding the energy the heater needs to supply to compensate the heat losses. For that a detailed analysis will be done and explained.

The analysis will start with calculating the heat needed to increase the temperature of the water with 1ºC. This is, from 24-25ºC. 24ºC has been assumed to be the minimum temperature for the proper cultivation of the algae. Thus, the water in the pond where the microalgae are placed will not vary more than 1ºC during its cultivation. Also, this variation will be only due to the heat losses through the glass. Consequently, all these calculations will be based on this value. To illustrate this principle, the temperature fluctuations of the summer situation are drawn below.

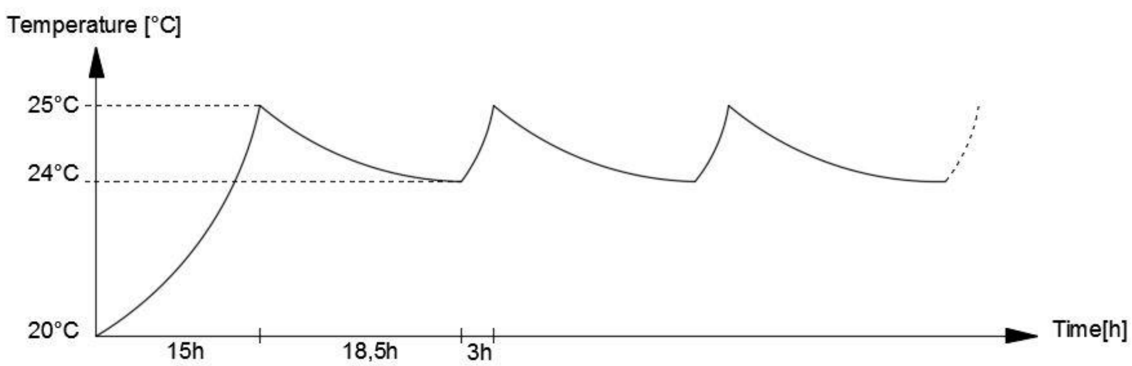

Figure 21 Temperature fluctuations in the cultivation pond over time in summer

Starting with the heat needed to increase the water temperature of the pond with 1ºC and following the same procedure as the last point:

$$Q_{stored} = m * C_P * \Delta T$$

Equation 20

Where:

- m is the mass in kg of the amount of water needed to heat [kg]
- C_P is the specific heat of water [J/kg.K]
- ΔT is the temperature gradient [K]

Comparing the formula with the previous one, only the value of the temperature gradient will not remain the same.

The temperature gradient, in this case, is the difference between the minimum and the maximum temperature in the pond. The minimum temperature is the water which will decrease to 24ºC due to the heat losses. The maximum, instead, is the temperature of the water required for the algae to grow which is 25ºC.

This results a temperature gradient of 1ºC.

Therefore, replacing the values in the unknown parameters:

$$Q_{stored} = 121880 \text{ kg} * 4{,}190 \, \frac{\text{kJ}}{\text{kg}\cdot\text{K}} * (25-24)\text{K} = 510677 \text{ kJ} <> 510{,}677 \text{ MJ}$$

As the time reference has chosen to be one hour:

$$Q_{stored} = \frac{510677 \text{ kJ}}{3600\text{s}} = 141{,}85 \text{ kW}$$

Thus, the energy needed to increase 121880 kg of water form 24-25ºC is 141,85 kW.

Assuming the temperature of the water will be heated in three hours, the amount of power needed for the heater without considering the heat losses is:

$$Q_{stored} = \frac{510677 \text{ kJ}}{3 * 3600\text{s}} = 47{,}28 \text{ kW}$$

For a wide analysis of the heat losses, the time needed for the heater to increase the temperature of the water from 24-25 ºC will be calculated. As the flow of heat and the losses for each season have been already calculated, through a simple calculation the time that this process takes up is:

$$Q_{cooling,summer} = \frac{510677 \text{ kJ}}{7{,}71 \, kW} = 66235{,}6 \, s \cong 18{,}5 \, h$$

$$Q_{cooling,spring} = \frac{510677 \text{ kJ}}{18{,}88 \, kW} = 27048{,}5 \, s \cong 7{,}5 \, h$$

$$Q_{cooling,winter} = \frac{510677 \text{ kJ}}{23{,}08 \, kW} = 22126{,}4 \, s \cong 6 \, h$$

$$Q_{cooling,autumn} = \frac{510677 \text{ kJ}}{13{,}88 \, kW} = 36792{,}3 \cong 10 \, h$$

It is clear that in summer the heat losses will be smaller than in winter and thus, as the results show, the time the water needs to cool down will increase during warmer months.

Once the time to cool down for every season is determined, the number of hours per week the heater has to work should be calculated. For that, through a cycle repetition approach made in Excel the hours the heater has to work in a week for the different seasons has been determined. The results of this calculations are the following:

- Total h heating in 93 days for summer: 318,86 h
- Total h heating in 93 days for spring: 637,71 h
- Total h heating in 8 days for winter: 61,71 h
- Total h heating in 16 days for autumn: 89,141h

It must be mentioned that the cycle repetition calculations have been made for one week as a reference. The accurate approach should have been done as a season reference. But, due to the complex of the calculation and the few variation in the final result this simpler approach has been chosen to be as the one for the heat fluxes analysis.

In the following paragraph the energy the heater needs to supply, with taking into account the heat losses will be calculated. For this, the power the heater supplies to the system in three hours will be considered. This power resulted to be 47,28 kW. Therefore:

$$Q_{heating,summer} = 318{,}86\ h * 47{,}28\ kW = 15075{,}56\ kWh$$

$$Q_{heating,spring} = 637{,}71\ h * 47{,}28\ kW = 30151{,}13\ kWh$$

$$Q_{heating,winter} = 61{,}71\ h * 47{,}28\ kW = 2917{,}85\ kWh$$

$$Q_{heating,autumn} = 89{,}14\ h * 47{,}28\ kW = 4214{,}67\ kWh$$

As a conclusion for this point, the total energy the heater needs to supply for each season, taking into account the heat losses produced during the temperature warming, has been determined. In the next point, the total power needed is being determined, that is, just the sum of all the previous energy flows during each season. Then:

$$Q_{heating,total} = 15075{,}56\ kWh + 30151{,}13\ kWh + 2917{,}85\ kWh + 4214{,}67\ kWh = 52359\ kWh$$

It must be said that increasing the temperature of the water needs to be done once for each cultivation cycle. That means, once the water is warm enough no more heat will be needed while the algae is being cultivated. The energy losses in the greenhouse, instead, are continuously running in the whole cultivation cycle. Thus, the hours each energy use for an entire cycle are not the same.

During the complete process of increasing the temperature of the microalgae for a proper cultivation, two energy flows have been considered. The first one considers raising the temperature with 5ºC from 20ºC to 25ºC only during the first cycle. The second one, on the other hand, considers the heat losses and measures the energy required for increasing the temperature from 24ºC to 25ºC.

The total energy needed for keeping the temperature at 25ºC is the sum of the previous energies calculated. Thus,

$$Q_{total,stored} = 52359\ \mathrm{kWh} + 709{,}84\ \mathrm{kWh} = 53069\ \mathrm{kWh}$$

To conclude this paragraph, the total energy required for maintaining the temperature of the algae at 25ºC during cultivation has resulted to be 53069 kWh.

Until this point all the energy flows calculated are ones that the system should supply and which increase the cost of the system. One flux of heat that is significant to consider is the radiation from the sun; energy that will not increase the cost of the system and that will help to improve the energy balance currently done by lowering the power supplied by the heater.

The radiation has been considered for Tampere, as it is a city situated central Finland. This is representative for the average of radiation in the Northern countries. This assumption was made as the radiation difference does not vary much between different locations.

The radiation per month has been taken from a solar irradiance calculator. Thus, the radiation for each month in Tampere results to be:

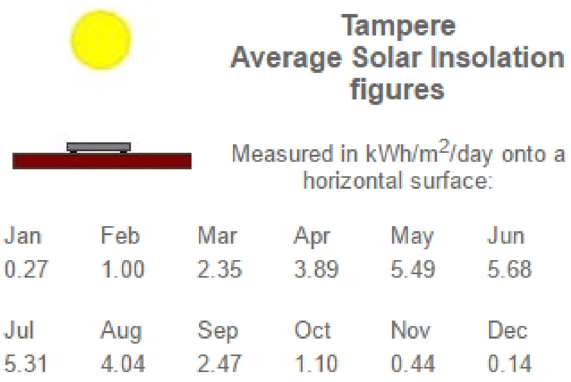

Figure 22 Tampere average solar insolation figures (Boxwell, 2017)

Taking the value of the months within the production year for the cultivation of microalgae, that is, from March to September, and multiplying it with the number of days each month has, gives:

Table 18 Radiation per month on a production year

	Solar insolation	Days per month	Radiation per month in $kWh/m^2/day$
March	2,35	31	72,85
April	3,89	30	116,7
May	5,49	31	170,19
June	5,68	30	170,4
July	5,31	31	164,61
August	4,04	31	125,24
September	2,47	30	74,1

The sum of all the radiations per month is then: 894,09 kWh/m^2 per production year.

When the radiation hits a structure, three different phenomena occur: part of the whole radiation is first reflected back to the outside, another part is then absorbed by the glass and finally the last one penetrates through the glass.

The g value or the solar factor is the proportion of solar radiation transmitted through the glass by all means. This is composed of the direct transmittance and that which is absorbed by the glass and reradiated inwards. This value is significant because only a small part of the radiation needs to be considered.

It is also important to consider not only the solar factor of the glass, but also the reflection and the solar factor of the water due to the amount of energy that will stay inside the greenhouse between the water and the glass. Because this phenomenon will be cyclic, the next diagram gives a schematic overview of this and the table below gives an overview of the values.

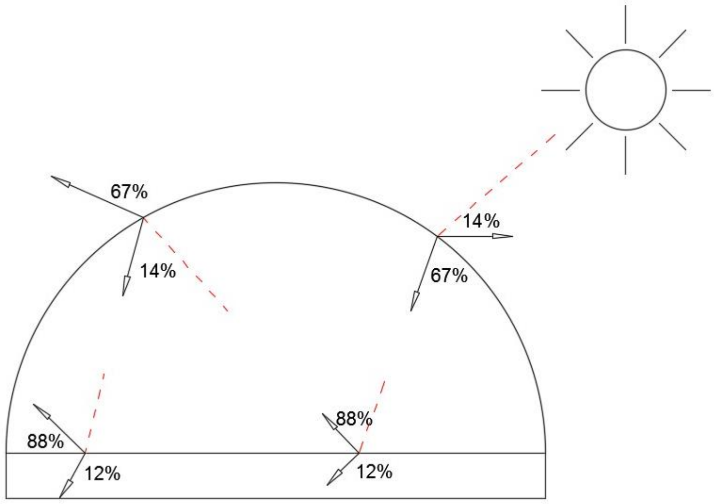

Figure 23 Schematic overview of the reflection and absorption fluxes in a greenhouse

Table 19 reflectance and g values for a greenhouse

	G value	Reflectance
Glass	67%	14%
Water	12%	88%

The g value of the glass used for this analysis is given before on the specification sheet of the glass. This means 67% of the total radiation will pass through the glass as the drawing above shows. Once this radiation has passed, it will reflect on the water and it will again reflect on the glass. The reflection component of the water turns out to be 88% of the total radiation that falls on the water. (Mills)

Two cycles were considered for the calculation of the of final energy stored in the water. That is, the radiation penetrates through the glass, reflects on the water, reflects on the glass again and finally it is absorbed by the water. This absorbed energy, and the energy coming from the glass that is first absorbed by the water will be summed to calculate the final energy absorbed by the water.

According to the result of the radiation per production year, the area is needed to determine the final value in kWh. The area was established to be $650{,}305m^2$. Thus,

$$E_{radiation} = 894{,}09\ kWh/m^2 * \ 650{,}305m^2 = 581431{,}2\ kWh$$

Considering the radiation per production year that was 324718 kWh and the solar value of the glass, the energy that first penetrates through the glass results to be:

$$E_1 = 581431{,}2\ kWh * 67\% = 389559\ kWh$$

According to Figure 23, the energy reflected and absorbed by the water is respectively:

$$E_{2,reflected} = 389559\ kWh * 88\% = 342811{,}8\ kWh$$

$$E_{2,absorbed} = \ 389559\ kWh * 12\% = 46747\ kWh$$

Following the same approach, the energy reflected from the glass is:
$E_3 = 342811{,}8\ kWh * 14\% = 47993{,}6\ kWh$

Besides, a part of this energy reflected will be reflected back onto the water. The other part will be absorbed. Then:

$E_{4,reflected} = 47993{,}6\ kWh * 88\% = 42234\ kWh$

$E_{4,absorbed} = 47993{,}6\ kWh * 12\% = 5759{,}2\ kWh$

The total energy absorbed by the water is calculated summing all the energy that is absorbed. Because it has been assumed for the calculations two cycles, two flows will be involved:

$$E_{final,absorbed} = E_{2,absorbed} + E_{4,absorbed}$$

Equation 21

This is:

$E_{final,absorbed} = 46747\ kWh + 5759{,}2\ kWh = 52506{,}2\ kWh$

As a result, the total energy absorbed by the water assuming two cycles is 52506,2 kWh. As a remark for this value can be said that to get a more accurate value, more cycles could be considered. This will result in a higher final absorbance value.

In this section, the total power needed for the heater to supply to the greenhouse has been determined. This energy was: 53069 kWh. Besides, in the last part the radiation was taken into account because of the positive contribution on the energy balance. This energy was: 52506,2 kWh.

It is clear then that, for completing the energy balance in the greenhouse, the positive fluxes have to be evaluated with the negative ones. The positives then, in this case, are the ones that need to be provide by the heater. That is, the power the heater needs to supply for rising the initial temperature and for compensating the heat losses. On the other hand, the negatives fluxes will be the ones that make this power supply decreased. That is, the radiation flux. Thus,

$Q_{heater} = 53069\ \mathrm{kWh} - 52506{,}2\ kWh = 563\ kWh$

To conclude this section, the energy the heater needs to supply to the pond, taking into account the heat losses and the radiation fluxes, has resulted to be 563 kWh.

6.1.2 Harvesting

After harvesting, an algae slurry is what remains and out of this it is possible to make biogas. Before the amount of algae slurry can be calculated, it is necessary to do a few other calculations. The first thing that is calculated is the settling velocity in the sedimentation tank.

6.1.2.1 Settling velocity

The settling velocity is the time needed for the particles to sink and this speed is calculated with the Stokes equation.

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

Equation 22

There are two types of algae which are commonly used: *Chlorella Vulgaris* and *Scenedesmus spp.* In these calculations, *Chlorella vulgaris* will be used and this type of algae has the following properties:

Table 20 Properties Chlorella Vulgaris

Properties *Chlorella Vulgaris*	
Density algae (ρ_s) [kg/m³]	1070
Cell diameter [µm]	30
Dynamic viscosity (µ) [Pa.s]	0,0013

The algae are cultivated in water of 25°C with a density of 1000kg/m³. With all these parameters, the calculations can be done, which gives:

$$Settling\ velocity = \frac{2}{9} * 9{,}81 * \frac{(15*10^{-6})^2}{0{,}0013} * (1070 - 1000) = 0{,}000026412 \text{ m/s}$$

= 0,095 m/h

= 2,282 m/day

6.1.2.2 Sedimentation tank design

The step is designing the sedimentation tank. It is possible to design the tank in different ways with different shapes but in this project a tank with a cylinder and cone above is chosen. This was chosen because it is important to have a slope that is large enough. If all the algae are settled there is a slurry but this slurry must slide easily out of the tank into the centrifugation tank. There is a reasonable slope needed for the slurry to slide easily. During the designing process, a few options for the slope were tried. These options can be seen below.

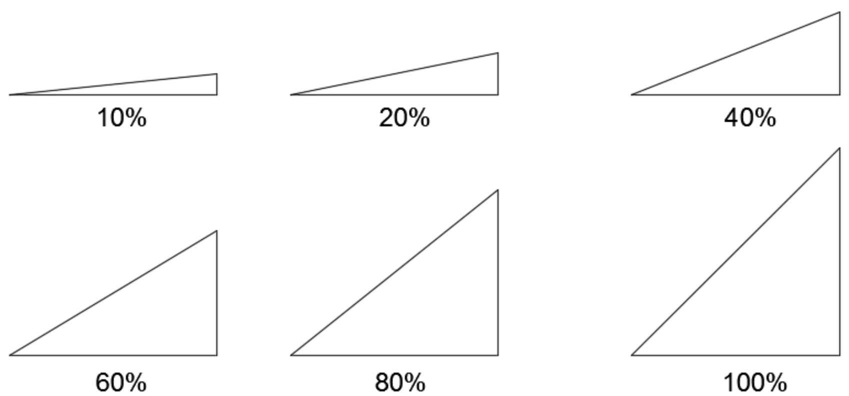

Figure 24 Options for the slope of the sedimentation tank

The slope of 60% turned out to be the most efficient. The slope of 10% is probably too low to get a good slide from the slurry and the slope of 100% is too steep. It is not efficient to have a slope that is too steep because otherwise the radius of the tank must be too big to get the same volume as for a cylinder. Therefore, an average value was chosen.

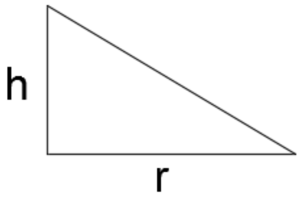

Figure 25 The chosen slope for the cone, with radius r and height h

The ratio between r and h for a slope of 60% would then be: h = 0,6*r. With this ratio, it is possible to calculate the volume of the cone with one unknown parameter. The formula for the volume of a cone is:

$$V_{con} = \frac{1}{3} * \pi * r^2 * h$$

Equation 23

But the total volume of the sedimentation tank consists of a cylinder and a cone so it is necessary to make a summation of both. The formula for the total volume then becomes:

$$V_{tot} = V_{cyl} + V_{con}$$

Equation 24

And the formula for the cylinder is:

$$V_{cyl} = \pi * r^2 * h$$

Equation 25

As mentioned before, the ratio between r and h is 0,6 for the cone. Also, a r/h ratio of 1,5 for the cylinder was taken. This was chosen because it is important to have a tank with a larger diameter than the height. If not, it takes too long to settle all the algae.

The whole cultivation pond is pumped in once into the sedimentation tank so it is necessary to make the tank large enough. From the calculations above, the volume of the cultivation pond is known which is 121,88 m^3. The total volume is known and it is possible to determine the radius of the tank and after that it is possible to determine the dimensions of the tank. To do this, the equation for calculating the total volume will be used. First, the radius will be determined from this and after that, with the radius the height will be calculated.

$$V_{tot} = \frac{1}{3}\pi * 0,6 * r^3 + \pi * 1,5 * r^3$$

$$\downarrow$$

$$r = \sqrt[3]{\frac{V}{\left(\frac{1}{3}\pi * 0,6 + 1,5 * \pi\right)}} = 2,84\ m$$

$$\downarrow$$

$$h = 1,5 * r = 4,25\ m$$

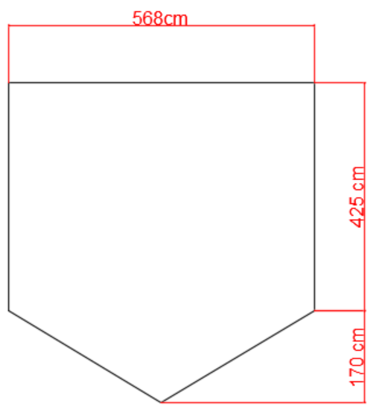

Figure 26 Dimensions of the settling tank

6.1.2.3 Settling time in the sedimentation tank

The settling time in the tank can be calculated with the next formula:

$$Settling\ time = \frac{Average\ height}{Settling\ velocity}$$

Equation 26

The height of the tank can be seen in Figure 34 and the settling time was calculated above. These parameters where used, giving the following results:

$$Settling\ time = \frac{(4{,}25 + 1{,}7/2)}{2{,}282} = 2{,}55\ days$$

6.1.2.4 Heat loss in the sedimentation tank

There will be a heat loss through the wall of the tank so it is very important to isolate the sedimentation tank. In the first calculations, a wall of 5mm steel and 50mm of Rockwool is taken for this, see Figure 27. These dimensions were just chosen and the purpose of the following calculations is to see if the isolation is enough.

It is important to have a low energy loss otherwise the energy demand will be too high. A solution to limit this energy loss is to place the sedimentation tank inside a building. Figure 28 shows a schematic view of the building with sedimentation tank inside.

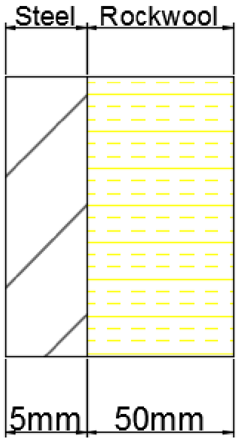

Figure 27 Cross-cut of the sedimentation tank wall

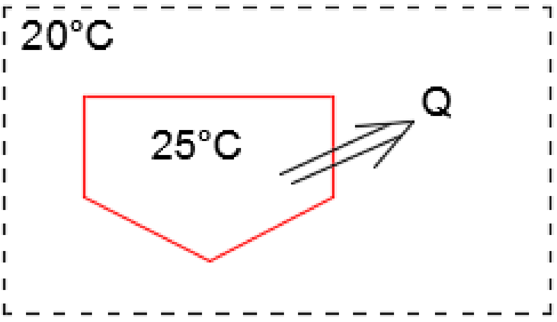

Figure 28 Schematic overview of the sedimentation wall

The total loss of the tank can be calculated with the next formula: (Sensible house, 2015)

$$Q = U * A * (\theta_i - \theta_e)$$

Equation 27

Where:

- Q is the heat loss [W]
- U is the heat transfer coefficient [W/m^2.K]
- A is the surface of the tank [m^2]
- θ_i is the temperature inside the tank [°C]
- θ_e is the temperature outside the tank but in the building [°C]

Before the total heat loss can be calculated is it necessary to first calculate the total heat transfer coefficient. The structure is built up in layers from the inside to the outside with steel, Rockwool and there is also a factor for the air outside. Along the inside there is no resistance factor for the air taken into account because the water is in contact with the steel.

First of all, the heat resistance for each layer is calculated with the next formula:

$$R = \frac{d}{\lambda}$$

Equation 28

With:

- R is the heat resistance from each layer [m^2.K/W]
- d is the thickness of the layer [m]
- λ is the heat conductivity coefficient [W/m.K]

If the heat resistance for each part is calculated, the total heat resistance be determined.

$$R_{tot} = R_{steel} + R_{insu} + R_{air}$$

Equation 29

Finally, the heat transfer coefficient (U) can be calculated.

$$U = \frac{1}{R_{tot}}$$

Equation 30

Using these calculations gives the following outcome:

Table 21 Calculation of heat transfer coefficient

	d [m]	λ [W/m.K]	R [m².K/W]
Steel	0,005	17	0,000294118
Rockwool	0,05	0,037	1,351351351
Air outside			0,13
			+
		R_{tot} [m².K/W]	1,4816
		U_{tot} [W/m².K]	0,6749

If the heat transfer coefficient is known, the next step is to calculate the surface that is in contact with a colder medium. This will be called the contour of the tank.

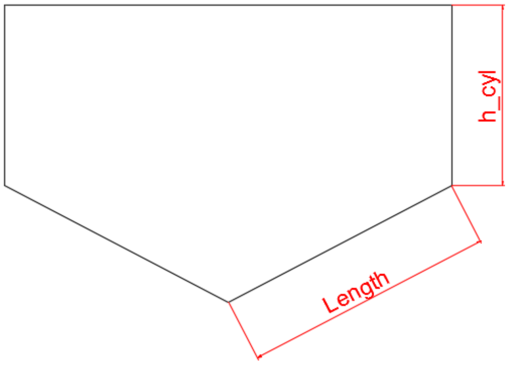

Figure 29 Sketch with the dimensions of the tank

The total surface of the contour (A) can be calculated as follows:

$$A = \pi * r^2 + \pi * d * h_{cyl} + \pi * r * l$$

Equation 31

$l = \sqrt{r^2 + h^2} = \sqrt{2{,}84^2 + 1{,}7^2} = 3{,}31\ m$

$A = \pi * 2{,}84^2 + \pi * 5{,}68 * 4{,}25 + \pi * 2{,}84 * 3{,}31 = 130{,}71\ m^2$

$\mathrm{Q} = 0{,}675 * 130{,}71 * (25 - 20) = 441{,}15\ \mathrm{W}$ ➔ with 5 cm insulation

To reduce the heat losses through the tank, it is possible to calculate everything again with 10 cm of Rockwool:

$Q = 0{,}353 * 130{,}71 * (25 - 20) = 230\ W$

Afterwards can be concluded that by an increasing thickness of the insulation, the heat losses do not significantly decrease. In further calculations, the tank with 5cm insulation (heat loss = 441,15 W) will be used. The rest water after the sedimentation flows back to the mixing tank and with this, the heat is taken to the tank. Therefore, it is important to know how much the water is cooling down in the sedimentation tank.

This can be calculated with the next formula:

$$Q = m * c * \Delta T$$

Equation 32

With:

- $m = V * \rho$
- Q is the power needed for the heat exchanger [W]
- m is the mass of the medium [kg]
- c is the specific heat capacity [kJ/K.kg] (for water 4,186 kJ/kg.K)
- ΔT is the temperature difference [°C or K]

This gives:

$m = V * \rho = 121{,}88\ m^3 * 1070 kg/m^3 = 130411{,}6\ kg$

The goal is to calculate the temperature between the begin situation, and the situation after the heat losses have occurred. Therefore, the formula has to be transformed, resulting in:

$$\Delta T = \frac{Q}{m*c} = \frac{441{,}15}{130411{,}6*4186} = 0{,}000000808°\mathrm{C}$$

The temperature will not decrease because of the thermal inertia of the water.

To conclude, because of the thermal inertia the temperature decrease is very small so it is possible to assume that there are no heat losses in the recycling flow. Hence, the heat losses from the pipes are not taken into account.

6.1.2.5 Choice of centrifuge

There are many different centrifuges with different dimensions. In paragraph 6.2.2.3, the flow was calculated from the sedimentation tank to the centrifugation tank, which is 6094 l/h.

It is important to find a centrifuge that has a sufficient capacity with a flow of 6094 l/h. On the other hand, the required power has to be as low as possible. When a high amount of energy for the centrifuge is required it has a negative impact on the energy balance

As centrifugation machine, the EVODOS 50 was chosen. This centrifuge has as maximum flow of 4000 l/h. As said before the flow from sedimentation towards centrifugation is higher so it has to be considered to place a second centrifuge or to find another solution.

All from (Evodos, sd)

Figure 30 EVODOS 25/50 (Evodos, sd)

6.1.3 Extraction

In this paragraph, the required components of extraction were dimensioned. First, the used method for extraction is explained with the important parameters. Second, calculations were made to determine the energy consumption per batch. The heat losses during extraction were also calculated. Finally, the total energy consumption during the extraction process was calculated with a summation of the different parts.

6.1.3.1 Lipid extraction

Lipids will be extracted with the supercritical CO_2 method, which is simple, clean and effective for the extraction of lipids for the production of biofuel. The energy need of the extraction process will be calculated with Apek's 2000psi mid-range production model. (Supercritical, 2017)

Figure 31 Extraction model (Supercritical, 2017)

Super critical carbon dioxide is used as a solvent in this method. Carbon dioxide gas is heated and compressed to a super critical liquid solvent which absorbs lipids from microalgae in an extraction tank. The liquid solvent is continuously pumped through the system. Saturated solvent is pumped out of the extraction tank and decompressed, turning the solvent into gas. Little post-processing is required because the solvent evaporates, giving the product a high purity.

The parameters of the process are shown in the table underneath. The long process is chosen because the lower pressure and temperature could save energy, even though the process time is longer.

Table 22 Parameters of lipid extraction process

Pressure	Temperature	Liquid flow	Process time
8274 kPa	314 K	2 L/min	90 min
5516 kPa	297 K	2 L/min	180 min

The 2000 psi model processes 10-13,6 kg in 24 hours, according to Apeks. The process takes three hours so it can be executed eight times in 24 hours. This means that the model processes 1,36 kg of mass at a time. This mass is placed in a stainless-steel extraction tank of five litres.

a) Calculations of energy losses in the extraction process

The extraction process requires energy to heat up the carbon dioxide, compress it, keep it warm and pump it around. The energy requirements will be calculated with the following parameters:

Q = heat [J]	c_p = specific heat [kJ/kg.K]
W = work [J]	n = number of moles
ρ = density [kg/m^3]	y = specific heat ratio
V_i = initial volume [m^3]	V_f = final volume [m^3]
P_i = initial pressure [Pa]	P_f = final pressure [Pa]
m = weight [kg]	T = temperature [K]
A = surface [m^2]	g = gravity [m/s^2]
k = thermal conductivity [W/m.k]	t = time [s]
R = gas constant [J/mol.K]	

b) Making supercritical carbon dioxide

Carbon dioxide will be supplied as a gas. The gas has to be heated and compressed above a critical point to become a supercritical fluid. In this way, supercritical carbon dioxide is formed (SC-CO_2). The heat required to get the carbon dioxide gas up to temperature, is calculated with the following formula.

$$Q = m * c_p * \Delta T = 0{,}833 * 1{,}98 * 35 = 57{,}7\ kJ/m^3\ of\ gas$$

The specific heat c_p and the density of carbon dioxide was taken from engineering toolbox. (Engineering Toolbox, 2017) The density of carbon dioxide is 1,98 kg/m^3, this is the weight. Every m^3 of gas that will be heated, will be compressed to 0,0456 m^3 of liquid CO_2. An amount of 0,36 m^3 is required, so 0,36/0,0456 is the amount of cubic metres of gas that is needed. 0,36/0,0456 = 7,89 m^3 of gas.

$$Q = 57{,}7 * 7{,}89 = 455 kJ/batch$$

The compression of carbon dioxide gas is calculated as an adiabatic compression. With adiabatic compression, no heat is exchanged to the surroundings. The work required to compress the carbon dioxide is calculated with the following formula:

$$W_{compression} = \frac{k(V_f^{1-\gamma} - V_i^{1-\gamma})}{1-\gamma}$$

Equation 33

A few values are needed to calculate the work. The initial volume V_i is chosen to be one m^3 and the specific heat ratio γ is taken from toolbox (Engineering Toolbox, 2017). The thermal conductivity k and the final volume have to calculated. The universal gas law and the adiabatic condition are used to calculate the thermal conductivity first and the final volume second.

$$P = \frac{nRT}{V} \rightarrow \ P_i = \frac{45 * 8{,}314 * 283}{1} = 106\ kPa$$

The next formula is used to calculate the thermal conductivity (k):

$$PV^\gamma = constant = k = \frac{nRT}{V} V^\gamma$$

Equation 34

Which gives:

$$k = PV^\gamma = 106 * 10^3 * 1^{1.28} = 106 * 10^3$$

The thermal conductivity is calculated, and the initial pressure is used to calculate the final volume. The final pressure is taken from the 2000 psi parameters, this is 5516 kPa. The adiabatic condition is used for the calculation:

$$P_i V_i^\gamma = P_f V_f^\gamma$$

Equation 35

After that, the final volume can be calculated:

$$V_f = \left(\frac{P_i V_i^{\gamma}}{P_f}\right)^{1/\gamma} = \left(\frac{106 * 10^3 * 1^{1,28}}{5516 * 10^3}\right)^{1/1,28} = 0,0456\, m^3$$

The work required for the compression can be calculated now because all the values are known.

$$W_{compression} = \frac{106 \cdot 10^3 (0,0456^{-0.28} - 1^{-0.28})}{1 - 1.28} = -520\, kJ\, per\, m^3 of\ gas$$

An amount of 520 kJ is needed to compress carbon to 0,0456 m³. One batch requires 360 litres so 0,36 m³ of liquid carbon dioxide. Calculating the ratio gives 4,105 kJ for one batch (three pounds of material).

c) Heat loss during the extraction process

The tank will lose heat to its surroundings. The amount of heat lost will be calculated with the formula below.

$$Q = \frac{k.A(T_{hot} - T_{cold})}{d} * t$$

Equation 36

The product layout (Supercritical, 2017) mentions that the machine requires a surrounding temperature between 16°C and 32°C. The surrounding temperature will be 20°C. The temperature in the process is 24°C. The product layout also mentions that the material is 304 stainless-steel. The thermal conductivity of this stainless steel was taken from ASM. (ASM, 2017) The thermal conductivity k is 16,2 W/m.K. The cylinder in which the process takes place has a volume of five litres, which can be achieved with a cylinder of 1 m in length and a diameter of 0,08 m. The surface on the cylinder will be calculated with the formula below.

$$A = 2\pi rh + 2\pi r^2 = 2 * \pi * 0,08 * 1 + 2 * \pi * 0,08^2 = 0,54\, m^2$$

The process lasts 180 minutes, so the time t is 10800 seconds. The thickness of the metal was chosen to be one centimetre for this system because that is strong enough to withstand the high temperature and pressure.

$$Q = \frac{16,2 * 0,54 * (24 - 20)}{0,01} = 3,50\, kJ\, per\, batch$$

d) Pumping the liquid carbon dioxide

$$W_{pump} = \int f(y)dy = V * g * \rho * \int y\ dy = 0,36 * 9,81 * 686 * 0,5 * 1,98^2 = 4,75\, kJ\, per\, batch$$

The density ρ, is taken from engineering toolbox. (Engineering Toolbox, 2017) Toolbox offers the density for liquid carbon dioxide at temperatures of 20°C and 30°C. The density for a temperature of 25°C was calculated. The height of the machine y, is taken from the 200-5LX20LD product layout provided by Apeks supercritical. (Supercritical, 2017)

Table 23 energy losses of sc-CO_2 extraction

Process	kJ per batch	kWh per batch	kJ per kg of algae	kWh per kg of algae
Warming up the carbon dioxide	445	0,12	327	0,09
Compressing the carbon dioxide	4105	1,14	3018	0,84
Heat losses	3,50	0,00	2,57	0,00
Pump	4,75	0,00	3,49	0,00
Total process	4558	1,26	3351	0,93

The lipid content in microalgae is in between 30% and 50%, depending on C/N ratio. It is estimated that the microalgae in this system will have an average lipid content of 40% and the extraction process will have an efficiency of 90%. The extraction tank will contain 1,36 kilograms of biomass. The extraction process will result in $1{,}36 * 0{,}4 * 0{,}9 = 0{,}49$ kg of extracted material per batch. One gram of lipids will contain about 9,3 kcal or 38911,2 J. One kilo of algae will contain 15,6 MJ and 14,0 MJ will be extracted. One batch of algae could contain 21,2 MJ, and 19,1 MJ will be extracted. Extraction requires 3,4 MJ for a kilo of algae, which is about a fifth of the energy gained from lipids. The energy won from dry algae will be 14,0 - 3,4 = 10,6 MJ. The sum of cultivation, harvesting, dewatering and additional drying should require less energy than 10,6 MJ per kg of lipids to make this application feasible. Therefore, the decision was made to use the residue from the algae after extraction to produce more energy by making biogas in the anaerobic digester. The extraction process takes 36% of the algae mass, so 64% will be left over for anaerobic digestion. Some energy in the algae is taken out in the extraction process, but the extraction process also functions as pre-treatment for the anaerobic digestion to make it easier to degrade. These two effects are estimated to be equally strong, so the residue algae have a similar biogas production to the whole algae. (Baisuo Zhao, 2014)

Six extraction tanks will be sufficient to extract lipids from all the ponds every week. The extraction of lipids with the supercritical CO_2 method gets 14 MJ or 3,89 kWh out of 1 kg algae, while spending 3,4 MJ or 0,93 kWh. It is not reasonable to spend about a quarter of the energy won from algae on getting it out of algae. Using the residue for anaerobic digestion is an option to make this application feasible.

6.1.4 Transformation

In this section, through a simple energy balance in the anaerobic digester, the energy needed and the energy extracted for the conversion of the microalgae into biogas will be calculated. The goal of all the following calculations is to analyse the feasibility of this crucial step in the process of biogas extraction.

First of all, it must be said that a scenario where all the microalgae are converted into biogas will be considered. This means that no high value products such as fertilizers or lipids are extracted after the harvesting step.

As mentioned in Chapter 5.2.4, an anaerobic digester is a device that breaks down the initial matter consisting of long chains of atoms into simpler ones, until it gets completely decomposed and thus, converted into biogas. The energy required for this process is given by a heater.

The aim of this section is to make an energy balance of the anaerobic digester. Thus, the energy that can be extracted through this device in the form of biogas will be calculated. For this goal, the energy needed for the heater and the input and output flows will also be required.

Starting with the calculations of the energy input in the heating system, the following equation has to be solved:

$$Q_{heater} = m_{dry\ matter} * Cp * \Delta T$$

Equation 37

Where:

- Q_{heater} is the power needed for the heating system [kW]
- m is the mass flow of microalgae that is inserted in the digester [kg/s]
- C_p is the heat capacity of the microalgae [kJ/kg.K]
- ΔT is the temperature difference between the temperature at which algae is introduced in the digester and the temperature needed in the anaerobic digester for the total conversion into biogas [K]

For obtaining the mass flow the output flow of the previous process must be considered, in this case, the harvesting part. Therefore, as it has already been calculated, the output flow of the harvesting part is 1218 l/h. This flow contains a mixture of water and algae, and for the requirements of the equation only the algae needs to be considered. It is also known that the concentration of algae in that mixture is 50 g/l. Thus, through a simple calculation the flow of this matter of algae can be found:

$$m_{dry\ matter} = 1218\ l/h * 50\ g/l = 60900\ g/h <> 0{,}0169\ kg/s$$

It is necessary to say that even with taking out the water in this flow not all these algae will be utilized for the extraction of biogas, as there is always some remaining matter that cannot be used for that purpose. This is the case with ashes when they are formed in the digester. They will remain as substrate, and no energy will be taken out of them.

When reporting microalgae biomass, the ash free dry weight (AFDW) or the volatile solids (digestible component) of the microalgae biomass is a percentage of the total solids and varies between species. The data in Table 24 includes the AFSW of some common microalgae species. The variation in AFDW can significantly affect the predictions for the theoretical biogas production potential for the anaerobic digestion of microalgae.

Table 24 Volatile solids or ash free dry weights (AFDW) as a percentage of the total solids (TS) of Chlorella Vulgaris (A.J. Ward, 2013)

Species	Fresh or salt water	VS and AFDW as % of TS
Chlorella Vulgaris	Fresh	93%
Chlorella Vulgaris	Fresh	90%

Consequently, according to the table above, the percentage of AFDW for *Chlorella Vulgaris* is 93% and 90% respectively. (A.J. Ward, 2013) An average of both then will be taken for this part, that is, a 92% of AFDW. A complete overview of the AFDW for different algae species can be found in Appendix V.

The AFDW shows the percentage of energy that can be extracted out of the total solids. Thus, for this calculation:

$$m_{\,algae} = 0{,}0169\ kg/s * 92\% = 0{,}0155\ kg/s$$

Then the mass flow of dry algae results to be 0,015 kg/s. This mass flow will be entirely destined to biogas production.

The next parameter to determine will be the specific heat. The heat capacity of the water will be considered, and not the specific heat of the algae. First of all, because there is no data available for the specific heat of *Chlorella Vulgaris*. Secondly, because the flow introduced in the digester contains 95% of water and 5% of *Chlorella Vulgaris* so it is more reasonable to consider the one of the water and not the one of the algae. Therefore, the specific heat considered is taken out of 'Heat Transfer: A Practical Approach' (A.Çengel, 2003) and has a value of:

$$C_{p\ (30º)} = 4{,}178\ \frac{\mathrm{kJ}}{\mathrm{kg}\cdot\mathrm{K}}$$

The next and final step for the calculation of the energy input in the digester is the gradient of the temperature inside this device.
The value of the heat capacity has been evaluated at a temperature of 30ºC. That is because the temperature at which the algae is introduced into the digester is 25ºC. On the other hand, the temperature the algae has to reach inside the anaerobic digester in order to be converted into biogas is 35ºC. Thus, an average temperature should be taken. This temperature, at which properties should be evaluated, is then 30ºC.

In conclusion, replacing all the parameters with their corresponding value, the energy introduced in the anaerobic digester needs to be:

$$Q_{heater} = m_{dry\ matter} * \mathrm{C}_p * \Delta T$$

Equation 38

$$Q_{heater} = 0{,}0155kg/s * 4{,}178\ \frac{\mathrm{kJ}}{\mathrm{kg}\cdot\mathrm{K}} * (35-25)\mathrm{K} = 0{,}648\ kJ/s <>\ 0{,}648\ \mathrm{kW}$$

Thus, the power of the heater required to convert the input microalgae into biogas results to be $0{,}648\ \mathrm{kW}$.

The next step is about determining the energy storage in the biogas obtained in the anaerobic digester. For that, the following equation must be solved:

$$Q_{extracted} = V * \mathrm{C}_p * \Delta T$$

Equation 39

First of all, the volume flow has to be found. For that, the methane production at 35ºC is taken out of 'Experimental study on a coupled process of production and anaerobic digestion of *Chlorella Vulgaris*' (Ras, 2010), where it can be seen, as the picture below shows, that regarding the amount of dry matter the litters of methane produced vary between 197-337 l of methane per kg of dry matter. An overview of the methane gas production of other microalgae species can be found in Appendix VI.

Table 25 Methane gas production during the anaerobic degradation of Chlorella Vulgaris *with different pre-treatment techniques and temperatures in batch investigations at the Hamburg University of Technology (Ras, 2010)*

Temperature [ºC]	Pre-treatment	CH_4 production [l CH_4/kg oDM]
35	None	197-337

When the dry matter introduced in the digester is known, then:

$$V = CH_4\, production * m_{dry\ matter}$$

Equation 40

Substituting:

$$V = 337 \frac{L_{CH4}}{kg_{of\ DM}} * 0{,}0155\ \frac{kg_{of\ DM}}{s} = 5{,}22 \frac{L_{CH4}}{s} <> 451{,}31\ \frac{m^3_{CH4}}{day}$$

As it is a theoretical approach, the highest value of biogas extraction was chosen ($337 \frac{L_{CH4}}{kg_{of\ DM}}$) .

The heat capacity for the biogas out of microalgae can vary depending on the temperature. In the article ‘Thermal characterization of microalgae under slow pyrolysis conditions’ (Scott Grierson, 2008) through a novel thermo-analytical technique known as computer Aided Thermal Analysis (CATA) the specific heat of reaction that occurs in each sample under unsteady-state heating conditions can be obtained. The results of this software can be seen in the following image:

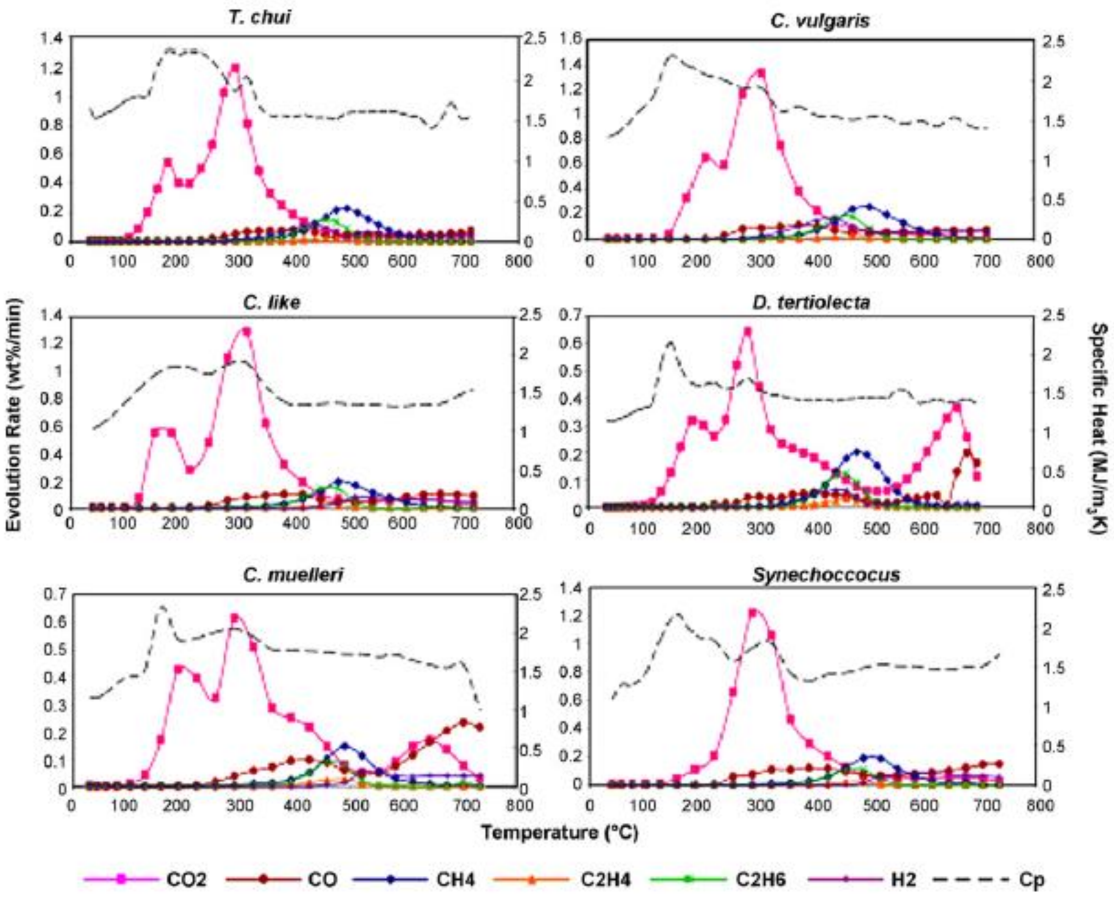

Figure 32 Rate of evolution of volatile compounds from pyrolysis of microalgae superimposed to the apparent specific heat for the heating rate of 10º/min (Scott Grierson, 2008)

As the figure above shows, at low temperatures the heat capacity of different types of microalgae do not have any large variations. Therefore, it can be said that, no matter the type of algae chosen, the energy extracted and thus the energy balance for the anaerobic digester at low temperatures will remain in similar ranges.

Getting back to the heart of the matter, as it has been chosen for this project, *Chlorella Vulgaris* will be analysed.
The figure below extracted from the previous image shows that the specific heat for a temperature between 25ºC and 35ºC is approximately 1,35MJ/ m^3K.

Nevertheless, as the data of the experiment are not provided in the article, an approximation has been made. The procedure of the outcome has been calculated as the next figure illustrates:

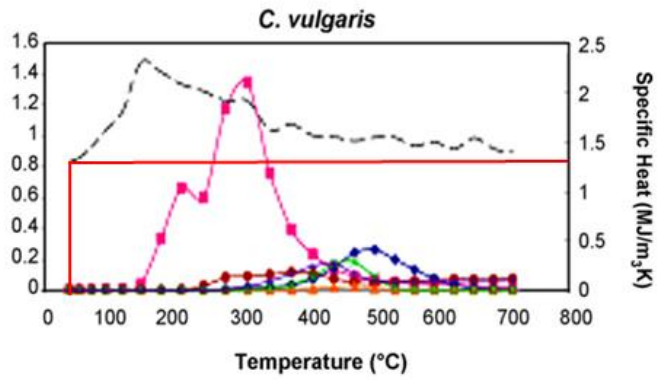

Figure 33 Rate of evolution of volatile compounds from pyrolysis of microalgae superimposed to the apparent specific heat for the heating rate of 10º/min (Scott Grierson, 2008)

The gradient of temperature needed for the energy extraction is the same as the one utilized for the power of the heater. Thus, 10ºC difference will be used for the equation of the biogas extraction.

Therefore, substituting the values on the missing factors:

$$Q_{extracted} = V * C_p * \Delta T$$

Equation 41

$$Q_{extracted} = 451{,}31 \frac{m^3_{CH4}}{day} * 1{,}35 \frac{MJ}{m^3_{CH4} \cdot K} * (35 - 25)K = 6092{,}69\ MJ/day$$

Finally, it can be said that the energy extracted in the anaerobic digester in the form of biogas is $6092{,}69\ MJ/day$.

To conclude this section, two important things have been calculated. The first one is the power needed in the heater for running the anaerobic digester. The second one is the energy extracted in form of biogas out of the microalgae introduced in the digester. Thus:

$Q_{heater} = 0{,}648\ \ kJ/day$

$Q_{extracted} = 6092{,}69\ Mj/day$

6.1.5 Upgrading

One of many products from anaerobic digestion is biogas. There are a few applications for biogas. The biogas produced would have to be upgraded depending on the application. The first application of choice is heating. Biogas does not require upgrading to be used for heating. It is wise to not upgrade the gas that will be used for heating because it costs energy to upgrade gas. Biogas can be applied to heat houses and the biogas plant must be heated for the production. Part of the gas produced from the plant will be used to warm the plant. Another application of biogas is to use it as a fuel for vehicles. Then, the gas must be upgraded to natural gas quality to be used as vehicle fuel.

It is chosen that the biogas will be upgraded with the physical absorption method because it is easy, it requires few infrastructures and it is cost effective. Pressurised water will be used as an absorbent in a counter-current. The water absorbs CO_2 and H_2S. The facility designed by Y. Xiao is used as an example. (Xiao, 2013) A schematic design of the facility can be found in Figure 34.

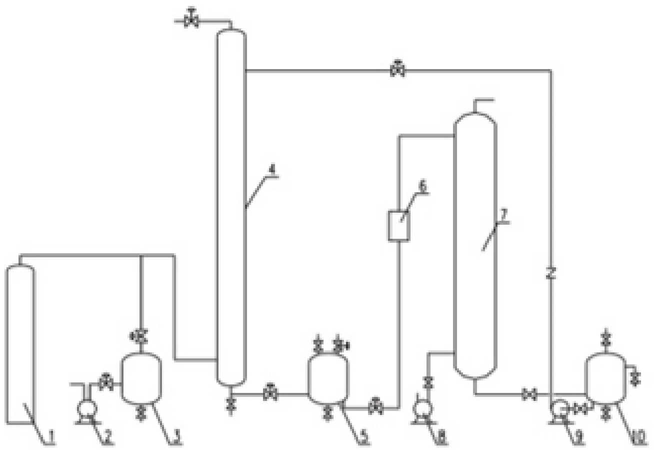

Figure 34 Facility for scrubbing biogas (Xiao, 2013)

Where:
1. CO_2 cylinder 2. Air compressor 3. Gas buffer tank 4. Absorption tower 5. Rich solution tank 6. Heat exchanger 7. Desorption tower 8. Air blower 9. Water pump 10. Lean solution tank.

The biogas is pumped into the absorption tower from the bottom with 400 l/h. Water is sprayed from the top with 200 l/h. Upgraded gas is collected from the top. Saturated water is drained from the bottom to the rich solution tank, from where it will pass through the heat exchanger before it enters the desorption tank. The water will lose its CO_2 and H_2S to air in the desorption tank. The water will be stored in the lean water tank after desorption. The water can be re-used in the absorption tank.

The water that leaves from the absorption tank will contain CO_2 and H_2S. This water can be used in the cultivation of algae. (Biogas in North America, 2013) Algae will consume CO_2 and H_2S as a nutrient. The facility can be significantly simplified when the waste water can go straight to the cultivation pond. An example of the simplified upgrading facility is shown in Figure 35. This experimental absorption system has a water pump and one air pump.

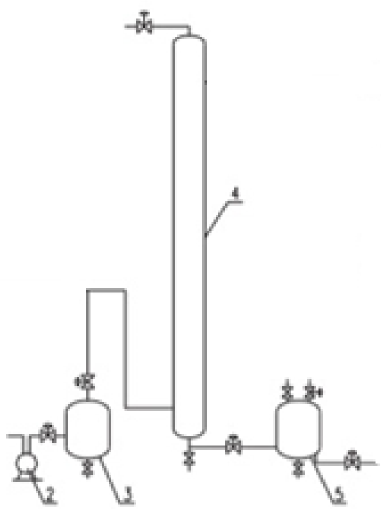

Figure 35 Simplified facility for scrubbing biogas (Xiao, 2013)

It would be interesting to buy an industrial scrubber device. There are few different types of scrubbers on the market such as the spray-chamber, cyclone spray, impingement, orifice and the venturi. The spray chamber has the lowest energy requirement and the lowest efficiency of 90% and the venturi scrubber has the highest energy need and the highest efficiency of 98%. (IEEE GlobalSpec, 2011)

One report from Daniel Mussatti reported typical fan and pump requirements for types of scrubbers. (Mussatti, 2002)

Table 26 Fan pump requirements (Mussatti, 2002)

Type of scrubber	Pressure gpm	Pump power watt	Fan power watt	Total energy need J/m^3
Wet cyclone	60	678,59	1864,25	7229,68
Venturi	20	173,75	2938,06	905,30
Jet venturi	70	2,45	0	6954,06

The venturi scrubber clearly requires the least amount of total energy per cubic metre of gas according to this report. The venturi type of scrubber would be preferred knowing that it has the most efficiency and it has a low energy need in Mussatti's report. It was found that another report showed that one example of an industrial venturi scrubber requires 3180 J/m^3 with a liquid/gas ratio of 9,2/170 m^3/h. (Harris, 1965) The venturi type scrubber has a significant difference in energy requirements in different situations. Further research on the venturi scrubber was done to get information on the energy requirements.

6.1.5.1 Venturi scrubber

The venturi scrubber uses the energy from the inlet gas stream to atomise the liquid being used to scrub the gas stream. A venturi scrubber has a converging section, a throat section and a diverging section. The gas stream enters the converging section from the top. The area decreases towards the throat, which increases the gas velocity. The gas should travel at very high velocities in the small throat section. The gas shears the liquid from its walls, producing an enormous number of very tiny droplets. The gas stream mixes with the fog of tiny droplets in the diverging section. This is where absorption happens.

Figure 36 Venturi scrubber (Liewendahl, 2012)

6.1.5.2 Wärtsilä: single entry open loop system

Wärtsilä, a Finnish manufacturer of power services, is a supplier for gas scrubbers. These scrubbers are used at boats to clean the gas exhaust from the engine. They will be used as an example for the scrubber that the algal plant will have because it is very representative of gas scrubbing with a focus on carbon dioxide. The system is a venturi type. A single entry open loop system is chosen as an example. Wärtsilä provides a product guide with the dimensions of the product. The dimensions can be found underneath. The scrubber dimensions mainly depend on the exhaust gas mass flow and the necessity to limit the gas velocity within the scrubber to 3-3,5 m/s. The scrubber can be chosen using the gas mass flow that is produced by the anaerobic digester or gas from the digester can be saved in a tank and pumped to the scrubber in a desired gas mass flow.

Table 27 Dimensions of single entry scrubber (Wärtsilä, 2014)

Dim.	Description	1 MW	2 MW	4 MW	6 MW	8 MW	11 MW	15 MW
	Exhaust Gas Mass Flow kg/s	2.15	4.30	8.60	12.90	17.20	23.65	32.25
A	Vessel Diameter (mm)	850	1350	1750	2000	2500	2900	3500
B	Overall Length (mm)	1730	2240	3295	3850	4660	5360	6250
B1	Overall width (mm)	1250	1580	1980	2240	2740	3140	3660
C	Outlet height (mm)	4020	4460	4835	5810	6150	6935	8205
D	Inlet height (mm)	4670	5200	7015	8495	9635	10665	12130
E	Drain below base (mm)	40	120	150	190	250	315	595
F	Scrubber inlet height (mm)	1480	1660	2050	2435	2985	3330	3680
X	Difference between bottom part and inlet (mm)	0	0	200	200	250	150	300
S	Distance between support (mm)	690	745	745	790	1015	1160	1260
N1	Inlet nominal bore (mm)	400	600	900	1100	1300	1500	1700
N2	Outlet nominal bore (mm)	400	600	850	1000	1100	1300	1600
N3	Drain nominal bore (mm)	150	200	273	400	400	450	500
	Dry weight (tonnes)	1.2	2.0	2.8	4.1	5.9	7.4	10.4
	Wet weight (tonnes)	1.5	2.7	3.7	5.4	8.6	11.5	16.9
Hw	Water level (mm)	600	500	435	420	550	580	610
	Water weight (tonnes)	0.30	0.7	1.0	1.3	2.8	4.1	6.5

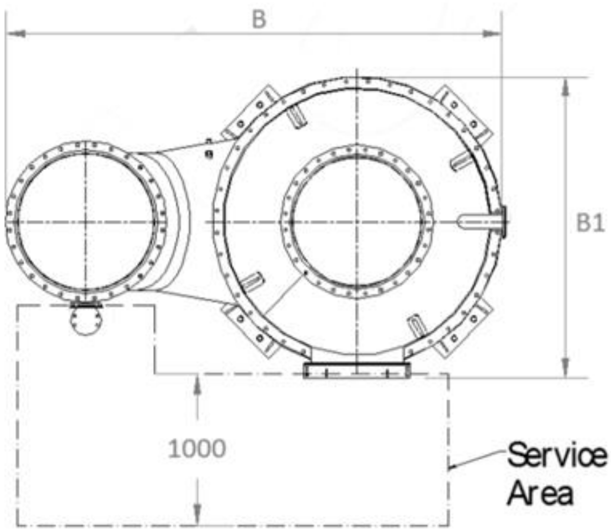

Figure 37 Single entry scrubber (Wärtsilä, 2014)

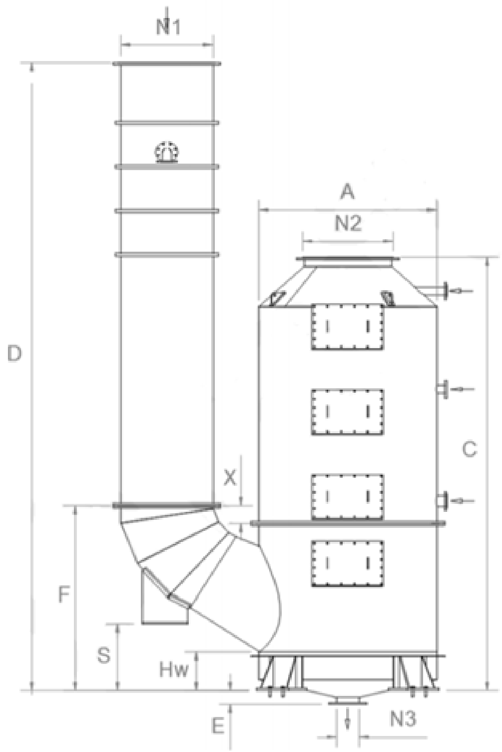

Figure 38 Single entry scrubber (Wärtsilä, 2014)

6.1.5.3 Energy need per cubic metre

The weight of the biogas has to be determined to know how much energy is required. It is known that raw biogas contains mainly methane, quite a lot of carbon dioxide and some traces of other compounds. The biogas content will be simplified to 60% methane and 40% carbon dioxide. Methane has a density of 0,656 kg/m^3 and carbon dioxide has a density of 1,98 kg/m^3. This adds up to a density of 1,19 kg/m^3 for the gas. One cubic metre of gas weighs 1,19 kg. The dimensions show that a gas mass flow of 2,15 kg/s will cost one J/s. This means that 1,19 kg/s requires a power of 0,55 J/s. So, one cubic metre requires 0,55 J for upgrading.

Scrubbed gas which contains a high amount of methane can be compressed to a high pressure. Compressed gas can be applied as an alternative for gasoline, diesel fuel and propane/LPG. Combustion of compressed gas produces less undesirable gas than gasoline, diesel fuel and propane or LPG, and it is also safer when it is spilled. It is safer because gas is lighter than air so it disperses quickly when released.

Gas will be compressed to a volume which is less than one percent of the volume is has at standard atmospheric pressure. The final pressure will be between 20 and 25 MPa (2900-3600 psi). The minimum amount of work it takes to compress gas can be calculated with the following formula:

$$W = n * R * T * ln\left(\frac{V_2}{V_1}\right)$$

Equation 42

Where:

- n is the number of moles in the gas
- R is the gas constant [J/mol.K]
- T is the temperature [K]
- V is the volume [m^3]

The amount of work needed to compress one cubic metre of gas is calculated. It is assumed that the gas will be 100% methane and the temperature will be 10°C. The gas will be compressed to one percent of the initial volume. The final volume V_2 will be a hundred times smaller than the initial volume V_1 so the fraction V_2/V_1 will equal 0,01 at for any volumes.

$$W = \frac{0{,}656}{0{,}016043} * 8{,}314 * 283{,}15 * \ln(0{,}01) = 4{,}43 * 10^5\ J$$

The compressor is assumed to have an efficiency of 80%, which means that 20% of the energy used is lost. The energy requirement is therefore higher than the minimum energy that is calculated. The amount of energy needed to compress one cubic metre of scrubbed gas with 80% efficiency is 553,75 kJ.

Going from anaerobic digestion to gasoline is clearer now. Upgrading and compressing gas to use biogas as an alternative for gasoline costs $0{,}55+553{,}75*10^5 = 554{,}3*10^5\ J/m^3$.

6.2 Chosen system

Since all the calculations from the process steps are made, is it necessary to design a system that can be used on an industrial scale. The calculations before are made for one pond. In the calculations from the harvesting a few exceptions were made because the flow rates from the following part were needed.

6.2.1 Explanation

In first instance, it is necessary to calculate the time that the algae must be in the cultivation pond. The growth rate for the algae is 25 g/m^2.day so the number of algae in the whole pond that grows per day is 10,16 kg/day. (Murry, Drosg, & et al., 2015) When the algae are ready to be pumped out of the cultivation pond, the concentration of algae is 0,5 g/l. For the whole pond this means that the total amount of algae is 60 kg. When compared with the total amount of algae, it can be said that the algae is ready to be harvested after six days.

To make the system efficient it is chosen to cultivate in six ponds. If the system is made with six ponds it is possible to pump one pond towards the sedimentation tank every day.

What resulted from the calculations in paragraph 6.1.2 is that the algae need 2,55 days to settle in the sedimentation tank. So, every three days it is possible to pump the algae suspension from sedimentation tank towards the centrifugation. Therefore, three sedimentation tanks were chosen for the system. The table below gives an overview of the process in days.

Table 28 Timeline of the process

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
Cultivation										
Sedimentation										
Centrifugation										

The algae suspension is pumped through the sedimentation and centrifugation parts but after these steps is there always an overflow of water, which may contain residues of nutrients. These overflows are pumped back into a mixing tank in the beginning of the system. The recycled water is pumped into the mixing tank and mixed with new nutrients. The water/nutrients suspension can be pumped again into the cultivation pond.

The following figure shows the system until centrifugation, containing all the flows and pumps. The red lines and pumps indicate the recycling parts of the system.

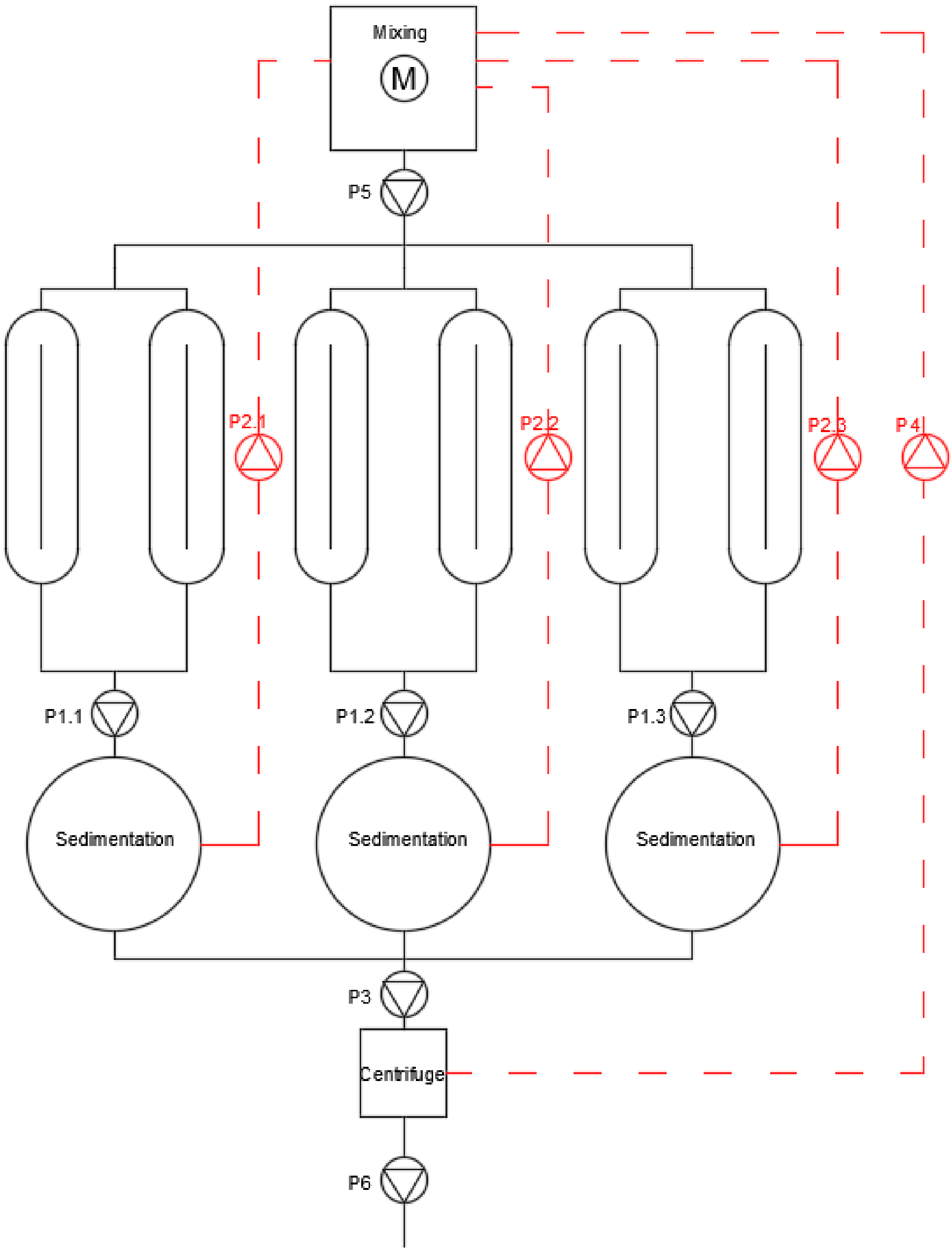

Figure 39 Process visualisation

6.2.2 Flows

The argumentation for the chosen system is done but the suspension flow from one part to another must also be calculated. This is done in the next chapter and like before it is split in the different system steps. The flows between different process steps have to calculated because they are necessary to make the energy balance of the whole system.

6.2.2.1 Cultivation

The process starts in the mixing tank, when the pump after the mixing tank fills the cultivation pond. The assumption was made to fill the cultivation tank in one hour which makes that the least amount of production time is used. The required energy for the pump will be calculated.

Pump cultivation pond full ➔ 1h ➔ 121880 l/h

Pump after cultivation ➔ 1h ➔ 121880 l/h

6.2.2.2 Sedimentation

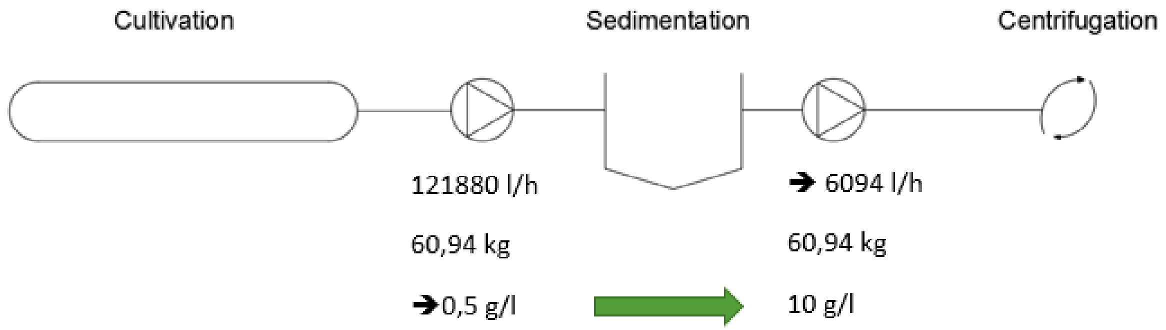

Figure 40 Schematic overview of sedimentation flows

In the pump after the sedimentation there is 10 g/l algae in the suspension, which gives a flow of 6094 l/h. (Collet & al., 2010) The rest of the water flows back into the mixing tank so the flow capacity of the pump for the recycling water should be at least 115786 l/h.

6.2.2.3 Centrifugation

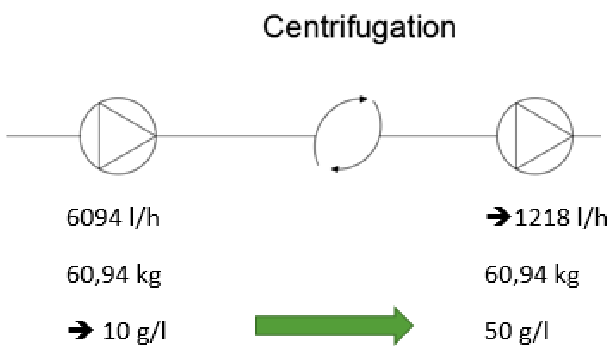

Figure 41 Schematic overview of centrifugation flows

The suspension after the centrifugation contains 50 g/l algae which makes that there is a flow of 1218 l/h. (Collet & al., 2010) The rest of the water flows back again to the mixing tank. The flow from the stream back to the mixing tank is 4876 l/h.

In total, there is an overflow of 120662 l/h. So, it can be said that theoretically almost all the water can be recycled. However, in practice it is not possible to re-use all the water because the nutrient content in recycling water is very low and also heat losses occur during the process (water heating up again).

6.2.3 Time schedule system

After the system with all its components and the flows are determined, it is possible to determine the time that is needed for each component. Thus, the time for doing one cycle can be defined and after that the amount of cycles during the production period can be defined.

Table 29 Time schedule system

<table>
<tr><th colspan="16">Time schedule system</th></tr>
<tr><td>Day</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td></tr>
<tr><td>Cultivation pond 1</td><td colspan="6">1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cultivation pond 2</td><td></td><td colspan="6">2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cultivation pond 3</td><td></td><td></td><td colspan="6">3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cultivation pond 4</td><td></td><td></td><td></td><td colspan="6">4</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cultivation pond 5</td><td></td><td></td><td></td><td></td><td colspan="6">5</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cultivation pond 6</td><td></td><td></td><td></td><td></td><td></td><td colspan="6">6</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sedimentation tank 1</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">1</td><td colspan="3">4</td><td></td><td></td><td></td></tr>
<tr><td>Sedimentation tank 2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">2</td><td colspan="3">5</td><td></td><td></td></tr>
<tr><td>Sedimentation tank 3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">3</td><td colspan="3">6</td><td></td></tr>
<tr><td>Centrifuge</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td></tr>
<tr><td>Anaerobic digestion</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="5">1</td></tr>
</table>

The time schedule is determined for the system with six cultivations ponds, three sedimentation tanks, a centrifuge and the anaerobic digestion tank. As said before, the production time is from March until September. As can be seen in the schedule above, one cycle takes 15 days so during the production period it is possible to do 14 cycles. This means that the whole production period will be 210 days. A further explanation for this is given in the next paragraph.

The goal of the process is to reach a continuous process and therefore it was chosen to start every cultivation pond one day after the previous one. From the second cycle on, the ponds are filled and work every day of the production period. With this, all the components have a continuous flow.

There is a special situation for the anaerobic digester because the duration of this process takes 28 days and the process starts on day 11. This means that at the end of the production period, the anaerobic digester will work almost a month longer. The process can work longer because the anaerobic digestion does not require light whereas the light is one of the most depending factors for the cultivation process. (S.Tedesco & Montingelli)

6.2.4 Operating hours

In this paragraph, all the operation hours for the different components were calculated so they can easily be used in the energy balance later. In first instance, a timeline was made with the operating hours that each component must work. This timeline for the operation hours is based on the time schedule of the system in Table 29. A remark for the following schedule is that the pumps are designed to work one hour to pump the suspension from one place to the other. They are based on the calculated working hours. The abbreviations can be found in the explanations below.

Table 30 Time schedule for the process components

Time schedule process components															
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
PW1															
PW2															
PW3															
LS															
HS1															
P1.1															
P1.2															
P1.3															
P2.1															
P2.2															
P2.3															
P3															
P4															
CF															
EX															
P5															
P6															
HS2															

6.2.4.1 Paddle wheel (PW1, PW2, PW3)

First, the working hours for the paddle wheel were calculated. As mentioned before, the system was designed to reach a continuous system. This means that the paddlewheel must work during the whole production period.

As can be seen in Table 30, one cycle takes 15 days and after that, the amount of days within the period from March to September was calculated.

$$March - September = 214\ days$$

The following factor that was determined, is the amount of cycles that can be done during the period.

$$Amount\ of\ cycles = \frac{214\ days}{15\ days} = 14{,}26\ cycles$$

The decision was made for doing 14 cycles within this period, even though this is shorter than the 214 days. The decision to round off to 14 cycles was made because otherwise the production period would have to be longer and there would not be enough light. The total number of production days will then be:

$$Amount\ of\ production\ days = 14\ days \ast 15\ days = 210\ days$$

With this, the operation hours for the paddlewheel can be calculated.

$$Operation\ hours\ paddlewheel = 210\ days \ast 24h = 5040\ hours$$

The paddle wheel must work for 5040 h.

6.2.4.2 Lighting system (LS)

The lighting system must work for 1681 hours as explained in Chapter 6.1.1.4.

6.2.4.3 Heating system (HS1)

The next chapter is about the operation hours for the heating system. The heating system has the same number of operating hours as the paddle wheel because the heating system must work during the entire production process.

$$Operation\ hours\ paddlewheel = 210\ days * 24h = 5040\ hours$$

6.2.4.4 Pumps 1.1-2.3 (P1.1-2.3)

As mentioned in the introduction of this chapter, the pumps are calculated to pump the suspension in one hour. The following pumps each work two hours per cycle, Table 30 gives a better explanation of this fact.

$$Operation\ hours\ pumps\ 1.1 - 2.3 = 2\ h/cycle\ * 14\ cycles = 28\ hours$$

6.2.4.5 Pump 3 (P3)

The following pump that is been calculated is pump 3. This pump provides the flow from the sedimentation tank to the centrifuge. The pump must work from day 10 to day 15 in the process and that means it must work for six days during one hour.

$$Operation\ hours\ pump\ 3 = 6\ days * 1\ h * 14\ cycles = 84\ hours$$

6.2.4.6 Pump 4 (P4)

Pump 4 pumps the recycled water after the centrifuge back to the mixing tank and must work at the same time as pump 3.

$$Operation\ hours\ pump\ 3 = 6\ days * 1\ h * 14\ cycles = 84\ hours$$

6.2.4.7 Centrifugation (CF)

In this paragraph, the operation time for the centrifugation cylinder will be determined. Since no specific value for the operation hours of a centrifugation tank could be found, the decision was made to make an assumption. So, like for all the pumps, the centrifugation cylinder is assumed to work for one hour per pond.

With the working hours of the centrifugation, the total operation time of the entire process can be calculated. In the time schedule system can be seen that after the start up stage the centrifugation works for every day, being 210 days.

6.2.4.8 Extraction (EX)

In this chapter, the operation hours of the extraction system will be determined. In each cycle, the extraction must work for one hour to extract the high value products out of the suspension. Six tanks are included in the system and they will work for 14 cycles. The operation hours are calculated as follows:

$$Operation\ hours\ extraction = 6\ tanks * 1\ h * 14\ cycles = 84\ hours$$

6.2.4.9 Pump 5 (P5)

The next component is the pump that pumps the slurry from the mixing tank to each pond every day. As mentioned above, the pumps work only for one hour during every day of the process, because the cultivation ponds work continuously.

$$Operation\ hours\ pump\ 5 = 210\ days * 1h = 210\ hours$$

6.2.4.10 Pump 6 (P6)

The pump P6 is the pump that pumps the slurry from the centrifugation to the extraction or anaerobic digester. As known from before, after the start of the procedure the pump has to work every day because the centrifugation provides the pump with suspension every day.

$$Operation\ hours\ pump\ 6 = 210\ days * 1h = 210\ hours$$

6.2.4.11 Heating system 2 (HS2)

The last component is the heating system for the anaerobic digester. The system time schedule shows that the anaerobic digester starts working on day 11. From that moment on, the anaerobic digester works for 210 days because every day, suspension is pumped from the centrifugation to the anaerobic digester. The process in the anaerobic digester takes 28 days. In first instance the amount of working days is calculated.

$$Operation\ days\ in\ anaerobic\ digester = 210\ days + 28\ days\ working\ time = 238\ days$$

If the amount of days for the process is known, it is possible to calculate the total operating hours.

$$Operation\ hours\ anaerobic\ digester = 238\ days * 24\ h = 5712\ hours$$

Knowing the total amount of operating hours, these values can be used for determining the energy balance.

7 Energy balance

In this chapter, the energy balance for this system will be covered. First, an explanation about what an energy balance is and how it can be made will be given. After that, the energy balances for three different scenarios will be made, being respectively 100% anaerobic digestion, 100% extraction and 50% anaerobic digestion - 50% extraction. The explanation and argumentation are based on the Belgian course book 'Energiebalansen' by Marc Lintermans. (Lintermans, 2014-2015)

The energy balance is required to investigate if producing biogas or high valuable products from microalgae grown in the Nordic climate is feasible.

7.1 Introduction

According to the law of conservation of energy, the total amount of energy, being the inputs and the outputs, is always the same. A device 'consumes' energy and transforms this energy input into a different energy output. It is not possible to have energy losses within the system or to 'create' energy. With energy losses is meant that a part of the energy inputs is transformed into an unusable energy form because energy cannot disappear. For example, an electric motor is used to convert electrical energy into mechanical energy. The efficiency of an electric motor is never 100% and these 'energy losses' occur in stator and rotor, which are the moving and non-moving parts of the motor. These losses will end up as unusable heat. (Lintermans, 2014-2015)

The drafting of an energy balance is basically the first step in optimising the energy consumption of a system. By creating the energy balance, it acquires the necessary insights and knowledge of the various energy flows. If all the energy flows are known, it is possible to make an energy balance. This balance gives a good overview of the energy consumption for the system and it shows which part of the system has the highest energy consumption. When this is known, an improvement of efficiency can be considered for the highest energy consumer.

Energy balance = visualising every energy flow from a system to get an overview of the total energy consumption.

7.2 Approach

In first instance, the dimensions of every part of the system had to be determined. When these were determined, the energy consumption per part could be calculated. All these energy consumptions were summarised in one table to give an overview of the total energy consumption of the algae production plant.

Three different scenarios were investigated, respectively 100% anaerobic digestion, 100% extraction and 50% anaerobic digestion - 50% extraction. The first energy balance deals with the scenario that all the cultivated algae will be transformed into biogas in the anaerobic digestion plant. In the second scenario, all the algae will flow to the extraction plant to extract lipids of the algae to make high valuable products. The third energy balance is a combination of both scenarios. Here, 50% of the algae will be transformed into biogas and the other 50% will be used to extract lipids out of it.

When all energy balances are made, a conclusion will be given for all these different scenarios and after that, options for improvements.

7.2.1 100% anaerobic digestion

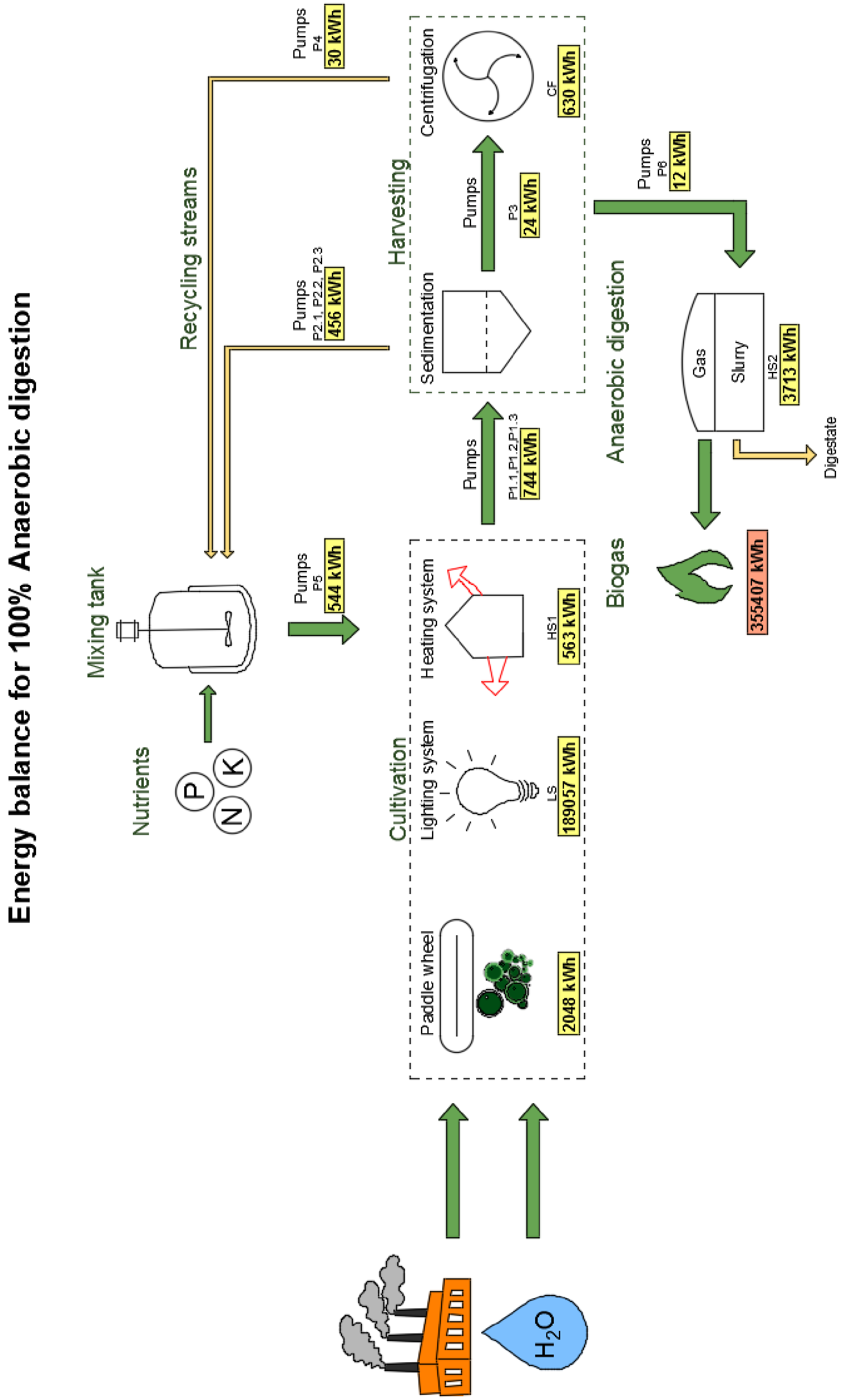

Figure 42 Energy balance for 100% AD

In this paragraph, the first scenario for the energy balance is given for 100% of anaerobic digestion. In this scenario, the output of the system is 100% of biogas so no extraction takes place. In first instance a drawing was made, which can be seen in Figure 42, of the entire system in which all the energy consumptions and the energy gains were visualised. The energy consumptions of the different components are given in the yellow boxes, and the energy gains are given in the red boxes.

On the energy balance, the cultivation and harvesting are subdivided into the smaller parts of these two process steps. The cultivation is divided in the paddle wheel, lighting system and the heating system for the ponds. The harvesting is divided in sedimentation and centrifugation, but for the sedimentation no energy is required because this process is based on gravitational energy. The energy balance includes pumps as well. These pumps are needed to transport the algae suspension or recycle water towards another part of the system.

Table 31 gives an overview of all the process components with their power, operating hours and energy consumption. The operation hours are based on a production year, which is from March until September. Every component is also labelled with a number and the area where this component is located, is also mentioned. The labelling number can also be found in the Figure 42 with the energy balance.

Table 31 Overview of all the energy consumptions for 100% AD

Number	Component	Area	Power [kW]	Operating hours [h]	Energy consumption [kWh]
PW1	Paddle wheel	*Cultivation*	0,14	5040	683
PW2	Paddle wheel	*Cultivation*	0,14	5040	683
PW3	Paddle wheel	*Cultivation*	0,14	5040	683
LS	Lighting system	*Cultivation*	112,20	1685	189057
HS 1	Heat system	*Cultivation*	*	*	563
P1.1	Pump	*Cultivation*	8,84	28	248
P1.2	Pump	*Cultivation*	8,84	28	248
P1.3	Pump	*Cultivation*	8,84	28	248
P2.1	Pump	*Harvesting*	5,43	28	152
P2.2	Pump	*Harvesting*	5,43	28	152
P2.3	Pump	*Harvesting*	5,43	28	152
P3	Pump	*Harvesting*	0,29	84	24
P4	Pump	*Harvesting*	0,36	84	30
CF	Centrifuge	*Harvesting*	3,00	210	630
EX	Extraction	*Extraction*	0,00	0	0
P5	Pump	*Mixing*	2,59	210	544
P6	Pump	*Extraction*	0,06	210	12
HS 2	Heat system	*AD*	0,65	5712	3713
				TOTAL	**197819**

First, the power was calculated for each component in the dimensioning part and the results were summarised in the table. It is important to note that the energy balance is based on the chosen system with six cultivation ponds, three sedimentation tanks, etc., as can be seen in Figure 42. Also, there is one paddle wheel in every pond, but they are driven per two by one engine. This means that there are three engines for the six paddle wheels. After that, with the power of each component, the operating hours of each component per production year were determined in Chapter 6.2.4. A remark in Table 31 is that the power and the operating hours of the heating system, indicated with an asterisk, depend on the seasons, as explained in Chapter 6.1.1.6.

The energy consumption is the power multiplied with the operating hours. Finally, the total energy consumption is a summation of all the individual energy consumptions.

As a conclusion for the first energy balance can be said that the cultivation system (192410 kWh), the heating system of the anaerobic digestion (3725 kWh) and harvesting (1140 kWh) are the three highest energy consumers of the whole system with this scenario of 100% anaerobic digestion. In percentages, the cultivation system consumes 97,3% of the total energy consumption. Second comes the anaerobic digestion with 1,9% and third the harvesting with 0,6%.

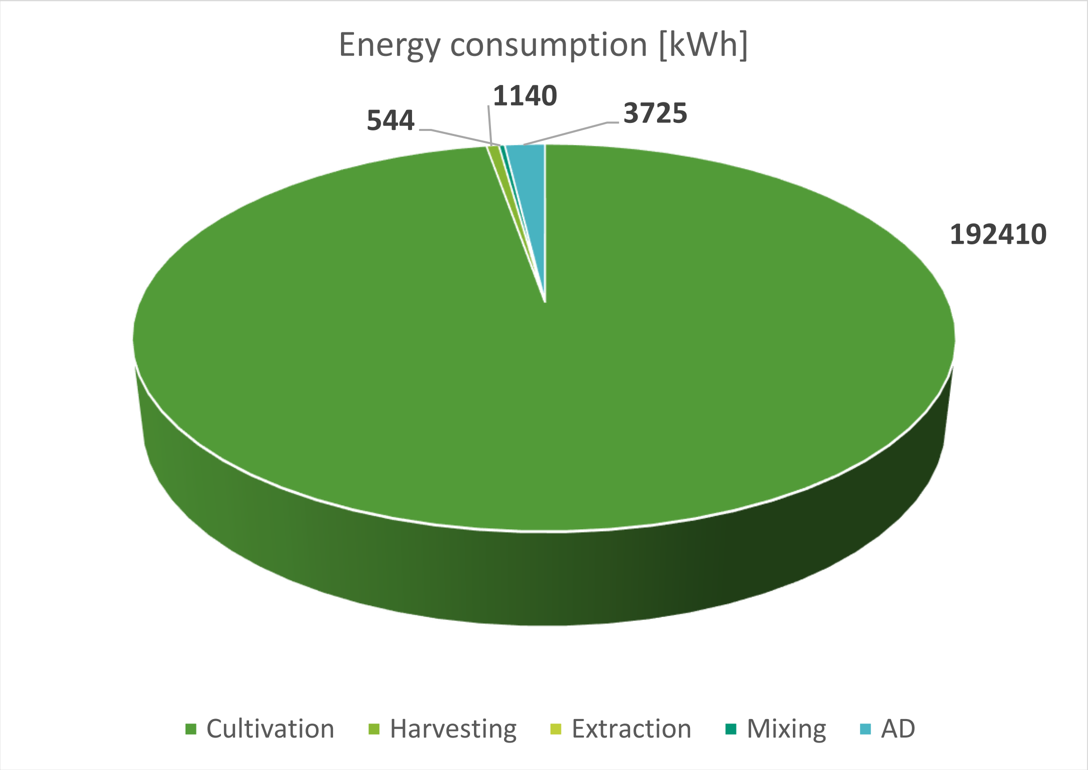

Figure 43 Energy consumption for 100% anaerobic digestion

To give a good overview of the energy balance, a visualisation was made to show the input and output of this scenario. This visualisation is made to see if the energy balance is positive or negative.

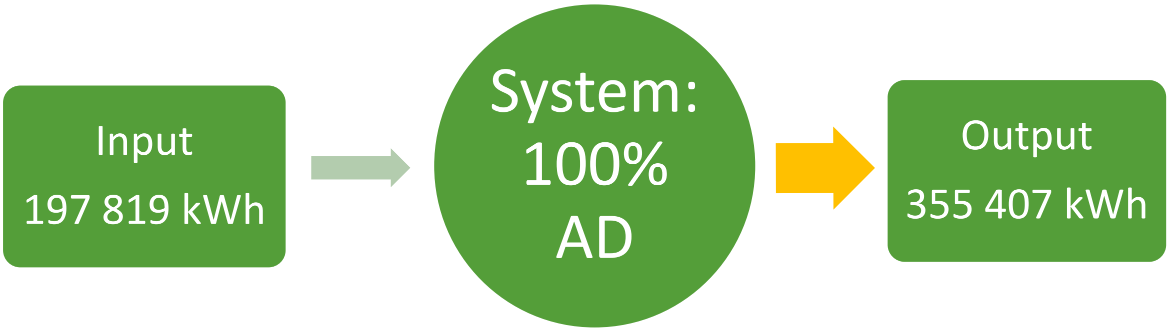

Figure 44 Result of the energy balance for 100% anaerobic digestion

For this scenario with 100% anaerobic digestion, the energy input of the system is 197819 kWh. The production plant produces 387503 kWh of biogas with this energy input. A comparison between these two values shows that if the production plant produces 100% biogas out of the algae, it results in a positive energy balance for this scenario.

7.2.2 100% extraction

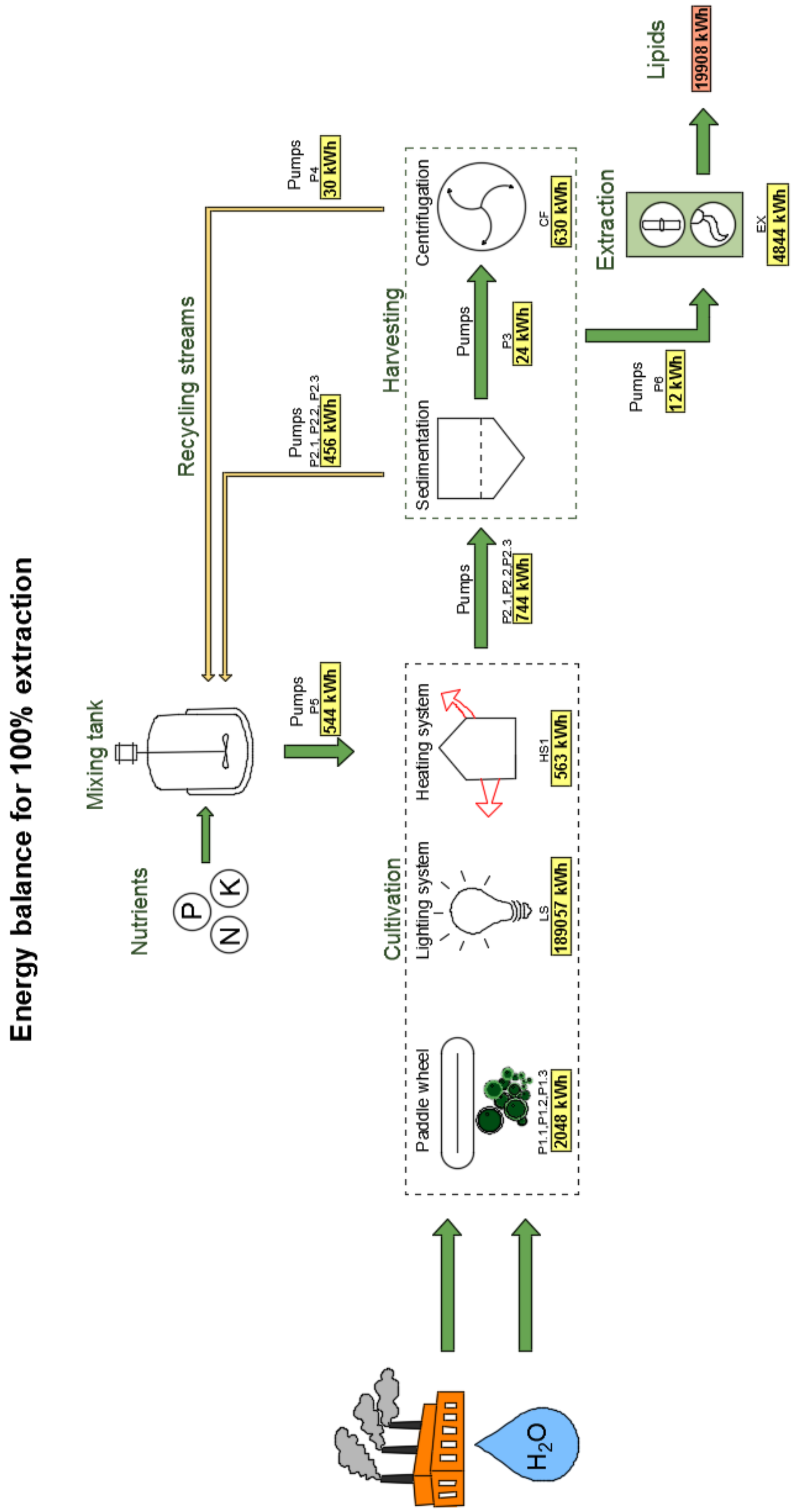

Figure 45 Energy balance for 100% extraction

The second energy balance was made for 100% extraction and will explained in the chapter below. As before, a drawing with all the energy flows was made. Compared with the energy balance from before, there is one difference. In for this energy balance, no anaerobic digestion will take place but instead all the matter will be used for extraction.

Until the centrifugation, the process is the same as before but in this case, the pump after the centrifugation pumps the suspension directly to the extraction tanks. In the extraction tank, the slurry is transformed into lipids or other high value products.

In the table below an overview of all the energy consumptions is given when 100% extraction is used.

Table 32 Overview of all the energy consumptions for 100% extraction

Number	Component	Area	Power [kW]	Operating hours [h]	Energy consumption [kWh]
PW1	Paddle wheel	*Cultivation*	0,14	5040	683
PW2	Paddle wheel	*Cultivation*	0,14	5040	683
PW3	Paddle wheel	*Cultivation*	0,14	5040	683
LS	Lighting system	*Cultivation*	112,20	1685	189057
HS 1	Heat system	*Cultivation*	*	*	563
P1.1	Pump	*Cultivation*	8,84	28	248
P1.2	Pump	*Cultivation*	8,84	28	248
P1.3	Pump	*Cultivation*	8,84	28	248
P2.1	Pump	*Harvesting*	5,43	28	152
P2.2	Pump	*Harvesting*	5,43	28	152
P2.3	Pump	*Harvesting*	5,43	28	152
P3	Pump	*Harvesting*	0,29	84	24
P4	Pump	*Harvesting*	0,36	84	30
CF	Centrifuge	*Harvesting*	3,00	210	630
EX	Extraction	*Extraction*	57,42	84	4844
P6	Pump	*Extraction*	0,06	210	12
P5	Pump	*Mixing*	2,59	210	544
HS 2	Heat system	*AD*	0,00	0	0
				TOTAL	**198950**

This table is almost the same as the one for 100% anaerobic digestion but the differences with the previous one are the values for extraction (EX) and the heating system (HS2). The calculations for this energy balance were done on the same way as the calculations for the first energy balance. So first, every component was dimensioned and second, the operation hours per component per production year were determined. Finally, the power of each component was multiplied with the operation hours and afterwards these values were summed up.

In this energy balance the components with the highest energy consumptions are again the lighting system and the heating system but the third highest value is the one for extraction. These values are further explained below with the graph.

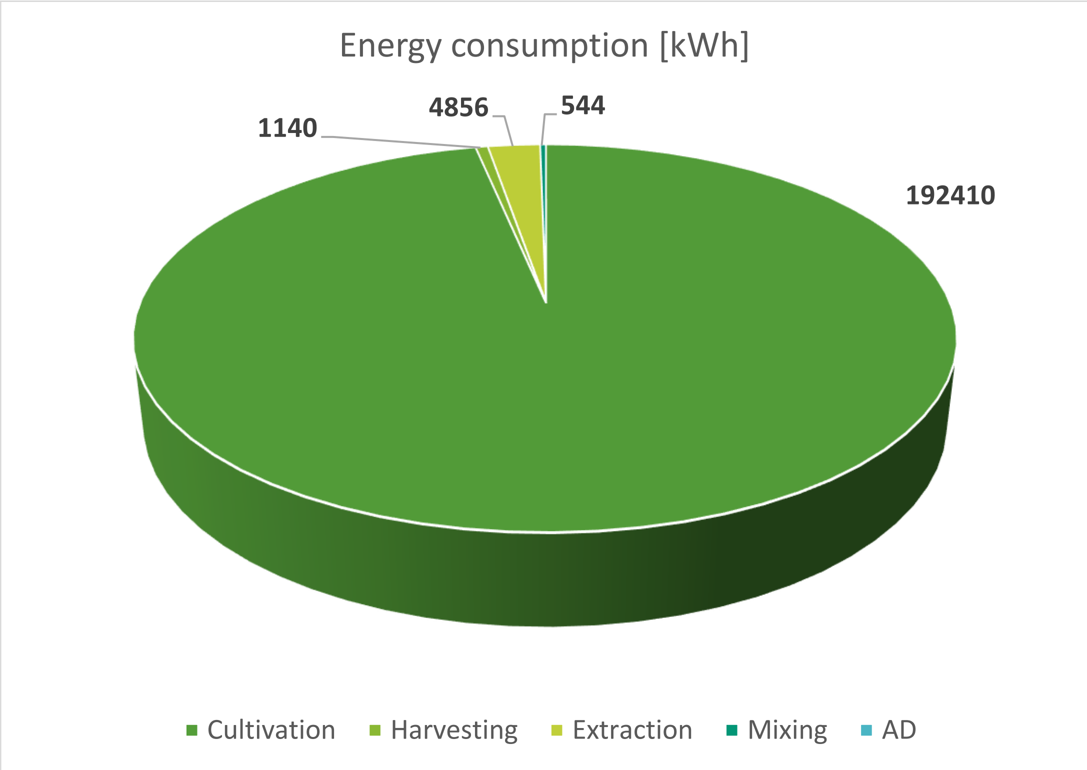

Figure 46 Energy consumption for 100% extraction

As mentioned before, the cultivation part takes more than 95% of the total energy consumption. The second largest energy consumer is the extraction with 2,5% of the total energy consumption. The cultivation and extraction parts account for 97,5% of the total consumption which is a lot because the amount of operation hours compared with mixing or harvesting is large.

The next figure gives a visualisation of the result of the energy balance for 100% extraction.

Figure 47 Result of the energy balance for 100% extraction

The total energy input for the system is 198950 kWh and the total energy output is 19908 kWh. The output is ten times smaller than the input. In conclusion, the energy balance for this scenario is negative because the output is smaller than the input.

7.2.3 50% anaerobic digestion – 50% extraction

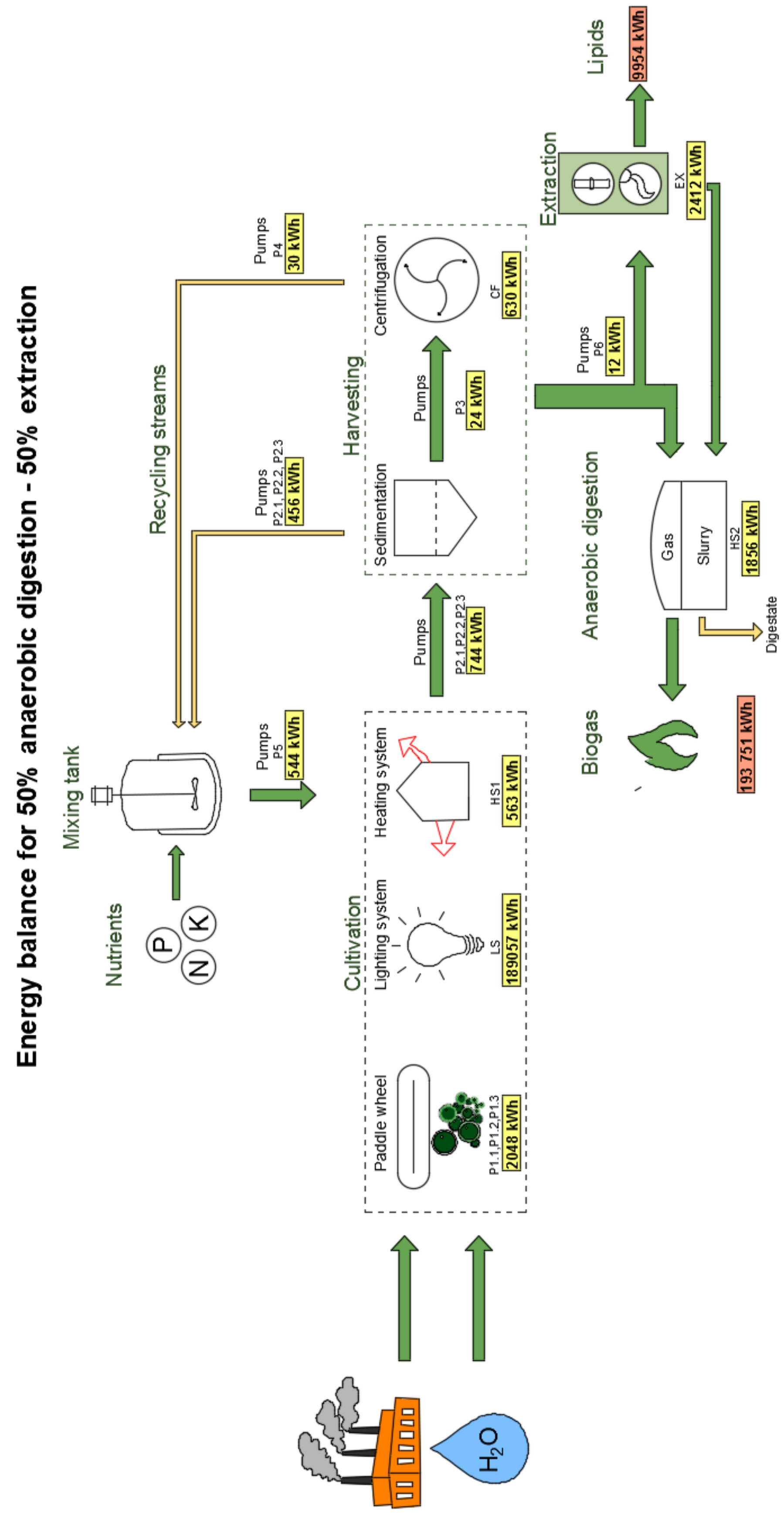

Figure 48 Energy balance for 50% AD-50% extraction

In this paragraph, the third scenario is explained. This scenario includes 50% anaerobic digestion and 50% extraction. This means that 50% of the produced algae flows to anaerobic digestion and 50% flows to the extraction plant. The table below gives an overview of the energy consumptions of this scenario.

Table 33 Overview of all the energy consumptions for 50% AD-50% extraction

Number	Component	Area	Power [kW]	Operating hours [h]	Energy consumption [kWh]
PW1	Paddle wheel	*Cultivation*	0,14	5040	683
PW2	Paddle wheel	*Cultivation*	0,14	5040	683
PW3	Paddle wheel	*Cultivation*	0,14	5040	683
LS	Lighting system	*Cultivation*	112,20	1685	189057
HS 1	Heat system	*Cultivation*	*	*	563
P1.1	Pump	*Cultivation*	8,84	28	248
P1.2	Pump	*Cultivation*	8,84	28	248
P1.3	Pump	*Cultivation*	8,84	28	248
P2.1	Pump	*Harvesting*	5,43	28	152
P2.2	Pump	*Harvesting*	5,43	28	152
P2.3	Pump	*Harvesting*	5,43	28	152
P3	Pump	*Harvesting*	0,29	84	24
P4	Pump	*Harvesting*	0,36	84	30
CF	Centrifuge	*Harvesting*	3,00	210	630
EX	Extraction	*Extraction*	28,71	84	2422
P6	Pump	*Extraction*	0,06	210	12
P5	Pump	*Mixing*	2,59	210	544
HS 2	Heat system	*AD*	0,325	5712	1856
				TOTAL	**198384**

As can be seen in Table 33, the total energy consumption of this scenario is 198384 kWh. The distribution of the energy consumptions is similar to the previous scenarios. Most of the energy consumption is from the lighting system just as in the previous energy balances. Noticeable in this table is that all the components consume energy in this scenario because both anaerobic digestion and extraction are used.

To visualise the energy consumptions, a pie chart was used. The next figure shows the distributions between all the different energy consumptions.

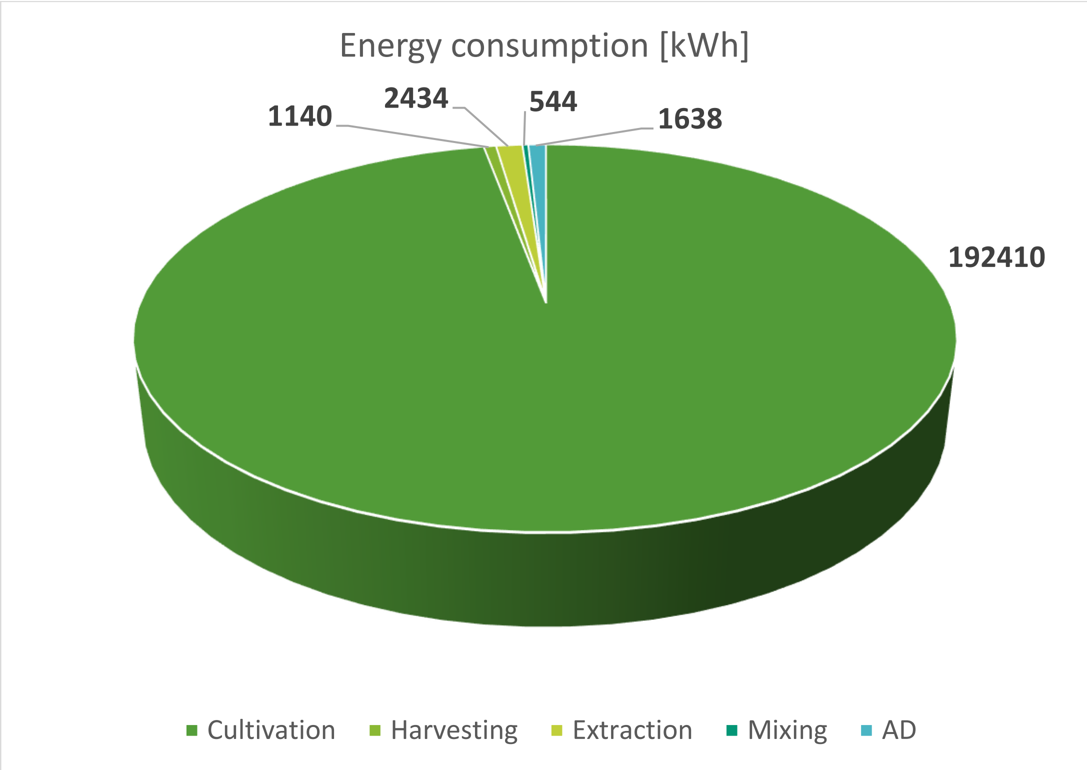

Figure 49 Energy consumption for 50% AD-50% extraction

In the next figure can be concluded that the cultivation system, the extraction and the anaerobic digestion consume the most energy in this scenario. Like the other scenarios, the cultivation system consumes the most with 97% of the total energy consumption. Second, the extraction has an energy consumption of 1,2%. Third, the anaerobic digestion consumes 0,9% of total energy consumption.

For this scenario, also a visualisation was made to compare the energy input and output. This can be seen in the next figure.

Figure 50 Result of the energy balance for 50% AD - 50% extraction

The system has an energy input of 198384 kWh and an energy output of 193751 kWh in this scenario. A comparison between those two values gives a slightly negative energy balance if 50% of the algae is transformed into biogas and the other 50% is extracted.

7.3 Improvement of energy balance

The three energy balances in the previous paragraphs had one major similarity, namely the high energy consumption of the lighting system. Only the first energy balance, with 100% biogas production, was positive. In conclusion, a technical optimisation is required to reduce or cover this very high energy consumption. If a solution can be found for this issue, the energy balances could become positive.

A solution to cover this energy consumption of the lighting system is to make use of solar panels, as mentioned before in paragraph 6.1.1.4.

7.3.1 Implementing solar panels

In the next paragraphs research is done to implement solar panels for covering the energy consumption of the lighting system. First, the number of solar panels that is required was calculated. Second, the dimensions of the required surface were calculated to determine if it is possible to place these panels near the production plant. Last, an economic calculation was made to determine the payback time of the solar panels to prove if it is feasible for an investment.

7.3.1.1 Introduction

Solar panels provide numerous benefits compared to a conventional thermal power plant. For example, there are the financial advantages and the energy is produced quickly. In addition, solar panels require little maintenance and they have a life span of at least 25 years. The benefits for the environment are the main advantage. (Maehlum, 2014)

The location of the plant has the largest influence on the dimensioning of the system. For this project, no specific location was allocated, only the Botnia-Atlantica region with the Nordic climate. Thus the calculations are based on general values. First, the total required power is calculated. The general value of 900 kWh/kW$_p$ is used to determine the power. (Sideria, 2017)

The equation is:

$$Power = energy\ consumption * \frac{energy\ production}{kW_p} = 189047\ kWh * 900\frac{kWh}{kW_p} = 210\ kW_p$$

The number of solar panels is based on the power per solar panel given by the manufacturer. The choice was made for the SunPower X22-360 for its high-power value per panel and high average efficiency. A brief overview is given in the table and picture below. The whole datasheet can be found in Appendix VIII. (SunPower, 2017)

Table 34 Specifications of the SunPower X22-360 (SunPower, 2017)

Data solar panel SunPower X22-360	
Width [m]	1,05
Length [m]	1,56
Power/Solar panel [kW$_p$]	0,36
Avg. Panel efficiency [%]	22
Open circuit voltage [V]	69,5
Short-circuit current [A]	6,48

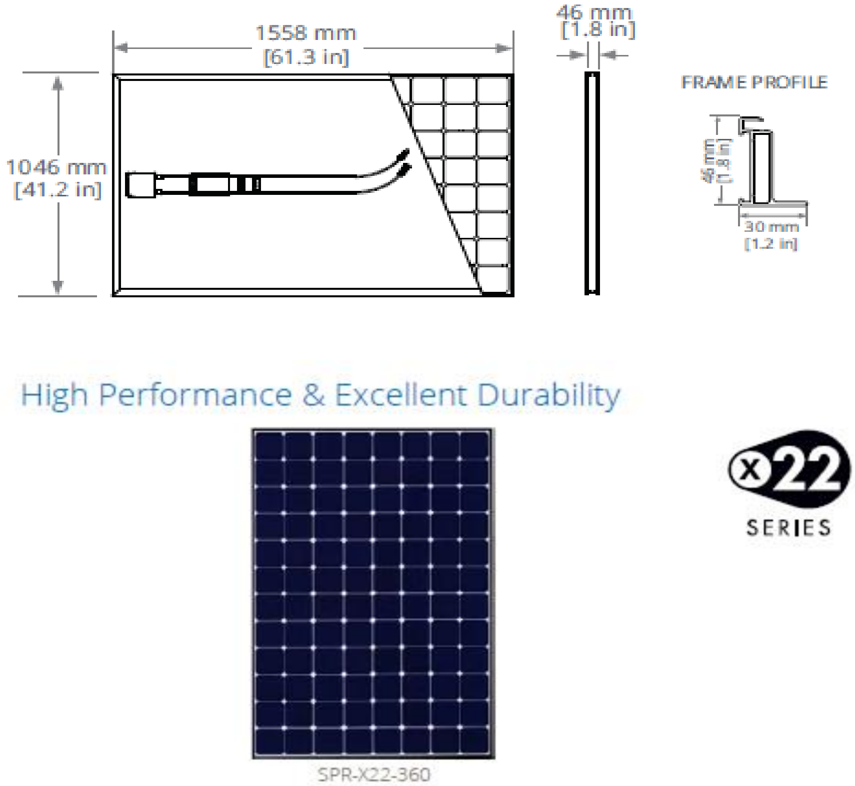

Figure 51 Technical specifications SunPower X22-360 (SunPower, 2017)

The number of solar panels that is required for producing 189047 kWh of energy can be determined with the power per solar panel and the total required power, calculated above.

$$Number\ of\ solar\ panels = \frac{Total\ power}{Power/solar\ panel} = \frac{210\ kW_p}{0.36\ kW_p} = 584$$

At first sight, this number of solar panels seems to be quite high. It must be kept in mind that this number of solar panels is demanded to generate equal energy as energy consumed with the lighting system. To criticise this value, further calculations are necessary to determine whether it is feasible or not.

7.3.1.2 Technical dimensions of solar panels

First, the surface is calculated with the dimensions per solar panel. To determine the surface, the total length and width of the photovoltaic power station is necessary. The technical dimensions of the SolarPower X22-360 given in Table 34 are used for these calculations.

First, it should be calculated how much panels fit next to each other in the width of the surface. Since no exact location was given, the assumption was made to take an available width of the surface of 100 metre. With that, the number of panels that can be placed next to each other per 100 metre can be calculated:

$$Number\ of\ solar\ panels\ in\ width = \frac{100\ m}{Width/panel} = \frac{100\ m}{1{,}05\ m} = 95$$

Now the number of lines required to put all solar panels can be calculated.

$$Number\ of\ lines = \frac{total\ number\ of\ solar\ panels}{number\ of\ solar\ panels\ in\ width} = \frac{584}{95} = 6{,}132 \rightarrow 7\ lines$$

The distance between these lines depends on the angle of the solar panels. When these panels are placed too close to each other, a line of solar panels will cast a shadow on another line of solar panels. This is must be avoided, because the energy production of solar panels is highly dependent on shading. For this application, an angle of 28° is used. This value is based on the height of the sun in Tampere, Finland. (Boxwell, 2017)

A picture of the calculator is shown below.

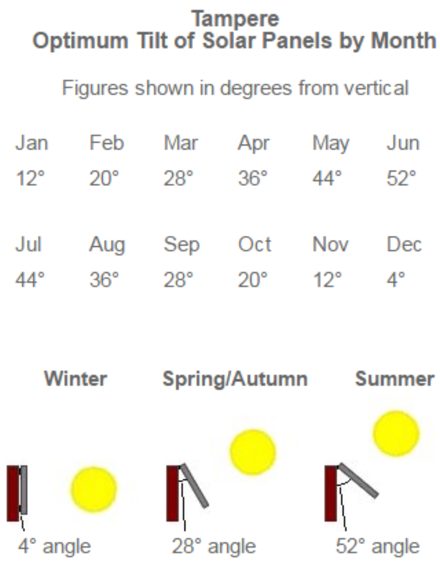

Figure 52 Solar angle calculator (Boxwell, 2017)

This figure shows the optimum angle for solar panels during every month of the year. A simplification was made by using the average angles for the four seasons. The figure shows that the required angle during the winter is 4°, during spring/autumn 28° and during summer 52°. The angle chosen for the calculations is 28° because it is the worst-case scenario for the solar panels. The solar panels can be adjusted to the position of the sun because they have an adjustable frame. The required angle of the solar panels during the winter can be neglected because the number of daylight is very low, so the production of energy is also very low. Another reason is that the algae production plant operates from March until September, so a battery station would be necessary to save this produced energy.

Next figure shows the situation of the lines of solar panels:

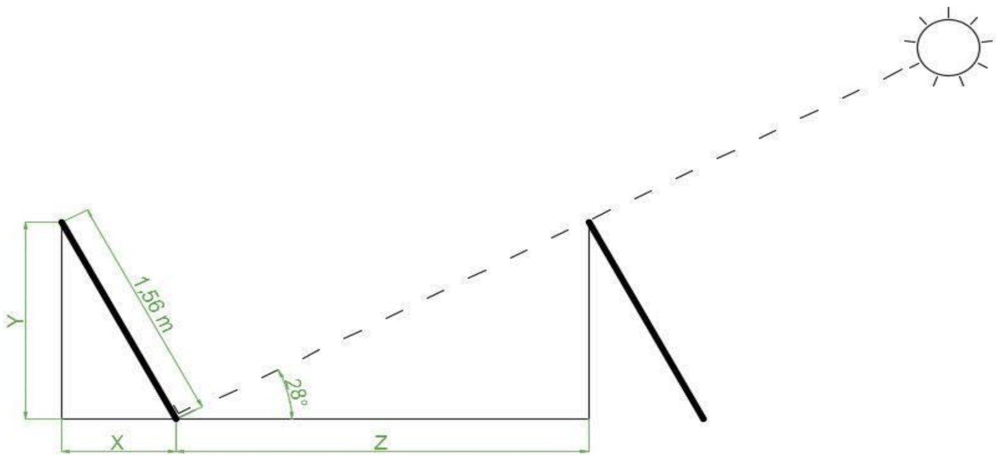

Figure 53 Distances of the solar panels

To calculate the distance between two lines of solar panels, Z, the dimensions X and Y are necessary to know. This is shown in the figure above. All the dimensions are calculated with trigonometric functions.

First, the height of the solar panels, Y, is calculated with the cosine:

$$Y = 1{,}56m * \cos 28° = 1{,}4\ m$$

Second, the length X is calculated with the sine:

$$X = 1{,}56m * \sin 28° = 0{,}73\ m$$

Third, the distance between two lines of panels, Z, can be calculated with the tangent:

$$Z = \frac{Y}{\tan 28°} = \frac{1{,}4\ m}{\tan 28°} = 2{,}6\ m$$

Now, the total distance of one line of solar panels is determined:

$$Distance = X + Z = 0{,}73\ m + 2{,}6\ m = 3{,}32\ m$$

This distance is the minimum required distance between two lines, so there is chosen for an extra margin of 5%. This value gives the total distance that takes place for one line:

$$Total\ distance\ per\ line = Distance + 5\% = 3{,}32\ m * 1{,}05 = 3{,}5\ m$$

With the total number of lines and the total distance per line, the total length of the photovoltaic field can be calculated:

$$Total\ length\ photovoltaic\ field = number\ of\ lines * \frac{total\ distance}{line} = 7 * 3{,}5\ m = 24{,}5\ m$$

Finally, the total surface of the photovoltaic field with the 584 solar panels can be calculated:

$$Surface = total\ length * total\ width = 24{,}5\ m * 100\ m = 2450\ m^2$$

At first sight, this appears to be a quite large surface required for the photovoltaic field, but compared to the surface of the cultivation system, they both have approximately the same surface.

Another important parameter is the payback time. To determine this, the investment cost is required. This can easily be calculated with the general value of 1,50 €/W_p. This value includes the investment and the installation of a solar panel. (Livios, 2017)

$$Total\ cost = 1{,}50\ €/W_p * total\ power = 1{,}50\ €/W_p * 210000\ W_p = €315000$$

The payback time of solar panels depends on several factors. These are:

- Price per solar panel
- Installation price
- Actual energy price
- Lifetime of the solar panels

The installation price is never accurately known and the actual energy price fluctuates through the year, so it is difficult to determine all these factors exactly. Therefore, the calculations were made with a general value. The payback time of the total photovoltaic field can now be determined with the price that these solar panels generate on electricity per year.

$$Payback\ time = \frac{Total\ cost}{(Total\ electricity * price\ per\ kWh)} = \frac{€315000}{\left(189047kWh * 0{,}15\frac{€}{kWh}\right)} = 11\ years$$

Concluding, it can be said that it is worthwhile to invest in these solar panels to reduce the energy consumption of the lighting system. The total price for investment and installation is rather high, but it is a normal price for a total number of 584 solar panels. A payback time of 11 years is approximately expected for this application. The average payback time is around 10 years. (Santhanam, 2015) However, the payback can be reduced, for example, by the existence of various grants if this is applicable in the Nordic countries.

In this project, the choice was made to invest in all the 584 solar panels. With all these solar panels, it is possible to neutralise the energy consumption of the lighting system. This will also have a positive effect on the energy balance.

7.3.2 100% anaerobic digestion

In this paragraph, an energy balance was made without the energy consumption of the lighting system. The solar panels will cover this energy consumption. Figure 54 shows the distribution of the different energy consumptions. These consumptions are given in a pie chart to visualise this.

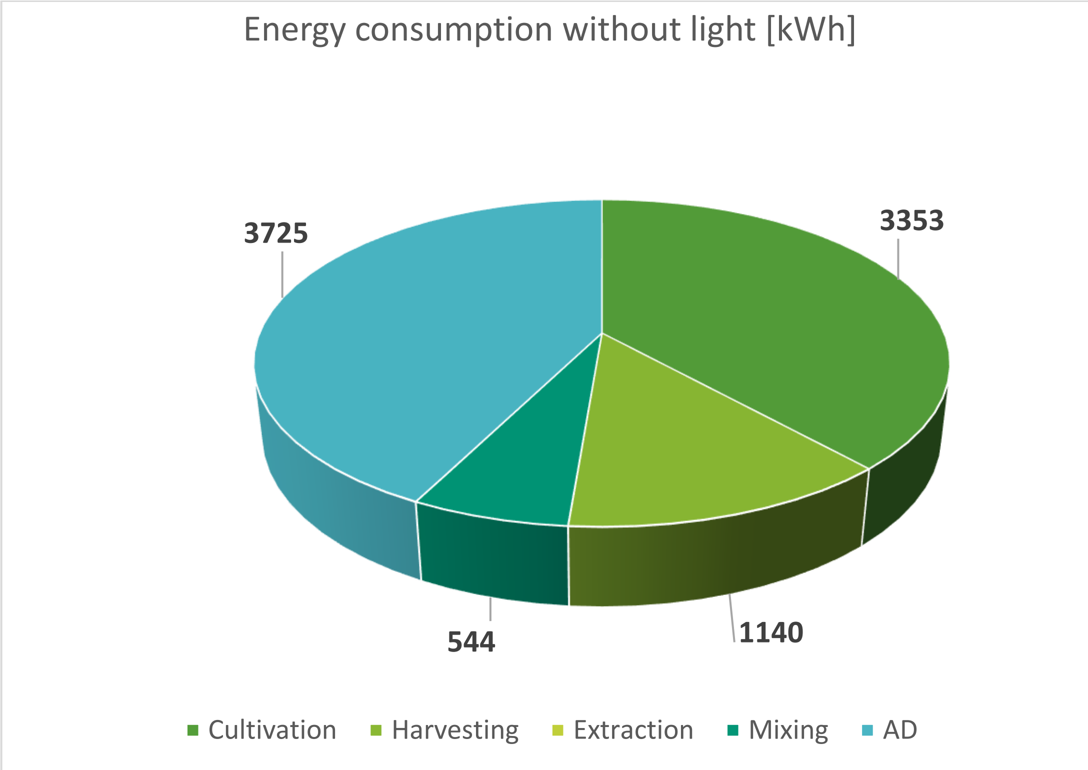

Figure 54 Energy consumption without light for 100% anaerobic digestion

For this scenario, the anaerobic digester is the highest energy consumer with 43% of the total energy consumption. Second, the cultivation system consumes 38% and third, the harvesting has an energy consumption of 13%. Compared to the previous energy balance with the lighting system included, the energy consumption of the cultivation part decreased with almost 60%. Anaerobic digestion and harvesting increased in percentage because the lighting system is not included in this energy balance. These two steps are now the two main energy consumers.

7.3.3 100% extraction

In this paragraph, a discussion of the results was made without considering the lighting. The lighting is not taken into account because it was chosen to use solar panels. As before, the results are visualised by means of a pie chart, and will be discussed below.

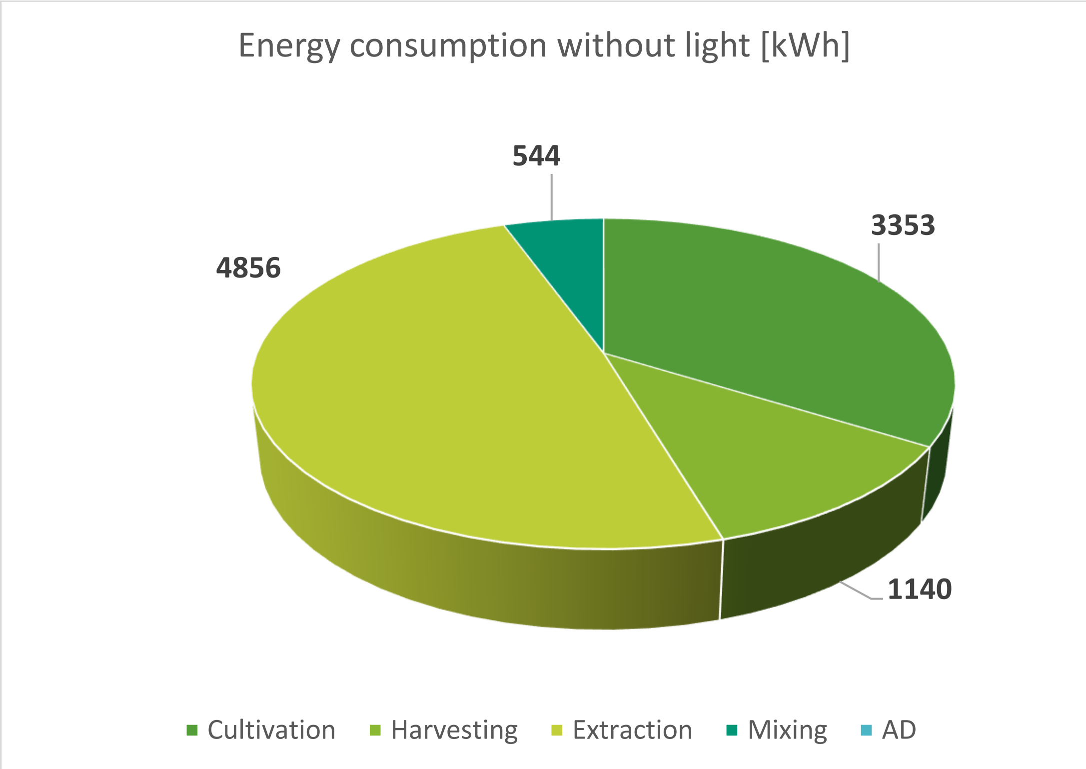

Figure 55 Energy consumption without light for 100% extraction

If the lighting is not considered the extraction accounts for 50% of the total energy consumption. This is an increase of over 40% compared to the situation with light. The extraction is in this case the largest energy consumer of the process. The major energy consumption for the process steps is moved from the cultivation to the extraction, so also for this situation, it can be concluded that light has a considerable influence on the energy balance.

In this new situation, the energy consumption for the cultivation is only 32% of the total energy consumption which is over 60% lower as before. Furthermore, the energy consumption for the other components remains the same but the total energy consumption is lower. This means that the percentage for each part is higher than before. It can be concluded that with this improvement, the extraction instead of the cultivation requires the most energy.

7.3.4 50% anaerobic digestion – 50% extraction

Finally, the situation with 50% anaerobic digestion and 50% extraction without considering the light was investigated. The same improvements as before were used.

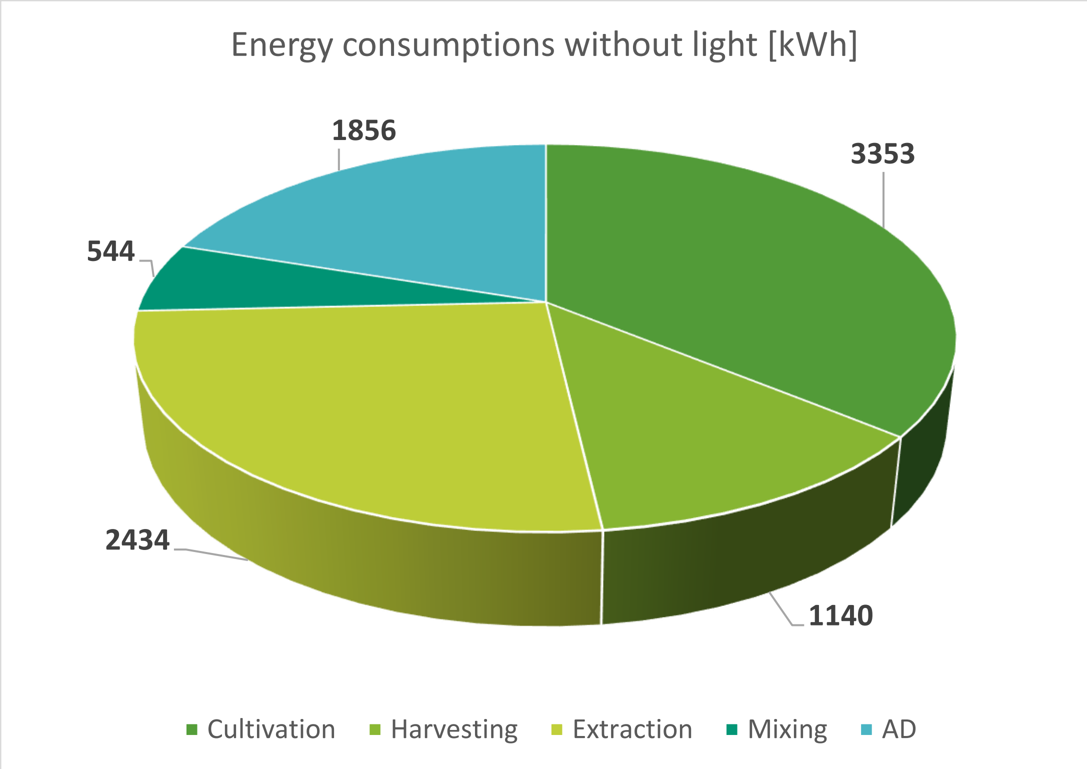

Figure 56 Energy consumption without light for 50% anaerobic digestion - 50% extraction

All the energy consumers are spread out over the different components of the system in this scenario. So, for the scenario 50% anaerobic digestion - 50% extraction cultivation still has de highest energy demand of the process with 36% of the total energy consumption. The second largest energy needs are for extraction and anaerobic digestion with respectively 26% and 20% of the total energy consumption.

In conclusion, cultivation is still the largest energy consumer for 50% anaerobic digestion – 50% extraction. However, in this case it is not a vast majority anymore.

8 Sensitivity analysis

The sensitivity analysis was done to understand the impact of variables on a given outcome. The impact of the climate and the bio-methane potential was analysed. The amount of daylight hours, the outside temperature and the BMP are the variables what were analysed. As a comparison, the energy need of one week of production is calculated in January, April, July and October. Even though during the months January and October there will be no production, these months are used to show the extremes and make the effect clearer.

8.1 Impact of daylight hours

The algae require light in the cultivation process to carry out photosynthesis. The aim is to have 24 hours of light for the cultivation every day. The number of daylight hours changes over the seasons, so during some periods more artificial light will be needed. The lighting system has a power of 112 kW.

Table 35 light analysis

	January	April	July	October
Daylight hours	6	15	19	10
Lighting hours per day	18	7	5	14
Lighting hours per week	126	49	35	98
Energy consumption per week [kWh]	114112	5488	3920	10976

The energy consumption of the lighting system changes significantly during the year. The largest difference is between winter and summer, where the energy consumption is 36 times higher in January than in July.

8.2 Impact of temperature

The water in the cultivation ponds should be 25°C when growing algae. The water source will be 20°C so all the water must be heated when starting the process. The energy requirement for warming up the water is calculated to be 2574 MJ.

$$Q_{water} = 122880\text{g} * 4190\frac{\text{J}}{\text{kg}\cdot\text{K}} * (25-20)\text{K} = 2574336\text{ kJ} <> 2574{,}336\text{ MJ}$$

$$Q = 2574{,}336\text{ MJ} = 215{,}93\text{ kWh}$$

Six ponds are used, and they all work for one week before the suspension goes to harvesting, so six ponds will have to be heated to a temperature of 25°C.

$$Q = 215{,}93 * 6 = 1295{,}58\text{kWh per week}$$

The greenhouse will lose warmth to the surroundings because of convection and has to be heated to stay on temperature. The sun irradiance adds heat to the greenhouse so the heat requirement will be the heat loss due to convection minus the sun irradiance.

The sun irradiance is dependent on the time of the year, so it is different every month. The power of the radiance was calculated in Chapter 6.1.1.6 and is displayed in the table below.

Table 36 energy of the sun irradiance

Month	kWh per day	kWh per week	Days	kWh/m² per month
Jan	0,27	1,89	31	8,37
Feb	1	7,00	28	28,00
Mar	2,35	16,45	31	72,85
Apr	3,89	27,23	30	116,70
May	5,49	38,43	31	170,19
Jun	5,68	39,76	30	170,40
Jul	5,31	37,17	31	164,61
Aug	4,04	28,28	31	125,24
Sep	2,47	17,29	30	74,10
Oct	1,1	7,70	31	34,10
Nov	0,44	3,08	30	13,20
Dec	0,14	0,98	31	4,34

The heat requirements are calculated below. The heat loss is a continuous process which goes on for 24 hours a day, and 7 days a week. One week has 168 hours. The values were calculated with the following formula:

$$Q_{requirement} = \frac{650{,}305m^2 * (25 - T_{outside})K}{0{,}844 \frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}} * 168hrs - Q_{irradiance}$$

Table 37 sensitivity analysis of the climate

	January	April	July	October
Average temperature [°C]	-6,6	1,7	15	4,3
Convection per week [kWh]	4090	3016	1294	2680
Irradiation per week [kWh]	1,89	27,23	37,17	7,70
Heat requirement [kWh]	4089	2989	1257	2672

The heat requirements change significantly with the seasons. For example, the heating system will have to work 3,25 times harder in January than in July. The heat requirement is approximately the same for the months April and October but the outside temperature is not the same in both months. The amount of light during these months has an influence on the heat requirement. The result of this analysis will be compared to the result of the lighting system in the next paragraph.

8.3 Other components

Some of the components are independent from light and temperature. Therefore, the energy consumption per week of these components was calculated separately in the following paragraph. The values for the working hours and power were taken from the energy balance. The energy requirement of other components in the algae bioenergy plant is summed up in the table underneath.

Table 38 regular energy requirements per week

Component	Working hours	Power [W]	Energy per week [kWh]
Cultivation: paddlewheel	24 hrs/day	67,70	11,37
Cultivation: pumps	0,93 hrs/week	8843,60	8,22
Cultivation: warming water	1 hour	1295,58	1295,58
Harvesting: pumps	0,93 hrs/week	5430,25	5,05
Harvesting: pump	2,8 hrs/week	285,80	0,80
Harvesting: pump	2,8 hrs/week	360,39	1,01
Harvesting: centrifugation	2,8 hrs/week	3000,00	8,40
Anaerobic digestion: heating	24 hrs/day	330,00	55,44
Total	**24 hrs, 7 days**	**Total**	**6654**

The components which are independent of the weather sum up to an energy need of 6654 kWh per week. Adding the components which are dependent on the weather will give the total energy usage.

8.4 Energy consumption in different seasons

As calculated above, the energy consumption for different weeks can be seen in Table 39. January represents winter, April is the spring, July is in the summer and October is in autumn.

Table 39 sensitivity analysis, energy consumption for different months (kWh)

	January	April	July	October
Lighting [kWh]	14112	5488	3920	10976
Heat requirements [kWh]	4088,56	2988,83	1257,28	2671,80
Other components [kWh]	6654,35	6654,35	6654,35	6654,35
Total	**24855**	**15131**	**11832**	**20302**

The difference between a week in July and a week in January is the most significant. A summer week like July requires about two-fifth of the energy that a winter week such as January needs. The energy needs for April and October are in between January and July but April is a better month to have an efficient system. It is advisable to make the system more energy efficient by not using it in cold months.

8.5 Methane production uncertainty

The anaerobic digester will produce somewhere between 197-337 litres of methane per kg of dry algae. (Ras, 2010) The amount of methane produced can be calculated by multiplying the CH_4 production with the mass flow [kg/s]. The mass flow is 0,0155 kg/s.

$$V_{maximum} = 337\ L_{CH4}/kg_{of\ DM} * 0{,}0155\ kg_{of\ DM}/s\ = 5{,}22\ L_{CH4}/s <> 451{,}31\ m^3_{CH4}/day$$

$$V_{minimum} = 197\ L_{CH4}/kg_{of\ DM} * 0{,}0155\ kg_{of\ DM}/s\ = 3{,}05\ L_{CH4}/s\ <> 263{,}82\ m^3_{CH4}/day$$

The amount of methane is used to calculate the amount of energy produced. The volume in m^3 will be multiplied with the specific heat [MJ/m^3.K] and the temperature difference [K] that it faces in the digester.

$$Q_{extracted,maximum} = 451{,}31\ m^3_{CH4}/day\ * 1{,}35\ MJ/m^3_{CH4} \cdot K * (35-25)K = 6092{,}69\ MJ/day$$

$$Q_{extracted,minimum} = 263{,}82\ m^3_{CH4}/day * 1{,}35\ MJ/m^3_{CH4} \cdot K * (35-25)K = 3561{,}57\ MJ/day$$

The maximum amount of energy extracted is around 6000 MJ and the minimum is around 3500 MJ. These values are converted to kWh in the following table.

Table 40 sensitivity analysis result of the BMP

	MJ/day	kWh/day	kWh/week	kWh/year
Maximum	6092,69	1692,41	11846,87	355407
Minimum	3561,57	989,33	6925,31	207759

The system is sensitive to the climate because the energy requirement for a production week can change between 11831,63 kWh in July and 24854,91 kWh in January. A production week in January requires 2,1 times more energy, therefore the system will be more effective when it is used in the warmer months only. The system is also sensitive to the uncertainty of the BMP, because the energy produced could be somewhere between 207759 kWh and 355407 kWh per year when all algae is used for biogas production. The minimum is 1,7 times less than the maximum. This uncertainty should be taken into account when planning an algae biorefinery plant.

9 Results and discussion

The Algae Energy project investigated the feasibility of growing algae in a Nordic climate by determining an energy balance for three different scenarios. The algae production process was split up in four parts: cultivation, harvesting, extraction, transformation and upgrading. Calculations were done to dimension all the required components of these parts.

The cultivation process includes four main components. First, the dimensions of the open raceway ponds were designed, based on a larger pond from earlier research. One pond is 63m x 6m and has a surface of 406 m^2. Six of these ponds are used in this project to provide a continuous cultivation flow of algae. The open raceway ponds will be installed outdoor and therefore placed in a greenhouse to protect every pond from the Nordic climate. These ponds require a lighting system for a steady growth in the Nordic climate. The lighting system includes 813 LED modules which consume 189047 kWh of energy every production year. Although this value is high, it is necessary to use this number of LED modules. The second important parameter for cultivating algae is the carbon dioxide supply. It was chosen to make use of flue gases that can be provided by industries. These flue gases are injected in the open raceway ponds. Thirdly, a heating system provides an optimal temperature between 24°C and 26°C in the open raceway ponds. The heat fluxes of the ponds were calculated first to determine the size of the heating system. The calculations were based on three types of heat fluxes: irradiation of the sun, convection through the glass and the heat produced by the heating system. Different seasons were considered in these calculations because they have a considerable influence on the size of the heating system. The heat loss in the winter is 23 kW and during the summer 7,7 kW. The total heat loss of one pond in a production year is 53069 kWh and the total heat gain from irradiance is 52506 kWh, thus the total energy consumption of the heating element is 563 kWh on annual base.

Harvesting is a process to separate the water from the algae slurry. Two techniques were used in this project: sedimentation and centrifugation. Since one sedimentation tank requires 2,5 day of sedimentation, three of these tanks were used to remove the majority of the water in order to get a continuous flow. After sedimentation, 6094 l/h of algae slurry flows to a centrifuge to remove the rest of the water. The size of the centrifuge is based on the flow after sedimentation and therefore a centrifuge, the Evodos 50, was selected. The power of this centrifuge is 3 kW and the energy consumption is 630 kWh every production year.

During extraction, lipids are extracted from the algae which can be used to make high valuable products. Six extraction tanks are considered to use. For every kilogram of algae, 3,89 kWh of energy is required to extract the lipids. This means that the total energy consumption in a production year would be 19908 kWh.

Transformation is the process that produces biogas out of algae. In this project, an anaerobic digester is used to produce 451,31 $m^3$of CH4 per day with an energy content of 1692,4 kWh.

Finally, an energy balance was made for three scenarios: 100% anaerobic digestion, 100% extraction and 50% anaerobic digestion – 50% extraction. The first scenario, 100% anaerobic digestion, consumes 197819 kWh of energy to produce 355407 kWh of biogas. The energy output is larger than the energy input, so the energy balance is positive. The second scenario, 100% extraction, has an energy consumption of 198950 kWh to produce 19908 kWh of high valuable products. This results in a very negative energy balance. The third scenario, 50% - 50%, consumes 198384 kWh to generate 193751 kWh of energy. This results in a slightly negative energy balance. To improve the energy balances, solar panels are added to improve the energy consumption of the lighting system. These solar panels will cover the total energy consumption of the lighting system. This results in positive energy balances for all three scenarios.

In general, it can be concluded that all the results of the calculations are reasonable. The only value that must be analysed critically is the power of the paddle wheel. This value seems too low with a power of 67,7 W. Several calculations were done to determine a reasonable power, but all these calculations resulted in the same range of power. For the calculations, most of the used values in this project are based on scientific papers. These values are indicated with a reference. Also, several assumptions were made for the calculations. As a remark for this project, the piping between the different process steps was not considered. This means that calculations for the pumps and the heat losses can give a distorted image.

10 Conclusions and recommendations

This project has given insights in the energy requirements of producing bioenergy from algae or producing high valuable products of it. This section will present the conclusions obtained in this project by answering the questions that were first raised in the introduction chapter. Those questions are the ones on which this project is based. First, the answers to the four sub-research questions will be given and with that, he main question can be answered.

The first sub question was *What could a production plant for algal biofuels in a Nordic climate look like?* No information was found for an existing algal biogas plant in the Nordic climate. The research on the Nordic climate resulted in the state of the art for the temperature and the daylight hours of various cities in Botnia-Atlantica. The average temperatures for these cities are displayed in Figure 57 and the average amount of daylight hours can be found in Figure 58. The average temperature and daylight hours are used to calculate the energy balance.

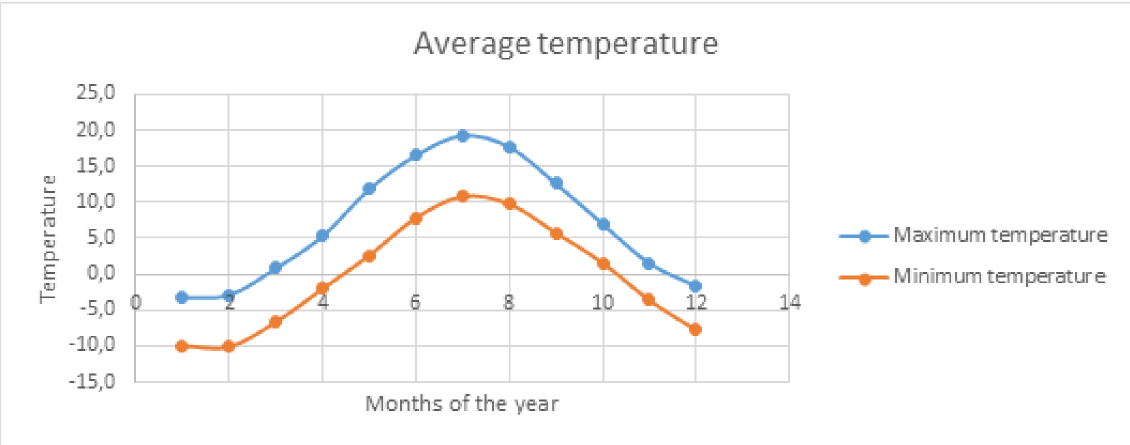

Figure 57 Average minimum and maximum temperatures

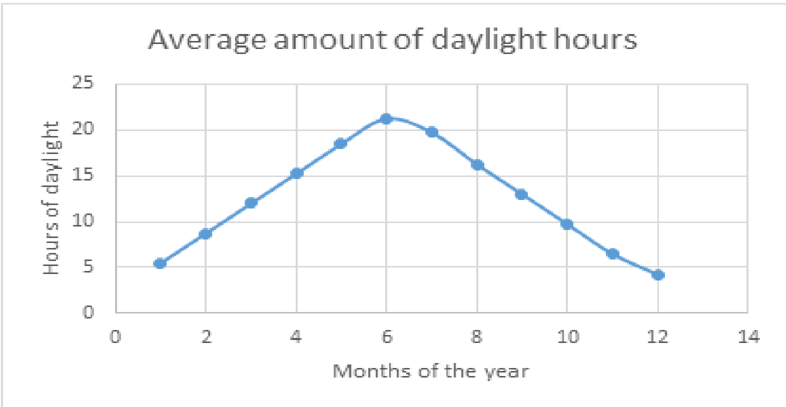

Figure 58 Average amount of daylight hours

To determine what the production plant could look like, state of the art research was done and with that, a production plant was designed. As it was developed in the project, the production plan is composed by four steps: cultivation, harvesting, extraction and transformation. Firstly, the algae is cultivated in six ponds within a greenhouse. Afterward, algae are separated from water in a sedimentation tank and a centrifuge due to their low concentration. The algae, already dried, goes to the extraction process where they are converted in high value products. Another path implies extracting biogas after the harvesting. Extraction and transformation process can be combined as the project shows.

Another question was *What is the production process for algal biogas and how does it work?* The production process is cultivation, harvesting, extraction and transformation. Algae are produced during six days, in six cultivation ponds. The biomass is harvested with a sedimentation and centrifugation step. The next step is extraction, which is an alternative for anaerobic digestion. Extraction is done with a solvent to get high-value products out of algae. The last step is transformation. Algae goes through anaerobic digestion to be transformed into biogas.

The next question was *What parameters have impact on the production process and how?* The main parameters are light, outside temperature, grow rate, cultivation temperature of algae and the bio-methane potential. The light impacts the production because the ponds will get light from a lighting system when the sun is not shining. This lighting system costs a lot of energy. The outside temperature influences the production process because the heating system has to work harder to keep the greenhouse at a temperature of 25 °C when it is cold outside.
The growth rate of algae impacts the cultivation time of the production process. This rate is a fixed parameter, so this parameter determines the cultivation time and the number of ponds. The number of ponds was chosen to be the same as the amount of days it costs to cultivate one pond so one pond can be harvested every day.
The cultivation temperature of algae is another parameter. Algae must be cultivated in water at a certain temperature to grow, this temperature is 20-29 °C for *Chlorella Vulgaris*. The production process is designed with a water temperature of 25 °C, which impacts the heat requirements of the greenhouse.
The bio-methane potential (BMP) is a parameter for the energy gain from anaerobic digestion. The BMP will be 197-337 litres of methane per kg of dry algae. The amount of methane that will come out of the algae is unsure and can be different than what was calculated with. This will have a significant impact, because the energy content of biogas is highly related to the bio-methane potential. The maximum BMP was used in the project, but using the minimum BMP will make the energy gain from anaerobic digestion 1,7 times smaller. This would change the results of the energy balance because for example, the output/input ratio for 100% anaerobic digestion will decrease from 1,80 to 1,06.

The final research question was *How to calculate the energy balance?* The energy balance is made by calculating all energy consumptions in a production scenario, adding them up and comparing them to the energy gain.

With the answers to these sub-questions, the main question could be answered. The main question was *What is the energy balance for the production of bioenergy and high value products from microalgae grown in Nordic climates?* The energy balance was calculated for three scenarios: 100% anaerobic digestion, 100% extraction and 50% for anaerobic digestion – 50% extraction. The ratio of the energy input and output is given in table 41. A higher ratio is preferred, because this means that the energy output is higher than the input.

Table 41 Energy balance ratios

	Without solar panels Energy output/input ratio	**With solar panels Energy output/input ratio**
100% anaerobic digestion	1,80	50
100% extraction	0,10	2
50% biogas, 50% extraction	0,98	20

In conclusion, the 100% anaerobic digestion system without solar panels is feasible because the ratio is higher than one. Also, all scenarios with solar panels have a positive energy balance.

Recommendations

Future tasks can be done to improve this project. Some of these tasks were not feasible within the given time, others were not done due to the lack of experience in this new matter. Tasks for a future project will be mentioned here.

First of all, a critical analysis should be done to the paddle wheel because of the low power value obtained in from the calculations. According to the result, a further investigation should be completed for the improvement of the cultivation part.

In the heat losses section, it has been assumed that the heater should supply all the heat needed to start the cultivation in three hours. If more or less time is assumed, more or less power is needed. That is, when the heat must be supplied in less hours, more power is needed in this element. Further investigations could determine the most feasible time for this process. Besides, in this part, inside the greenhouse two cycles have been considered for the radiation fluxes. For a more accurate result more cycles should have been measured. An iteration programme is recommended for a more precise result.

As mentioned in the limitations section, no processes outside the defined boundaries have been considered. For further research, a storage tank will be recommended after the anaerobic digester. Biogas pipelines to supply households, power plants or gas stations for vehicles could be an option as well. Another significant consideration for reducing the total heat input will be considering reflowing the remains of the extraction to the anaerobic digester so more biogas can be extracted out of the same initial matter. The heat that the substrate has after the digester could be utilized for different applications. Those applications will improve the total efficiency of the process.

Another significant factor to be considered in further investigations will be the lighting system. This process is the one that has the most influence on the final energy balance, because it is the one that requires the most energy input. The feasibility of the project will vary in a positive way if this parameter is changed. Thus, further options should be researched.

A possible step of this project could have been a Life Cycle Analysis (LCA), which could have been useful as a technique to assess environmental impact associated with all the stages involved in the system. Besides, a 3D model could be designed to facilitate the understanding of the different processes associated.

An economic analysis is recommended to get a greater understanding of the system, and to ensure the feasibility of the project. Although the positive energy balance seems to make the system achievable, it may not be profitable.

List of figures

List of tables

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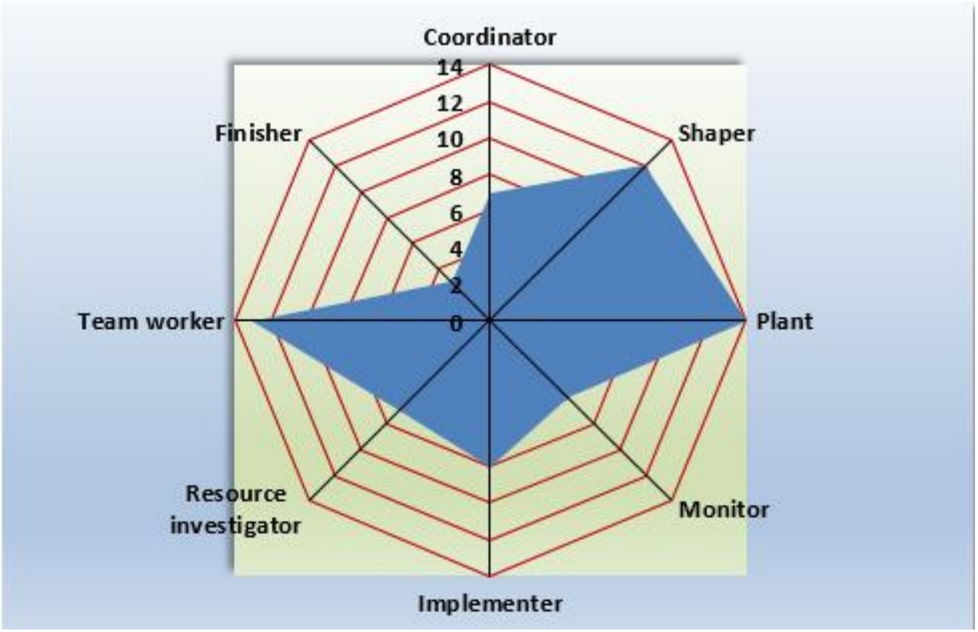
Appendices

Appendix I: Results of Belbin test

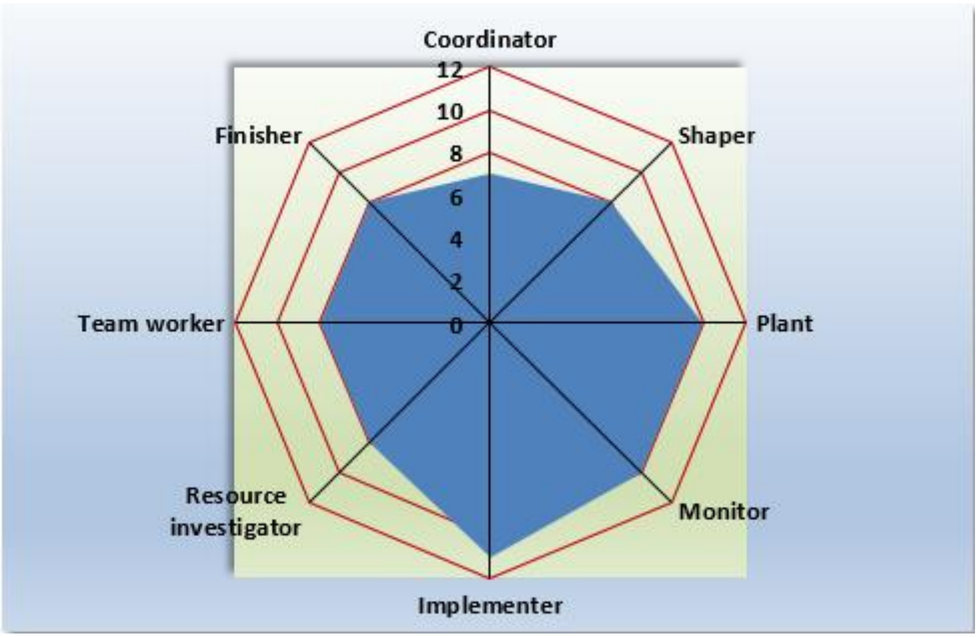
Every team member has done the Belbin test and the results can be seen on the next pages.

Alba Maqueda



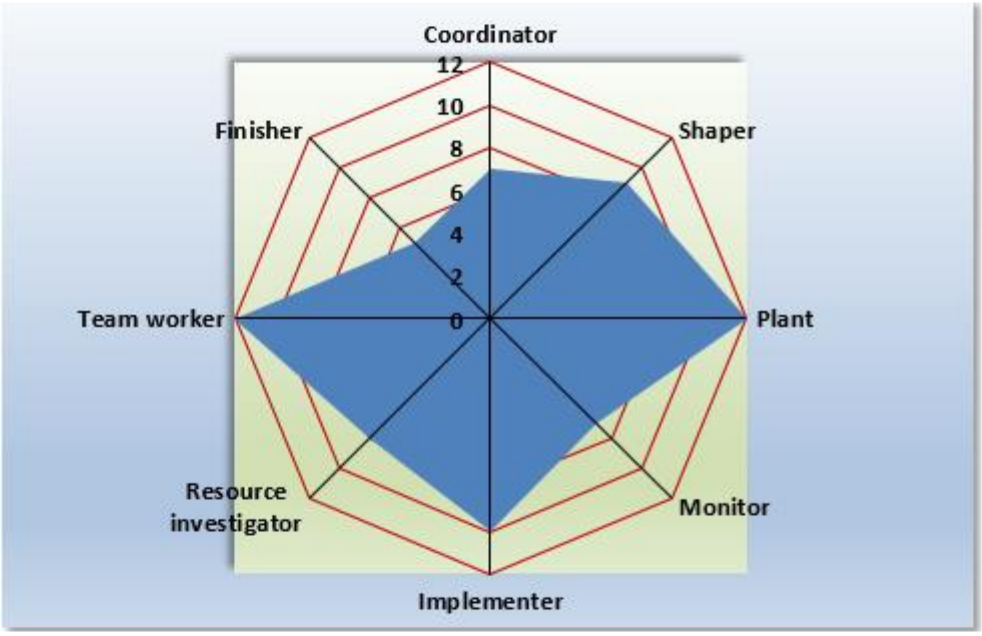
Result: Team worker, Plant, Shaper

Jelle Milbou



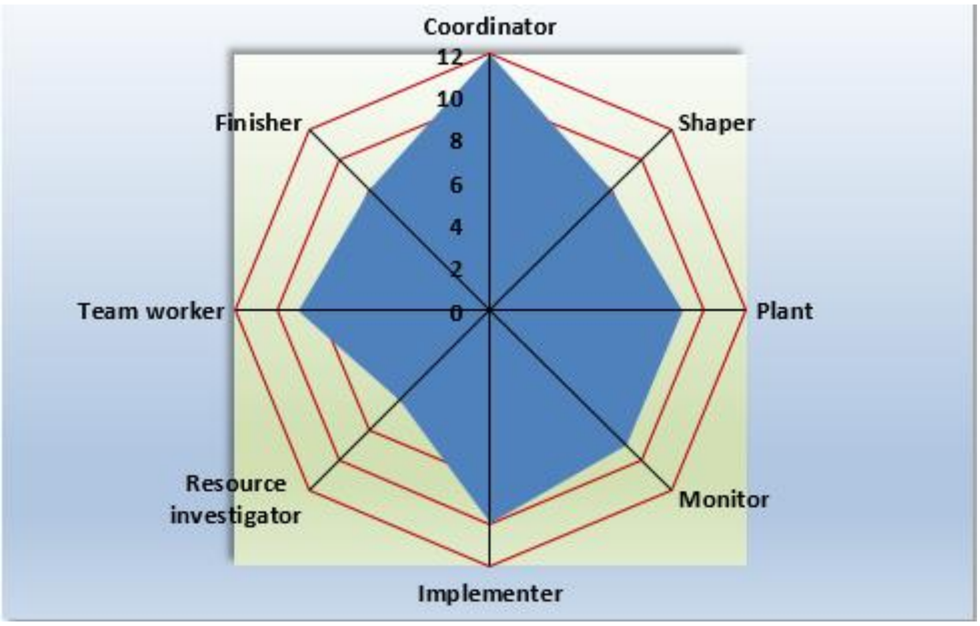
Result: Implementer, Monitor, Plant

Michiel Boeren



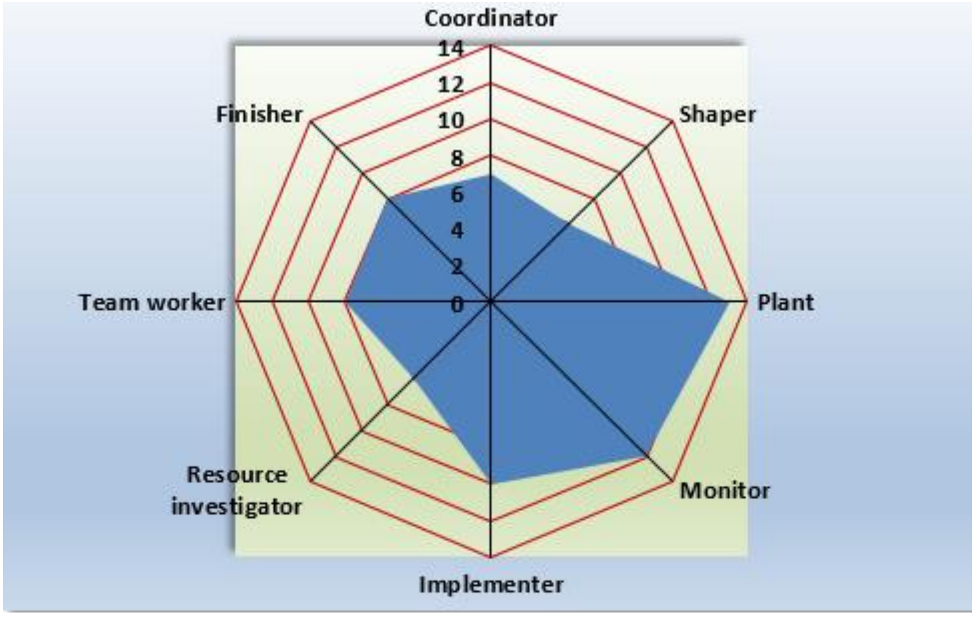
Result: Team worker, Plant, Implementer

Saskia van de Kerkhof



Result: Coordinator, Implementer, Plant

Lisette Spiering



Result: Plant, Monitor, Implementer

Conclusion

The result of these questionnaires tells us the team members all have one different role and have similar roles compared to each other. What can also be concluded is that everyone has the role ‘plant’, which can be useful to give creative solutions in the project. The major weakness of the group would be communication looking at the weakness of the role ‘plant’. Huge attention should be given to good communication between the team members and the supervisors to achieve success in this project. Another weakness of a plant might be that he/she has a lot of ideas without completing them. However, there is a monitor and coordinator in the group who can manage all the ideas.

The missing roles in this team are a finisher and a research investigator, so the team should collaborate well and do extra effort to compensate for the skills the team lacks. Other strong aspects of the group are teamwork and structured work because almost everybody is an implementer and team worker.

The group consists of three engineers which would be extremely useful for the calculations and general knowledge in our project. The other two team members are also very useful because of their different fields of study, being Physics and International Food & Agribusiness. They can give different insights during this project to achieve a good solution.

Appendix II: MS project Gantt chart

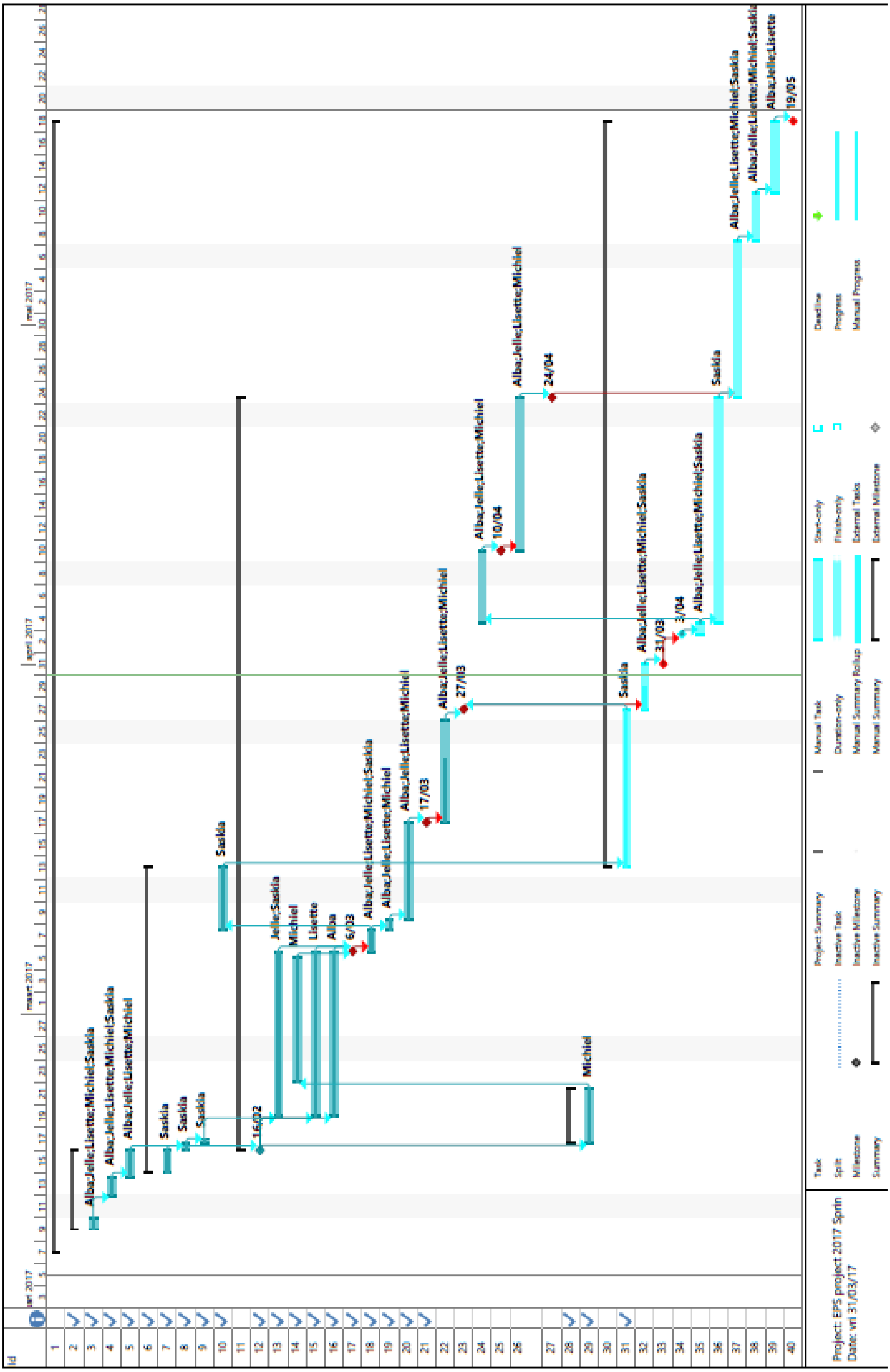
1/4

Id		Taa	Task Name	Duur	Begindatum	Einddatum	Voorafgaande taken	Resourcenamen
1			**Algae Energy**	**82,14 dagen**	**woe 8/02/17**	**vri 19/05/17**		
2			**Management**	**5,43 dagen**	**vri 10/02/17**	**don 16/02/17**		
3			Plan of requirements	1 dag	vri 10/02/17	vri 10/02/17		Alba;Jelle;Lisette;Michiel;Saskia
4			Belbin test	2 dagen	maa 13/02/17	din 14/02/17	3	Alba;Jelle;Lisette;Michiel;Saskia
5			Risk assessment	2,43 dagen	din 14/02/17	don 16/02/17	4	Alba;Jelle;Lisette;Michiel
6			**Identity**	**21,43 dagen**	**woe 15/02/17**	**maa 13/03/17**		
7			Design: Logo	2 dagen	woe 15/02/17	don 16/02/17		Saskia
8			Design: business cards	1 dag	don 16/02/17	vri 17/02/17	7	Saskia
9			Word template for the report	0,14 dagen	vri 17/02/17	vri 17/02/17	8	Saskia
10			Design: website on wordpress	4 dagen	woe 8/03/17	maa 13/03/17	18	Saskia
11			**System analysis**	**53,29 dagen**	**don 16/02/17**	**maa 24/04/17**		
12			Analysis Approach	0 dagen	don 16/02/17	don 16/02/17	5	Alba;Jelle;Lisette;Michiel;Saskia
13			Cultivation research	12 dagen	maa 20/02/17	maa 6/03/17	12;9	Jelle;Saskia
14			Harvesting research	8 dagen	don 23/02/17	maa 6/03/17	29	Michiel
15			Extraction research	12 dagen	maa 20/02/17	maa 6/03/17	12	Lisette
16			Transformation research	12 dagen	maa 20/02/17	maa 6/03/17	12	Alba
17			*Algae research: done*	*0 dagen*	*maa 6/03/17*	*maa 6/03/17*	*13;15;14;16*	*Alba;Jelle;Lisette;Michiel;Saskia*
18			Reading all other research information	2 dagen	maa 6/03/17	woe 8/03/17	17	Alba;Jelle;Lisette;Michiel;Saskia
19			Energy balance: meeting about the approach	1 dag	woe 8/03/17	don 9/03/17	18	Alba;Jelle;Lisette;Michiel
20			Dimensioning process components	7,57 dagen	don 9/03/17	vri 17/03/17	19	Alba;Jelle;Lisette;Michiel
21			*dimensioning done*	*0 dagen*	*vri 17/03/17*	*vri 17/03/17*	*20*	*Alba;Jelle;Lisette;Michiel*
22			Calculating first energy balance	6 dagen	vri 17/03/17	maa 27/03/17	21	Alba;Jelle;Lisette;Michiel
23			*First energy balance done*	*0 dagen*	*maa 27/03/17*	*maa 27/03/17*	*22;31*	*Alba;Jelle;Lisette;Michiel*
24			Sensitivity analysis	4,86 dagen	din 4/04/17	maa 10/04/17	35	Alba;Jelle;Lisette;Michiel
25			*Sensitivity analysis done*	*0 dagen*	*maa 10/04/17*	*maa 10/04/17*	*24*	*Alba;Jelle;Lisette;Michiel*
26			Energy balance: calculating different situations	11 dagen	maa 10/04/17	maa 24/04/17	25	Alba;Jelle;Lisette;Michiel
27			*Energy balance: different situations*	*0 dagen*	*maa 24/04/17*	*maa 24/04/17*	*26*	*Alba;Jelle;Lisette;Michiel*
28			**State of the art**	**3 dagen**	**vri 17/02/17**	**woe 22/02/17**		
29			Nordic climate analysis	3 dagen	vri 17/02/17	woe 22/02/17	12	Michiel
30			**Deliverables**	**55 dagen**	**maa 13/03/17**	**vri 19/05/17**		
31			Documentation different processes	11,43 dagen	maa 13/03/17	maa 27/03/17	10	Saskia
32			Creating powerpoint presentation	4,57 dagen	maa 27/03/17	vri 31/03/17	23	Alba;Jelle;Lisette;Michiel;Saskia
33			*Powerpoint presentation finished*	*0 dagen*	*vri 31/03/17*	*vri 31/03/17*	*32*	*Alba;Jelle;Lisette;Michiel;Saskia*
34			Midterm presentation	1 dag	vri 31/03/17	maa 3/04/17	33	Alba;Andreas;Jelle;Lisette;Michiel;Saskia
35			Discussion about the midterm presentation	1 dag	maa 3/04/17	din 4/04/17	34	Alba;Jelle;Lisette;Michiel;Saskia
36			Documentation energy balances	16 dagen	din 4/04/17	maa 24/04/17	35	Saskia
37			Documentation the final report	11 dagen	maa 24/04/17	maa 8/05/17	36;27	Alba;Jelle;Lisette;Michiel;Saskia
38			Creating final presentation	5 dagen	maa 8/05/17	vri 12/05/17	37	Alba;Jelle;Lisette;Michiel;Saskia
39			Practising presentation	5 dagen	vri 12/05/17	don 18/05/17	38	Alba;Jelle;Lisette
40			***Final presentation***	***0 dagen***	***vri 19/05/17***	***vri 19/05/17***	***39***	***Alba;Andreas;Jelle;Lisette;Michiel;Saskia***

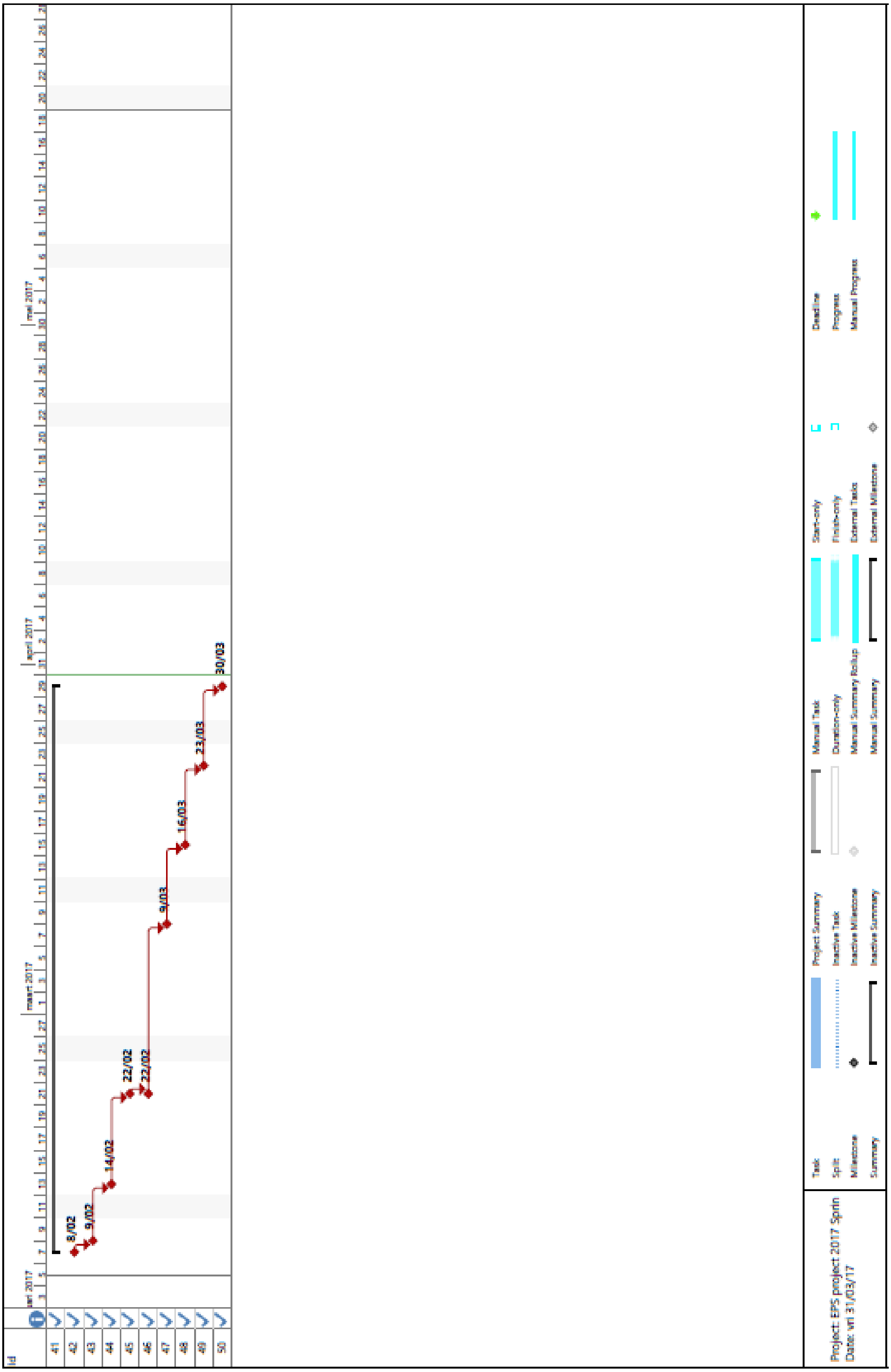
2/4

Id		Taa	Task Name	Duur	Begindatum	Einddatum	Voorafgaande taken	Resourcenamen
41			**Meetings**	**41,14 dagen**	**woe 8/02/17**	**don 30/03/17**		
42			Meeting 1	0 dagen	woe 8/02/17	woe 8/02/17		Alba;Andreas;Jelle;Lisette;Michiel;Saskia
43			Lecture about algae	0 dagen	don 9/02/17	don 9/02/17	42	Alba;Andreas;Jelle;Lisette;Michiel;Saskia
44			Meeting 2	0 dagen	din 14/02/17	din 14/02/17	43	Alba;Andreas;Jelle;Lisette;Michiel;Saskia
45			Meeting 3	0 dagen	woe 22/02/17	woe 22/02/17	44	Alba;Andreas;Jelle;Lisette;Michiel;Saskia
46			Meeting 4	0 dagen	woe 22/02/17	woe 22/02/17	45	Alba;Andreas;Jelle;Lisette;Michiel;Saskia
47			Meeting 5	0 dagen	don 9/03/17	don 9/03/17	46	Alba;Andreas;Jelle;Lisette;Michiel;Saskia
48			Meeting 6	0 dagen	don 16/03/17	don 16/03/17	47	Alba;Andreas;Jelle;Lisette;Michiel;Saskia
49			Meeting 7	0 dagen	don 23/03/17	don 23/03/17	48	Alba;Andreas;Jelle;Lisette;Michiel;Saskia
50			Meeting 8	0 dagen	don 30/03/17	don 30/03/17	49	Alba;Andreas;Jelle;Lisette;Michiel;Saskia

3/4



4/4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Project: EPS project 2017 Sprin
Date: vri 31/03/17

Appendix III: Potential of different species of microalgae as a viable production of biogas

Microalgae species	C/N Ratio	Methane yield	Loading rate
Arthrospira maxima	4.3–5.33	173 mL g^{-1} VS	500 mg/TS/L
Arthrospira platensis	N/R	481 mL g^{-1} VS	2000 mg/TS/L
Blue green algae	N/R	366 mL g^{-1} VS	281.96 mg/VS/L
Chlamydomonas reinhardtii	N/R	587 mL g^{-1} VS	2000 mg/TS/L
Chlorella kessleri	N/R	335 mL g^{-1} VS	2000 mg/TS/L
Chlorella sp., Pseudokirchneriella sp. and Chlaqmydomas sp.	N/R	0.28–0.60 m^3/kg/VS	402 mg VS
Chlorella sp., Scenedesmus, Euglena and Oscillatoria	N/R	300–800 mL g^{-1} VS	N/R
Chlorella sp., Scenedesmus	N/R	170–320 mL g^{-1} VS	1.44–2.89 g/VS/L
Chlorella sorokiniana	N/R	212 mL g^{-1} VS	N/A
Chlorella vulgaris	N/R	403 mL g^{-1} VS	2 g/VS/L
Chlorella vulgaris	N/R	286 mL g^{-1} VS	5000 mg/VS/L
Chlorella vulgaris	6	240 mL g^{-1} VS	1000 mg/VS/L
Chlorella vulgaris	N/R	189 mL g^{-1} VS	N/R
Chlorella vulgaris	N/R	0.40–0.45 L	2677–6714 mg (COD)
Dunaliella	N/R	440 mL g^{-1} VS	910 mg/VS/L
Dunaliella salina	N/R	505 mL g^{-1} TS	2000 mg/TS/L
Dunaliella tertiolecta	N/R	24 mL g^{-1} VS	5000 mg/VS/L
Durvillea Antarctica	N/R	492 mL g^{-1} VS	3000 mg/dry/TS/d
Euglena gracilis	N/R	485 mL g^{-1} VS	2000 mg/TS/L
Lake Chaohu natural population consortium	N/R	295 mL g^{-1} VS	N/R
Macroystis pyrifera and Durvillea Antartica(50% blend)	N/R	540 mL g^{-1} VS	3000 mg/dry/TS/d
Macroystis pyrifera	N/R	545 mL g^{-1} VS	3000 mg/dry/TS/day
Microcystis sp.	N/R	70.33–153.51 ml	1500–6000 mg/VS
Nannochloropsis oculata	N/R	204 mL g^{-1} VS	N/R
Nannochloropsis salina (lipid extracted biomass)	4.4	130 mL g^{-1} VS	2000 mg/l/VS
Phaeodactylum tricornutun	N/R	0.35 L g^{-1} COD	1.3 ± 0.4–5.8 ± 0.9
Scenedesmus obliquus	N/R	287 mL g^{-1} VS	2000 mg/TS/L
Scenedesmus obliquus	N/R	240 mL g^{-1} VS	2000 mg/VS/L
Scenedesmus sp.	N/R	170 mL g^{-1} COD	1000 mg/COD/L
Scenedesmus sp. (single stage)	N/R	290 mL g^{-1} VS	18,000 mg/VS/L
Scenedesmus sp. (two stage) Note: 46 mL/g/VS Hydrogen	N/R	354 mL g^{-1} VS	18,000 mg/VS/L
Scenedesmus sp. *and Chlorella* sp.	N/R	16.3–15.8 ft^3	7.8–9.2 ft^3/lb (VS)
Scenedesmus sp. *and Chlorella* sp.	6.7	143 mL g^{-1} VS	4000 mg/VS/L
Spirulina Leb 18	N/R	0.79 g/L	72,000 mg/L/TS
Spirulina maxima	4.16	0.35–0.80 m^3	20–100 kg/m^3 (VS)
Spirulina maxima	N/R	320 mL g^{-1} VS	910 mg/VS/L
Spirulina maxima	N/R	330 mL g^{-1} VS	22,500 mg/VS/L
Spirulina platensis UTEX1926	N/R	0.40 m^3 kg	N/R
Tetraselmis	7.82	0.25–0.31 L g^{-1} VS	2000 mg/VS
C/N ratio-[127]			
Waste water grown community	N/R	497 mL g^{-1} TS	2.16 g/L/TS
Zygogonium sp.	N/R	344 mL g^{-1} TS	N/R

Methane production from the anaerobic digestion of microalgae biomass reported in scientific literature. (Ward, Lewis, & Green, 2014)

Appendix IV: Theoretical methane potential of different algae species

Species	Carbon	Hydrogen	Nitrogen	Oxygen	Calculated methane potential (ml/g/VS)
Chlorogloeopsis fritschii	54.4 ± 2.1	6.9 ± 0.5	7.3 ± 0.3	31.4	309
Spirulina platensis	55.7 ± 0.4	6.8 ± 0.1	11.2 ± 0.1	26.4	319
Chlorella vulgaris	52.6 ± 0.8	7.1 ± 0.1	8.2 ± 0.2	32.2	283
Scenedesmus dimorphus	53.4 ± 0.6	7.8 ± 0.2	7.9 ± 0.1	31.0	260
Wastewater consortium	49.4 ± 0.1	6.7 ± 0.1	9.3 ± 0.2	21.6	347
Wastewater consortium (lipid extracted)	45.9 ± 1.9	6.2 ± 0.1	9.3 ± 0.9	23.6	303
Nannochlorospsis sp. (lipid extracted)	49.7	7.1	5.8	26.7	340
Nannochlorospsis sp.	47.6	6.6	5.5	21.7	383
Nannochlorospsis sp. (low lipid)	52.0	7.5	4.8	22.4	414
Nannochlorospsis sp. (high lipid)	51.5	7.3	4.5	22.4	414

Biochemical analysis of microalgae species and their theoretical methane potential calculated from the mean carbon, nitrogen and oxygen values. (Ward, Lewis, & Green, 2014)

Appendix V: AFDW content for microalgae species

Species	Fresh or saltwater	VS and AFDW as % of TS
Arthrospira maxima	Brackish	80–93%
Blue green algae	Fresh	94%
Chorella vulgaris	Fresh	93%
Chorella vulgaris	Fresh	90%
Chlorogloeopsis fritschii	Salt	92%
Dunaliella sp.	Saltwater	82%
Isochrysis galbana	Saltwater	86%
Nannochloropsis oculata	Saltwater	45%
Nannochloropsis salina	Fresh	77%
Nannochloropsis sp.	Saltwater	93%
Nitzschia closterium	Saltwater	78%
Phaeodactylum tricornutum	Fresh	82%
Porphyridium cruentum	Saltwater	91%
Scenedesmus dimorphus	Fresh	88%
Scenedesmus obliquus	Fresh	72%
Scenedesmus sp.	Fresh	60%
Spirulina maxima	Saltwater	86%
Spirulina platensis	Salt	92%
Spirulina platensis	Fresh	93%
Wastewater consortium	Fresh	88%
Wastewater consortium (lipid extracted)	Fresh	86%

The volatile solids or ash free fry weights (AFDW) as a percentage of the total solids (TS) reported for microalgae species (A.J. Ward, 2013)

Appendix VI: Methane gas production during AD for *Chlorella Vulgaris*

Temperature [°C]	Pretreatment	CH_4 production [l CH_4/kg oDM]
35	None	197 - 337
35	Ultrasound: 0; 19; 56; 146; 290 Wh/l	230; 235; 240; 280; 340
35	French press: 0; 35; 69; 104 bar	280; 290; 375; 400
35	Enzymatically[1)], T=35, 20h	362
35	Enzymatically[1)], T=45, 20h	435
55	None	414-475

Methane gas production during the anaerobic degradation of *Chlorella Vulgaris* with different pre-treatment techniques and temperatures in batch investigations at the Hamburg University of Technology. (Ras, 2010)

Appendix VII: Philips datasheet of the LED lighting

Specifications

The right colors for your growing needs

The GreenPower LED production module is available in the different colors that a plant can use most effectively at the different stages of its development:

Blue (B)	positive effects on compactness and hardening
White (W)	working light / full spectrum
Deep red (DR)	most efficient for photosynthesis, vegetative reproduction and stimulating shoot development
Far red (FR)	positive effect on generative properties, flower formation and rooting

Product name	Power*	Photon flux	Ordering code	
	W	Micromol/s **	12NC (global)	6NC (NAM)
Deep Red/Blue – DR/B				
GP LED production DR/B 120 LB	23	50	9290 009 08806	301887
GP LED production DR/B 120 LB LO	12	25	9290 009 09006	303321
GP LED production DR/B 150 LB	29	62.5	9290 009 08906	301895
GP LED production DR/B 150 LB LO	15	31	9290 009 10006	303339
GP LED production DR/B 120 MB	23	50	9290 009 43106	303289
GP LED production DR/B 120 MB LO	12	25	9290 009 43506	303347
GP LED production DR/B 150 MB	29	62,5	9290 009 43206	303297
GP LED production DR/B 150 MB LO	15	31	9290 009 43606	303354
GP LED production DR/B 120 HB	23	50	9290 009 43306	303305
GP LED production DR/B 120 HB LO	12	25	9290 009 09806	303388
GP LED production DR/B 150 HB	29	62,5	9290 009 43406	303313
GP LED production DR/B 150 HB LO	15	31	9290 009 09906	303396
Deep Red/Blue/ Far Red (when far red is required) – DR/B/ FR				
GP LED production DR/B/FR 120 LB	23	50	9290 009 09106	301903
GP LED production DR/B/FR 150 LB	29	62.5	9290 009 09206	301911
GP LED production DR/B/FR_2 120 MB	23	50	9290 009 10106	301929
GP LED production DR/B/FR_2 150 MB	29	62.5	9290 009 09306	301945
GP LED production DR/B/FR_3 120 MB	23	50	9290 009 43706	303404
GP LED production DR/B/FR_3 150 MB	29	62.5	9290 009 43806	303412
GP LED production DR/B/FR_4 120 HB	23	50	9290 009 43906	303420
GP LED production DR/B/FR_4 150 HB	29	62.5	9290 009 44006	303495
Deep Red/White (if work light is needed) – DR/W				
GP LED production DR/W 120 LB	24	50	9290 009 09506	301952
GP LED production DR/W 120 LB LO	12	25	9290 009 09406	303511
GP LED production DR/W 150 LB	30	62.5	9290 009 09606	301960
GP LED production DR/W 150 LB LO	15	31	9290 009 10206	303529
Deep Red/White/ Far Red – DR/ W/FR				
GP LED production DR/W/FR 120 LB	24	50	9290 009 09706	301978
GP LED production DR/W/FR 150 LB	30	62.5	9290 009 10306	302018
Monocolors				
GP LED production DR 120	23	50	9290 009 44106	303537
GP LED production DR 150	29	62,5	9290 009 44206	303545
GP LED production FR 120	24	50	9290 009 44306	303578
GP LED production FR 150	30	62,5	9290 009 44406	303586
GP LED production B 120 LO	15	25	9290 009 44506	303594
GP LED production B 150 LO	18	31	9290 009 44606	303602
Accessory				
GP LED prod module female connector			9290 009 70106	302026
GP LED Cabletree production module			9290 009 93006	

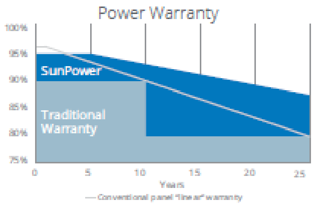
* Typically at 230 V / ** Typically at 25 °C / 77 °F ambient

The properties of the different LED lighting systems. (Philips, 2017)

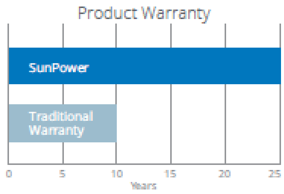
Appendix VIII: Datasheet Sunpower X22-360

SunPower® X-Series Residential Solar Panels | X22-360

SunPower Offers The Best Combined Power And Product Warranty



More guaranteed power: 95% for first 5 years, −0.4%/yr. to year 25 [7]



Combined Power and Product defect 25-year coverage that includes panel replacement costs [8]

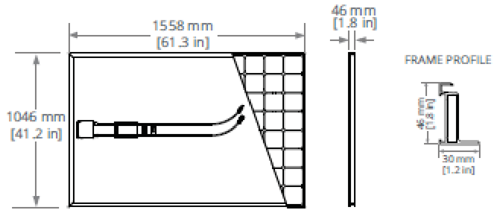
Electrical Data	SPR-X22-360
Nominal Power (Pnom)[11]	360 W
Power Tolerance	+5/-0%
Avg. Panel Efficiency[12]	22.2%
Rated Voltage (Vmpp)	60.6 V
Rated Current (Impp)	5.94 A
Open-Circuit Voltage (Voc)	69.5 V
Short-Circuit Current (Isc)	6.48 A
Max. System Voltage	600 V UL & 1000 V IEC
Maximum Series Fuse	15 A
Power Temp Coef.	–0.30% / ° C
Voltage Temp Coef.	-167.4 mV / ° C
Current Temp Coef.	3.5 mA / ° C

REFERENCES:

1 All comparisons are SPR-X21-345 vs. a representative conventional panel: 250 W, approx. 1.6 m², 15.3% efficiency.
2 Typically 8–10% more energy per watt, BEW/DNV Engineering "SunPower Yield Report," Jan 2013.
3 SunPower 0.25%/yr degradation vs. 1.0%/yr conv. panel. Campeau, Z. et al. "SunPower Module Degradation Rate," SunPower white paper, Feb 2013; Jordan, Dirk "SunPower Test Report," NREL, Q1-2015.
4 "SunPower Module 40-Year Useful Life" SunPower white paper, May 2015. Useful life is 99 out of 100 panels operating at more than 70% of rated power.
5 Highest of over 3,200 silicon solar panels, Photon Module Survey, Feb 2014.
6 1% more energy than E-Series panels, 8% more energy than the average of the top 10 panel companies tested in 2012 (151 panels, 102 companies), Photon International, Feb 2013.
7 Compared with the top 15 manufacturers. SunPower Warranty Review, May 2015.
8 Some restrictions and exclusions may apply. See warranty for details.
9 X-Series same as E-Series, 5 of top 8 panel manufacturers tested in 2013 report, 3 additional panels in 2014. Ferrara, C., et al. "Fraunhofer PV Durability Initiative for Solar Modules: Part 2". Photovoltaics International, 2014.
10 Compared with the non-stress-tested control panel. X-Series same as E-Series, tested in Atlas 25+ Durability test report, Feb 2013.
11 Standard Test Conditions (1000 W/m² irradiance, AM 1.5, 25° C). NREL calibration Standard: SOMS current, LACCS FF and Voltage.
12 Based on average of measured power values during production.
13 Type 2 fire rating per UL1703:2013, Class C fire rating per UL1703:2002.
14 See salesperson for details.

Tests And Certifications	
Standard Tests[13]	UL1703 (Type 2 Fire Rating), IEC 61215, IEC 61730
Quality Certs	ISO 9001:2008, ISO 14001:2004
EHS Compliance	RoHS, OHSAS 18001:2007, lead free, REACH SVHC-163, PV Cycle
Sustainability	Cradle to Cradle (eligible for LEED points)[14]
Ammonia Test	IEC 62716
Desert Test	10.1109/PVSC.2013.6744437
Salt Spray Test	IEC 61701 (maximum severity)
PID Test	Potential-Induced Degradation free: 1000 V[9]
Available Listings	UL, TUV, JET, CEC

Operating Condition And Mechanical Data	
Temperature	–40° F to +185° F (–40° C to +85° C)
Impact Resistance	1 inch (25 mm) diameter hail at 52 mph (23 m/s)
Appearance	Class A+
Solar Cells	96 Monocrystalline Maxeon Gen III
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-65, MC4 compatible
Weight	41 lbs (18.6 kg)
Max. Load	Wind: 62 psf, 3000 Pa, 305 kg/m² front & back Snow: 125 psf, 6000 Pa, 611 kg/m² front
Frame	Class 1 black anodized (highest AAMA rating)



Please read the safety and installation guide.

The properties of the SunPower X22-360 solar panels. (SunPower, 2017)

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European Project Semester, spring 2017
Novia University of Applied Sciences, Vaasa

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